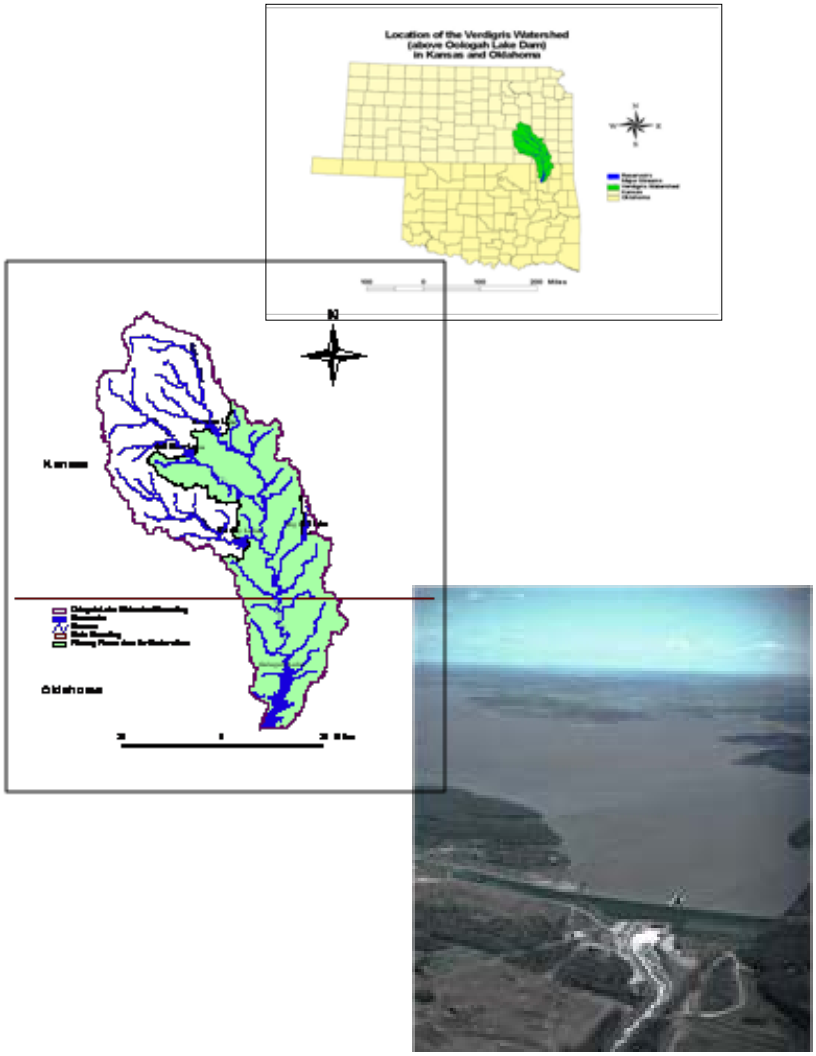
Responses to Climate Change

Utilization of Regional Climate Science Programs in Reservoir and Watershed Risk-Based Assessments

Pilot Study



30 October 2014

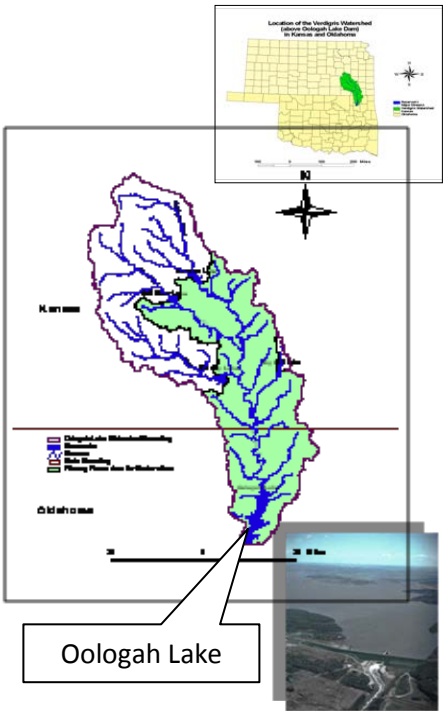
Executive Summary

Utilization of Regional Climate Science Programs in Reservoir and Watershed Risk-Based Assessments

Background and Summary of Study Activities

One-hundred-and-seventeen of the more than 600 multi-purpose USACE reservoir projects include storage for water supply. Collectively they provide enough water to supply the average household needs of about 85 million Americans for a year. Our changing climate will increase the criticality of effectively managing these national water assets for future generations.

Approaches to assessing climate change risks are generally classified as either "top-down" modeling assessments or "bottom-up" threshold analyses (e.g. Miller and Yates, 2006; Freas et al., 2008; Stratus Consulting and MWH Global, 2009). However, it should be noted that these two approaches are not mutually exclusive and water managers often incorporate elements of both, either in series or in parallel.



The study area is the Oologah Lake and watershed in Northeast Oklahoma and Southeast Kansas. The pilot study team's "top-down" approach utilized climate projection data sets, provided by the University of Oklahoma (OU), to evaluate potential future: 1) reservoir yield and water quality, and 2) soil and water conditions in the watershed. OU's climate subject matter experts (SMEs) are affiliated with multiple federal programs. The pilot, therefore, provided a proof-of-concept demonstration of how the U.S. Army Corps of Engineers can utilize climate projection data sets, developed by other federal/university programs associated with the National Oceanic and Atmospheric Administration and the Department of Interior Climate Science Centers, in water resource study activities. Details of the Oologah Lake watershed reservoir yield and soil and water conditions assessments are documented in Technical Supplements 1 and 2. The following is a summary of tentative results:

Reservoir Yield Analysis

- All 112 ensemble projections were in a consensus agreement that future conditions will be warmer over the Oologah Lake watershed, with a median increase in temperature among all models of +4.76˚F by the year 2050.

- No consensus existed with respect to future precipitation trends in the Oologah Lake watershed. Half of the models in the ensemble projections predict an increase in annual rainfall by the year 2050, while the other half predicts a decrease in annual rainfall. Most of the models fall within a ± 10% range by the year 2050 based on current climatology.

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

- The Oologah Lake watershed receives (on average) approximately 10 inches of snowfall a year, which equates to 1-2 inches of liquid equivalent precipitation. Some of this precipitation may shift to rainfall.

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- The Variable Infiltration Capacity (VIC) model simulated inflow hydrograph exhibited good skill when replicating the critical period. The timing and duration of historical droughts, including the 1952-1957 drought of record, was generally correct.

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

- Most of the model ensemble projections suggests that firm yield will not change significantly over time.

- "Reconnaissance" level modeling from pre-existing U.S. Bureau of Reclamation climate-projection hydrographs has potential to advance SMART Planning initiatives. For this pilot the methodology exhibited skill in reproducing water supply trends from the "feasibility" level modeling but had higher magnitudes of firm yield.

- Stresses that were considered did not include increased demand from users. History has shown that demand increases during heat waves that are associated with droughts. The record use by the Tulsa Metropolitan Water Authority occurred in August 2011.

- Based on the modeling results, Oologah Lake appears to be well positioned to meet future water supply obligations, particularly since no future additional allocations are contracted.

Oologah Lake Watershed Analysis

- Application of watershed and reservoir simulation models in the evaluation of climate projections can provide insight into future expected conditions.

- Both watershed and reservoir models have detailed input requirements and need to be evaluated and assessed using measured data to determine relative accuracy.

- NARCCAP projections generally resulted in lower average annual runoff, and reduced vegetative biomass production.

- CMIP3 projections revealed consistent whole watershed outputs including reduced runoff, higher evapotranspiration, lower sediment export, and lower vegetative biomass production.

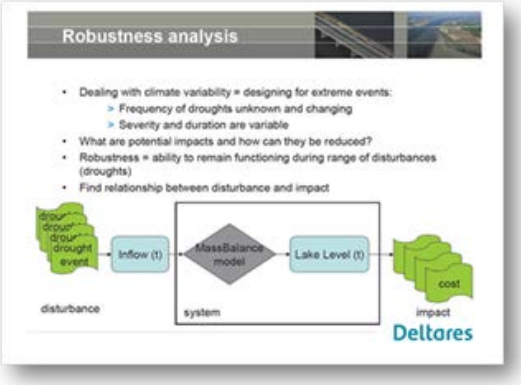
- Reservoir simulations comparing baseline and climate projections revealed reservoir water temperature increases, and dissolved oxygen concentration decreases.

- With respect to available 'optimal fish habitat', increasing water temperature and subsequent lower dissolved oxygen concentrations in all climate projections (compared to the baseline simulation), resulted in decreased whole-lake water volume, through the growing season, suitable for optimal fish activity.

Executive Summary

Utilization of Regional Climate Science Programs in Reservoir and Watershed Risk-Based Assessments

During the summer of 2013 the USACE Institute for Water Resources facilitated the participation of a Visiting Scholar who conducts research at Deltares. Deltares is an independent institute for applied research in the Netherlands. The Visiting Scholar, with support from IWR and Tulsa District SMEs, conducted a preliminary Oologah Lake "bottom-up" type assessment referred to as robustness analysis. The robustness analysis tentatively identified theoretical drought thresholds that could impact recreation and municipal and industrial water users. This research continued into the spring of 2014 through partial funding by the Netherland's Knowledge for Climate program and follow-on support by IWR and Tulsa District SMEs.



Potential Next Steps

Assuring the long-term sustainability of reservoirs that provide storage for water supply is becoming increasingly important and complex as infrastructure ages, sedimentation accumulates, climate changes, and financial needs outweigh budgets. Therefore, risk-based strategic planning that takes an Integrated Water Resources Management (IWRM) approach is necessary to effectively prioritize problems and identify step-wise approaches to implement solutions.

Regarding the climate change component of an IWRM approach, a step-wise process that mirrors the USACE dam and levee safety programs could be considered. A "Responses to Climate Change Screening Portfolio Risk Assessment (RCCSPRA) would help determine strategic long-term prioritized next steps associated with: 1) additional detailed investigations, 2) changes in management strategies, and 3) recapitalization strategies.

A potential next step would be a pilot demonstration of a RCCSPRA using selected reservoirs with water supply storage in a USACE District. The pilot would demonstrate the following conceptual 3 phase process:

1. Phase 1: Initial Portfolio Screening. Use existing information associated with each reservoir to determine how much of the available USACE water supply storage is contracted. Reservoirs with, say, 75% of the storage contracted would be considered for Phase 2 analysis. The assumption in the Phase 1 analysis is that reservoirs with less than 75% of the storage contracted would have sufficient contingency if the water supply would decrease and/or demands increase due to foreseeable future climate change.

2. Phase 2: Asset Prioritization. A "bottom – up" type assessment would identify an initial risk ranking for each of the reservoirs that were not screened out in the Phase 1 analysis. The risk Probability Factor would be based on robustness analysis, along with existing Bureau of Reclamation climate projection data. The robustness analysis would be based on interviews with contract holders and USACE SMEs. The risk Consequence Factor would be based on the population impacted by USACE M&I storage contracts. The assumptions are that the probability of populations being impacted by reservoirs that are less robust would be greater and the larger the population impacted by the contracted M&I water storage the greater the consequences.

3. Phase 3: Prioritized Climate Projection Analysis. A "top – down" type assessment would identify a refined risk ranking for the reservoirs that were not screened in the Phase 2 assessment:

   a. Develop hydrographs for each reservoir by simulating runoff from bias-corrected, spatially-disaggregated statistically downscaled climate projections with the Variable Infiltration Capacity (VIC) model. This data could potentially be developed by regional Department of Interior Climate Science

Utilization of Regional Climate Science Programs in Reservoir and Watershed Risk-Based Assessments Centers.

b. Use numerical routing to transform these hydrographs into long-term simulation of pool elevations so that droughts could be identified and the critical period for each could be determined.

c. Assign a priority rating to each reservoir based on the potential impacts to reservoir yield due to climate change: 1 Severe, 2 Moderate, 3 Low, 4 Negligible.

A graphical representation of the 3 Phase process is shown Figures 1-3. Following the Phase 3 assessment, a conceptual "Next Steps" framework concept strategy would be developed by SMEs and water supply storage customers.

Figure 1. 3 Phase Responses to Climate Change Screening Portfolio Risk Assessment (RCCSPRA)

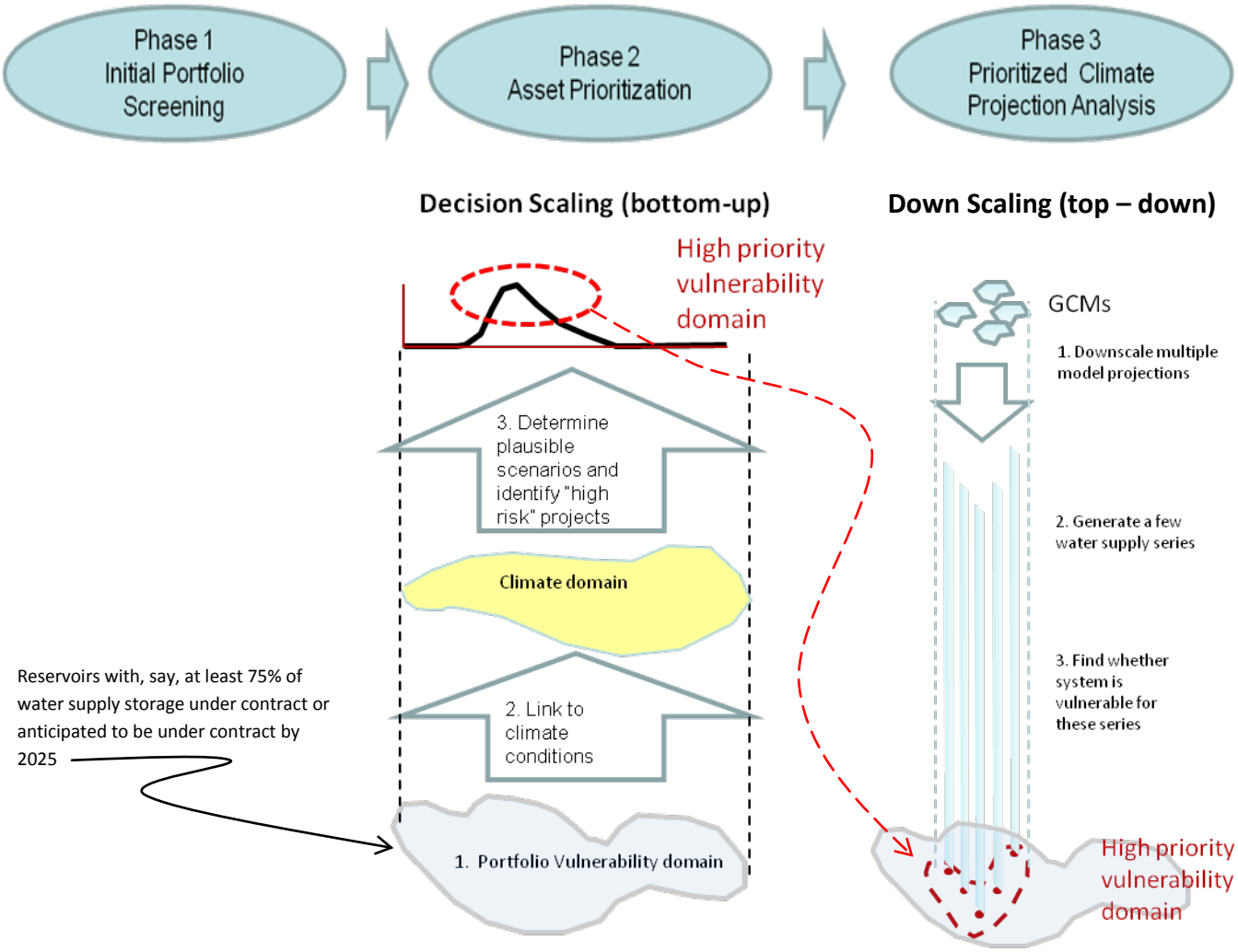
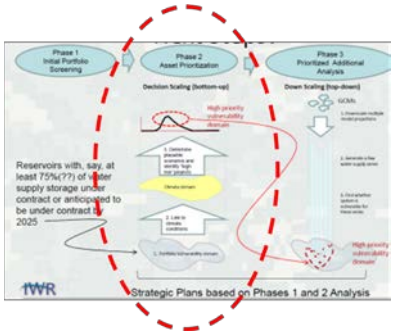
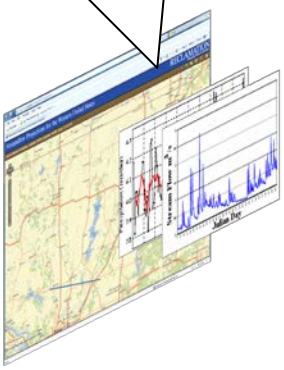
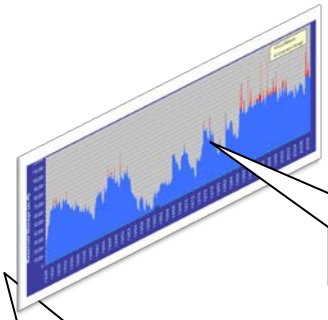


Figure 2. Phase 2 Asset Prioritization



Temperature and Precipitation Data associated with 112 climate projections from 16 statistically downscaled GCM's





Reservoir firm yield scenarios associated with future climate projections

1. "Reconnaissance" level modeling from pre-existing U.S. Bureau of Reclamation climate-projection hydrographs is conducted to identify climate change trends. The climate change trends information is used to identify a range of climate change thresholds used for the robustness analysis.

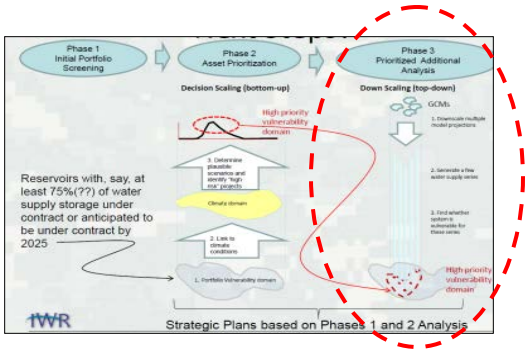
Robustness Analysis, based on user and USACE SME interviews and reconnaissance level climate change data is used to help develop a Probability Factor.

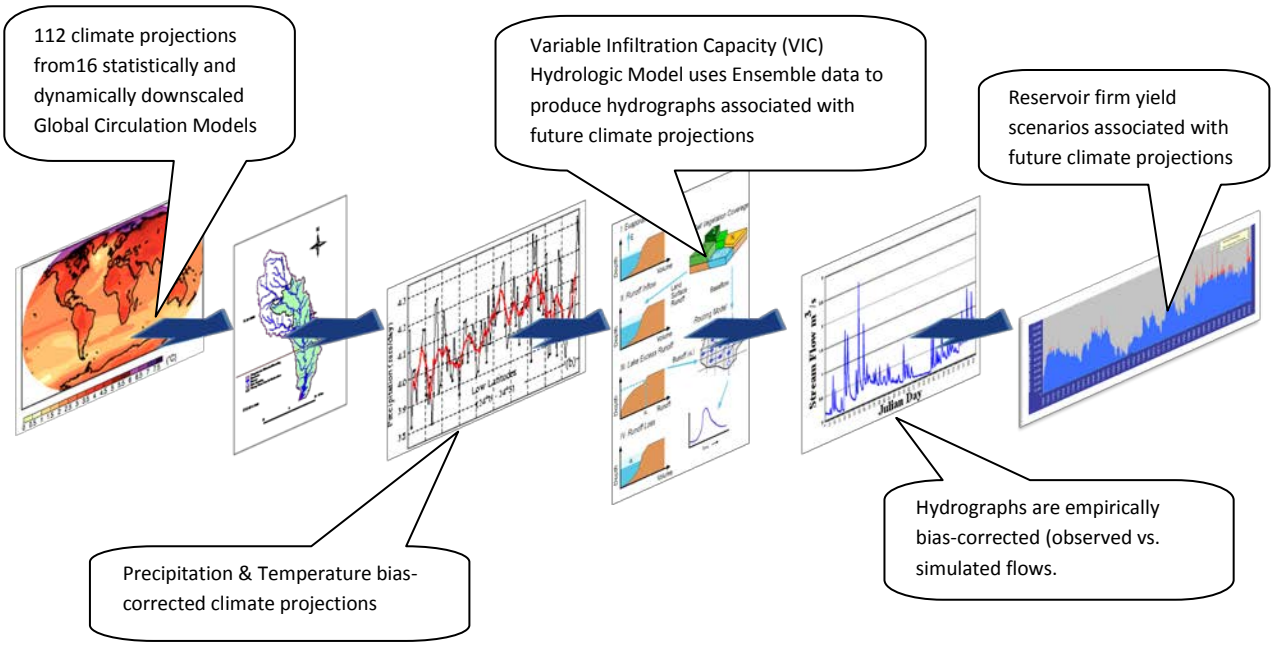
Consequence Factor is based on population impacted by USACE M&I storage contracts

Determination of Risk Rating

Probability Factor	Consequence Factor: High	Medium	Low	None
High	High	High	Medium	None
Medium	High	Medium	Low	None
Low	Medium	Low	Low	None
None	None	None	None	None

Figure 3. Phase 3 Prioritized Climate Projection Analysis





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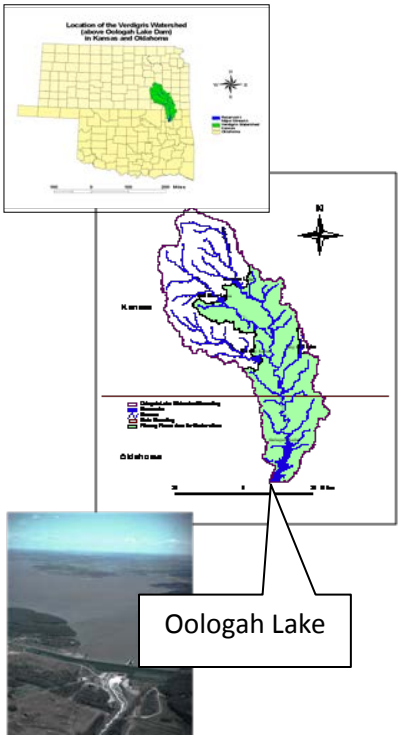
Technical Supplements

1 Water Supply Yield Modeling at Oologah Lake (Oklahoma) with Downscaled Climate Projections

2 Climate Change Analysis In the Verdigris River Watershed in Oklahoma and Kansas, And Oologah Lake, Using SWAT and CE-QUAL-W2

1. Background.

One-hundred-and-seventeen of the more than 600 multi-purpose USACE reservoir projects include storage for water supply. Collectively, they provide enough water to supply the average household needs of about 85 million Americans for a year. As we look to the future, the impacts of climate change will increase the criticality of effectively managing these national water assets for future generations. Recognizing these challenges, the goal of this pilot study is to demonstrate a sustainable local, tribal, state and Federal government risk management process associated with climate change impacts to evaluate potential future: 1) reservoir yield and water quality, and 2) soil and water conditions in the watershed. The Information generated during this process will help decision makers determine next planning steps. This pilot study could also serve as a template for other reservoirs and watersheds.



1.1 Study Area.

The study area is the Oologah Lake and watershed in Northeast Oklahoma and Southeast Kansas. Oologah Lake is located 27 miles northeast of Tulsa, Oklahoma, on the Verdigris River at river mile 90.2, in Rogers County, Oklahoma. The pilot study area encompasses approximately 2,335 square miles. The dam at Oologah Lake provides the southernmost terminus of the study area. The study area extends north-northwestward upstream of Oologah Lake along the Verdigris River and its tributaries to the northernmost end of the study, the dams at the four lakes upstream of Oologah Dam operated by the Tulsa District: Elk City Lake, Pearson-Skubitz Big Hill Lake, Fall River Lake, and Toronto Lake. The Verdigris River originates in the Flint Hills of Chase County, Kansas, and flows generally southeast from the vicinity of Madison to Neodesha, Kansas, and then in a southerly direction to its confluence with the Arkansas River, about 5 miles northeast of Muskogee, Oklahoma . The drainage area above Oologah Dam is elliptical, covers 4,339 square miles, and is approximately 100 miles long and 45 miles wide. Of the total drainage area above Oologah Dam, approximately 77% (3,354 square miles) is situated in Kansas with the remaining 23% (985 square miles) situated in Oklahoma.

1.2 Current Climate.

Climate in the study area is influenced by its position within the interior of the continent. Hot continental summers and cool winters are characteristic of this region. Mean temperatures in January range from a minimum of 22 degrees Fahrenheit (°F) to a maximum of 45°F, with mean summer temperatures ranging from 68°F to a maximum mean of 91°F. Mean annual precipitation is 44 to 45 inches.

1.3 Current Problem/Concern.

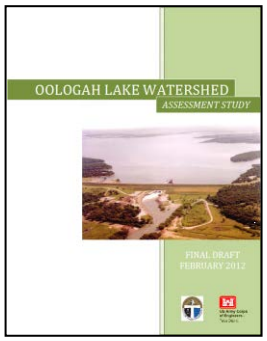
Oologah Lake is an important water supply source for the City of Tulsa and surrounding communities. It supplies approximately fifty percent of the potable water for the metropolitan area as well as to rural water suppliers throughout northeastern Oklahoma. Concerns have been expressed by the City of Tulsa and other Oklahoma agencies regarding potential habitat and water quality impairments related to sedimentation, turbidity (suspended sediment), and nutrient loading, especially from nitrogen and phosphorus. An additional concern is the long-term sustainability of the Lake Oologah firm yield (approximately 343k acre-feet or 154 mgd).

2. Purpose and Scope

2.1 Central Question Being Addressed and Methods Tested

The central question being addressed is: How can information from regional federal climate science programs be used in water resource model assessments and associated risk management decision making by local, tribal, state, and federal interests? What is the value of information from a detailed assessment compared to a reconnaissance-level assessment?

2.2 Previous Work that this Project Builds On.



The Oologah Lake Watershed Assessment study was conducted to identify potential causes of and solutions to impairment issues arising from the uncontrolled portions of the Verdigris River Basin upstream of Oologah Lake and in the Oologah Lake aquatic ecosystem. The City of Tulsa, in partnership with the Corps, seeks to understand what, if any, proactive measures could be implemented to restore and/or improve conditions in the lake and watershed before the lake aquatic environment degrades further and becomes both difficult and costly to restore, improve, and sustain. This Pilot Study builds on the Oologah Lake Watershed Assessment by addressing potential climate change scenarios. The climate data generated from this project was incorporated into an existing Soil and Water Assessment Tool (SWAT) and a water quality (CE-QUAL-W2) models developed as part of the Oologah Lake Watershed Assessment study.

This RCC project also builds upon climate change research associated with the 2012 Update of the Oklahoma Comprehensive Water Plan (OCWP) by "continuing the advancement of a thorough understanding of Oklahoma's climate and weather and the associated impacts on Oklahoma's water users and citizens." Results from this RCC project includes information from literature review associated with the following OCWP Climate Change study that was funded through the Bureau of Reclamation's 2011 WaterSMART Program: Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods.

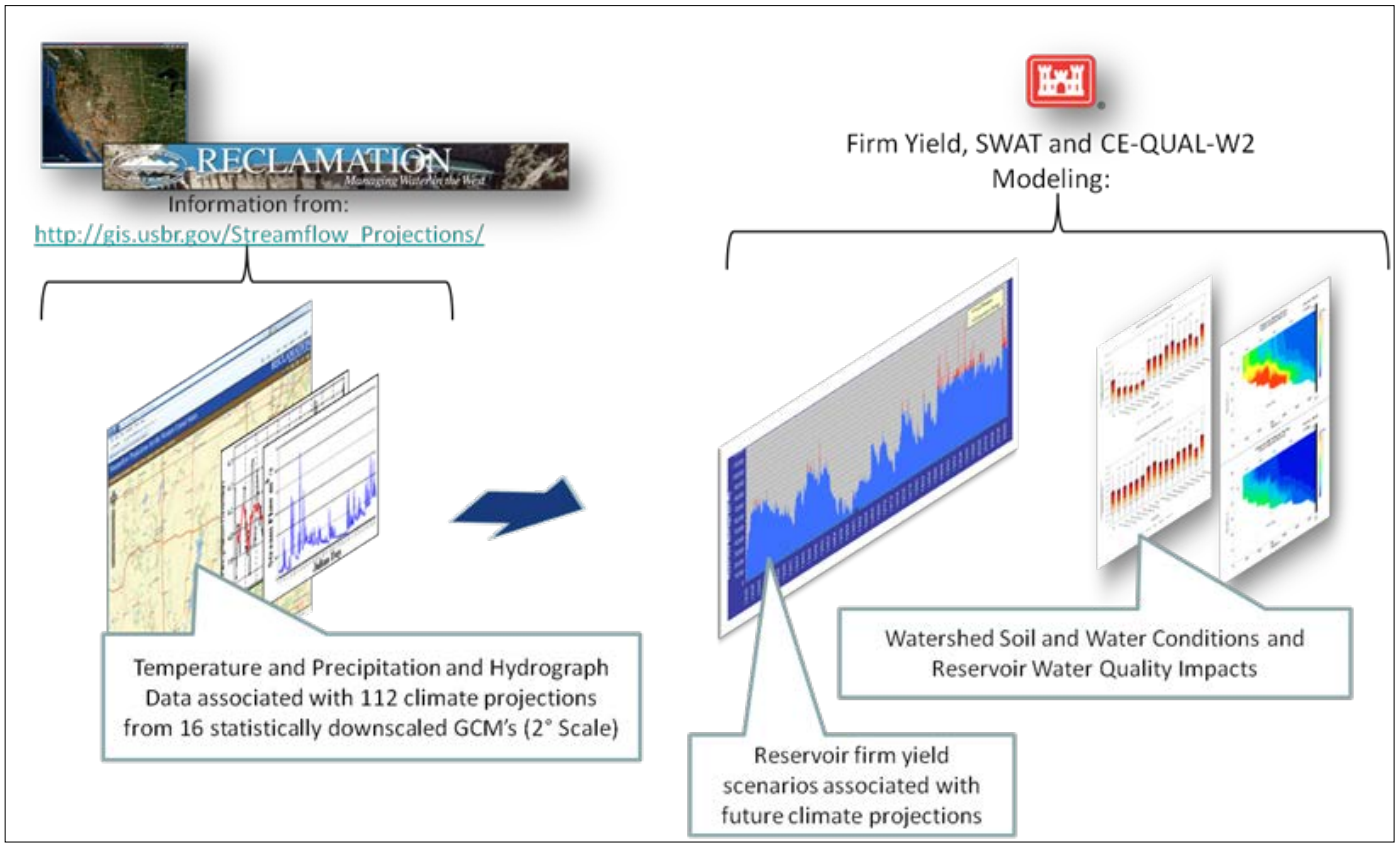
In the short-term, information from this project will provide planners and decision makers a concept of the sensitivity of changes in sediment and nutrient loading and reservoir yield to various climate change scenarios associated with the Verdigris River watershed. The long-term benefit of this project is the identification of a collaborative multi-organization science-based process that is repeated as climate science advances.

3. Methodology / Approach

The pilot study demonstrated a Western States Federal Agency Support Team (WestFAST) field-level approach to applying climate science by leveraging regional federal programs. The WestFAST is a collaborative initiative between federal agencies with water management responsibilities in the West. WestFAST was created to support the Western States Water Council and Western Governors' Association, regarding water resources. Programs included NOAA's Southern Climate Impacts Planning

Program (SCIPP) and DOI's South-Central Climate Science Center at the University of Oklahoma. Because the understanding of potential issues associated with climate change is important to many interests the pilot study also included collaboration with other local, tribal, state, Federal and NGO stakeholders.

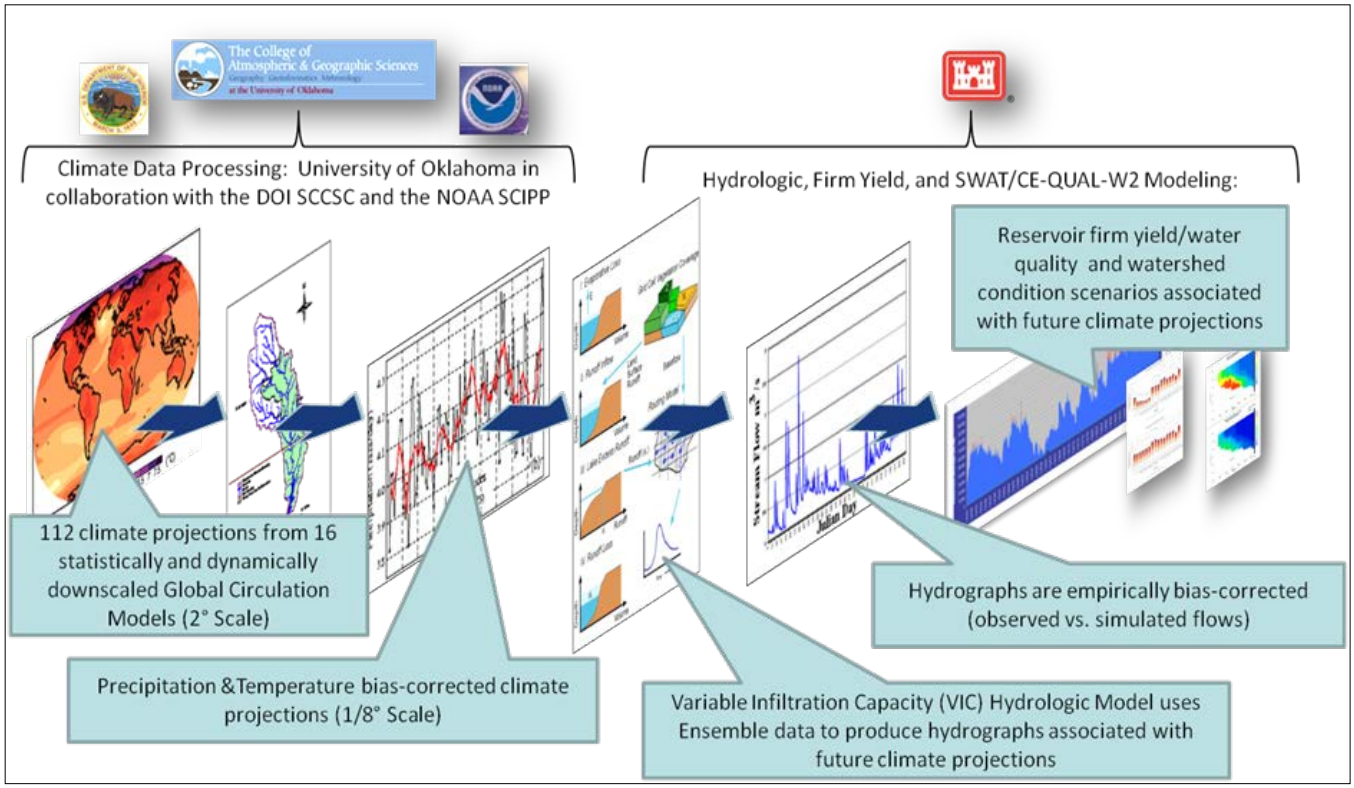
The Phase 1 Assessment of the pilot demonstrated a "reconnaissance" or "state water plan" level of detail by utilizing existing streamflow projections developed by the U.S. Bureau of Reclamation for western states. This information is located at: http://gis.usbr.gov/Streamflow_Projections/. A graphic illustration of the Phase 1 Assessment is shown below.



Phase 2 of the pilot provided an example of a more detailed or "feasibility" level approach to evaluate climate change impacts to reservoir yield and water quality and soil and water conditions in the watershed. Climate projection datasets were collected, using a variety of global climate models, regional climate models and statistical downscaling. Data for each climate model and statistically downscaled dataset were compared to observed conditions. "Ensembles" of future projections were then developed. The Variable Infiltration Capacity (VIC)[1] model was benchmarked with a historical dataset, and then the ensembles were run through VIC to provide output for incorporation into existing Lake Oologah and watershed models. Output included time-series hydrographs for a 50-year planning

[1] Refer to: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml

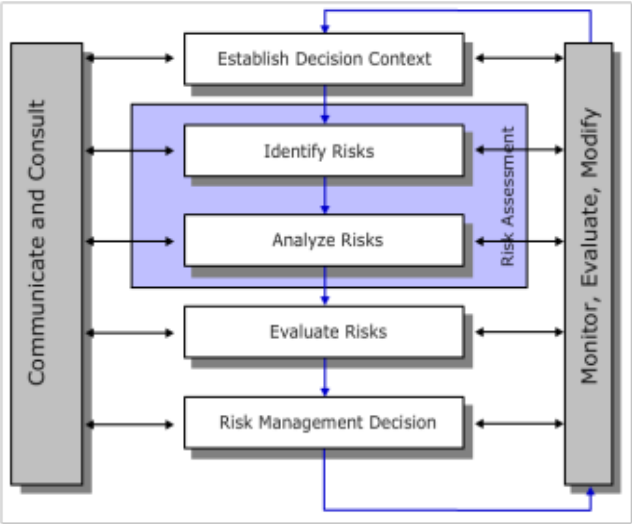
horizon that was used for watershed and reservoir simulation and yield studies. The following graphic illustrates the Phase 2 Assessment.



Phase 1 and Phase 2 results were compared to each other to help determine the value of the information added by investing additional time and money required for the Phase 2 "feasibility" level approach. Details of the Phase 1 and 2 analyses are shown in Technical Supplements 1 and 2.

Integrated with these activities was the initial concept application of the USACE 5-step "Risk Informed Decision Making Process".

1. Establish Decision Context
2. Identify Risks
3. Analyze Risks and Formulate Plans
4. Evaluate Risks
5. Risk Management Decision



3.1 The Decision Context.

This step includes leveraging information from multiple resources to identify: a) potential risks, b) measurable objectives, c) decision making criteria, d) evident uncertainties, and e) questions to be answered in subsequent steps. The primary information resources included the Oologah Lake Watershed Assessment Study; existing climate change research accomplished by the Oklahoma Climatological Survey (OCS), including research under the NOAA-funded Southern Climate Impacts Planning Program (SCIPP); and the climate change assessments previously described.

3.1.1 Potential Risks (Problems and Opportunities) and Objectives

Oologah Lake is an important water supply source for the City of Tulsa and surrounding communities. It supplies approximately fifty percent of the potable water for the metropolitan area as well as to rural water suppliers throughout northeastern Oklahoma. Concerns have been expressed by the City of Tulsa and other Oklahoma agencies regarding potential habitat and water quality impairments related to sedimentation, turbidity (suspended sediment), and nutrient loading, especially from nitrogen and phosphorus. City officials, in applying some lessons learned from issues and actions at their other reservoir system supplying the other half of their potable water, adopted a pro-active approach to management activities

at Oologah Lake to determine what, if any, pre-emptive cost-effective actions would prevent the same issues experienced at their other reservoir system from happening at Oologah Lake.

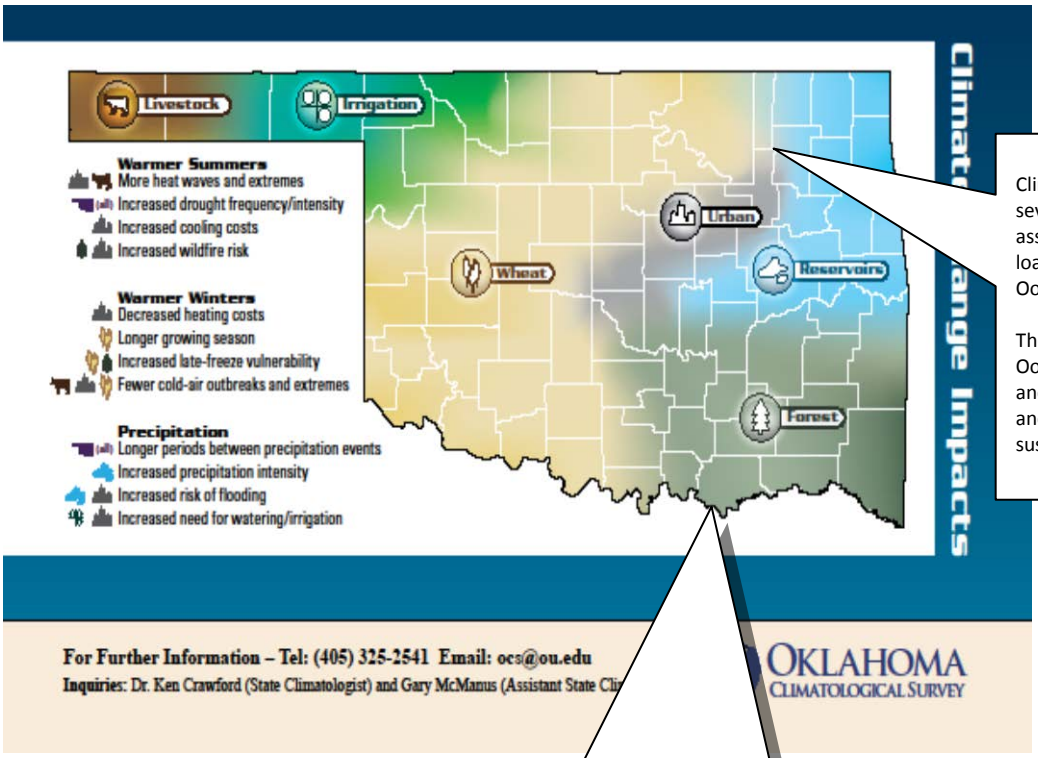
Repeated occurrences of lake-wide algae blooms at the City's other water source had increased substantially and severely impacted water quality, thereby requiring modifications to water treatment processes to mitigate the effects of excessive nutrient loading and reduce taste and odor issues. These impairments became severe enough that litigation became necessary to correct the problems and reduce the contaminants reaching those lakes. The litigation process is costly and can delay measures to improve water supply systems. Through the initiation of the Oologah Lake Watershed Assessment, potential sources of impairments were identified and evaluated, with the possibility of identifying future pre-emptive actions that could reduce the likelihood that severe problems would be encountered at Oologah Lake.

The science-based approach used in Lake Oologah Lake Watershed Assessment utilized linked watershed and lake models capable of simulating: (1) effects of watershed restoration efforts on the transport of habitat-degrading substances from the uncontrolled portions of the watershed to Oologah Lake and (2) the resulting habitat response in Oologah Lake. Accordingly, the scope of study involved considerable efforts of data collection and development of this planning tool for evaluating site-specific "base-line" conditions, based on historical climate information, in the study area.

Potential Impacts of Climate Change in the Lake Oologah Watershed

The complexity of Oklahoma's water environment results, in part, from the type of precipitation that occurs across the state. Much of Oklahoma's precipitation is convective in nature, resulting in isolated thunderstorms, lines of complexes of multiple thunderstorms, and embedded thunderstorms in winter low-pressure systems. These convective events result in river floods, flash floods, significant ice storms, and the occasional blizzard. On the other end of the water-supply spectrum are seasonal to multi-year droughts. The OCS expects the following climate change scenarios and the associated impacts in Oklahoma to be realistic should the projected range of warming materialize for the remainder of the 21st century:

- The warm season becomes longer and arrives earlier.
- The cool season warms and shortens which leads to a longer frost-free period and growing season.
- Earlier maturation of winter wheat and orchard crops leave them more vulnerable to late freeze events.
- Increased year-round evaporation from the ground and transpiration from green vegetation
- Drought frequency and severity increases, especially during the summer.
- Drier and warmer conditions will increase the risk of wildfires.
- Rain-free periods will lengthen, but individual rainfall events will become more intense.
- More runoff and flash flooding will occur.



Potential Problems and Opportunities
Climate change could potentially increase the severity of existing water resources problems associated with sediment and nutrient loading, reservoir yield, sustainability of Lake Oologah, and other related problems.

There are long-term opportunities n the Oologah Lake watershed to implement robust and adaptive solutions that address sediment and nutrient loading, reservoir yield, reservoir sustainability, and other related problems

Potential Problems and Opportunities

Climate change could potentially increase the severity of existing water resources problems in the Oologah Lake watershed associated with sediment and nutrient loading, reservoir yield, sustainability of Lake Oologah, and other related problems.

There are long-term opportunities in the Oologah Lake Watershed to implement robust and flexible solutions that address sediment and nutrient loading, reservoir yield, reservoir sustainability, and other related problems.

The following provides a discussion that relates the goals, problems, opportunities and objectives of this Pilot Study.

The Oologah Lake Watershed Assessment was conducted to develop a science-based planning tool to compare management measures and identify basin-wide watershed strategies with two inter-related goals: 1) provide for the restoration of degraded habitat in the Verdigris River basin above Oologah Lake in Oklahoma and Kansas, and 2) provide for the restoration of the aquatic ecosystem of Oologah Lake via reduction of habitat-degrading substances transported from the watershed to the lake.

Recognizing that information will be updated in the future based on advances in climate science, long-term problems, opportunities, and objectives; along with interim Pilot Study objectives; are summarized in the following Table.

Potential Problems	Long-Term Opportunities	Long-Term Objectives	Pilot Study Interim Objectives Accomplished
In addition to existing conditions in the Lake Oologah watershed; increases in the frequency and severity of droughts, increases in sediment and nutrient loading associated with more severe storm events/runoff, increases in evaporation, and longer warm seasons could adversely affect: • aquatic and other ecosystems • water quality and water treatment costs • long-term dependable availability of water (yield) for municipal and industrial uses	There are long-term opportunities in the Oologah Lake Watershed to implement robust and flexible solutions, capable of adapting to a changing climate, that accomplish the following: • restore/improve aquatic and other ecosystems, • improve water quality, • control water treatment cost, • increase the life of Lake Oologah and its associated water supply storage capacity, and • assure cost-effective long-term sources and availability of municipal and industrial water for the City of Tulsa and surrounding communities.	• Continue collaborative locally-led planning processes, along with the use of the existing science-based planning tool, and take into account potential risks associated with climate change. • Develop a "shared vision" watershed management plan for the Lake Oologah watershed that is comprehensive, flexible and periodically updated based on new information.	*Demonstrate a Western States Federal Agency Support Team (WestFAST)[2] field-level approach to apply climate science by leveraging regional federal programs.* The College of Atmospheric and Geographic Sciences at the University of Oklahoma, working through National Oceanic and Atmospheric Administration's Southern Climates Impacts Planning Program and Department of Interior's South-Central Climate Science Center, provided data to develop a theoretical range of reservoir yield impact scenarios for Lake Oologah due to projected changes in climate. The climate data was utilized in existing SWAT and CE-QUAL-W2 models that were developed during the Oologah Lake Watershed Assessment study. Model outputs were used to help assess potential climate change impacts. Integrated with these activities will be the initial concept application of the USACE 5-step "Risk Informed Decision Making Process".

[2] The WestFAST is a collaborative initiative between 11 Federal agencies with water management responsibilities in the West. WestFAST was established to support the Western States Water Council, and the Western Governors' Association, in coordinating Federal efforts regarding water resources. Refer to: http://www.westgov.org/wswc/WestFAST.htm.

3.1.2 Decision Making Criteria

Based on the results of this pilot study, the following screening criteria would initially be used for future next steps.

Completeness is the extent to which a given alternative plan provides and accounts for all necessary investments of other actions to ensure the realization of planned effects.

Effectiveness is the extent to which an alternative plan alleviates the specified problems and achieves specified opportunities

Efficiency is the extent to which an alternative plan is the most cost-effective means of alleviating the specified problems and realizing the specified opportunities, consistent with protecting the Nation's environment. Each alternative plan will include measures to mitigate effects on fish and wildlife resources.

Acceptability is the workability and viability of the alternative plan with respect to acceptance by watershed stakeholders and plan's compatibility with existing laws, regulations, and public policies.

3.1.3 Evident Uncertainties

Unresolved questions about the Earth's climate are categorized as "climate forcings" and "climate feedbacks". Climate forcings are the initial drivers of climate shift. Climate feedbacks are processes that change as a result of a change in forcing, and cause additional climate change. Examples of uncertainties associated with climate forcings include solar irradiance, aerosols, dust, smoke, and soot. Some examples of uncertainties associated with climate feedbacks include clouds, carbon cycles, and precipitation. Additional information on these uncertainties is available at:
http://climate.nasa.gov/uncertainties/

Other examples of uncertainties include estimating and modeling long-term future population, land use, conservation practices, and dependable yield/sustainability of Lake Oologah.

The future application of the Monte Carlo method may be useful to help determine how uncertainties affect the sensitivity/adaptiveness, performance or reliability of alternatives.

3.2 Risk Assessment: Identify Risks

Risks include potential habitat and water quality impairments related to sedimentation, turbidity (suspended sediment), and nutrient loading, especially from nitrogen and phosphorus. An additional concern is the long-term sustainability of the Lake Oologah firm yield.

3.3 Risk Assessment: Analyze Risks and Formulate Plans

Best Management Practices (BMPs) can reduce the amounts of soil and nutrients that are exported from land surfaces. Keeping soils and nutrients on the fields and out of the rivers and streams benefits both the ecosystem and society. Stewardship practices can provide for a healthy environment while increasing the productivity of the land.

During the Lake Oologah Watershed Assessment study, traditional BMPs alternatives were evaluated through the modeling process based on historical climate information.

Traditional BMP measures were selected largely because the dominance of private land in the watershed meant that implementation was envisioned to happen more at the local level at multiple locations. Many NRCS programs already in place in the study area that are cost-shared with farmers, ranchers, communities, and other individuals, utilize the same or similar conservation practices to those the Corps has modeled in this assessment. The conservation BMPs are described in detail below.

Vegetated Filter Strips. Vegetated filter strips consist of strips of tall, residual native grasses or native grasses and forbs, planted along waterways. Filter strips function to trap sediments, fertilizers, pesticides, and other pollutants before they reach streams and/or lakes. Filter strips can vary in width and provide herbaceous habitat for wildlife and enhance watershed functions.

Conservation Tillage on Cropland. This is defined as those practices designed to enhance soil surface and surface layer crop residue on the soil surface. This conservation technique can reduce sheet and rill erosion, reduce wind erosion, improve soil organic matter content, reduce carbon dioxide losses from the soil, reduce soil particulate emissions, increase plant available moisture, and provide food and escape cover for wildlife.

No-Till Conservation. This activity consists of farm management practices that reduce tilling to improve soils and enable the soil to better act like a sponge and reduce runoff from cropland. Crop stubble and/or residue from the previous crop are left in the field to cover at least two-thirds of the soil surface. By leaving the crop residue and reducing or eliminating tillage, soils are protected from water and wind erosion, they retain moisture, runoff is reduced, and wildlife habitat is improved.

Grassed Waterways Within Croplands. Grassed waterways are shaped or graded channels that are planted with suitable vegetation (non-crop species) that convey surface water at a non-erosive velocity to a stable outlet. The purpose of these waterways is to convey runoff from terraces, diversions, or other water concentrations without causing erosion or flooding. This conservation practice reduces gully erosion and protects and/or improves water quality.

Pasture Management. This generally means native or introduced forage species are planted and managed for optimum growth. Selected plant species must provide adequate ground cover, canopy cover, and good root mass and vegetative retardance to protect the soil against water and wind erosion. The benefits expected from improved pasture management techniques include reducing soil erosion and improve water quality. Additional benefits indirectly related to water quality include maximizing forage for livestock, adequate forage supply on a continuous basis (balance of supply and demand) so as to prevent overgrazing of fields, and improve livestock nutrition and health.

Wetlands. Wetlands provide numerous environmental benefits such as wildlife habitat, groundwater recharge, sediment and nutrient control, and non-point source pollution control. Wetlands have been recognized as highly productive systems for fish and wildlife species. According to the US Fish and Wildlife Service, wetlands provide habitat for 60 to 70 percent of the animal species listed as threatened or endangered. Benefits of wetlands are nearly the same as the benefits of riparian areas.

Improved Riparian Zones. Riparian areas consist of plantings of trees, shrubs, and grasses that provide habitat restoration as well as reduce sediment and pollutants in both surface runoff and ground water before those pollutants reach a waterbody. Riparian areas create shade and improve habitat for aquatic and terrestrial species. Corridors facilitate the movement of organisms through landscapes; therefore, continuous corridors are preferable to fragmented corridors. Benefits include increased landscape diversity, reduced source and non-point source pollution, decreased levels of sediment and contaminants, increased infiltration of surface runoff, increased groundwater recharge and aquifer volumes, decreased flow velocities, increased stream stability, reduced channel downcutting, decreased streambank erosion, decreased streambank failure, decreased water temperature, and decreased instream sediment.

Sediment Ponds. This practice involves constructing a basin to collect and store debris or sediment. This practice applies where physical conditions or land ownership preclude treatment of a sediment source by installation of erosion control measures to keep soil in place. Sediment ponds/basins provide the following benefits: they preserve the capacity of reservoirs, wetlands, ditches, canals, diversion waterways, and streams; prevent undesirable deposition of soil on bottom lands; they trap sediments originating from disturbed sites; and reduce or abate pollution by providing basins for deposition and storage of silt, sand, gravel, stone, agricultural waste solids, and other detritus.

3.4 Risk Evaluation

In the evaluation step, the significance contributions or effects of individual plans are quantified and rated. Alternative BMPs were modeled and evaluated in the Oologah Lake Watershed Assessment study. Additional analysis would be used to evaluate how BMPs would reduce the risk of potential climate change problems associated with water temperature increases and reduced dissolved oxygen.

3.5 Risk Management Implementation Decision

Additional information is needed to make informed decisions regarding the implementation of large-scale BMPs or other alternatives. However, there is sufficient information available to warrant the need for additional risk-based watershed analyses as climate science state-of-the-art advances.

4. Results and Lessons Learned

The reservoir yield, watershed, and water quality analyses provided a proof-of-concept demonstration of how the U.S. Army Corps of Engineers can utilize climate projection data sets developed by other federal/university programs associated with the National Oceanic and Atmospheric Administration, Department of Interior Climate Science Centers, and Bureau of Reclamation.

Simplified processes are needed to more efficiently leverage the climate science and related resources associated multiple federal agencies.

Consider working with DOE, DOI, EPA, NASA, NOAA, NRCS and others on efforts that would lead to policy that provides for the efficient transfer of funds between agencies for climate science technical support. This initiative would advance the leveraging of federal technical resources and promote a collaborative national approach to the development and field application of climate science.

As previously discussed the Phase 1 Assessment of this pilot demonstrated a "reconnaissance" or "state water plan" level of detail by utilizing existing streamflow projections developed by the U.S. Bureau of Reclamation for western states. This information is located at: http://gis.usbr.gov/Streamflow_Projections/. Phase 2 of the pilot provided an example of a more detailed or "feasibility" level approach to evaluate climate change impacts to reservoir yield and water quality and soil and water conditions in the watershed. Results of the Phase 1 and 2 activities are documented in Technical Supplements 1 and 2. The following is a summary of tentative results:

Reservoir Yield Analysis

- All 112 ensemble projections were in a consensus agreement that future conditions will be warmer over the Oologah Lake watershed, with a median increase in temperature among all models of +4.76˚F by the year 2050.

- No consensus existed with respect to future precipitation trends in the Oologah Lake watershed. Half of the models in the ensemble projections predict an increase in annual rainfall by the year 2050, while the other half predicts a decrease in annual rainfall. Most of the models fall within a ± 10% range by the year 2050 based on current climatology.

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

- The Oologah Lake watershed receives (on average) approximately 10 inches of snowfall a year, which equates to 1-2 inches of liquid equivalent precipitation. Some of this precipitation may shift to rainfall.

- The Variable Infiltration Capacity (VIC) simulated inflow hydrograph exhibited good skill when replicating the critical period. The timing and duration of historical droughts, including the 1952-1957 drought of record, was generally correct.

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

- Most of the model ensemble projections suggests that firm yield will not change significantly over time.
- "Reconnaissance" level modeling from pre-existing U.S. Bureau of Reclamation climate-projection hydrographs has potential to advance SMART Planning initiatives. For this pilot the methodology exhibited skill in reproducing water supply trends from the "feasibility" level modeling but had higher magnitudes of firm yield.

- Stresses that were considered did not include increased demand from users. History has shown that demand increases during heat waves that are associated with droughts. The record use by the Tulsa Metropolitan Water Authority occurred in August 2011.

- Based on the modeling results, Oologah Lake appears to be well positioned to meet future water supply obligations, particularly since no future additional allocations are contracted.

Oologah Lake Watershed Analysis

- Application of watershed and reservoir simulation models in the evaluation of climate projections can provide insight into future expected conditions.

- Both watershed and reservoir models have detailed input requirements and need to be evaluated and assessed using measured data to determine relative accuracy.

- NARCCAP projections generally resulted in lower average annual runoff, and reduced vegetative biomass production.

- CMIP3 projections revealed consistent whole watershed outputs including reduced runoff, higher evapotranspiration, lower sediment export, and lower vegetative biomass production.

- Reservoir simulations comparing baseline and climate projections revealed reservoir water temperature increases, and dissolved oxygen concentration decreases.

- With respect to available 'optimal fish habitat', increasing water temperature and subsequent lower dissolved oxygen concentrations in all climate projections (compared to the baseline simulation), resulted in decreased whole-lake water volume, through the growing season, suitable for optimal fish activity.

5. Potential Next Steps

Assuring the long-term sustainability of reservoirs that provide storage for water supply is becoming increasingly important and complex as infrastructure ages, sedimentation accumulates, climate changes, and financial needs outweigh budgets. Therefore, risk-based strategic planning that takes an Integrated Water Resources Management (IWRM) approach is necessary to effectively prioritize problems and identify step-wise approaches to implement solutions.

Regarding the climate change component of an IWRM approach, a step-wise process that mirrors the USACE dam and levee safety programs could be considered. A "Responses to Climate Change Screening Portfolio Risk Assessment (RCCSPRA) would help determine strategic long-term prioritized next steps associated with: 1) additional detailed investigations, 2) changes in management strategies, and 3) recapitalization strategies.

A potential next step would be a pilot demonstration of a RCCSPRA using selected reservoirs with water supply storage in a USACE District. The pilot would demonstrate the following conceptual 3 phase process:

1. Phase 1: Initial Portfolio Screening. Use existing information associated with each reservoir to determine how much of the available USACE water supply storage is contracted. Reservoirs with, say, 75% of the storage contracted would be considered for Phase 2 analysis. The assumption in the Phase 1 analysis is that reservoirs with less than 75% of the storage contracted would have sufficient

contingency if the water supply would decrease and/or demands increase due to foreseeable future climate change.

2. Phase 2: Asset Prioritization. A "bottom – up" type assessment would identify an initial risk ranking for each of the reservoirs that were not screened out in the Phase 1 analysis. The risk Probability Factor would be based on robustness analysis, along with existing Bureau of Reclamation climate projection data. The robustness analysis would be based on interviews with contract holders and USACE SMEs. The risk Consequence Factor would be based on the population impacted by USACE M&I storage contracts. The assumptions are that the probability of populations being impacted by reservoirs that are less robust would be greater and the larger the population impacted by the contracted M&I water storage the greater the consequences.

3. Phase 3: Prioritized Climate Projection Analysis. A "top – down" type assessment would identify a refined risk ranking for the reservoirs that were not screened in the Phase 2 assessment:

a. Develop hydrographs for each reservoir by simulating runoff from bias-corrected, spatially-disaggregated statistically downscaled climate projections with the Variable Infiltration Capacity (VIC) model. This data could potentially be developed by regional Department of Interior Climate Science Centers.

b. Use numerical routing to transform these hydrographs into long-term simulation of pool elevations so that droughts could be identified and the critical period for each could be determined.

c. Assign a priority rating to each reservoir based on the potential impacts to reservoir yield due to climate change: 1 Severe, 2 Moderate, 3 Low, 4 Negligible.

A graphical representation of the 3 Phase process is shown Figures 1-3. Following the Phase 3 assessment, a conceptual "Next Steps" framework concept strategy would be developed by SMEs and water supply storage customers.

Figure 1. 3 Phase Responses to Climate Change Screening Portfolio Risk Assessment (RCCSPRA)

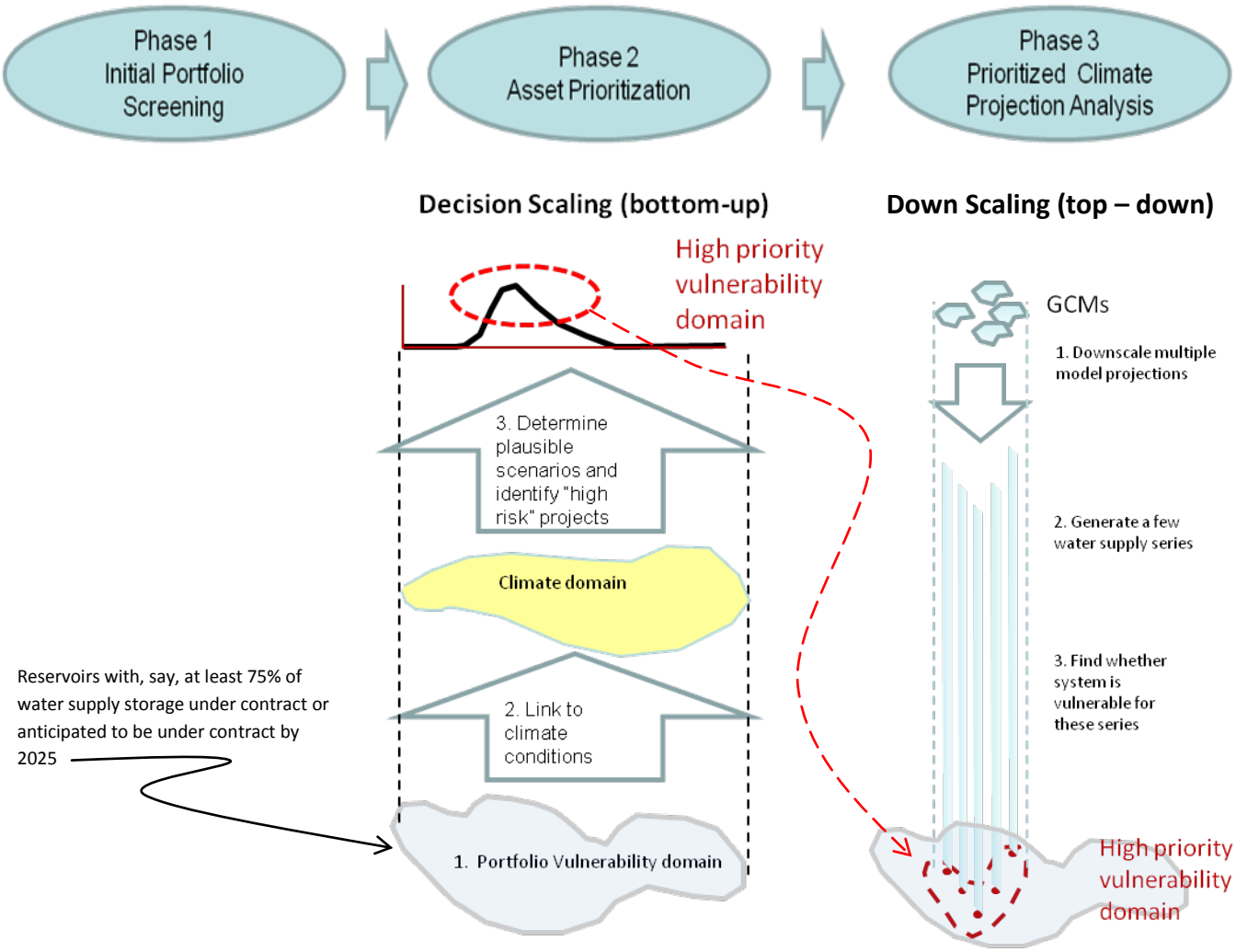
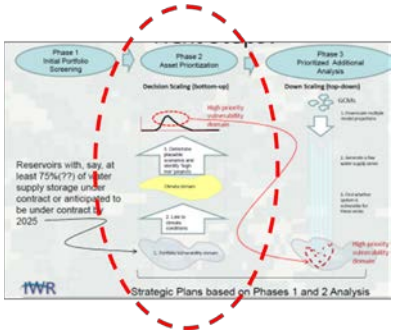
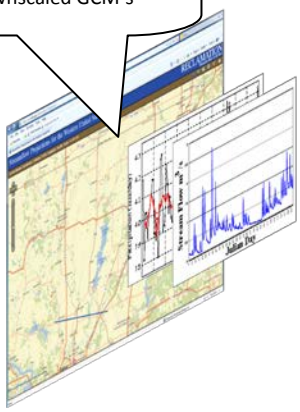
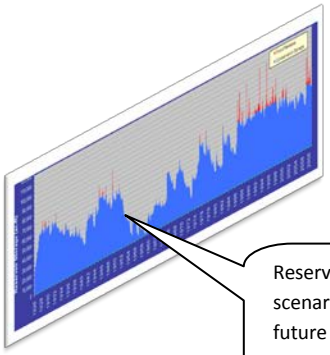


Figure 2. Phase 2 Asset Prioritization



Temperature and Precipitation Data associated with 112 climate projections from 16 statistically downscaled GCM's





Reservoir firm yield scenarios associated with future climate projections

1. "Reconnaissance" level modeling from pre-existing U.S. Bureau of Reclamation climate-projection hydrographs is conducted to identify climate change trends. The climate change trends information is used to identify a range of climate change thresholds used for the robustness analysis.

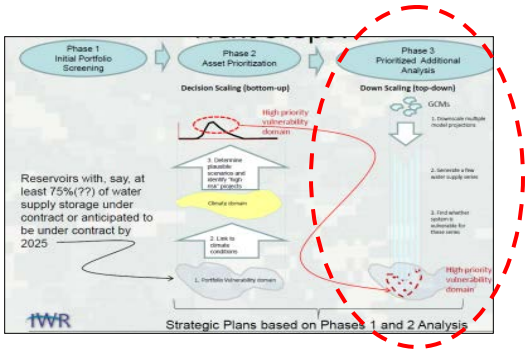
Robustness Analysis, based on user and USACE SME interviews and reconnaissance level climate change data is used to help develop a Probability Factor.

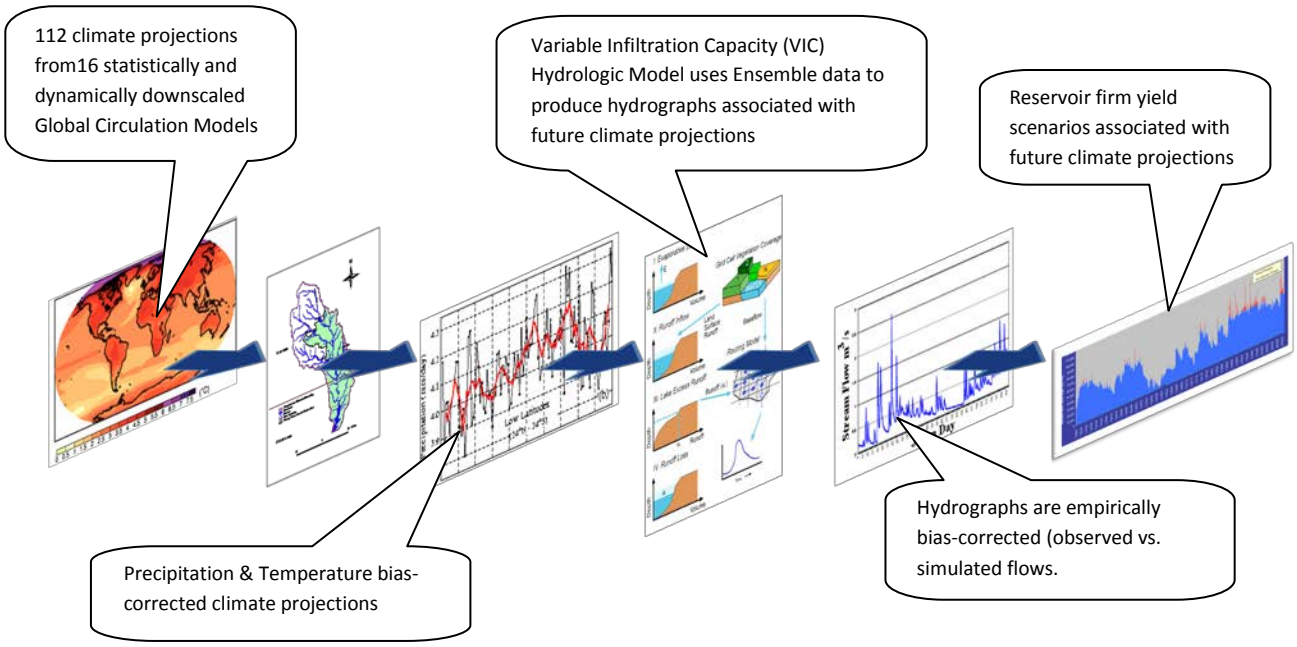
Consequence Factor is based on population impacted by USACE M&I storage contracts

Determination of Risk Rating

Probability Factor	Consequence Factor: High	Medium	Low	None
High	High	High	Medium	None
Medium	High	Medium	Low	None
Low	Medium	Low	Low	None
None	None	None	None	None

Figure 3. Phase 3 Prioritized Climate Projection Analysis





a. Develop hydrographs for each reservoir by simulating runoff from bias-corrected, spatially-disaggregated statistically downscaled climate projections with the Variable Infiltration Capacity (VIC) model. This data could potentially be developed by regional Department of Interior Climate Science Centers.

b. Use numerical routing to transform these hydrographs into long-term simulation of pool elevations so that droughts could be identified and the critical period for each could be determined.

c. Assign a priority rating to each reservoir based on the potential impacts to reservoir yield due to climate change: 1 Severe, 2 Moderate, 3 Low, 4 Negligible.

Technical Supplement 1

DRAFT

US Army Corps of Engineers

Institute for Water Resources

Water Supply Yield Modeling at Oologah Lake (Oklahoma) with Downscaled Climate Projections

March 2013

EXECUTIVE SUMMARY

Modeling of future water supply in Oologah Lake, located on the Verdigris River in Nowata and Rogers Counties, Oklahoma, was performed as part of a research effort titled "Reservoir and Watershed Risk-Based Assessments – Oologah Lake and Watershed Responses to Climate Change Pilot Study." Oologah Lake fulfills approximately 50 percent of the potable water needs of the Tulsa, Oklahoma metropolitan area, which has a total population of nearly 1 million people. Concerns have been expressed by the City of Tulsa and state agencies concerning the long-term sustainability of water quality and water supply.

As part of this study, the future availability of water supply in Oologah Lake was analyzed using two approaches. The first approach, a "reconnaissance" level of detail, relied on an existing set of hydrographs that were developed by the U.S. Bureau of Reclamation for selected site in the western United States. The second approach, a "feasibility" level of detail, relied on the development of hydrographs specific to the Oologah Lake watershed.

A set of 112 hydrographs was developed by colleagues at the University of Oklahoma by simulating runoff from bias-corrected, spatially-disaggregated (BCSD) statistically downscaled climate projections with the Variable Infiltration Capacity (VIC) model. Numerical routing was then used to transform these hydrographs into a long-term simulation of pool elevations so that droughts could be identified and the critical period for each could then be determined as well. A mass balance approach was used, and iteration proceeded automatically through all time steps in the spreadsheet until an outflow value was found that resulted in a single minimum pool elevation of 592.0 feet, which constituted the occurrence of both the critical period and the firm yield.

All 112 ensemble projection hydrographs (A1b, A2, and B1 emissions scenarios) were routed through the yield model for the entire study period ending in the year 2098. Changes in precipitation in conjunction with changes in evapotranspiration and hydrologic runoff produced ensembles that, for the most part, indicate no major changes in firm yield.

Development of firm yield modeling from the pre-existing U.S. Bureau of Reclamation climate-projection hydrographs matched the trends observed from the firm yield modeling using hydrographs developed as part of this study, but the

magnitude was higher for all three emissions scenarios. Based on this finding, the “reconnaissance” level of detail is useful when drawing conclusions about water supply trends but cannot be used to assess the magnitude of firm yield without additional correction.

The results of this study suggest that stresses resulting from climate change at Oologah Lake will not increase over time, and that existing water supply contracts will continue to be met. Furthermore, the capacity for additional water supply contracts currently exist, and the modeling results suggest that this additional capacity will continue to exist in the future. Oologah Lake therefore appears to be well positioned to meet future water supply obligations.

PURPOSE

The primary objective of this research project was to determine how information form regional federal climate science programs can be used in water resource model assessments and associated risk management decision making by local, tribal, state, and federal interests.

By analyzing water supply at Oologah Lake, the assessment considered what combination of drought duration and magnitude would cause the reservoir to no longer meet its contracts. The findings of this assessment can be used to consider the customer's potential vulnerability to drought by determining alternative sources of supply, what conservation measures could be employed, and how much water demand exists during drought. A review of performance during historical droughts is one method that can be used for the assessment.

This project was completed with funding from the U.S. Army Corps of Engineers (USACE) Institute for Water Resources, and was specifically developed for the Responses to Climate Change program. Climate model forcing data were developed by Lei Qiao, Yong Hang, Renee McPherson, and Mark Shafer at the University of Oklahoma. Water quality modeling was developed by David Gade, U.S. Army Corps of Engineers, Tulsa District. The study was managed by Gene Lilly, U.S. Army Corps of Engineers, Tulsa District.

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

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INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has numerous water supply contracts at reservoirs in the Tulsa District (SWT). Among these multi-purpose projects is Oologah Lake, located on the Verdigris River in Nowata and Rogers Counties, Oklahoma.

Oologah Lake fulfills approximately 50 percent of the potable water needs of the Tulsa, Oklahoma metropolitan area, which has a total population of nearly 1 million people. Concerns have been expressed by the City of Tulsa and state agencies concerning the long-term sustainability of water quality and water supply. This pilot study seeks to answer these questions by incorporating 1) water resource model assessments and 2) risk management decision making by local, tribal, state, and federal interests.

As part of this study, the future availability of water supply in Oologah Lake was analyzed using two approaches. The first approach, a “reconnaissance” level of detail, relied on an existing set of hydrographs that were developed by the U.S. Bureau of Reclamation for selected sites in the western United States. The second approach, a “feasibility” level of detail, relied on the development of hydrographs specific to the Oologah Lake watershed.

Both approaches incorporated downscaled climate change projections derived from the World Climate Research Programme’s 3rd phase of the Coupled Model Intercomparison Project (CMIP3), which were used as the basis for the analysis. This study utilized the Variable Infiltration Capacity (VIC) hydrologic model to examine a range of climate change scenarios in order to determine whether or not the federal water supply contractual obligations will be met during future climate conditions. In other words, how vulnerable are the water supply contracts at Oologah Lake to climate change?

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

Collaboration on this project with researchers at the University of Oklahoma was beneficial given the technical expertise that has been gained through similar efforts. The selection of Oologah Lake for this pilot study complements the 2012 update of the Oklahoma Comprehensive Water Plan (OCWP) by "continuing the advancement of a thorough understanding of Oklahoma's climate and weather and the associated impacts on Oklahoma's water users and citizens."

PROJECT DESCRIPTION

Oologah Lake is located at mile 90.2 on the Verdigris River, approximately 22 miles northeast of Tulsa in Rogers and Nowata Counties, Oklahoma (Figure 1). It is a multi-purpose project for flood control, water supply, recreation, navigation, and fish and wildlife. The project was designed to provide maximum flood protection on the Lower Verdigris and Arkansas Rivers when operated in conjunction with the Arkansas River Basin System. This system is part of the multi-purpose plan for flood control, generation of hydroelectric power, navigation, and allied water uses on the Arkansas River and its tributaries in Kansas, Arkansas, and Oklahoma.

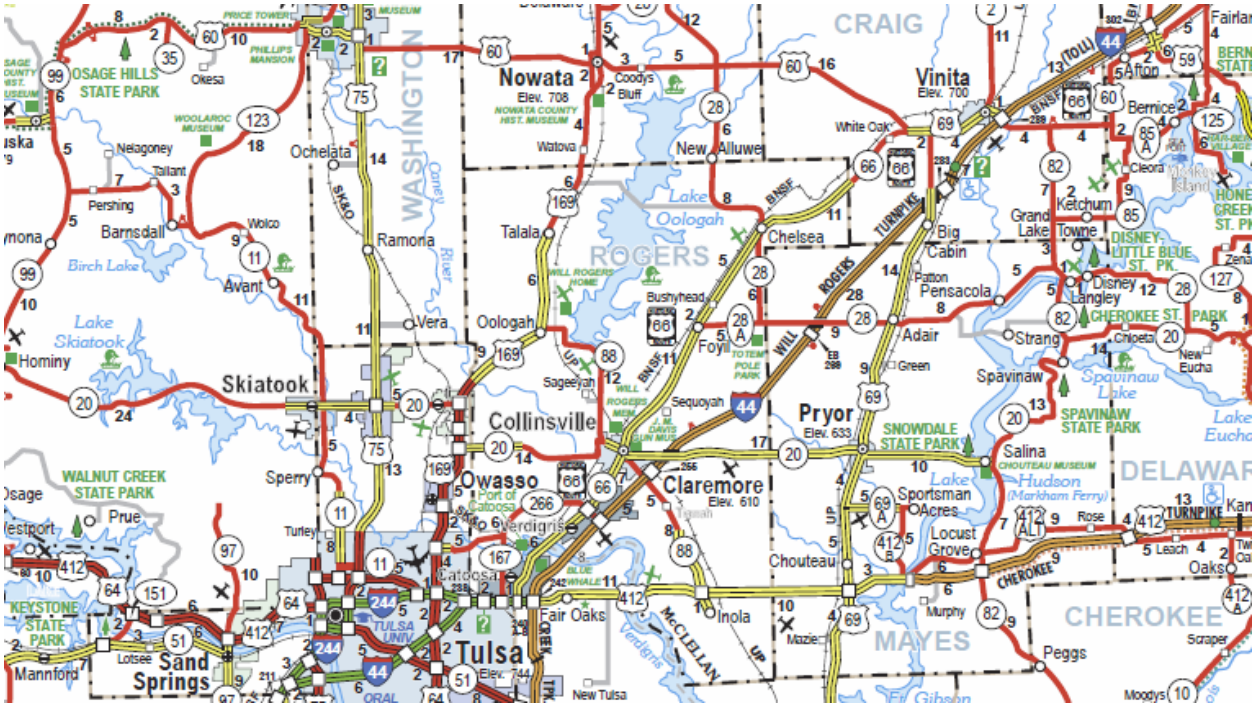

FIGURE 1: Map of region surrounding Marion Reservoir (Kansas Department of Transportation).

The Verdigris River rises in the Flint Hills of Chase County, Kansas, and flows generally southeast from the vicinity of Madison to Neodesha, Kansas, and then in a southerly direction to its confluence with the Arkansas River, about 5 miles

northeast of Muskogee, Oklahoma. The river basin is roughly elliptical in shape, with a total area of 8,303 square miles, of which 4,339 square miles are above the Oologah Dam and is divided as follows: 3,354 square miles in Kansas and 985 square miles in Oklahoma. The principal tributaries are the Fall and Elk Rivers that enter from the right bank in Kansas and the Caney River and Bird Creek that enter from the right bank in Oklahoma downstream from Oologah Dam. The Verdigris River navigation system extends from the Arkansas River upstream about 50 miles to the Tulsa Port of Catoosa. Considerable channel widening and straightening along with construction of Newt Graham and Chouteau Locks and Dams have improved the water carrying capability of the channel. The valley floor varies from approximate elevation 510.0 near its confluence with the Arkansas River and the mouth of the main stem to approximately 1000.0 in the upper reaches of the basin. The slope of the river near its source averages about 3.7 feet per mile and the navigation channel has a total rise of 42 feet in 50 miles.

The climate of the Verdigris River watershed is characterized by moderate winters and long summers with high temperatures. Rainfall usually occurs as high intensity, local thunderstorms occurring primarily in the late spring and early fall months. Mean annual precipitation is nearly 40 inches. The Gulf of Mexico is the source of much of the precipitation which falls on the basin.

Most major storms in the Oologah Lake drainage basin have occurred in April through June and September through November. Thunderstorms and the remnants of hurricanes are the type of storms that produce most high runoff events in the basin. The largest storm in the historical record, September 26 to October 5, 1986, produced an average of 10.65 inches of rainfall over the basin. This storm was a combination of a stalled cold front and the remnant of a Pacific hurricane. Time of year and antecedent soil moisture condition are major factors that determine the runoff from a given storm. Thus, some lesser rainfall storms have resulted in runoff equal to or greater than storms of higher rainfall. Periods of excessive rainfall and drought tend to be cyclical (Figure 2).

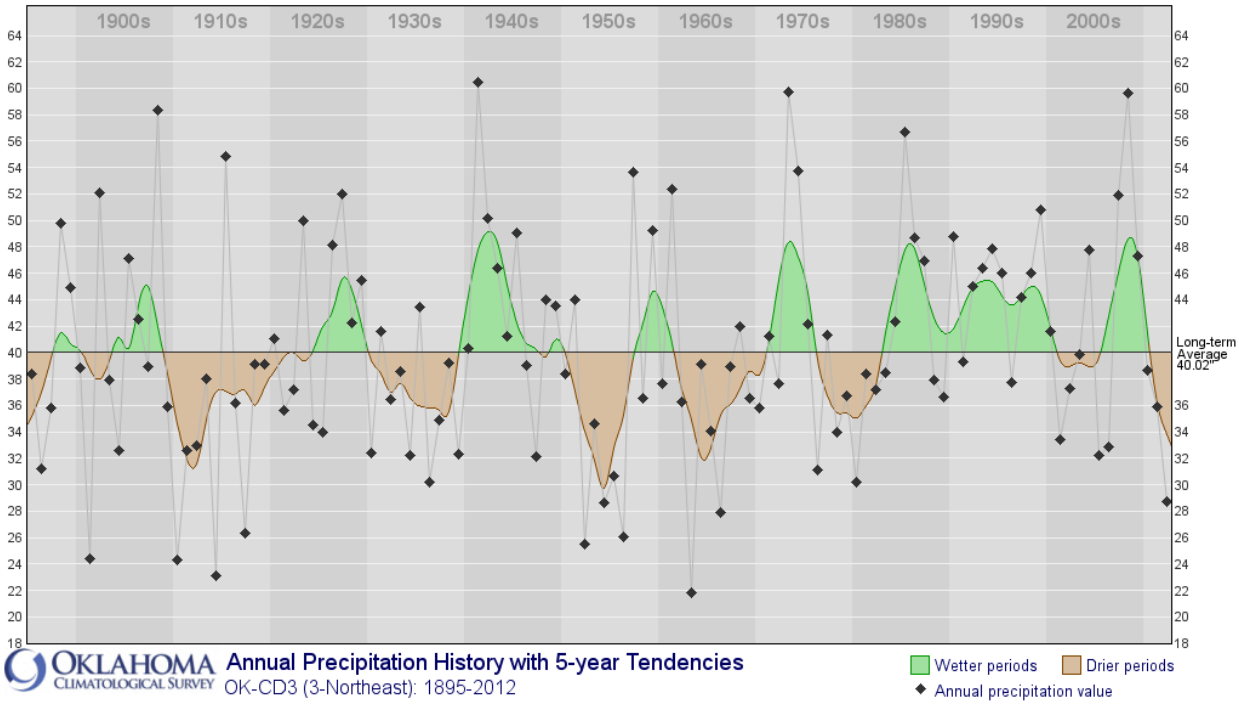

FIGURE 2: Annual precipitation climatology for the Oologah Lake watershed, 1895-2012 (Oklahoma Climatological Survey).

There have been several prolonged periods of drought recorded in the Oologah Lake watershed since 1900. One of the most prolonged (and most severe) occurred between 1952 and 1957 (Figure 3). During this period, 15 months of severe drought and 12 months of extreme drought were recorded. The lowest Palmer Drought Severity Index (PDSI) value during this period was -5.55, which is the second lowest on record for the watershed. The most severe drought of record occurred during the 1910s, with a PDSI of -6.09. Other extreme droughts include 1936-1940, 1962-1967, and 2011-present. In addition to these exceptional droughts, there have been many years with consecutive dry months.

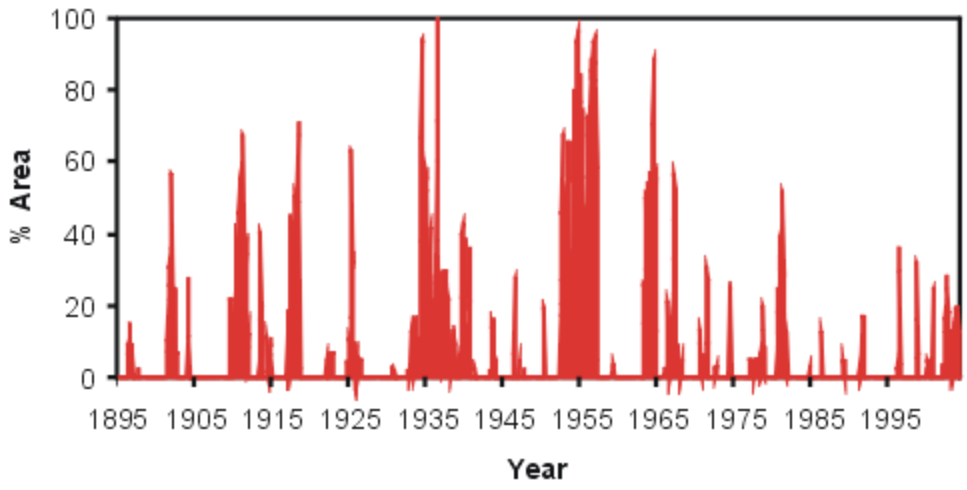

FIGURE 3: Percent area of the Arkansas-White-Red River basin experiencing severe to extreme drought, 1895-2004 (http://drought.unl.edu/).

The drought of 1952-57 occurred across much of the Great Plains. Conditions during the "Dust Bowl" of the 1930s were more severe in many locations, but this drought pre-dated stream flow records across much of the region (Figure 4). The 1950s drought affected an area ranging from the Texas panhandle to central and eastern Colorado, western Kansas and central Nebraska; all of these areas experienced prolonged drought conditions. The Oologah Lake watershed experienced severe to extreme drought conditions during much of the five-year period, which peaked in 1956. The PDSI reached a low in September 1956. The recurrence interval for the 1950s drought was estimated at 50 years. As a result of its severity, this drought is defined as the critical drought for water supply studies at Oologah Lake and many other reservoirs across the region.

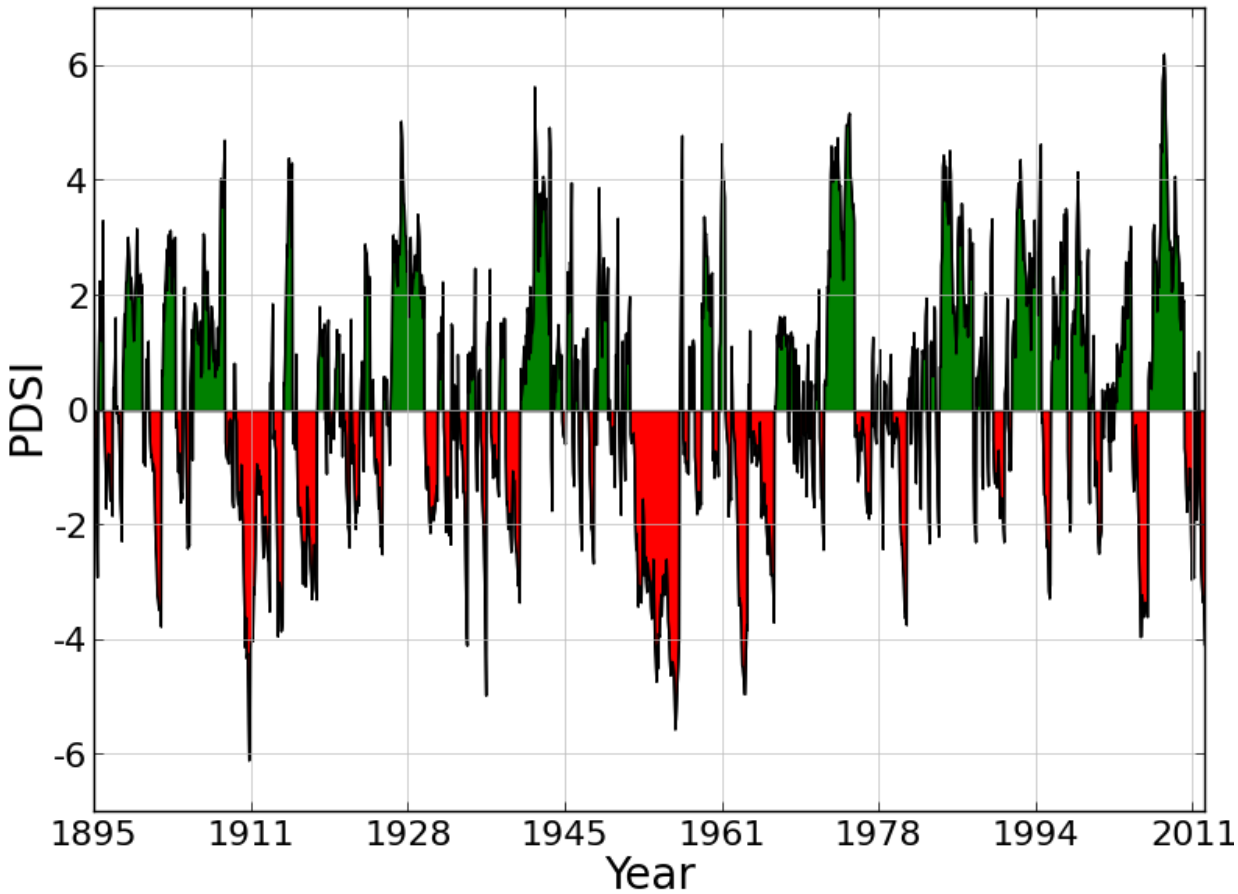

FIGURE 4: Historical record of the Palmer Drought Severity Index (PDSI) for the Oologah Lake watershed.

Construction of Oologah Lake was authorized by the Flood Control Act of 28 June 1938 (Committee Document No. 1, 75th Congress, 1st Session). The River and Harbor Act of 24 July 1946 was amended by the Secretary of the Army to reassign the storage provided in Oologah Lake for hydroelectric power production to municipal and industrial water supply and to make such storage available for such purposes under the Water Supply Act of 1958. Construction of the dam began in 1950. The initial development was for the construction of the main embankment and outlet works, an uncontrolled saddle spillway at the site of the final gated spillway, and an emergency overflow area at the site of the final dike embankment. The initial top of conservation pool was elevation 608.0, with a top of flood control pool at elevation 651.0. The final stage of development was the construction of the gated spillway and the dike embankment. The final

development resulted in a conservation pool elevation of 638.0 and a flood control pool elevation of 661.0. Conservation pool fill (final development) occurred on 29 July 1972.

The incremental capacity of the conservation pool in Oologah Lake is 545,300 acre-feet. Water supply accounts for 342,600 acre-feet, or 62.8%, of the conservation pool volume. The remaining volume in the conservation pool is reserved for navigation (168,000 acre-feet) and sediment (34,700 acre-feet).

All but 15,595 acre-feet (4.6%) of designated water supply is under contract. The largest contracted user of water supply is the Tulsa Metropolitan Water Authority, which has an allocation for 285,450 acre-feet of storage (55.9% of the usable storage in the conservation pool). This agreement, dated 12 December 1984, superseded an agreement dated 04 December 1956 that gave the Tulsa Metropolitan Water Authority the contractual right to 38,000 acre-feet of water supply storage.

Other contractual users of water supply storage in Oologah Lake include the City of Claremore, Oklahoma, the City of Collinsville, Oklahoma, the Town of Chelsea, Oklahoma, Public Service Company of Oklahoma, and several rural water districts. Water supplied to the City of Tulsa, the City of Collinsville, and the Public Service Company of Oklahoma is taken from a 66-inch conduit in the wet well on the right side of the intake structure. The invert elevation of the water supply pipe is 565.5. All other users take water directly from the lake.

Water supply users are responsible for regulating the withdrawal or use of water from Oologah Lake, including the measurement of the amount of water that is being withdrawn. Accounting procedures for conservation storage have been developed to regulate the withdrawal by each water supply user. Inflows, after deductions for downstream water rights and losses, are applied to the storage account of the user in proportion to contracted storage. When a user has 50 percent or less of contracted storage remaining, they will be notified frequently throughout the critical period. If the storage becomes depleted, no additional withdrawal will be made without an additional contract.

The Oklahoma Water Resources Board (OWRB) has issued water rights on the Verdigris River below Oologah Lake. Releases from inflow to satisfy downstream water rights are made at the request of the OWRB. No withdrawal

from storage in the lake will be made for downstream water rights unless the water rights holder has contracted storage available in the lake.

Oologah Lake has 168,000 acre-feet of navigation storage in the conservation pool to provide minimum flow requirements for navigation during drought periods. This storage will yield 126 cfs (81.3 MGD).

MODEL DEVELOPMENT

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

Output from the VIC (and routing) model was required for the determination of reservoir firm yield. For the Oologah Lake water supply study, these hydrographs were used to create a mass balance depicting storage:

$$Storage(t) = max(Storage(t-1) + Inflow(t) - Release(t), storage\ capacity) \qquad (1)$$

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

Iterative simulation is required to evaluate Equation 1 for the reservoir over a period of simulation. Each time step is not only dependent upon its variables but also upon the variables carried over from the previous time step. Although water impoundment in Oologah Lake didn't begin until 1963, RiverWare simulated pool elevations dating to 1940 were available from USACE (Tulsa District). Climate

projection hydrographs used in this study were available beginning in 1950, however, so the initial date of the routing simulation was set as the first day of that year (01 Jan 1950). Daily ordinates were modeled through an ending date of 31 Dec 2098. Therefore, nearly 55,000 daily records were analyzed. In order to minimize the effects of flood control operations on water supply routing, the data interval was converted to a monthly record, resulting in 1,800 computational steps per projection.

For this study, firm yield was calculated using elevation-area-capacity data generated from the 2010 Oologah Lake bathymetric survey (Figure 5). Mass balance routing was used in conjunction with a monthly time step and an assumption that during the course of any given month, flood operations would lower the reservoir elevation to the conservation pool. A simulated inflow hydrograph was used for the routing computation, which was originally developed for the USACE (Tulsa District) RiverWare model that includes Oologah Lake. The data was provided as a daily time step and subsequently re-averaged to a monthly time step. Additionally, routing was performed using estimated monthly flows from 1923-1959 that were published in 1962.

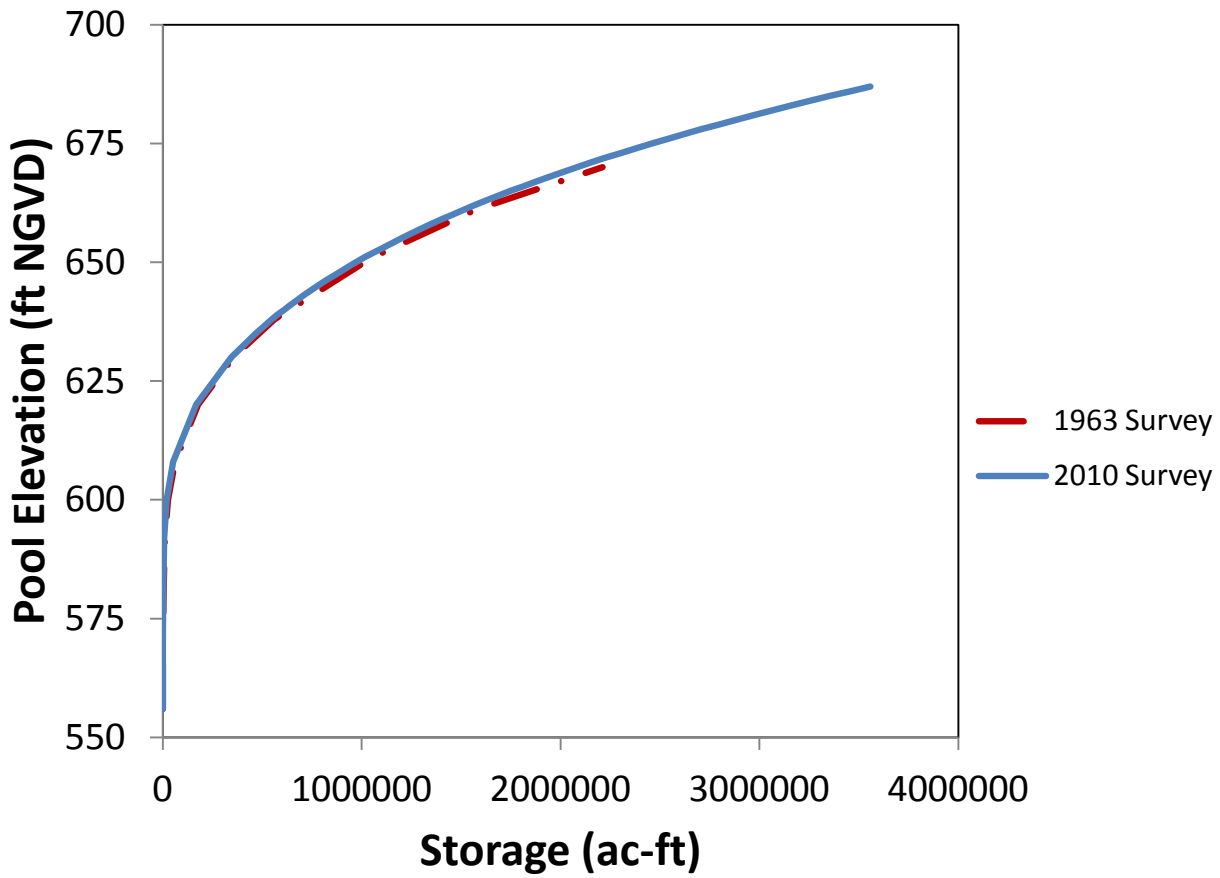

FIGURE 5: Storage curve for Oologah Lake.

An elevation of 638.0 feet was entered for the first day of the routing simulation (01 Jan 1950) since this is the elevation at which 100% of conservation storage is filled. The initial storage value was calculated through linear interpolation by comparing the initial elevation with the elevation-capacity curve, and each subsequent storage value was computed as a mass balance combining the storage, precipitation, evaporation, and differential flow volumes from the previous time step. Once the storage value was determined for the current time step, elevation was calculated through linear interpolation by comparing the storage value (as volume) with the elevation-area-capacity curve. The iterative calculation then continues step-by-step to the next successive time ordinate.

Since significant changes in reservoir storage tend to occur on the order of days or even weeks, a decision was made to carry out the analysis using a monthly time step. This decision was supported in part by the assumption that flood

storage in Oologah Lake could be neglected during the analysis because the pool would likely only remain above the top of conservation pool for periods of time not exceeding one month. By adopting a monthly time step, in other words, the total number of records could be significantly reduced while justifying the exclusion of flood control rules from the simulation. The number of records was subsequently reduced from nearly 55,000 to 1,800.

The mass balance for any given monthly record relies upon the previous month for calculation, so a change to any of the 1,800 monthly records requires that the remaining records be recalculated as well. The only practical ways in which this analysis could be carried out were by 1) using a simulation model such as HEC-ResSim or WSROUT, 2) by using a spreadsheet method, or 3) by using a specialized mathematical programming and analysis environment such as MATLAB. Since the data can be easily manipulated in the form of a matrix, hydrographs that were generated from the A1b, A2, and B1 climate projections in the VIC model were delivered for this phase of the project in MATLAB format.

Hydraulic routing in MATLAB was performed by iterating between the bottom of the conservation pool (which is the minimum allocated water supply storage of the reservoir), elevation 592.0 feet, and the top of the conservation pool (which is the maximum allocated water supply storage of the reservoir), elevation 638.0 feet. By setting up the model in this manner, iteration proceeded automatically through all time steps until an outflow value was found that resulted in a single minimum pool elevation of 592.0 feet. This outflow value is the constant rate of withdrawal from the conservation pool that is required to meet water supply allocation, which is by definition the firm yield.

The historical firm yield corresponding to the 1956 critical period was then computed twice – from the 1923-1959 observed inflow period of record dataset that was published in the 1962 water control manual and from the 1950-1999 RiverWare simulated inflow period of record dataset – in order to test the accuracy of the RiverWare dataset. Hydraulic routing of the 1923-1959 observed inflow period of record dataset resulted in a firm yield of 457 cfs, which is consistent with the total firm yield (the sum of water supply, navigation, and sediment storage requirements) reported in the Oologah Lake water control manual. Firm yield was then computed using the 1950-1999 RiverWare simulated inflow period of record dataset, resulting in a value of 450 cfs. This relatively minor difference, which can be explained by residual bias in the RiverWare model, nonetheless indicates that the RiverWare simulated inflow

period of record dataset is capable of replicating the historical dataset (Figure 6). Since the climate projections available for this study have a period of availability beginning in 1950, the observed 1923-1959 inflow period of record does not provide a substantial overlap period for calibration. The RiverWare simulated inflow period of record was therefore carried forward as the historical dataset to be used for bias correction.

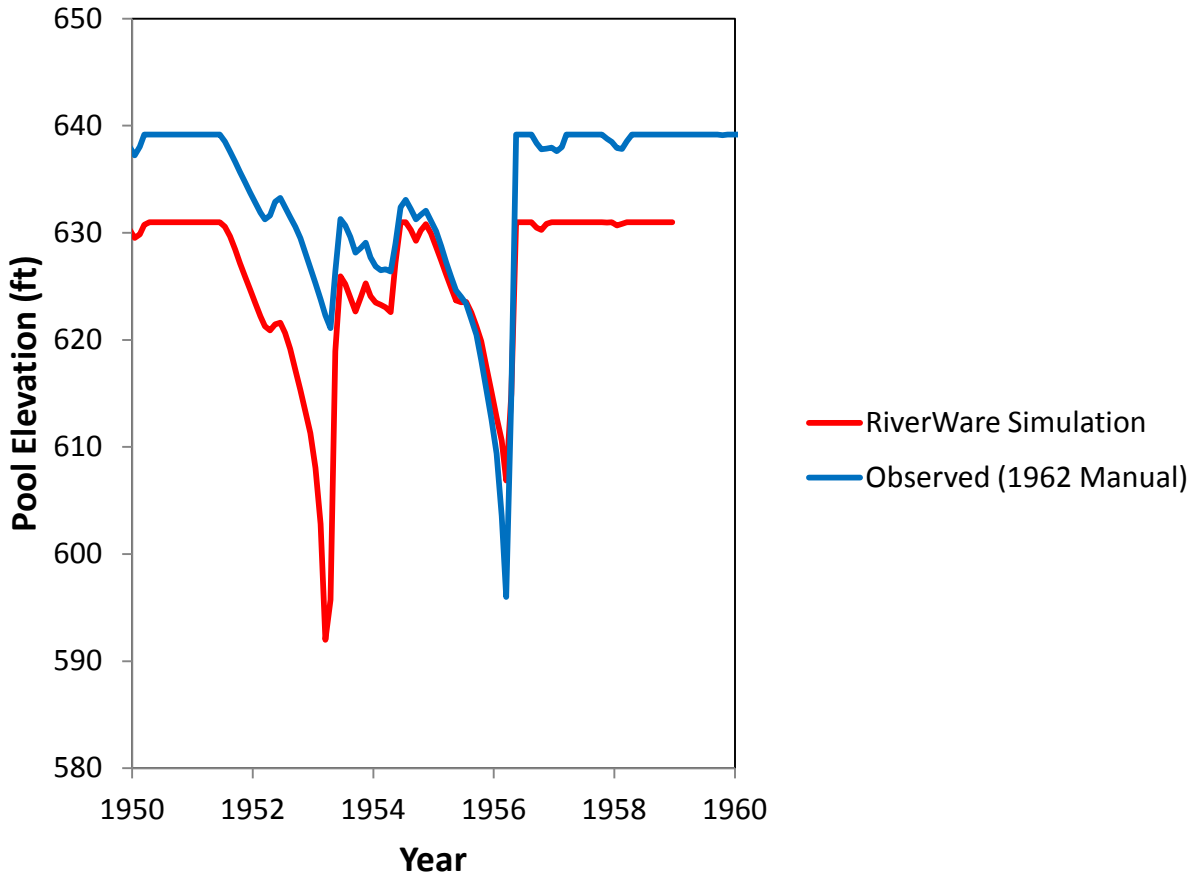

FIGURE 6: Monthly observed and simulated Marion Reservoir firm yield calculations (as critical period), 1949-2008.

Following the computation of historical firm yield from the observed and RiverWare simulated inflow periods of record, firm yield was then calculated from the VIC simulated inflow hydrograph that was generated from the historical overlap period (1950-1999). Hydraulic routing of the VIC simulated inflow hydrograph matched the timing of the timing of the historical critical period to within six months (Figure 7).

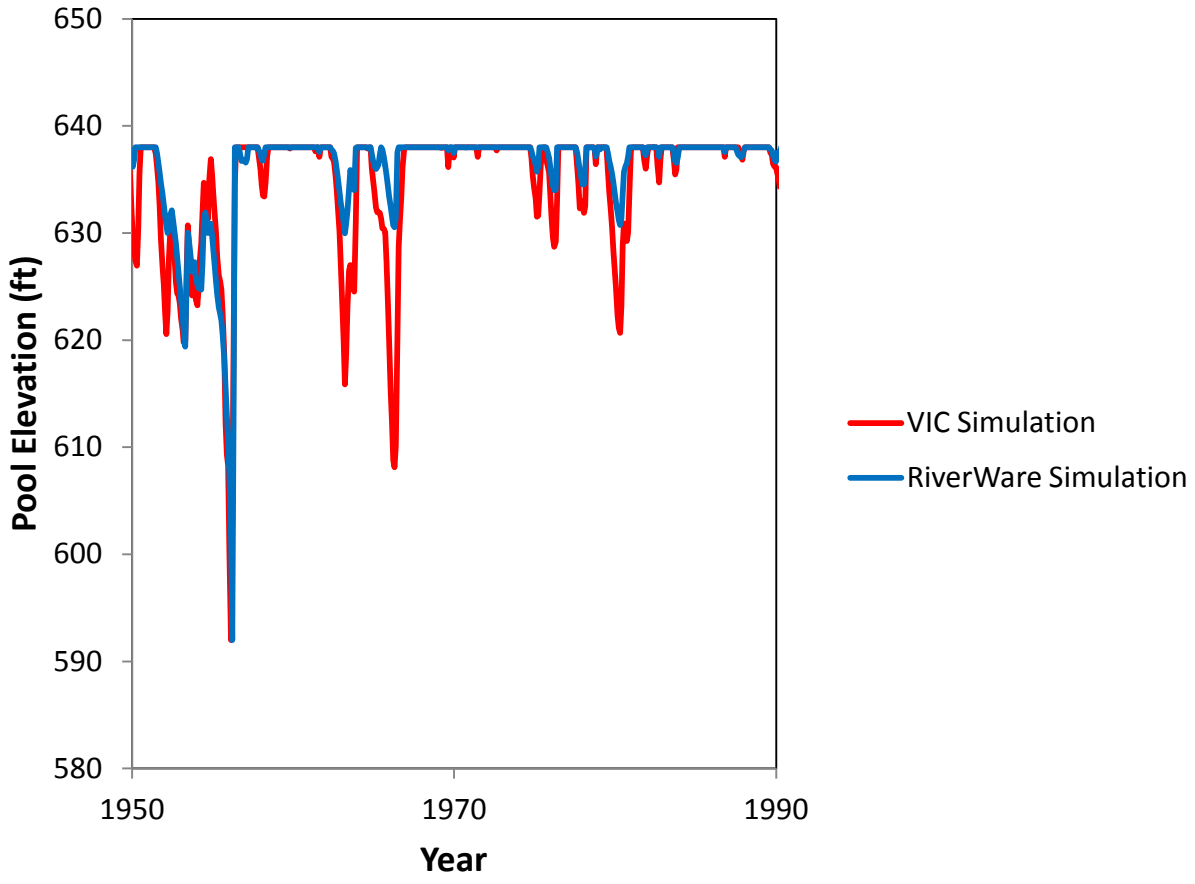

FIGURE 7: Comparison of critical period analysis between the VIC and RiverWare simulated inflow hydrographs.

However, a significant discrepancy was noted in firm yield magnitude between the two hydrographs, highlighting the imperfect match of physical processes between the VIC model and actual processes that occur in the watershed. The computed historical firm yield resulting from the VIC simulation hydrograph, 1250 cfs, was nearly three times higher than the accepted firm yield values calculated from both the observed inflow period of record and the RiverWare simulated inflow period of record.

Significant bias remained in the simulated inflow hydrograph following VIC model calibration, additional bias correction was therefore necessary. This correction was performed by independently taking the observed and simulated inflow hydrographs from the historical overlap period (1950-1999) and developing a cumulative distribution function (CDF) for each. The CDF was constructed by

taking the full hydrograph for the observed dataset, binning the data by month, and then assigning probabilities to the data by applying the Weibull formula:

$$P = \frac{m}{n+1} \tag{2}$$

This expression requires that the data be sorted so that rank (*m*) is compared to the total number of data points in the series (*n*). The calculation is performed for each of the data points, resulting in a CDF for each of the monthly datasets. The same procedure was then repeated for the simulated dataset. Following the development of both cumulative distribution functions for each of the monthly datasets, each of the simulated monthly CDFs was then compared with the observed monthly CDFs. A ratio between the observed and simulated value for each probability pair was then computed, and this ratio was designated as the bias correction factor corresponding to the specific probability (Figure 8).

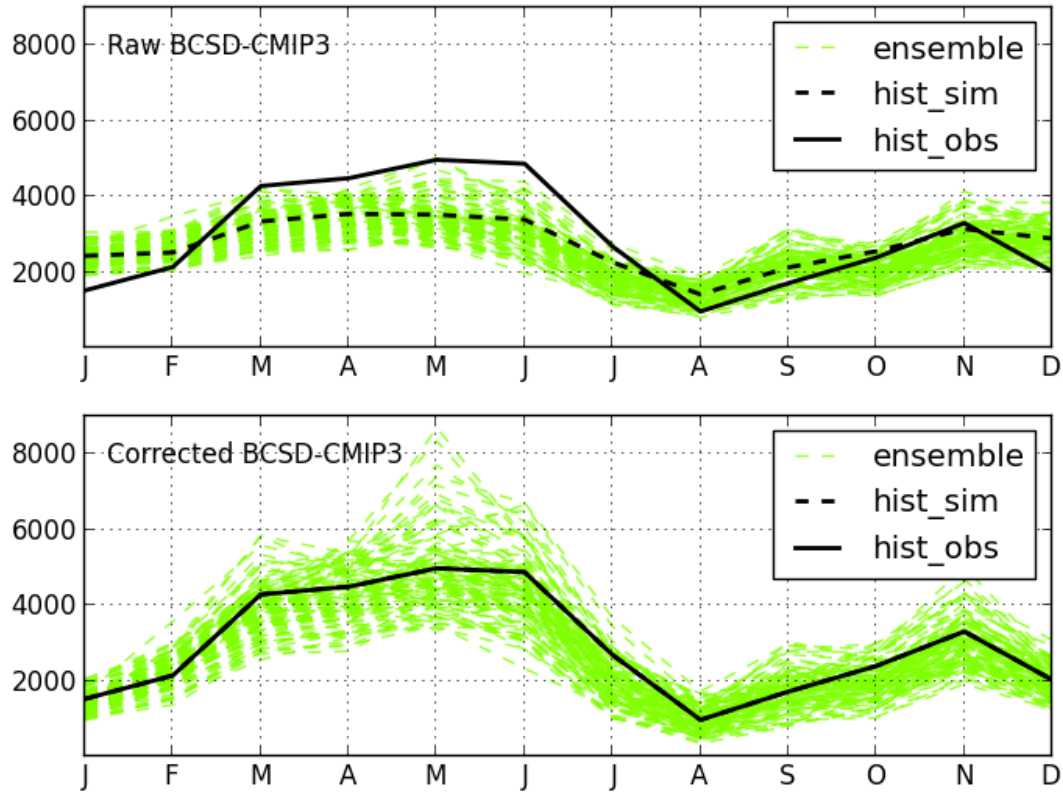

FIGURE 8: Inflow hydrograph ordinates for Oologah Lake plotted as monthly CDF averages; the historical observed and historical simulated distributions, which overlap, have been bias corrected, and the resulting correction factors have been applied to the model projections.

After the bias correction factors were computed for the range of probabilities of each of the monthly distributions, they were then applied to the ordinates of the VIC historical simulation hydrograph. As shown in Figure 8, the uncorrected ensemble hydrographs did not carry enough rainfall runoff volume during the spring months, which is typically the “wet” season within the Oologah Lake watershed. Once the bias correction step was performed, the ensemble hydrographs were shifted up during this time period, representing an increase in total runoff volume.

Application of the bias correction factors to the simulated hydrograph period within the historical overlap period improved the correlation between the two datasets (Figure 9). Although some bias remains, the adjustment to the simulated hydrograph during the historical overlap period compares favorably with the computed firm yield from the observed dataset.

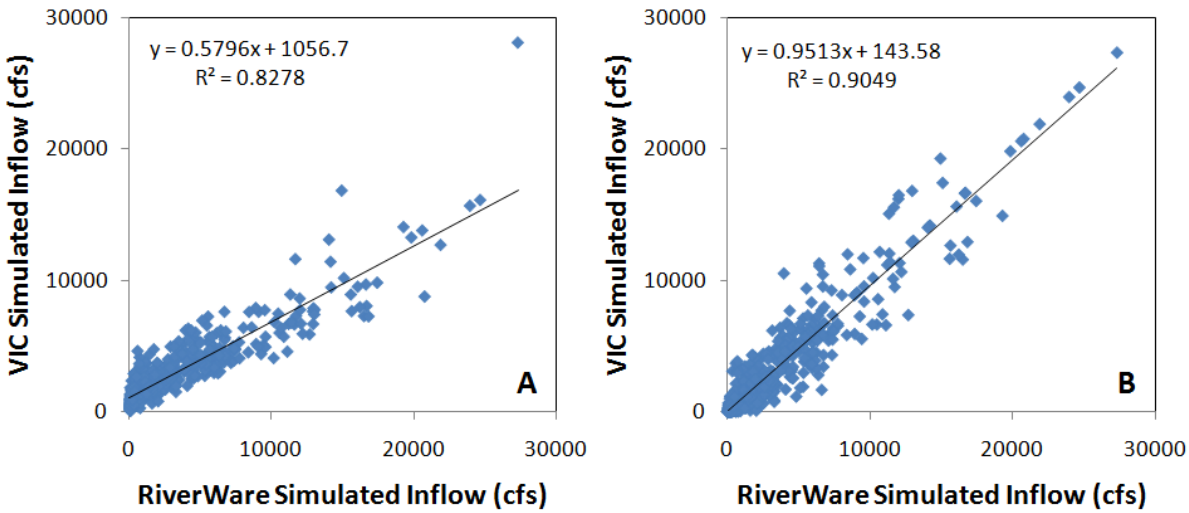

FIGURE 9: Improvement in correlation between A) historical observed and VIC simulated monthly hydrographs without additional bias correction and B) historical observed and VIC simulated monthly hydrographs with additional bias correction developed from cumulative distribution functions of monthly-binned ordinates.

Implementation of this additional bias correction did improve the performance of the VIC simulated inflow hydrograph in the firm yield computation, lowering the resulting value from 1250 cfs to 760 cfs. This remains significantly higher than the firm yield calculated from the observed and RiverWare simulated historical datasets, however, and the computation also resulted in a second critical period during the 1960s drought. Sources of the remaining bias include 1) a continuation of the mismatch between the physical processes in the VIC model versus what is observed in nature, and perhaps more importantly, 2) a difference in hydrograph ordinates between the RiverWare and VIC historical simulations. In fact, the historical inflow hydrograph used in the VIC simulation was derived

from the Lenapah, Oklahoma USGS stream gage on the Verdigris River. While this gage is in the general proximity of Oologah Lake, it is approximately 20 miles upstream from the reservoir pool at a normal loading condition, and therefore does not account for runoff volume along this additional river reach nor runoff that directly interacts with the lake surface. The non-linear distribution of this additional runoff with respect to the hydrograph used for the VIC simulation may be influencing the firm yield computation.

With the understanding that the firm yield computation resulting from the VIC simulation was higher than the accepted value, the analysis was carried forward. Bias correction factors developed from the monthly CDF were applied to each of the hydrographs generated with VIC from the 112 unique climate projections that were analyzed in the study. Specifically, all time-series data in each of the 112 climate projection hydrographs were assigned correction factors from the appropriate monthly CDF corresponding to each ordinate. Since the correction factors were distributed across a range of probabilities, linear interpolation was used to develop the corrected hydrographs.

RESULTS AND DISCUSSION

Projected temperature and precipitation trends from each of the 112 BCSD model projections were analyzed in order to support conclusions drawn from the A2, B1, and A1b emissions scenarios yield studies. In order to look at a "snapshot" of these variables, a planning horizon of 40 years was chosen. Both of these variables were analyzed based on the year 2050 for the Oologah Lake watershed.

Temperature provided the most straightforward analysis with regard to climate variability across the watershed. All models projected an increase in mean temperature through the year 2050, and based on Weibull position plotting, the median increase in mean temperature was projected to be +4.76˚F (Figure 10). A mean temperature increase of at least 2.96˚F was forecasted by 90% of the simulation models. Maurer and Hidalgo (2008) found that the BCSD method reproduced temperature with greater skill than precipitation.

Precipitation simulations for the year 2050 were evenly split with half of the models predicting more annual rainfall and the other half predicting less. The majority of the models predicted that the change in annual rainfall will be +/- 10%. Within the Oologah Lake watershed, this is within +/- 4 inches, which falls within the current range of annual rainfall variability. The watershed receives (on average) approximately 10 inches of snowfall a year, which equates to 1-2 inches of liquid equivalent precipitation. It can be assumed that the model consensus trend to a warmer climate by year 2050 will shift most of this precipitation to rainfall.

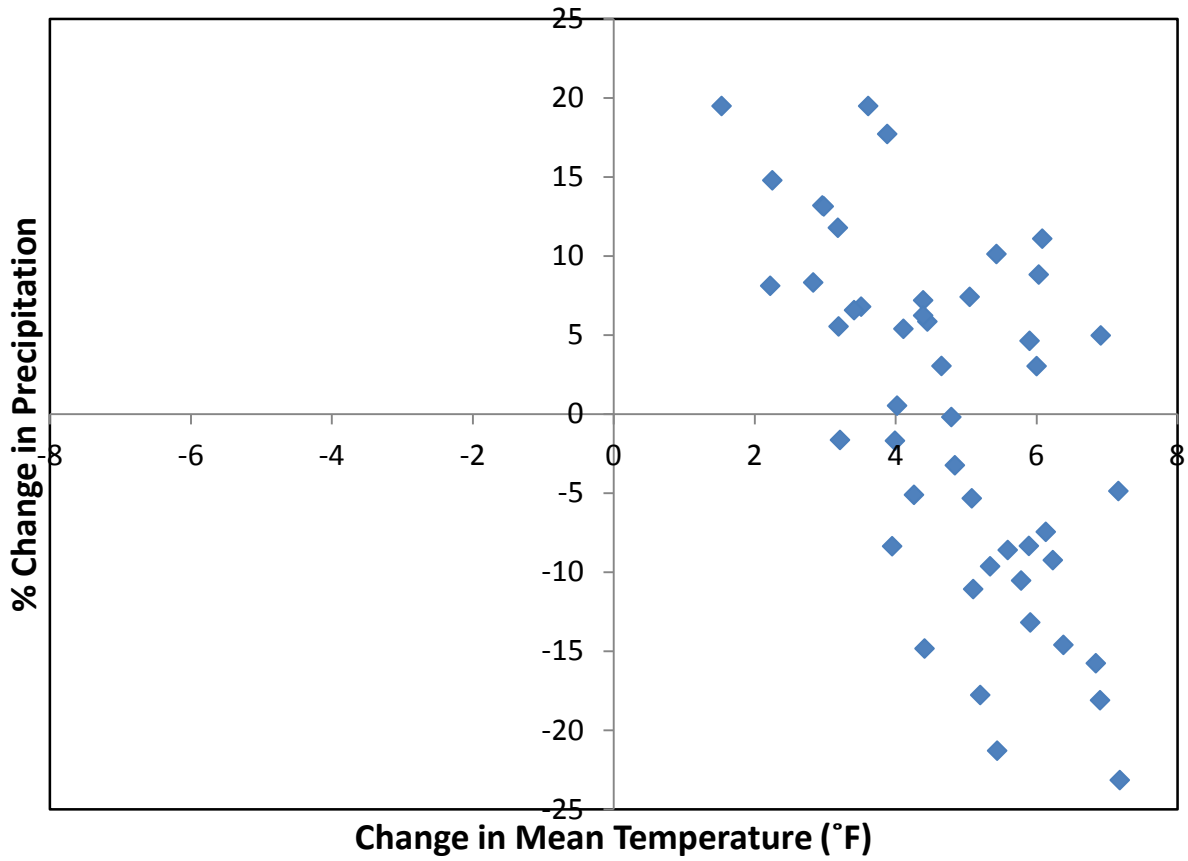

FIGURE 10: Quadrant plot of year 2050 temperature and precipitation for the Oologah Lake watershed denoting "cooler, wetter," "cooler, drier," "warmer, wetter," and "warmer, drier" conditions.

The A1b projections, which represent a balance between fossil fuels and "green" energy resources, were previously investigated for future trends in temperature and precipitation within an adjacent watershed. These projections all forecasted warmer temperatures through the end of the study period. The change in annual mean air temperature (from present conditions) by year 2098 across the model ensemble ranged from +2°C to +8°C (Figure 11).

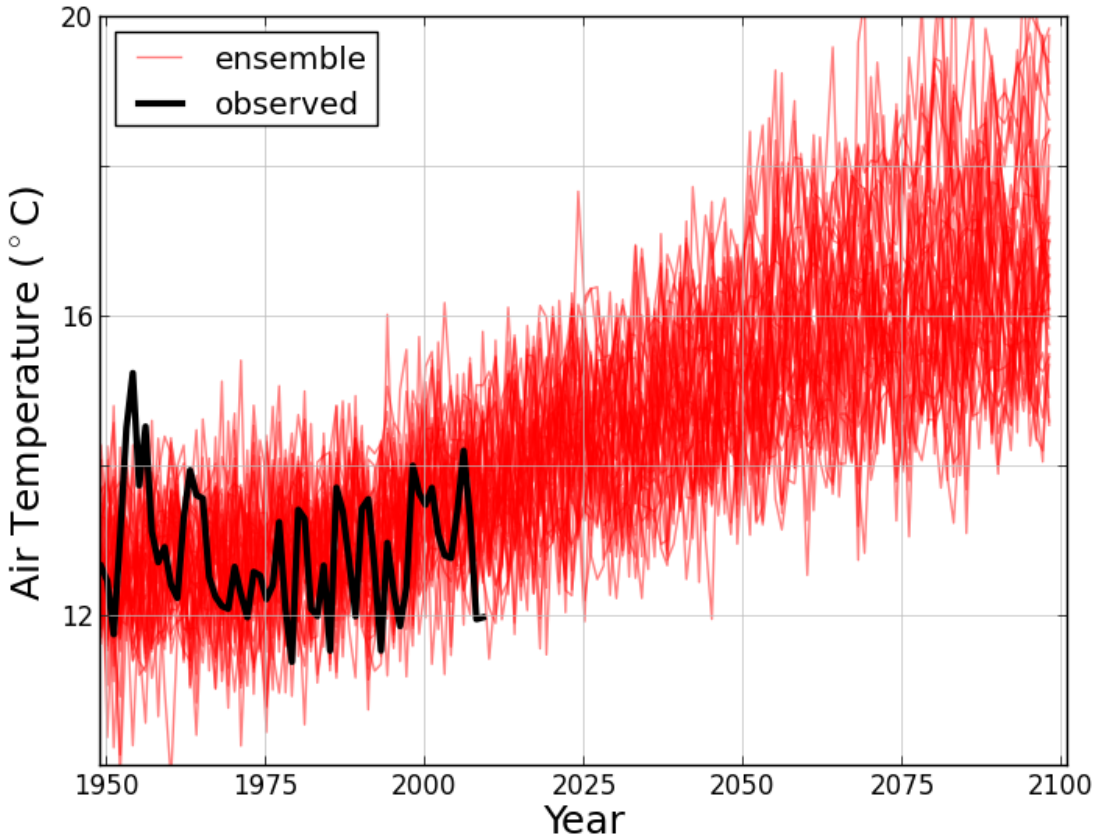

FIGURE 11: A1b emissions scenario model projections for annual mean air temperature through the year 2098. The observed temperature trend is plotted through the year 2009.

Model results were less straightforward with respect to future precipitation trends. It was demonstrated with the A1b projections that the climate models forecast a warmer future. However, no clear precipitation trend emerged from the ensemble of A1b projections, which was consistent with the findings that were presented in Figure 12. The A1b ensemble mean did increase by 50 mm/year over the duration of the simulation, equivalent to an increase of 2 inches of annual precipitation (Figure 12).

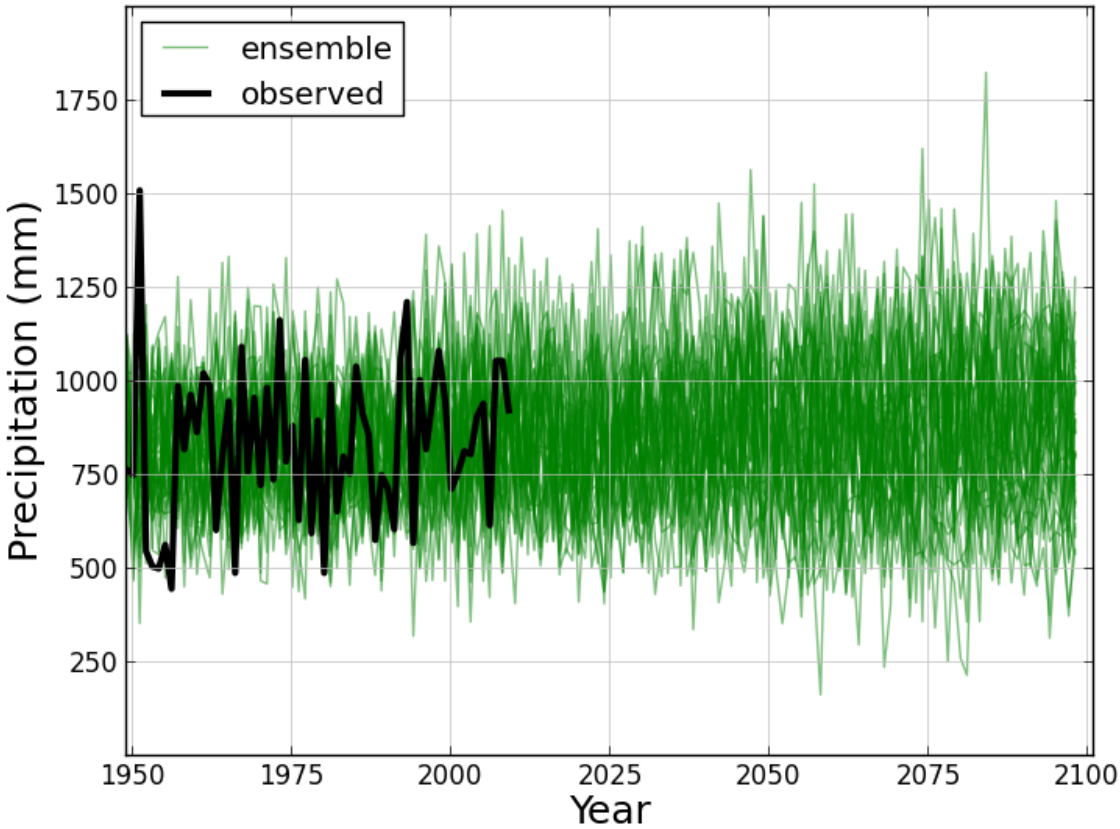

FIGURE 12: A1b emissions scenario model projections for annual precipitation through the year 2098. The observed precipitation trend is plotted through the year 2009.

Results from the A2 emission scenario were more aggressive than the A1b scenario with respect to the rise in mean annual air temperature during the future simulation period. This does not necessarily imply an increased risk for drought in the Oologah Lake watershed, however, as many of these model projections also forecast a wetter future.

Each of the A1b and A2 model projection hydrographs, generated by running the VIC output through the routing code developed by Lohmann (1998), were then adjusted using the CDF procedure discussed in the previous section. Results from the B1 emissions scenario were omitted from the yield analysis since it represents a greater departure from a fossil fuel economy than either the A2 or

A1b scenarios, which may be less realistic than the latter two scenarios. The resulting hydrographs showed no appreciable change in mean stream flow through the year 2098. Not surprisingly, the variation in stream flow increased by the end of the study period, an indication that the uncertainty of the model results was increasing as well (Figure 13).

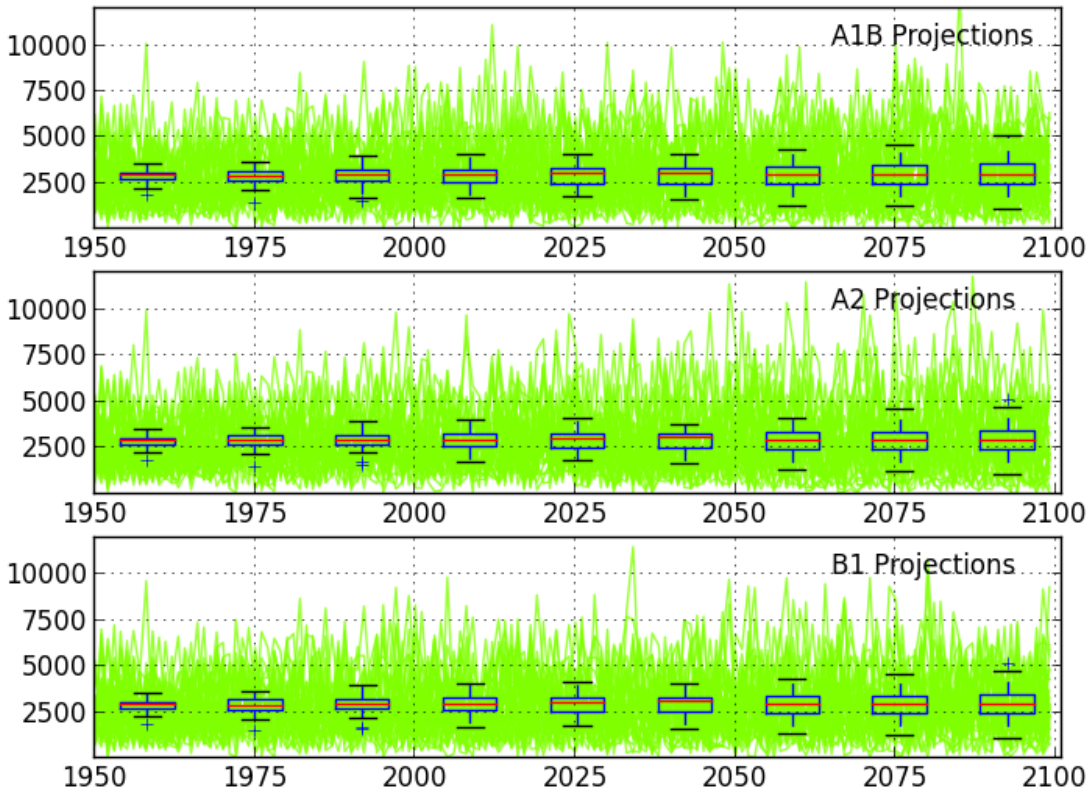

FIGURE 13: Inflow hydrographs (annual mean) computed for Oologah Lake from the A1b and A2, and B1 model projections; Box plots depict 30-year period means.

The current water supply storage under contract in Oologah Lake is 327,005 acre-feet, which is 95% of the allocated water supply storage in the reservoir. Additional yield is required for the McClellan-Kerr Arkansas River Navigation System. Since all but 5% of the water supply storage in the reservoir is under

contract, capacity is nearly maximized. Any significant decrease in firm yield will jeopardize the existing contracts.

All 112 ensemble projections (A1b, A2, and B1 emissions scenarios) were routed through the yield model for the entire study period ending in the year 2098. Changes in precipitation in conjunction with changes in evapotranspiration and hydrologic runoff produced ensembles that, for the most part, indicate no major changes in firm yield (Figure 14).

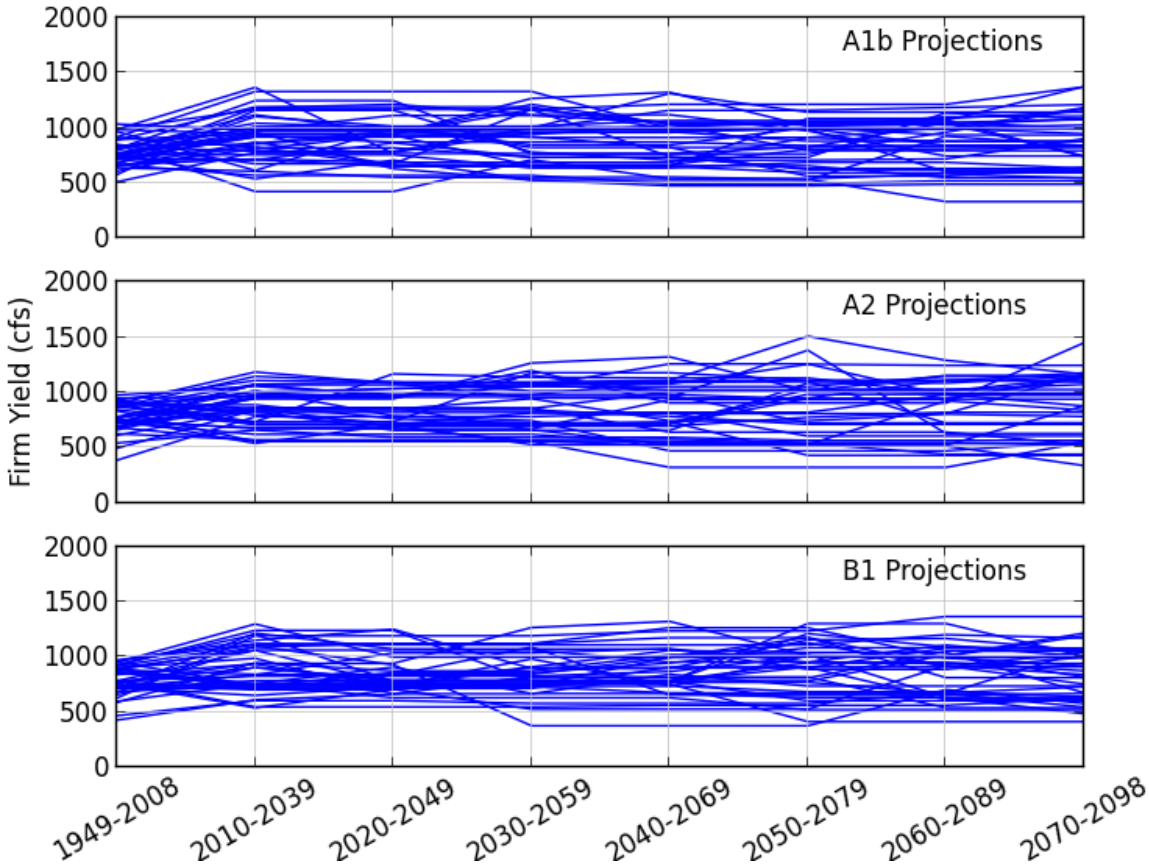

FIGURE 14: Firm yield for the A1b, A2, and B1 emissions scenarios, calculated from hydrographs developed as part of this study ("feasibility" level); the upper and lower bounds of 30-year ensemble mean firm yields for all A1b and A2 emissions scenarios are plotted as shaded areas.

Hydrographs that were previously developed by the U.S. Bureau of Reclamation from the ensemble climate projections were then compared with the hydrographs

generated in this study in order to determine if a “reconnaissance” level of detail is sufficient to draw conclusions about water supply availability (USBR, 2012). Although the U.S. Bureau of Reclamation hydrographs were not available for the Oologah Lake watershed, they were available for the adjacent Hulah Lake watershed.

The Hulah Lake watershed is smaller in aerial coverage than the Oologah Lake watershed, so adjustments to the hydrographs were necessary before yield modeling could be performed. Historical hydrographs from both lakes for the period 1940-2008 were generated in RiverWare. These hydrographs were then compared with one another using the CDF and Weibull plotting formula described in the previous section. Correction factors developed from the monthly CDF were applied to each of the 112 unique climate projection hydrographs obtained from the U.S. Bureau of Reclamation. Two assumptions were required in order for this approach to be valid: 1) uniform coverage of precipitation across both watersheds, and 2) similar watershed characteristics, including soil moisture and infiltration properties.

Once these hydrographs were assigned correction factors from the appropriate monthly CDF corresponding to each ordinate, they were routed through the yield model for the entire study period ending in the year 2098. Firm yield for the A1b, A2, and B1 emissions scenarios were calculated as 30-year ensemble mean values and plotted in Figure 15.

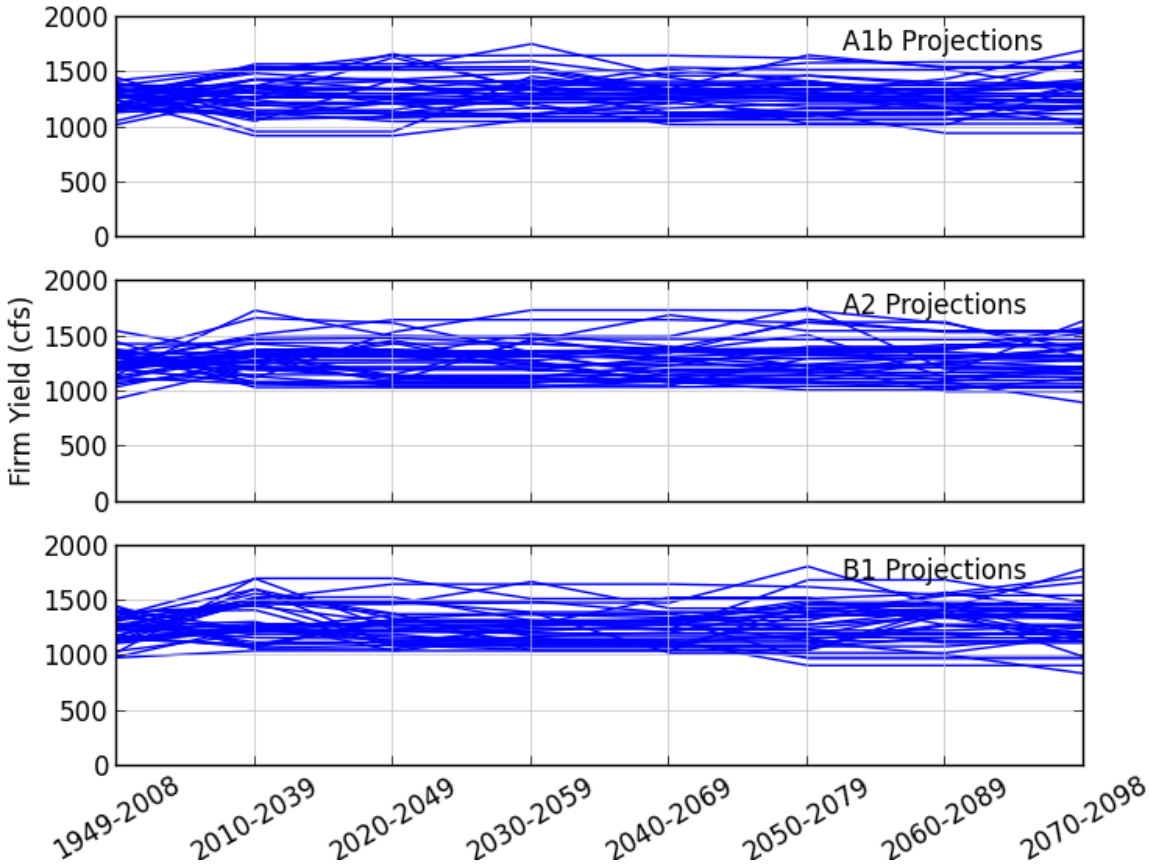

FIGURE 15: Firm yield for the A1b, A2, and B1 emissions scenarios, calculated from previously developed U.S. Bureau of Reclamation hydrographs ("reconnaissance" level); the upper and lower bounds of 30-year ensemble mean firm yields for all A1b and A2 emissions scenarios are plotted as shaded areas.

Development of firm yield modeling from the pre-existing U.S. Bureau of Reclamation climate-projection hydrographs matched the trends observed from the firm yield modeling using hydrographs developed as part of this study, but the magnitude was higher for all three emissions scenarios. Based on the trends, this method produced ensembles that indicate no major changes in firm yield, which is consistent with the "feasibility" level of detail.

Ideally, another bias-correction step would be performed in conjunction with the pre-existing U.S. Bureau of Reclamation climate-projection hydrographs in order to address the discrepancy in the magnitude of firm yield. Unfortunately, the

VIC-simulated historical hydrograph necessary for bias correction was not provided by the U.S. Bureau of Reclamation as part of the packaged hydrograph data. Without this additional information, the "reconnaissance" level of detail is useful when drawing conclusions about water supply trends but cannot be used to assess the magnitude of firm yield.

The magnitude of the "feasibility" level of detail firm yield calculations for the 1949-2008 historical period are also higher than the accepted RiverWare simulated inflow firm yield for the same period. This is likely a result of both 1) residual model bias and 2) different input hydrographs. Instead of focusing on the computed magnitude of the firm yield, it is perhaps more meaningful to interpret the trends in firm yield through the future planning periods.

Projections of the mean firm yield do provide insight about model trends (in this case, the trend for both emissions scenarios is nearly stationary). Mean ensemble values of firm yield are too general for water supply planning. Firm yield is event driven (i.e. historical drought), and knowledge of whether or not a dependable volume of water can be delivered to a customer is a key element in planning and executing the terms of a water supply contract.

Existing contracts at Oologah Lake, which are permanent, require a dependable yield of 239 ft^3/s, with an additional 130 ft^3/s required for the McClellan-Kerr Arkansas River Navigation System. The basis for this firm yield requirement stems from the original design of the reservoir, which assumed that the capacity of Oologah Lake would decrease by 64,000 acre-feet over a 50-year period (it is also noted in the 1956 report titled "Oologah Reservoir Design Memorandum No. 8: Hydrology" that the expected sedimentation would decrease by 24,000 acre-feet if Elk City and Neodesha Reservoirs were constructed; Elk City Lake was completed in 1966). This rate of sedimentation has not been realized. The most current capacity table for the project, which was updated in 2010, indicates that the actual volume of the reservoir has only decreased by 3,400 acre-feet.

TABLE 1: 50-year reservoir capacity used as the basis for original yield routing in 1956.

CAPACITY OF OOLOGAH RESERVOIR INITIALLY AND AFTER 50 YEARS OF SEDIMENTATION

Elevation (feet, m.s.l.)	Capacity (acre-feet) Initial	After 50 years
570	220	0
580	2,100	0
590	7,300	0
600	24,380	11,600
610	70,740	51,300
620	169,300	142,300
630	346,500	311,500
640	614,100	570,500
650	977,800	923,100
660	1,462,000	1,398,000
670	2,091,000	2,027,000
680	2,888,000	2,824,000

Navigation requirements were documented in a 1968 report titled "Water Requirements for Navigation on Verdigris River at Lock and Dam No. 18." In this report, it was determined that based on the expected volume of barge traffic, the dependable yield not already allocated to municipal water storage would be necessary for navigational purposes. Firm yield was originally calculated as 369 ft^3/s based on the 50-year capacity table, with 239 ft^3/s (154,000,000 gal/day) required for municipal water supply and 130 ft^3/s (81,300,000 gal/day) required for navigation. The original basis for the 154,000,000 gal/day municipal withdrawal appears to have been a request from the City of Tulsa in 1956 for a yield of 100,000,000 gal/day combined with requirements from other original customers, including several smaller communities and the Public Service Co. of Oklahoma.

Since the 50-year rate of sedimentation has not been realized, the actual firm yield of the reservoir (calculated as 450 ft^3/s in this study) is significantly higher than the firm yield on which the present water supply allocation is based. In fact, it is possible that an additional 57,000 ac-ft/yr may be available for contract or other use. Yield modeling for the A1b, A2, and B1 scenarios indicates that future trends will be similar to present conditions with no discernable upward or downward shifts in mean firm yield. Most of the projections are in agreement

with this trend, providing a relative confidence that existing contracts with the municipalities and rural water districts that rely on supply in Oologah Lake will be met (Table 2). Additionally, 15,595 acre-feet is presently allocated but not under contract, and when combined with the sedimentation volume that has not been realized over the 50-year planning horizon, as much as 65,000 ac-ft/yr of additional dependable yield is currently available in the reservoir.

TABLE 2: Terms of existing Oologah Lake water supply contracts.

Customer	Approval Date	Storage (Acre-Feet)	Yield (ft^3/s)
Rogers County RWD #4	7/05/1985	1590	1.1
Public Service Co. of Oklahoma	5/08/1985	20990	14.6
Rogers County RWD #3	2/08/1985	5960	4.1
Nowata County RWD #1	3/07/1985	200	0.1
City of Collinsville	6/26/1985	6670	4.6
Tulsa Metropolitan Water Authority	2/08/1985	285450	198.5
City of Claremore	9/19/1988	445	0.3
Washington County RWD #3	9/22/1992	4170	2.9
Town of Chelsea	4/02/1982	1530	1.1
Not Under Contract	N/A	15595	10.8

The envelope of possible future outcomes, based on climate projections from the A1b and A2, and B1 emissions scenarios, suggests that future firm yield will not differ significantly from current firm yield. The upper and lower bounds of the analysis expand with respect to time due to model uncertainty, but given the nearly stationary behavior of the ensemble means, the model consensus portrays future water supply conditions that look similar to present day. Most of the ensembles do not show a decrease in firm yield through the end of the study period. Based on these results, the existing contracts at Oologah Lake appear to be sustainable through the lifetime of the agreements with additional contract capacity that is not currently utilized.

A prudent approach to managing water supply contracts at Oologah Lake may therefore include monitoring firm yield on a regular interval such as a moving 30-year mean. The existing water supply contracts expire between the years 2021 and 2039, and prior to the expiration of these agreements and presumable extension of new agreements, the future firm yield analysis can be recomputed, taking advantage of new climate forcings and general improvements in the state

of climate modeling. Upper and lower firm yield thresholds can be set that trigger analysis, either because additional contracts are sought or because changing conditions have jeopardized existing contracts. If, for example, a firm yield threshold on the lower bound is reached, then an individual projection or collection of projections that track closely with the threshold criteria can be analyzed in greater detail to make informed decisions about future water supply contracts.

Unlike coastal or mountainous areas where changes in sea level or snowpack elevation may be more easily observed, climate impacts on water supply reservoirs in the Great Plains are less obvious. Climate projection ensembles do not show pronounced uniformity in precipitation changes in this region, although the ensemble mean does trend toward more net precipitation. It is not known for certain if the currently available set of climate model projections represents a wide distribution of possibilities, but the likely answer is no. Many climate change uncertainties exist with respect to modeling, and currently available climate projections certainly do not capture all of these. The complexity of atmospheric processes and feedback loops, ranging from physical processes to chemical composition, are far too complex to be completely represented in what can be termed a state-of-the-art model. This statement is not meant to imply that modern climate models lack sophistication. They are highly complex and numerically intensive, but as with any technology, they will improve with time. While the answers that these models provide offer an educated guess, remember that it is still important to see their solutions as one of many possible outcomes. As knowledge advances, so too will the ability to forecast the viability of water resources.

Climate modeling, although still in its infancy, can be used to draw important conclusions regarding the Oologah Lake watershed. The models unanimously predict warmer temperatures in the future. Half of them predict in increase in annual precipitation. Most of the models indicate that future precipitation will remain within +/- 10% of current annual values. When viewed as an ensemble, the model projections do not suggest that stream flow will change appreciably during the future.

The results of this study suggest that stresses resulting from climate change at Oologah Lake will not increase over time, and that existing water supply contracts will continue to be met. Furthermore, the capacity for additional water

supply contracts currently exist, and the modeling results suggest that this additional capacity will continue to exist in the future.

SUMMARY OF FINDINGS

- All 112 ensemble projections were in a consensus agreement that future conditions will be warmer over the Oologah Lake watershed, with a median increase in temperature among all models of +4.76˚F by the year 2050.

- No consensus existed with respect to future precipitation trends in the Oologah Lake watershed. Half of the models in the ensemble projections predict an increase in annual rainfall by the year 2050, while the other half predicts a decrease in annual rainfall. Most of the models fall within a ± 10% range by the year 2050 based on current climatology.

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

- The Oologah Lake watershed receives (on average) approximately 10 inches of snowfall a year, which equates to 1-2 inches of liquid equivalent precipitation. Some of this precipitation may shift to rainfall.

- The VIC simulated inflow hydrograph exhibited good skill when replicating the critical period. The timing and duration of historical droughts, including the 1952-1957 drought of record, was generally correct.

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

- Most of the model ensemble projections suggests that firm yield will not change significantly over time.

- "Reconnaissance" level modeling from pre-existing U.S. Bureau of Reclamation climate-projection hydrographs exhibited skill in reproducing water supply trends from the "feasibility" level modeling but had higher magnitudes of firm yield.

- Stresses that were considered did not include increased demand from users. History has shown that demand increases during heat waves that are associated with droughts. The record use by the Tulsa Metropolitan Water Authority occurred in August 2011.

- Based on the modeling results, Oologah Lake appears to be well positioned to meet future water supply obligations, particularly since no future additional allocations are contracted.

REFERENCES

AMEC (2011). Oklahoma Comprehensive Water Plan: Climate Impacts to Streamflow. Prepared for the Oklahoma Water Resources Board.

Hartmann, D. L. (1997). Our Changing Climate: Reports to the Nation on Our Changing Planet. http://www.atmos.washington.edu/~dennis/RTN4.pdf.

IPCC (2000). Special Report on Emissions Scenarios. ISBN 92-9169-113-5.

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D.P. (1998). Regional Scale Hydrology: I. Formulation of the VIC-2L Model Coupled to a Routing Model. *Hydrological Sciences*, 43(1): 131-142.

Maurer, E.P. and Hidalgo, H.G. (2008). Utility of Daily vs. Monthly Large-Scale Climate Data: An Intercomparison of Two Statistical Downscaling Methods. *Hydrology and Earth System Sciences*, 12: 551-563.

USACE (1956). Oologah Reservoir Design Memorandum No. 8: Hydrology. Hydrology and Hydraulics Branch, Tulsa District.

USACE (1962). Reservoir Regulation Manual for Oologah Reservoir. Hydrology and Hydraulics Branch, Tulsa District.

USACE (1975). Oologah Lake Regulation Manual. Hydrology and Hydraulics Branch, Tulsa District.

USACE (1990). Drought Contingency Plan: Lower Verdigris River, Kansas. Hydrology and Hydraulics Branch, Tulsa District.

USACE (2010). Methods for Storage/Yield Analysis. Hydrologic Engineering Center.

USBR (2010). Climate Change and Hydrology Scenarios for Oklahoma Yield Studies. Technical Memorandum 86-68210-2010-01.

USBR (2011). West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections. Technical Memorandum 86-68210-2011-01.

USBR (2012). West-Wide Climate Risk Assessments: Projected Streamflow. Retrieved from http://www.usbr.gov/WaterSMART/wcra/flowdata/index.html.

Werner, A.T. (2011). BCSD Downscaled Transient Climate Projections for Eight Select GCMs over British Columbia, Canada. Pacific Climate Impacts Consortium.

Wood, A.W., Leung, L.R., Sridhar, V., and Lettenmaier, D.P. (2004). Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. *Climatic Change*, 62: 189-216.

Technical Supplement 2

Climate Change Analysis In the Verdigris River Watershed In Oklahoma and Kansas, And Oologah Lake, Using SWAT and CE-QUAL-W2

March 2013

US Army Corps of Engineers

Institute for Water Resources

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Introduction

As an aid in the development of a watershed assessment for the Verdigris River Watershed above Oologah Lake (USACE-Tulsa District, 2012), two simulation modeling tools were employed to compile and evaluate data describing the watershed and reservoir. Assessing the impacts of climate change projections on water quality is an extended application of these calibrated models.

The location of the Verdigris watershed, above the Oologah Lake dam, is shown in Figure 1. The watershed covers approximately 4,300 square miles (11,100 km^2) and includes portions of Craig, Nowata, Washington, and Rogers counties in Oklahoma, and Lyon, Chase, Coffey, Greenwood, Butler, Woodson, Wilson, Neosho, Elk, Montgomery, Chautauqua, and Labette counties in Kansas.

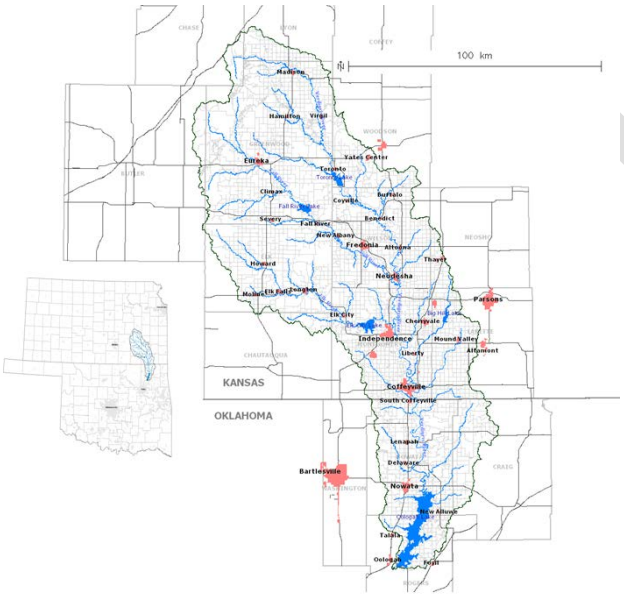

Figure 1. Location of the Verdigris River Watershed, above the Oologah Lake Dam, in Oklahoma and Kansas.

Verdigris Watershed SWAT Modeling

The Soil and Water Assessment Tool (SWAT), AVSWAT-X for SWAT2005 (Neitsch, Arnold, Kiniry, Srinivasan, & Williams, 2004), a basin-scale model functioning within ArcView 3.2a (ESRI, 1996), was selected to process digital information to estimate annual average sediment yield, and nitrogen and phosphorus loading, from the Verdigris River watershed above the Oologah Lake dam, by generalized land use. SWAT, developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS), is a basin-scale model "... developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time" (Neitsch, Arnold, Kiniry, & Williams, 2005). The model is physically based in that it requires specific information about weather, hydrology, soil properties, topography, vegetation, and land management (Gassman, Reyes, Green, & Arnold, 2007).

Modeling of the Verdigris River watershed above the Oologah Lake dam required spatially referenced digital data describing elevation, land use/cover, soil types and attributes, and weather. Additionally,

historical stream discharge from available gaging stations within the watershed, water quality and storage data from streams, ponds and reservoirs, specific crop types and areal extent (by county), livestock types and densities (by county), and commercial fertilizer applications (by county) were collected and used for model calibration and data input to the model.

The Verdigris River watershed above the Oologah Lake dam is defined by four 8-digit USGS hydrologic cataloging units (HUCs) including 11070101 (Upper Verdigris, Kansas), 11070102 (Fall, Kansas), 11070103 (Middle Verdigris, Kansas and Oklahoma) and 11070104 (Elk, Kansas). Each of these 8-digit HUCs was further subdivided into subbasins approximating 14-digit HUCs, resulting in a total of 99 subbasins for the full watershed, averaging 11,200 hectares (Figure 2).

Land use/cover in the Verdigris River watershed above the Oologah Lake dam, derived from National Land Cover Data (NLCD, (USDA/NRCS, 2001)), is summarized in Table 1. Based on the NLCD data, unmanaged grasslands account for 44.6% of the total area (grasslands plus shrubland), managed pasture/hay land 30.5%, croplands 11.0%, forests 8.4%, and the remainder is distributed between other minor land uses. Soils data incorporated into the model (USDA-NRCS, 2007) indicates the most common soil series present in the watershed, by percent total watershed area, are Clime (10.58%, silty clay), Eram (8.66%, clay loam), Dennis (7.75%, silt loam), Kenoma (6.65%, silt loam), and Bates (5.95%, loam). The functional unit in the SWAT model is termed a 'hydrologic response unit' (HRU). An HRU represents a land use/soil type combination within a subbasin. The calibrated/validated SWAT model of the full Verdigris River watershed above the Oologah Lake dam resulted in 2,899 HRUs, or an average of about 29 HRUs per subbasin.

Table 1. Land use/cover from NLCD data (USDA/NRCS, 2001) for the Verdigris River watershed above the Oologah Lake dam.

NLCD Description	Hectares	% Area
Open Water	28,150	2.54%
Low Intensity Residential	2,590	0.23%
High Intensity Residential	2,670	0.24%
Commercial/Industrial/Transportation	2,810	0.25%
Bare Rock/Sand/Clay	120	0.01%
Quarries/Strip Mines/Gravel Pits	850	0.08%
Transitional	540	0.05%
Deciduous Forest	83,430	7.53%
Evergreen Forest	2,420	0.22%
Mixed Forest	7,040	0.64%
Shrubland	33,050	2.98%
Grasslands/Herbaceous	460,670	41.57%
Pasture/Hay	337,920	30.49%
Row Crops	112,290	10.13%
Small Grains	9,690	0.87%
Urban/Recreational Grasses	1,390	0.13%
Woody Emergents	10,130	0.91%
Emergent Herbaceous Wetlands	12,410	1.12%
	1,108,170	100.00%

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Figure 2. **Subbasin divisions, streams, and major reservoirs in the Verdigris River Watershed above the Oologah Lake Dam.**

Weather data, driving the original watershed model, collected from 17 Cooperative Observer Program (COOP) weather stations in and near the Verdigris River watershed for calendar years 1955 through 2005, included daily precipitation and daily minimum and maximum air temperature. SWAT generates runoff using the SCS curve number equation (Soil Conservation Service, 1972).

Hydrologic calibration of the model required historical daily mean discharge data from unregulated gaging stations in the watershed. Discharge data from 17 available gaging stations in the watershed were obtained from the USGS National Water Information System Web Interface (NWIS) (USGS, 2006) and from the U.S. Army Corps of Engineers (USACE). Hydrologic calibration (1960–1990) and validation (1991–2005) resulted in Nash-Sutcliffe Efficiency (Nash & Sutcliffe, 1970) values of 0.90 or better for annual stream discharge at the Verdigris River gage just above Oologah Lake. Water quality calibration and validation resulted in average annual concentration relative errors of less than 10% for total suspended solids (TSS) and total phosphorus (TP), and less than 15% for total nitrogen (TN), at the Verdigris River gage just above Oologah Lake.

Watershed modeling, based on measured weather data for the period 1955 through 2005 and summarized over a 50-year period (1956-2005), indicated that crop land uses contributed majority fractions of total sediment and organic nutrient loading. Estimated annual average pollutant loading to Oologah Lake included nearly 800,000 metric tons of sediment, in excess of 4,000,000 kilograms of TN, and more than 650,000 kilograms of TP.

Oologah Lake CE-QUAL-W2 Reservoir Modeling

CE-QUAL-W2 (Cole & Wells, 2008) was the lake/reservoir model selected to evaluate the in-lake effects of watershed inputs to Oologah Lake as part of the assessment for the Verdigris River Watershed above Oologah Lake (USACE-Tulsa District, 2012). CE-QUAL-W2 is a two-dimensional,

longitudinal/vertical, hydrodynamic and water quality model capable of predicting water surface elevations, velocities, temperatures, and a broad range of water quality constituents including hydraulic residence time, multiple inorganic suspended solids groups, multiple phytoplankton groups, ammonium, nitrate plus nitrate, bioavailable phosphorus, dissolved and particulate organic matter, and dissolved oxygen (DO), among others. The model can easily simulate long-term water quality responses in estuaries, rivers, and reservoirs.

Data required for model development and application include geometric data describing the waterbody of interest; initial conditions (time of simulation, water temperature and constituent concentrations, inflows and outflows); boundary conditions describing upstream inflows, tributary and non-point inflows, downstream outflows, lateral withdrawals, and evaporation; surface boundary conditions describing location, air temperature, dew point temperature, wind speed and direction, wind sheltering, cloud cover, short wave solar radiation, and light attenuation; hydraulic parameters describing horizontal and vertical dispersion and diffusion coefficients, and bottom friction; kinetic parameters including multiple coefficients used to make adjustments in the calibration process; and finally, calibration data to provide initial and boundary conditions and to assess model performance during calibration (Cole & Wells, 2008).

Bathymetry data were derived from a sediment survey performed by the USACE in 2000. CE-QUAL-W2 requires that the reservoir be divided into longitudinal segments and vertical layers that can vary in length and height. One main branch and three side branches were identified for Oologah Lake, resulting in a total of 45 active segments (Figure 3). GRASS GIS (GRASS Development Team, 2011) was used to generate 0.5 meter vertical layers within each segment, and to determine average layer lengths (Figure 4).

Daily reservoir inflow, release, and water level (elevation) data were obtained from USACE-Tulsa District Water Control Data System (USACE-Tulsa District, 2006). Data collected from the Verdigris River near Lenapah, OK (VR-2), and Big Creek near Childers, OK (BC-1) from calendar years 2000 through 2005 were used to generate water quality constituent boundary data input for the CE-QUAL-W2 Oologah Lake model. Using measured hydrodynamic, temperature, and water quality data from Oologah Lake for the period from year 2000 through 2005, model outputs were compared to observed values, and reservoir model parameters were adjusted to generate a calibrated reservoir model.

The calibrated reservoir water quality model effectively reproduced measured Oologah Lake elevation (relative error = 0.37%), volume, water temperature (relative error = 3.27%) and DO (relative error = 5.83%), nutrient, algae, and TSS concentrations for a six year period (2000 through 2005).

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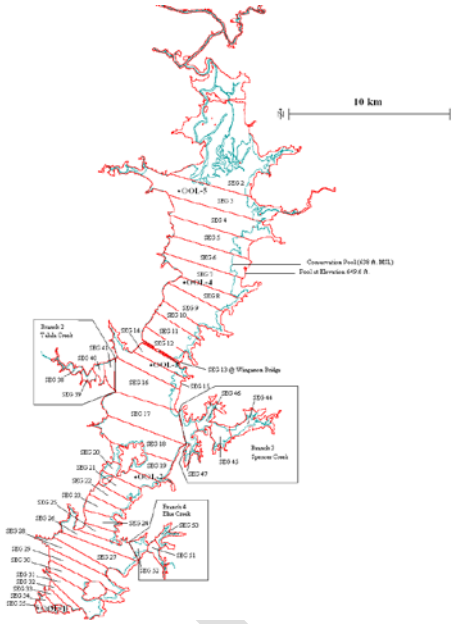

Figure 3. **Oologah Lake segmentation schematic showing conservation pool elevation (blue), lake area at surface elevation of 198 meters (red), modeled segment divisions (red), modeled branches (black outline), and water quality sampling locations.**

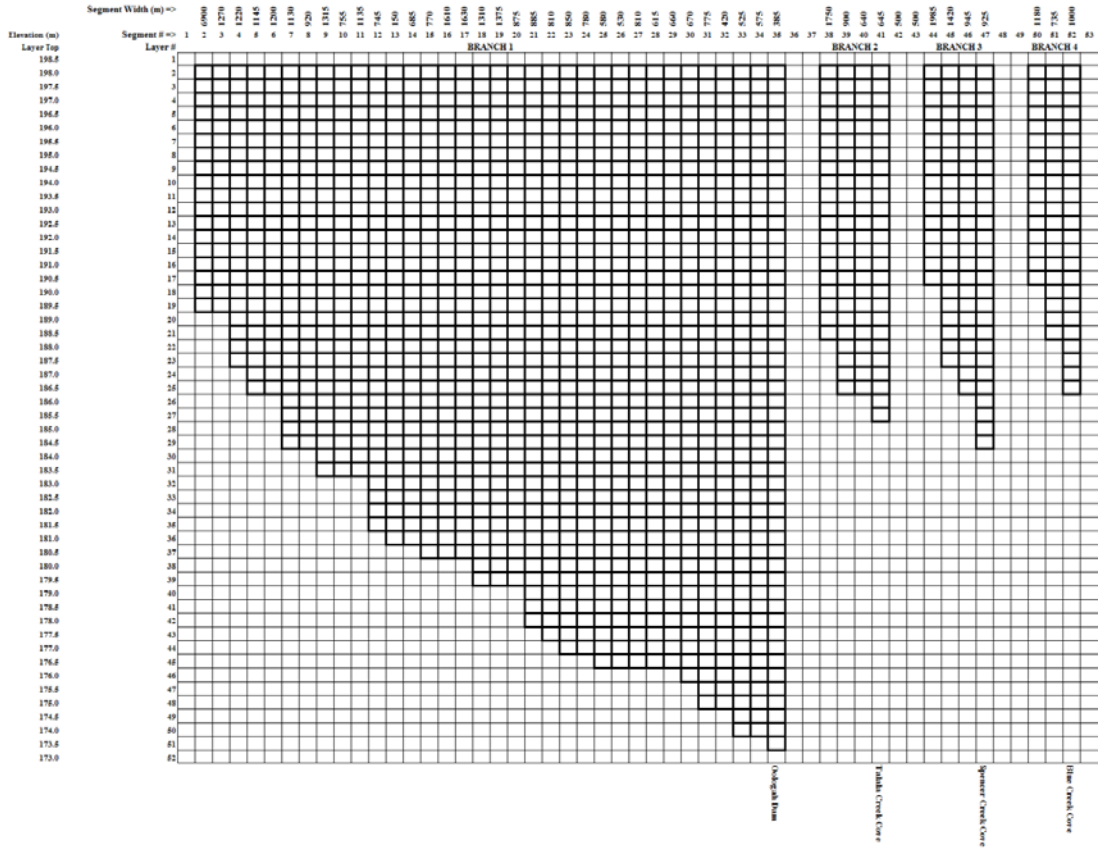

Figure 4. **Oologah Lake CE-QUAL-W2 model grid as side view schematic (segment widths not to scale).**

Assessment of Climate Projections

Assessment of potential climate change effects using watershed and reservoir models is increasingly common, although assessments typically involve either a watershed or reservoir focus. Assessment using SWAT frequently includes simulation of atmospheric CO_2 increases, and defined increases and/or decreases in temperature and precipitation inputs. Jha, Arnold, Gassman, Giorgio, & Gu (2006) modeled Upper Mississippi River Basin streamflow using SWAT with doubled CO_2 concentrations, increasing temperatures, variable precipitation scenarios, and six climate change scenarios. Ficklin, Luo, Luedeling, & Zhang (2009) used SWAT to model increasing atmospheric CO_2 concentrations, increasing temperatures, and variable precipitation in the San Joaquin watershed in California. Dynamically downscaled North American Regional Climate Change Assessment Program (NARCCAP) climate projections were modeled in the Lower Missouri River Basin by Qiao, Pan, Hermann, & Hong (Submitted 2013) using SWAT. Generally, results indicate increases in streamflow with increasing CO_2 levels, decreases in runoff and water yield with increasing temperatures, potential shifts in plant growth patterns, shifts in timing and quantities of seasonal streamflows, and pollutant load quantities corresponding with runoff volume and timing.

CE-QUAL-W2 has been used to assess climate change effects generally focusing on alterations in inflows, inflow temperatures, and air temperature. Obregon, et al. (2012) manipulated air temperature, inflow rates, and phosphorus loads to assess algal concentrations in Deer Creek Reservoir (Utah). Fang, Shrestha, Groeger, Lin, & Jao (2007) modeled variable inflows and increasing temperature scenarios in the Amistad Reservoir (Texas). Results indicated increasing water temperature alters water quality, although algal concentrations were more sensitive to phosphorus inputs. Water temperature increases also lead to earlier and longer-term stratification periods, but strength of stratification is generally diminished due to decreased differences in surface and bottom water temperatures.

A spreadsheet methodology was developed to extract reservoir model daily inputs (inflow, reservoir elevation, outflow, meteorology, constituent concentrations) from watershed model outputs. This allowed for the evaluation of the effects of land management practices in the watershed on the reservoir in the watershed assessment study. This same methodology was employed to evaluate effects of climate change projections on quantity and quality of exports from the watershed to Oologah Lake, and on water quality within Oologah Lake.

Measured daily minimum and maximum temperature, and daily precipitation at the 17 COOP stations (calendar years 1955-2005) were input into the calibrated SWAT model of the Verdigris River Watershed, and routed through the calibrated CE-QUAL-W2 model of Oologah Lake, serving as the baseline for comparison to the future climate projections. The SWAT input/output manual (Neitsch, Arnold, Kiniry, Srinivasan, & Williams, 2004) recommends a one year 'warm-up' period for hydrologic cycle equilibration. Year 1955 served as the equilibration period for the baseline simulation, run through year 2005, resulting in a 50-year simulation. Oologah Lake storage began in 1963 and the current conservation pool was filled in 1972 (USACE-Tulsa District, 1996). The simulations developed for baseline watershed outputs, reservoir inputs, and reservoir responses focused on the available measured climate data for the period 1955-2005, and were run with a functioning reservoir for the entire period of record. All climate projection scenarios were run for 31-year periods with a one year equilibration period resulting in 30-year simulation results.

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NARCCAP and statistically downscaled Bias Corrected and Spatial Disaggregation - Coupled Model Intercomparison Project Phase 3 (CMIP3) weather data were provided by colleagues at the University of Oklahoma (Qiao, et al., submitted 2013). NARCCAP projections, eight different combinations of regional and global climate models, included data for the future time period years 2038 through 2069. CMIP3 included data projections for years 1950 through 2099. NARCCAP and CMIP3 projections, including daily precipitation, daily maximum and minimum temperature, and daily average wind speed were provided in a one-eighth degree grid. Grid points within the boundary of the Verdigris River Watershed were extracted for each climate projection (Figure 5) for input into the SWAT model of the Verdigris River watershed. SWAT model routines selected the extracted climate grid point nearest to the centroid of each subbasin.

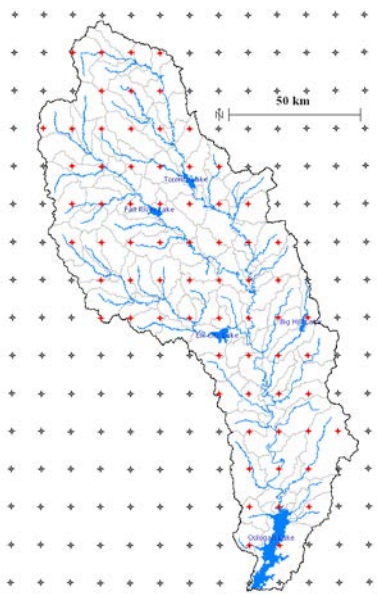

Figure 5. **Extracted 1/8th degree grid points (red) of climate projections used for input into the SWAT model of the Verdigris River Watershed above the Oologah Lake Dam.**

The eight NARCCAP projections were all input through the SWAT and CE-QUAL-W2 models for the time period 2039 through 2069. NARCCAP projections are designated as a regional climate model (RCM)/global climate model (GCM) combination (e.g., CRCM-cgcm3). Of the 112 CMIP3 climate projections provided, only three were modeled, representing the high, medium, and low hydrographs based on yield modeling (David Williams, USACE, personal communication). The SWAT and CE-QUAL-W2 modeled time period for these three projections was 2010 through 2080, divided into three overlapping 31-year periods (2010 through 2040, 2030 through 2060, and 2050 through 2080). CMIP3 high, medium, and low projections are designated as CMIP3H, CMIP3M, and CMIP3L, respectively, throughout this report, with simulation year range added as a suffix (e.g., CMIP3H1040).

All modeled climate projections in this study use the 'A2' emission scenario (Intergovernmental Panel on Climate Change (IPCC), 2000). The SWAT model has the capability of incorporating altered atmospheric CO_2 concentration. Measured average annual atmospheric CO_2 concentrations at Mauna Loa, HI for the period 1959 through 2012 were obtained from the National Oceanic and Atmospheric Administration Earth System Research Laboratory website (NOAA-ESRL). A simple linear trend

evaluation of historical data allowed for a conservative estimation of future atmospheric CO_2 concentrations (Figure 6). Because the SWAT model allowed just one value per simulation run, the mean value per simulated period was selected for input into SWAT climate projection simulations. The baseline period CO_2 concentration modeled was 350 ppm. Concentrations selected for other modeled periods included 450ppm for 2039-2069, 410 ppm for 2010-2030, 440 ppm for 2030-2060, and 470 ppm for 2050-2080.

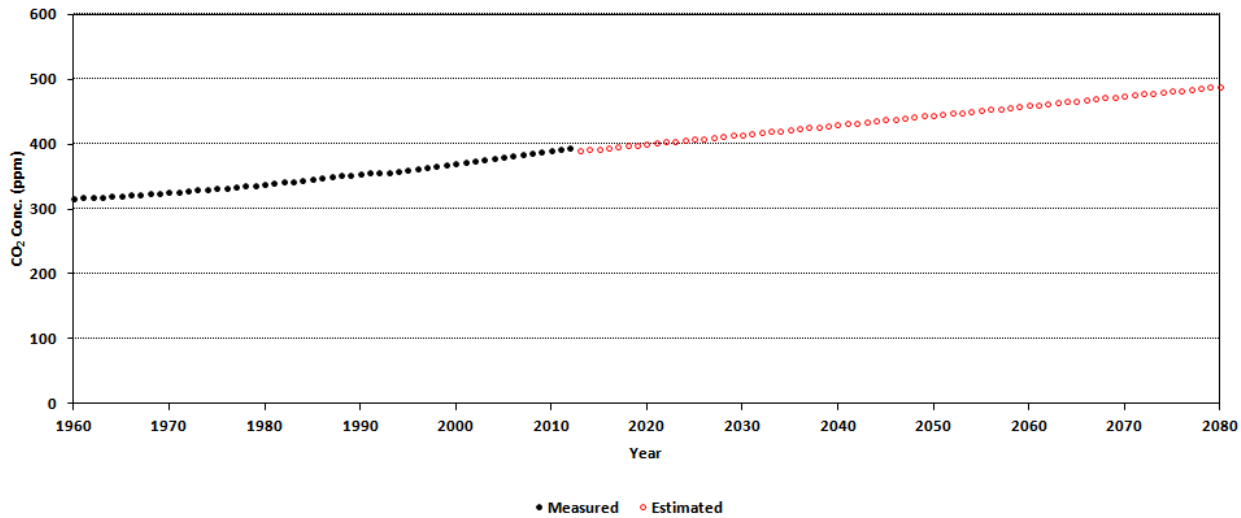

Figure 6. **Measured (NOAA-ESRL) average annual atmospheric CO_2 concentrations at Mauna Loa, HI and estimated future atmospheric CO_2 concentrations.**

SWAT Baseline Results

Baseline watershed modeling indicates greatest average monthly constituent (sediment, nitrogen, and phosphorus) loadings to Oologah Lake are positively correlated with discharge to the lake. Highest average monthly discharge to the lake occurs in April, May, and June, and highest average sediment, nitrogen, and phosphorus loadings occur in those same months.

Selected model outputs of the 50-year baseline SWAT simulation are summarized in Table 2. Basin-wide average monthly runoff tends to correspond to average monthly precipitation. Average annual surface runoff for the full watershed, over the 50-year simulation period was 191.0 mm. Evapotranspiration peaks in June and July, while the warmest months are July and August. Highest sediment export rates tend to occur in April, May, and June. Highest average monthly inflows to Oologah Lake tend to occur in May and June, with an annual average of 85.2 m^3/s. Average annual sediment loading is estimated to be 2,360 metric tons per day. TN loading to Oologah Lake averages 11,730 kg/d, and TP averages 1,812 kg/d.

Table 2. **Baseline SWAT outputs for the Verdigris Watershed above the Oologah Lake Dam, and Oologah Lake based on measured precipitation and temperature for the period 1956 – 2005.**

	Verdigris Watershed Monthly and Annual Averages 1956 - 2005				Oologah Lake Monthly and Annual Averages 1956 - 2005				
MONTH	**Precip. (mm)**	**Runoff (mm)**	**Evapo-Transpiration (mm)**	**Sediment Export (t/ha)**	**Air Temperature (°C)**	**Inflow (m^3/s)**	**Sediment Loading (t/d)**	**Total Nitrogen Loading (kg/d)**	**Total Phosphorus Loading (kg/d)**
JAN	32.4	10.0	16.5	0.06	1.7	71.2	1,311	9,305	998
FEB	38.6	12.4	24.5	0.09	4.7	79.8	1,853	9,638	1,385
MAR	74.4	15.9	41.7	0.14	9.6	84.6	2,480	11,800	1,943
APR	89.0	15.6	60.1	0.26	15.4	85.4	2,954	16,080	2,589
MAY	130.5	25.6	88.1	0.42	20.0	114.8	4,386	23,667	3,789
JUN	134.8	28.0	109.3	0.25	24.6	138.4	4,214	19,083	2,794
JUL	96.9	13.5	103.4	0.08	27.5	73.7	1,581	7,590	1,073
AUG	92.1	9.6	78.5	0.05	27.0	40.8	786	3,620	557
SEP	107.4	17.7	58.4	0.10	22.5	70.8	2,068	7,798	1,519
OCT	87.9	17.5	41.5	0.12	16.3	89.6	2,786	10,723	2,054
NOV	67.7	16.6	22.1	0.11	9.5	97.0	2,589	11,562	1,976
DEC	44.0	8.9	15.8	0.06	3.8	77.8	1,344	9,942	1,079
TOT/AVG	**994.6**	**191.0**	**659.2**	**1.72**	**15.3**	**85.2**	**2,360**	**11,730**	**1,812**

SWAT Simulated NARCCAP and CMIP3 Projections

SWAT simulations of climate projections were primarily assessed by comparing outputs to baseline (1956-2005) inflow to Oologah Lake, and sediment, TN, and TP loading to Oologah Lake. Included in Figure 7 and Figure 8 are comparisons of baseline annual average precipitation and temperature inputs to climate projection estimates, NARCCAP and CMIP3 projections, respectively. Long-term trends in either annual measured precipitation or climate projections are not visually obvious. Long-term increasing trends in measured average annual temperature, especially with respect to measured average annual minimum temperatures, can be visually discerned. All climate projections indicate increasing temperature trends.

Summarized in Table 3 are basin-wide watershed model comparisons of baseline and climate projections with respect to annual average precipitation, runoff, evapotranspiration, sediment export, and herbaceous biomass production. On a whole watershed basis, climate projections (both NARCCAP and CMIP3) indicate variable differences from baseline results for all parameters listed with the exception of runoff and biomass production. Basin-wide annual average runoff differences of climate projections, from the baseline, range from 0.6% to -80.6%, while herbaceous biomass production was clearly lower in all climate projections ranging from -7.3% to -70.1%. Annual precipitation differences range from 7.1% greater than to 43.9% lower than baseline. Average annual basin-wide sediment export rates varied around baseline simulation results in NARCCAP simulations ranging from 69.2% lower to 133.1% higher. CMIP3 simulations all resulted in lower basin-wide average annual sediment export rates with differences from baseline ranging from -22.3% to -62.7%. NARCCAP projection simulations of evapotranspiration ranged from 5.0% greater than to 29.7% less than baseline estimates, while all CMIP3 projection simulations resulted in higher rates of evapotranspiration.

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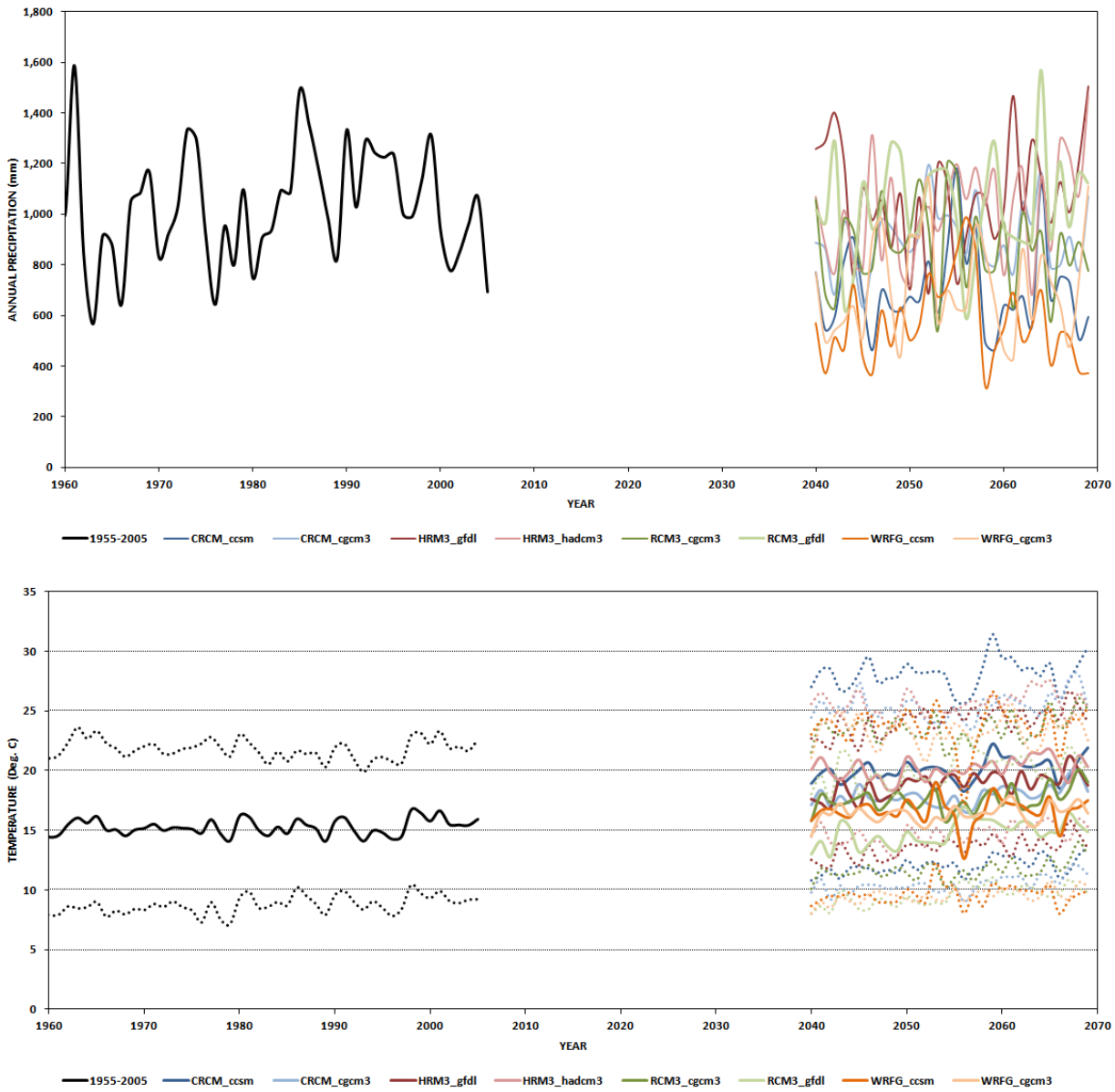

Figure 7. **Comparison of measured (1956-2005, 'black' lines) and NARCCAP projected (2040-2069, colored lines) annual precipitation (top) and average annual air temperature (bottom, including average annual maximum and minimum – dotted lines) at Oologah Lake.**

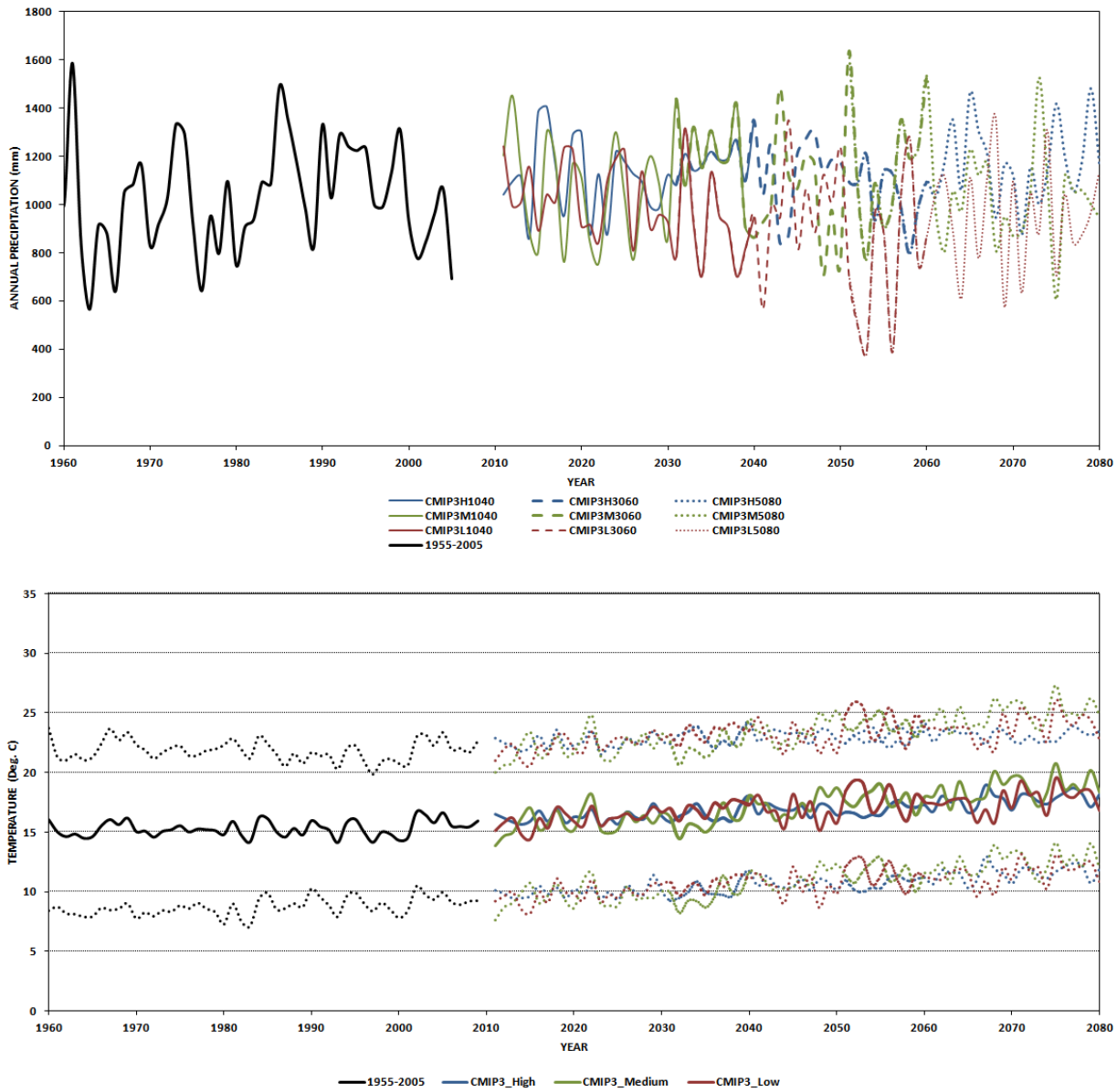

Figure 8. **Comparison of measured (1956-2005, 'black' lines) and CMIP3 high, medium and low projections (2011-2040, 2031-2060, and 2051-2080, colored lines) annual precipitation (top) and average annual air temperature (bottom, including average annual maximum and minimum – dotted lines) at Oologah Lake.**

Table 3. Basin-wide percent differences from SWAT baseline for selected average annual parameters.

		Precip. (mm/yr)	Runoff (mm/yr)	Evapo-Transporation (mm/yr)	Sediment Export (t/ha/yr)	Biomass Production (t/ha/yr)
	Baseline (1956-2005) Basin-Wide Averages	994.6	191.0	659.2	1.7	7.6
	Projections	Percent (%) Difference from Baseline				
NARCCAP 2040-2069	CRCM_ccsm	-31.4	-80.6	-9.3	-55.7	-70.1
	CRCM_cgcm3	-12.9	-59.0	5.0	-38.7	-56.0
	HRM3_gfdl	4.8	-2.9	-0.2	96.3	-64.7
	HRM3_hadcm3	-0.2	-9.2	-4.5	133.1	-67.4
	RCM3_cgcm3	-11.3	-36.6	-4.4	-14.4	-42.4
	RCM3_gfdl	4.2	0.6	-2.2	20.9	-27.0
	WRFG_ccsm	-43.9	-69.8	-29.7	-62.1	-48.2
	WRFG_cgcm3	-32.8	-65.9	-17.6	-69.2	-30.9
CMIP3 2011-2040 2031-2060 2051-2080	CMIP3H1040	7.1	-28.8	16.6	-24.0	-12.4
	CMIP3H3060	4.7	-38.4	17.1	-33.8	-14.2
	CMIP3H5080	5.7	-34.1	17.1	-26.0	-21.0
	CMIP3M1040	1.0	-38.6	13.6	-39.3	-7.3
	CMIP3M3060	7.0	-29.3	16.0	-22.3	-13.8
	CMIP3M5080	-0.5	-44.3	13.1	-27.5	-27.1
	CMIP3L1040	-6.3	-48.5	9.1	-46.6	-15.6
	CMIP3L3060	-16.6	-60.1	0.9	-52.1	-28.2
	CMIP3L5080	-17.6	-67.4	2.0	-62.8	-29.1

Average monthly precipitation and temperature differences between the baseline simulation and the climate projection scenarios are presented in Figure 9 (NARCCAP projections) and Figure 10 (CMIP3 projections). NARCCAP precipitation projections reveal a moderate shift in the seasonal period of peak precipitation with highest average monthly precipitation occurring one to two months earlier in the year at magnitudes comparable to the baseline period. Consistent across all NARCCAP projections are lower average monthly precipitation quantities from mid-summer through the fall months. Average monthly air temperatures in NARCCAP projections are consistently higher (except 'HRM3_hadcm3', an apparent outlier) through the bulk of the growing season from April through September. CMIP3 average monthly precipitation projections vary about baseline precipitation with no apparent positive or negative visual trend, while CMIP3 projections of average monthly temperatures are consistently higher throughout the year.

SWAT baseline (1956-2005) outputs of inflow, sediment, TN, and TP loading to Oologah Lake are compared to climate projection SWAT outputs as percent difference from average monthly baseline values in Table 4, Table 5, Table 6, and Table 7, respectively. The same data is presented graphically in Figure 11 (NARCCAP projections) and Figure 12 (CMIP3 projections) along with average monthly precipitation and temperature differences.

NARCCAP projections indicate generally lower average monthly inflow to the lake with the exception of three projections showing significantly higher inflow early in the year (January through April) corresponding to the seasonal shift in peak precipitation. Similarly, average monthly sediment, TN, and TP loading to Oologah Lake are generally lower than baseline loads for the bulk of the year with the

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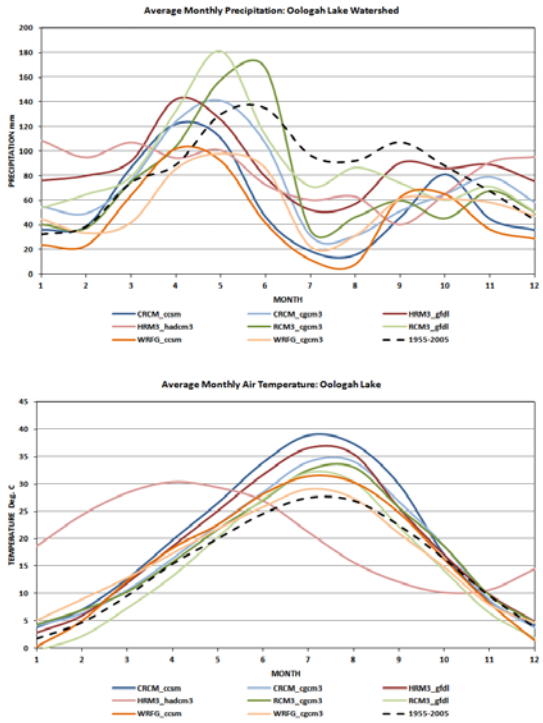

Figure 9. **Comparison of baseline (1956-2005) and NARCCAP projections (all 2040-2069) average monthly basin-wide precipitation and air temperature at Oologah Lake.**

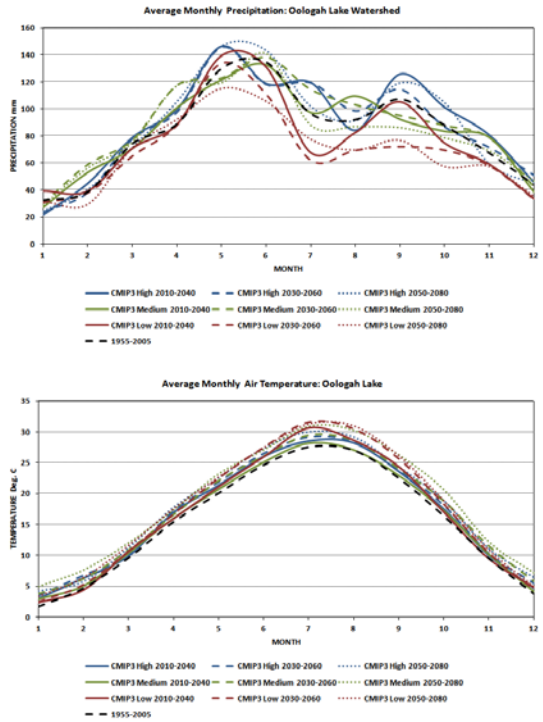

Figure 10. **Comparison of baseline (1956-2005) and CMIP3 projections (2011-2030, 2031-2060, and 2051-2080) of average monthly basin-wide precipitation and air temperature at Oologah Lake.**

Table 4. Inflow to Oologah Lake: Percent difference of climate projections from baseline (1956-2005).

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
	Baseline Inflow to Oologah Lake (m^3/s)	**71.2**	**79.8**	**84.6**	**85.4**	**114.8**	**138.4**	**73.7**	**40.8**	**70.8**	**89.6**	**97.0**	**77.8**	**85.2**
	Projections	**Percent (%) Difference from Baseline**												
NARCCAP 2040-2069	**CRCM_ccsm**	-70	-73	-74	-45	-73	-93	-99	-100	-100	-94	-91	-85	**-82**
	CRCM_cgcm3	-28	-23	-40	-27	-38	-68	-87	-97	-99	-88	-79	-52	**-59**
	HRM3_gfdl	125	128	78	114	30	-49	-64	-66	-68	-48	-17	30	**15**
	HRM3_hadcm3	161	126	91	23	-30	-67	-69	-33	-68	-58	-7	80	**7**
	RCM3_cgcm3	-40	-50	-53	-29	5	19	5	-56	-78	-84	-68	-52	**-35**
	RCM3_gfdl	20	99	47	86	95	30	11	-19	-54	-69	-60	-29	**17**
	WRFG_ccsm	-76	-74	-73	-48	-55	-82	-93	-99	-87	-88	-86	-80	**-77**
	WRFG_cgcm3	-57	-58	-72	-69	-65	-77	-88	-92	-82	-79	-71	-50	**-71**
CMIP3 2011-2030 2031-2060 2051-2080	**CMIP3H1040**	-7	-11	-27	-27	-19	-45	-27	-39	-16	-25	11	19	**-18**
	CMIP3H3060	-2	-23	-39	-33	-24	-45	-33	-41	-23	-50	-28	8	**-29**
	CMIP3H5080	-17	-25	-52	-24	-28	-29	-29	-39	-10	-19	-18	-6	**-25**
	CMIP3M1040	-4	-10	-11	-23	-36	-54	-43	-45	-53	-55	-14	-3	**-30**
	CMIP3M3060	-14	1	-9	3	-19	-41	-33	-24	-45	-35	-9	8	**-19**
	CMIP3M5080	-34	-21	-39	-9	-22	-44	-60	-58	-63	-55	-32	-24	**-37**
	CMIP3L1040	-41	-29	-47	-42	-37	-42	-61	-68	-35	-61	-48	-44	**-45**
	CMIP3L3060	-56	-54	-57	-45	-37	-63	-68	-78	-75	-80	-62	-54	**-59**
	CMIP3L5080	-49	-58	-64	-51	-61	-75	-66	-63	-74	-83	-71	-60	**-65**

Table 5. Sediment load to Oologah Lake: Percent difference of climate projections from baseline (1956-2005).

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
	Baseline Sediment Load to Oologah Lake (t/d)	**1,310**	**1,853**	**2,480**	**2,954**	**4,386**	**4,214**	**1,581**	**786**	**2,068**	**2,786**	**2,589**	**1,344**	**2,360**
	Projections	**Percent (%) Difference from Baseline**												
NARCCAP 2040-2069	**CRCM_ccsm**	-52	-65	-76	-25	-88	-98	-100	-100	-100	-96	-97	-91	**-83**
	CRCM_cgcm3	-12	-14	-49	-20	-55	-81	-98	-100	-100	-87	-82	-56	**-63**
	HRM3_gfdl	413	269	93	198	3	-71	-75	-51	-64	-47	9	130	**46**
	HRM3_hadcm3	643	267	153	0	-41	-72	-74	-15	-78	-54	72	407	**54**
	RCM3_cgcm3	-50	-78	-66	-42	15	42	-21	-80	-90	-89	-68	-52	**-36**
	RCM3_gfdl	46	161	13	77	110	19	-5	-51	-71	-89	-76	-32	**17**
	WRFG_ccsm	-69	-68	-69	-26	-55	-88	-97	-100	-90	-95	-91	-80	**-74**
	WRFG_cgcm3	-54	-68	-87	-74	-76	-81	-97	-93	-77	-79	-70	-33	**-75**
CMIP3 2011-2030 2031-2060 2051-2080	**CMIP3H1040**	-54	-21	-42	-45	-25	-57	-45	-74	3	-37	16	-3	**-31**
	CMIP3H3060	-36	-51	-62	-52	-35	-57	-53	-72	-5	-70	-38	10	**-45**
	CMIP3H5080	-54	-43	-72	-21	-39	-40	-52	-59	26	-31	-47	-26	**-37**
	CMIP3M1040	-30	-16	-6	-36	-54	-71	-54	-68	-63	-66	-10	-25	**-44**
	CMIP3M3060	-46	3	-14	-6	-38	-52	-46	-43	-48	-45	-15	-3	**-31**
	CMIP3M5080	-60	-25	-51	-6	-34	-60	-84	-72	-69	-59	-35	-33	**-46**
	CMIP3L1040	-58	-39	-68	-62	-48	-50	-84	-92	-28	-79	-56	-58	**-58**
	CMIP3L3060	-74	-65	-68	-55	-38	-76	-84	-94	-78	-82	-63	-67	**-66**
	CMIP3L5080	-65	-81	-72	-61	-76	-84	-72	-69	-80	-92	-79	-77	**-77**

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Table 6. **Total nitrogen load to Oologah Lake: Percent difference of climate projections from baseline (1956-2005).**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
	Baseline Total Nitrogen Load to Oologah Lake (kg/d	**9,305**	**9,638**	**11,800**	**16,080**	**23,667**	**19,083**	**7,590**	**3,620**	**7,798**	**10,723**	**11,562**	**9,942**	**11,730**
	Projections	**Percent (%) Difference from Baseline**												
NARCCAP 2040-2069	**CRCM_ccsm**	-6	-13	-38	13	-76	-94	-99	-100	-100	-90	-84	-73	**-61**
	CRCM_cgcm3	-4	16	-21	16	-34	-66	-90	-98	-99	-84	-75	-46	**-43**
	HRM3_gfdl	267	293	144	224	19	-57	-65	-46	-55	-35	8	58	**64**
	HRM3_hadcm3	374	300	284	47	-53	-65	-57	38	-52	-35	53	188	**66**
	RCM3_cgcm3	-38	-51	-42	-12	24	32	-5	-60	-78	-84	-61	-49	**-23**
	RCM3_gfdl	19	111	24	52	77	20	-11	-40	-67	-82	-67	-28	**13**
	WRFG_ccsm	-64	-53	-58	-20	-53	-81	-94	-99	-81	-86	-81	-70	**-65**
	WRFG_cgcm3	-46	-48	-68	-60	-68	-77	-89	-89	-74	-73	-65	-39	**-65**
CMIP3 2011-2030 2031-2060 2051-2080	**CMIP3H1040**	-29	-12	-20	-19	-17	-46	-36	-47	12	-16	20	0	**-18**
	CMIP3H3060	-11	-32	-34	-25	-26	-46	-42	-41	8	-49	-21	7	**-27**
	CMIP3H5080	-26	-23	-48	-1	-33	-35	-39	-30	25	-15	-25	-16	**-24**
	CMIP3M1040	-18	-5	-10	-19	-41	-53	-48	-46	-48	-55	2	-23	**-31**
	CMIP3M3060	-31	14	-4	19	-26	-45	-37	-20	-32	-32	-6	-13	**-18**
	CMIP3M5080	-37	-2	-22	25	-22	-51	-68	-49	-52	-49	-25	-27	**-28**
	CMIP3L1040	-36	-21	-45	-40	-36	-40	-68	-72	-15	-65	-43	-43	**-42**
	CMIP3L3060	-54	-40	-46	-38	-28	-65	-73	-80	-67	-75	-55	-45	**-51**
	CMIP3L5080	-40	-52	-52	-35	-62	-77	-67	-59	-69	-83	-65	-57	**-60**

Table 7. **Total phosphorus load to Oologah Lake: Percent difference of climate projections from baseline (1956-2005).**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
	Baseline Total Phosphorus Load to Oologah Lake (kg/d)	**998**	**1,385**	**1,943**	**2,589**	**3,789**	**2,794**	**1,073**	**557**	**1,519**	**2,054**	**1,976**	**1,079**	**1,812**
	Projections	**Percent (%) Difference from Baseline**												
NARCCAP 2040-2069	**CRCM_ccsm**	23	-12	-42	14	-86	-98	-100	-100	-100	-90	-91	-79	**-65**
	CRCM_cgcm3	16	4	-36	11	-45	-74	-97	-99	-99	-85	-77	-43	**-50**
	HRM3_gfdl	396	268	77	192	-13	-73	-75	-45	-61	-45	2	102	**44**
	HRM3_hadcm3	568	266	210	-1	-61	-66	-58	43	-66	-43	54	320	**53**
	RCM3_cgcm3	-37	-70	-49	-19	15	23	-44	-80	-85	-86	-59	-45	**-33**
	RCM3_gfdl	52	133	-6	39	61	-6	-39	-61	-74	-87	-72	-23	**0**
	WRFG_ccsm	-51	-45	-54	-17	-59	-86	-96	-100	-80	-87	-83	-69	**-65**
	WRFG_cgcm3	-28	-55	-82	-62	-70	-75	-94	-85	-67	-70	-60	-12	**-65**
CMIP3 2011-2030 2031-2060 2051-2080	**CMIP3H1040**	-60	-16	-27	-28	-20	-55	-44	-66	24	-23	18	-18	**-24**
	CMIP3H3060	-31	-45	-45	-32	-30	-54	-51	-55	12	-56	-23	11	**-34**
	CMIP3H5080	-50	-30	-57	0	-37	-40	-55	-41	34	-22	-40	-30	**-30**
	CMIP3M1040	-35	-3	-8	-22	-46	-60	-53	-55	-52	-57	4	-35	**-35**
	CMIP3M3060	-53	21	-14	10	-35	-53	-45	-34	-34	-37	-10	-27	**-26**
	CMIP3M5080	-62	-3	-35	15	-33	-58	-82	-60	-54	-52	-30	-41	**-37**
	CMIP3L1040	-41	-20	-57	-50	-40	-44	-81	-82	-14	-73	-46	-54	**-48**
	CMIP3L3060	-60	-44	-53	-43	-31	-74	-82	-88	-71	-75	-57	-56	**-57**
	CMIP3L5080	-43	-68	-59	-39	-67	-80	-69	-65	-70	-88	-66	-63	**-66**

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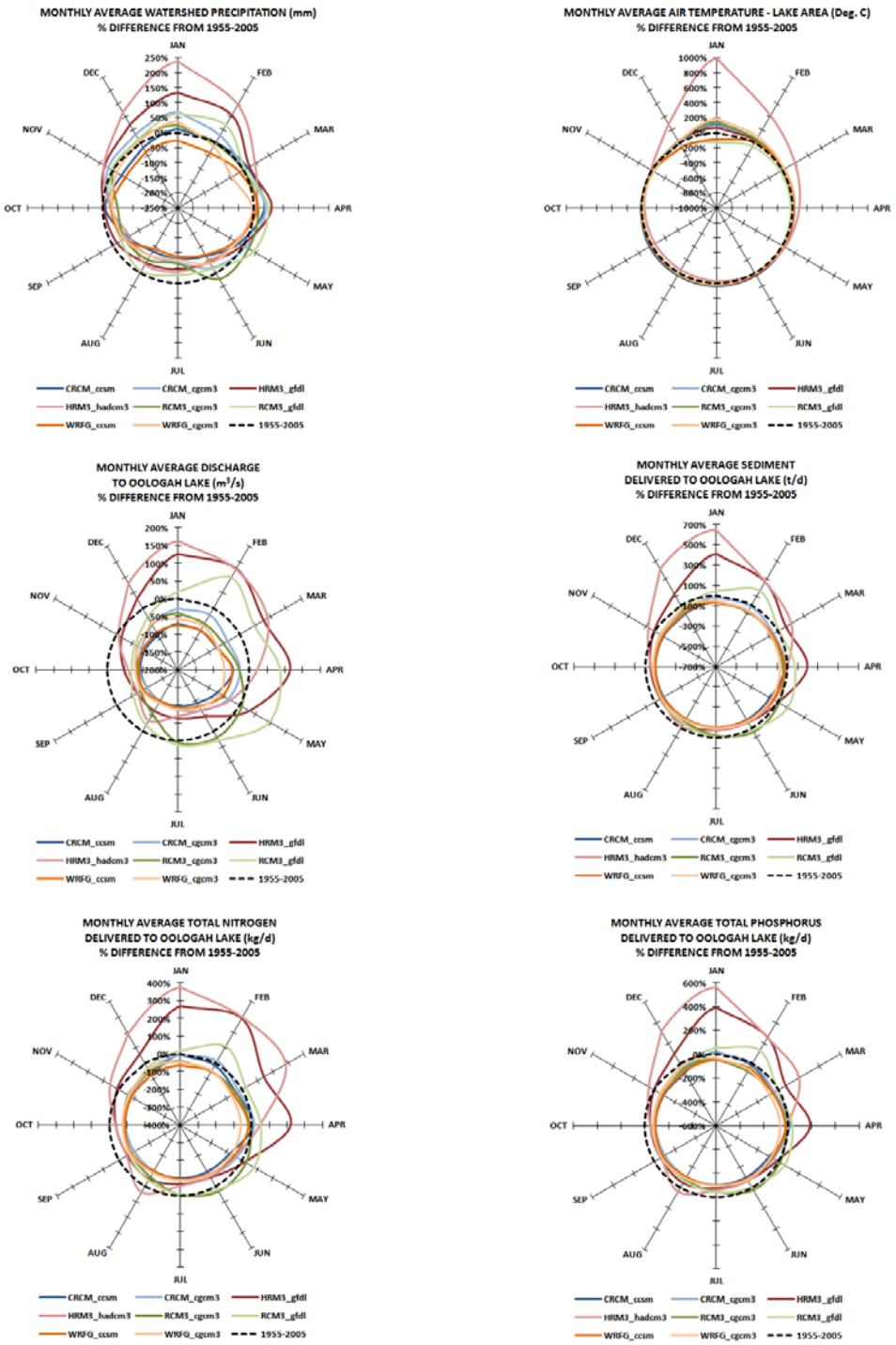

Figure 11. **Radial graphics illustrating percent difference from baseline (1956-2005) of NARCCAP projections (2040-2069) comparing monthly average precipitation (top left), air temperature (top right), and SWAT estimated discharge (center left), sediment (center right), total nitrogen (bottom left), and total phosphorus (bottom right).**

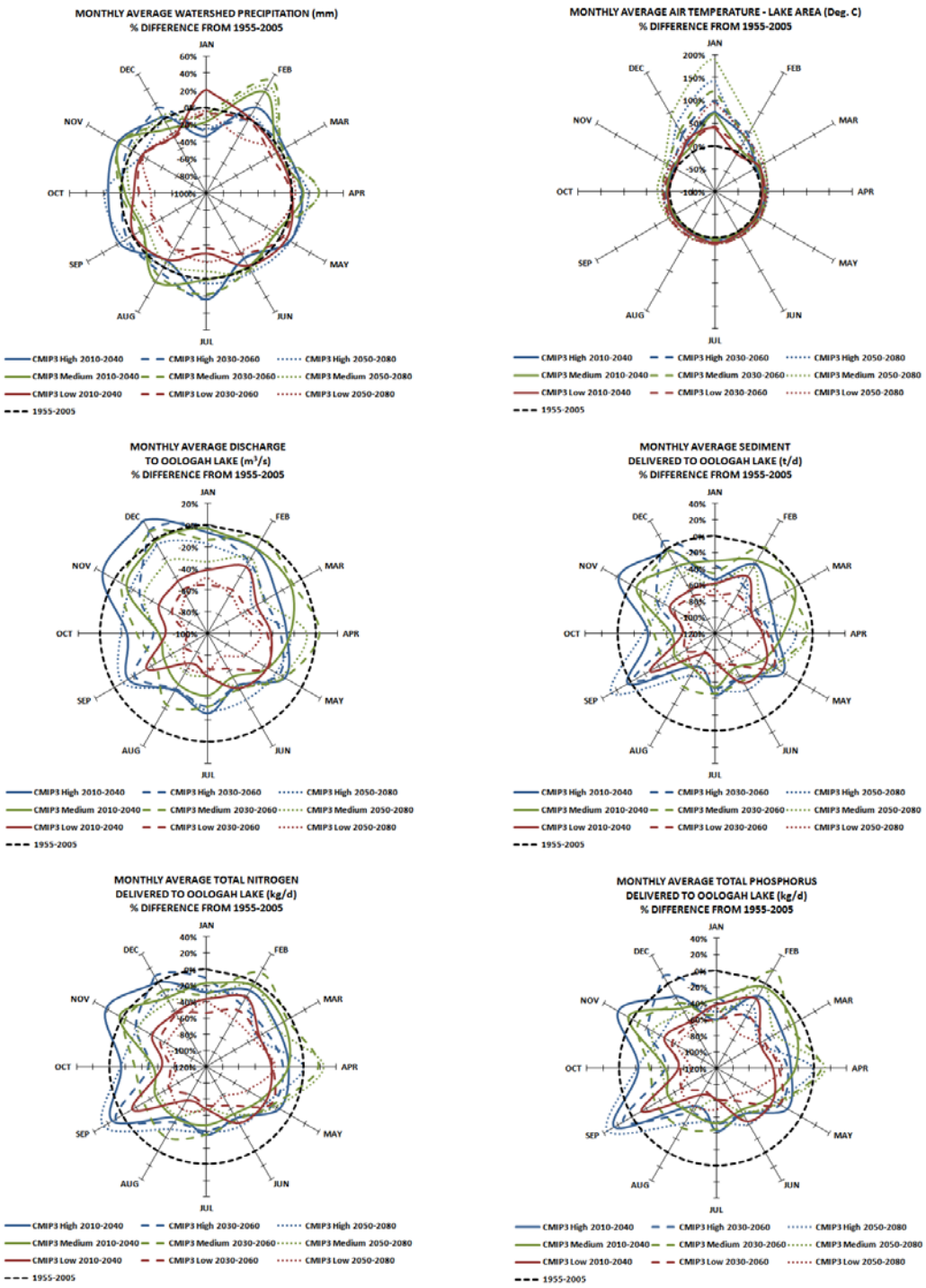

Figure 12. **Radial graphics illustrating percent difference from baseline (1956-2005) of CMIP3 projections (2011-2030, 2031-2060, and 2051-2080) comparing monthly average precipitation (top left), air temperature (top right), and SWAT estimated discharge (center left), sediment (center right), total nitrogen (bottom left), and total phosphorus (bottom right).**

exception of three projections (HRM3_gfdl, HRM3_hadcm3, and RCM3_gfdl**)** showing positive percent differences in January, February, March, and April. The simulated average annual increase of flow into Oologah Lake for these three projections results in average annual increases in constituent loading over the baseline estimate. CMIP3 projections indicate generally lower inflow to Oologah Lake, and correspondingly lower sediment, TN, and TP loading through the bulk of the year compared to baseline outputs.

Summarized below in Table 8 are estimates of average annual SWAT simulated climate at Oologah Lake, inflow, and sediment and nutrient loading to Oologah Lake under all modeled scenarios. While climate projections of average annual precipitation vary about the baseline Oologah Lake annual average of 1,030 mm per year, average annual air temperature is at least one-half degree higher in all projections except one (NARCCAP, 'RCM3_gfdl'). Similarly, the average annual maximum air temperature is higher in all projections, with the same exception, and the average annual minimum temperature is higher for climate projections in all cases. Average annual inflow to Oologah Lake is estimated to be lower in most projections with the exception of three NARCCAP projections. While average annual precipitation is higher than baseline in six CMIP3 projections, average annual inflow to Oologah Lake is lower than baseline in all eight projections. Average annual pollutant loading estimates to Oologah Lake (sediment, TN, and TP) correspond to average annual inflow, indicating lower expected loading in all cases except for the three NARCCAP scenarios where inflow is higher than the baseline.

Table 8. A comparison of baseline and climate projection annual average summary of SWAT simulated climate at Oologah Lake, and inflow and loading to Oologah Lake.

		Avg. Annual Precip. (mm)	Avg. Annual Temp. (°C)	Avg. Annual Max. Temp. (°C)	Avg. Annual Min. Temp. (°C)	Avg. Annual Inflow (m^3/s)	Avg. Annual Sediment Load (t/d)	Avg. Annual Total Nitrogen Load (kg/d)	Avg. Annual Total Phosphorus Load (kg/d)
	Baseline	**1,030**	**15.3**	**21.8**	**8.7**	**85.2**	**2,360**	**11,730**	**1,812**
NARCCAP	**CRCM_ccsm**	704	20.1	28.1	12.0	15.0	410	4,550	637
	CRCM_cgcm3	902	17.9	25.4	10.5	34.9	875	6,712	908
	HRM3_gfdl	1,074	18.8	24.2	13.5	98.4	3,457	19,244	2,615
	HRM3_hadcm3	1,018	20.2	25.6	14.7	91.2	3,625	19,496	2,766
	RCM3_cgcm3	874	17.6	23.6	11.6	55.1	1,501	8,980	1,218
	RCM3_gfdl	1,032	14.8	20.1	9.5	99.4	2,762	13,263	1,808
	WRFG_ccsm	569	16.6	23.7	9.6	19.7	604	4,087	625
	WRFG_cgcm3	712	16.4	23.3	9.5	24.7	581	4,050	627
CMIP3	**CMIP3H1040**	1,137	16.4	22.7	10.0	69.7	1,622	9,659	1,382
	CMIP3H3060	1,122	16.8	23.1	10.5	60.8	1,298	8,575	1,191
	CMIP3H5080	1,132	17.5	23.6	11.3	64.1	1,483	8,965	1,276
	CMIP3M1040	1,094	15.9	22.2	9.6	59.5	1,327	8,112	1,172
	CMIP3M3060	1,134	17.0	23.3	10.8	69.2	1,635	9,603	1,348
	CMIP3M5080	1,068	18.4	24.7	12.1	53.5	1,269	8,458	1,144
	CMIP3L1040	997	16.4	22.6	10.1	46.6	1,002	6,846	942
	CMIP3L3060	898	17.2	23.5	10.9	34.7	797	5,740	787
	CMIP3L5080	896	17.7	24.0	11.5	29.6	548	4,671	623

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CE-QUAL-W2 Simulations of Baseline, NARCCAP, and CMIP3 Projections

CE-QUAL-W2 simulations of Oologah Lake were prepared using outputs from the SWAT model describing physical and chemical inputs to Oologah Lake, including climate data (daily average air temperature and precipitation) extracted from the subbasin containing Oologah Lake. CE-QUAL-W2 model outputs allow for comparisons of baseline and projected climate in-lake variables at multiple locations in the lake. Focus for this effort was restricted to physical and chemical water quality at the whole-lake level. Constituents compared to baseline (1956-2005) include water temperature, DO concentration, TN concentration, TP concentration, TSS concentration, and CHLa concentration. Additionally, a comparison of combined factors, water temperature and DO concentration, was used to evaluate 'optimal fish habitat' across climate projection scenarios.

Because reservoir model inputs were derived from SWAT outputs, and because certain SWAT climate projection scenarios resulted in the temporary extinction of Oologah Lake, due to extended periods of minimal precipitation and resulting low or nonexistent inflows, several climate projections are not represented in CE-QUAL-W2 output results. In particular, NARCCAP projections 'CRCM_ccsm' and 'WRFG_ccsm', and CMIP3 projection 'CMIP3L5080' resulted in the extinction of Oologah Lake. Additionally, projection 'CMIP3L3060' resulted in the extinction of the lake beyond simulated year 2052. This simulation was salvaged by running the CE-QUAL-W2 simulation for this projection for a truncated 22-year period (2031-2052).

Summarized in Table 9 are CE-QUAL-W2 simulated average annual lake-wide temperature, and DO, TN, TP, CHLa, and TSS concentrations for the baseline (1956-2005) and all climate projections. As would be anticipated with projected increasing air temperature, lake-wide average annual water temperature is higher for all modeled climate projections. NARCCAP projections showed increases from 0.6 to 29.0% over the baseline average annual water temperature. CMIP3 projections were also simulated to result in higher average annual water temperatures with increases over the baseline, ranging from 0.4 to 12.4%, with temporally increasing temperatures apparent within high, medium, and low scenarios. Decreases from baseline of average annual lake-wide DO concentrations were observed in most simulations, partly because of the inverse relationship between water temperature and DO concentration. Higher than baseline average annual lake-wide TN concentrations were simulated for all but one ('WRFG_cgcm3') climate projections with differences ranging from -0.5 to 47.1%. TN concentration increases are likely due to higher rates of organic matter decay, at warmer water temperatures, for a greater fraction of the annual cycle. Organic matter was modeled in CE-QUAL-W2 as being comprised of 8% organic nitrogen. TP average annual lake-wide concentrations of NARCCAP projections varied about the baseline concentration with percent differences ranging from -24.1 to 19.0%, while all CMIP3 projections resulted in lower concentrations. While phosphorus is also a product of decaying organic matter (0.5% phosphorus), the small fraction resulting in soluble forms are rapidly taken up by phytoplankton, or are adsorbed to suspended sediment particles and removed from the system by settling. Lake-wide average annual CHLa concentrations in all climate projection scenarios were simulated to decrease from baseline with reductions ranging from -33.0 to -8.2%. The reduction in average annual phytoplankton biomass is likely due to photic zone temperatures exceeding optimal ranges, especially in the mid to late summer months, and reduced whole-lake average annual TP concentrations. Finally, average annual lake-wide TSS concentrations showed variable responses under NARCCAP projections with differences from baseline ranging from -70.9 to 54.5 %. CMIP3 projections consistently revealed average annual TSS concentrations below the baseline value.

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Table 9. **Oologah Lake CE-QUAL-W2 modeled average annual lake-wide temperature (Temp.), dissolved oxygen concentration (DO), total nitrogen concentration (TN), total phosphorus concentration (TP), chlorophyll-a concentration (CHLa), and total suspended solids concentration (TSS) for the baseline period (1956-2005) and NARCCAP and CMIP3 climate projections.**

		Temp. (°C)	DO (mg/l)	TN (mg/l)	TP (µg/l)	CHLa (µg/l)	TSS (mg/l)
	Baseline Lake-Wide (1956-2005)	**16.16**	**9.49**	**0.78**	**58.65**	**4.85**	**16.04**
	Climate Projections	**Average Annual Value (% Difference from Baseline)**					
NARCCAP 2040-2069	**CRCM_ccsm**	---	---	---	---	---	---
	CRCM_cgcm3	18.02 (11.5)	9.12 (-3.9)	1.01 (29.4)	51.17 (-12.8)	3.39 (-30.2)	6.84 (-57.4)
	HRM3_gfdl	18.42 (14.0)	8.97 (-5.5)	1.13 (45.7)	69.73 (18.9)	4.16 (-14.2)	24.14 (50.5)
	HRM3_hadcm3	20.85 (29.0)	8.34 (-12.1)	1.14 (47.1)	69.78 (19.0)	3.46 (-28.7)	24.78 (54.5)
	RCM3_cgcm3	17.90 (10.8)	9.02 (-4.9)	0.86 (10.3)	48.43 (-17.4)	3.51 (-27.6)	10.03 (-37.5)
	RCM3_gfdl	16.25 (0.6)	9.49 (0.0)	0.81 (4.7)	52.57 (-10.4)	4.46 (-8.2)	18.28 (14.0)
	WRFG_ccsm	---	---	---	---	---	---
	WRFG_cgcm3	16.71 (3.4)	9.49 (0)	0.77 (-0.5)	44.52 (-24.1)	3.25 (-33)	4.67 (-70.9)
CMIP3 2011-2030 2031-2060 2051-2080	**CMIP3H1040**	16.83 (4.1)	9.33 (-1.7)	0.88 (12.6)	53.18 (-9.3)	4.39 (-9.5)	11.52 (-28.2)
	CMIP3H3060	17.10 (5.8)	9.24 (-2.6)	0.9 (15.7)	51.01 (-13.0)	4.15 (-14.5)	9.32 (-41.9)
	CMIP3H5080	17.63 (9.1)	9.16 (-3.4)	0.88 (12.7)	50.8 (-13.4)	4.24 (-12.6)	10.64 (-33.7)
	CMIP3M1040	16.23 (0.4)	9.48 (-0.1)	0.84 (8.2)	50.96 (-13.1)	4.08 (-16.0)	10.14 (-36.8)
	CMIP3M3060	17.38 (7.5)	9.22 (-2.8)	0.84 (8.5)	50.39 (-14.1)	3.96 (-18.4)	12.37 (-22.9)
	CMIP3M5080	18.17 (12.4)	8.99 (-5.2)	0.91 (17.0)	48.9 (-16.6)	3.56 (-26.7)	9.95 (-38.0)
	CMIP3L1040	16.87 (4.4)	9.36 (-1.3)	0.88 (13.0)	48.18 (-17.9)	3.78 (-22.2)	7.64 (-52.4)
	CMIP3L3060	17.31 (7.1)	9.3 (-2.0)	0.94 (20.6)	48.26 (-17.7)	3.51 (-27.8)	7.89 (-50.8)
	CMIP3L5080	---	---	---	---	---	---

Pictured in Figure 13 and Figure 14 are comparisons of average annual baseline percent whole-lake volume water temperature, DO concentration, TN concentration, TP concentration, TSS concentration, and CHLa concentration, to NARCCAP and CMIP3 projections, respectively.

With respect to water temperature, NARCCAP projections tend to follow the baseline curve from about 3 °C up to temperatures near 28 °C. The graphic indicates a higher percentage of average annual whole-lake water volume above 28.5 °C simulated for all NARCCAP projections. Most NARCCAP simulations revealed lower whole-lake volumes of cold (<3 °C) water. The average annual whole-lake volume percentage of DO concentration for NARCCAP projections tends to follow the baseline curve except for mid-to-low level DO concentrations (4.5 to 6.0 mg/l) where the climate projections are estimated to have higher average annual whole-lake volumes. The generally lower percentage of whole-lake average annual water volume in NARCCAP projections between 6.75 and 9 mg/l is due in part to the inverse relationship between DO concentration and water temperature. TN concentrations in the range of 0.75 mg/l and higher were simulated to occupy higher average annual whole-lake volumes for most NARCCAP projections. This result is assumed to be caused by higher average annual whole-lake water volumes at temperatures conducive to higher rates of organic matter decay. Average annual whole-lake water volume percentages of low-level TP concentrations (10-50 µg/l) in NARCCAP simulations were simulated to be higher, also due in part to higher rates of organic matter decay, and lower than baseline

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water volumes at concentrations up to near 90 µg/l. No distinguishable differences were noted between average annual whole-lake water volume percentages at varying TSS concentrations with some projections higher and some lower than baseline at all concentrations. Finally, NARCCAP average annual whole-lake volume percentages with CHLa concentrations between 5 and 35 µg/l were simulated to be lower than the baseline simulation.

CMIP3 CE-QUAL-W2 simulations revealed similar patterns with subtly more definition of differences from the baseline simulation. Cold (<3.5 °C) waters accounted for less average annual whole-lake volume in CMIP3 simulations than the baseline, and high temperature water (>28.5 °C) accounted for higher volumes in CMIP3 simulations. CMIP3 whole-lake water volumes with DO concentrations between 4.5 and 6.0 mg/l exceeded those of the baseline, while CMIP3 volumes at concentrations >12 mg/l were generally lower than the baseline simulation. The percent whole-lake volumes with TN concentrations ranging from 0.6 to greater than 1.1 mg/l were higher than baseline for all CMIP3 simulations. Low level TP concentrations (10 to 40+ µg/l) were shown to occupy greater than baseline whole-lake water volumes in CMIP3 projections, while at concentrations above 50 µg/l all CMIP3 simulations revealed lower whole-lake water volumes. For TSS and CHLa concentrations, CMIP3 projections were simulated to be lower than baseline whole-lake water volumes throughout the concentration range.

As a final comparison of baseline and climate projection reservoir modeling, the combined factors of temperature and dissolved oxygen were assessed to estimate 'optimal fish habitat'. Data based on the U.S Fish and Wildlife Service's Habitat Suitability Index (HSI) model for a representative fish, the gizzard shad (Williamson & Nelson, 1985), indicate water temperature and DO concentrations, conducive to growth and reproduction, are within the ranges of 10 to 30 °C and greater than 5 mg/l, respectively. CE-QUAL-W2 version 3.71 (Cole & Wells, 2011) offers the ability to assess a waterbody's habitat suitability based on combined factors. Graphic of comparisons of average monthly habitat suitability between the baseline simulation (1956-2005) and NARCCAP projections (Figure 15), and CMIP3 projections (Figure 16) are shown below. Both graphics reveal approximately the same information. Beginning in May and continuing through October, the combined factors of higher than baseline water temperatures and lower than baseline DO concentrations, result in a reduction of the whole-lake volume suitable for optimal fish growth and reproduction, under all climate projection scenarios.

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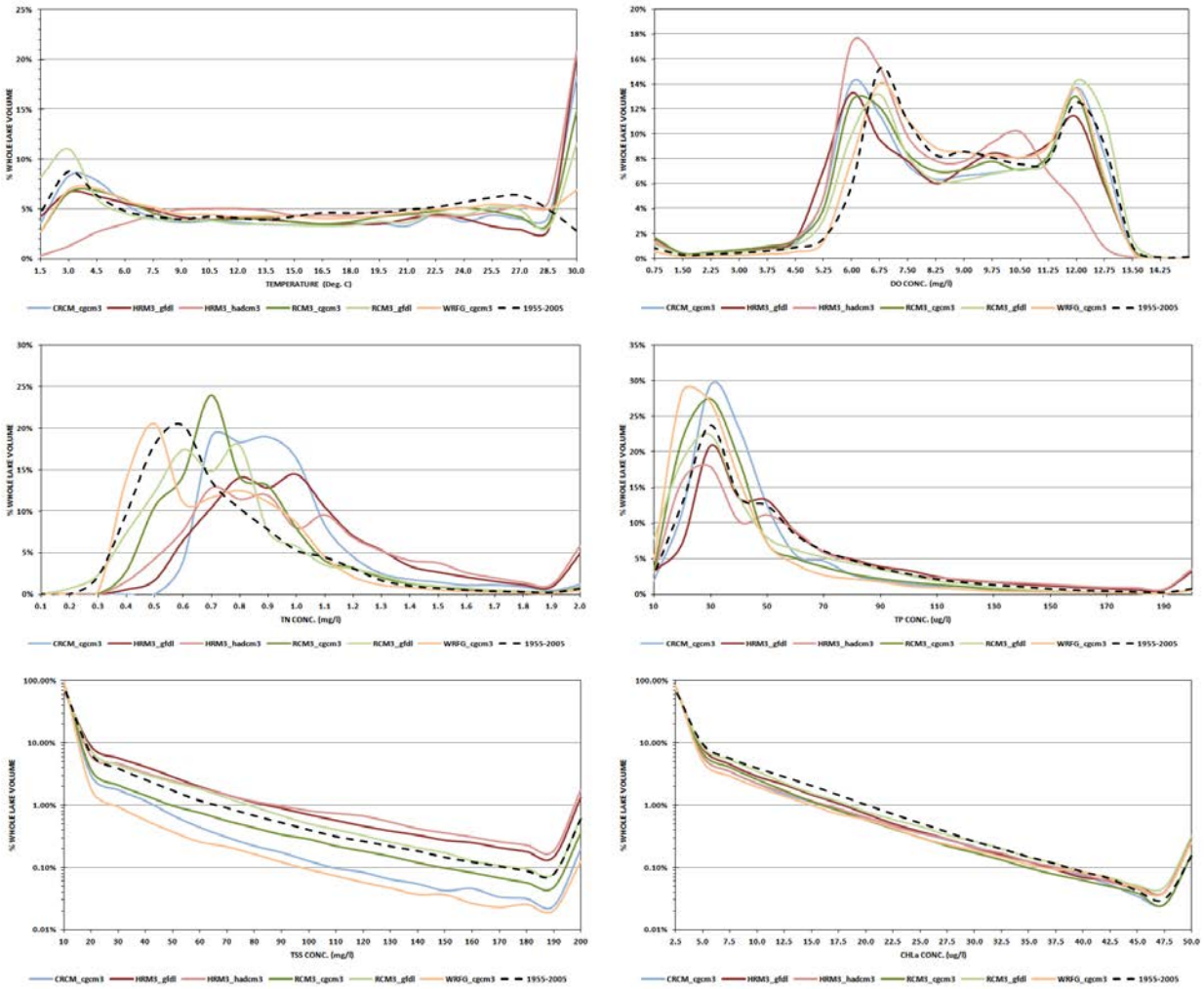

Figure 13. **Comparisons between CE-QUAL-W2 estimated average annual baseline (dashed black line, 1956-2005) and NARCCAP climate projections (2040-2069) of whole-lake volume percentages of water temperature (upper right), dissolved oxygen concentration (upper left), total nitrogen concentration (center left), total phosphorus concentration (center right), total suspended solids concentration (TSS, lower left), and chlorophyll-a concentration (CHLa, lower right).**

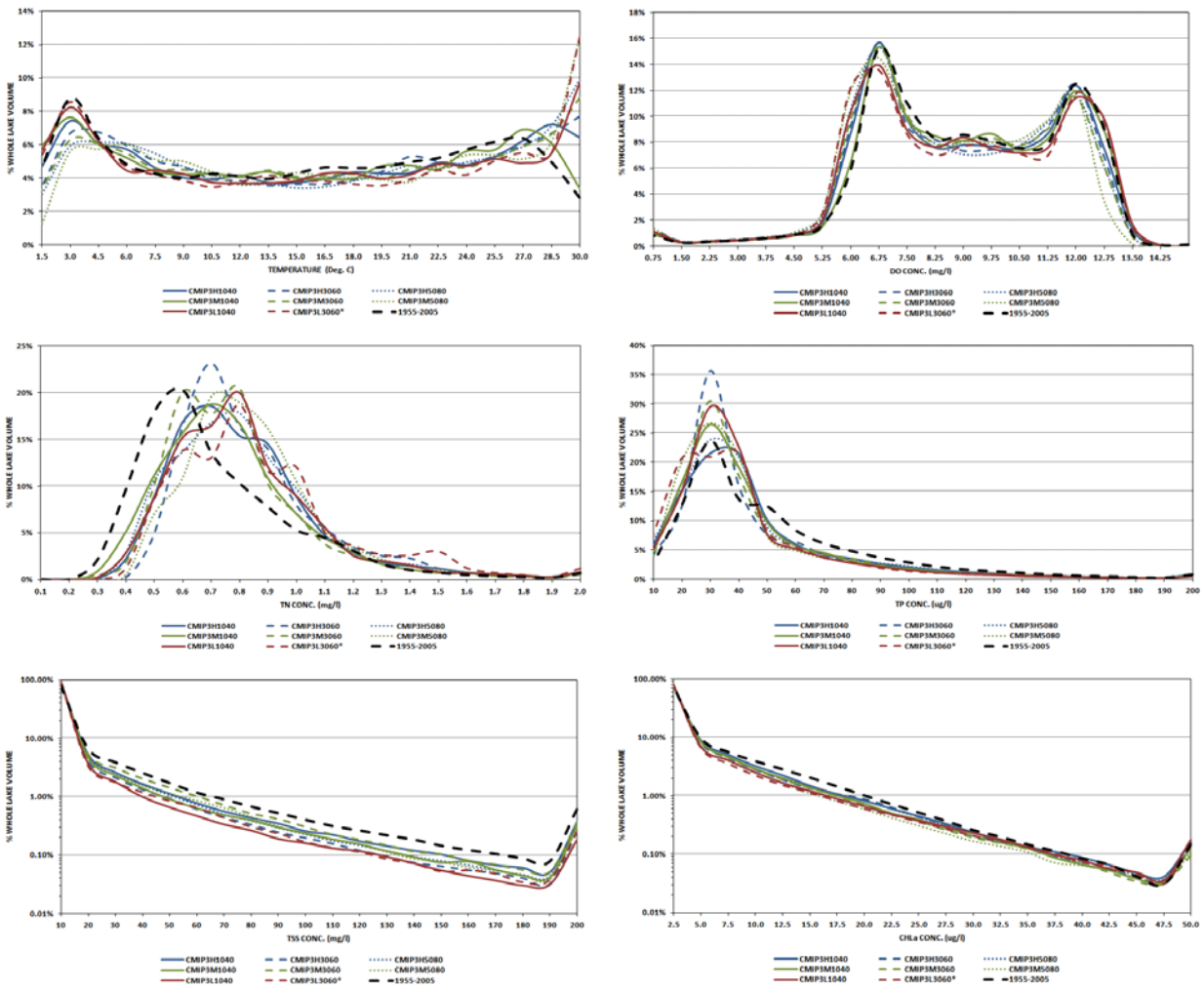

Figure 14. **Comparisons between CE-QUAL-W2 estimated average annual baseline (dashed black line, 1956-2005) and CMIP3 climate projections (2011-2030, 2031-2060, and 2051-2080) of whole-lake volume percentages of water temperature (upper right), dissolved oxygen concentration (upper left), total nitrogen concentration (center left), total phosphorus concentration (center right), total suspended solids concentration (TSS, lower left), and chlorophyll-a concentration (CHLa, lower right).**

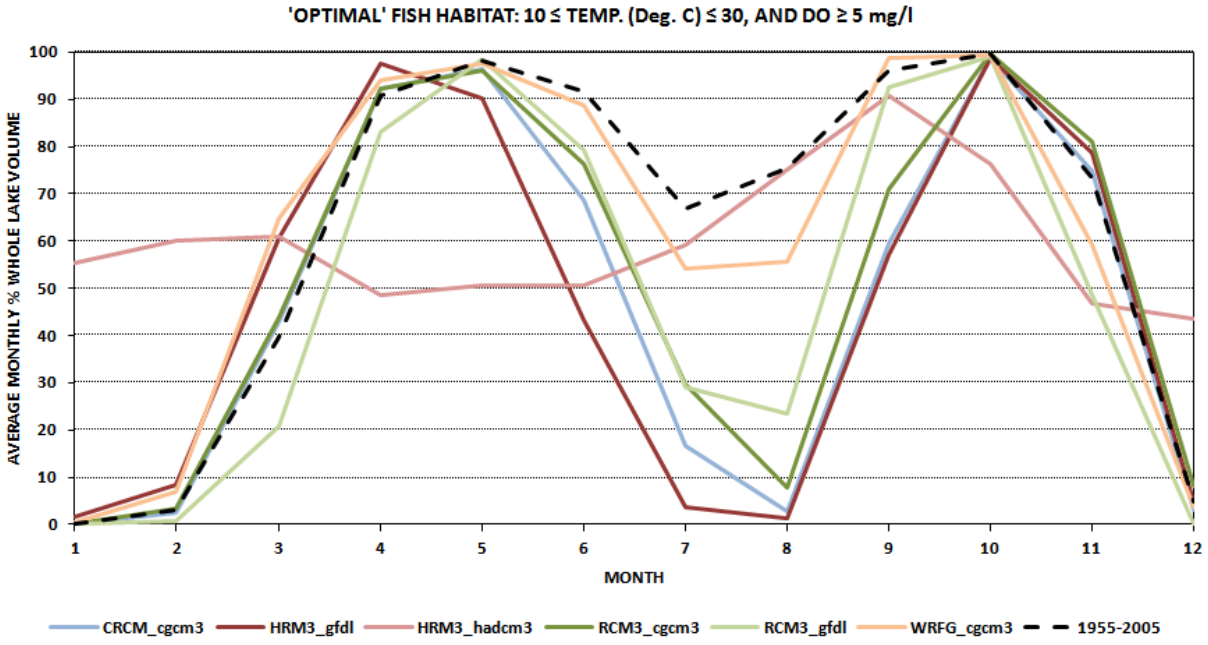

Figure 15. **Comparison of CE-QUAL-W2 estimated baseline (1956-2005) and NARCCAP projections (2040-2069) whole-lake volume average monthly 'optimal fish habitat'.**

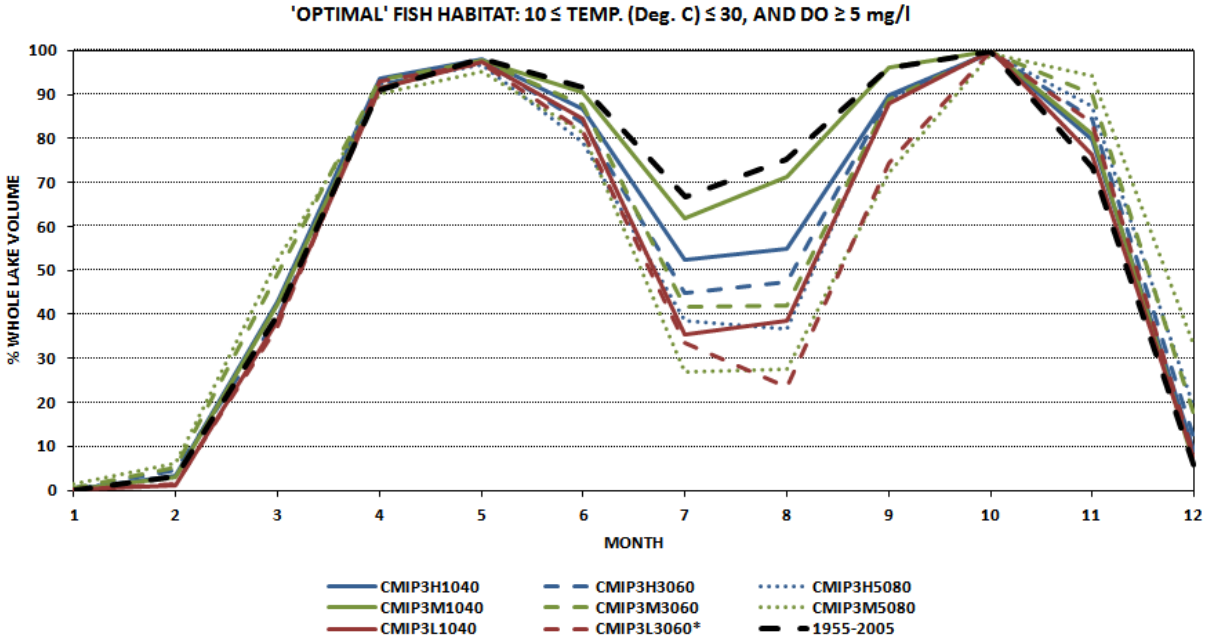

Figure 16. **Comparison of CE-QUAL-W2 estimated baseline (1956-2005) and CMIP3 projections (2011-2030, 2031-2060, and 2051-2080) whole-lake volume average monthly 'optimal fish habitat'.**

Conclusions

The application of watershed and reservoir simulation models (SWAT and CE-QUAL-W2) in evaluation of climate change scenarios can provide insight into expected future conditions in a watershed system. Development of calibrated models which can reasonably simulate past, present, and future conditions is not trivial. Watershed and reservoir simulation models have detailed input requirements, and model outputs must be evaluated and assessed, using measured data, to determine relative accuracy. Because application of these two models was established in an earlier assessment of the Verdigris Watershed above the Oologah Lake dam, an application of climate change analysis to this watershed system was feasible. Both models are inherently receptive to input of altered climate data. Climate inputs drive the SWAT model, and are an integral driver of the CE-QUAL-W2 model.

NARCCAP and CMIP3 future climate projection inputs of daily temperatures and precipitation generally correspond predicting an increasing trend in air temperature and stable to diminishing quantities of average annual precipitation. Processing of NARCCAP climate projection data through the SWAT model indicated variable whole-watershed outputs compared to a baseline period. NARCCAP projections generally resulted in lower average annual runoff, and reduced vegetative biomass production. CMIP3 projections processed through SWAT revealed more consistent whole watershed outputs including reduced runoff, higher evapotranspiration, lower sediment export, and lower vegetative biomass production.

Comparing modeled baseline and NARCCAP watershed inputs to Oologah Lake, climate projections revealed a shift in timing of inflows to the lake, and a corresponding change in the timing of pollutant loading to the lake. Pollutant loading to the lake, relative to quantities of watershed generated runoff, was reduced in some of the projections, and higher in others. CMIP3 watershed modeled projections revealed more consistency between projections compared to baseline results. Average monthly and annual inflow, and pollutant loading to Oologah Lake, was generally reduced.

CE-QUAL-W2 simulations comparing baseline and climate projections revealed reservoir water temperature increases, and dissolved oxygen concentration decreases. While total nitrogen loading to Oologah Lake was reduced in most climate projections, average annual whole-lake total nitrogen concentrations were simulated to be consistently higher, likely due to increased rates of organic matter decay and dissolution. Reduced total phosphorus loading, simulated in a majority of the climate projections, resulted in generally lower average annual whole-lake concentrations. Lake primary productivity, assessed using simulated concentrations of the algal pigment chlorophyll-a, was generally reduced under all climate projections. Again, because of simulated reduced runoff in the majority of climate projections, total suspend solids carried into the lake were generally reduced, compared to baseline conditions, resulting in generally lower in-lake concentrations. Finally, considering the combined factors of temperature and dissolved oxygen concentration relative to available ‘optimal fish habitat’, increasing water temperature and subsequent lower dissolved oxygen concentrations in all climate projections (compared to the baseline simulation), resulted in decreased whole-lake water volume, through the growing season, suitable for optimal fish activity.

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Literature Cited

Cole, T. M., & Wells, S. A. (2008). *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.6. User Manual.* Washington, DC: U.S. Army Corps of Engineers.

Cole, T. M., & Wells, S. A. (2011). *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71*. Portland, OR: Department of Civil and Environmental Engineering, Portland State University.

ESRI. (1996). *ArcView GIS version 3.2a.* Redlands, CA: Environmental Systems Research Institute.

Fang, X., Shrestha, R., Groeger, A. W., Lin, C.-J., & Jao, M. (2007). Simulation of Impacts of Streamflow and Climate Conditions on Amistad Reservoir. *Journal of Contemporary Water Research & Education*(137), 14-20.

Ficklin, D. L., Luo, Y., Luedeling, E., & Zhang, M. (2009). Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology*, 16-29.

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE*, 50(4): 1211-1250.

GRASS Development Team. (2011). Geographic Resources Analysis Support System (GRASS GIS) Software, Version 6.4.1. USA: Open Source Geospatial Foundation. Retrieved from http://grass.osgeo.org

Intergovernmental Panel on Climate Change (IPCC). (2000). *Special Report on Emissions Scenarios.* Cambridge, U. K.: Cambridge University Press.

Jha, M., Arnold, J. G., Gassman, P. W., Giorgio, F., & Gu, R. R. (2006). Climate Change Sensitivity Assessment on Upper Mississippi River Basin Streamflows Using SWAT. *Journal of the American Water Resources Association*, 997-1015.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models. Part I: a discussion of principles. *Journal of Hydrology, 10*, 282-290.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2005). *Soil and Water Assessment Tool: Theoretical Documentation, Version 2005.* Temple, TX: Grassland, Soil and Water Research Laboratory, ARS.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R., & Williams, J. R. (2004). *Soil and Water Assessment Tool: Input/Output Documentation, Version 2005.* Temple, TX: Grassland, Soil and Water Research Laboratory - Agricultural Research Service.

NOAA-ESRL. (n.d.). *U.S. Department of Commerce | National Oceanic and Atmospheric Administration*. Retrieved March 2013, from Earth System Research Laboratory | Global Monitoring Division : http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html

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Literature Cited (continued)

Obregon, O., Williams, G. P., Nelson, E. J., Miller, J. B., Gonzolez, N. A., & Swain, N. R. (2012). Simulated Climate Change Effects in Deer Creek Reservoir with a Two-Dimensional Model. *World Environmental and Water Resources Congress 2012: Crossing Boundaries* (pp. 3443-3451). ASCE.

Qiao, L., Hong, Y., McPherson, R., Shafer, M., Williams, D., Gade, D., & Lilly, D. (submitted 2013). Climate change and hydrological response in the trans-state Oologah Lake watershed - Evaluating dynamically downscaled NARCCAP and statistically downscaled CMIP3 simulations with VIC model. *Water Resources Management*.

Qiao, L., Pan, Z., Hermann, R., & Hong, Y. (Submitted 2013). Hydrological Variability and Uncertainty in the Lower Missouri River Basin Based on NARCCAP Simulations and SWAT Model. *Journal of the American Water Resources Association*, 45.

Soil Conservation Service. (1972). Section 4: Hydrology. In SCS, *National Engineering Handbook.*

USACE-Tulsa District. (1996). *Oologah Lake, Verdigris River, Oklahoma: Water Control Manual.* Tulsa, OK: Department of the Army, Tulsa District, Corps of Engineers.

USACE-Tulsa District. (2006). *Monthly Charts for Oologah Lake: USACE-Tulsa District*. Retrieved from Monthly Charts for Oologah Lake: USACE-Tulsa District: http://www.swt-wc.usace.army.mil/OOLOcharts.html

USACE-Tulsa District. (2012). *Oologah Lake Watershed Assessment Study: Final Draft March2012.* Tulsa: USACE-Tulsa District.

USDA/NRCS. (2001). *National Land Cover Dataset.* Fort Worth: USDA/NRCS - National Cartography & Geospatial Center.

USDA-NRCS. (2007). *Soil Data Mart: USDA-NRCS*. Retrieved from Soil Data Mart: USDA-NRCS: http://soildatamart.nrcs.usda.gov/

USGS. (2006). *USGS: National Water Information System: Web Interface*. Retrieved from USGS: National Water Information System: Web Interface: http://waterdata.usgs.gov/nwis/dv/?referred_module=sw

Williamson, K. L., & Nelson, P. C. (1985). *Habitat suitability index models and instream flow suitability curves: Gizzard Shad.* U.S. Fish and Wildlife Service.

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