SOUTH CENTRAL
CLIMATE ADAPTATION SCIENCE CENTER

Evaluation of sustainable water availability in drought prone watersheds in Southeastern Oklahoma

Final Report
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AquaStrategies
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Section 1. Administrative Information

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Awarding Agency/Entity	**Recipient**	**Amount**
US Geological Survey / The University of Oklahoma	US Geological Survey / The University of Oklahoma	$115,166
	Aqua Strategies	$136,760
	Subtotal	**$251,926**
The Chickasaw Nation and Choctaw Nation	The Chickasaw Nation and Choctaw Nation (In-kind)	$72,552
	Aqua Strategies	$19,800
	Subtotal	**$92,352**
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Section 2. Public Summary

During the severe drought of 2010-2015, several communities in southeast Oklahoma nearly ran out of water. Some of these communities rely on streams and rivers as their sole source of water, and when these sources almost ran dry, it left them searching for alternatives and wondering how to manage future water uncertainty. To address these challenges this study used historical and climate projections through the end of the century to model potential impacts to individual water permits, and to estimate projected supply-demand curves for the most water vulnerable communities. This study focused on local communities within the Red River Basin in both the Chickasaw Nation and Choctaw Nation territories.

Additionally, this study examined relationships between occupancy of stream fishes and flow metrics during both wet and dry climactic periods between 1961-2010. Results indicated significant occurrence relationships for 77 stream fishes, but there were only two seasonal differences in relationships with flow timing metrics (date of annual maximum, date of annual minimum). Although simple relationships were found between stream fish occurrence and other factors of the flow regime (duration, magnitude, rate of change), the timing metrics of high and low flows were context dependent.

Results show that approximately half of the municipal water permits have decreased projected reliability when compared to historical reliability, and that these permit reliabilities are projected to decrease over the coming century. Most of the permits with significant decreases in reliability are located within the Chickasaw Nation territory.

Both the Chickasaw Nation and Choctaw Nation are expected to provide support, or are already providing support, to the entities identified as having future water needs. With a better understanding of these projected water needs and when they may occur, investigating alternative water sources or water conservation efforts for these entities can now begin.

Section 3. Project Summary

During the severe drought of 2010-2015, several communities in southeast Oklahoma nearly ran out of water. Some of these communities rely on streams and rivers as their sole source of water, and when these sources almost ran dry, it left them searching for alternatives and wondering how to continue growing and manage this water uncertainty. The possibility of climate change has these communities further concerned, primarily because they don't know what, if any, water needs they may have in the future.

Previously, the USGS, Choctaw Nation and Chickasaw Nations collaborated on the study titled *Impacts of Climate Change on Flows in the Red River Basin* (2016) to apply a range of possible climate change scenarios to the Red River watershed to determine future water availability. The previous study provided watershed-wide estimates of future impacts to water resources, but not at the level of detail needed to make decisions on the local scale by communities.

This study built on the results of the previous study to model water permits and develop water supply-demand projections for the most water vulnerable communities within the Chickasaw Nation or Choctaw Nation territories. These projections will provide specific data to help communities with long-range water planning efforts. In addition, this study examined the context dependency of relationships between stream fish occurrence (nearly 100 species) and flow metrics calculated over relatively wet ((1968–1975, 1983–1998, and 2006–2010) and dry periods (1961–1967, 1976–1982, and 1999–2005) of the study period (1961-2010). Project results and findings on the flow-ecology relationships are not discussed here but are provided in Appendix A (Examining stream fish occurrence related to flow metrics during wet and dry seasons in the Kiamichi River and surrounding catchments).

This study used previously generated streamflow data developed from climate projection scenarios and a historical scenario. A total of 18 climate projection scenarios were previously used from a combination of two downscaling methods, three Global Climate Models, and three Representative Concentration Pathways. These scenario data were then input into a Variable Infiltration Capacity (VIC) model to generate streamflow, evaporation and precipitation results. Since the VIC model does not simulate the effects of water permit diversions or reservoir operations, a water availability model was also developed but not refined enough for this study's objectives.

A RiverWare water availability model from the previous 2016 study was refined over the Chickasaw Nation and Choctaw Nation territories in the Red River Basin to model the effects of individual water permits, smaller tributaries and streams, and small local reservoirs that communities often rely on for water supply. The RiverWare model is capable of modeling water permit diversions, the prior appropriation system which dictates a water permit's priority order, river compacts, as well as complex reservoir operations. All legal water permits located within the modeled region were included and were modeled using their fully authorized yearly permitted amount, without return flows. This refined RiverWare model was then used to model all scenarios on a daily timestep.

Model results show that approximately half of the municipal water permits have decreased projected reliability when compared to historical reliability. Overall, these permit reliabilities are also projected to continue decreasing over the coming decades. Most of the permits with significant decreases in reliability are located in the western portion of the model region, in the Chickasaw Nation territory.

With these model results project staff targeted municipal water supply entities with the least reliable water permits, distributing questionnaires and holding individual meetings with some of them. These questionnaires and meetings allow project staff to better understand existing and projected water demands, and other water sources such as water contracts or groundwater permits. These collected data, along with model results, were used to develop supply-demand curves and data for these entities. These results indicate the following entities may have project water needs within the next forty years: City of Tishomingo, Marshall County Water Corporation (MCWC), and the City of Ada. The City of Ada's projected water needs may be overestimated due to their reliance on groundwater and local springs, which the VIC surface water model may not have captured well.

Both the Chickasaw Nation and Choctaw Nation have been actively investing in a comprehensive regional water planning initiative for their jurisdictional territories and have a strong interest in supporting communities in meeting their water needs. As a result of this project it is expected that both the CN and CNO will provide support, or are already providing support, to the entities identified as having future water needs. With a better understanding of these projected water needs and when they may occur, investigating alternative water sources or water conservation efforts for these entities can now begin.

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Section 4. Report Body

1 Purpose and Objectives

Several times during the severe drought of 2010-2015, communities within the Chickasaw Nation (CN) and Choctaw Nations' (CNO) jurisdictional territories were precariously close to running out of water. The most impacted communities were those that rely more heavily, or exclusively, on direct river diversions to supply the needs of their customers. For example, the City of Tishomingo draws water exclusively from Pennington Creek. During the worst part of the drought, the City reported that very little water was flowing over the weir, which was a short distance downstream of the City's intake. Similarly, the City of Durant gets all of its water from the Blue River. In 2011, no water was flowing in the river below the intake, causing the regulatory agency – the Oklahoma Water Resources Board – to intervene, to protect downstream water users. The City of Durant subsequently built an emergency, temporary connection to Lake Durant in order to meet the needs of its citizens.

Communities that rely on more than one source of water – especially if those sources consist of both groundwater and surface water – may be less vulnerable to shortages. However, in regions where demand for water is high compared to the amount of water available, the prospect of worse droughts in the future is sobering. In these situations, actions to reduce demand while seeking to expand water supply should begin as soon as possible. The problem is, most communities do not know how much "new" water they may need. By building on a recent study of the effects of climate change on the Red River Basin, this study will help determine which communities have future water needs and how much water may be required.

Severe droughts also have ecological consequences. Habitat fragmentation and loss are major threats to the integrity of freshwater ecosystems. There is a wide range of human activities with the potential to fragment freshwater systems, including construction of physical barriers, riverscape alteration via changes in land-use practices, and channel modifications that simplify aquatic habitat templates. However, species inhabiting these systems have varying degrees of tolerance and resiliency to fragmentation and loss because a number of natural phenomena also fragment freshwater ecosystems, including ecosystem contraction and drying during drought. There can be differences in the degree of habitat alteration, isolation, and permanency associated with the natural versus anthropogenic fragmentation, and these differences influence how species respond to habitat disturbances. For example, severe droughts can dramatically alter hydrologic connectivity of stream systems and have long lasting effects on the composition and structure of aquatic communities. Moreover, the persistence of drought or increase in frequency (not necessarily natural) can alter fish assemblage structure substantially.

A common scenario during severe droughts is the reduction of a stream to a series of isolated pools and larger downstream refuges. Recovery of most species from drought scenarios such as this is relatively rapid once connectivity is restored despite the acute nature of this type of disturbance, but there is potential for fundamental and persistent shifts in assemblage structure and function following drought (especially if severe or prolonged). The effects are likely dependent upon the specifics of the system and its constituent species, as well as the duration and severity of the drought event. However, it is difficult to generalize as relatively few studies have been conducted that evaluate the effects of drought on aquatic assemblages outside of desert streams or short-term changes (i.e., immediately following drought). Furthermore, how the effects of anthropogenic habitat fragmentation interact with those

induced by drought influence the persistence and recovery trajectory of fishes and other stream residents is unknown.

A better understanding of how drought and fragmentation of watersheds interact to structure aquatic communities, alter the vulnerability of species to local extirpation, and determine the trajectory of recovery from disturbance is needed to inform proactive conservation and management actions. The critical need for this understanding is most clearly illustrated not only by the relatively recent drought, but also the predictions of climate models that suggest regional drought is likely to become more frequent and more severe as climatic patterns shift over the next 50-100 years. The objective of the ecological portion of this project was to examine the effects of previous droughts on fish populations in southeast Oklahoma, and determine which species or traits appear to be the most vulnerable to future drought episodes. Due to data limitations (i.e., fish surveys duplicated in data bases and recent surveys being omitted from the modeled time frame), we focused on determining stream fish occurrence relationships with flow metrics during wet and dry periods between 1961-2010. This examination allowed us to determine the context dependency of flow relationships during substantial climactic shifts. More fish survey records and finer-scale hydrology would be needed to develop a colonization-extinction model.

2 Background

In 2015, the CN, CNO and collaborators at the University of Oklahoma delivered a report to the South Central Climate Science Center describing expected future hydrology for the entire Red River Basin (Kellogg et al., 2016). Generally speaking, we can expect the western portions of the Red River Basin to be drier in the future, while the eastern portions may be wetter. In between, there may not be any measurable impacts – at least in the medium term and for average annual flows. In the longer term, however, the entire basin can expect warmer temperatures, longer and deeper droughts, and more extreme flooding events. The extent to which future hydrologic regime changes prove to be problematic for water providers.

The drought that began in late 2010 and the steady increase of interest in southeast Oklahoma water by outside parties persuaded the CN and CNO to begin looking at the water needs for communities in their jurisdictional territories. A subsequent permit application for over 100,000 acre-feet per year of water out of the Kiamichi Basin (in Choctaw Territory) by Oklahoma City triggered the filing of a federal law suit by the CN and CNO against the State of Oklahoma and Oklahoma City. The resulting Water Settlement (2016), signed by President Obama in December 2016, provides water to meet the future needs of Oklahoma City, while protecting lake levels and flows in the Kiamichi Basin. The Water Settlement also calls for collaboration between the CN, CNO, and the State, and for future water right applications to be scrutinized by a technical committee, using a common hydrologic model. It is expected that the RiverWare model refined through this study will be the model of choice for these future deliberations. CN and CNO are now in the implementation stages of the Water Settlement.

2.1 Geographic Scope

The Red River Basin covers portions of states stretching from the State of New Mexico, all the way to the Mississippi River, which subsequently flows into the Gulf of Mexico. The Red River itself also forms a large portion of the southern border of Oklahoma. The study's model will contain the Red River Basin from its headwaters to Oklahoma's eastern border, as shown in Figure 1.

With this study focusing primarily on the portion of the basin occupied by the Chickasaw Nation and Choctaw Nation, a refined subset of the overall model will be produced for this region. This region, called the spatially refined model, corresponds to Oklahoma Comprehensive Water Plan planning basins that overlap the Chickasaw Nation and Choctaw Nation jurisdictional territories within the Red River Basin, which is also shown in Figure 1. The refined model region's southern and western edge are the Oklahoma border with Texas and Arkansas, respectively.

The Chickasaw Nation and Choctaw Nation jurisdictional territories represent approximately 15% of the Red River Basin, or some 13,800 square miles, and cover almost 27 percent of the State of Oklahoma, occupying 22 counties in the southeast quadrant. The Red River watershed covers over 75% of the Chickasaw Nation and Choctaw Nation territories.

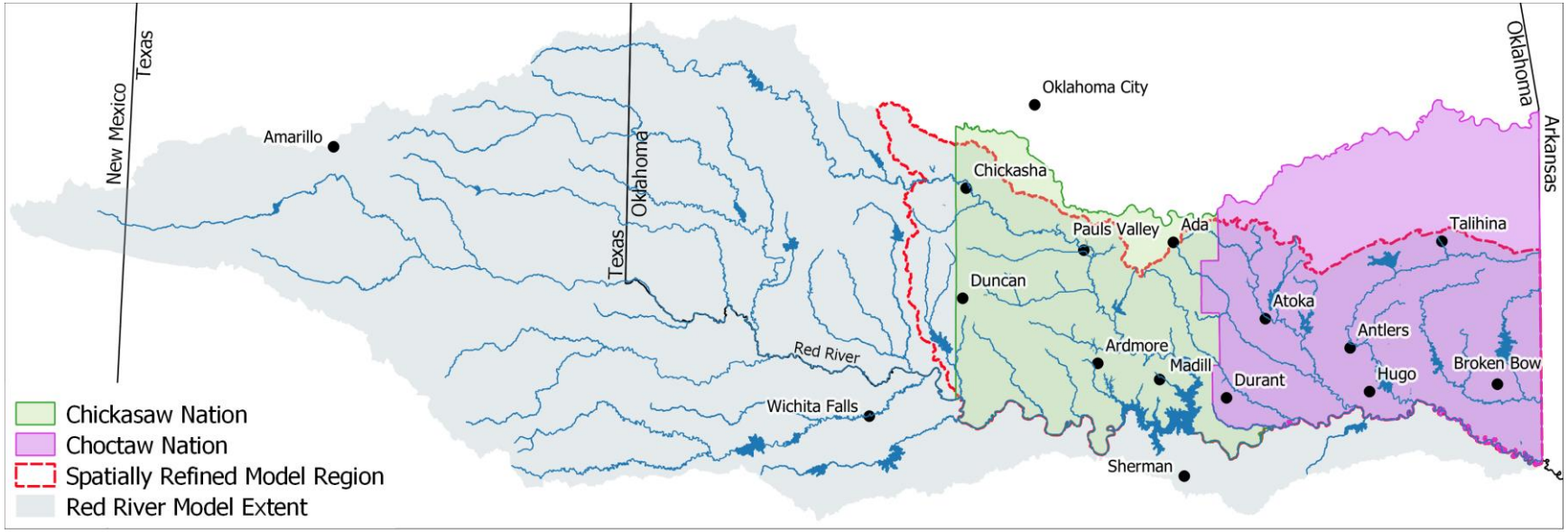

Figure 1. Overview of the Red River model extent, including the spatially refined model region and the Chickasaw Nation and Choctaw Nation jurisdictional territories.

3 Organization and Approach

The goal of the study is to identify communities vulnerable to surface water shortages across southeast Oklahoma and quantify any shortfalls in a water supply-demand curve into the future. Moreover, we aimed to assess the impacts of wet and dry cycles on flow-ecology relationships in the region. Understanding the context dependency of these relationships provides insight to how fish respond to climatic shifts. To accomplish the goals of the study, project staff will reference the *Impacts of Climate Change on Flows in the Red River Basin* (Kellogg et al., 2016) study that targeted the Red River Basin as a whole.

In the 2016 study, several different Global Climate Models (GCMs), downscaling techniques and Representative Concentration Pathways (RCPs) were used to develop an ensemble of 27 plausible climate scenarios for the future of the basin. These climate datasets were used as input into a grid-based large-scale Variable Infiltration Capacity (VIC) model that was built to simulate natural flow for the Red River and its major tributaries. Flows from the VIC model were used as input into a RiverWare water availability model of the basin. The RiverWare model covered the entire Red River basin and simulated daily flow for the period 1976 to 2099, allowing project staff working on the study to compare historic flow conditions to those expected under a changed climate.

The Red River RiverWare model from the 2016 study provided a broad view of the basin, however it is not at a fine enough scale to answer specific questions for individual water providers. For example, Pennington Creek is important to the City of Tishomingo, but was too small to be modeled explicitly in the previous RiverWare model. Elsewhere in the model, water diversions have been lumped, geographically, to reduce the computational requirements. This study will focus on the CN and CNO regions, producing a more refined model that is not overly computationally expensive and will allow project staff to achieve the stated study objectives.

As part of the Chickasaw Nation and Choctaw Nation Regional Water Plan, the CN and CNO have been visiting with communities across their entire 22-county region. To date the CN and CNO have met with over 60 water providers in southeast Oklahoma. While every community has water issues they are dealing with, not all are facing vulnerabilities due to a lack of supply. The ones that are typically rely on surface water, either because there is no groundwater available (physically or legally), or because of the proximity to a surface water body, or both. Project staff have good existing working relationships with these communities, and will work with these communities to estimate supply and demand projections, and potentially support mitigation strategies to address any projected water needs. These future strategies might include demand-reducing measures such as conservation or improved leak detection and repair, but will also target supply enhancement strategies such as indirect potable reuse, groundwater development and supply regionalization.

While the hydrologists worked with the water providers, the ecologists compiled fisheries data sets and built relationships with the modeled flow data (see Appendix A). The ecologists examined stream occurrence relationships with flow metrics in both wet and dry periods associated with the study time period (1961-2010). They delineated six time periods during the study years, with three dry seasons (1961–1967, 1976–1982, and 1999–2005) and three wet seasons (1968–1975, 1983–1998, and 2006–2010). They compiled fish survey records from multiple sources and attached them to stream segments throughout the study area. The most recent and significant drought (2010-2013) could not be included

in the study due to the temporal span of the modeled hydrology data. We modeled species detection and occurrence relationships using the hierarchical framework described by MacKenzie et al. (2002).

3.1 RiverWare Background

Water availability modeling is used to determine surface water impacts from reservoirs and surface water diversions under a variety of hydrologic inflow scenarios. This study uses the RiverWare (2020) water availability model, which is a river system modeling tool developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES[1]).

RiverWare is used extensively in the western United States for water rights administration. The US Army Corps of Engineers (USACE) uses RiverWare in districts for real-time flood control operations. RiverWare has the capabilities to model complex reservoir operations, water user diversions, return flows, prior appropriation, channel routing, and more. RiverWare's interface allows for visual diagnosis and editing, and results can be easily graphed or exported for additional analysis. Even though RiverWare has extensive functionality, it is not a rainfall-runoff model and flows input into the system need to be generated separately.

RiverWare's dynamic set of tools makes it the state of the art in water resources availability modeling. RiverWare can model a reservoir's unique operating requirements, such as limiting releases to reduce flooding downstream reaches, low flow release requirements, hydropower requirements, or seasonal operational targets. RiverWare can also be used to model a state's prior appropriation system and can assign water ownership to states or private owners. Additionally, it can be used to satisfy interstate river compacts. RiverWare's robust functionality allows for even the most complicated river systems to be modeled by using state of the art methods and providing the flexibility to write unique procedures to represent reservoirs and river systems.

Figure 2 shows a portion of the RiverWare model, with model objects such as reservoirs, reaches, control points and confluences.

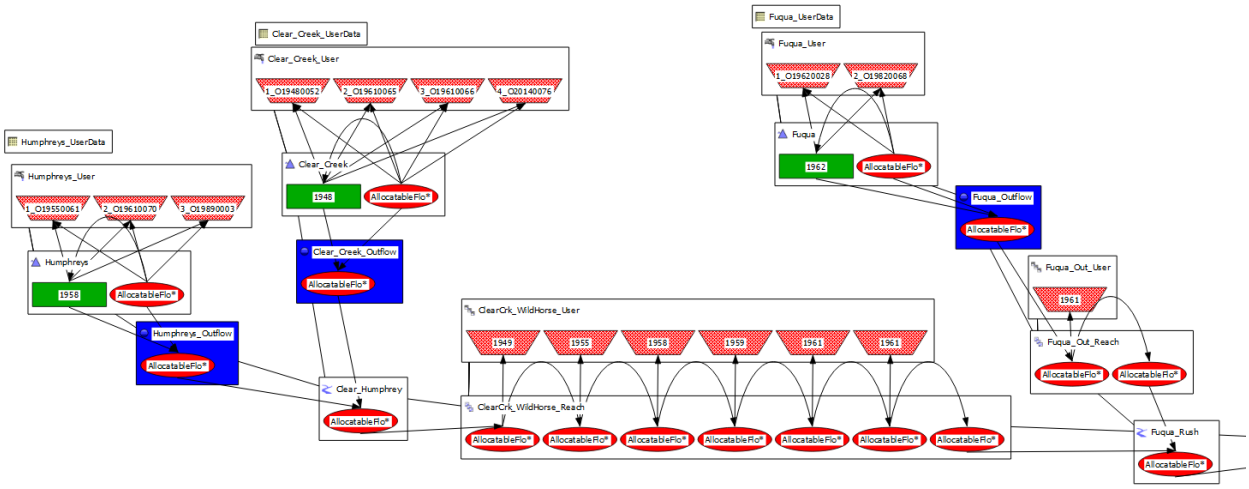

Figure 2. RiverWare model objects in the Lower Washita watershed, showing Wildhorse Creek, Lake Humphreys, Clear Creek Lake and Lake Fuqua.

[1] http://www.riverware.org/

4 RiverWare Model Development

The RiverWare model from the *Impacts of Climate Change on Flows in the Red River Basin* (2016) study was used as a starting point for this study. The model was initially developed from two separate U.S. Army Corps of Engineers Southwestern Division (USACE SWD) RiverWare models. These USACE SWD models simulated Lake Kemp and the Wichita River, and reservoirs and streams in the Red River basin from Lake Texoma down to Shreveport, LA. More information on these models can be found in *Impacts of Climate Change on Flows in the Red River Basin* (2016).

The *Impacts of Climate Change on Flows in the Red River Basin* (2016) study models were combined and expanded to include additional regions, including rivers and reservoirs upstream of Lake Texoma. All water permits in Texas and Oklahoma were included in the model, and many were combined to decrease computation time and simplify the model building process. Only major reservoirs were included and many small tributaries, such as Pennington Creek in Oklahoma, were not included. For the purposes of that study the approach was appropriate.

The previous RiverWare model is the starting point for this study's RiverWare model, but was not yet refined enough to discern hydrologic impacts on a small scale nor for individual water permits. Since many water permits had been lumped, it excluded the possibility of individually modeling these water permits, which is one of the objectives of this study. Additionally, only major reservoirs were in the previous model, excluding small to medium sized reservoirs that are commonly locally owned and often serve as sole water sources for communities or rural water providers.

Even so, using the previous model significantly decreased staff efforts compared to building a new model. Another significant advantage to using the previous model was that both models use the same input datasets (VIC model outputs) and simulation timeframes. Additionally, the previous model had already developed and incorporated reach routing, and major reservoirs and their operations. The following sections describe how this study's RiverWare model was further adapted from the previous model, as well as the input data used to run model scenarios.

4.1 Model Disaggregation

The spatially refined model region aligns with the Oklahoma Comprehensive Water Plan (OCWP) Planning Basins that are located within the Red River Basin and the Chickasaw Nation and Choctaw Nation jurisdictional territories. The RiverWare model was disaggregated to include smaller tributaries, all water permits, and lakes or reservoirs that are associated with a municipal water permit. This process required additional input data, such as incremental inflow to streams, rivers and reservoirs, reservoir evaporation and precipitation, and at times baseflow. These input data are discussed in Section 4.7.

Disaggregating the previous model started with project staff identifying new incremental inflow locations that would increase modeling accuracy and improve the representation of water permits across the watershed. These new locations were identified based on a number of factors, including the presence of a municipal water permit, a reservoir with an associated municipal water permit, a large number of water permits that were previously grouped, or a large watershed area having limited flow input locations in the previous model. Overall, the process of identifying new model inflow locations, the corresponding additional model reaches, and adding reservoirs were conducted to best represent municipal water permits within the spatially refined model region.

Once new inflow locations were identified, river reaches, reservoirs and water permits were added in the model, with each water permit being individually represented. All modeled inflow locations, reaches, and reservoirs within the spatially refined model region are shown in Figure 3.

Smaller tributaries within the model often have an inflow location at the bottom of the tributary and upstream of its confluence with a larger river. When viewing Figure 3, these inflow locations and smaller tributaries are difficult to identify, so Table 4 in Appendix E provides a list of them. Additionally, while entire reaches are not always modeled, nor are some smaller streams or tributaries, their contributing streamflow are still accounted for in the model. Furthermore, even though the state border between Oklahoma and Arkansas represents a model boundary instead of a watershed boundary, contributing streamflow from Arkansas are included in the model, where applicable.

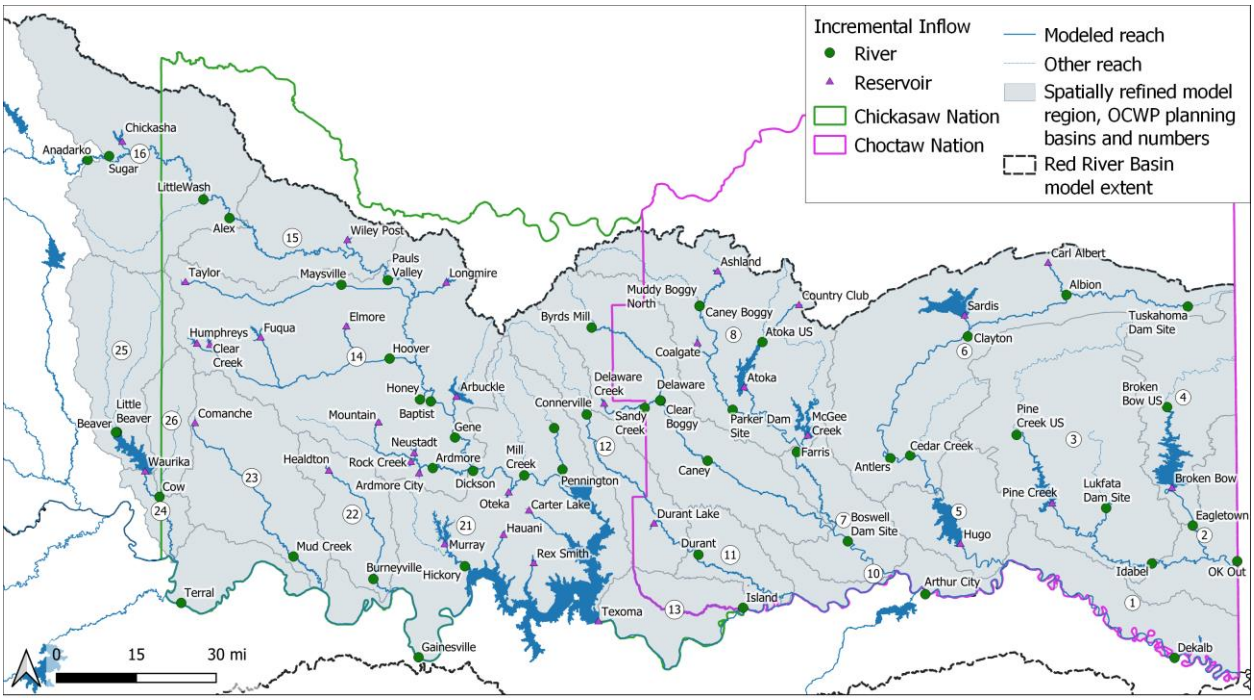

Figure 3. Inflow locations within the spatially refined model region. Model inflow locations outside of the spatially refined model region are not shown.

4.2 Surface Water Permits

Both Oklahoma and Texas surface water laws follow the Prior Appropriation Doctrine, simply translated as first in time, first in right. A senior water permit holder has the right to divert the full permitted diversion amount before a junior water permit holder (e.g. a permit with a later priority date). A surface water permit's ability to divert its full permitted amount is not guaranteed. The State of Oklahoma, through the Oklahoma Water Resources Board, grants surface water permits based on average annual streamflow.

Surface water permits for Oklahoma (OWRB, 2017) and Texas (TCEQ, 2018a) are included in the RiverWare water availability model and are recent as of November 2017 and January 2018 for Oklahoma and Texas, respectively. No temporary permits, term water permits, riparian rights, or domestic use set asides were included. All water permits were modeled in RiverWare by using their fully authorized yearly permitted amount, and assuming no return flows. This scenario is often used in a worst-case scenario, or in determining the largest possible impacts to streamflow, water permits and reservoirs.

Since this study is focused on quantifying the full potential impacts to climate change and using these data for water planning, this scenario was identified as the most appropriate for this study.

Monthly water use coefficients (or demand distribution coefficients) were assigned by water permit type (e.g. municipal, industrial, agricultural) and were referenced from the Texas Water Availability Mode (TCEQ, 2018b) for the Red River Basin, shown in Figure 4. The water permit yearly amount was multiplied by the water use coefficient to determine each month's water usage. All modeled water permits and the associated diversion amounts, are shown for the study area in Figure 5. Within the study area Oklahoma has a total of 818,626 AFY of water permits diversions, while Texas has a total of 986,328 AFY of water permits[2], for a total of 1,804,954 AFY of modeled water permits diversions.

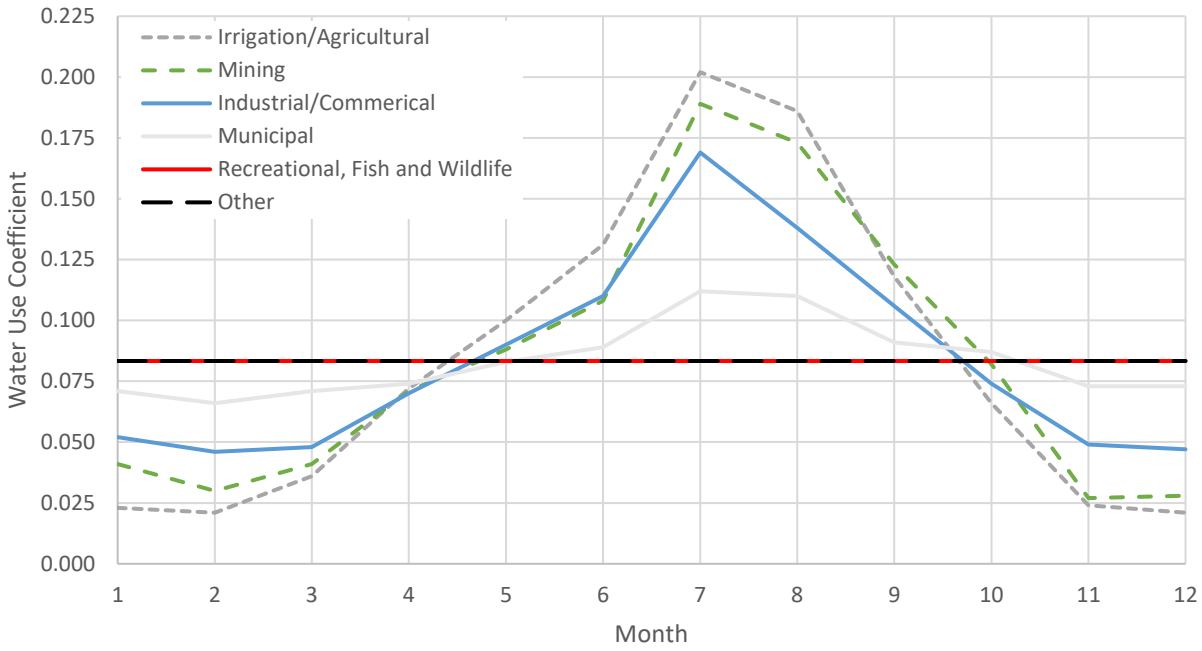

Figure 4. Monthly demand distribution coefficients by water use type for water permits in Texas and Oklahoma (TCEQ, 2018b).

[2] Texas water right number 5230 with a priority date of 6/27/1914 has a maximum permitted diversion amount of 135,331 AFY, but only a maximum consumptive use of 600 AFY. This water permit's diversion amount in the RiverWare model is 600 AFY.

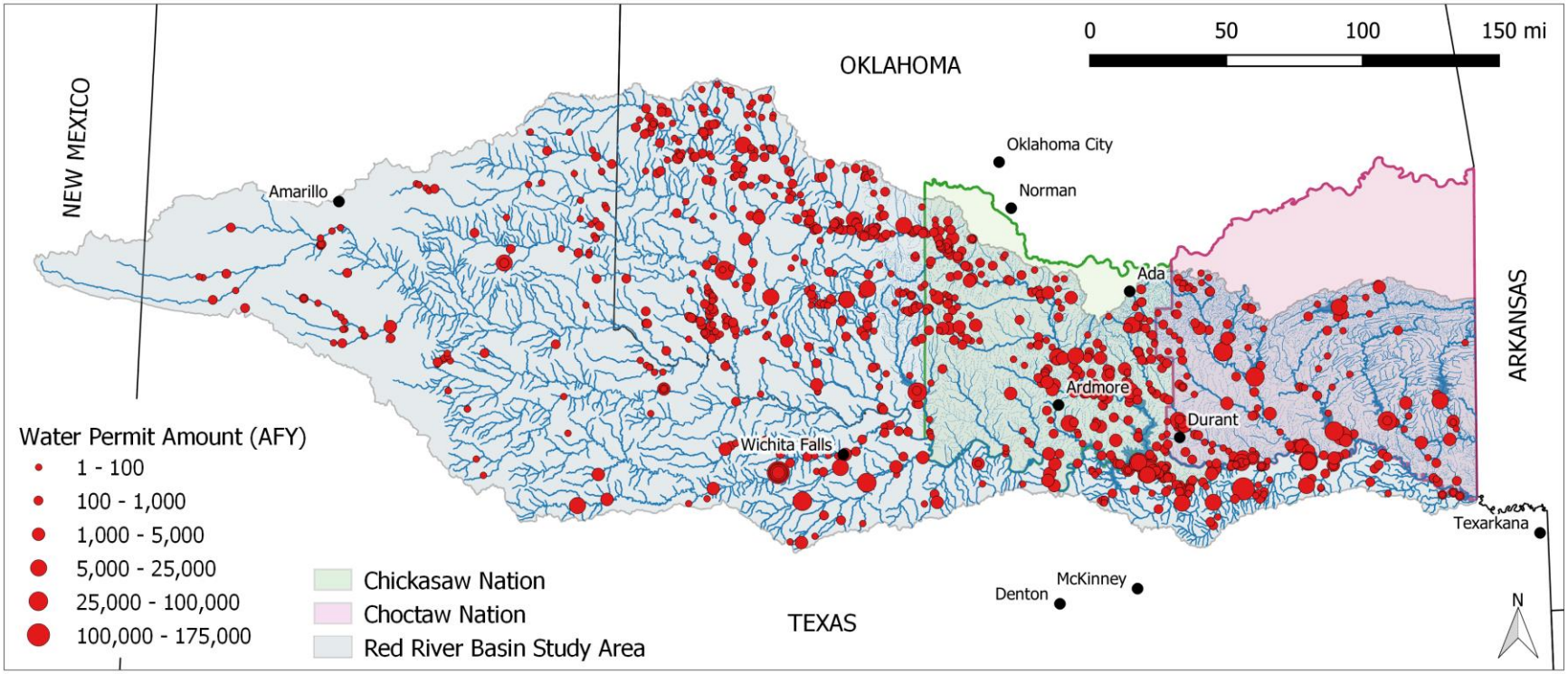

Figure 5. Modeled surface water permits in Oklahoma and Texas, showing the annual water permit amount, study area and the Choctaw and Chickasaw Nation boundaries.

4.3 Additional Reservoirs

Only major reservoirs were included in the previous RiverWare model. Since this study focuses on local municipal water permits, any reservoir in the spatially refined model region that was associated with a municipal water permit was included in the RiverWare model. A total of 25 reservoirs were added into this model, resulting in a total of 46 reservoirs modeled in total. Figure 6 shows all reservoirs in the spatially refined model region. Outside the spatially refined model region, no reservoirs were added or removed from the previous model. All modeled reservoirs, along with pertinent information, are listed in Table 6 in Appendix E.

Elevation-area-capacity (EAC) tables, which provide a relationship between a reservoir's elevation and its corresponding volume and surface area, are an important modeling component and used to estimate reservoir evaporation and direct precipitation. EAC tables were available through the Oklahoma Water Resources Board (2018), USACE Water Control Manuals, or Texas Water Development Board (2018), when available. USACE operated reservoirs used EAC tables within the Water Control Manuals, which at times are different than available OWRB EAC tables. While nearly all of the added reservoirs had known capacities, most of the EAC tables were unknown and estimated by using maximum depth and surface area data from Lakes of Oklahoma Third Edition[3] (2015), and the NRCS[4]. Some applicable data were also provided by local municipalities.

[3] http://www.owrb.ok.gov/news/publications/lok/lok.php

[4] NRCS and USDA shapefile of Oklahoma dams provided through the Oklahoma Office of Geographic Information and the Oklahoma Conservation Commission, 2012.

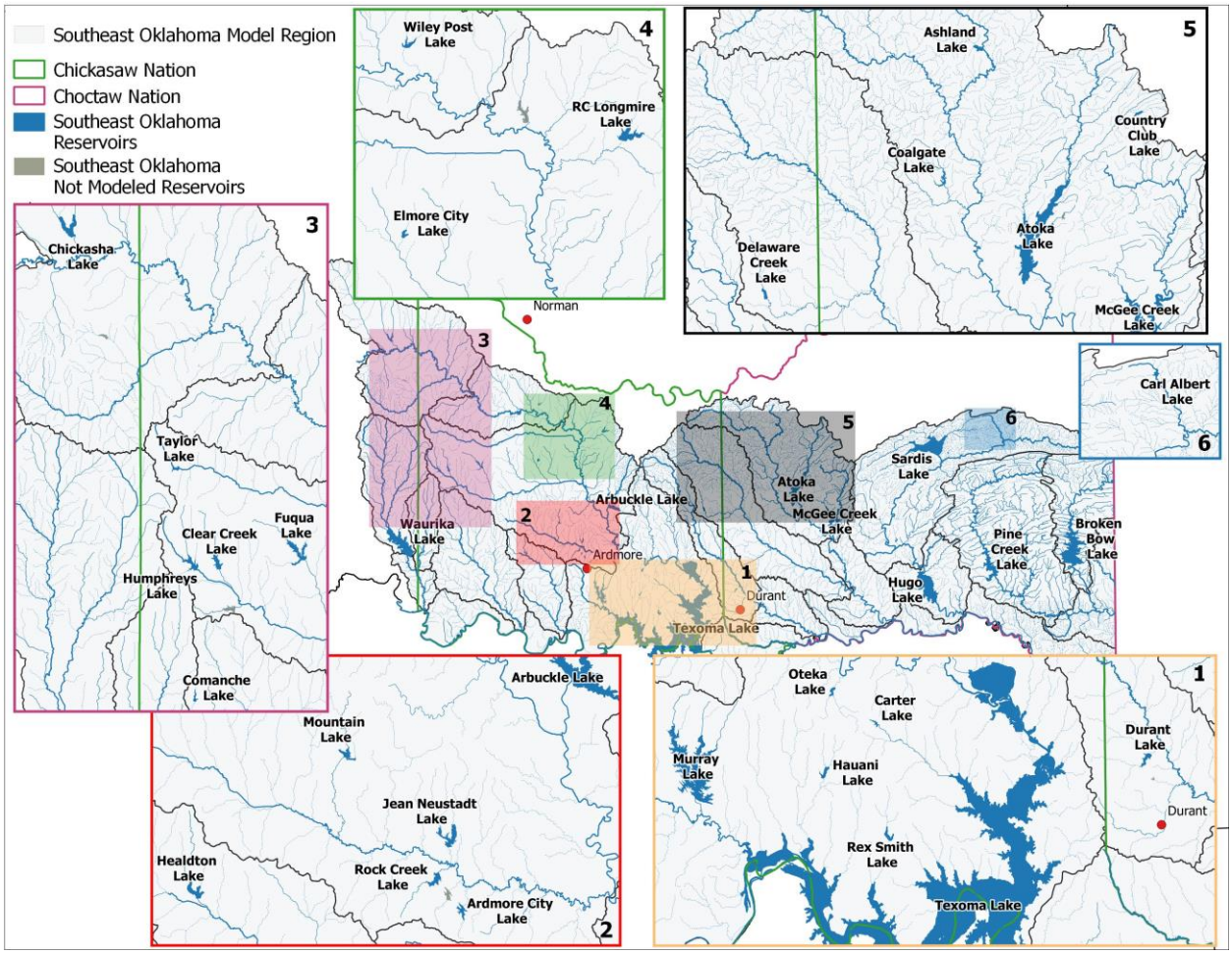

Figure 6. Modeled reservoirs in the spatially refined model region. Colored rectangles are more detailed insets.

4.4 Reservoir Operations

4.4.1 Reservoir Physical Operations

Most of the reservoirs in the *Impacts of Climate Change on Flows in the Red River Basin* (2016) study follow the USACE SWD operational methods. During a flood event these methods work to equitably balance storage across multiple reservoirs in a basin and limit downstream flooding. These methods and other operational requirements, such as low-flow releases, seasonal operating levels, or hydropower releases, were incorporated within the RiverWare model and based off of the original USACE RiverWare models and available Water Control Manuals that were provided for this study and the previous study. These models and manuals contained important reservoir information integrated in the model, such as:

- Elevation-area-capacity tables
- Outlet rating curves
- Emergency flood control schedule
- Operational levels or seasonal operational levels
- Low flow release requirements
- Flood flow downstream routing times

More information on these operational algorithms and methods can be found in the RiverWare USACE-SWD Manual[5] or in the *Development and Use of USACE-SWD Flood Control Hydropower Algorithms in RiverWare* (Daylor, J., et al, 2006).

The remaining non-USACE SWD reservoirs in the *Impacts of Climate Change on Flows in the Red River Basin* (2016) study were modeled using other provided data from either the Texas Water Development Board or the Oklahoma Water Resources Board and this previous study should be referenced for this additional information.

The remaining reservoirs, those that were added into this study's model, have an operational goal to fill to capacity, defined as either the normal pool elevation or conservation pool elevation. No active operation of these added reservoirs, such as seasonal operating levels, were assumed to occur as these reservoirs are rarely actively managed or do not have the infrastructure to be actively managed. During flood events these reservoirs will spill or release water that is above their defined normal pool or conservation pool elevation.

4.4.2 Reservoirs and Prior Appropriation

A reservoir's ability to store inflows is based upon the prior appropriation system in both Texas and Oklahoma. In Texas, the surface water permit defines the maximum amount of water that can be stored, while in Oklahoma there is no legal permit issued to reservoirs. Even so, a reservoir's ability to store water in Oklahoma is still bound to the prior appropriation system and it receives a priority date corresponding to the oldest surface water diversion permit that is associated with the reservoir. If an Oklahoma reservoir did not have a water permit associated with it, it was assigned a priority date junior to all other water permits in the basin. Unless it was otherwise stated in a water control manual or a legal permit, reservoirs in Oklahoma were assumed to have a maximum storage amount associated with the stated storage capacity, which was often defined by the normal or conservation pool elevation.

When a reservoir is not full but is receiving upstream inflows, according to prior appropriation a senior user is entitled to these inflows first, and can require all upstream junior users to curtail use until the senior user has satisfied its water needs. Since many small to medium sized reservoirs in Oklahoma are not actively managed, having only a spillway at the normal or conservation pool elevation, releasing inflows to a senior downstream user when the reservoir's water elevation is below the spillway can be physically impossible or not operationally practical. Even with these potential physical limitations Oklahoma reservoirs were modeled to satisfy the state's prior appropriation system and to have the ability to pass reservoir inflows to more senior users, if needed. Additionally, the Oklahoma Water Resources Board (OWRB) can require a reservoir to release reservoir inflows to a downstream senior user, perhaps through a siphon or through a temporary method.

In these instances, Oklahoma reservoirs would not be required to release existing storage, only reservoir inflows. This situation also applies to water permit holders that can divert from a reservoir. These users, during curtailment for a downstream senior water permit holder, cannot divert from reservoir inflows but can divert from existing reservoir storage.

[5] http://www.riverware.org/PDF/RiverWare/documentation/USACE_SWD.pdf

4.5 Reach Routing

Reach routing approximates how streamflow travels downstream in a river channel. Routing was incorporated into the RiverWare model to more realistically represent how flows travel down a basin. The RiverWare step response method was selected for this model and is commonly used within USACE-SWD RiverWare models. This method routes streamflow using coefficients, where each coefficient represents a percentage of flow that occurs in a specific future or present timestep. The total number of lag coefficients depends on the total lag length being modeled, with all coefficients summing to 1.

When available for reaches, step response coefficients were referenced from the original USACE flood routing models. For reaches without these data, the USACE Water Control Manuals' reported peak travel times were referenced. These peak travel times were used to fit the peak of a standard gamma distribution curve. The fitted distribution curve was then used to estimate each timesteps' coefficient. A gamma distribution was also used for all remaining reaches, with the peak travel time being identified based on similar reaches.

4.6 Red River Compact

In 1955 the United States granted the States of Arkansas, Louisiana, Oklahoma and Texas the ability to enter into a compact for appropriating waters in the Red River and its tributaries (Red River Compact Commission, 1970). These States approved the Red River Compact in May of 1978, which defines the use, control, and distribution of waters in the Red River and its tributaries (Red River Compact Commission, 2015). Water ownership is distributed according to reaches and a reaches' sub-basins. Modeled and applicable reaches are shown in Figure 7.

Normally, a state has unrestricted use of waters in a particular sub-basin if the sub-basin is entirely within that respective state. Typically, for sub-basins that cross state lines, water is apportioned to each state on an annual percentage basis. An example of these distributions is given for Reach I, which contains the upper Red River Basin from the headwaters to the beginning of Lake Texoma's Denison Dam[6]:

- Sub-basin 1 (tributaries and streams starting in Texas and flowing in Oklahoma): Annual flow is apportioned 60% to Texas and 40% to Oklahoma
- Sub-basin 2 (tributaries and streams solely in Oklahoma): Oklahoma has free and unrestricted use of the water
- Sub-basin 3 (tributaries and streams solely in Texas): Texas has free and unrestricted use of the water
- Sub-basin 4 (main stem of the Red River, including Lake Texoma): Oklahoma and Texas are both apportioned 200,000 acre-feet per year, with any additional quantities apportioned 50% to Oklahoma and 50% to Texas.

[6] Reference Article IV of the Red River Compact for additional information

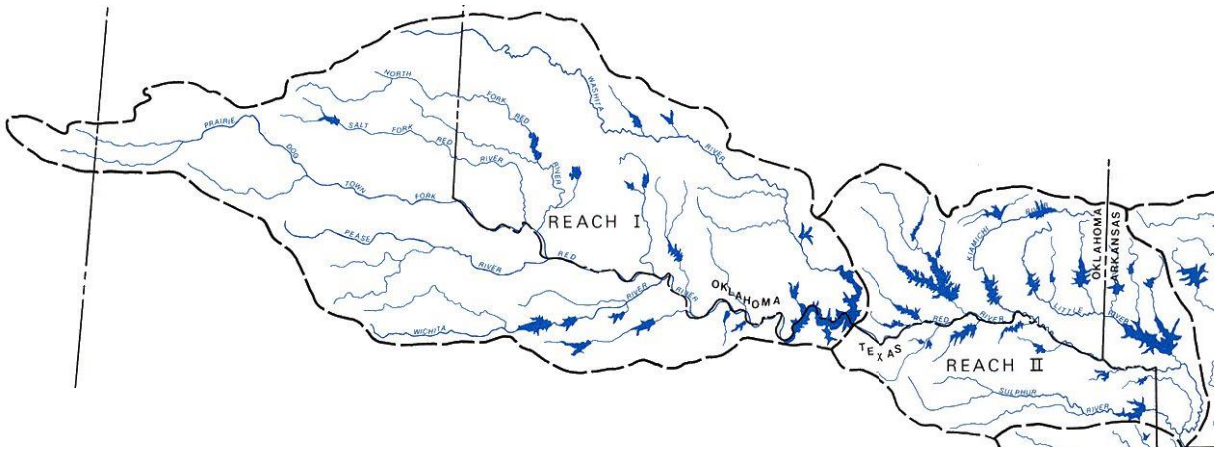

Figure 7. Red River Compact reaches applicable to the RiverWare model (OWRB, 2020a).

The Red River Compact's applicable reaches and sub-basins have been incorporated into the RiverWare model. This was accomplished either by annual water tracking, such as the case for Reach I Sub-basin 1, or by assigning ownership to flows within a basin (i.e. Reach I, Sub-basin 4 – main stem of the Red River). RiverWare's accounting system allows for water ownership (e.g. Texas apportioned or Oklahoma apportioned) and the ability to divide incremental inflows to specified water owners by using RiverWare rules. The model was designed such that a state and corresponding water permits associated with that state, can only access its owned water, as apportioned according to the Red River Compact.

4.7 Model Inputs

The term model inputs are used in this study to describe the main data inputs required to run a modeling scenario, including: incremental inflows, reservoir evaporation and direct reservoir precipitation. Most model inputs were provided from the *Impacts of Climate Change on Flows in the Red River Basin* (2016) study. This study generated these inputs and goes into more detail than is covered here and it should be referenced for any additional information not mentioned in this report.

4.7.1 Global Climate Models

To study the effects of climate change, Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2011) were used. GCMs provide gridded simulations of past and future climate, with the CMIP5 being comprised of over 50 GCMs and the primary source for GCM output data (IPCC, 2013).

There are three main categories of uncertainty in GCM climate change projections. The first being how each GCM is constructed, the second being natural variability (e.g. El Nino, solar fluctuations), and the third being the extent to which humans may alter the atmosphere through greenhouse gas emissions (Hawkins and Sutton, 2009). The third uncertainty is often represented through four possible future atmospheric compositions, called Representative Concentration Pathways (RCPs; Vuuren et al., 2011). RCPs represent different radiative forcing levels reached in 2100 compared to pre-industrial values. The four RCPs: RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 are representative of the smallest (RCP 2.6) to largest (RCP 8.5) increase in global mean temperature.

The *Impacts of Climate Change on Flows in the Red River Basin* (2016) study identified a subset of three GCMs, based on models that performed well over the study area and represented CMIP5 uncertainty. The final GCMs selected in that study and used herein include the CCSM4 (U.S. National Atmospheric

Research), MIROC5 (University of Tokyo et al.), and MPI-ESM-LR (Max Planck Institute for Meteorology). Additionally, to capture a full range of RCPS while considering the timeline of this study and the 2016 study, only RCP 2.6, RCP 4.5 and RCP 8.5 were used.

Due to the relatively large grid resolution of GCMs it is often necessary to generate finer resolution climate projections at a more local scale, which can produce information that is more relevant for stakeholders and local researchers. There are a number of techniques for obtaining finer scale climate projection data, the most practical for studies of this nature being statistical downscaling methods. These methods find relationships between the larger GCM model outputs and finer-scale variables such as gridded historical observation data (i.e. LIVNEH). The 2016 study identified three downscaling techniques:

- Cumulative Density Function Transform (CDFt; Vrac and Michelangeli, 2009)
- Equi-Distant Quantile Mapping (EDQM; Li et al., 2010)
- Bias Correction Quantile Mapping (BCQM; Ho et al., 2012)

The BCQM downscale technique and corresponding GCM model results were removed from this study because it reportedly misrepresented extreme values in the 2016 study. All the remaining identified GCMs, RCPs and downscaling techniques were used in this study, resulting in a total of 18 unique climate projection scenarios.

4.7.2 VIC Rainfall-Runoff Model

With these climate projection scenarios and their corresponding atmospheric data, a rainfall-runoff model was then used to generate simulated natural flows for the study area. The 2016 study used the Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Liang et al., 1996), which is a macroscale, semi-distributed water and energy balance hydrologic model that is commonly used in climate change impact studies over various basin scales (Abdulla et al., 1996; Christenson and Lettenmaier, 2007; Elsner et al., 2010; Maurer et al., 2002; Maurer, 2007; Nijssen et al., 2001; Xue et al., 2016). The VIC model is capable of simulating surface runoff, baseflow, canopy interception, evapotranspiration and other hydrological processes at daily or sub-daily timesteps. The VIC model is forced by meteorological data, including: precipitation, maximum and minimum temperature, wind, vapor pressure, incoming longwave and shortwave radiation, and air pressure.

The VIC model was calibrated and validated in the 2016 study by using the LIVNEH observational dataset (Livneh et al., 2013) and a novel multisite calibration method (MSCC; Xue et al., 2016). Livneh is a gridded meteorological dataset developed from observed historical measurements. The MSCC used long-term U.S. Geological Survey streamgage data to automate and calibrate the VIC model. This method was shown to achieve better model performance across a large basin compared to a single-site calibration at a basin's outlet.

The USGS streamgage data are not naturalized flows, which are estimated flows in a watershed without any human intervention or activity, such as reservoirs, diversions or discharges. Naturalized flows, which are normally used as inflow inputs into a water availability model, are not available for the model region and this study uses already developed input data from the 2016 study.

The calibrated VIC model was run for all 18 of the climate projection scenarios, producing gridded output data for the entire Red River Basin. The gridded inflow data, or simulated natural flows, were then assigned to RiverWare inflow locations, including control points and reservoirs. The inflow data are

incremental flow, representing watershed runoff downstream of the next upstream inflow location. The gridded VIC data also included reservoir evaporation and direct precipitation data, which were assigned to each reservoir in the model.

Baseflow

When compared to historical streamflow data the VIC inflow data from the *Impacts of Climate Change on Flows in the Red River Basin* (2016) study did not accurately represent low flow conditions in the Blue River basin or the Pennington Creek watershed. Baseflow in these basins often represent the vast majority of streamflow during dry periods and being able to estimate it is vital to generate accurate RiverWare model results in these basins. Since rerunning and recalibrating the VIC model for new incremental inflow for these basins was not within the scope of this study, another approach was used.

The baseflow separation program within the Texas A&M Soil and Water Assessment Tool (USDA, 2018) was used to separate baseflow from total streamflow from historical USGS streamgage data across the two basins. These baseflow data were then compared to the historical inflow data generated from the VIC model and compared against periods of low flow to estimate a reasonable historical baseflow value.

To be able to represent baseflow increases and decreases as a result of different climate projection scenarios instead of using a historical estimation of baseflow, the baseflow value was estimated as a percentage of the average inflow for each scenario. This approach allows for a better and more adaptive representation of low flow periods for all inflow scenarios.

By analyzing the baseflow separation data only one location in each basin was assigned baseflow according to this method. These locations are the Connerville control point in the Blue River basin, and the Reagan control point in the Pennington Creek watershed. The Mill Creek watershed was also investigated for adding baseflow, but the VIC inflow data sufficiently represented baseflow when compared to USGS streamgage data.

5 Project Results, Analysis and Findings

The RiverWare model was run on a daily timestep for the historical and climate projection scenarios, and model results were processed from 1976 through 2005 and 2010 through 2099 for each scenario, respectively. These time periods are consistent with the previous 2016 study's analysis.

5.1 Municipal Water Rights

Model results for municipal surface water permits within the spatially refined model region are shown in Figure 8 and summarized in Table 1 and Table 2. Figure 8 shows the change in reliability for all non-irrigation purpose water permits and shows the coefficient of variation for the climate projection scenarios. These tables show shortages and reliabilities for the historical scenario and climate projection scenarios. The climate scenario results in these tables are an average of all climate projection scenarios. Reliability in this report is defined as the demand amount supplied divided by the desired demand amount.

Multiple municipal water permits associated with a single entity were combined[7] and for an entity with more than one water right, the overall reliability is a weighted average based on each individual permit's diversion amount. A list of the water permits associated with each entity are provided in Table 5 in Appendix E.

Frequency duration curves for the most unreliable municipal entities and their corresponding surface water permits are provided in Appendix B. These figures show the frequency and magnitude of yearly and monthly surface water permit shortages for each municipal entity.

Approximately half of the municipal water supply entities that rely on surface waters have projected water shortages. Overall, these entities also have decreased projected reliability when compared to historical reliability, and projected reliability tends to decrease over the coming decades. The entities with the largest decreases in reliability, when compared to historical reliability, include: City of Elmore, City of Healdton, City of Chickasha, Marshall County Water Corporation, Madill County Water Corporation, City of Duncan, and City of Durant. The City of Chickasha does not currently use their largest water right on Lake Chickasha, so these results may not be currently applicable.

As seen in Figure 8, the entities with the largest decrease in reliability are primarily within Chickasaw Nation territory. These entities often have a large coefficient of variation (COV), which is a measure of variation between scenario results and its corresponding projected shortages and projected reliabilities.

It is also important to note that the VIC model's flow inputs into RiverWare were calibrated and validated with streamgage data from medium to large watersheds. When considering the VIC model's overall scale and grid sizes of approximately 60 square miles, it may have more uncertainty in representing water permits with watersheds less than 60 square miles or local springs that some water permits rely heavily on. This increased uncertainty for certain municipal entities may result in unrealistically low or high reliability and shortage values.

[7] Some entities had water permits with a primary purpose other than public supply, such as irrigation or recreation/fish/wildlife. Only water permits within the spatially refined model region and with the primary purpose of municipal supply were combined for an entity.

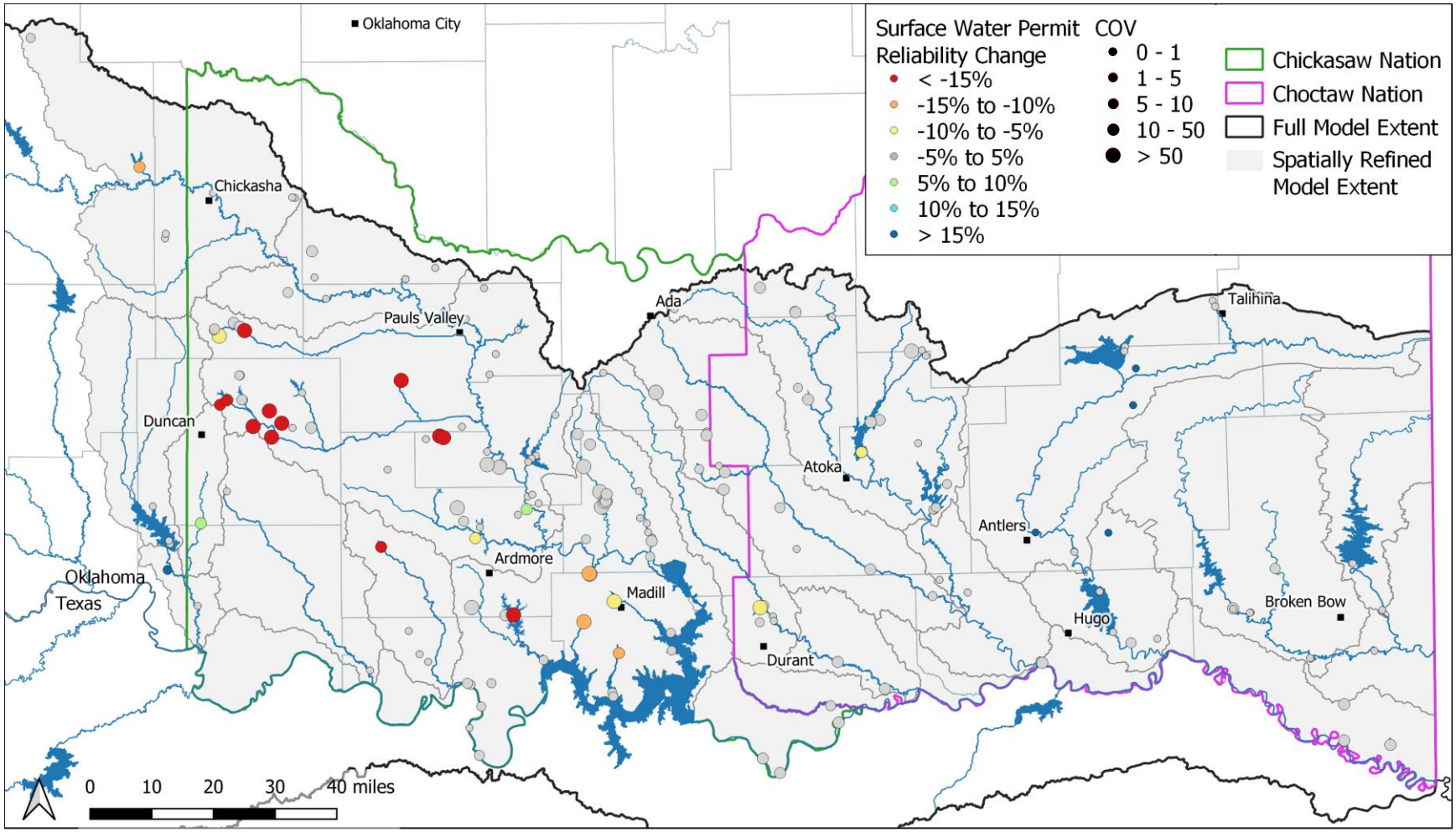

Figure 8. Change in reliability within the spatially refined model region for non-irrigation purpose surface water permits. Reliability change is the difference between an average of all climate scenarios (2070 – 2099) and the historical scenario (1976 – 2005). The coefficient of variation is also shown for the climate projection scenarios.

Table 1. Modeling results summary for municipal water permit shortages. Climate scenario results are an average of all modeled climate projections.

Municipal Surface Water Permit Entities	Total Surface Water Permit Amount (AFY)	Number of Municipal Surface Water Permits	Average Historical Shortage, cfs (1976 - 2005)	Average Historical Shortage, AFY (1976 - 2005)	Climate Scenarios' Average Shortage (cfs)				Climate Scenarios' Average Shortage (AFY)				Shortage Increase (2070 - 2099 minus Historical averages), cfs
					2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099	2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099	
Ada, City of	8,700	2	7.7	5,604	7.0	7.2	7.7	7.3	5,059	5,228	5,609	5,307	0.01
Baptist General Convention of OK	1,008	1	0.63	455	0.5	0.5	0.6	0.5	361	382	409	384	-0.06
Elmore City, City of	238	1	0.02	18	0.10	0.12	0.13	0.11	71	85	96	80	0.11
Madill Public Works Authority	3,442	3	0.87	631	0.79	1.01	1.30	1.00	570	732	939	727	0.43
Marshall County Water Corporation	3,126	3	0.59	424	0.56	0.75	0.99	0.75	404	540	714	540	0.40
Southern Oklahoma Water Corporation	192	1	0.08	61	0.06	0.06	0.06	0.06	40	42	44	42	-0.02
Healdton, City of	1,473	1	0.11	79	0.22	0.31	0.41	0.30	160	223	300	218	0.31
Tishomingo, City of	7,520	3	2.2	1,580	1.63	1.76	2.00	1.79	1,177	1,274	1,448	1,298	-0.18
Chickasha, City of	5,274	2	0.56	409	0.53	0.94	1.32	0.89	384	682	953	644	0.75
Valliant, City of	614	1	0.14	103	0.13	0.15	0.16	0.15	95	107	114	105	0.02
Durant, City of	12,342	3	1.6	1,178	1.48	1.81	2.34	1.84	1,072	1,311	1,693	1,334	0.71
Wapanucka Public Works Authority	320	1	0.04	32	0.04	0.04	0.05	0.04	26	29	36	30	0.01
Duncan, City of	8,253	4	0.07	47	0.41	0.88	1.10	0.76	298	634	797	552	1.04
Oklahoma City, City of	131,667	3	3.7	2,710	4.1	6.9	11.8	7.3	2,993	4,976	8,550	5,294	8.07
Mack Alford Correctional Center	180	1	0.005	3	0.004	0.01	0.01	0.01	3	5	9	5	0.01
Bryan County RWS & SWM #2	1,860	3	0.11	81	0.10	0.11	0.12	0.11	69	82	86	79	0.01
Smith, Bryant & Mavis	1,900	1	0.08	61	0.08	0.10	0.10	0.09	60	71	75	68	0.02
Ardmore, City of	5,202	3	0.07	51	0.04	0.08	0.14	0.08	29	55	104	60	0.07
Coalgate Public Works Authority	7,832	3	0.001	1	0.03	0.06	0.19	0.09	24	46	137	66	0.19
Marlow, City of	1,877	1	0	0	0.002	0.003	0.04	0.01	1	2	29	10	0.04
Atoka, City of	10,000	2	0.06	43	0.05	0.09	0.18	0.10	37	67	134	76	0.13
Arbuckle Area Council	457	1	0	0	0	0	0.01	0.003	1	0	5	2	0.01
Bridgeview Camp A Corp	3	1	0	0	0	0	0	0	0	0	0	0	0
Buncombe Creek View	1	1	0	0	0	0	0	0	0	0	0	0	0
Tourism & Recreation, Dept of	78	1	0	0	0	0	0	0	0	0	0	0	0

Municipal Surface Water Permit Entities	Total Surface Water Permit Amount (AFY)	Number of Municipal Surface Water Permits	Average Historical Shortage, cfs (1976 - 2005)	Average Historical Shortage, AFY (1976 - 2005)	Climate Scenarios' Average Shortage (cfs)				Climate Scenarios' Average Shortage (AFY)				Shortage Increase (2070 - 2099 minus Historical averages), cfs
					2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099	2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099	
University of Oklahoma	7	1	0	0	0	0	0	0	0	0	0	0	0
Arbuckle Master Conservancy Dist	24,000	2	0.04	28	0	0	0.05	0.02	0	0	37	12	0.01
Idabel Public Works Authority	4,929	2	0.01	6	0.01	0.01	0.02	0.01	9	11	11	10	0.01
Antlers Public Works Authority	758	2	0.07	54	0	0	0	0	0	0	0	0	-0.07
Broken Bow Public Works Authority	10,660	2	0.001	1	0	0	0	0	0	0	0	0	-0.001
Chickasaw National Recreation Area	100	1	0	0	0	0	0	0	0	0	0	0	0
Comanche Public Works Authority	300	1	0	0	0	0	0	0	0	0	0	0	0
Davis, City of	25	1	0	0	0	0	0	0	0	0	0	0	0
Hughes Co Rural Water District #2	300	1	0	0	0	0	0	0	0	0	0	0	0
Hugo Municipal Authority	30,500	2	0.003	2	0	0	0	0	0	0	0	0	-0.003
Kiowa, Town of	302	2	0	0	0	0	0	0	0	0	0	0	0
Latimer Co Rural Water District #2	1,000	1	0	0	0	0	0	0	0	0	0	0	0
Lindsay, City of	31	1	0	0	0	0	0	0	0	0	0	0	0
Maysville, Town of	700	2	0	0	0	0	0	0	0	0	0	0	0
McCurtain Co Rural Water Dist #1	2,000	1	0	0	0	0	0	0	0	0	0	0	0
Mountain Fork Water Supply Corp	1,711	2	0	0	0	0	0	0	0	0	0	0	0
Murray State College	300	1	0	0	0	0	0	0	0	0	0	0	0
Pauls Valley, City of	3,361	1	0	0	0	0	0	0	0	0	0	0	0
Pushmataha Co Rural Water Dist #3	700	2	0	0	0	0	0	0	0	0	0	0	0
Sardis Lake Water Authority	6,000	1	0.001	1	0	0	0	0	0	0	0	0	-0.001
Talihina Public Works Authority	1,800	2	0	0	0	0	0	0	0	0	0	0	0
Waurika Project Master Cnsrvncy Dst	44,806	2	0	0	0	0	0	0	0	0	0	0	0
Note: entities are arranged in order of their corresponding water permits' reliability (2070 – 2099 climate scenario average), with the least reliable entity listed first													

Table 2. Modeling results summary for municipal surface water permit reliabilities. Climate scenario results are an average of all modeled climate projections.

Municipal Surface Water Permit Entities	Total Surface Water Permit Amount (AFY)	Number of Municipal Surface Water Permits	Average Historical Reliability, % (1976 - 2005)	Climate Scenarios' Average Reliability (%)				Change in Reliability (2070 - 2099 avg minus historical)	Least Reliable Water Permit Ranking (2070-2099 scenario avg)
				2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099		
Ada, City of	8,700	2	38.3%	44.7%	42.7%	37.9%	41.7%	-0.4%	1
Baptist General Convention of OK	1,008	1	57.2%	66.6%	64.5%	61.6%	64.3%	4.4%	2
Elmore City, City of	238	1	92.9%	71.8%	66.7%	61.7%	68.1%	-31.2%	3
Madill Public Works Authority	3,442	3	82.1%	83.7%	79.0%	73.0%	79.2%	-9.1%	4
Marshall County Water Corporation	3,126	3	86.6%	87.2%	82.8%	77.2%	82.8%	-9.4%	5
Southern Oklahoma Water Corporation	192	1	69.9%	80.8%	80.0%	78.6%	79.8%	8.7%	6
Healdton, City of	1,473	1	94.5%	89.3%	85.1%	79.9%	85.4%	-14.7%	7
Tishomingo, City of	7,520	3	80.8%	85.6%	84.4%	82.0%	84.0%	1.2%	8
Chickasha, City of	5,274	2	92.4%	93.1%	87.5%	82.6%	88.2%	-9.8%	9
Valliant, City of	614	1	85.0%	86.2%	84.3%	83.3%	84.6%	-1.7%	10
Durant, City of	12,342	3	90.9%	91.5%	89.6%	86.5%	89.4%	-4.4%	11
Wapanucka Public Works Authority	320	1	90.6%	92.6%	91.6%	89.4%	91.2%	-1.2%	12
Duncan, City of	8,253	4	99.4%	96.5%	92.6%	90.6%	93.5%	-8.8%	13
Oklahoma City, City of	131,667	3	98.1%	97.8%	96.3%	93.6%	96.1%	-4.4%	14
Mack Alford Correctional Center	180	1	98.3%	98.6%	97.5%	95.3%	97.3%	-3.0%	15
Bryan County RWS & SWM #2	1,860	3	96.5%	97.0%	96.4%	96.2%	96.5%	-0.3%	16
Smith, Bryant & Mavis	1,900	1	97.1%	97.3%	96.8%	96.6%	97.0%	-0.5%	17
Ardmore, City of	5,202	3	99.0%	99.4%	98.9%	97.5%	98.7%	-1.5%	18
Coalgate Public Works Authority	7,832	3	100%	99.7%	99.4%	98.3%	99.2%	-1.7%	19
Marlow, City of	1,877	1	100%	99.9%	99.9%	98.5%	99.5%	-1.5%	20
Atoka, City of	10,000	2	99.6%	99.7%	99.4%	98.7%	99.3%	-0.9%	21
Arbuckle Area Council	457	1	99.9%	99.9%	99.9%	98.8%	99.6%	-1.1%	22
Bridgeview Camp A Corp	3	1	100%	100%	100%	99.7%	99.9%	-0.3%	23
Buncombe Creek View	1	1	100%	100%	100%	99.7%	99.9%	-0.3%	23
Tourism & Recreation, Dept of	78	1	100%	100%	100%	99.7%	99.9%	-0.3%	23
University of Oklahoma	7	1	100%	100%	100%	99.7%	99.9%	-0.3%	23

Municipal Surface Water Permit Entities	Total Surface Water Permit Amount (AFY)	Number of Municipal Surface Water Permits	Average Historical Reliability, % (1976 - 2005)	Climate Scenarios' Average Reliability (%)				Change in Reliability (2070 - 2099 avg minus historical)	Least Reliable Water Permit Ranking (2070-2099 scenario avg)
				2010 - 2039	2040 - 2069	2070 - 2099	2010 - 2099		
Arbuckle Master Conservancy Dist	24,000	2	99.90%	100%	100%	99.80%	99.90%	0%	27
Idabel Public Works Authority	4,929	2	99.90%	99.90%	99.80%	99.80%	99.80%	-0.10%	27
Antlers Public Works Authority	758	2	93.50%	100%	100%	100%	100%	6.50%	29
Broken Bow Public Works Authority	10,660	2	100%	100%	100%	100%	100%	0%	29
Chickasaw National Recreation Area	100	1	100%	100%	100%	100%	100%	0%	29
Comanche Public Works Authority	300	1	100%	100%	100%	100%	100%	0%	29
Davis, City of	25	1	100%	100%	100%	100%	100%	0%	29
Hughes Co Rural Water District #2	300	1	99.90%	100%	100%	100%	100%	0.10%	29
Hugo Municipal Authority	30,500	2	100%	100%	100%	100%	100%	0%	29
Kiowa, Town of	302	2	99.90%	100%	100%	100%	100%	0.10%	29
Latimer Co Rural Water District #2	1,000	1	100%	100%	100%	100%	100%	0%	29
Lindsay, City of	31	1	100%	100%	100%	100%	100%	0%	29
Maysville, Town of	700	2	100%	100%	100%	100%	100%	0%	29
McCurtain Co Rural Water Dist #1	2,000	1	100%	100%	100%	100%	100%	0%	29
Mountain Fork Water Supply Corp	1,711	2	100%	100%	100%	100%	100%	0%	29
Murray State College	300	1	100%	100%	100%	100%	100%	0%	29
Pauls Valley, City of	3,361	1	100%	100%	100%	100%	100%	0%	29
Pushmataha Co Rural Water Dist #3	700	2	100%	100%	100%	100%	100%	0%	29
Sardis Lake Water Authority	6,000	1	100%	100%	100%	100%	100%	0%	29
Talihina Public Works Authority	1,800	2	100%	100%	100%	100%	100%	0%	29
Waurika Project Master Cnsrvncy Dst	44,806	2	100%	100%	100%	100%	100%	0%	29

5.2 Vulnerable Municipal Water Supply Entities

Model results from Table 1 and Table 2 show projected shortages and reliabilities for municipal surface water rights, but these data need to be analyzed within a larger context of a municipal water entity. Entities may not use their entire permit amount due to existing demands, may rely on other water sources (e.g. groundwater), may purchase or sell water to other water entities, or may have increased or decreased water demands in the future. These additional factors, together with model results, were considered in identifying municipal water supply entities that are vulnerable due to existing or future water needs.

Project staff sent out questionnaires and held meetings with communities with significant projected surface water shortages to quantify communities' current usage, other water sources (e.g. groundwater), water contracts with other entities, and projected water demands. Due to the CN and CNO ongoing regional water planning efforts, a number of communities had already been visited or sufficient data was already available. Project staff did not receive questionnaires or responses from some communities. In total, project staff received responses from a number of entities and met for further discussions with three communities: City of Atoka, City of Coalgate, and Bryan County Rural Water District #2. Section 8 Stakeholder Engagement discusses these activities in more detail.

The questionnaire and meeting data were combined with projected water demands (OCWP, 2012), previous CN and CNO community meeting data, other water provider survey data (Aqua Strategies, 2015), and this study's model results to estimate water needs (i.e. water demand minus water supply), which are shown in Table 3. From these data supply-demand curves were also developed and are provided in Appendix C. Table 3 and the generated supply-demand curves assumes the following:

- Any applicable groundwater permit amounts are 100% reliable
- Any water supply contracts (i.e. purchasing or selling) are 100% reliable
- Infrastructure limitations (e.g. water treatment plant capacity, pump capacities) are not considered

The entities with estimated water needs within the next forty years are: City of Tishomingo, Marshall County Water Corporation (MCWC), and the City of Ada. Their projected water needs within the next forty years range from 5 to 1,047 AFY. Other entities, such as the Wapanucka Public Works Authority, Madill Public Works Authority, and the City of Durant, have future projected water needs after 2060. Overall, most entities with or without projected water needs have decreased yearly available water (i.e. increase in shortages) as well as decreased projected reliability over the coming decades. Appendix C and Table 3 can be referenced to better estimate projected water needs by entity.

The City of Ada relies heavily on the local Bird's Mill Spring and the corresponding water permits have a projected and historical reliability of around 40%. This low reliability, and corresponding projected water needs may be due to the VIC model's overall scale and grid sizes, which may have underrepresented these localized inflows within the model. Additionally, a number of entities, including the City of Ada, did not provide current demand data, which if provided may result changes to projected water needs. These communities are noted in Table 3.

A number of entities with significant projected water shortages were not included in Table 3 nor were supply-demand curves generated for them. This was either due to no available demand projections, no current usage estimates, or the water entity was not within the refined model region or the CN or CNO territories. These entities include: Baptist General Convention of OK, "Smith, Bryant & Mavis", and the City of Oklahoma City.

Table 3. Summary of projected water needs for the most vulnerable water supply entities. Water need is water supply minus water demand.

Municipal Water Supply Entities	Current Water Sources[1], AFY			Combined Water Sources, AFY	Current Estimated Demand[2] (AFY)	Yearly Averaged Projected Water Need (AFY)				Yearly Averaged Projected Water Need (cfs)				Maximum Monthly Projected Water Need (cfs)			
	Surface Water Permit(s)	Groundwater Permits	Other Sources or Contracts			2020 - 2039	2040 - 2059	2060 - 2079	2080 - 2099	2020 - 2039	2040 - 2059	2060 - 2079	2080 - 2099	2020 - 2039	2040 - 2059	2060 - 2079	2080 - 2099
Tishomingo, City of	7,520	-	-	7,520	650	0	5	1,350	3,985	0	0.01	1.86	5.50	0	1.23	5.06	8.85
Marshall County Water Corp [3]	3,126	-	-9	3,117	2,158	111	1,047	2,472	3,790	0.15	1.45	3.41	5.24	1.51	3.80	5.33	7.46
Ada, City of	8,700	1,908	1,200	11,808	5,376 [(4)]	10	83	341	772	0	0.12	0.47	1.07	0	0.48	0.83	1.34
Wapanucka Public Works Authority	320	-	-	320	77	0	0	4	55	0	0	0.01	0.08	0	0.03	0.14	0.28
Madill Public Works Authority	3,442	-	-64.4	3,378	672	0	0	0	15	0	0	0	0.02	0	0	0.18	1.39
Durant, City of	12,342	-	-681	11,661	5,090	0	0	0	0	0	0	0	0	0	0	0.70	3.28
Elmore City, City of	238	-	-	238	80 [(4)]	0	0	0	0	0	0	0	0	0	0	0	0.10
Healdton, City of	1,473	-	-	1,473	439 [(4)]	0	0	0	0	0	0	0	0	0	0	0	0.06
Mack Alford Correctional Center [5]	180	-	-	180	146	0	0	0	0	0	0	0	0	0	0	0	0.04
Ardmore, City of	5,202	890	13,783	19,875	8,287	0	0	0	0	0	0	0	0	0	0	0	0
Atoka, City of	10,000	-	-129	9,871	1,116	0	0	0	0	0	0	0	0	0	0	0	0
Bryan County RWS & SWM #2	1,860	122	-	1,982	809	0	0	0	0	0	0	0	0	0	0	0	0
Chickasha, City of	5,274	-	5,848	11,122	3,135	0	0	0	0	0	0	0	0	0	0	0	0
Coalgate Public Works Authority	7,832	336	491	8,659	672	0	0	0	0	0	0	0	0	0	0	0	0
Duncan, City of	8,253	98	14,935	23,286	5,056 [(4)]	0	0	0	0	0	0	0	0	0	0	0	0
Marlow, City of	1,877	-	-	1,877	811 [(4)]	0	0	0	0	0	0	0	0	0	0	0	0
Southern Oklahoma Water Corporation	192	1,126	1,741	3,059	1,288	0	0	0	0	0	0	0	0	0	0	0	0
Valliant, City of	614	-	-	614	130	0	0	0	0	0	0	0	0	0	0	0	0

[1] Only water permits with a municipal use were included. Water contract amounts are negative if selling or positive if purchasing to/from an entity. Contract amounts were referenced from either questionnaires and interviews from this study or water provider surveys (Aqua Strategies, 2015) and were the best available information at the time of this report.

[2] Existing and future demands were referenced from either questionnaires and interviews from this study, OWRB provided water use summary reports (2020b), OCWP published data (2012), or water provider surveys (Aqua Strategies, 2015). Entities often only provided current demands, so OCWP published future demands were also used. These OCWP future demands (from 2020 through 2060) were shifted by aligning the projected 2020 demands with reported entity demands, which allowed for more realistic future demand projections based on current reported demands.

[3] The Marshall County Water Corporation includes surface water permits from "Little, Dan and Prudence"

[4] No current estimated demands were provided and values were either referenced from OCWP (2012) projected 2020 demands or from water provider surveys (Aqua Strategies, 2015) that were older than 4 years.

[5] The Mack Alford Correctional Center did not have OCWP (2012) demand projections so a constant demand projection associated with the reported current demand was used

5.3 Reservoir Results

Elevation and storage frequency-duration curves were produced for reservoirs in the spatially refined model region, which are provided in Appendix D. These figures show the historical scenario (LIVNEH) and the average for each RCP group of scenarios (i.e. RCP 2.6, RCP 4.5, RCP 8.5).

When comparing the climate projection scenarios to the historical scenario, median storage volumes decrease across most reservoirs, with some of the larger reservoir (i.e. Broken Bow, Sardis) exhibiting very small differences in median volumes between scenarios. On the whole the smaller locally owned reservoirs have larger projected decreases in median storage volumes, when compared to the historical scenario.

The reservoirs with the most significant projected decreases in median storage volumes when compared against historical volumes include: Lake Chickasha, Rock Creek Reservoir, Comanche Lake, Rex Smith Lake, and Clear Creek Lake. These reservoirs correspond to water permits owned by the following entities, respectively: City of Chickasha, City of Ardmore, Comanche Public Works Authority, Marshall County Water Corporation, and the City of Duncan.

6 Conclusions and Recommendations

Model results indicate that municipal water permits with decreased reliability, when compared to historical reliability, are primarily located in the western portion of the spatially refined model. These permits also tend to continue decreasing in reliability over the coming decades. Water permits with a significant decrease in reliability often have large variation between the climate projection results and its corresponding projected shortages and projected reliabilities.

When comparing these results within the broader context of a water entities' existing and future demands, and their other water sources, the following entities may have projected water needs within the next forty years: City of Tishomingo, Marshall County Water Corporation (MCWC), and the City of Ada. The City of Ada's projected water needs may be overestimated due to their reliance on a local spring, which the VIC surface water model may not have captured well. Over the coming decades approximately half of the modeled municipal water permits will see decreases in available water as well as decreases in water reliability.

With no recent water demands for some entities, including the City of Ada, projected water needs may change with updated demand data. Additionally, since elevation-area-capacity tables were estimated for many of the small locally owned reservoirs (see Appendix E), there is uncertainty in the model results for these projected reservoir levels, associated water permit results and their corresponding entities' projected water needs (if applicable). Obtaining these data would allow for more accurate estimates of projected water needs where applicable.

Both the Chickasaw Nation and Choctaw Nation have been actively investing in a comprehensive regional water planning initiative for their jurisdictional territories and have a vested interest in supporting communities in meeting their water needs. As a result of this study it is expected that both the CN and CNO will provide support, or are already providing support, to the entities identified as having future water needs. With a better understanding of these projected water needs and when they may occur, investigating alternative water sources or water conservation efforts for these entities can now begin.

7 Outreach and Products

As discussed throughout the report, it is expected that both the CN and CNO will provide support to the entities identified as having water needs. In fact, support for certain communities identified in this study are ongoing. One example is the Chickasaw Nation's work with the City of Tishomingo on water treatment plant improvements and identifying an alternative water source. These mitigation strategies, in particular identifying a new water source, will increase their water supply and is expected to remove the projected shortages and water needs detailed in this report.

The Chickasaw Nation is also looking at ways to support the Southern Oklahoma Water Corporation (SOWC), who have reached out for support in identifying an alternative water source, upgrading their undersized water infrastructure, and addressing disinfection by-products issues.

Another example is the City of Durant, which the Choctaw Nation has been working with to address distribution system losses. The City, through support from the Choctaw Nation, was recently awarded a grant to install smart water meters across the City. These meters will help target and reduce distribution system losses. This mitigation strategy will help decrease the City's water demands and decrease future water needs.

8 Stakeholder Engagement

As part of this study and report, a questionnaire that focused on documenting existing water sources (e.g. surface water, groundwater, other water contracts), current and future water demands, and water related needs or issues, were sent to the following water entities:

- City of Ada
- City of Ardmore
- City of Atoka
- Baptist General Convention of OK
- Bryan County RWS & SWM #2
- City of Chickasha
- Coalgate Public Works Authority
- City of Elmore
- City of Duncan
- City of Durant
- Mack Alford Correctional Center
- Madill Public Works Authority
- City of Marlow
- Marshall County Water Corporation
- Southern Oklahoma Water Corporation
- City of Tishomingo
- City of Valliant
- Wapanucka Public Works Authority

Project staff were not able to find contact information for the "Smith, Bryant and Mavis" water permit entity.

Staff from the Chickasaw Nation and Choctaw Nation also had individual meetings with staff at the following municipal water supply entities: City of Atoka, City of Coalgate, and Bryan County Rural Water District #2. These meetings allowed project staff to go into more detail about the respective entities' water issues and collect more detailed data for this study. Project staff had previously met with a number of other entities and these data were also used within this study. The provided data from these questionnaires and meetings helped project staff develop projected water needs as described in Section 5.2.

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Appendix A – Examining stream fish occurrence related to flow metrics during wet and dry seasons in the Kiamichi River and surrounding catchments

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SUMMARY

We examined stream occurrence relationships with flow metrics in both wet and dry periods associated with the study time period (1961-2010). We delineated six time periods during the study years, with three dry seasons (1961–1967, 1976–1982, and 1999–2005) and three wet seasons (1968–1975, 1983–1998, and 2006–2010). We compiled fish survey records from multiple sources and attached them to stream segments throughout the study area. The most recent and significant drought (2010-2013) could not be included in the study due to the temporal span of the hydrology data. Our streamflow metrics did not vary considerably by wet or dry season. Daily discharge, and skewness of metrics were generally greater with more variability in the wet season. We modeled species detection and occurrence relationships using the hierarchical framework described by MacKenzie et al. (2002). We found significant occurrence relationships for 77 stream fishes, but there were only two seasonal differences in relationships with flow timing metrics (date of annual maximum, date of annual minimum). Occurrence probability decreased significantly in the dry seasons in relation to date of annual maximum flow (TH1) for 10 stream fishes. This relationship resulted in a weak positive relationship with increasing TH1 in the dry seasons and a weak negative relationship in the wet seasons for all 10 stream fishes. Occurrence probability decreased with increasing annual minimum flow (TL2) in the dry seasons and increased in the wet seasons. Several other species had relationships with annual minimal flow, but it did not vary between wet and dry seasons. We also found significant relationships with five magnitude and duration flow metrics, but they also did not vary by season. There was only one relationship for two stream fishes where occurrence was related to rate of change (i.e., Bluntnose Minnow and Brook Silverside).

STUDY OBJECTIVE

METHODS

Seasons and sites

We divided the study years (1961–2010) into wet and dry climatic periods based on mean annual rainfall (National Climatic Data Center 2020) for Oklahoma climate division nine (Oklahoma Climatological Survey 2020). The seasons were delineated using a lowess (i.e., locally weighted scatterplot smoothing smoothing line) (Cleveland 1979) in the software Python (version 2.7.10, https://www.python.org/) that identified time periods with above-average and below-average precipitation from 1895–2015. The delineation resulted in six time periods during the study years, with three dry seasons (1961–1967, 1976–1982, and 1999–2005) and three wet seasons (1968–1975, 1983–1998, and 2006–2010).

We defined sites as a length of stream between second-order tributaries (hereafter segments, Figure 1). Segments are a meaningful scale to examine fish flow ecology because hydrologic characteristics can change abruptly at tributary junctions in the stream network (Frissell et al. 1986). We used second-order tributaries to define segments to eliminate very small or ephemeral first-order streams. Segments were derived from the National Hydrography Dataset (U.S. Geological Survey 2020). We dissolved the NHD streamflow polylines into a single feature using ArcMap (version 10.4.1, ESRI, Red

Lands, California) and reclassified the lines based on intersections with second-order or higher tributary junctions.

Fish surveys

We compiled stream fish assemblage surveys from a variety of agencies and online databases (Table A1). For online databases, we used the terms "fish" and "fishes" to search all Oklahoma counties within the study area from 1961–2010. Data were screened to remove duplicate surveys (~60%). Each unique survey was spatially referenced to a segment nested in a level-three ecoregion (hereafter ecoregion; Ouachita Mountains or South-Central Plains) using ArcMap based on the latitude and longitude. We assigned coordinates to surveys that did not provide a latitude and longitude if the location description was adequate to identify the appropriate site. Surveys without an adequate site description or located outside of the study area were removed from the dataset. We treated a segment as a new site for each time period it was surveyed. However, surveys in multiple time periods was relatively uncommon. Only 133 segments had surveys in more than one time period, only 68 had surveys in more than two time periods, and only two had surveys in all six time periods. We considered repeat surveys within a segment in the same time period spatial replicates with replacement (Kendall and White 2009). In addition to the detection (one) or non-detection (zero) of each fish species, we also compiled the survey date, collector identification (e.g., agency or scientist), and sampling gear type (if reported) for each survey. For surveys that were known specimen donations (i.e., not assemblage-level samples), we assigned an "NA", rather than a zero, to the remainder of the species to avoid artificially reducing detection probability. This treatment results in a missing observation for the associated survey, with no influence on detection or occurrence probability estimates (MacKenzie et al. 2002). Surveys with ≤5 species detections were also treated as donations if we lacked confidence in an assemblage-level sample (e.g., collector was an individual versus an agency). In the rare instance that fish surveys occurred in a first-order stream (n = 3 streams), we assigned the survey to the downstream segment. Lastly, we eliminated fish species with detections at <5 segments. The final dataset included 767 surveys (n = 470 in wet seasons and n = 297 in dry seasons) across 315 segments (n = 564 total sites) and 96 species (Table A2).

Streamflow metrics

We characterized the streamflow regime (Poff et al. 1997) of each segment across the time periods using a suite of metrics. For each segment in each of the six time periods, we calculated 171 flow metrics (median option) using EflowStats (version 5.0.1, median option, Kennen et al. 2007; USGS 2019) based on mean daily discharge estimates from the streamflow model. As expected, many of the flow metrics were highly correlated. We retained metrics based on Pearson's pairwise correlation coefficient (r) to achieve a comprehensive variable set that represented each flow regime component (i.e., frequency, magnitude, duration, rate of change, and timing) with a minimal number of variables. For example, r was > |0.80| between median daily discharge and 54 other flow metrics. Thus, we retained median daily discharge to provide a surrogate for numerous measures of flow magnitude. The reduced variable set comprised 15 flow metrics, where eight flow metrics were natural-log transformed due to right-skewed distributions (Table 1). The absolute value of r was < 0.68 for all 105 pairwise comparisons and >0.50 for only three (Table A3). We also quantified the relative flow magnitude (RFM) of each segment during the time of the fish survey to account for associated variation in species detection probability. We characterized stream discharge (cfs) for each segment using the median daily value for each month-year combination (hereafter median Q). RFM was calculated as median Q / segment drainage area (km^2). Drainage area values for segments were obtained from the National hydrography dataset.

Occupancy modeling

We modeled species detection and occurrence relationships using the hierarchical framework described by MacKenzie et al. (2002). For the detection component of the model (hereafter detection model), we included RFM, drainage area, segment length, and measures of time as covariates. Drainage area provided a characterization of stream size to account for variation in detection probability associated with species abundance relationships. We used segment length to account for variation in detection probability associated with proportional coverage (i.e., we hypothesized that, on average, a single survey at longer segments would have a lower detection probability than shorter segments). We natural-log transformed RFM, drainage area, and segment length due to right-skewed distributions. We used the month of the survey (hereafter time of year) to account for general seasonal trends associated with detection probability (e.g., water temperature). Time of year was quantified using the integers 1–6, where one was January and December, two was February and November, three was March and October, four was April and September, five was May and August, and six was June and July. We used the month-year combination of the survey (hereafter time of study) to account for increases or decreases in detection probability related to changes in species abundance across the study period. Time of study was quantified using the integers 1–600, where 1 was January 1961 and 600 was December 2010. Season was treated as factor (dry or wet), with dry as the reference. The absolute value of *r* was < 0.38 for all detection predictor variables (Table A4). We included an RFM-season interaction term to allow detection probability relationships with relative flow conditions to vary by wet and dry periods. We allowed all detection model parameters to vary by a species factor. These species coefficients were modeled as deflections around the group mean hyperparameter governed by a probability distribution, where the coefficients "shrink" towards a central tendency (Dorazio and Royle 2005; Gelman and Hill 2007; Kruschke 2015). We also allowed each species detection intercept to vary by collector (1–14, Table A5) and time period (1–6) using grouping factors (i.e., "random intercepts", Wagner et al. 2006; Gelman and Hill 2007) to account for unexplained variation in detection probability. We did not include sampling gear type in the model because it was only reported for 17% of the surveys. We used a *t* distribution, rather than a normal distribution, for species deflections and grouping factors to account for heavy tails and improve model fit (Lee and Thompson 2008; Kruschke 2013). The detection model can be written as:

$$\text{logit}(p_{ij}) = \Sigma_{k=1}^{96}\alpha_{0k} + \Sigma_{k=1}^{96}\alpha_{SEASONk[ij]} + \Sigma_{m=1}^{4}\Sigma_{k=1}^{96}\Sigma_{n=1}^{4}\beta_{mk}X_{n[ij]} +$$

$$\Sigma_{m=5}^{8}\Sigma_{k=1}^{96}\Sigma_{n=1}^{4}\beta_{mk}X_{n[ij]} * SEASON_{[ij]} + \Sigma_{k=1}^{96}\gamma_{t[ij]} + \Sigma_{k=1}^{96}\tau_{c[ij]}, \text{ for } i = 1, 2..N, \text{ for } j = 1,..J$$

$$\alpha_{0k} \sim t(\mu, \sigma^2, \upsilon)$$

$$\beta_{mk} \sim t(\mu, \sigma^2, \upsilon)$$

$$\gamma_t \sim t(0, \sigma^2, \upsilon), \text{ for } t = 1, 2....6,$$

$$\tau_c \sim t(0, \sigma^2, \upsilon), \text{ for } c = 1, 2....20,$$

where p_{ij} is species detection probability for survey *j* at segment *i*, α_{0k} is the species *k* deflection from the group-mean intercept, α_{WETk} is the season factor for species *k*, where dry is the reference, β_{mk} is the species *k* deflection from the group-mean for slope *m*, X_n is a detection covariate, γ_t is the grouping factor for time period *t*, τ_c is the grouping factor for collector *c*, μ is the group mean for the associated

species coefficients, and υ is the normality parameter for the associated *t* distribution. For the occurrence component of the model (hereafter occurrence model), we included the 15 streamflow metrics as species occurrence covariates (Table 1). Each flow metric varied by both season and species using the same model structure described for the detection model. The absolute value of *r* was < 0.31 between season and flow metric covariates (Table A3). We also included an ecoregion factor (South-Central Plains or Ouachita Mountains) to account for relationships with species distributions not associated with the streamflow metrics (e.g., endemics), with the South-Central Plains as the reference level. We allowed each species intercept to vary by time period (1–6) using a grouping factor. The occurrence model can be written as:

$$\text{logit}(\Psi_i) = \Sigma_{k=1}^{96}\alpha_{0k} + \Sigma_{k=1}^{96}\alpha_{1k[i]} + \Sigma_{k=1}^{96}\alpha_{SEASONk[i]} + \Sigma_{m=1}^{15}\Sigma_{k=1}^{96}\Sigma_{n=1}^{15}\beta_{mk}X_{n[i]} +$$

$$\Sigma_{m=16}^{30}\Sigma_{k=1}^{96}\Sigma_{n=1}^{15}\beta_{mk}X_{n[i]} * SEASON_{[i]} + \Sigma_{k=1}^{96}\gamma_{t[i]}, \text{ for } i = 1, 2..N,$$

$$\alpha_{0k} \sim t(\mu, \sigma^2, \upsilon)$$

$$\beta_{mk} \sim t(\mu, \sigma^2, \upsilon)$$

$$\gamma_t \sim t(0, \sigma^2, \upsilon), \text{ for } t = 1, 2....6,$$

where Ψ_i is species occurrence probability for survey *j* at segment *i*, α_{0k} is the species *k* is the species *k* deflection from the group-mean intercept, α_{1k} is the ecoregion factor for species *k*, α_{WETk} is the season factor for species *k*, where wet is the reference, β_{mk} is the species *k* deflection from the group-mean for slope *m*, X_n is an occurrence flow metric covariate, γ_t is the grouping factor for time period *t*, μ is the group mean for the associated species coefficients, and υ is the normality parameter for the associated *t* distribution. All covariates were standardized to a mean of zero and a variance of one to improve interpretation of model coefficients.

We fit models using the program JAGS (Plummer 2003) called from the statistical software R (version 3.5.3; R Development Core Team 2019) using the package jagsUI (Kellner 2018). We used broad uniform priors for species coefficients and main effects and vague gamma priors for associated standard deviations (Kéry and Royle 2016). Posterior distributions for coefficients were estimated using Markov chain Monte Carlo methods with 100,000 iterations after a 25,000 iteration burn-in phase. We assessed convergence using the Brooks-Gelman-Rubin statistic ($\hat{R}$, Gelman and Rubin 1992), where values < 1.1 for all model parameters indicates adequate mixing of chains (Kruschke 2015; Kellner 2018).

We used a two-step process to simplify the model and retain only significant detection and occurrence relationships. We began by fitting the most complex model and examining the detection RFM-season interaction term. We removed this term if none of the 95% highest density intervals (hereafter HDIs, Kruschke 2013; Kéry and Royle 2016) for species coefficients overlapped zero. If this interaction term was removed, we refit the model and used the aforementioned criteria to examine and remove, if applicable, the season indicator variable coefficient and slopes for detection covariates. If the interaction term was not removed, we proceeded in the same fashion without refitting the model. We used the same backward-selection process to examine flow metric relationships in the occurrence model, where we also examined the ecoregion indicator variable in step two.

Lastly, we examined fit of the final model using posterior predictive distributions and diagnostic plots. The final model was assessed using $\hat{c}$ from the chi-squared goodness-of-fit test described by MacKenzie and Bailey (2004), where a value between 1.00–1.02 indicates adequate fit (Kéry and Royle 2016). We also examined histograms of all species coefficients and grouping factors to ensure distributional assumptions were reasonably met.

RESULTS

Streamflow metrics

Most streamflow metrics did not vary considerably between the dry and wet seasons (Table 1). The mean, standard deviation (SD), and range was similar between the seasons for 12 of 15 flow metrics. Median daily discharge (MA2) was both greater and more variable in the wet seasons. Skewness in flow record (MH19) was also greater in the wet seasons. Although the mean was similar between the seasons for variability in fall rate (RA4), the SD and both the lower and upper extent of the range was approximately double in the wet seasons.

Occupancy modeling

There was at least one significant detection relationship for 56 stream fishes (Table 2). The most common detection relationship was associated with drainage area (*n* = 40 stream fishes). Detection probability increased significantly with increasing drainage area for 27 stream fishes and decreased for 13 stream fishes. Detection probability increased significantly for 17 stream fishes with increasing RFM. Detection probability decreased significantly with increasing time of year for nine stream fishes and decreased for Bigeye Shiner and Orangebelly Darter. There were no significant detection relationships with segment length and time of study. Surprisingly, detection relationships with RFM did not vary significantly between the wet and dry seasons for any stream fishes. Moreover, detection probability did not differ significantly between the wet and dry seasons for any stream fishes.

There was at least one significant occurrence relationship for 77 stream fishes, with significant seasonal differences for two flow metrics (Table 3). The most common significant relationship was with ecoregion. Occurrence probability increased for 46 stream fishes with the South-Central Plains and decreased for 16 stream fishes. Sixty stream fishes had a significant occurrence relationship with at least one flow metric, representing four elements of the flow regime (*n* = 12 metrics). Species occurrence probabilities were significantly different between the dry season and wet season for two timing covariates. Occurrence probability decreased significantly in the dry seasons in relation to date of annual maximum flow (TH1) for 10 stream fishes. This relationship resulted in a weak positive relationship with increasing TH1 in the dry seasons and a weak negative relationship in the wet seasons for all 10 stream fishes (Table 3 and Figure 1). Conversely, occurrence probability increased significantly in the wet seasons in relation to variability in the date of annual minimum flow (TL2) for 16 stream fishes. The seasonal relationships were stronger than TH1 and similar for all 16 stream fishes. Occurrence probability decreased with increasing TL2 in the dry seasons and increased in the wet seasons (Table 3 and Figure 2). Twelve additional stream fishes had a simple relationship (i.e., a significant relationship that did not vary between the seasons) with TL2. Occurrence probability decreased with increasing TL2 for all 12 stream fishes (Table 3). There were no simple significant relationships with TH1, but five stream fishes had a significant relationship with variability in the date of annual maximum flow (TH2). Occurrence probability decreased with increasing TH2 for Carmine Shiner, Dollar Sunfish, redhorse spp., Smallmouth Bass, and Striped Shiner. There were significant simple relationships with five magnitude flow metrics. The direction of the occurrence relationships with variability across annual flows (MA42) and MA2 varied among stream fishes. Occurrence probability increased with increasing MA42 for 12 stream fishes and decreased for nine stream fishes. Occurrence probability increased with increasing MA2 for 15 stream fishes and decreased for Blackstripe Topminnow and Orangebelly Darter. The direction of the occurrence relationships with MH19, low flow index (ML15), and median of yearly coefficient of variation (MA3) did not vary among stream fishes. Occurrence probability decreased with

increasing MH19 for 14 stream fishes, increasing ML15 for 10 stream fishes, and increasing MA3 for Bigeye Shiner, Leopard Darter, Mountain Madtom, Orangebelly Darter, and Smallmouth Bass. There were significant simple relationships with three duration flow metrics. The direction of the occurrence relationships with low flow pulse duration (DL16) differed for one species. Occurrence probability decreased with increasing DL16 for 14 stream fishes and increased for Smallmouth Bass. The direction of the occurrence relationships with variability of annual minimum of 90-day moving average flow (DL10) did not vary among stream fishes. Occurrence probability increased with increasing DL10 for 11 stream fishes. Only one stream fish species had a relationship with DH14, where occurrence probability increased with increasing flood duration (DH14) for Brook Silverside. There was a significant simple relationship with one rate of change flow metric for two stream fishes. Occurrence probability increased with increasing variability in fall rate (RA4) for Bluntnose Minnow and Brook Silverside. There were no significant occurrence relationships with any frequency flow metrics or any simple significant relationships with season (i.e., occurrence probability was not different between the seasons) for any stream fishes).

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Table 1. Reduced set of flow metrics and summary statistics used to identify flow regime relationships for 96 stream fishes calculated using EflowStats (see Kennen et al. 2007 for detailed descriptions of flow metric calculations). † indicates metrics that were natural-log transformed for the analysis. SD is standard deviation.

Metric (EflowStats code)	Mean ± SD (range) - Dry	Mean ± SD (range) - Wet
† Flood duration (DH14; dimensionless)	3.19 ± 0.78 (2.06–5.41)	2.94 ± 0.53 (2.21–4.70)
† Low flow pulse duration (DL16; number of days)	20.33 ± 20.26 (4.50–89.00)	16.92 ± 16.41 (6.00–89.00)
Variability of annual minimum of 90-day moving average flow (DL10; percent)	69.87 ± 36.22 (8.21–179.49)	67.43 ± 34.51 (2.50–165.20)
† Flood frequency (FH10; number/year)	2.32 ± 1.51 (1.00–13.00)	2.05 ± 1.01 (1.00–9.00)
Variability in high pulse count (FH2; number/year)	41.69 ± 17.17 (8.68–108.27)	36.71 ± 12.32 (0.00–82.03)
† Low flow index (ML15; dimensionless)	0.05 ± 0.06 (0.00–0.31)	0.05 ± 0.04 (0.00–0.24)
† Median daily discharge (MA2; cfs)	374.03 ± 773.16 (0.31–3912.21)	556.89 ± 1230.02 (1.21–6497.01)
† Median of yearly coefficient of variation (MA3; dimensionless)	105.84 ± 22.48 (64.10–173.45)	99.57 ± 16.32 (68.97–139.63)
Skewness in flow record (MH19; dimensionless)	-0.07 ± 0.81 (-1.48–2.38)	0.46 ± 0.79 (-1.83–2.73)
† Variability across annual flows (MA42; dimensionless)	1.25 ± 0.47 (0.67–2.95)	1.09 ± 0.38 (0.61–2.67)
† Variability in fall rate (RA4; percent)	160.41 ± 48.54 (41.79–389.99	187.78 ± 95.18 (73.59–829.67)
Date of annual maximum flow (TH1; day of year)	82.39 ± 92.44 (0.25–360.06)	101.86 ± 124.16 (0.35–365.22)
Variability in date of annual maximum flow (TH2; day)	57.02 ± 10.19 (30.76–79.53)	62.32 ± 10.24 (36.57–79.57)
Date of annual minimum flow (TL1; day of year)	277.70 ± 42.37(43.00–363.00)	265.17 ± 43.60 (7.00–364.00)
Variability in date of annual minimum flow (TL2; day)	37.92 ± 16.50 (12.67–73.95)	41.12 ± 11.92 (10.92–72.97)

Table 2. Detection model coefficients for species intercepts, significant species relationships, and group mean hyperparameters. Coefficients are reported on the logit scale from posterior distributions as the mode with associated 95% highest density intervals (HDIs). RFM is relative flow magnitude, LHDI is the lower HDI, UHDI is the upper HDI, SD is standard deviation, and v is a normality parameter. Intercepts are interpreted as estimated detection probability at mean levels of covariates. Other coefficients are interpreted with all other variables held constant.

Coefficient	Mode (LHDI, UHDI)
American Pickerel – Intercept	-0.57 (-1.27, 0.18)
American Pickerel – Drainage area	-0.57 (-0.93, -0.25)
Banded Pygmy Sunfish – Intercept	-0.96 (-1.89, 0.14)
Banded Pygmy Sunfish – Drainage area	-0.67 (-1.28, -0.13)
Bantam Sunfish – Intercept	-2.05 (-3.23, -0.82)
Bigeye Shiner – Intercept	0.79 (0.12, 1.50)
Bigeye Shiner – Time of year	0.35 (0.11, 0.60)
Black Bullhead – Intercept	-2.24 (-3.09, -1.37)
Black Crappie – Intercept	-1.60 (-2.71, -0.37)
Black Crappie – RFM	0.52 (0.17, 1.11)
Blackside Darter – Intercept	-2.14 (-3.78, -0.65)
Blackspot Shiner – Intercept	-2.27 (-3.14, -0.91)
Blackspot Shiner – Drainage area	-0.71 (-1.15, -0.22)
Blackspotted Topminnow – Intercept	-1.19 (-1.92, -0.41)
Blackspotted Topminnow – Drainage area	0.73 (0.30, 1.16)
Blackstripe Topminnow – Intercept	-0.36 (-1.01, 0.33)
Blackstripe Topminnow – RFM	0.25 (0.08, 0.45)
Blackstripe Topminnow – Time of year	-0.30 (-0.55, -0.09)
Blacktail Shiner – Intercept	-0.75 (-1.51, 0.07)
Blacktail Shiner – Time of year	-0.27 (-0.52, -0.05)
Blue Catfish – Intercept	-3.39 (-5.01, -0.86)
Blue Sucker – Intercept	-5.07 (-6.95, -2.93)
Blue Sucker – Drainage area	1.14 (0.36, 1.89)
Bluegill – Intercept	0.15 (-0.51, 0.81)
Bluegill – RFM	0.18 (0.01, 0.35)
Bluehead Shiner – Intercept	-2.87 (-4.29, -1.21)
Bluntnose Darter – Intercept	-3.27 (-4.16, -2.40)
Bluntnose Minnow – Intercept	0.06 (-0.62, 0.74)
Brook Silverside – Intercept	0.69 (0.00, 1.32)
Buffaloes – Intercept	-3.17 (-4.27, -1.90)
Buffaloes – Drainage area	0.80 (0.38, 1.22)
Buffaloes – RFM	0.46 (0.11, 0.95)
Bullhead Minnow – Intercept	-0.94 (-1.80, -0.10)
Bullhead Minnow – Drainage area	0.88 (0.53, 1.23)

Bullhead Minnow – Time of year	-0.34 (-0.59, -0.10)
Carmine Shiner – Intercept	-1.87 (-2.61, -1.00)
Carmine Shiner – Drainage area	1.05 (0.25, 1.48)
Carpsuckers – Intercept	-1.52 (-3.79, 1.25)
Carpsuckers – Drainage area	0.91 (0.05, 1.64)
Channel Catfish – Intercept	-2.18 (-2.96, -1.38)
Channel Catfish – Drainage area	0.65 (0.36, 0.97)
Channel Catfish – Time of year	-0.24 (-0.45, -0.03)
Channel Darter – Intercept	-2.17 (-2.95, -1.39)
Channel Darter – Drainage area	1.31 (0.75, 1.78)
Chub Shiner – Intercept	-5.05 (-6.66, -2.78)
Chub Shiner – Drainage area	1.98 (1.19, 2.77)
Chubsuckers – Intercept	-1.93 (-2.76, -0.98)
Chubsuckers – Drainage area	-1.11 (-1.58, -0.60)
Common Carp – Intercept	-4.02 (-5.23, -2.88)
Common Shiner – Intercept	-3.04 (-5.15, -1.40)
Creek Chub – Intercept	-3.39 (-4.61, -1.68)
Crystal Darter – Intercept	-2.55 (-4.07, -0.98)
Cypress Darter – Intercept	-3.20 (-4.10, -2.20)
Cypress Darter – Drainage area	-0.60 (-1.22, -0.08)
Dollar Sunfish – Intercept	-1.77 (-2.97, -0.66)
Dollar Sunfish – RFM	0.46 (0.10, 1.00)
Dusky Darter – Intercept	-0.82 (-1.53, -0.04)
Emerald Shiner – Intercept	-2.39 (-3.13, -1.66)
Emerald Shiner – Drainage area	1.26 (0.96, 1.59)
Emerald Shiner – Time of year	-0.31 (-0.51, -0.09)
Flier – Intercept	-1.55 (-2.72, -0.37)
Freckled Madtom – Intercept	-1.93 (-2.71, -1.16)
Freckled Madtom – Drainage area	0.78 (0.27, 1.25)
Freshwater Drum – Intercept	-2.78 (-3.87, -1.50)
Freshwater Drum – Drainage area	0.76 (0.22, 1.17)
Ghost Shiner – Intercept	-2.66 (-3.76, -1.32)
Ghost Shiner – Drainage area	0.80 (0.27, 1.21)
Gizzard Shad – Intercept	-2.69 (-3.49, -1.91)
Gizzard Shad – Drainage area	1.24 (0.92, 1.57)
Gizzard Shad – RFM	0.29 (0.02, 0.57)
Golden Shiner – Intercept	-1.81 (-2.54, -1.18)
Golden Shiner – Drainage area	-0.38 (-0.68, -0.11)
Green Sunfish – Intercept	0.30 (-0.33, 0.92)
Green Sunfish – Drainage area	-0.40 (-0.62, -0.15)
Green Sunfish – RFM	0.20 (0.03, 0.36)

Harlequin Darter – Intercept	-2.21 (-3.55, -0.95)
Johnny Darter – Intercept	-1.82 (-2.81, -0.71)
Kiamichi Shiner – Intercept	-2.47 (-3.42, -1.68)
Kiamichi Shiner – Drainage area	-0.98 (-1.60, -0.50)
Lampreys – Intercept	-2.51 (-3.60, -1.27)
Largemouth Bass – Intercept	-0.77 (-1.46, -0.12)
Largemouth Bass – RFM	0.75 (0.54, 1.00)
Leopard Darter – Intercept	-1.37 (-2.32, -0.41)
Logperch – Intercept	-1.24 (-1.94, -0.55)
Logperch – RFM	0.19 (0.01, 0.41)
Longear Sunfish – Intercept	1.23 (0.57, 1.97)
Longnose Gar – Intercept	-3.68 (-4.64, -2.63)
Longnose Gar – Drainage area	0.62 (0.19, 1.01)
Longnose Gar - RFM	0.35 (0.05, 0.74)
Mimic Shiner – Intercept	-2.24 (-3.29, -0.98)
Mississippi Silvery Minnow – Intercept	-3.27 (-4.43, -1.82)
Mississippi Silvery Minnow – Drainage area	0.64 (0.18, 1.14)
Mountain Madtom – Intercept	-0.60 (-2.59, 1.35)
Neotropical silversides – Intercept	-3.83 (-4.86, -2.87)
Neotropical silversides – Drainage area	1.39 (1.00, 1.83)
Orangebelly Darter – Intercept	0.40 (-0.25, 1.08)
Orangebelly Darter – Time of year	0.23 (0.03, 0.44)
Orangespotted Sunfish – Intercept	-1.61 (-2.43, -0.69)
Orangethroat Darter – Intercept	-0.51 (-1.42, 0.38)
Ouachita Shiner – Intercept	-1.51 (-2.36, -0.58)
Pallid Shiner – Intercept	-3.49 (-4.56, -2.50)
Peppered Shiner – Intercept	-3.07 (-4.56, -1.28)
Pirate Perch – Intercept	-1.64 (-2.41, -0.93)
Pirate Perch – Drainage area	-0.35 (-0.65, -0.03)
Plains Minnow – Intercept	-4.24 (-6.84, -1.24)
Plains Minnow – Drainage area	1.13 (0.15, 2.20)
Pugnose Minnow – Intercept	-2.19 (-3.33, -0.83)
Red Shiner – Intercept	-1.38 (-2.11, -0.49)
Red Shiner – Drainage area	0.96 (0.61, 1.29)
Red Shiner – Time of year	-0.23 (-0.49, -0.02)
Redear Sunfish – Intercept	-1.74 (-2.40, -1.03)
Redear Sunfish – RFM	0.27 (0.05, 0.51)
Redfin Shiner – Intercept	-0.36 (-0.98, 0.23)
Redfin Shiner – Drainage area	-0.59 (-0.85, -0.37)
Redhorses – Intercept	-1.49 (-2.18, -0.78)
Redhorses – Drainage area	0.67 (0.27, 1.06)

Redspotted Sunfish – Intercept	-1.51 (-2.47, -0.58)
Redspotted Sunfish – RFM	0.29 (0.01, 0.64)
Ribbon Shiner – Intercept	-2.71 (-3.52, -1.75)
River Darter – Intercept	-3.37 (-4.54, -2.08)
River Darter – Time of year	-0.28 (-0.59, -0.01
Sand darters – Intercept	-3.60 (-4.90, -2.07)
Sand darters – Drainage area	0.76 (0.14, 1.41)
Sand Shiner – Intercept	-1.39 (-2.52, -0.24)
Shoal Chub – Intercept	-5.01 (-6.74, -2.77)
Shoal Chub – Drainage area	1.56 (0.82, 2.31)
Shortnose Gar – Intercept	-4.19 (-5.73, -2.60)
Silver Chub – Intercept	-5.33 (-7.66, -2.51)
Silver Chub – Drainage area	1.65 (0.69, 2.59)
Silverband Shiner – Intercept	-4.76 (-6.29, -2.35)
Silverband Shiner – Drainage area	1.72 (0.86, 2.40)
Slender Madtom – Intercept	-2.39 (-3.88, -0.84)
Slenderhead Darter – Intercept	-1.66 (-2.79, -0.24)
Slough Darter – Intercept	-2.07 9-2.87, -1.35)
Slough Darter – Drainage area	-0.38 (-0.67, -0.13)
Smallmouth Bass – Intercept	-0.63 (-1.46, 0.29)
Spotted Bass – Intercept	-0.87 (-1.55, -0.17)
Spotted Bass – RFM	0.25 (0.07, 0.45)
Spotted Gar – Intercept	-2.52 (-4.02, -1.24)
Spotted Sucker – Intercept	-2.71 (-3.53, -1.91)
Steelcolor Shiner – Intercept	-0.54 (-1.22, 0.20)
Steelcolor Shiner – Drainage area	1.18 (0.82, 1.54)
Stonerollers – Intercept	1.03 (0.32, 1.77)
Stonerollers – Drainage area	-0.36 (-0.67, -0.08)
Stonerollers – RFM	0.27 (0.07, 0.48)
Striped Shiner – Intercept	-0.69 (-1.46, 0.11)
Suckermouth Minnow – Intercept	-1.98 (-3.18, -0.67)
Tadpole Madtom – Intercept	-1.95 (-2.94, -0.61)
Temperate basses – Intercept	-4.00 (-5.00, -3.02)
Temperate basses – Drainage area	1.30 (0.88, 1.75)
Temperate basses – RFM	0.34 (0.03, 0.74)
Threadfin Shad – Intercept	-4.25 (-5.32, -3.13)
Threadfin Shad – Drainage area	1.28 (0.79, 1.80)
Threadfin Shad – Time of year	-0.28 (-0.60, -0.01)
Warmouth – Intercept	-1.31 (-2004, -0.66)
Western Mosquitofish – Intercept	-0.01 (-0.64, 0.63)
Western Mosquitofish – Time of year	-0.28 (-0.50, -0.08)

Western Starhead Minnow – Intercept	-0.95 (-2.19, 0.29)
White Crappie – Intercept	-1.71 (-2.47, -0.93)
White Crappie – Drainage area	0.46 (0.14, 0.81)
White Crappie – RFM	0.37 (0.09, 0.69)
Yellow Bullhead – Intercept	-1.22 (-1.89, -0.54)
Yellow Bullhead – Drainage area	-0.43 (-0.69, -0.17)
Yellow Bullhead – RFM	0.30 (0.12, 0.51)
Intercept species mean	-1.97 (-2.33, -1.65)
Intercept SD	1.46 (1.19, 1.79)
Intercept ν	27.32 (4.86, 107.03)
Drainage area species mean	0.22 (0.05, 0.39)
Drainage area SD	0.71 (0.58, 0.86)
Drainage area ν	30.92 (5.19, 109.21)
RFM species mean	0.14 (0.08, 0.20)
RFM SD	0.20 (0.12, 0.27)
RFM ν	17.57 (1.65, 101.61)
Time of year species mean	-0.09 (-0.14, -0.03)
Time of year SD	0.18 (0.12, 0.24)
Time of year ν	24.83 (2.87, 124.51)
Collector SD	0.86 (0.70, 1.00)
Collector ν	6.66 (2.00, 66.04)

Table 3. Occurrence model coefficients for species intercepts, significant species relationships, and group mean hyperparameters. Coefficients are reported on the logit scale from posterior distributions as the mode with associated 95% highest density intervals (HDIs). Wet is wet seasons, SCP is South Central Plains, MA3 is coefficient of variation of annual daily flows, TH1 is date of annual maximum daily flow, DH14 is flood duration, ML15 is low flow index, DL16 is low flow pulse duration, MA2 is median daily mean flow, MH19 is skewness in annual maximum flows, MA42 is variability across annual flows, DL10 is variability of annual minimum of 90-day moving average flow, RA4 is variability in fall rate, TH2 is variability in date of annual maximum daily flow, and TL2 is variability in date of annual minimum daily flow, LHDI is lower HDI, UHDI is upper HDI, SD is standard deviation, and v is a normality parameter. Species intercepts are interpreted as estimated occurrence probability at mean levels of covariates in the Ouachita Mountains in the dry season. Other coefficients are interpreted with all other variables held constant.

Coefficient	Mode (LHDI, UHDI)
American Pickerel – Intercept	-0.39 (-1.32, 0.65)
American Pickerel – Wet	0.08 (-0.52, 0.74)
American Pickerel – SCP	2.08 (0.83, 3.51)
American Pickerel – TH1	0.19 (-0.15, 0.53)
American Pickerel – MA42	-1.01 (-1.92, -0.40)
American Pickerel – TL2	-0.24 (-0.51, 0.07)
American Pickerel – Wet * TH1	-0.39 (-0.85, -0.02)
American Pickerel – Wet * TL2	0.67 (0.13, 1.36)
Banded Pygmy Sunfish – Intercept	-5.25 (-7.36, -3.51)
Banded Pygmy Sunfish – SCP	5.02 (3.29, 7.32)
Banded Pygmy Sunfish – MA42	-1.13 (-2.15, -0.33)
Bantam Sunfish – Intercept	-5.25 (-8.55, 2.97)
Bantam Sunfish – SCP	5.13 (2.83, 9.04)
Bigeye Shiner – Intercept	4.14 (2.78, 6.17)
Bigeye Shiner – Wet	0.02 (-0.72, 0.45)
Bigeye Shiner – SCP	-3.86 (-5.81, -2.48)
Bigeye Shiner – MA3	-0.74 (-1.37, -0.18)
Bigeye Shiner – ML15	-0.68 (-1.16, -0.21)
Bigeye Shiner – MA42	-0.49 (-0.99, -0.03)
Bigeye Shiner – DL10	0.44 (0.06, 0.97)
Bigeye Shiner – TL2	-0.23 (-0.51, 0.07)
Bigeye Shiner – Wet * TL2	0.77 (0.15, 1.46)
Black Bullhead – Intercept	-1.20 (-2.55, 0.66)
Black Bullhead – SCP	4.12 (1.72, 9.79)
Black Crappie – Intercept	-3.31 (-4.86, -1.72)
Black Crappie – SCP	3.05 (1.65, 6.14)
Black Crappie – MH19	-0.24 (-0.54, -0.05)
Blackside Darter – Intercept	-3.04 (-4.96, -1.72)

Blackspot Shiner – SCP	-2.91 (-4.91, -1.36)
Blackspotted Topminnow – Intercept	1.28 (-0.01, 2.79)
Blackspotted Topminnow – SCP	-2.42 (-3.95, -1.17)
Blackspotted Topminnow – ML15	-0.65 (-1.40, -0.10)
Blackspotted Topminnow – DL16	-1.23 (-1.92, -0.63)
Blackspotted Topminnow – MA42	-1.05 (-1.94, -0.38)
Blackspotted Topminnow – DL10	0.48 (0.08, 1.14)
Blackspotted Topminnow – TL2	-0.25 (-0.14, 2.92)
Blackstripe Topminnow – Intercept	0.97 (-0.14, 2.92)
Blackstripe Topminnow – SCP	1.47 (0.11, 3.02)
Blackstripe Topminnow – MA2	-0.92 (-1.92, -0.03)
Blackstripe Topminnow – MA42	-0.91 (-1.73, -0.25)
Blackstripe Topminnow – TL2	-0.29 (-0.70, -0.04)
Blacktail Shiner – Intercept	-2.16 (-3.13, -1.19)
Blacktail Shiner – Wet	0.11 (-0.43, 0.92)
Blacktail Shiner – SCP	3.60 (2.19, 7.21)
Blacktail Shiner – TH1	0.14 (-0.35, 0.46)
Blacktail Shiner – TL2	-0.22 (-0.49, 0.07)
Blacktail Shiner – Wet * TH1	-0.47 (-1.07, -0.08)
Blacktail Shiner – Wet * TL2	0.64 (0.02, 1.35)
Blue Catfish – Intercept	-3.26 (-6.74, 1.46)
Blue Sucker – Intercept	-1.67 (-6.06, 5.11)
Bluegill – Intercept	1.79 (0.77, 3.29)
Bluegill – SCP	5.82 (2.97, 12.26)
Bluegill – DL16	-0.53 (-1.04, -0.08)
Bluegill – MA2	1.02 (0.32, 1.85)
Bluegill – MA42	0.78 (0.04, 1.74)
Bluegill – DL10	0.47 (0.10, 1.10)
Bluegill – TL2	-0.26 (-0.54, -0.02)
Bluehead Shiner – Intercept	-3.80 (-6.68, -0.53)
Bluehead Shiner – SCP	3.56 (0.96, 9.58)
Bluntnose Darter – Intercept	1.00 (-1.28, 5.70)
Bluntnose Minnow – Intercept	2.81 (1.46, 5.16)
Bluntnose Minnow – Wet	0.09 (-0.47, 0.67)
Bluntnose Minnow – SCP	-3.87 (-5.98, -2.60)
Bluntnose Minnow – TH1	0.16 (-0.25, 0.48)
Bluntnose Minnow – RA4	0.31 (0.01, 0.76)
Bluntnose Minnow – TL2	-0.28 (-0.66, -0.05)
Bluntnose Minnow – Wet * TH1	-0.44 (-0.97, -0.06)
Brook Silverside – Intercept	2.78 (1.80, 4.61)
Brook Silverside – Wet	0.06 (-0.44, 0.68)

Brook Silverside – SCP	-2.44 (-3.99, -1.41)
Brook Silverside – DH14	0.59 (0.05, 1.16)
Brook Silverside – MA2	0.69 (0.11, 1.35)
Brook Silverside – MH19	-0.23 (-0.49, -0.02)
Brook Silverside – RA4	0.33 (0.07, 0.76)
Brook Silverside – TL2	-0.24 (-0.51, 0.01)
Brook Silverside – Wet * TL2	0.67 (0.01, 1.35)
Buffaloes – Intercept	-2.68 (-4.70, -0.47)
Buffaloes – SCP	5.76 (2.01, 11.97)
Buffaloes – MA2	1.14 (0.05, 2.62)
Bullhead Minnow – Intercept	-1.61 (-2.72, -0.69)
Bullhead Minnow – Wet	0.12 (-0.36, 0.89)
Bullhead Minnow – SCP	2.84 (1.62, 4.93)
Bullhead Minnow – TH1	0.21 (-0.15, 0.53)
Bullhead Minnow – DL16	-0.85 (-1.64, -0.22)
Bullhead Minnow – MA2	1.04 (0.40, 1.76)
Bullhead Minnow – MA42	1.35 (0.57, 2.11)
Bullhead Minnow – Wet * TH1	-0.43 (-0.94, -0.06)
Carmine Shiner – Intercept	2.55 (0.09, 5.98)
Carmine Shiner – Wet	0.10 (-0.48, 0.81)
Carmine Shiner – SCP	-2.08 (-4.75, -0.05)
Carmine Shiner – ML15	-0.71 (-1.66, -0.04)
Carmine Shiner – TH2	-0.60 (-1.27, -0.06)
Carmine Shiner – TL2	-0.22 (-0.51, 0.08)
Carmine Shiner – Wet * TL2	0.74 (0.04, 1.64)
Carpsuckers – Intercept	-4.34 (-6.95, -1.45)
Carpsuckers – SCP	3.95 (1.71, 11.30)
Channel Catfish – Intercept	-0.58 (-1.98, 1.18)
Channel Catfish – SCP	4.40 (1.46, 11.54)
Channel Catfish – TL2	-0.26 (-0.56, -0.01)
Channel Darter – Intercept	4.06 (1.30, 7.40)
Channel Darter – SCP	-3.01 (-5.87, -0.54)
Channel Darter – ML15	-0.87 (-2.01, -0.12)
Channel Darter – DL10	0.55 (0.07, 2.32)
Chub Shiner – Intercept	-1.21 (-0.72, 4.38)
Chubsuckers – Intercept	1.17 (-0.72, 4.38)
Chubsuckers – MA42	-1.17 (-2.35, -0.23)
Common Carp – Intercept	-2.50 (-5.14, 0.71)
Common Carp – SCP	6.28 (1.76, 12.64)
Common Shiner – Intercept	-3.12 (-5.80, 0.87)
Creek Chub – Intercept	0.35 (-2.37, 5.37)

Crystal Darter – Intercept	-4.69 (-7.29, -1.93)
Crystal Darter – SCP	2.23 (-0.10, 4.78)
Crystal Darter – ML15	-0.91 (-1.98, -0.02)
Cypress Darter – Intercept	-0.96 (-3.22, 2.94)
Cypress Darter – SCP	4.36 (0.91, 10.44)
Dollar Sunfish – Intercept	-3.47 (-4.88, -1.96)
Dollar Sunfish – SCP	2.37 (1.11, 4.18)
Dollar Sunfish – ML15	-0.64 (-1.37, -0.08)
Dollar Sunfish – MA42	-0.82 (-1.73, -0.09)
Dollar Sunfish – TH2	-0.54 (-1.18, -0.04)
Dusky Darter – Intercept	0.59 (-0.42, 1.86)
Dusky Darter – Wet	0.10 (-0.41, 0.81)
Dusky Darter – TH1	0.18 (-0.20, 0.49)
Dusky Darter – DL16	-0.80 (-1.47, -0.26)
Dusky Darter – MA2	1.91 (1.03, 2.91)
Dusky Darter – MH19	-0.24 (-0.51, -0.05)
Dusky Darter – MA42	0.75 (0.15, 1.58)
Dusky Darter – DL10	0.55 (0.15, 1.29)
Dusky Darter – Wet * TH1	-0.40 (-0.91, -0.20)
Emerald Shiner – Intercept	1.47 (-0.39, 4.74)
Emerald Shiner – SCP	4.61 (0.37, 10.84)
Flathead Catfish – Intercept	-0.71 (-2.31, 1.58)
Flathead Catfish – MA2	2.97 (1.25, 7.11)
Flathead Catfish – MH19	-0.22 (-0.51, -0.01)
Flier – Intercept	-5.89 (-9.04, -3.62)
Flier – SCP	5.42 (3.32, 9.14)
Flier – DL16	-0.93 (-2.14, -0.01)
Freckled Madtom – Intercept	1.27 (-0.14, 3.89)
Freckled Madtom – DL10	0.71 (0.16, 2.52)
Freshwater Drum – Intercept	-2.04 (-4.04, 0.55)
Freshwater Drum – SCP	4.78 (1.77, 10.86)
Freshwater Drum – DL16	-0.99 (-2.25, -0.05)
Ghost Shiner – Intercept	-1.97 (-3.89, 0.18)
Ghost Shiner – Wet	0.05 (-0.63, 0.67)
Ghost Shiner – SCP	2.63 (0.15, 8.40)
Ghost Shiner – TH1	0.16 (-0.32, 0.50)
Ghost Shiner – DL16	-1.23 (-2.69, -0.20)
Ghost Shiner – MA42	1.22 (0.07, 2.87)
Ghost Shiner – Wet * TH1	-0.41 (-1.08, -0.02)
Gizzard Shad – Intercept	-0.39 (-1.98, 1.61)
Gizzard Shad – Wet	0.11 (-0.50, 0.83)

Gizzard Shad – SCP	6.27 (2.84, 12.37)
Gizzard Shad – TH1	0.17 (-0.24, 0.51)
Gizzard Shad – Wet * TH1	-0.43 (-1.12, -0.01)
Golden Shiner – Intercept	-0.73 (-2.07, 0.66)
Golden Shiner – SCP	6.21 (2.81, 11.84)
Green Sunfish – Intercept	5.81 (3.58, 9.49)
Harlequin Darter – Intercept	-3.73 (-5.77, -1.41)
Harlequin Darter – SCP	2.39 (0.34, 4.99)
Harlequin Darter – MA2	1.85 (0.17, 4.66)
Johnny Darter – Intercept	0.09 (-1.31, 2.57)
Johnny Darter – Wet	0.12 (-0.43, 0.93)
Johnny Darter – SCP	-2.38 (-4.52, -0.90)
Johnny Darter – TH1	0.18 (-0.24, 0.46)
Johnny Darter – Wet * TH1	-0.44 (0.98, -0.06)
Kiamichi Shiner – Intercept	1.74 (-0.23, 5.24)
Kiamichi Shiner – Wet	0.05 (-0.60, 0.64)
Kiamichi Shiner – SCP	-2.33 (-5.28, -0.58)
Kiamichi Shiner – TL2	-0.22 (-0.51, 0.09)
Kiamichi Shiner – Wet * TL2	0.80 (0.07, 1.88)
Lampreys – Intercept	0.47 (-1.74, 3.94)
Largemouth Bass – Intercept	2.46 (1.23, 4.29)
Largemouth Bass – SCP	4.94 (1.63, 11.63)
Largemouth Bass – MA2	1.20 (0.21, 2.30)
Largemouth Bass – MH19	-0.24 (-0.51, -0.04)
Leopard Darter – Intercept	-0.97 (-2.25, 0.70)
Leopard Darter – SCP	-3.39 (-5.52, -1.66)
Leopard Darter – MA3	-0.97 (-2.42, -0.10)
Logperch – Intercept	1.72 (0.27, 4.32)
Logperch – MA2	1.48 (0.15, 3.58)
Logperch – MH19	-0.23 (-0.55, -0.02)
Longear Sunfish – Intercept	6.38 (4.18, 9.38)
Longear Sunfish – Wet	0.07 (-0.55, 0.76)
Longear Sunfish – TH1	0.17 (-0.32, 0.49)
Longear Sunfish – Wet * TH1	-0.42 (-1.00, -0.06)
Longnose Gar – Intercept	2.57 (-0.13, 7.51)
Mimic Shiner – Intercept	-0.30 (-2.03, 2.43)
Mimic Shiner – MA2	1.48 (0.50, 2.56)
Mississippi Silvery Minnow – Intercept	-4.18 (-7.72, -1.16)
Mississippi Silvery Minnow – SCP	5.61 (2.19, 12.67)
Mountain Madtom – Intercept	-4.27 (-5.88, -2.56)
Mountain Madtom – MA3	-0.77 (1.71, -0.04)

Mountain Madtom – MA2	1.13 (0.27, 2.30)
Mountain Madtom – MH19	-0.25 (-0.61, -0.04)
Neotropical silversides – Intercept	-0.90 (-3.62, 3.26)
Neotropical silversides – SCP	5.93 (1.50, 12.69)
Orangebelly Darter – Intercept	4.55 (2.86, 7.43)
Orangebelly Darter – SCP	-3.34 (-5.82, -1.90)
Orangebelly Darter – MA3	-0.76 (-1.55, -0.11)
Orangebelly Darter – DL10	0.79 (0.23, 2.71)
Orangespotted Sunfish – Intercept	-0.25 (-1.35, 1.12)
Orangespotted Sunfish – SCP	0.77 (-0.66, 2.65)
Orangespotted Sunfish – DL16	-0.95 (-1.80, -0.25)
Orangespotted Sunfish – MA42	0.65 (0.04, 1.49)
Orangethroat Darter – Intercept	-2.63 (-3.66, -1.63)
Orangethroat Darter – Wet	0.13 (-0.35, 0.87)
Orangethroat Darter – SCP	2.32 (1.30, 3.38)
Orangethroat Darter – ML15	-1.03 (-1.70, -0.49)
Orangethroat Darter – MA42	-1.06 (-1.76, -0.49)
Orangethroat Darter – TL2	-0.24 (-0.52, 0.02)
Orangethroat Darter – Wet * TL2	0.68 (0.06, 1.51)
Ouachita Shiner – Intercept	0.28 (-1.05, 1.85)
Ouachita Shiner – Wet	0.04 (-0.69, 0.61)
Ouachita Shiner – SCP	-4.53 (-6.99, -2.60)
Ouachita Shiner – TH1	0.20 (-0.14, 0.50)
Ouachita Shiner – DL10	0.52 (0.06, 1.27)
Ouachita Shiner – TL2	-0.28 (-0.67, -0.04)
Ouachita Shiner – Wet * TH1	-0.40 (-0.85, -0.03)
Pallid Shiner – Intercept	-0.62 (-2.68, 3.22)
Pallid Shiner – SCP	3.70 (0.30, 10.87)
Peppered Shiner – Intercept	-1.27 (-3.70, 3.70)
Pirate Perch – Intercept	-2.01 (-3.33, -0.79)
Pirate Perch – SCP	7.39 (3.60, 13.41)
Pirate Perch – MH19	-0.24 (-0.62, -0.07)
Pirate Perch – TL2	-0.26 (-0.59, -0.02)
Plains Minnow – Intercept	-4.03 (-8.67, 1.96)
Pugnose Minnow – Intercept	-0.76 (-2.55, 2.58)
Pugnose Minnow – SCP	-1.90 (-4.51, -0.16)
Pugnose Minnow – MH19	-0.23 (-0.51, -0.02)
Pugnose Minnow – DL10	0.54 (0.08, 1.63)
Red Shiner – Intercept	-0.65 (-1.70, 0.65)
Red Shiner – Wet	0.09 (0.40, 0.83)
Red Shiner – SCP	2.14 (0.79, 7.33)

Red Shiner – TH1	0.15 (-0.34, 0.44)
Red Shiner – MA42	1.08 (0.27, 1.99)
Red Shiner – Wet * TH1	-0.47 (-1.09, -0.09)
Redear Sunfish – Intercept	-0.86 (-1.97, 0.42)
Redear Sunfish – Wet	0.11 (-0.49, 0.93)
Redear Sunfish – SCP	5.36 (2.50, 11.96)
Redear Sunfish – TH1	0.14 (-0.38, 0.47)
Redear Sunfish – Wet * TH1	-0.45 (-0.99, -0.05)
Redfin Shiner – Intercept	2.38 (1.06, 4.00)
Redfin Shiner – SCP	2.82 (0.36, 9.71)
Redfin Shiner – DL16	-1.36 (-2.08, -0.79)
Redhorses – Intercept	2.35 (0.68, 5.43)
Redhorses – SCP	-1.14 (-3.47, 0.60)
Redhorses – DL10	0.45 (0.01, 1.27)
Redhorses – TH2	-0.76 (-1.69, -0.13)
Redhorses – TL2	-0.25 (-0.58, -0.01)
Redspotted Sunfish – Intercept	-3.17 (-4.60, -1.89)
Redspotted Sunfish – SCP	3.35 (1.80, 5.81)
Redspotted Sunfish – MA42	-1.01 (-1.89, -0.32)
Ribbon Shiner – Intercept	-0.25 (-2.10, 2.92)
Ribbon Shiner – SCP	4.92 (1.19, 11.09)
River Darter – Intercept	-1.42 (-3.93, 2.74)
Sand darters – Intercept	-1.74 (-4.27, 2.51)
Sand Shiner – Intercept	-3.67 (-5.55, -2.13)
Sand Shiner – SCP	2.45 (0.83, 4.54)
Sand Shiner – MA42	1.31 (0.60, 2.50)
Shoal Chub – Intercept	-2.53 (-7.02, 4.02)
Shortnose Gar – Intercept	-2.27 (-5.56, 2.06)
Shortnose Gar – SCP	4.20 (0.68, 10.85)
Silver Chub – Intercept	-2.73 (-7.79, 3.88)
Silverband Shiner – Intercept	-1.51 (-5.53, 4.08)
Slender Madtom – Intercept	-1.67 (-3.37, 0.24)
Slender Madtom – SCP	-3.20 (-6.44, -0.69)
Slenderhead Darter – Intercept	-1.38 (-2.93, 0.50)
Slenderhead Darter – Wet	0.07 (-0.56, 0.68)
Slenderhead Darter – TH1	0.17 (-0.25, 0.49)
Slenderhead Darter – DL16	-0.65 (-1.49, -0.04)
Slenderhead Darter – DL10	0.60 (0.17, 1.69)
Slenderhead Darter – Wet * TH1	-0.41 (-0.95, -0.04)
Slough Darter – Intercept	-1.29 (-2.55, 0.03)
Slough Darter – Wet	0.10 (-0.47, 0.83)

Slough Darter – SCP	6.71 (3.79, 12.47)
Slough Darter – TH1	0.17 (-0.25, 0.48)
Slough Darter – Wet * TH1	-0.43 (-0.99, -0.04)
Smallmouth Bass – Intercept	-1.08 (-1.97, -0.11)
Smallmouth Bass – Wet	-0.08 (-0.99, 0.35)
Smallmouth Bass – SCP	-2.38 (-3.64, -1.30)
Smallmouth Bass – DL16	0.75 (0.19, 1.50)
Smallmouth Bass – TH2	-0.44 (-0.88, -0.02)
Smallmouth Bass – TL2	-0.24 (-0.54, 0.05)
Smallmouth Bass – Wet * TL2	0.87 (0.26, 1.59)
Spotted Bass – Intercept	2.36 (1.04, 4.51)
Spotted Gar – Intercept	-2.23 (-3.36, -0.80)
Spotted Gar – DL16	-1.24 (-2.21, -0.54)
Spotted Gar – MA2	1.67 (0.88, 2.82)
Spotted Sucker – Intercept	1.20 (-0.67, 4.14)
Spotted Sucker – SCP	4.61 (0.32, 12.37)
Spotted Sucker – TL2	-0.26 (-0.55, -0.01)
Steelcolor Shiner – Intercept	3.21 (1.39, 6.72)
Steelcolor Shiner – Wet	0.12 (-0.32, 0.81)
Steelcolor Shiner – SCP	-3.00 (-6.12, -1.40)
Steelcolor Shiner – TH1	0.15 (-0.29, 0.46)
Steelcolor Shiner – ML15	-0.51 (-1.06, -0.05)
Steelcolor Shiner – MA42	-1.09 (-1.81, -0.52)
Steelcolor Shiner – TL2	-0.25 (-0.55, -0.01)
Steelcolor Shiner – Wet * TH1	-0.44 (-0.98, -0.03)
Stonerollers – Intercept	5.20 (3.65, 8.37)
Stonerollers – Wet	0.06 (-0.48, 0.62)
Stonerollers – SCP	-4.80 (-7.98, -3.21)
Stonerollers – TH1	0.18 (-0.20, 0.51)
Stonerollers – ML15	-0.61 (-1.10, -0.16)
Stonerollers – TL2	-0.22 (-0.48, 0.08)
Stonerollers – Wet * TH1	-0.39 (-0.85, -0.01)
Stonerollers – Wet * TL2	0.58 (0.03, 1.20)
Striped Shiner – Intercept	-2.61 (-3.64, -1.63)
Striped Shiner – Wet	0.08 (-0.45, 0.68)
Striped Shiner – SCP	1.92 (0.88, 3.12)
Striped Shiner – ML15	-1.36 (-2.19, -0.80)
Striped Shiner – MA42	-0.94 (-1.67, -0.34)
Striped Shiner – TH2	-0.46 (-1.01, -0.04)
Striped Shiner – TL2	-0.24 (-0.52, 0.03)
Striped Shiner – Wet * TL2	0.80 (0.13, 1.58)

Suckermouth Minnow – Intercept	-3.90 (-6.03, -1.85)
Suckermouth Minnow – MA42	1.41 (0.50, 2.69)
Tadpole Madtom – Intercept	-1.26 (-2.79, 1.18)
Tadpole Madtom – SCP	1.58 (0.02, 6.57)
Tadpole Madtom – MA2	1.44 (0.16, 2.78)
Temperate basses – Intercept	-0.14 (-2.73, 4.76)
Temperate basses – SCP	5.50 (0.29, 12.15)
Threadfin Shad – Intercept	0.05 (-2.79, 5.21)
Warmouth – Intercept	0.39 (-0.73, 1.71)
Warmouth – SCP	5.07 (2.14, 11.55)
Warmouth – DL16	-1.04 (-1.87, -0.39)
Warmouth – TL2	-0.27 (-0.60, -0.02)
Western Mosquitofish – Intercept	0.62 (-0.29, 1.64)
Western Mosquitofish – SCP	6.65 (3.52, 12.49)
Western Mosquitofish – DL16	-0.67 (-1.21, -0.17)
Western Mosquitofish – MA2	0.62 (0.01, 1.29)
Western Mosquitofish – MH19	-0.22 (-0.46, -0.02)
Western Mosquitofish – MA42	1.24 (0.57, 2.07)
Western Starhead Minnow – Intercept	-6.07 (-9.47, -4.02)
Western Starhead Minnow – SCP	4.56 (2.57, 8.06)
White Crappie – Intercept	-1.45 (-2.60, -0.20)
White Crappie – SCP	3.17 (1.71, 5.21)
White Crappie – DL16	-0.89 (-1.88, -0.12)
White Crappie – MA42	1.29 (0.26, 2.46)
Yellow Bullhead – Intercept	4.29 (2.07, 8.58)
Intercept species mean	-0.60 (-1.31, 0.11)
Intercept SD	2.89 (2.31, 3.64)
Intercept ν	18.79 (0.85, 108.22)
Wet species mean	0.07 (-0.21, 0.32)
Wet SD	0.20 (0.01, 0.60)
Wet ν	21.78 (1.77, 110.43)
SCP species mean	2.05 (1.14, 3.14)
SCP SD	3.67 (2.87, 4.71)
SCP ν	28.72 (4.22, 114.79)
MA3 species mean	-0.25 (-0.47, -0.05)
MA3 SD	0.47 (0.21, 0.70)
MA3 ν	24.23 (2.14, 114.95)
TH1 species mean	0.19 (-0.03, 0.42)
TH1 SD	0.11 (0.01, 0.30)
TH1 ν	23.13 (1.49, 102.17)
DH14 species mean	0.24 (0.02, 0.45)

DH14 SD	0.50 (0.22, 0.76)
DH14 v	23.10 (2.52, 111.85)
ML15 species mean	-0.29 (-0.48, -0.11)
ML15 SD	0.50 (0.28, 0.74)
ML15 v	19.16 (1.17, 101.35)
DL16 species mean	-0.49 (-0.69, -0.31)
DL16 SD	0.56 (0.37, 0.76)
DL16 v	20.17 (2.43, 108.27)
MA2 species mean	0.63 (0.39, 0.91)
MA2 SD	0.80 (0.47, 1.13)
MA2 v	17.02 (1.12, 105.10)
MH19 species mean	-0.21 (-0.33, -0.10)
MH19 SD	0.07 (0.00, 0.22)
MH19 v	22.26 (1.31, 109.57)
MA42 species mean	-0.02 (-0.27, 0.24)
MA42 SD	0.85 (0.65, 1.11)
MA42 v	28.71 (4.29, 118.90)
DL10 species mean	0.35 (0.18, 0.53)
DL10 SD	0.25 (0.03, 0.53)
DL10 v	15.89 (0.13, 105.64)
RA4 species mean	0.22 (-0.21, 0.78)
RA4 SD	0.21 (0.02, 0.42)
RA4 v	22.50 (1.70, 113.62)
TH2 species mean	-0.20 (-0.34, -0.07)
TH2 SD	0.33 (0.18, 0.49)
TH2 v	24.44 (2.94, 115.37)
TL2 species mean	-0.25 (-0.42, -0.08)
TL2 SD	0.08 (0.01, 0.23)
TL2 v	22.83 (1.98, 109.54)
Wet * TH1 species mean	-0.36 (-0.63, -0.13)
Wet * TH1 SD	0.20 (0.01, 0.38)
Wet * TH1 v	20.89 (1.19, 93.02)
Wet * TL2 species mean	0.31 (0.07, 0.56)
Wet * TL2 SD	0.42 (0.23, 0.62)
Wet * TL2 v	25.63 (3.00, 114.49)
Time period SD	0.50 (0.22, 0.72)
Time period v	20.93 (1.40, 122.61)

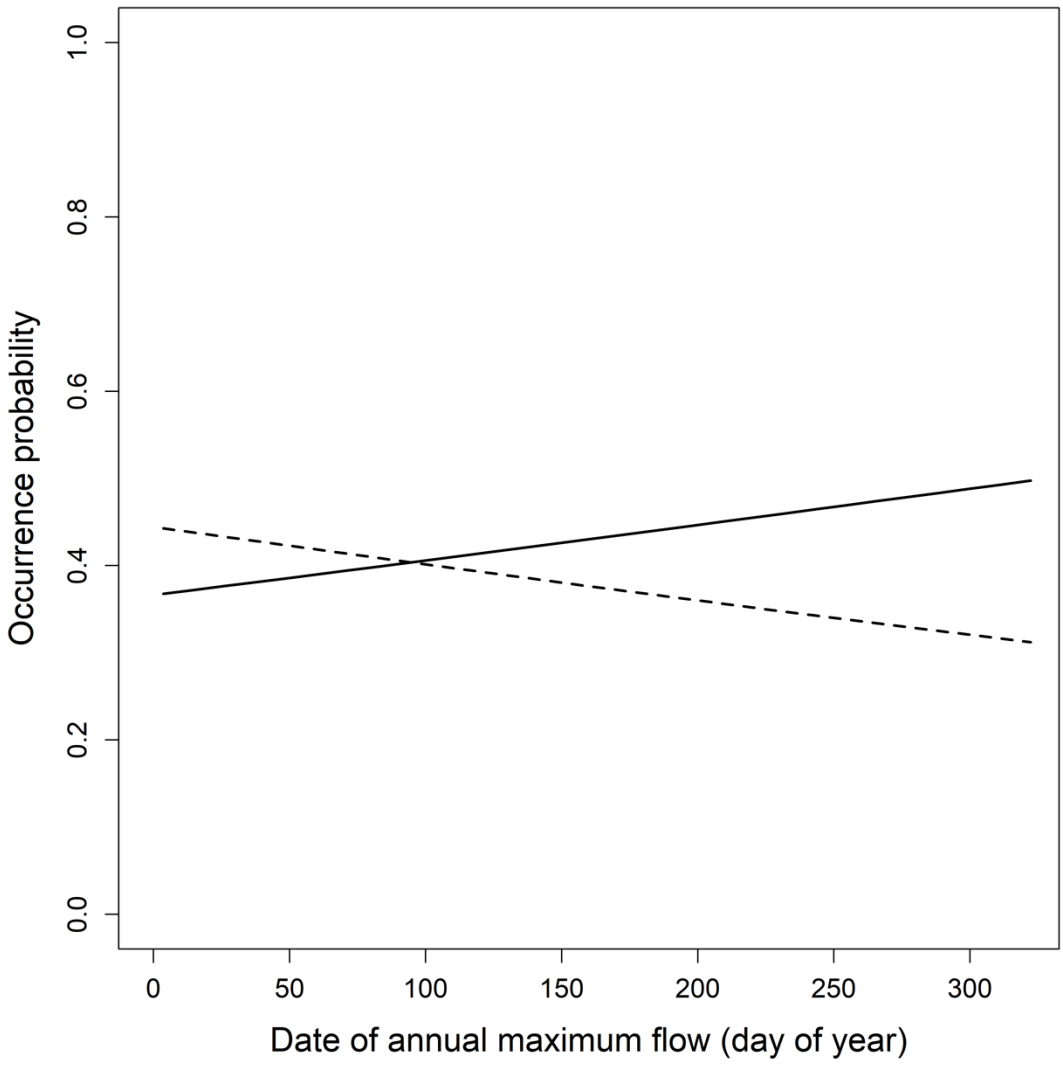


Figure 1. Relationship between occurrence probability and TH1 in the dry seasons (solid line) and wet seasons (dashed line). The relationship is depicted for American Pickerel *Esox americanus*. Nine additional stream fishes had the same general relationship (Table 3).

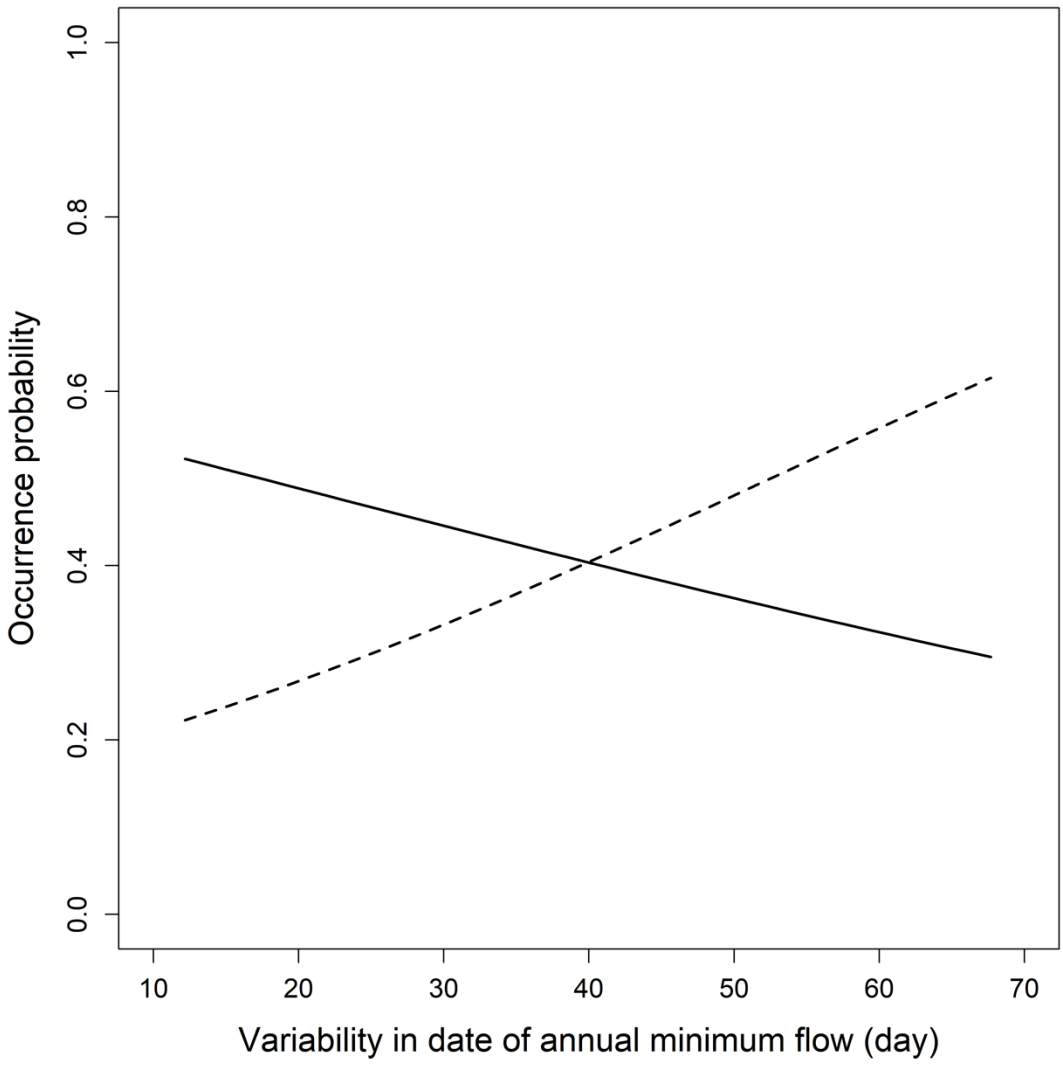


Figure 2. Relationship between occurrence probability and TL2 in the dry seasons (solid line) and wet seasons (dashed line). The relationship is depicted for American Pickerel *Esox americanus*. Fifteen additional stream fishes had the same general relationship (Table 3).

Supplementary Material

Table A1. Data sources for stream fish assemblage surveys compiled from 1961–2010. Footnotes denote contact(s) for datasets not available online.

Data source
iDigBio (www.idigbio.org/)
MARIS (www.sciencebase.gov/catalog/item/51c45ef1e4b03c77dce65a84)
Oklahoma Conservation Commission (www.ok.gov/conservation/)[1]
Oklahoma Museum of Natural History (www.samnoblemuseum.ou.edu/)
Oklahoma Water Resources Board (www.owrb.ok.gov/)[2]
VertNet (www.vertnet.org/index.html)
William Matthews and Edie Marsh-Matthews (DOI:10.5061/dryad.2435k)

1 Cheryl Cheadle (cheryl.cheadle@conservation.ok.gov) and Jason Ramming (jason.ramming@conservation.ok.gov)

2 Chris Adams (chris.adams@owrb.ok.gov)

Table A2. Scientific name and common name for 96 stream fishes of the Kiamichi River basin.

Species	Common name
Ameiurus melas	Black Bullhead
Ameiurus natalis	Yellow Bullhead
Ammocrypta spp.	Sand darters
Aphredoderus sayanus	Pirate Perch
Aplodinotus grunniens	Freshwater Drum
Campostoma spp.	Stonerollers
Carpiodes spp.	Carpsuckers
Centrarchus macropterus	Flier
Crystallaria asprella	Crystal Darter
Cycleptus elongatus	Blue Sucker
Cyprinella lutrensis	Red Shiner
Cyprinella venusta	Blacktail Shiner
Cyprinella whipplei	Steelcolor Shiner
Cyprinus carpio	Common Carp
Dorosoma cepedianum	Gizzard Shad
Dorosoma petenese	Threadfin Shad
Elassoma zonatum	Banded Pygmy Sunfish
Erimyzon spp.	Chubsuckers
Esox americanus	American Pickerel
Etheostoma chlorosomum	Bluntnose Darter
Etheostoma gracile	Slough Darter
Etheostoma histrio	Harlequin Darter
Etheostoma nigrum	Johnny Darter
Etheostoma proeliare	Cypress Darter
Etheostoma radiosum	Orangebelly Darter
Etheostoma spectabile	Orangethroat Darter
Fundulus blairae	Western Starhead Topminnow
Fundulus notatus	Blackstripe Topminnow
Fundulus olivaceus	Blackspotted Topminnow
Gambusia affinis	Western Mosquitofish
Hybognathus nuchalis	Mississippi Silvery Minnow
Hybognathus placitus	Plains Minnow
Hybopsis amnis	Pallid Shiner
Ichthyomyzon spp.	Lampreys
Ictalurus furcatus	Blue Catfish
Ictalurus punctatus	Channel Catfish
Ictiobus spp.	Buffaloes
Labidesthes sicculus	Brook Silverside
Lepisosteus oculatus	Spotted Gar

Lepisosteus osseus	Longnose Gar
Lepisosteus platostomus	Shortnose Gar
Lepomis cyanellus	Green Sunfish
Lepomis gulosus	Warmouth
Lepomis humilis	Orangespotted Sunfish
Lepomis macrochirus	Bluegill
Lepomis marginatus	Dollar Sunfish
Lepomis megalotis	Longear Sunfish
Lepomis microlophus	Redear Sunfish
Lepomis miniatus	Redspotted Sunfish
Lepomis symmetricus	Bantam Sunfish
Luxilus chrysocephalus	Striped Shiner
Luxilus cornutus	Common Shiner
Lythrurus fumeus	Ribbon Shiner
Lythrurus snelsoni	Ouachita Shiner
Lythrurus umbratilis	Redfin Shiner
Macrhybopsis storeriana	Silver Chub
Macrhybopsis hyostoma	Shoal Chub
Menidia spp.	Neotropical silversides
Micropterus dolomieu	Smallmouth Bass
Micropterus punctulatus	Spotted Bass
Micropterus salmoides	Largemouth Bass
Minytrema melanops	Spotted Sucker
Morone spp.	Temperate Basses
Moxostoma spp.	Redhorses
Notemigonus crysoleucas	Golden Shiner
Notropis atherinoides	Emerald Shiner
Notropis atrocaudalis	Blackspot Shiner
Notropis boops	Bigeye Shiner
Notropis buchanani	Ghost Shiner
Notropis ortenburgeri	Kiamichi Shiner
Notropis percobromus	Carmine Shiner
Notropis perpallidus	Peppered Shiner
Notropis potteri	Chub Shiner
Notropis shumardi	Silverband Shiner
Notropis stramineus	Sand Shiner
Notropis volucellus	Mimic Shiner
Noturus eleutherus	Mountain Madtom
Noturus exilis	Slender Madtom
Noturus gyrinus	Tadpole Madtom
Noturus nocturnus	Freckled Madtom

Opsopoeodus emiliae	Pugnose Minnow
Percina caprodes	Logperch
Percina copelandi	Channel Darter
Percina maculata	Blackside Darter
Percina pantherina	Leopard Darter
Percina phoxocephala	Slenderhead Darter
Percina sciera	Dusky Darter
Percina shumardi	River Darter
Phenacobius mirabilis	Suckermouth Minnow
Pimephales notatus	Bluntnose Minnow
Pimephales vigilax	Bullhead Minnow
Pomoxis annularis	White Crappie
Pomoxis nigromaculatus	White Crappie
Pteronotropis hubbsi	Bluehead Shiner
Pylodictis olivaris	Flathead Catfish
Semotilus atromaculatus	Creek Chub

Table A3. Pearson's pairwise correlation coefficients (*r*) among 15 streamflow metrics (covariates) and the season indicator variable used in the occurrence component of the model (see Table 1 for description of flow metrics). Technically, this was a point-biserial correlation for comparisons between season and covariates; however, this calculation is simply a special case of *r* (Freund et al 2010).

	DH14	DL16	DL10	FH10	FH2	ML15	MA2	MA3	MH19	MA42	RA4	TH1	TL1	TH2	TL2	Season
DH14	1	-0.07														
DL16	-0.07	1														
DL10	-0.06	0.52	1													
FH10	0.36	-0.33	0.04	1												
FH2	0.03	0.45	0.47	-0.15	1											
ML15	-0.37	0.08	-0.32	-0.43	0.05	1										
MA2	-0.27	0.08	-0.19	-0.45	0.18	0.24	1									
MA3	0.67	-0.40	-0.07	0.54	-0.22	-0.46	-0.48	1								
MH19	-0.30	0.15	0.04	-0.10	0.11	0.13	-0.01	-0.20	1							
MA42	0.46	0.03	0.32	0.18	0.34	-0.23	-0.11	0.33	0.02	1						
RA4	-0.10	0.10	-0.08	-0.12	-0.09	0.03	-0.25	0.02	0.46	-0.10	1					
TH1	-0.28	-0.15	-0.04	0.02	-0.21	0.02	-0.02	-0.05	-0.07	-0.17	0.01	1				
TL1	0.01	0.24	0.13	-0.26	0.20	0.30	0.04	-0.03	0.04	0.15	-0.11	-0.09	1			
TH2	-0.39	-0.05	0.23	-0.07	-0.08	-0.01	0.10	-0.18	0.03	-0.19	0.00	0.17	-0.02	1		
TL2	-0.08	-0.07	0.03	-0.03	0.10	0.16	0.06	0.00	-0.11	-0.09	-0.18	0.01	0.06	-0.06	1	
Season	-0.18	-0.07	-0.03	-0.10	-0.17	0.11	0.05	-0.13	0.30	-0.20	0.17	0.08	-0.13	0.24	0.11	1

Table A4. Pearson's pairwise correlation coefficients (*r*) among predictor variables used in the detection component of the model. Technically, this was a point-biserial comparison between the indicator variable season and covariates; however, this calculation is simply a special case of *r* (Freund et al 2010).

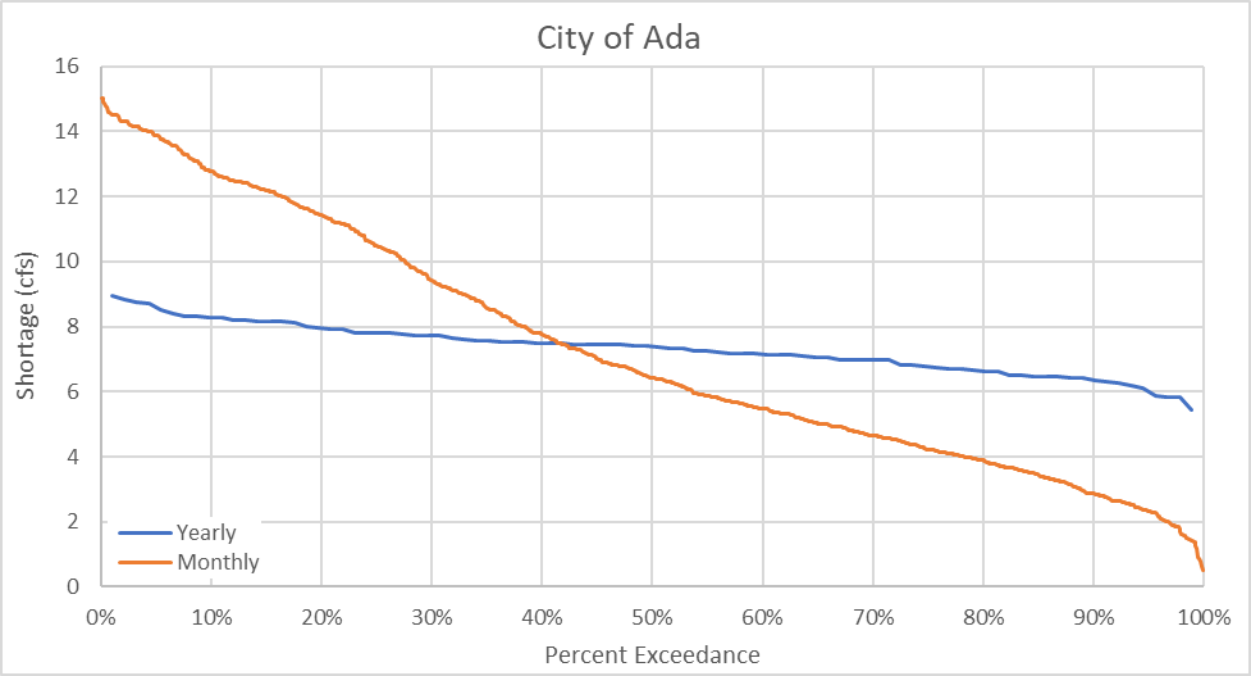
	Time1	Time2	RFI	Season
Time1	1			
Time2	-0.09	1		
RFI	-0.04	-0.05	1	
Season	-0.03	0.13	0.37	1

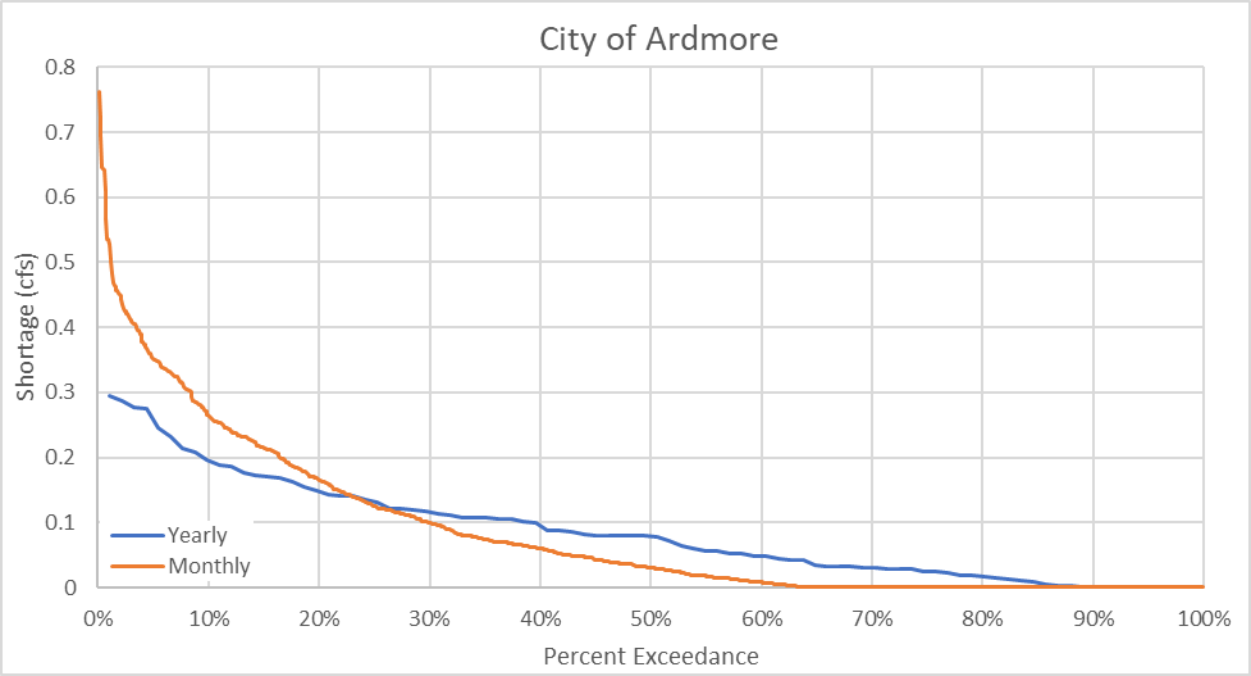
Table A5. Collector descriptions used for the grouping factor in the detection model and the proportion of surveys. Surveys were pooled among the datasets by predominant collectors (i.e., ≥10 surveys, see also Table A1).

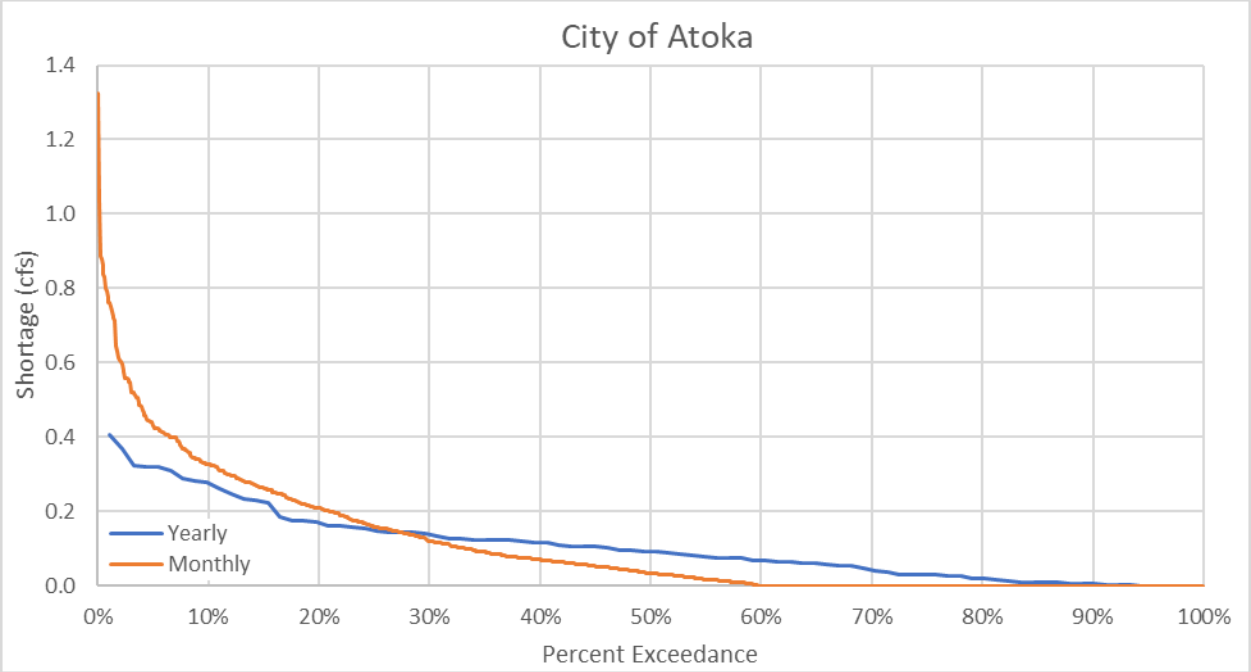
ID	Collector	Proportion of surveys
1	Jim Felley et al.	0.02
2	Keith Gido et al.	0.01
3	Bill Matthews et al.	0.09
4	Avril Ming et al.	0.03
5	Oklahoma Department of Wildlife Conservation	0.06
6	Oklahoma Conservation Commission	0.17
7	Illinois Natural History Survey	0.04
8	Oklahoma Water Resources Board	0.06
9	Oklahoma Department of Environmental Quality	0.06
10	Jimmie Pigg et al	0.22
11	Steven Secor et al	0.02
12	Chris Taylor et al	0.06
13	Matt Winston et al	0.06
14	Miscellaneous collector	0.10

Appendix B – Municipal Water Permit Figures

Shortage frequency-duration curves for the most unreliable surface water permits for municipal entities, from Section 5.1. Data are daily averages of all climate scenarios, from 2010 through 2099. This approach is different than an average across each scenario's frequency-duration curve values. The approach used here may not represent an individual scenario's frequency-duration curve well, nor its high and low probability values.



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Shortage (cfs)
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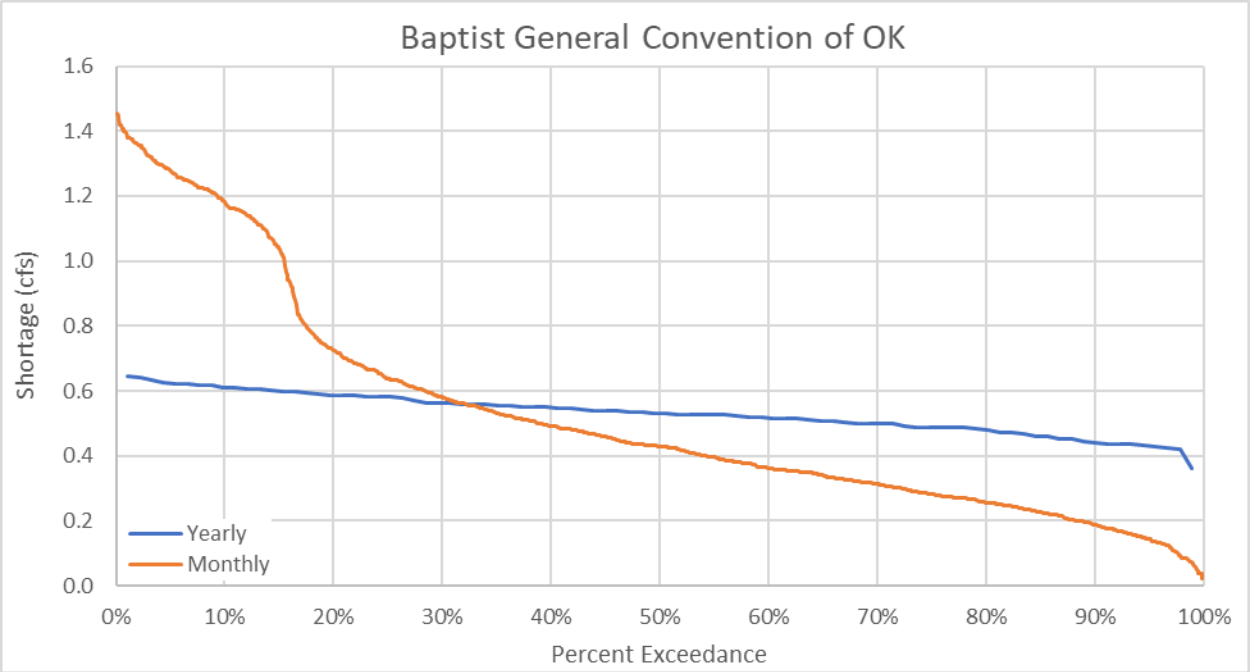
1.0
0.8
0.6
0.4
0.2
0.0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance


Baptist General Convention of OK
Shortage (cfs)
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1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Yearly
Monthly
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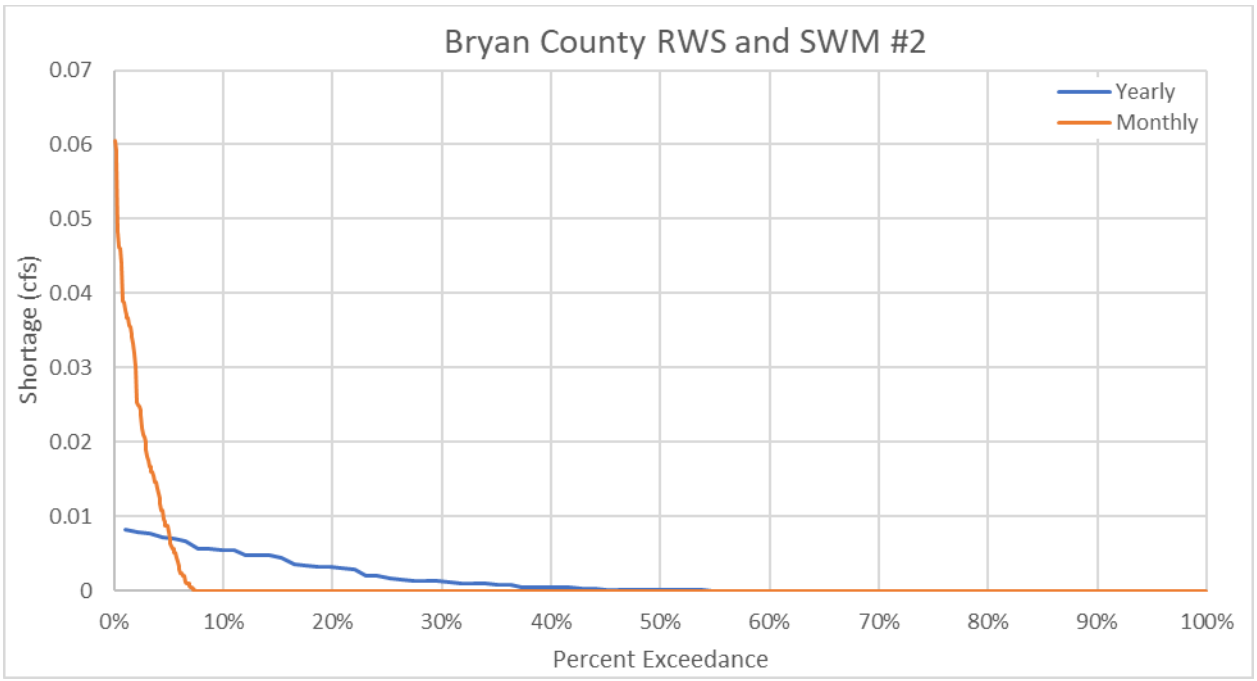
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance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Monthly
Shortage (cfs)
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0.05
0.04
0.03
0.02
0.01
0
0%
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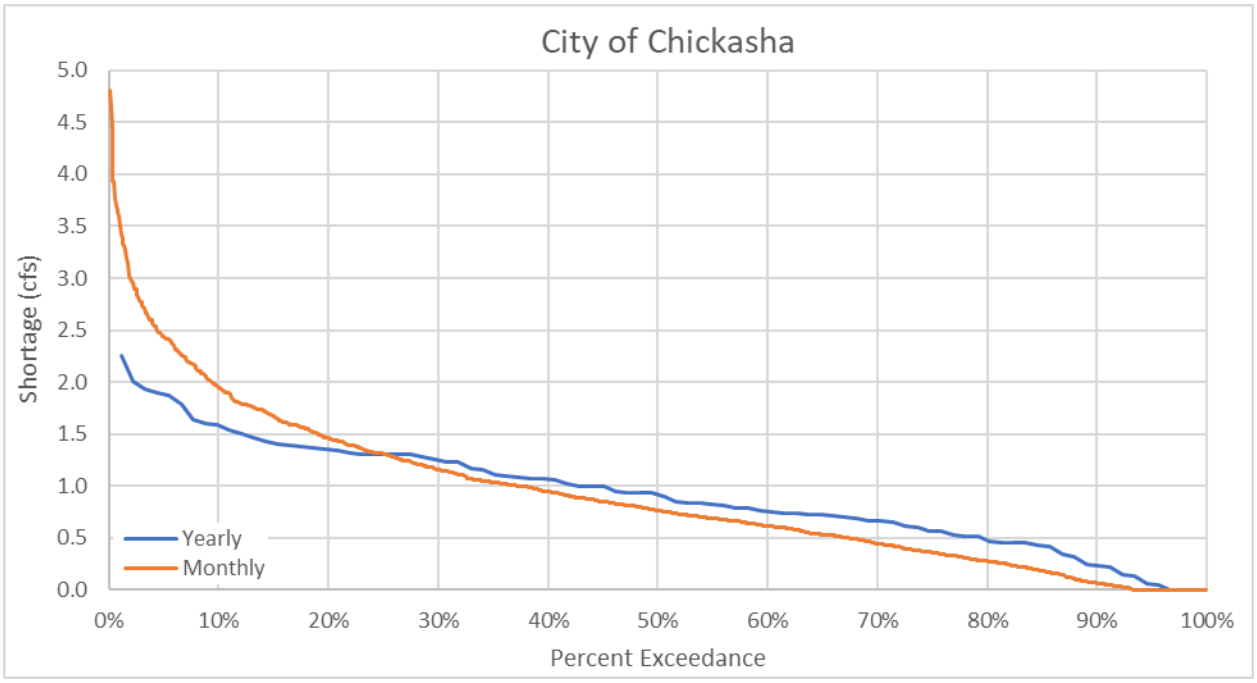
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance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3.0
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2.0
1.5
1.0
0.5
0.0
Yearly
Monthly
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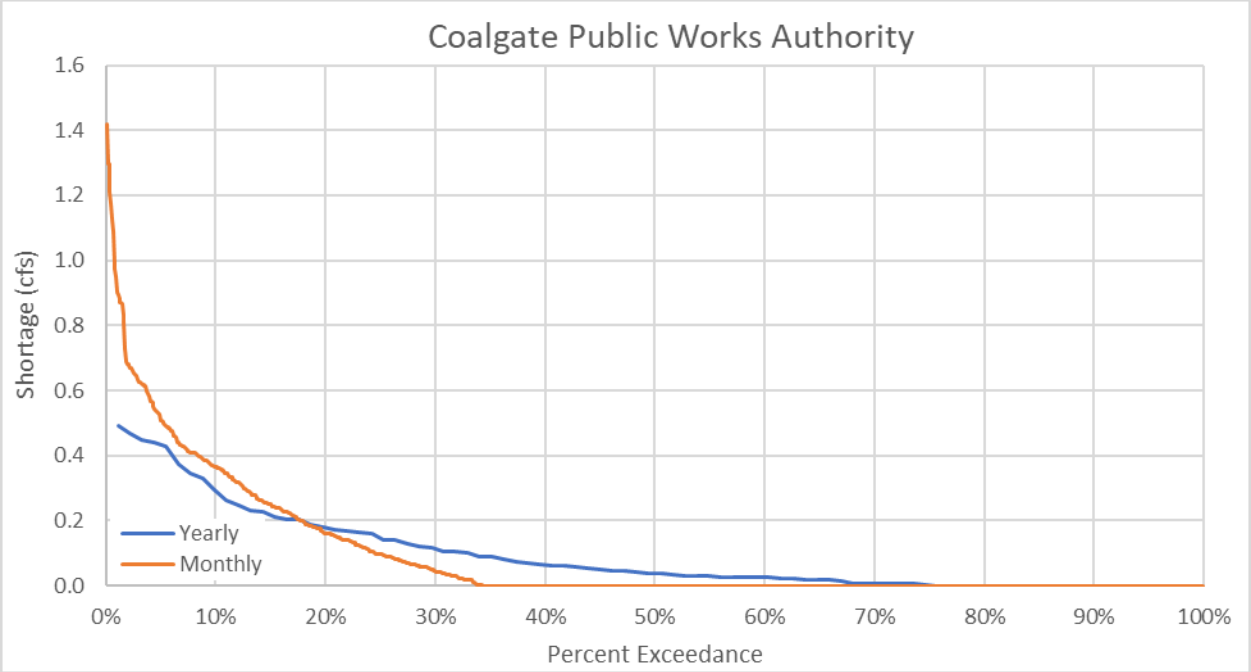
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance


Coalgate Public Works Authority
Shortage (cfs)
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0.8
0.6
0.4
0.2
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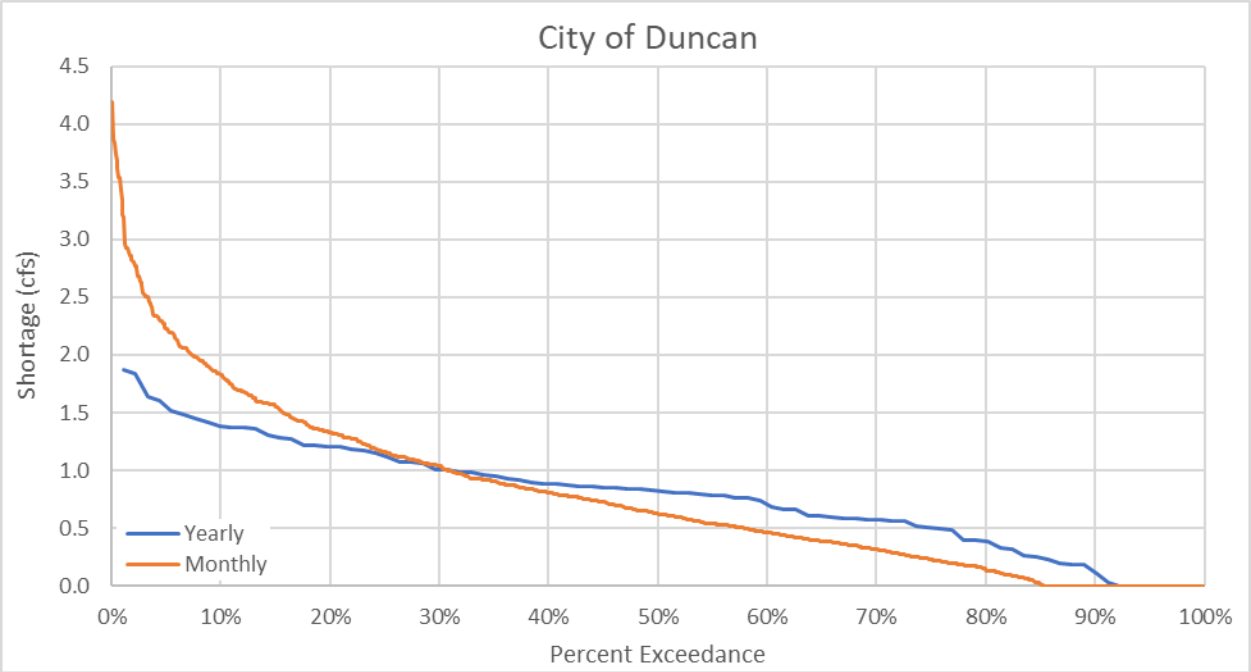
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance


City of Duncan
Shortage (cfs)
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3.5
3.0
2.5
2.0
1.5
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0.0
Yearly
Monthly
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20%
30%
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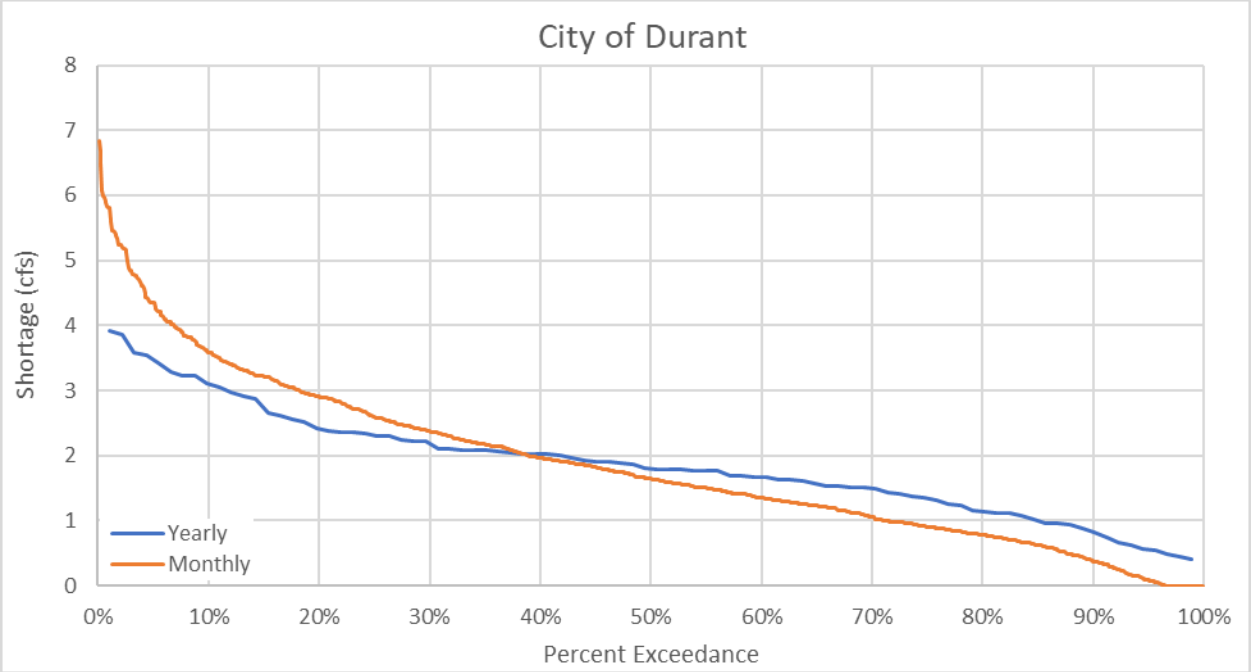
60%
70%
80%
90%
100%
Percent Exceedance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Shortage (cfs)
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3
2
1
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Yearly
Monthly
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30%
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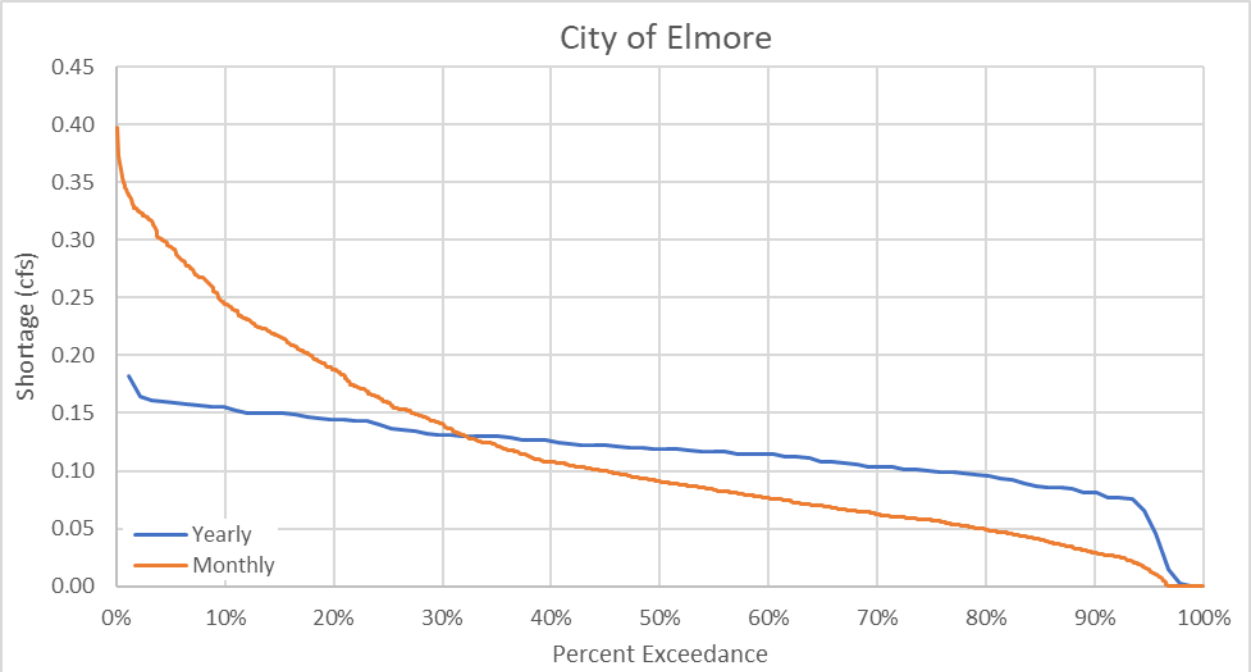
50%
60%
70%
80%
90%
100%
Percent Exceedance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0.10
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Monthly
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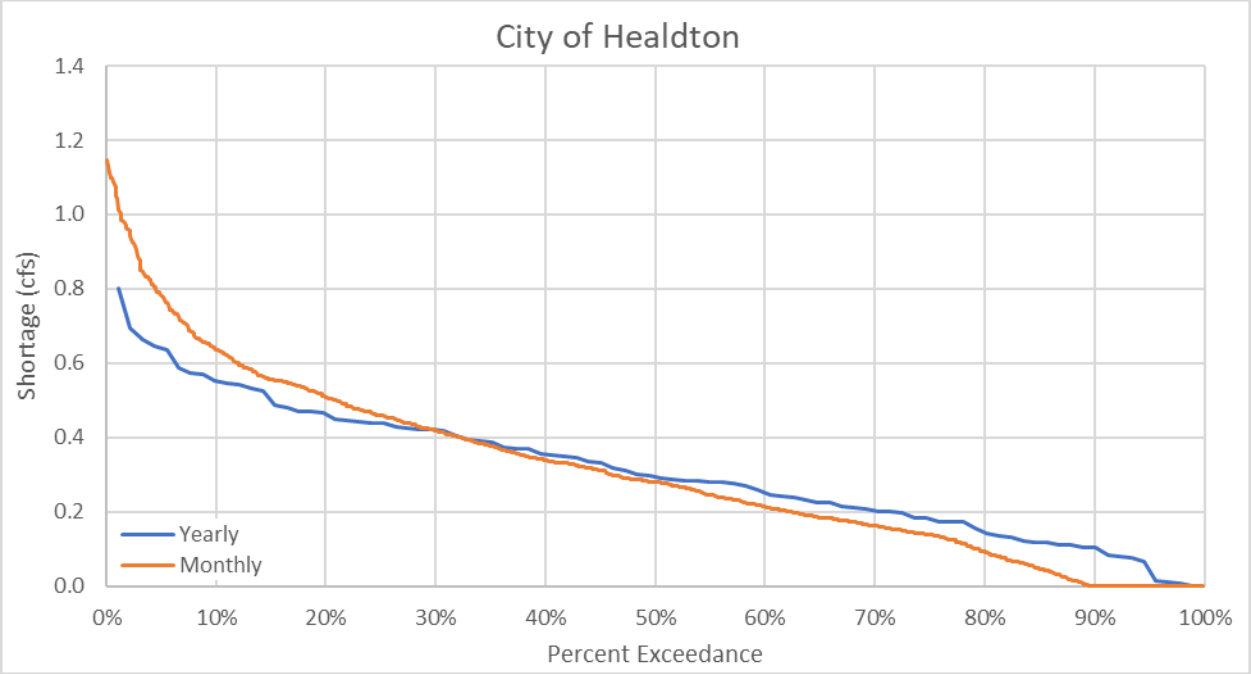
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance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Yearly
Monthly
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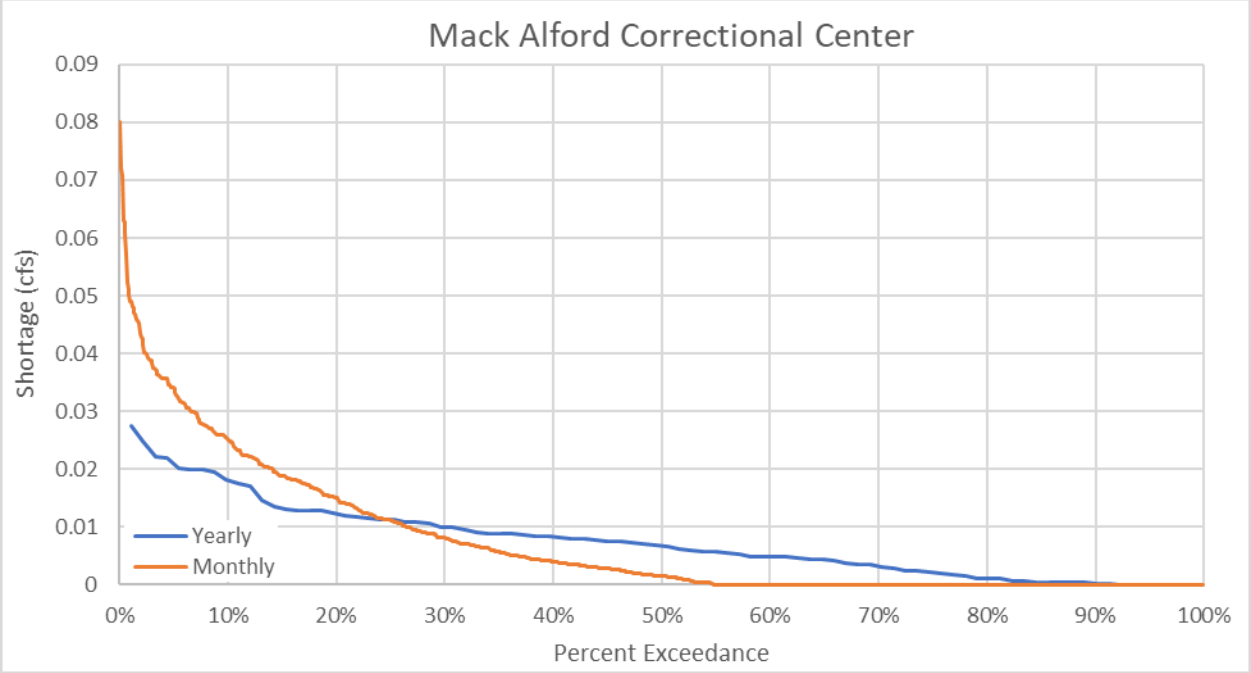
60%
70%
80%
90%
100%
Percent Exceedance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0.01
0
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Monthly
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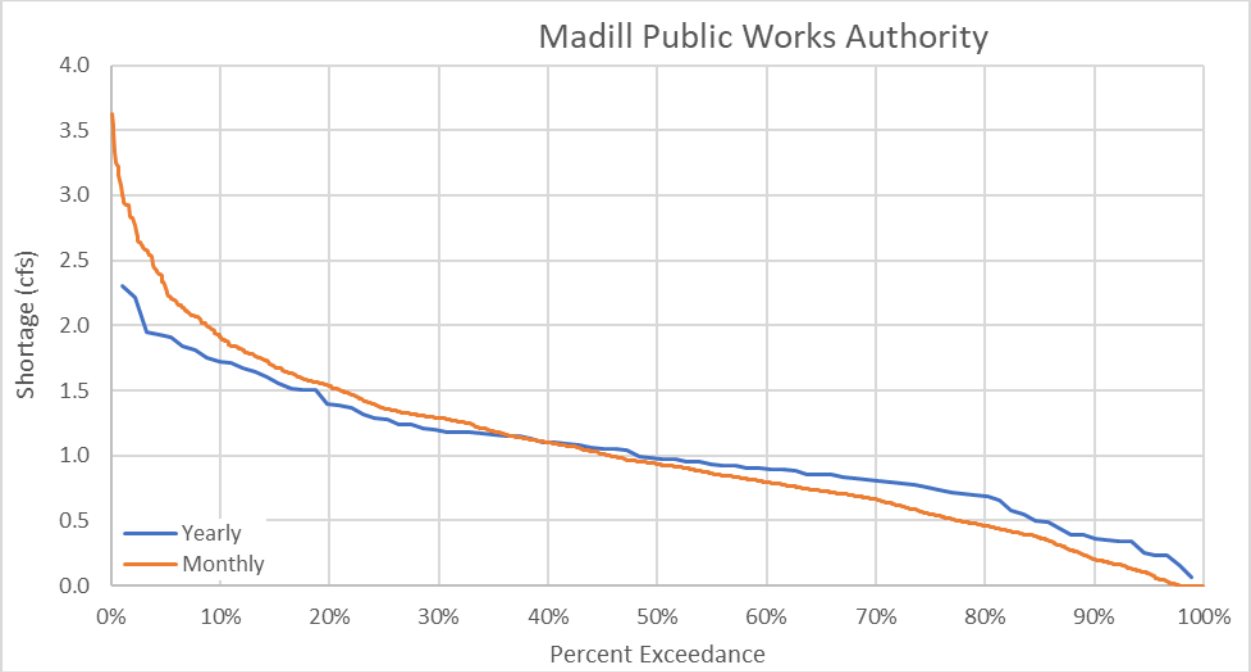
60%
70%
80%
90%
100%
Percent Exceedance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2.0
1.5
1.0
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Monthly
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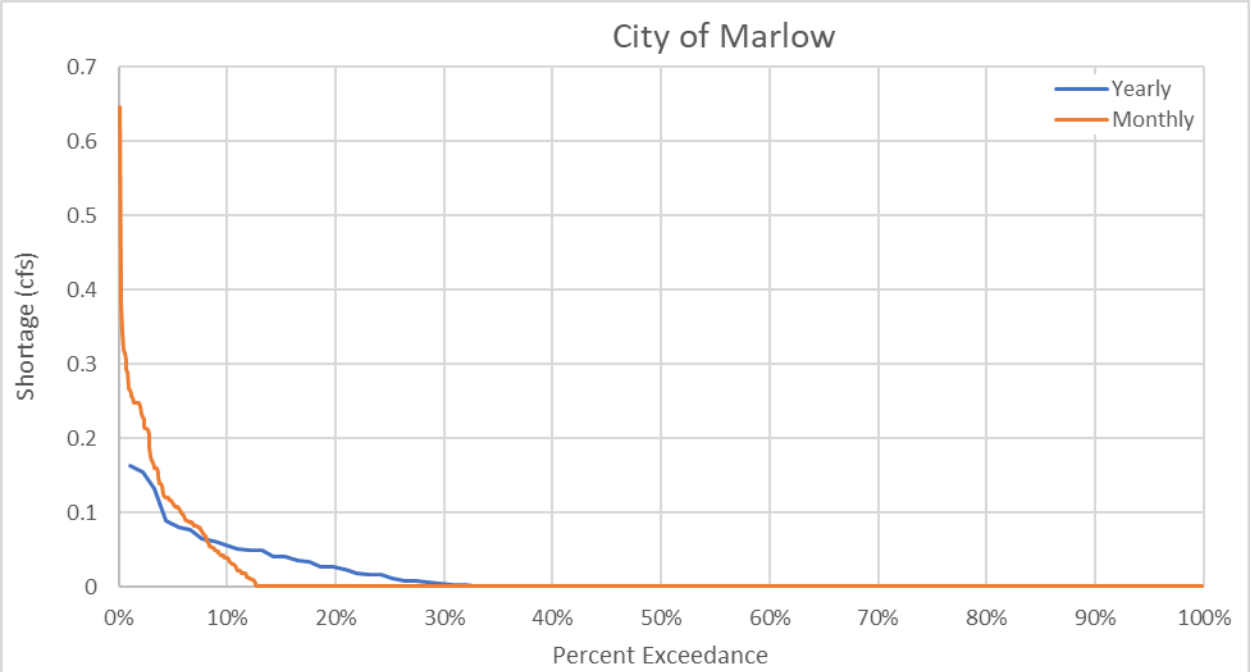
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance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0.1
0
Yearly
Monthly
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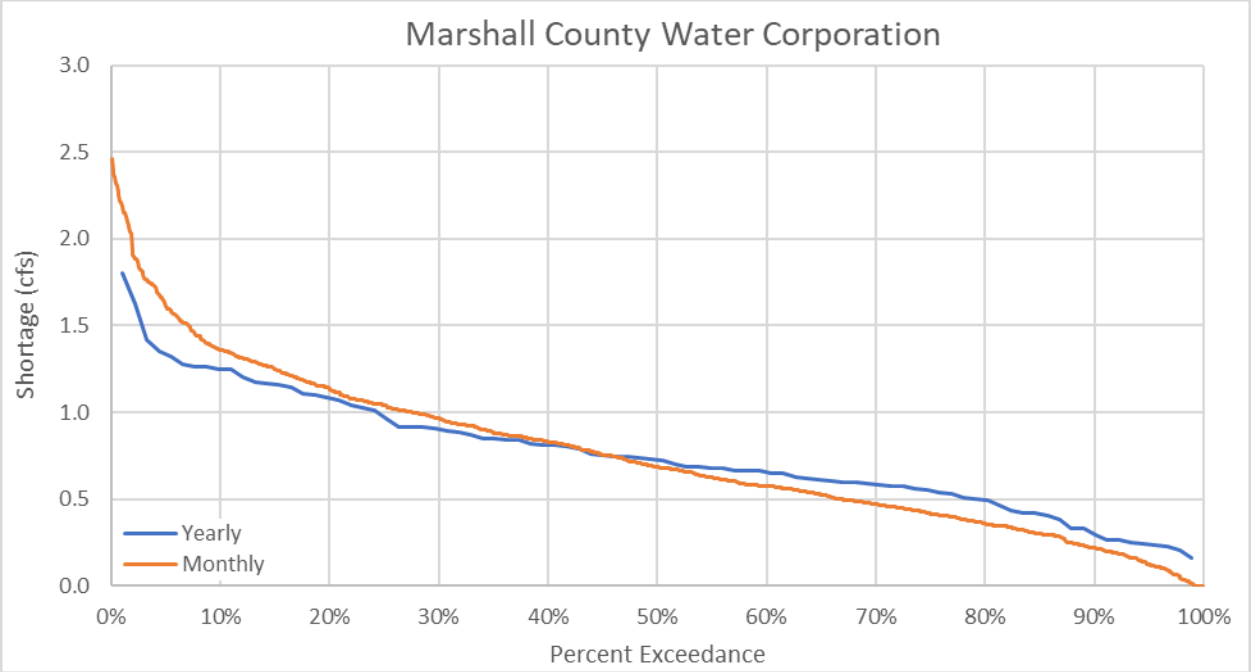
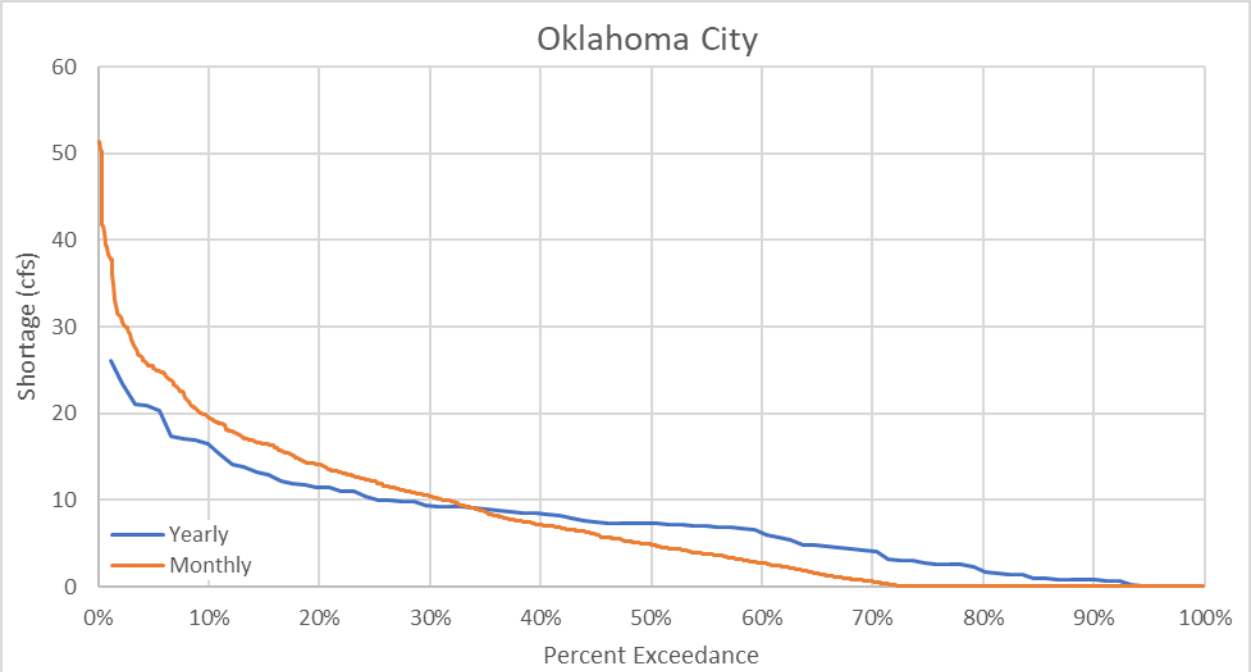
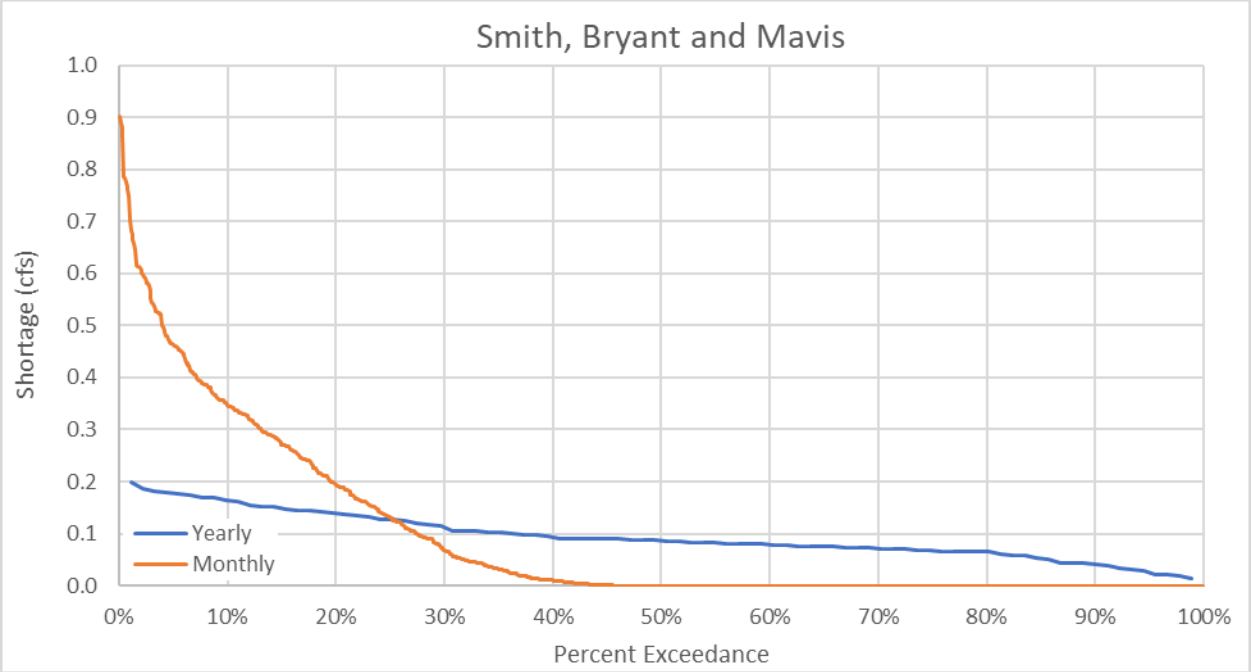
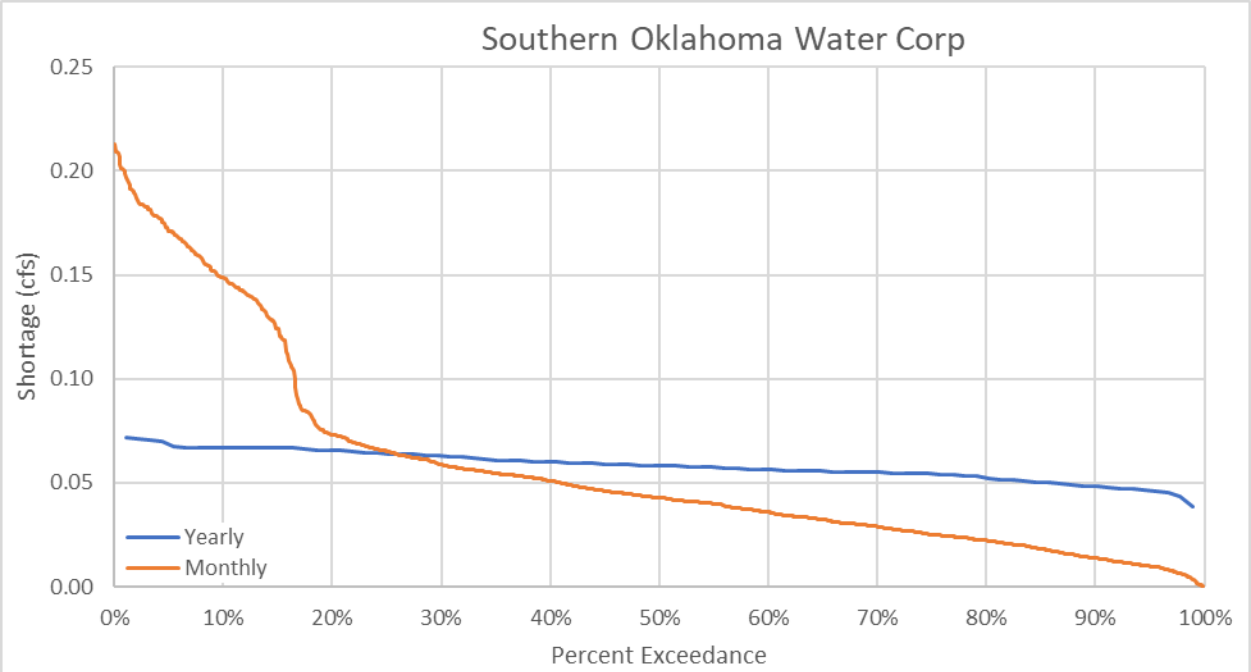
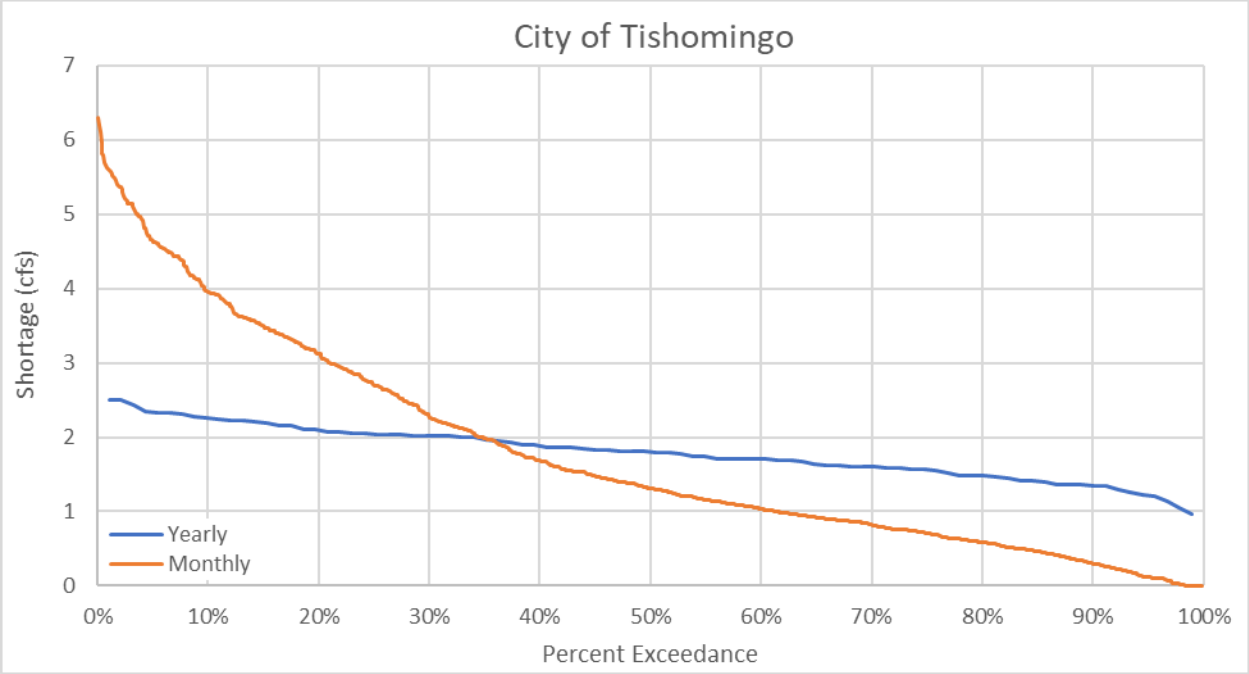
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

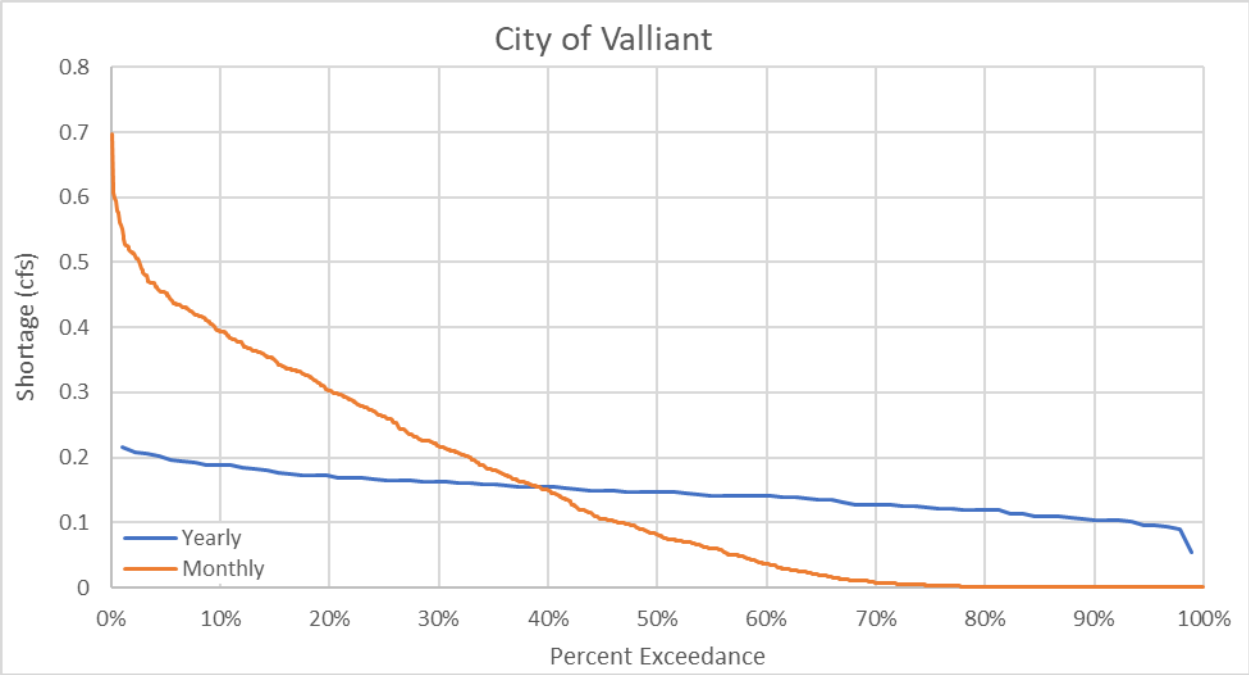

Marshall County Water Corporation
Shortage (cfs)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

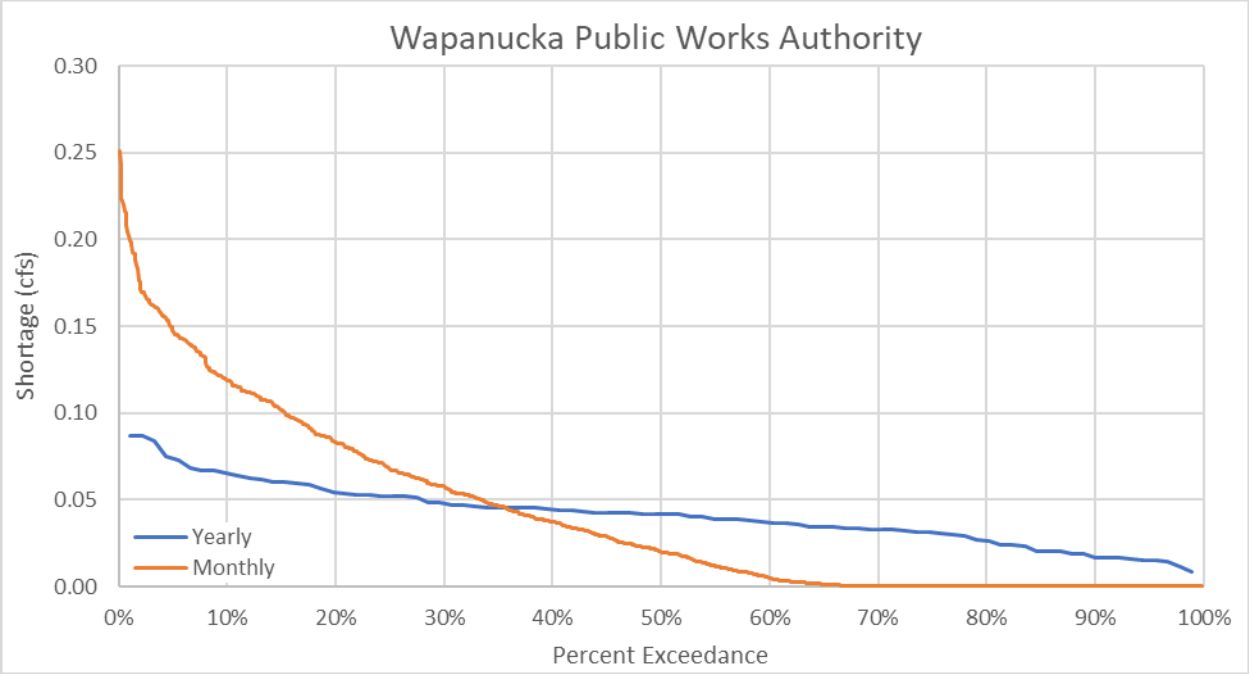

Oklahoma City
Shortage (cfs)
60
50
40
30
20
10
0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance


Smith, Bryant and Mavis
Shortage (cfs)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance


Southern Oklahoma Water Corp
Shortage (cfs)
0.25
0.20
0.15
0.10
0.05
0.00
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

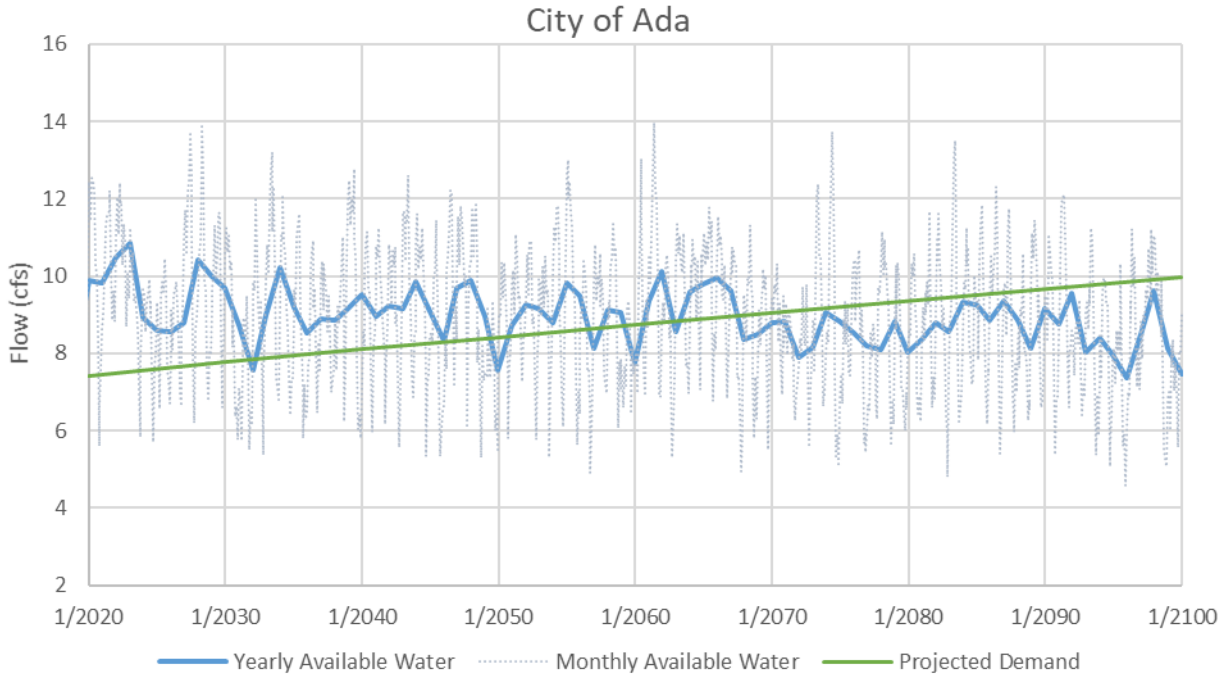

City of Tishomingo
Shortage (cfs)
7
6
5
4
3
2
1
0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

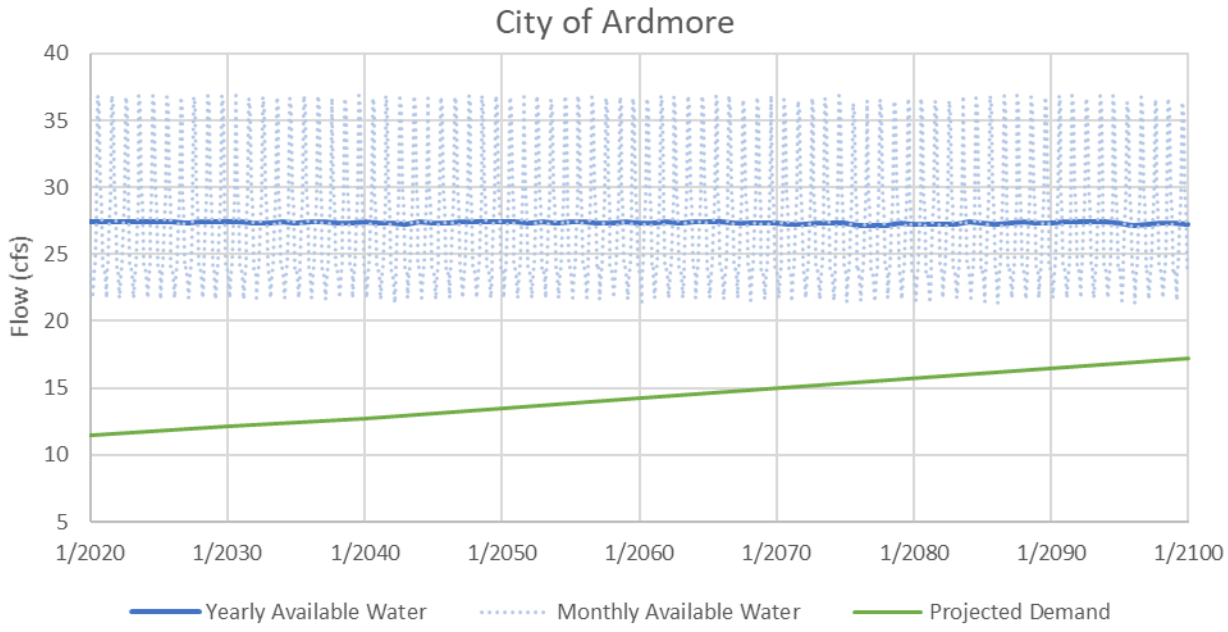

City of Valliant
Shortage (cfs)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

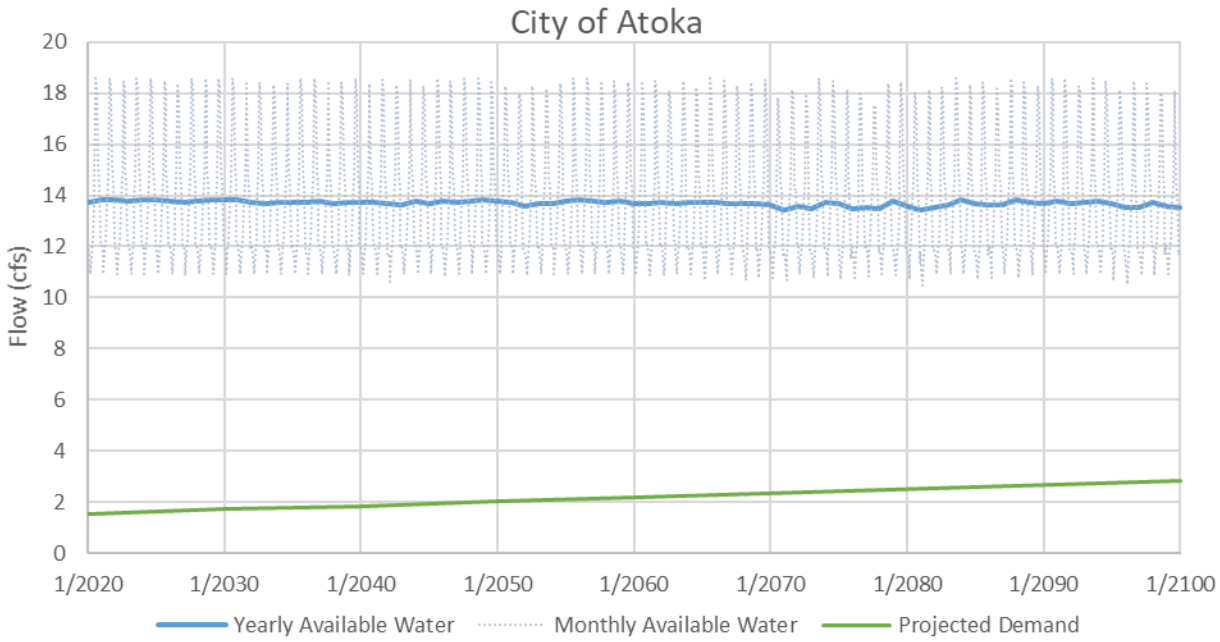

Wapanucka Public Works Authority
Shortage (cfs)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Yearly
Monthly
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Exceedance

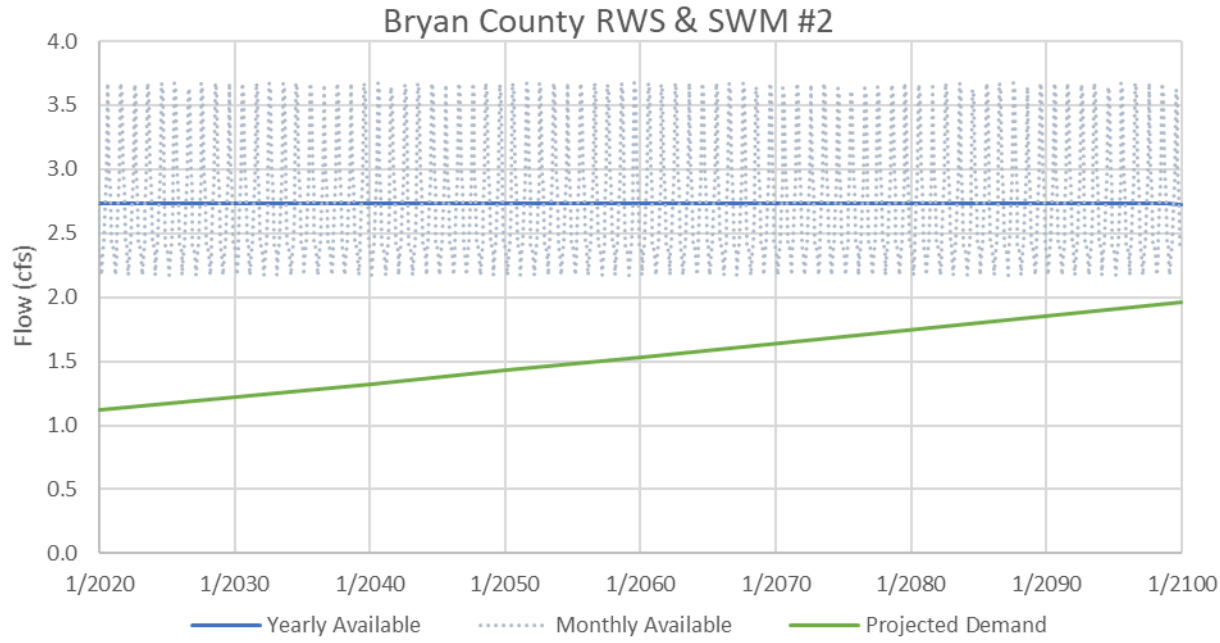
Appendix C - Supply-demand Curves

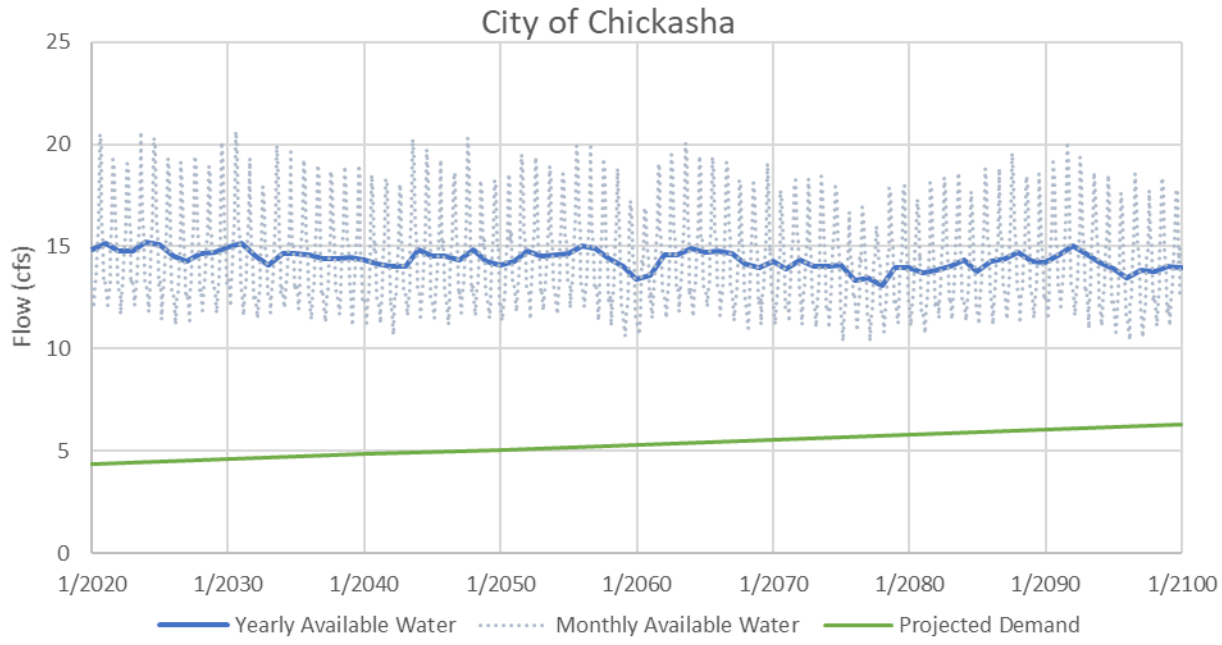
The figures below are supply-demand curves associated with Table 3 in Section 5.2.

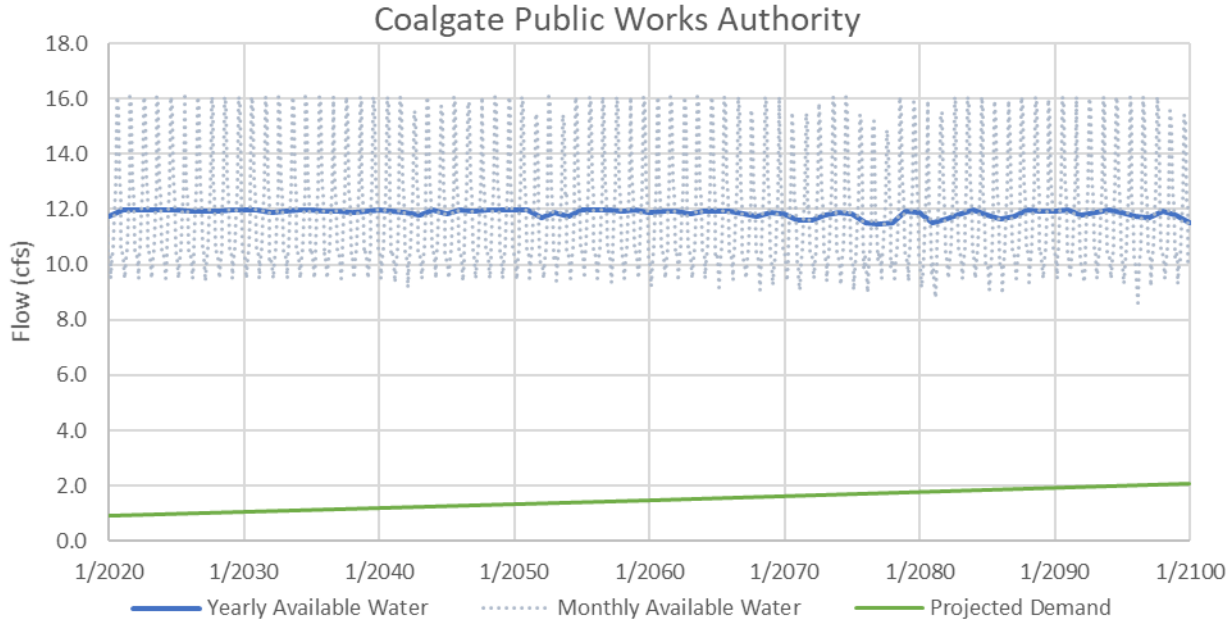


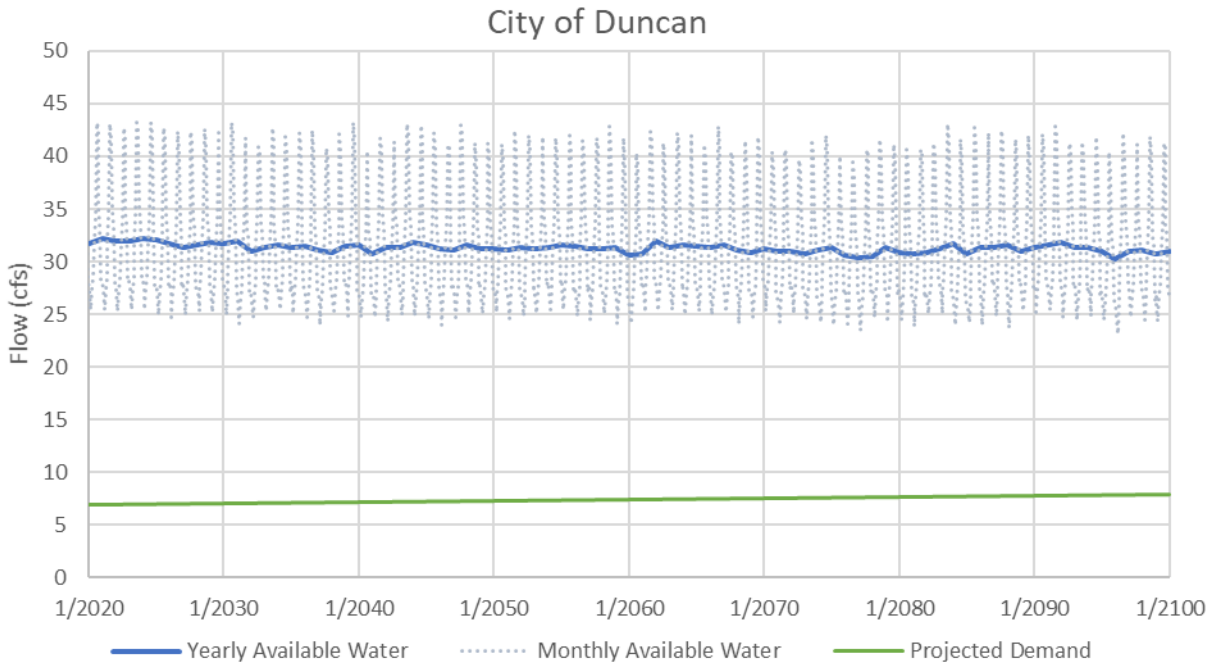


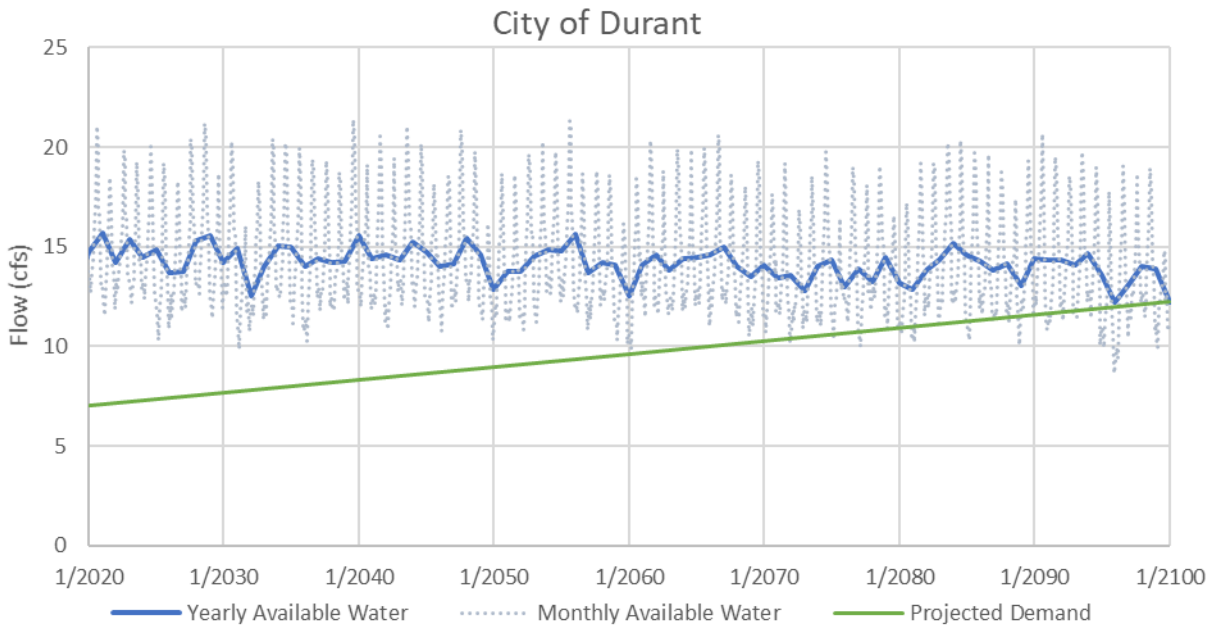

City of Atoka
Flow (cfs)
20
18
16
14
12
10
8
6
4
2
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

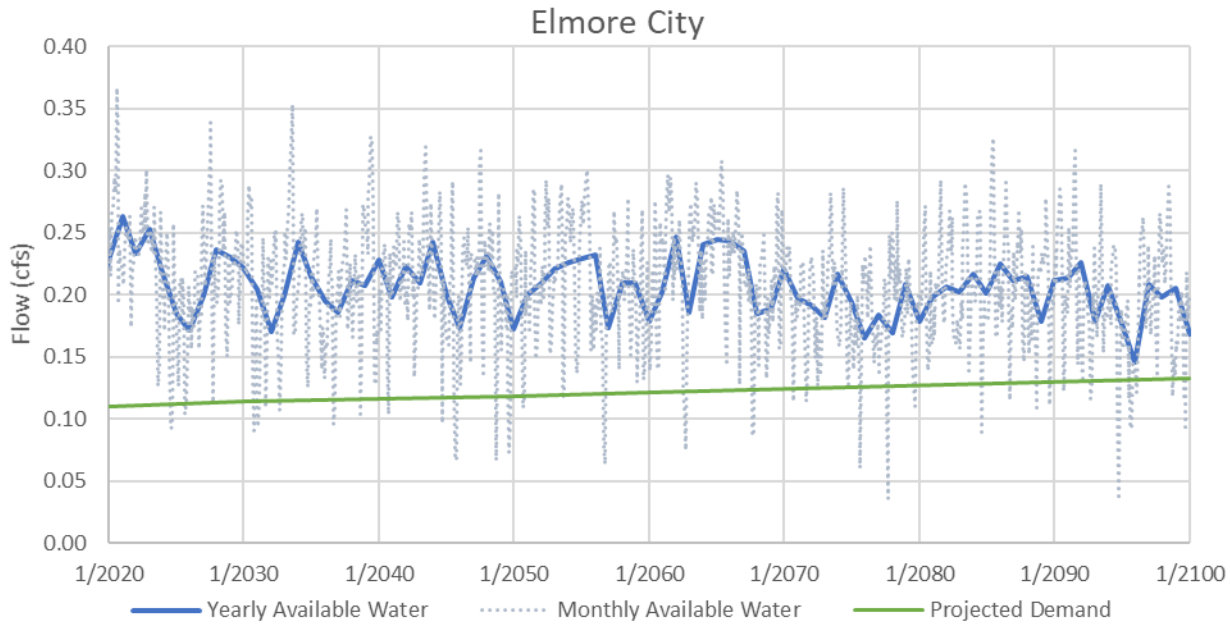

Bryan County RWS & SWM #2
Flow (cfs)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available
Monthly Available
Projected Demand

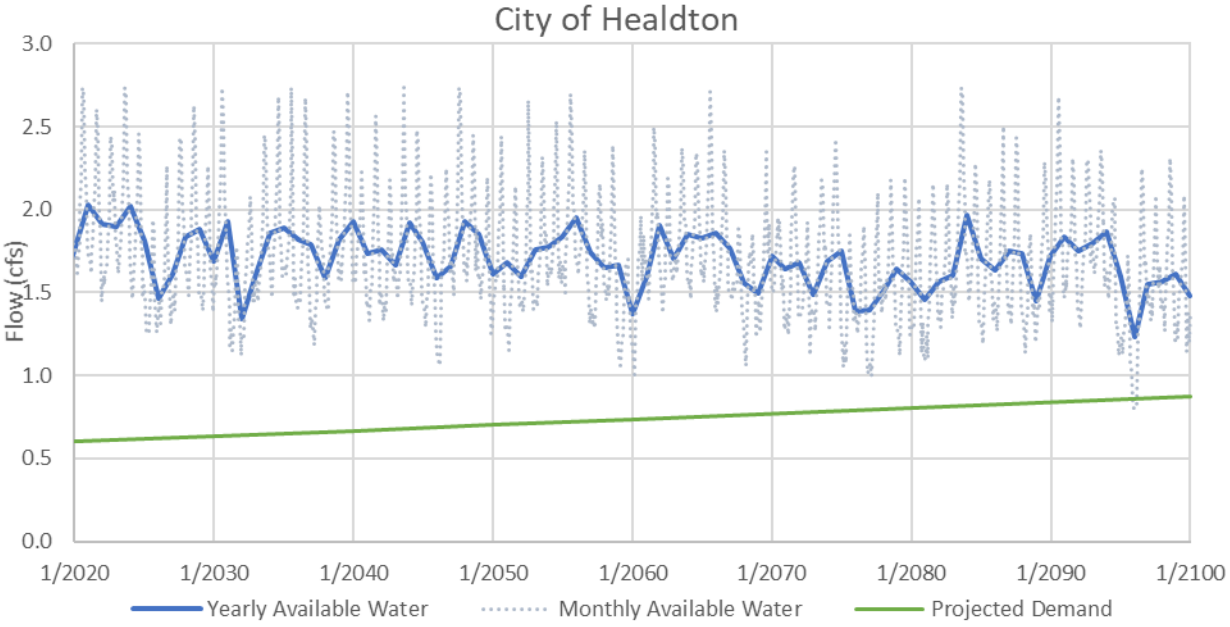

City of Chickasha
Flow (cfs)
25
20
15
10
5
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

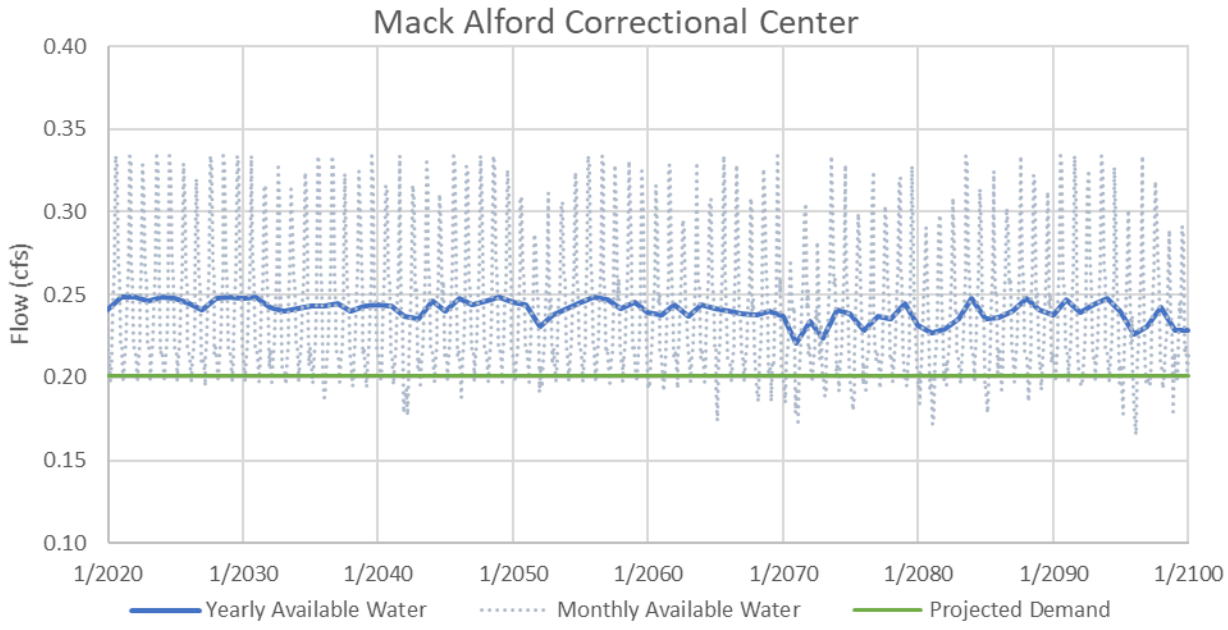

Coalgate Public Works Authority
Flow (cfs)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

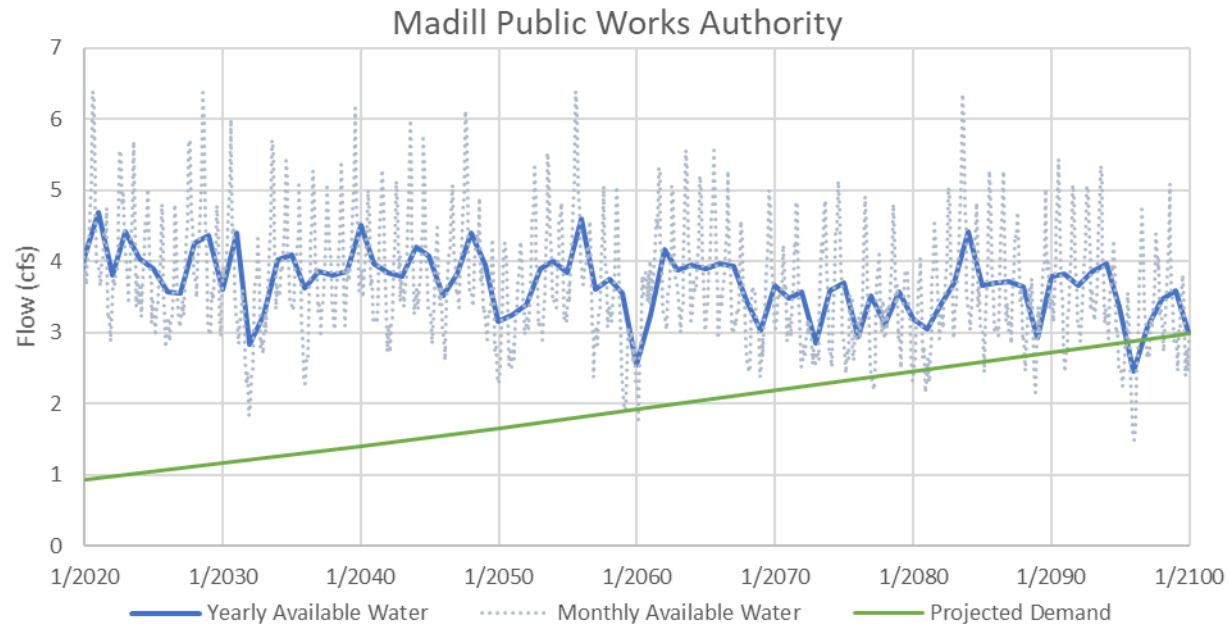

City of Duncan
Flow (cfs)
50
45
40
35
30
25
20
15
10
5
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

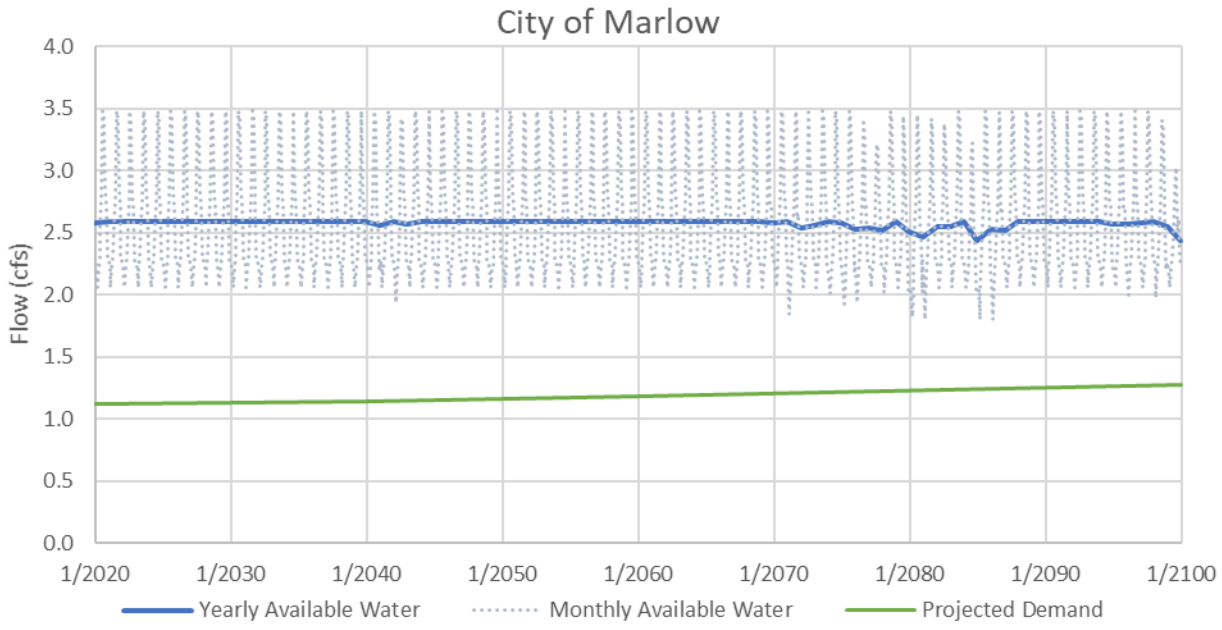

City of Durant
Flow (cfs)
25
20
15
10
5
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

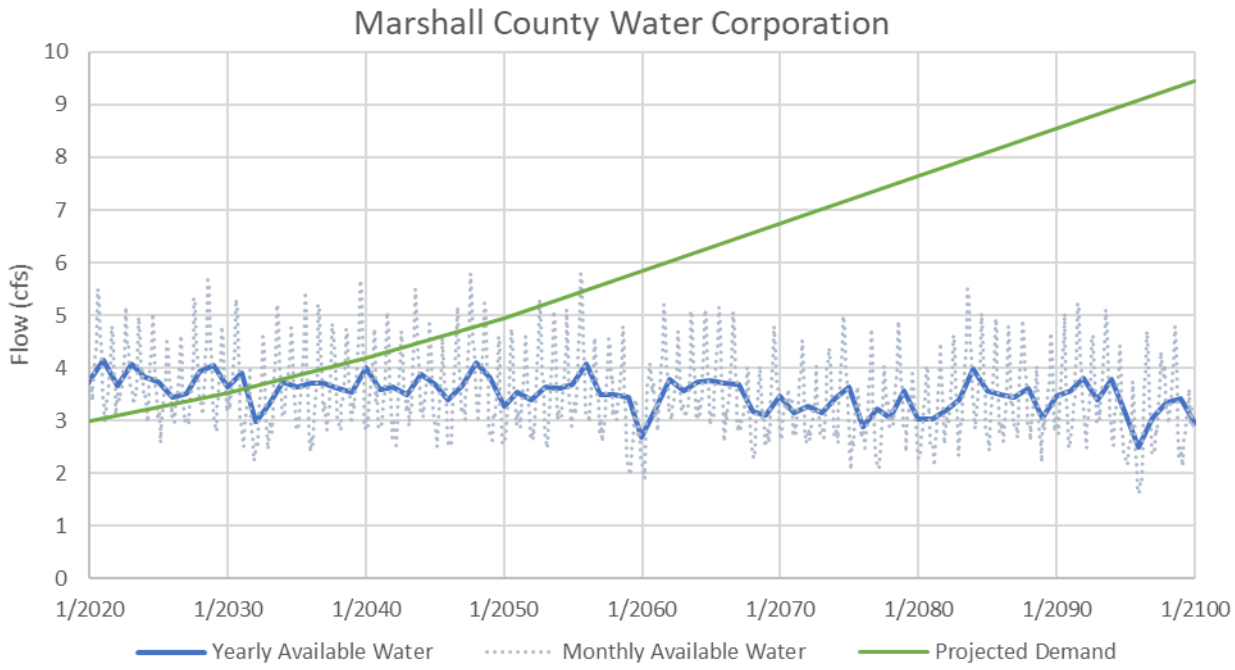

Elmore City
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

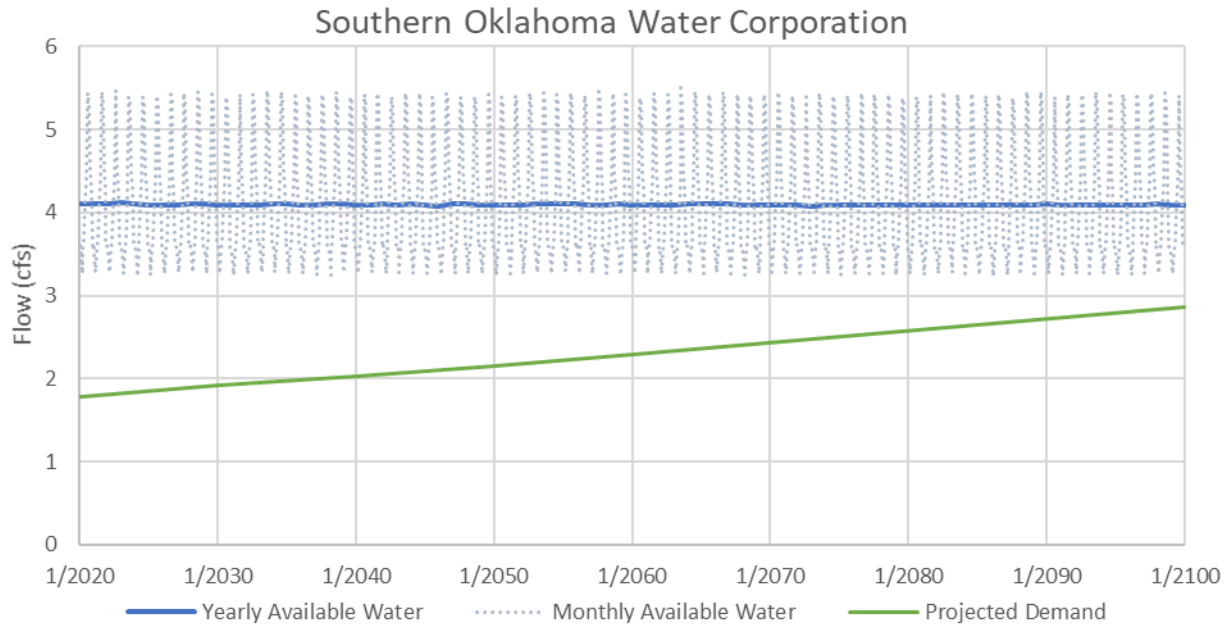

City of Healdton
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

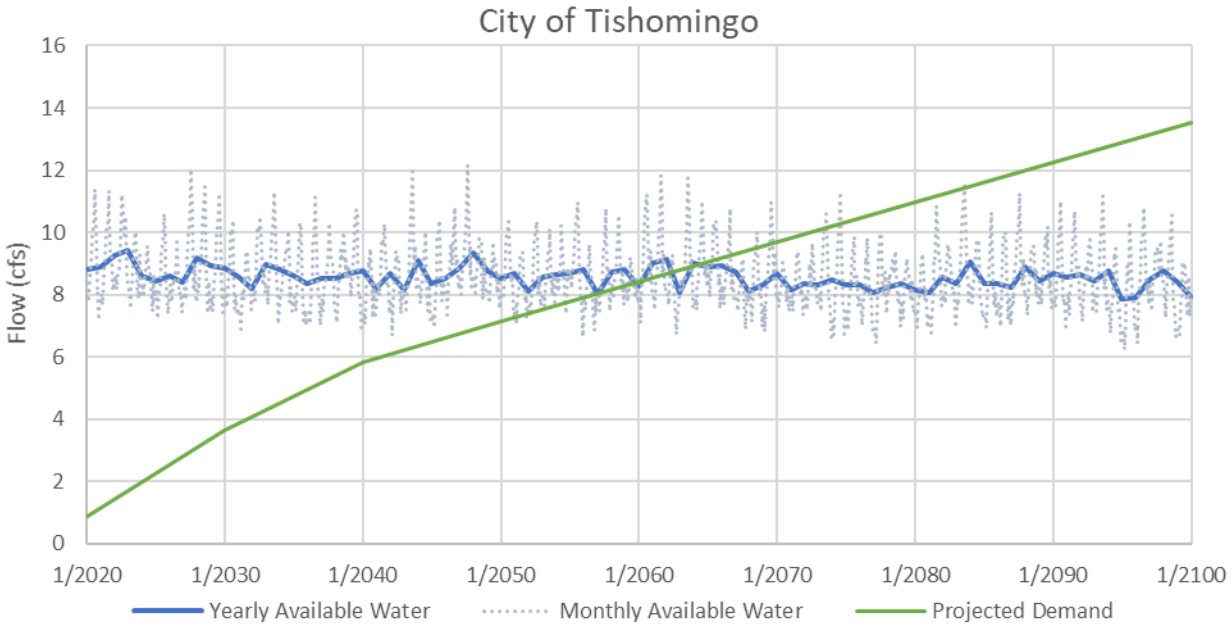

Mack Alford Correctional Center
0.40
0.35
0.30
0.25
0.20
0.15
0.10
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

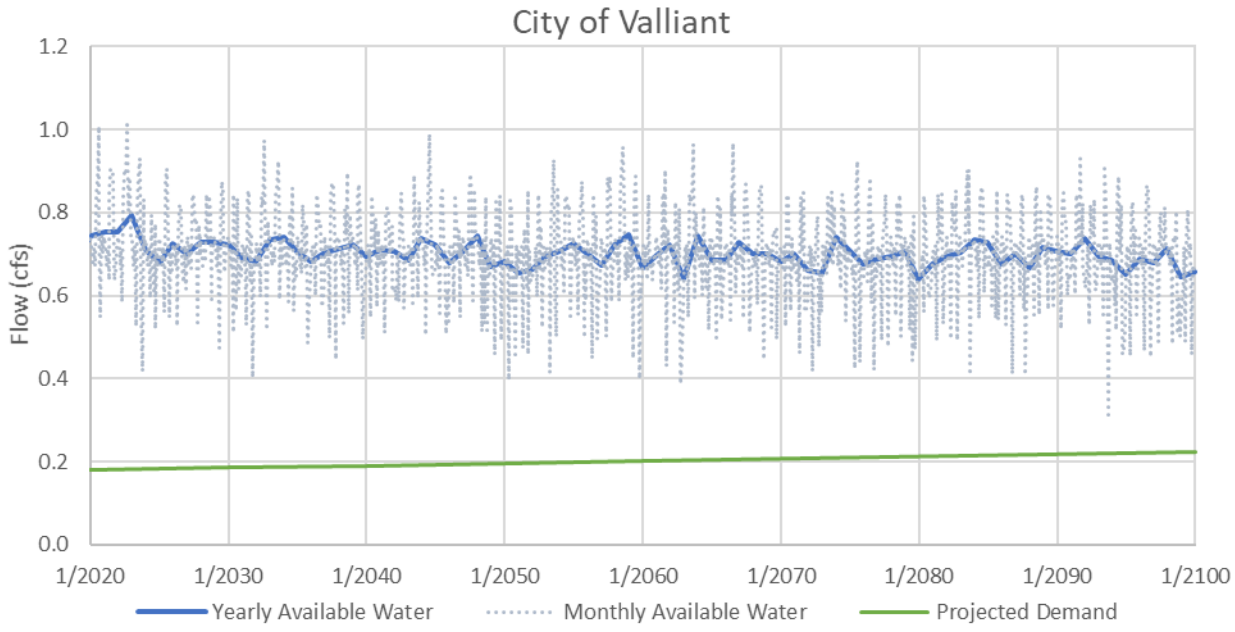

Madill Public Works Authority
7
6
5
4
3
2
1
0
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

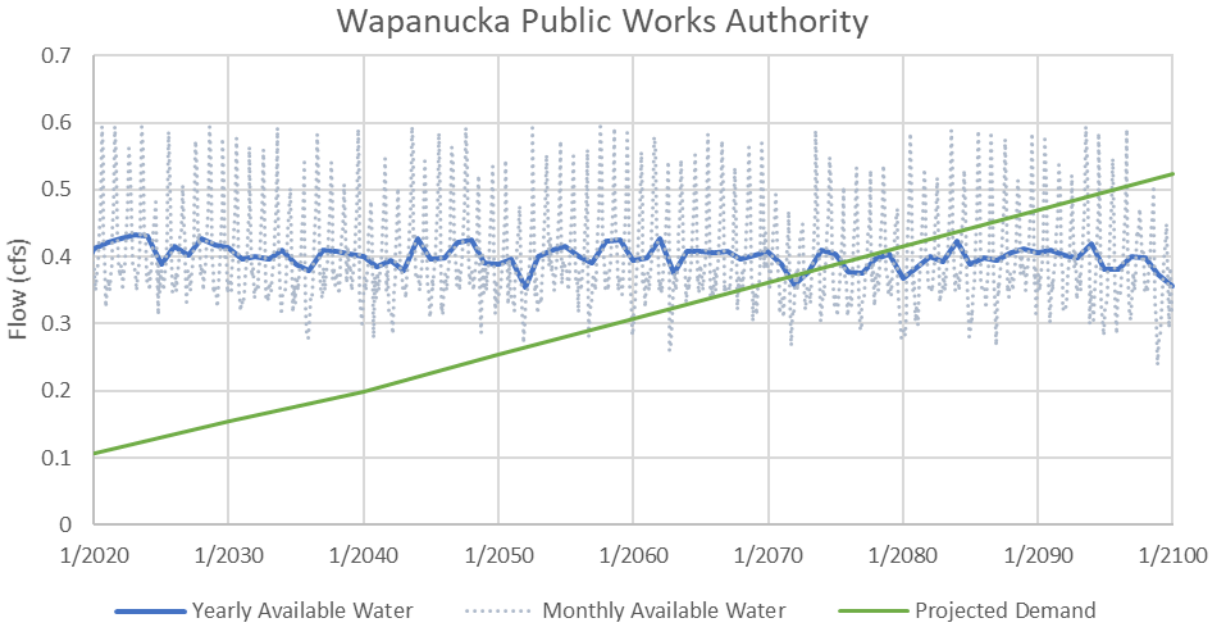

City of Marlow
Flow (cfs)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand


Marshall County Water Corporation
Flow (cfs)
10
9
8
7
6
5
4
3
2
1
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand


Southern Oklahoma Water Corporation
Flow (cfs)
6
5
4
3
2
1
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

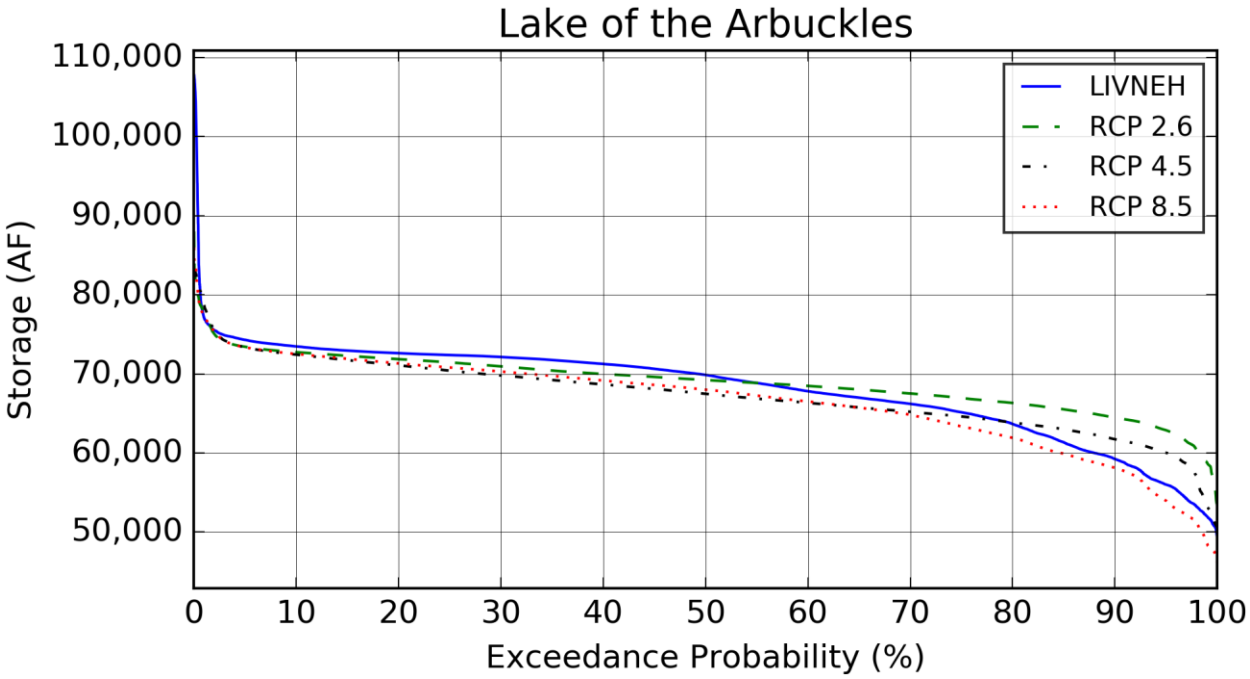

City of Tishomingo
Flow (cfs)
16
14
12
10
8
6
4
2
0
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

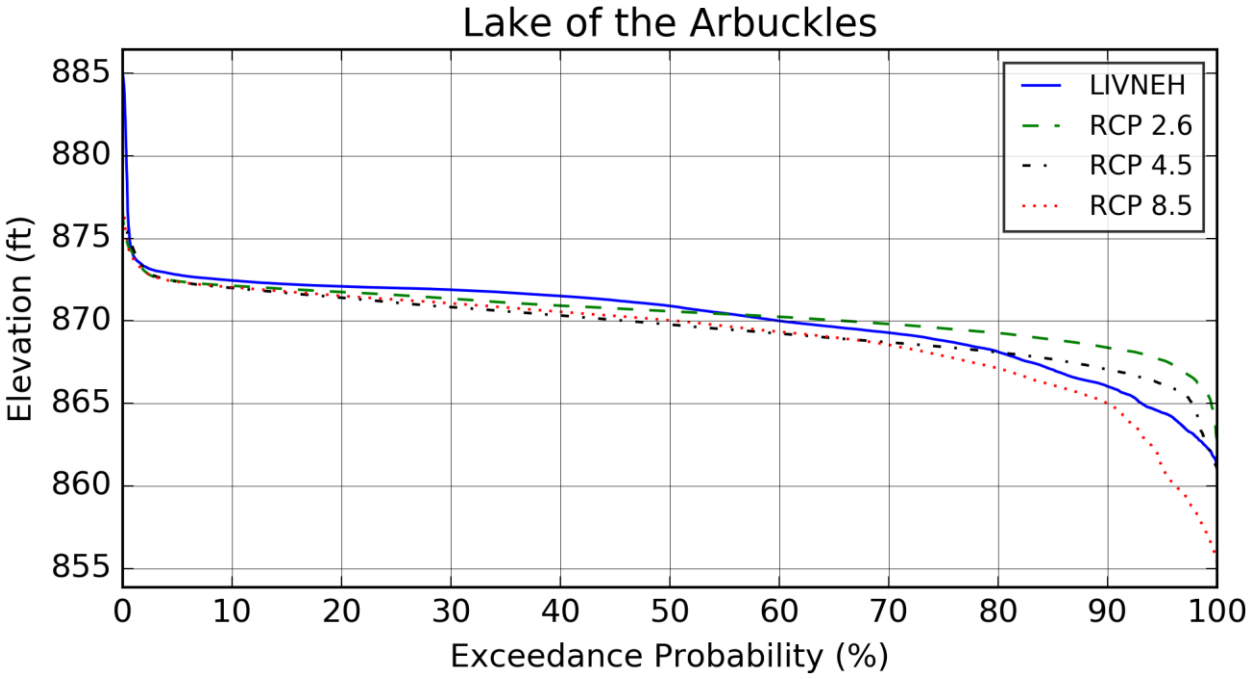

City of Valliant
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

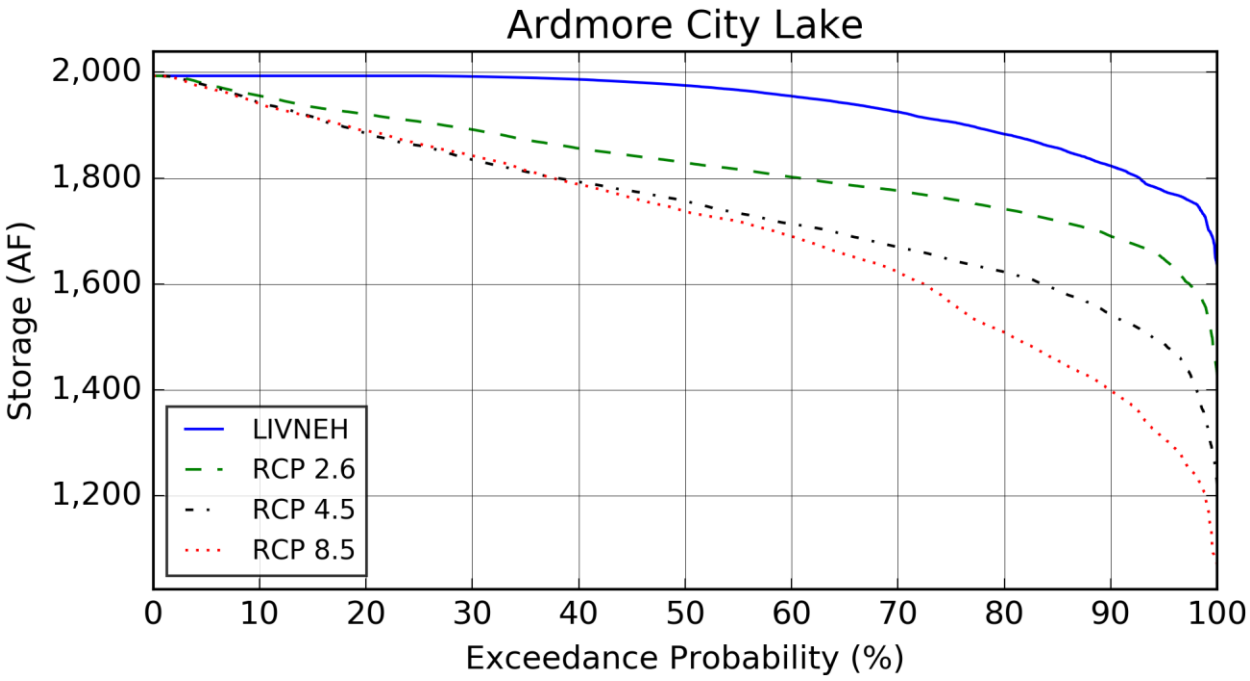

Wapanucka Public Works Authority
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Flow (cfs)
1/2020
1/2030
1/2040
1/2050
1/2060
1/2070
1/2080
1/2090
1/2100
Yearly Available Water
Monthly Available Water
Projected Demand

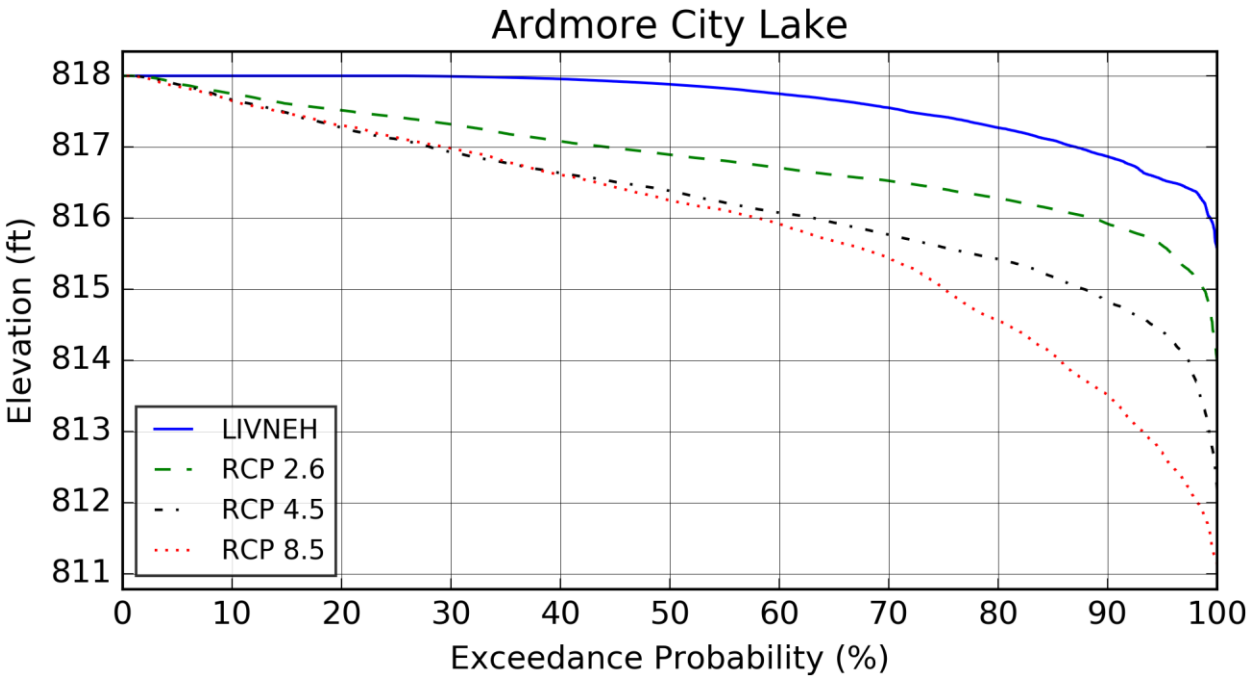
Appendix D – Reservoir Figures

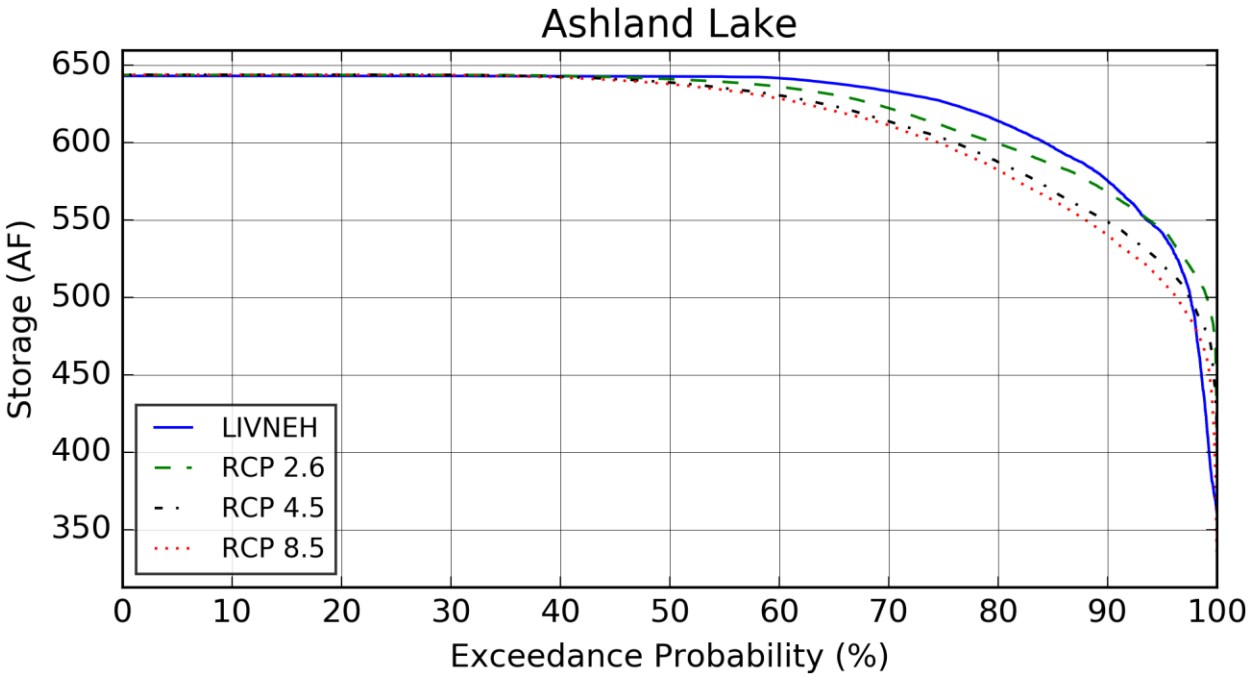
Figures below are frequency-duration curves (elevation and storage) for reservoirs in the spatially refined model region. Reservoirs without a published elevation-area-capacity table only have a storage-duration curve. The LIVNEH scenario data is from 1976 through 2005 and the climate projection scenarios data are from 2070 through 2099. The climate projection scenarios shown are daily averages across each RCP group. This approach is different than an average across each scenario's frequency-duration curve values. The approach used here may not represent an individual scenario's frequency-duration curve well, nor its high and low probability values.

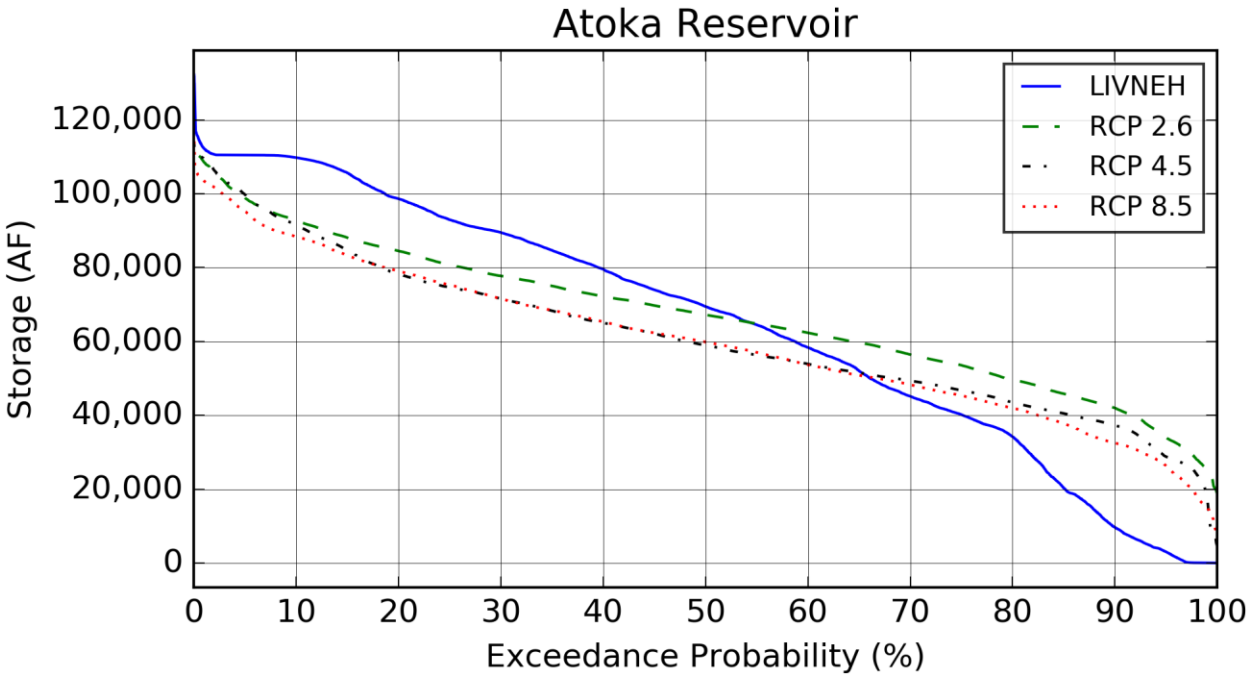


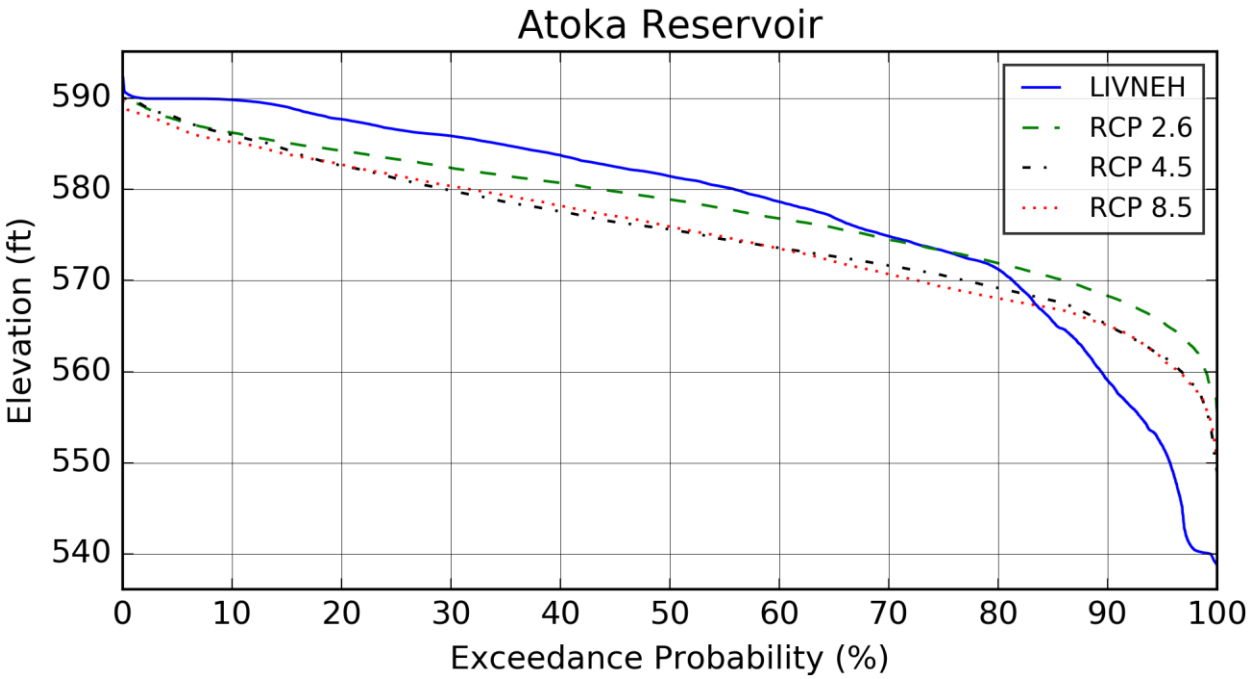


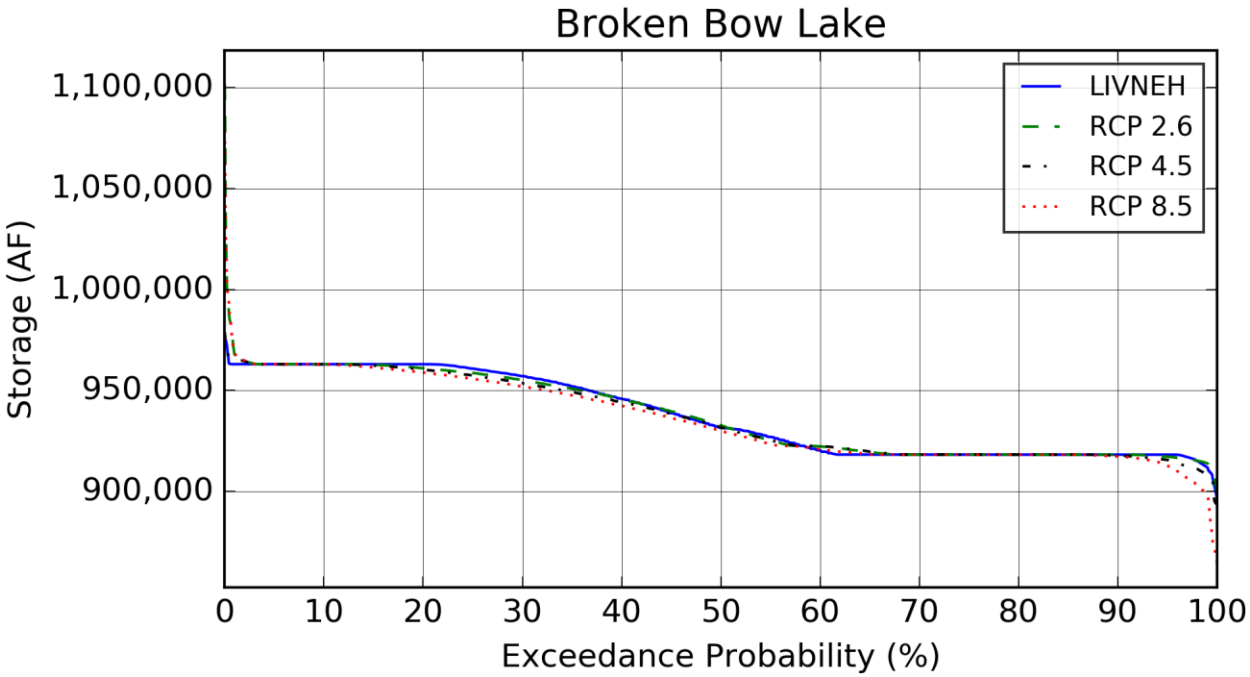

Ardmore City Lake
Storage (AF)
2,000
1,800
1,600
1,400
1,200
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

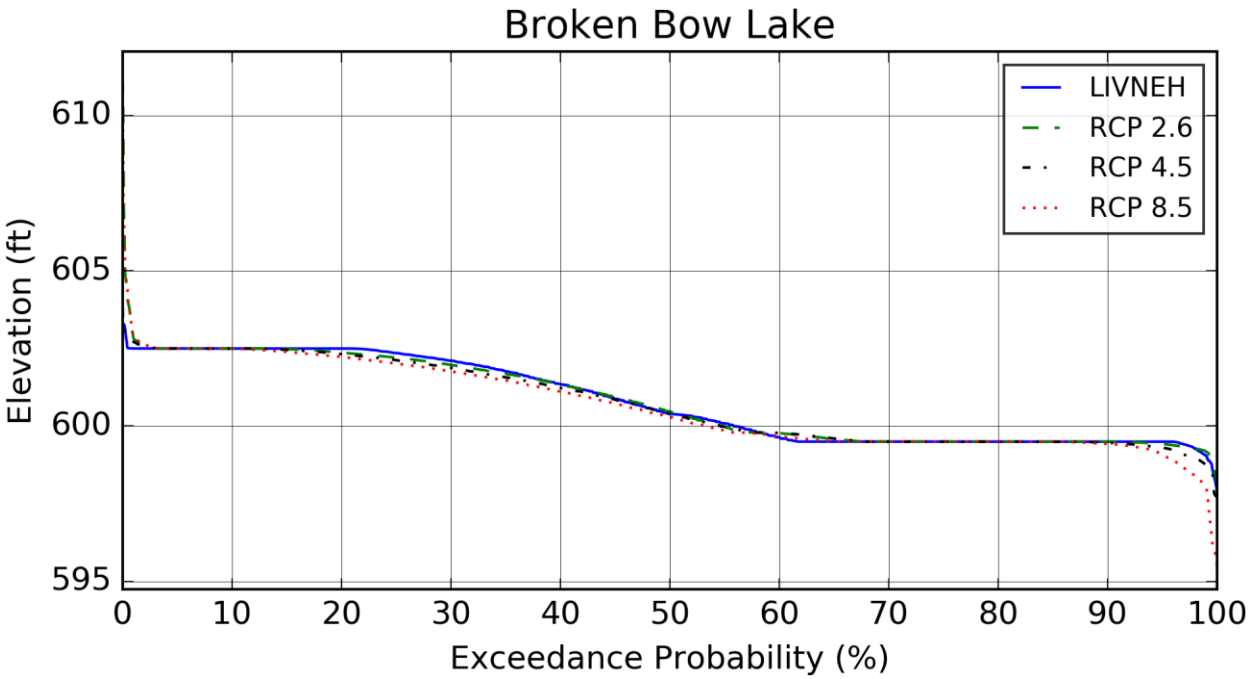

Ardmore City Lake
Elevation (ft)
818
817
816
815
814
813
812
811
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

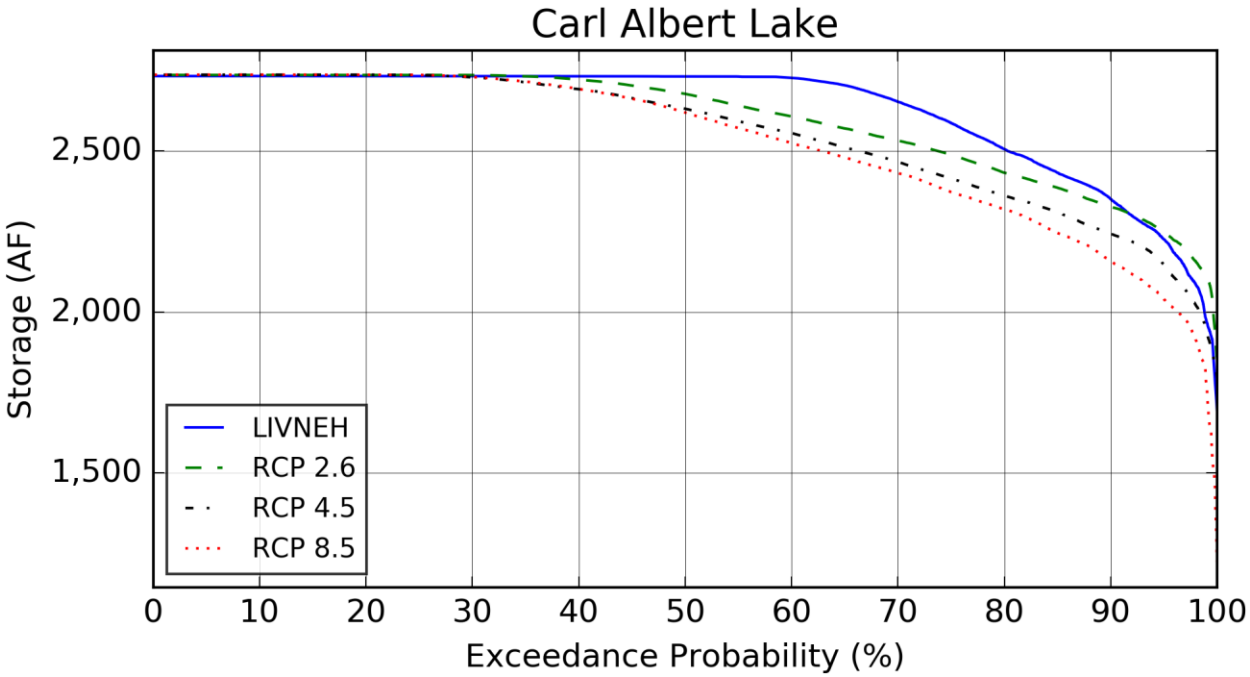

Ashland Lake
Storage (AF)
650
600
550
500
450
400
350
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

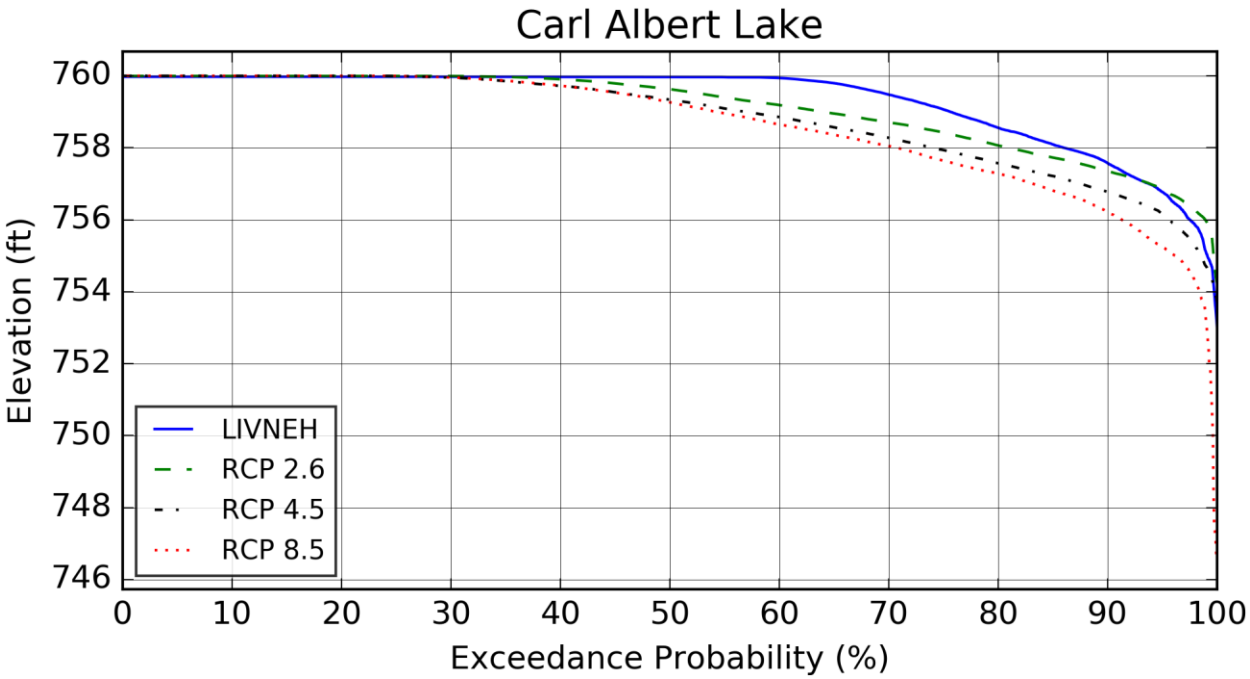

Atoka Reservoir
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

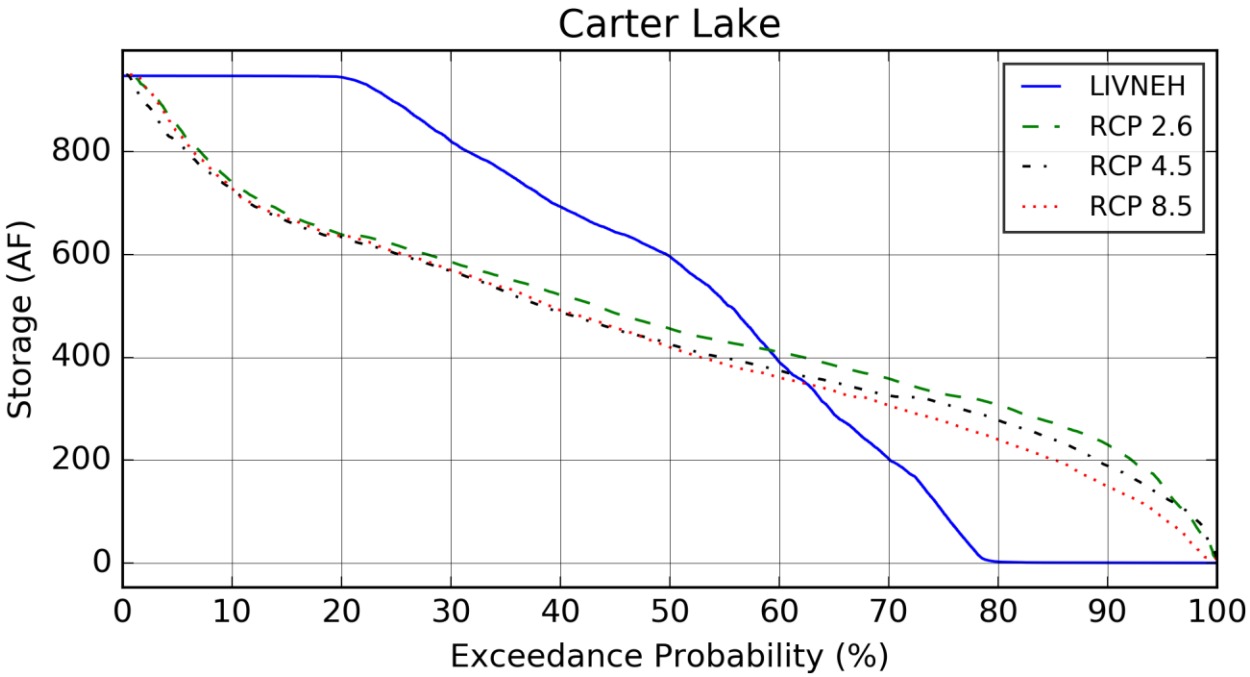

Atoka Reservoir
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Elevation (ft)
590
580
570
560
550
540
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

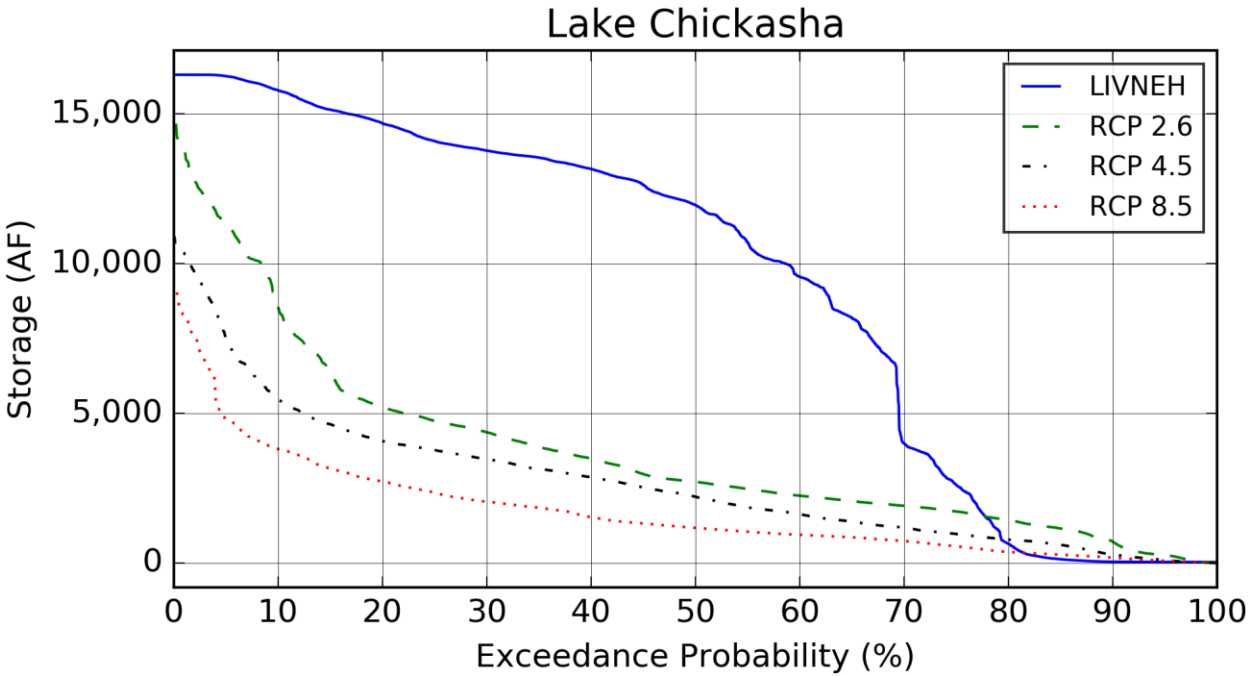

Broken Bow Lake
Storage (AF)
1,100,000
1,050,000
1,000,000
950,000
900,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

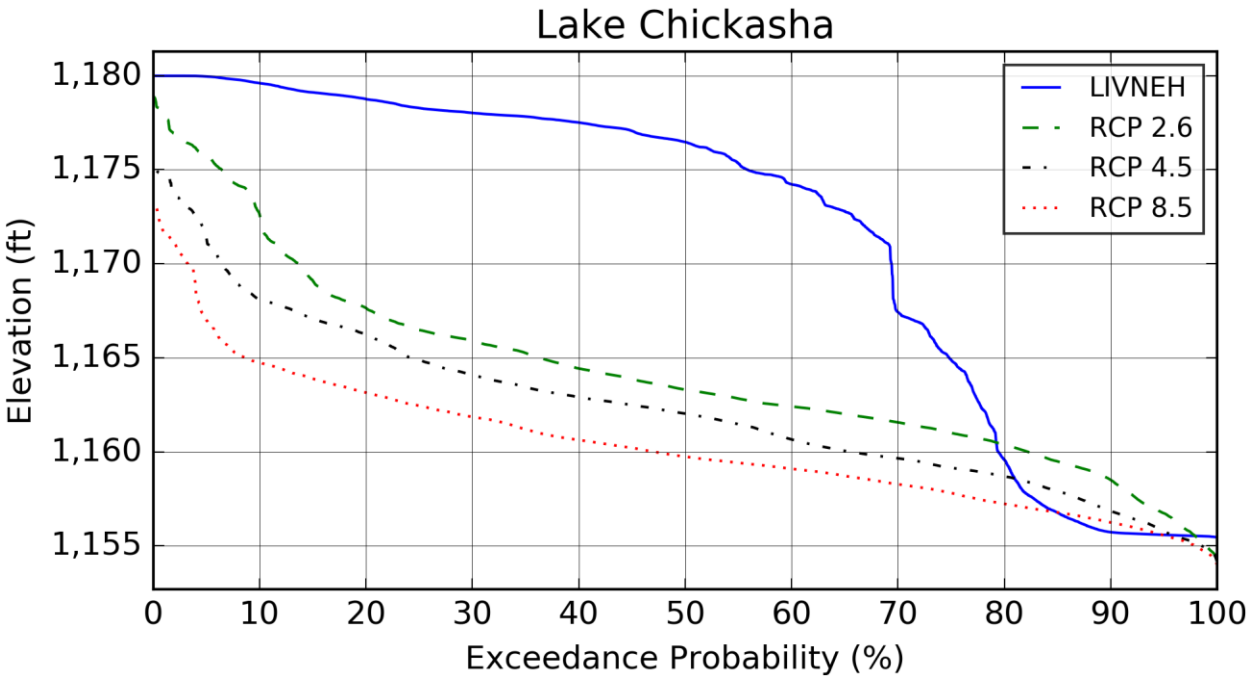

Broken Bow Lake
Elevation (ft)
610
605
600
595
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

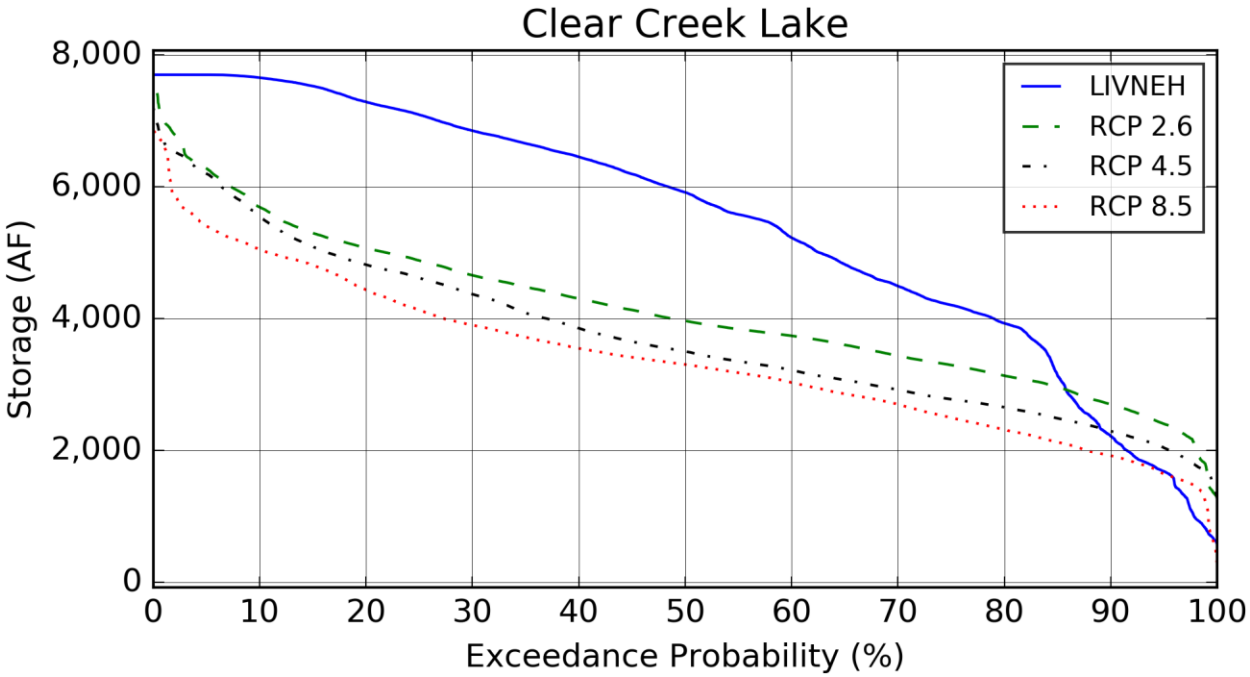

Carl Albert Lake
Storage (AF)
2,500
2,000
1,500
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

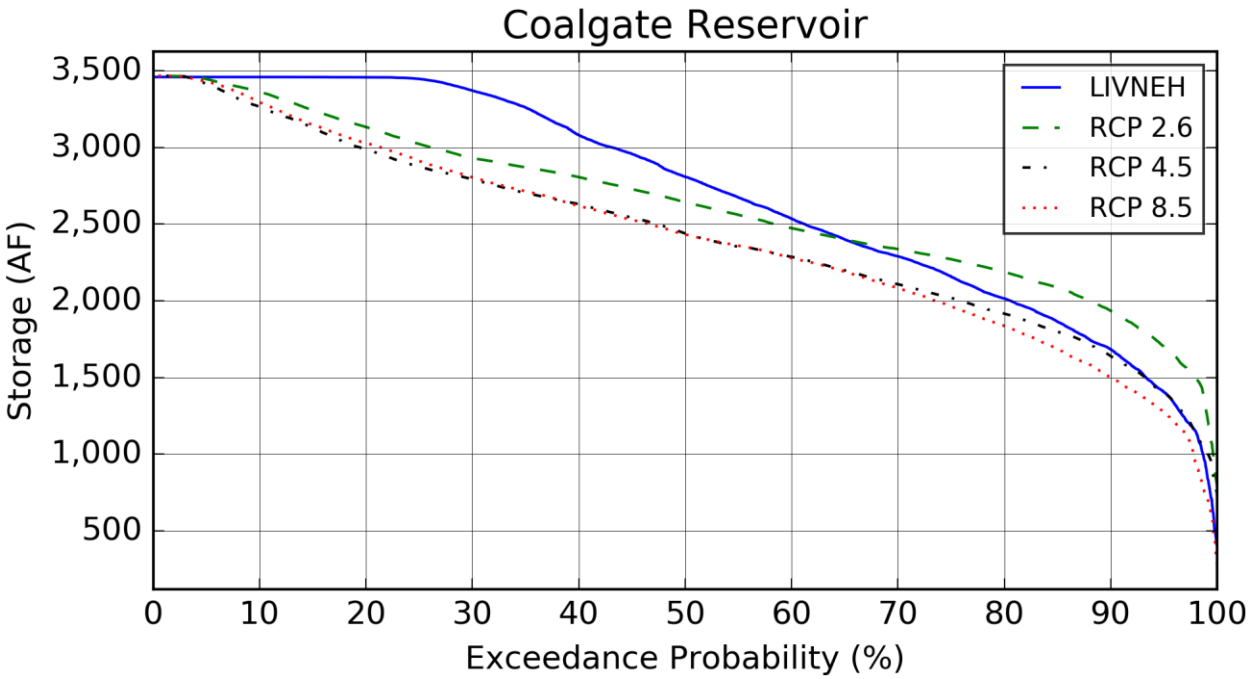

Carl Albert Lake
Elevation (ft)
760
758
756
754
752
750
748
746
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

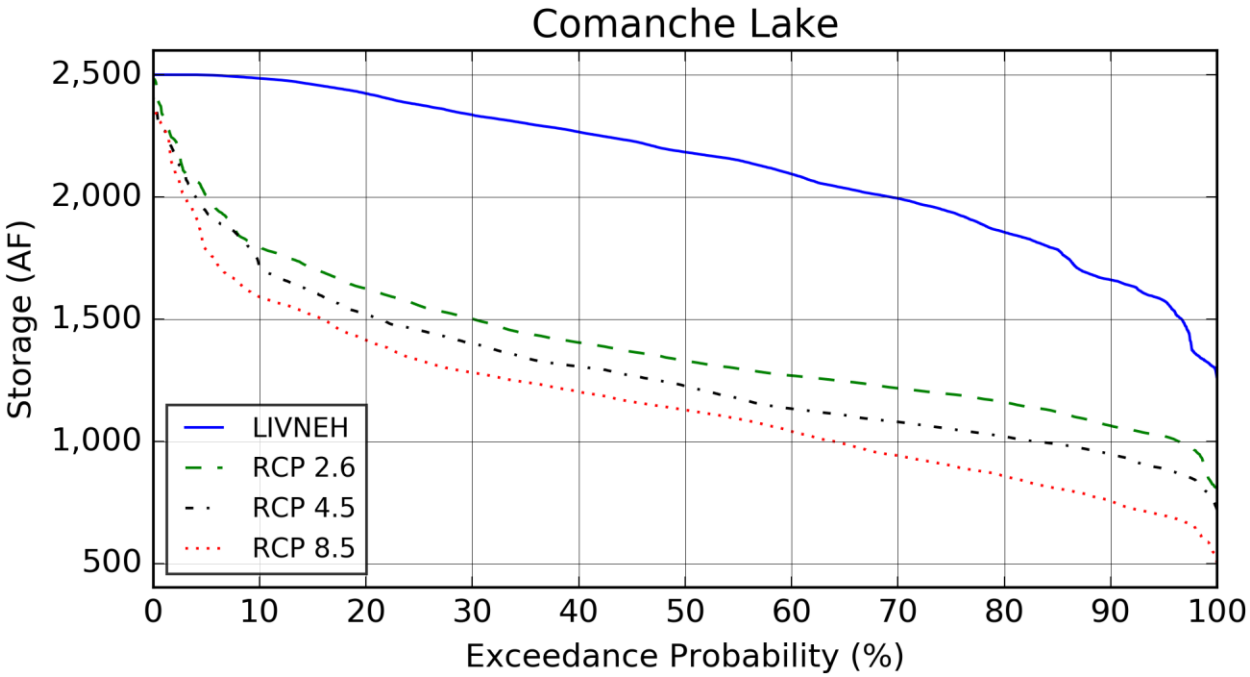

Carter Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
0
200
400
600
800
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

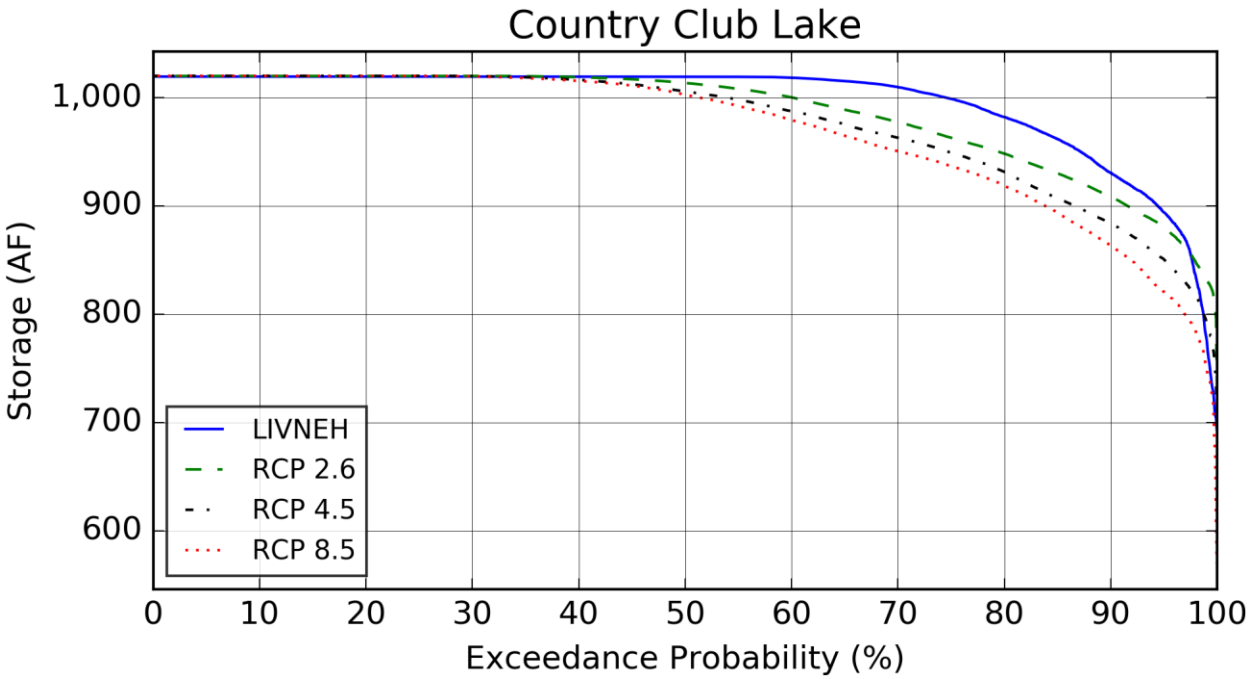

Lake Chickasha
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
15,000
10,000
5,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

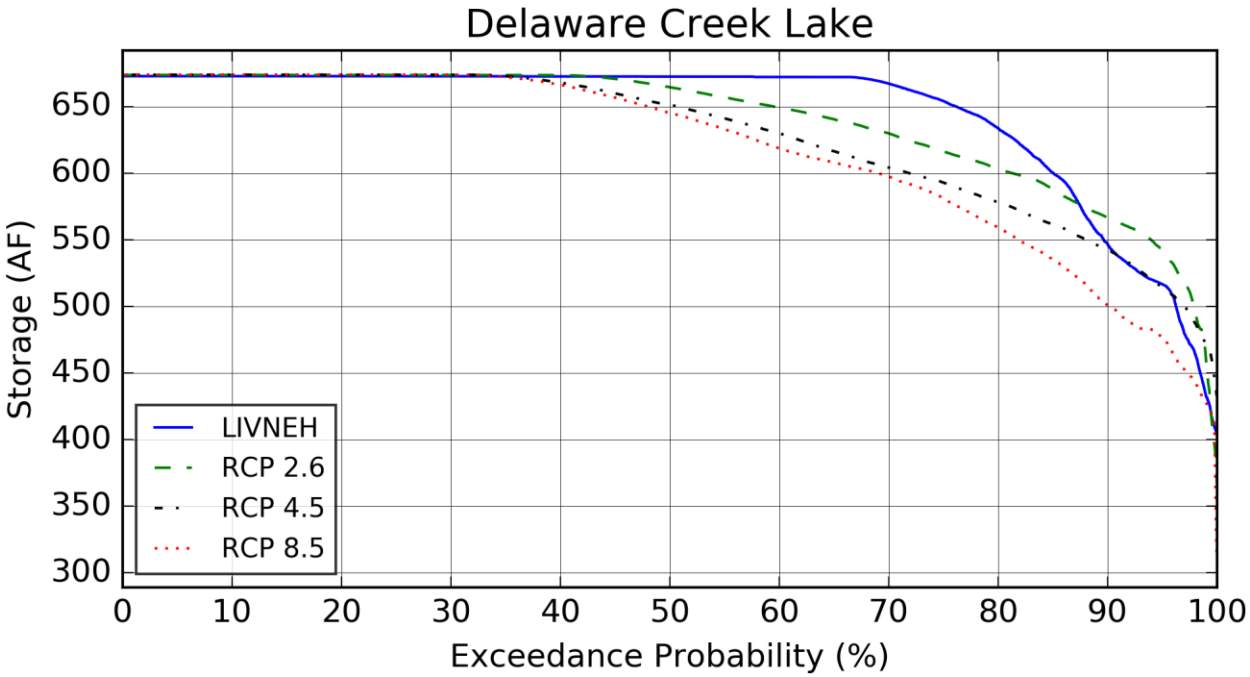

Lake Chickasha
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Elevation (ft)
1,180
1,175
1,170
1,165
1,160
1,155
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

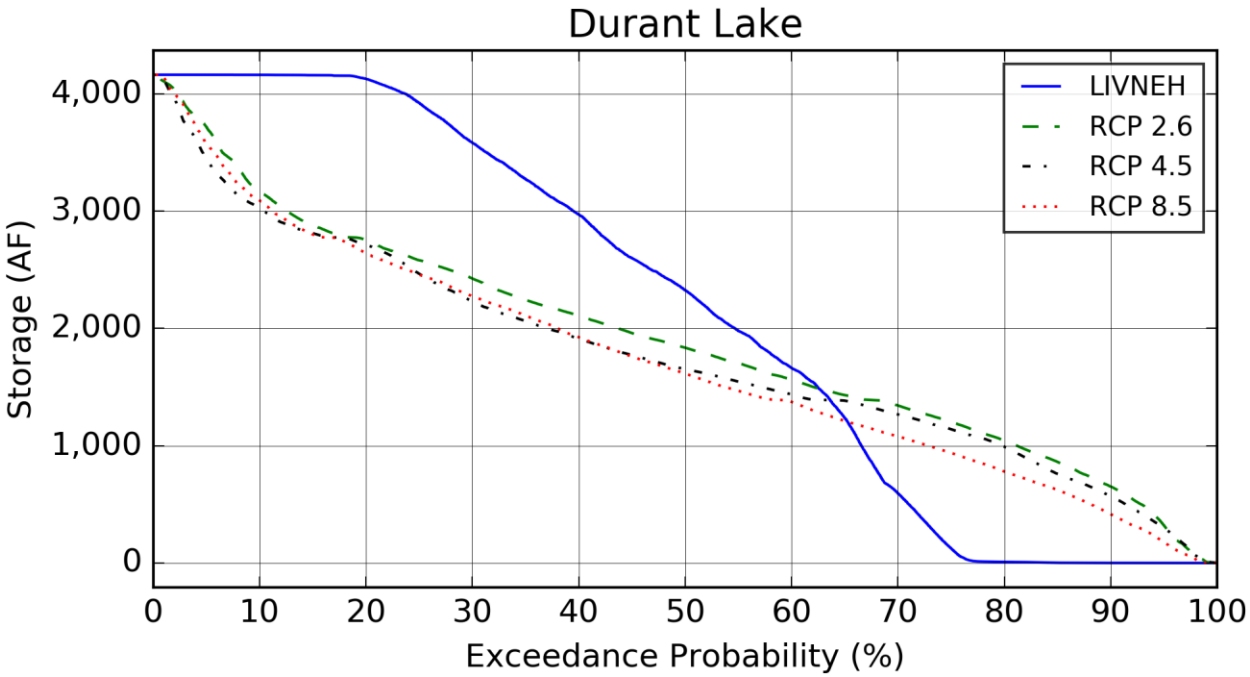

Clear Creek Lake
Storage (AF)
8,000
6,000
4,000
2,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

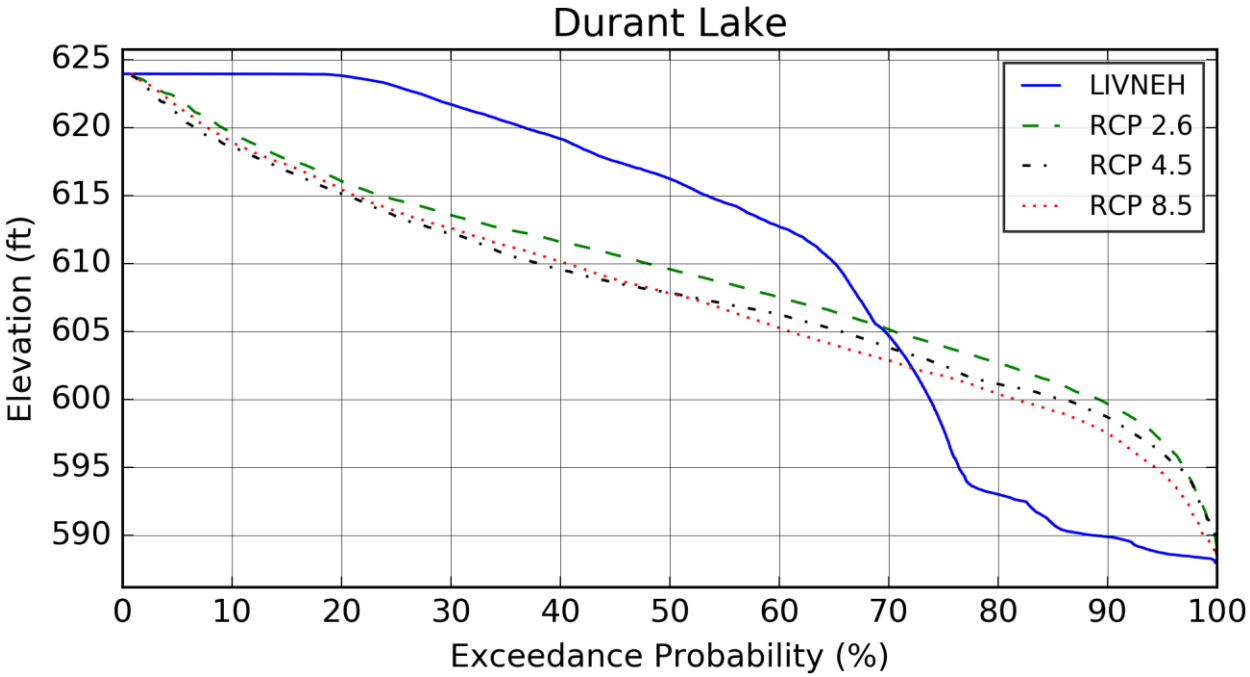

Coalgate Reservoir
Storage (AF)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

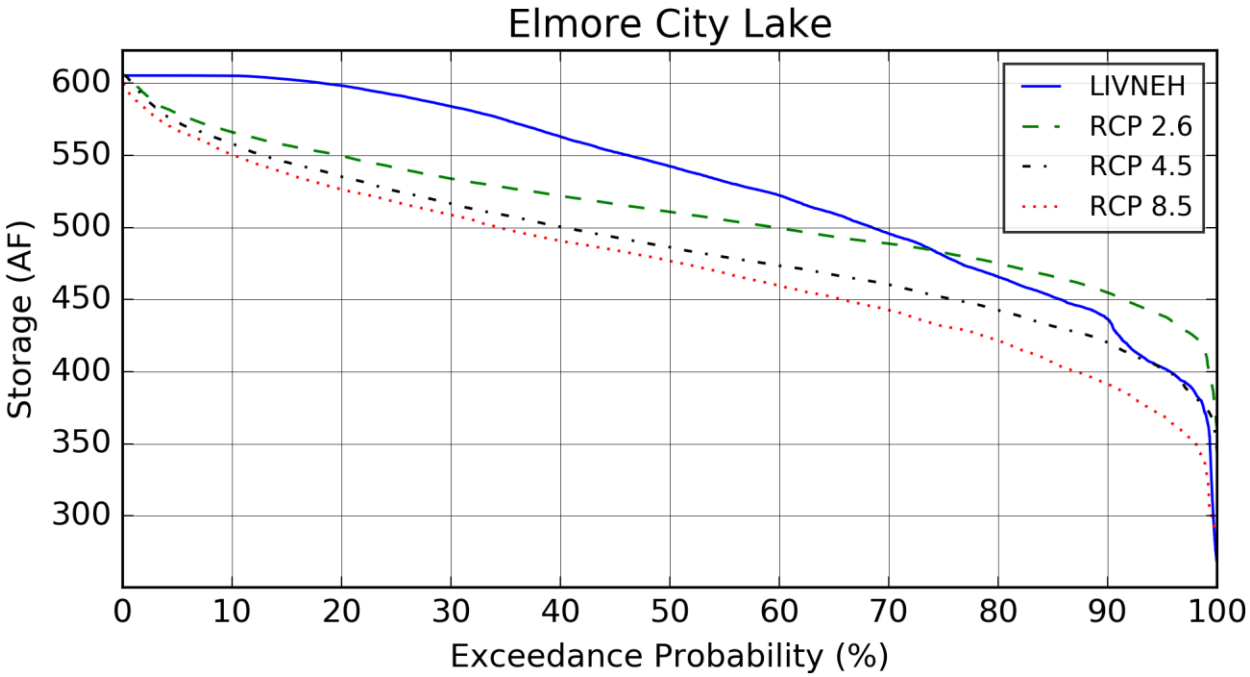

Comanche Lake
Storage (AF)
2,500
2,000
1,500
1,000
500
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

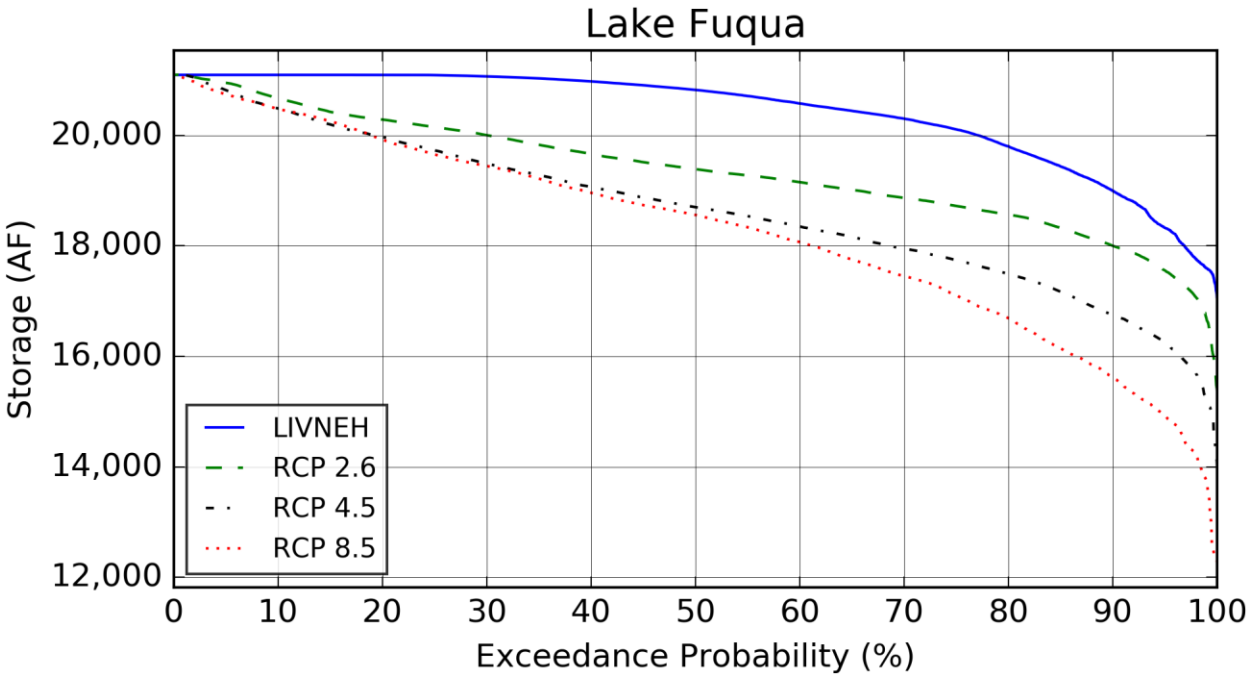

Country Club Lake
Storage (AF)
1,000
900
800
700
600
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

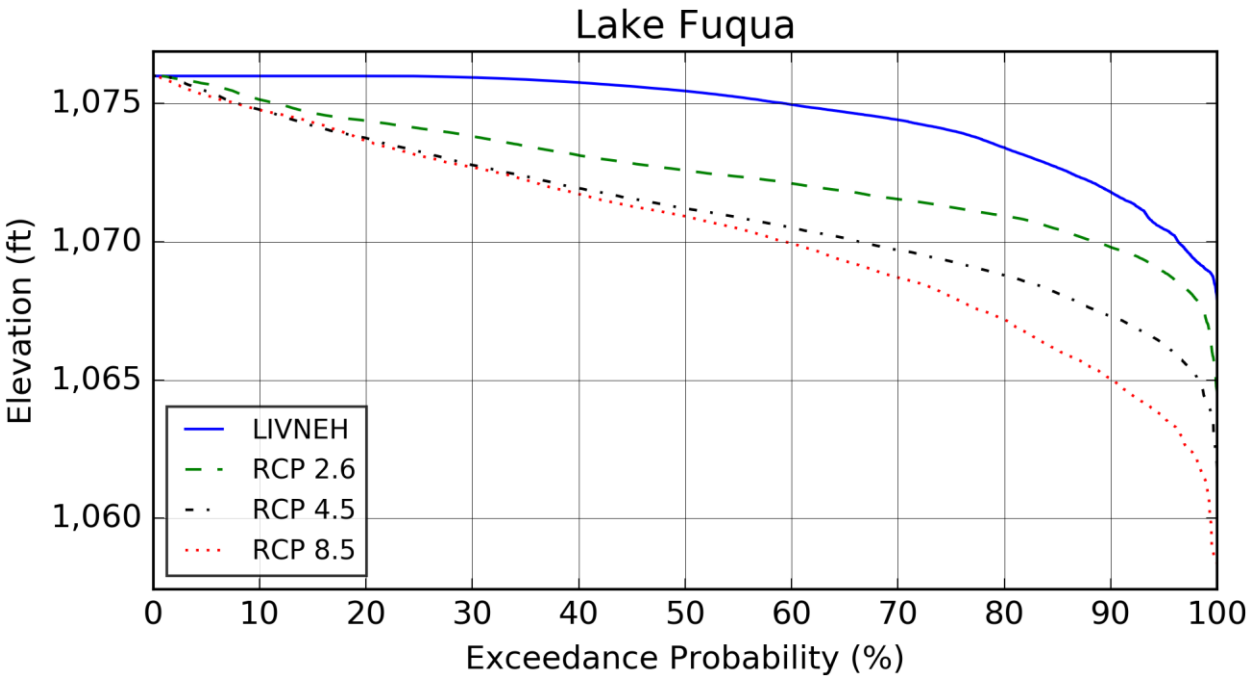

Delaware Creek Lake
Storage (AF)
650
600
550
500
450
400
350
300
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

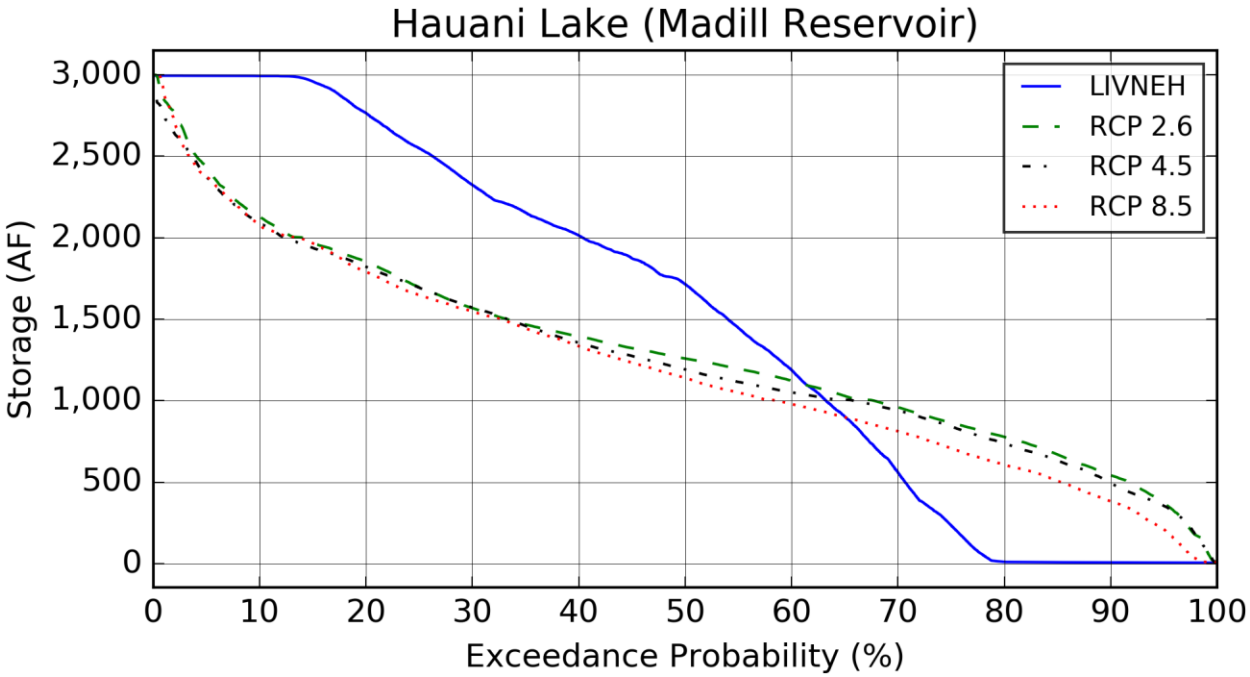

Durant Lake
Storage (AF)
4,000
3,000
2,000
1,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

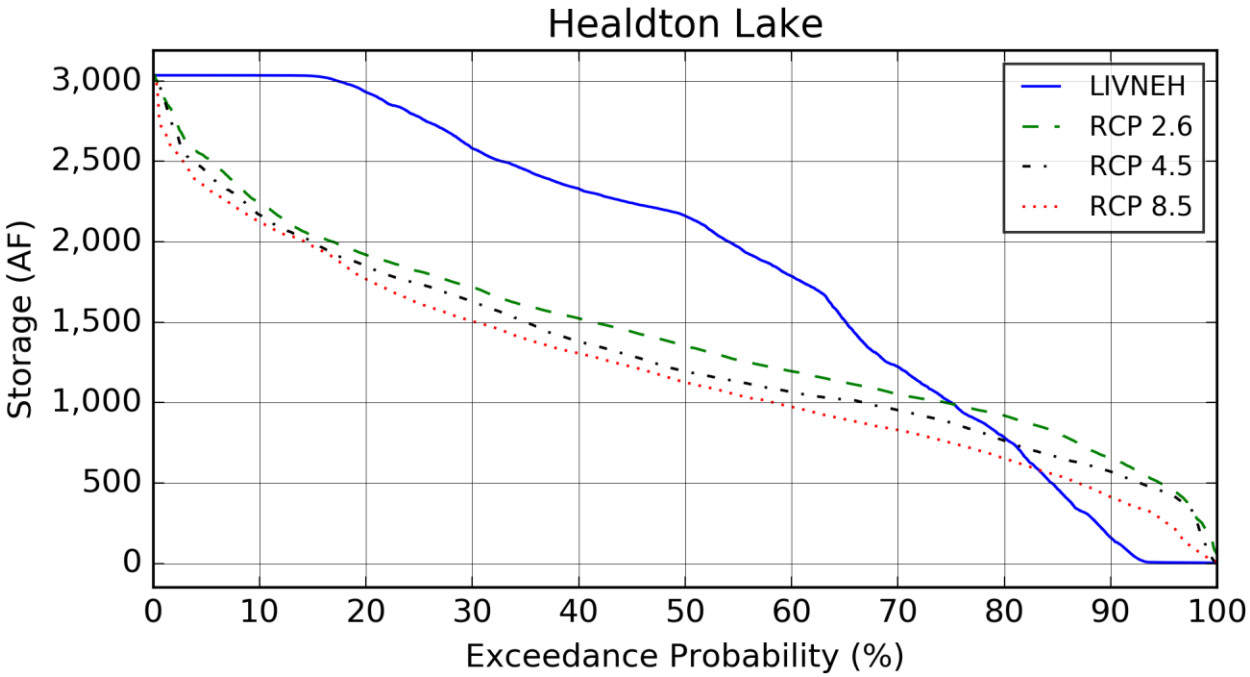

Durant Lake
Elevation (ft)
625
620
615
610
605
600
595
590
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

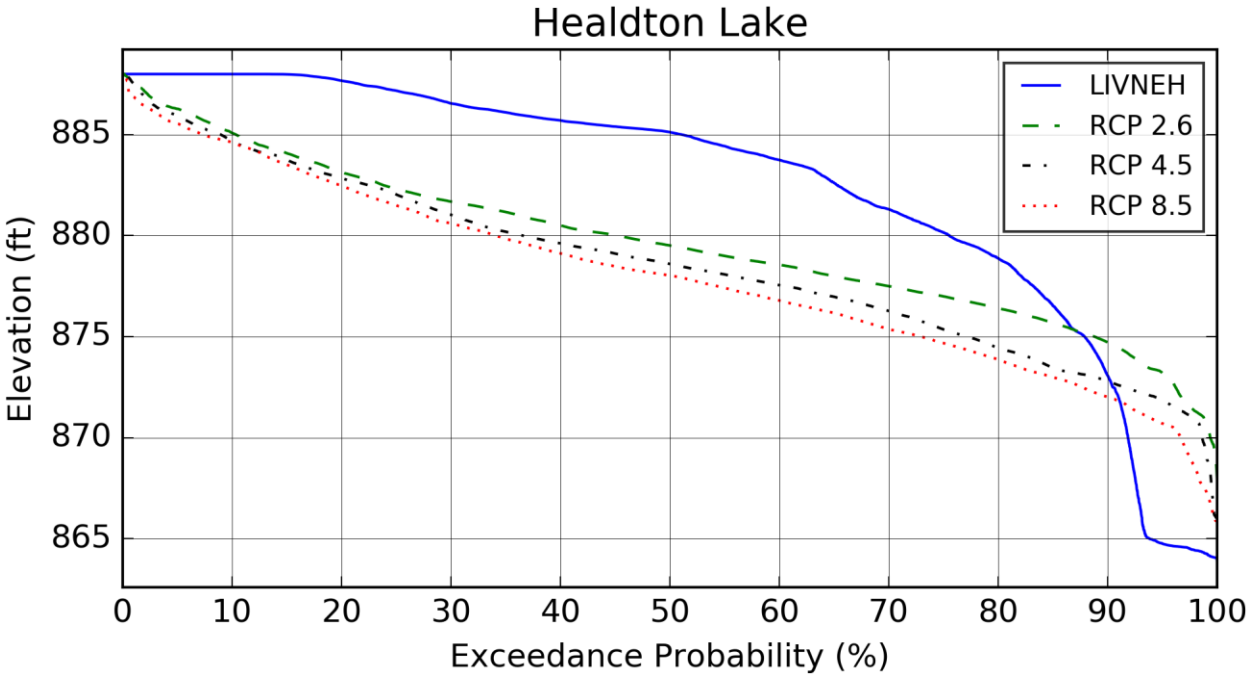

Elmore City Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
600
550
500
450
400
350
300
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

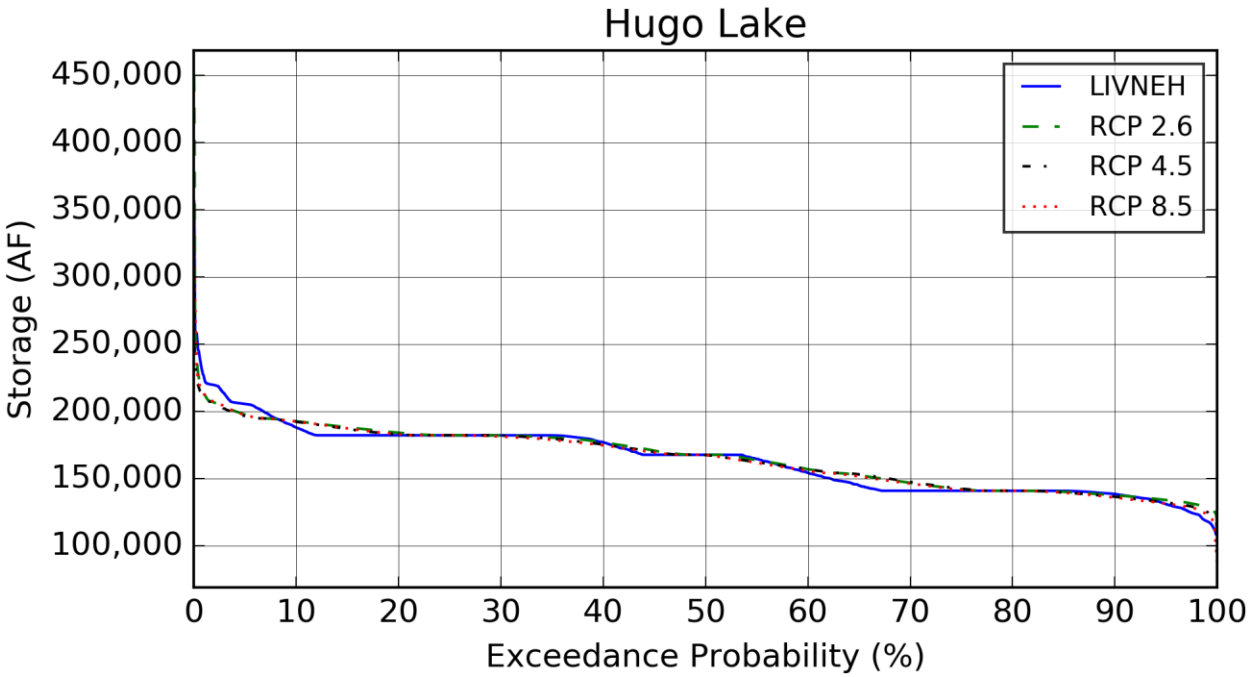

Lake Fuqua
Storage (AF)
20,000
18,000
16,000
14,000
12,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

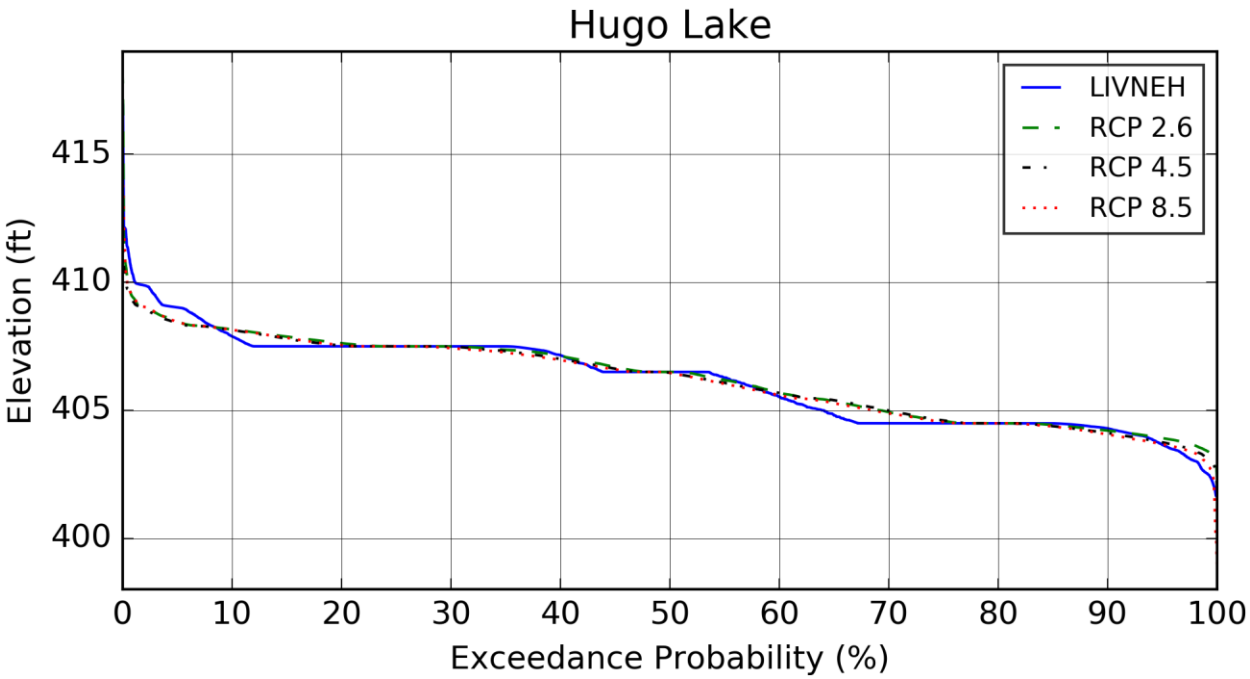

Lake Fuqua
Elevation (ft)
1,075
1,070
1,065
1,060
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

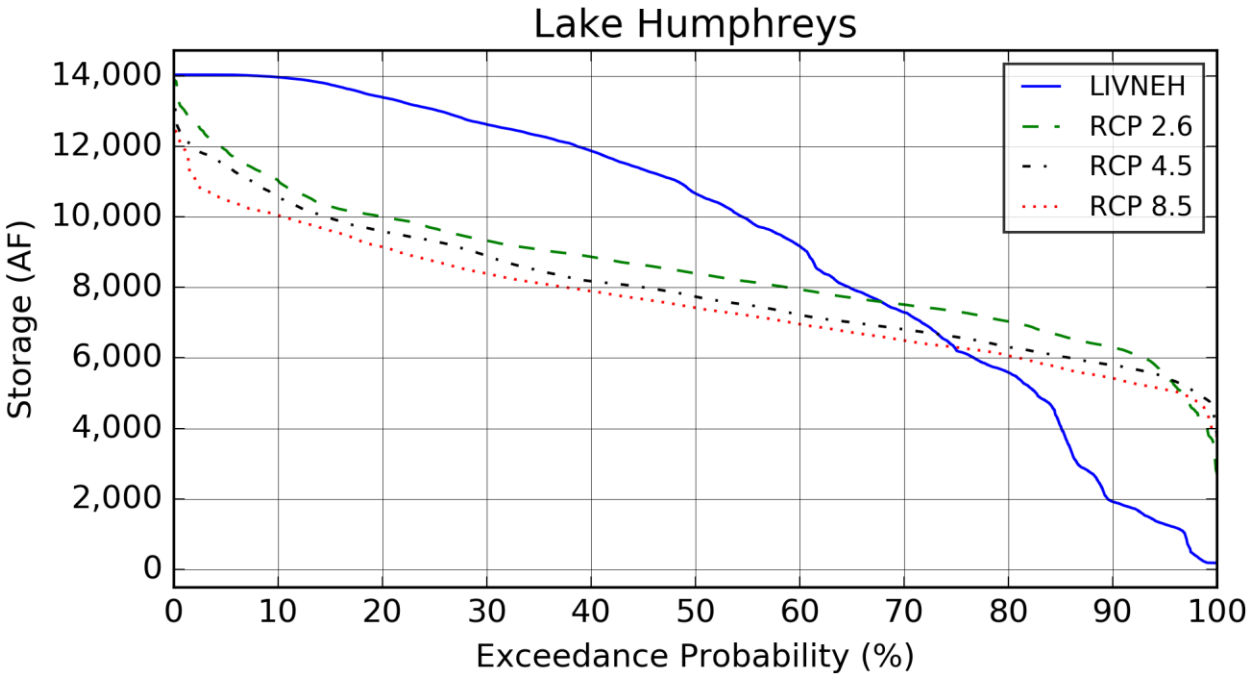

Hauani Lake (Madill Reservoir)
Storage (AF)
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

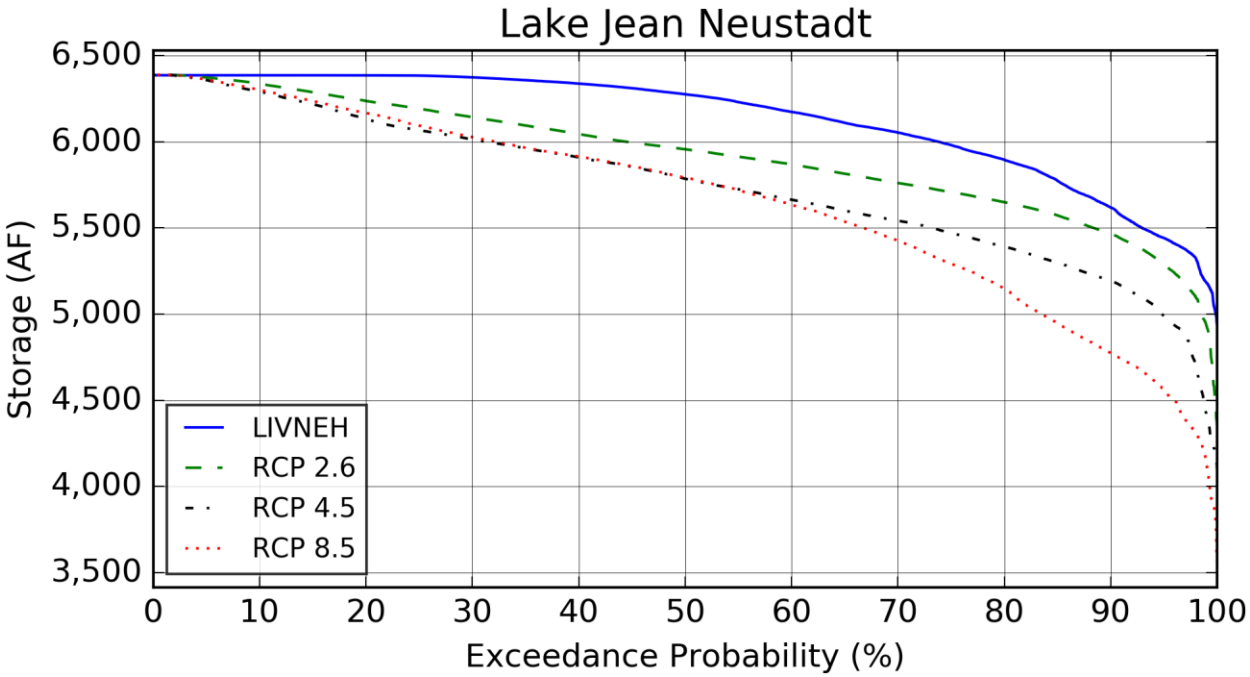

Healdton Lake
Storage (AF)
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

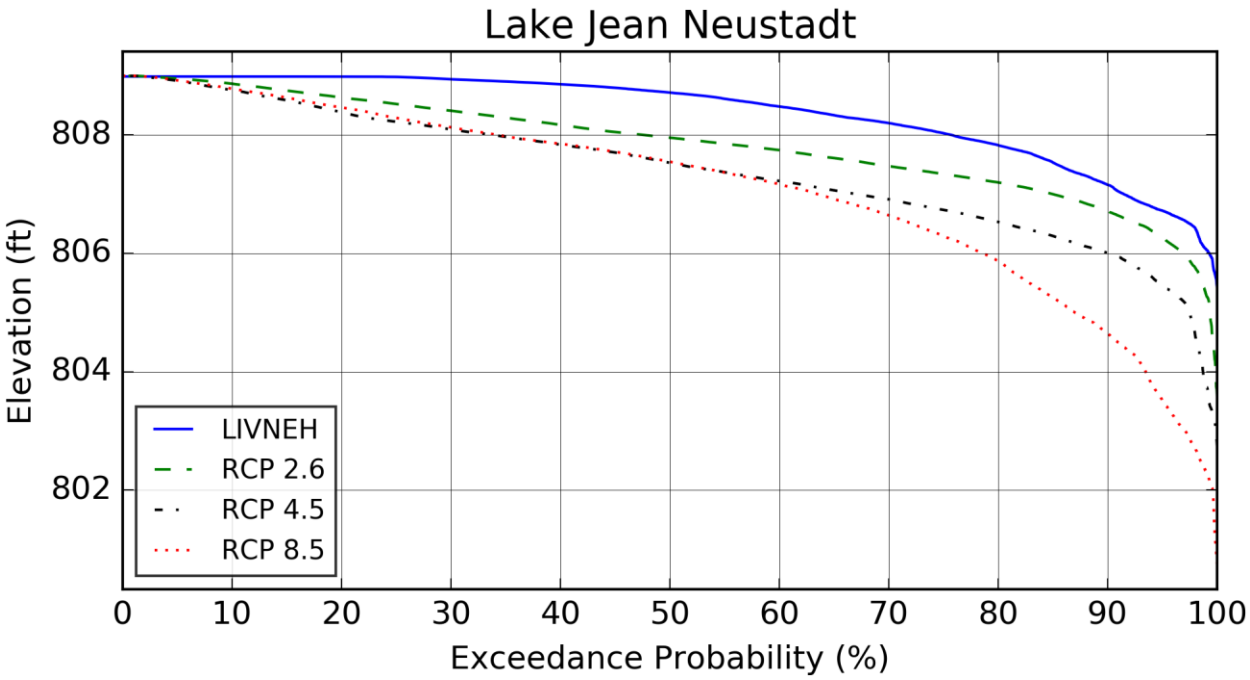

Healdton Lake
Elevation (ft)
885
880
875
870
865
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

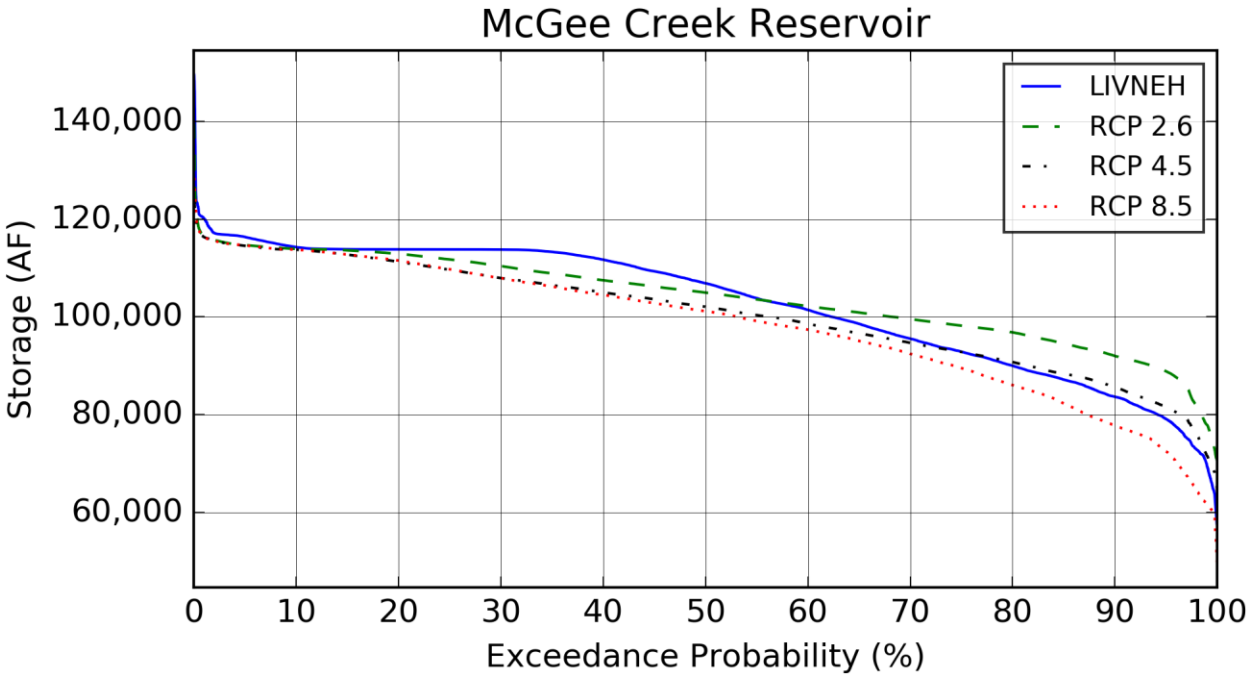

Hugo Lake
Storage (AF)
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

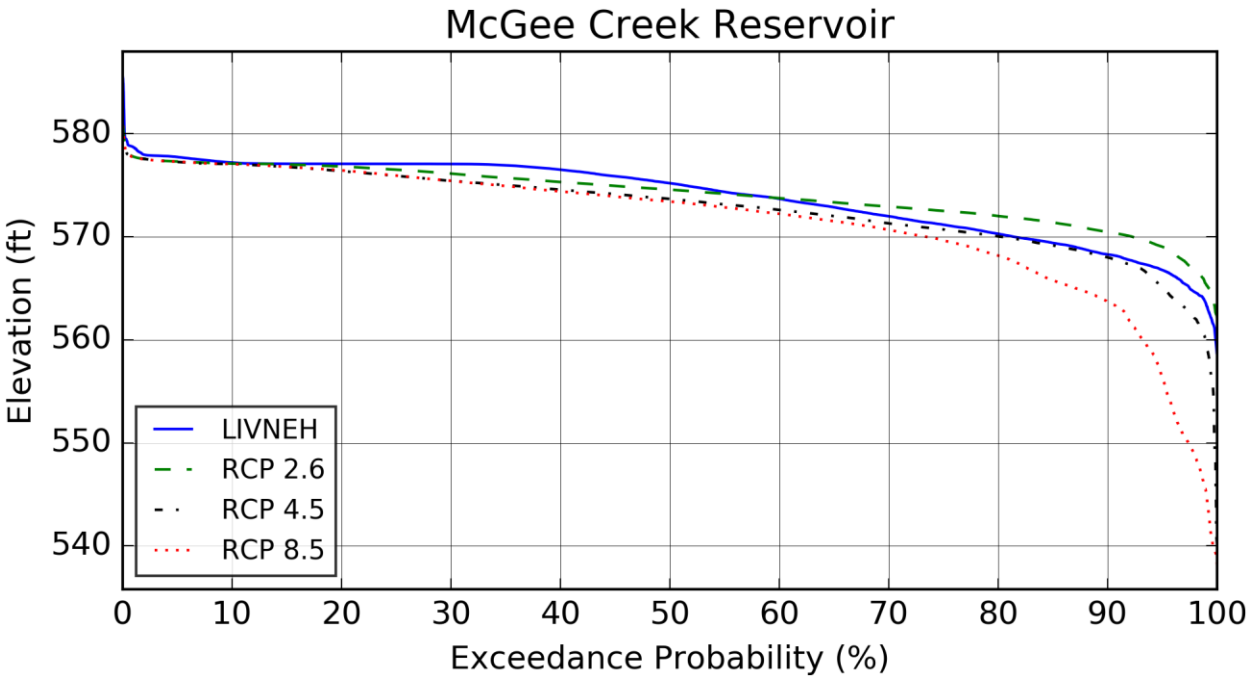

Hugo Lake
Elevation (ft)
415
410
405
400
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

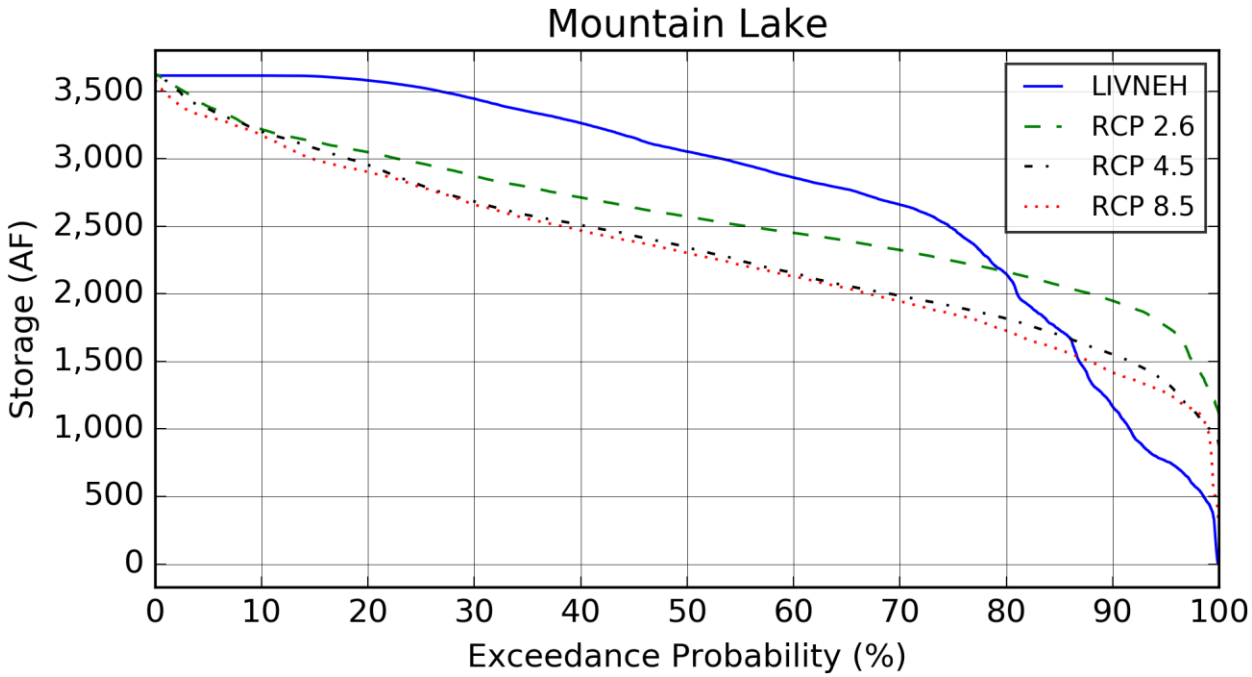

Lake Humphreys
Storage (AF)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

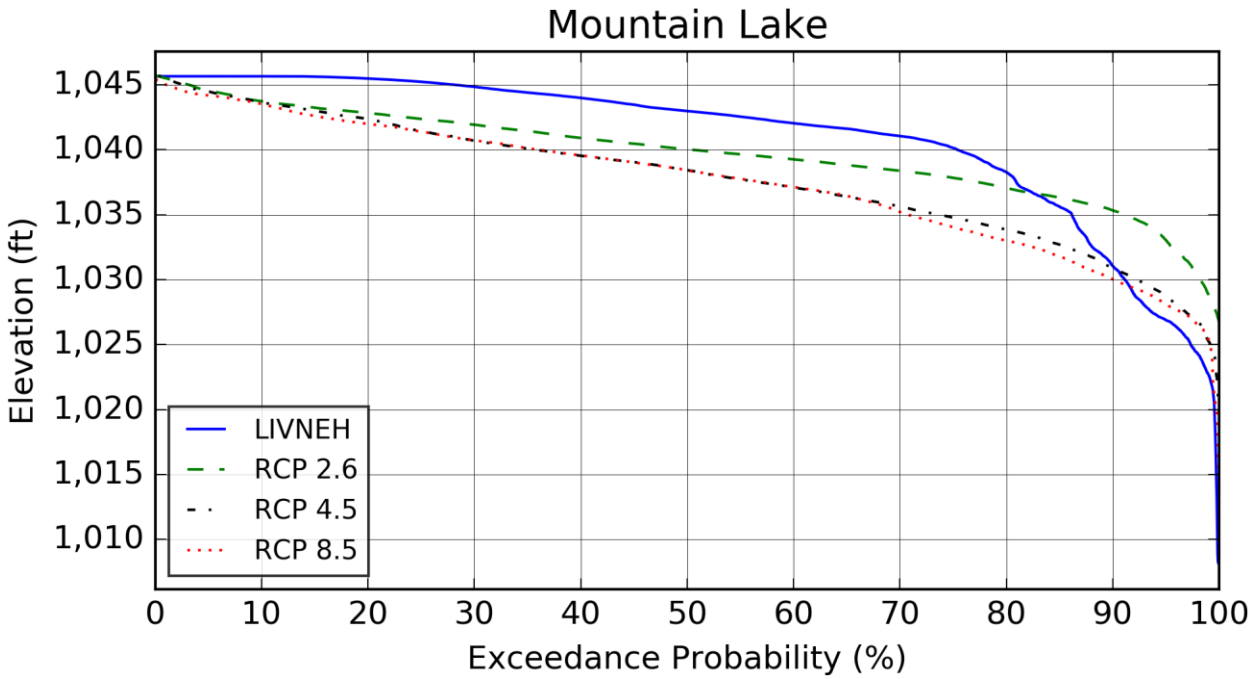

Lake Jean Neustadt
Storage (AF)
6,500
6,000
5,500
5,000
4,500
4,000
3,500
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

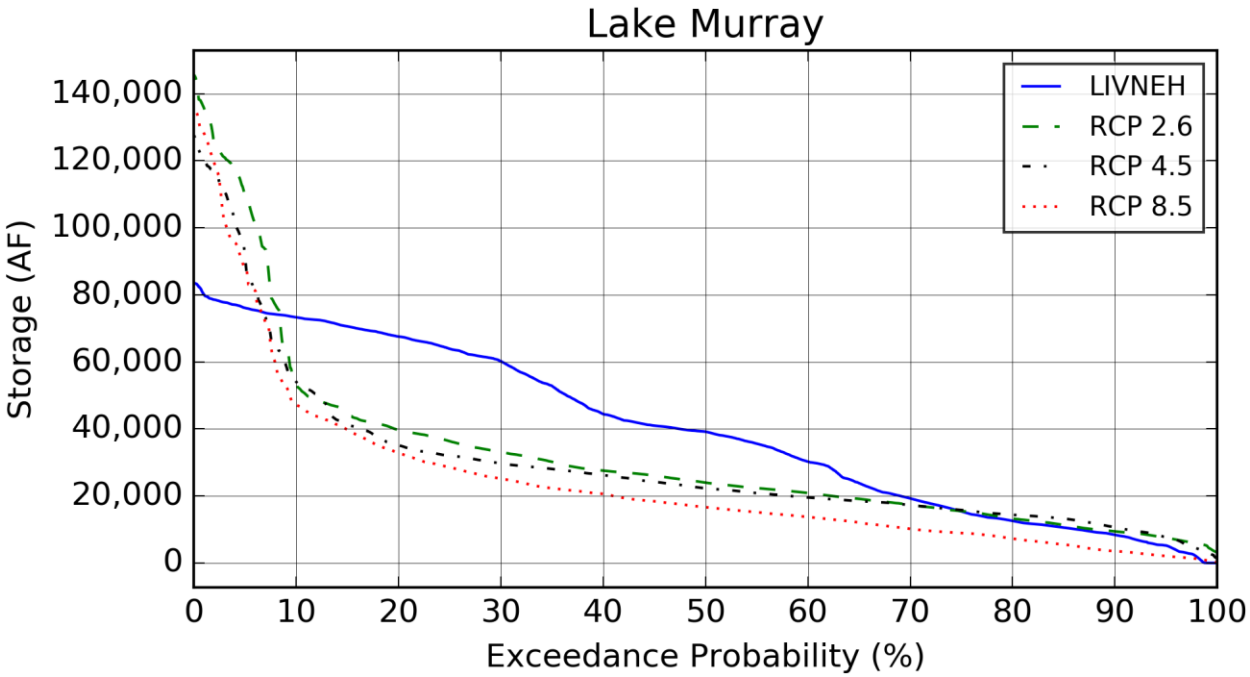

Lake Jean Neustadt
Elevation (ft)
808
806
804
802
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

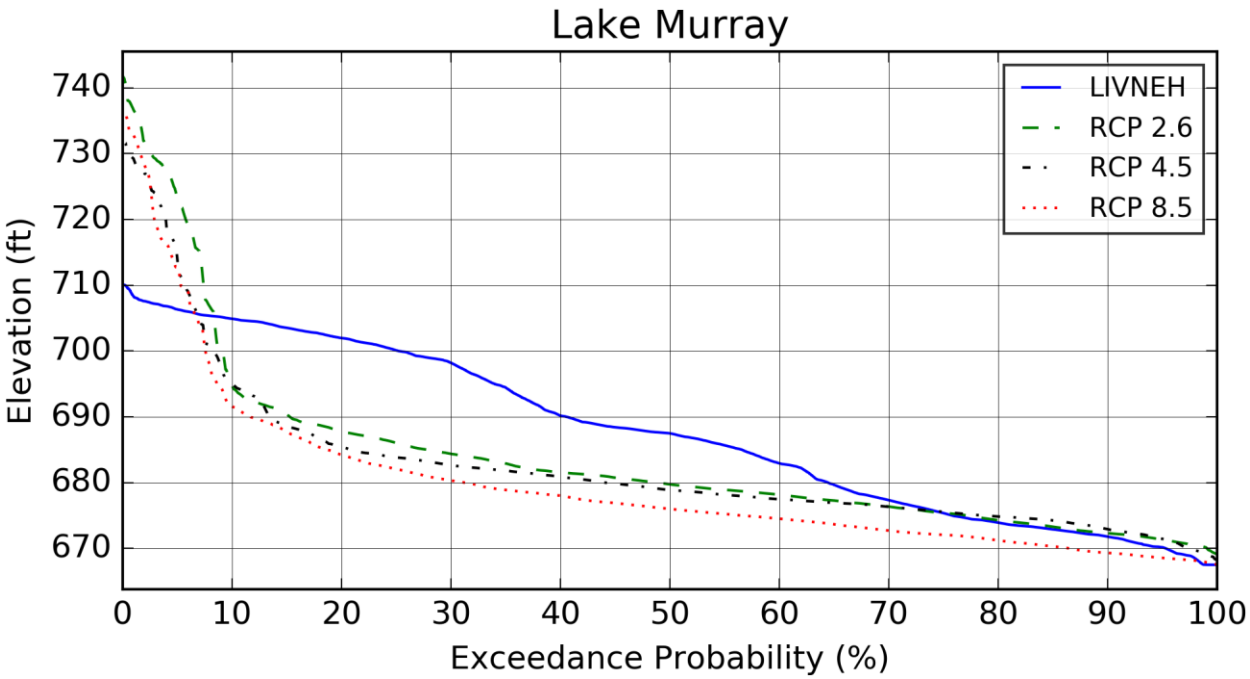

McGee Creek Reservoir
Storage (AF)
140,000
120,000
100,000
80,000
60,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

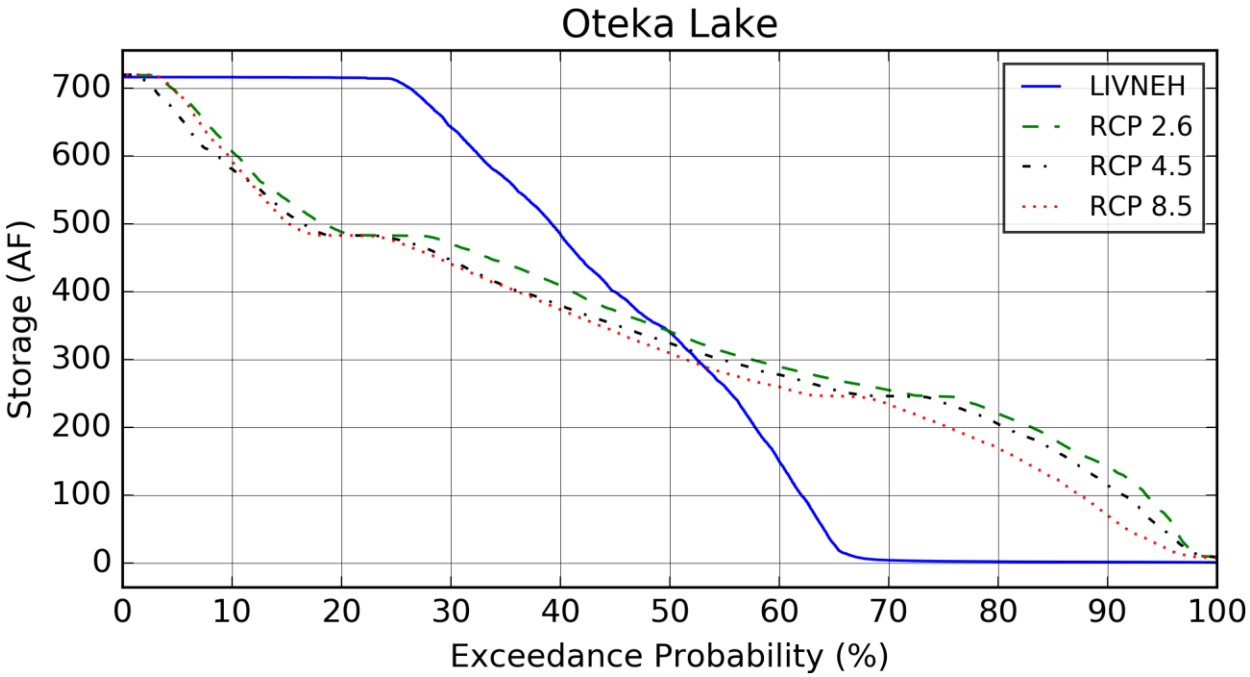

McGee Creek Reservoir
Elevation (ft)
580
570
560
550
540
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

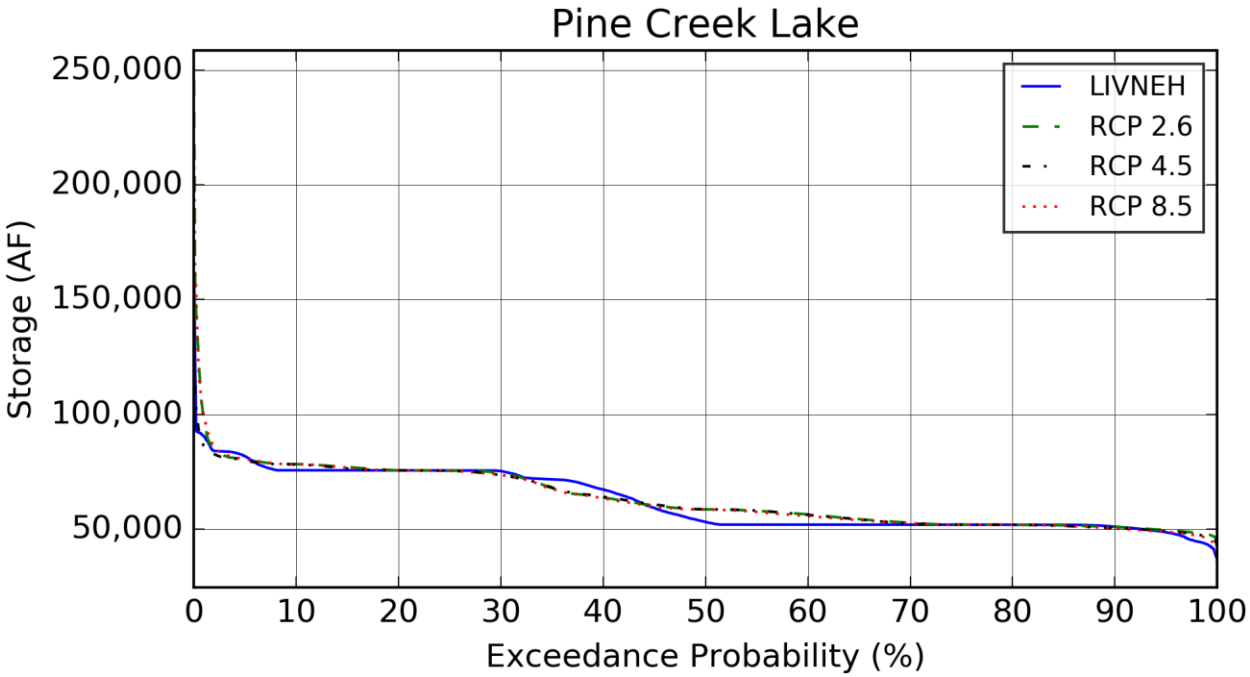

Mountain Lake
Storage (AF)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

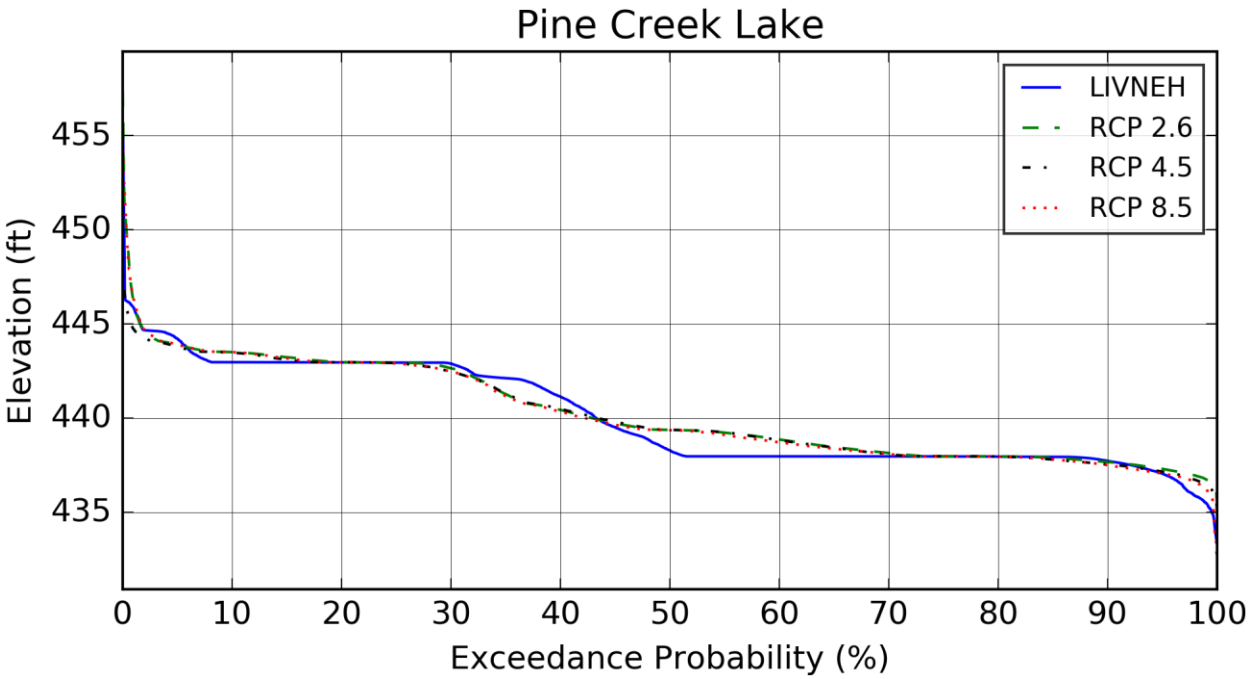

Mountain Lake
Elevation (ft)
1,045
1,040
1,035
1,030
1,025
1,020
1,015
1,010
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

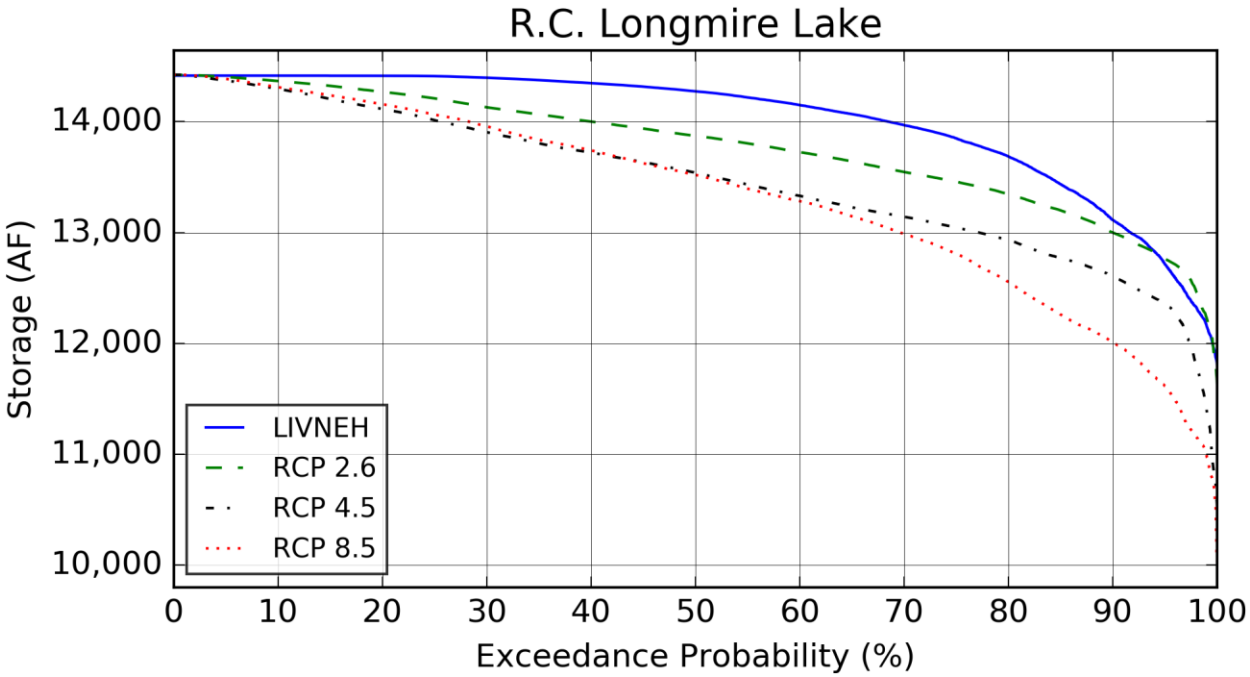

Lake Murray
Storage (AF)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

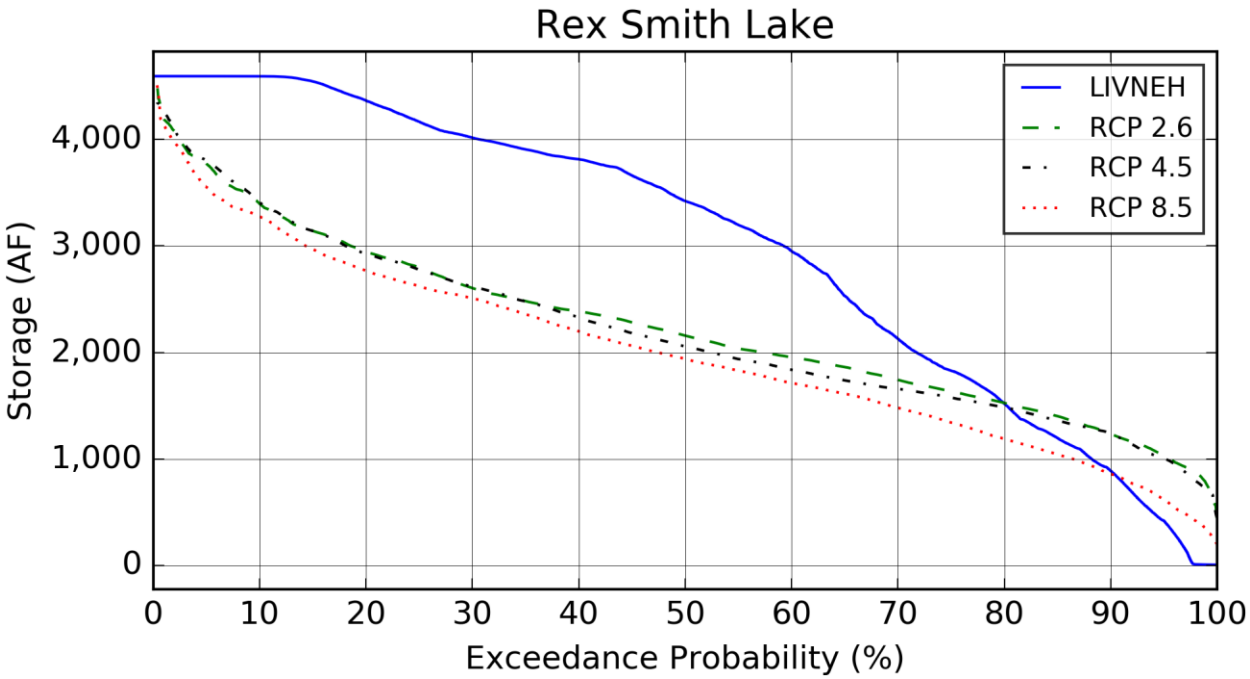

Lake Murray
Elevation (ft)
740
730
720
710
700
690
680
670
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

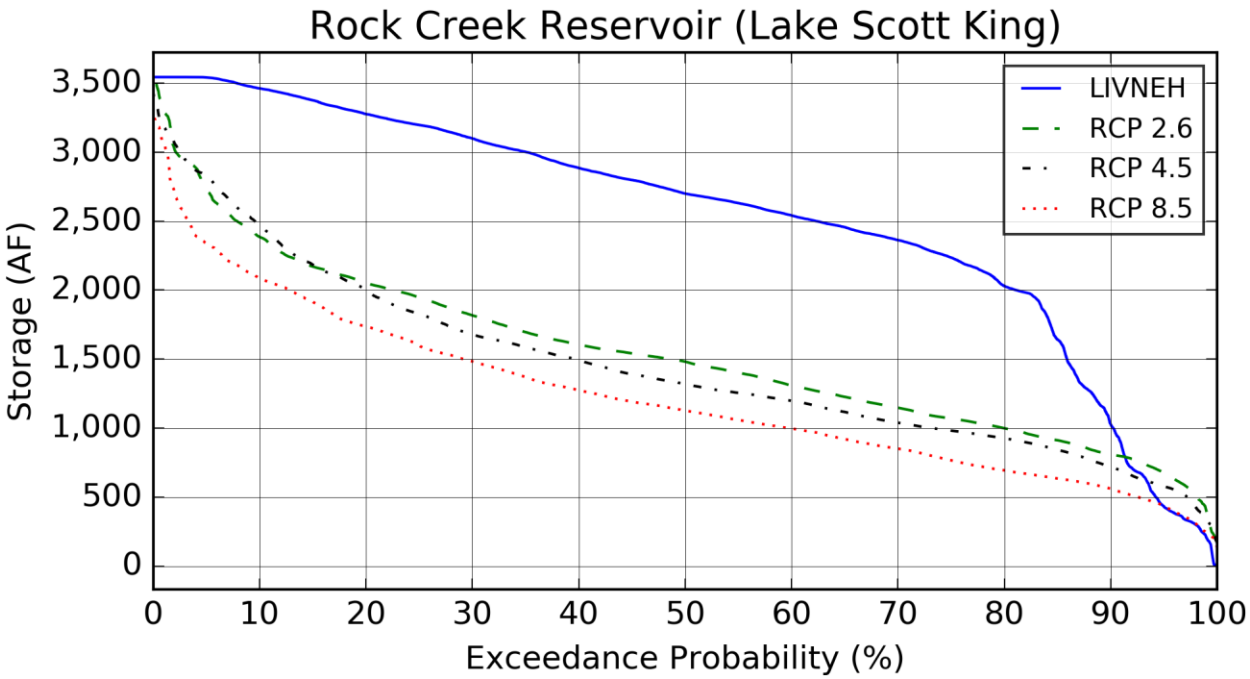

Oteka Lake
Storage (AF)
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60
70
80
90
100

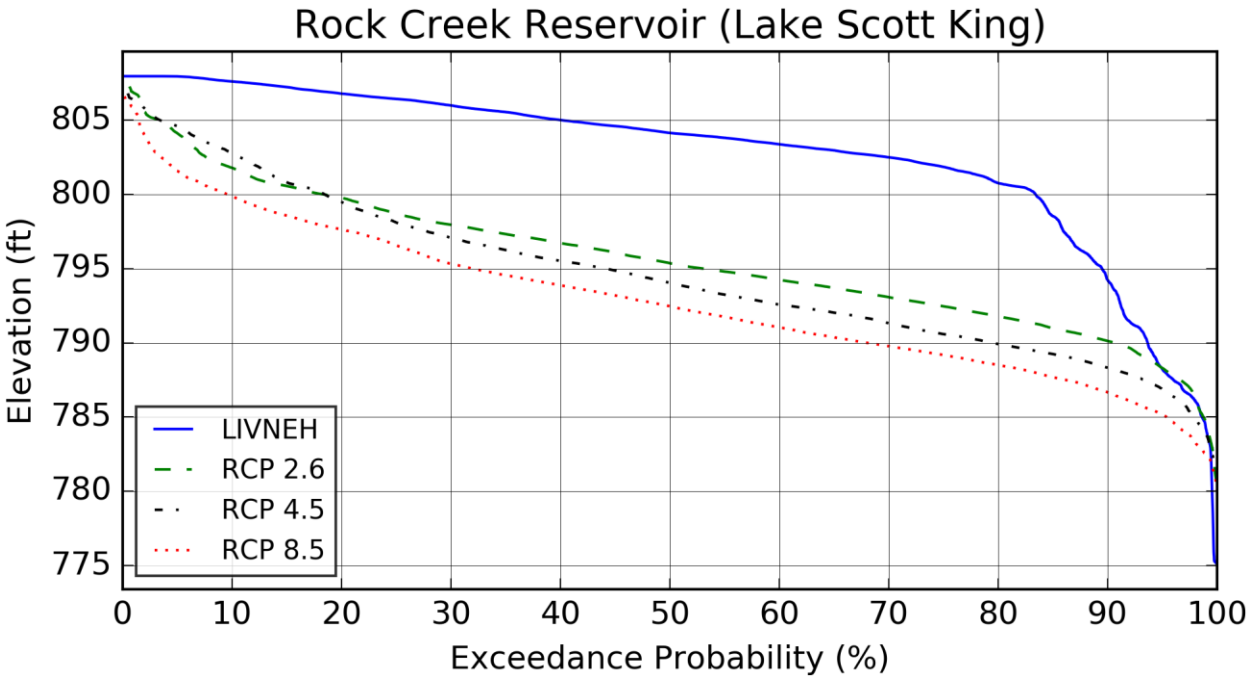

Pine Creek Lake
250,000
200,000
150,000
100,000
50,000
Storage (AF)
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

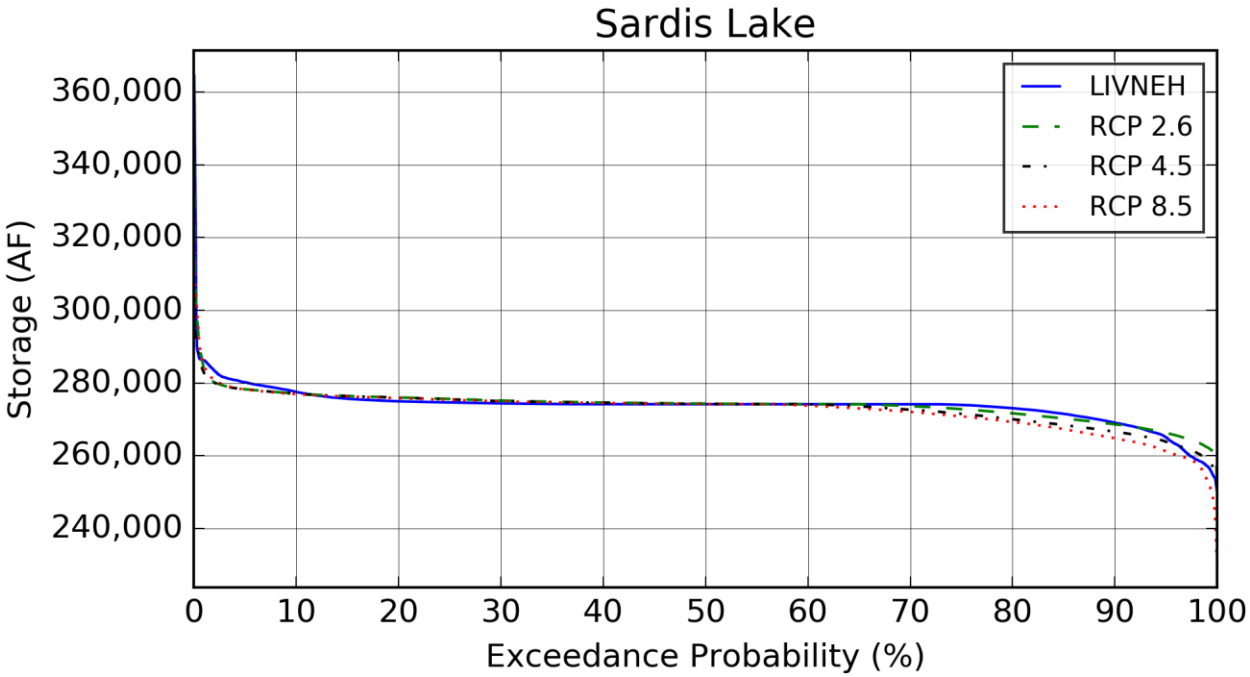

Pine Creek Lake
455
450
445
440
435
Elevation (ft)
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

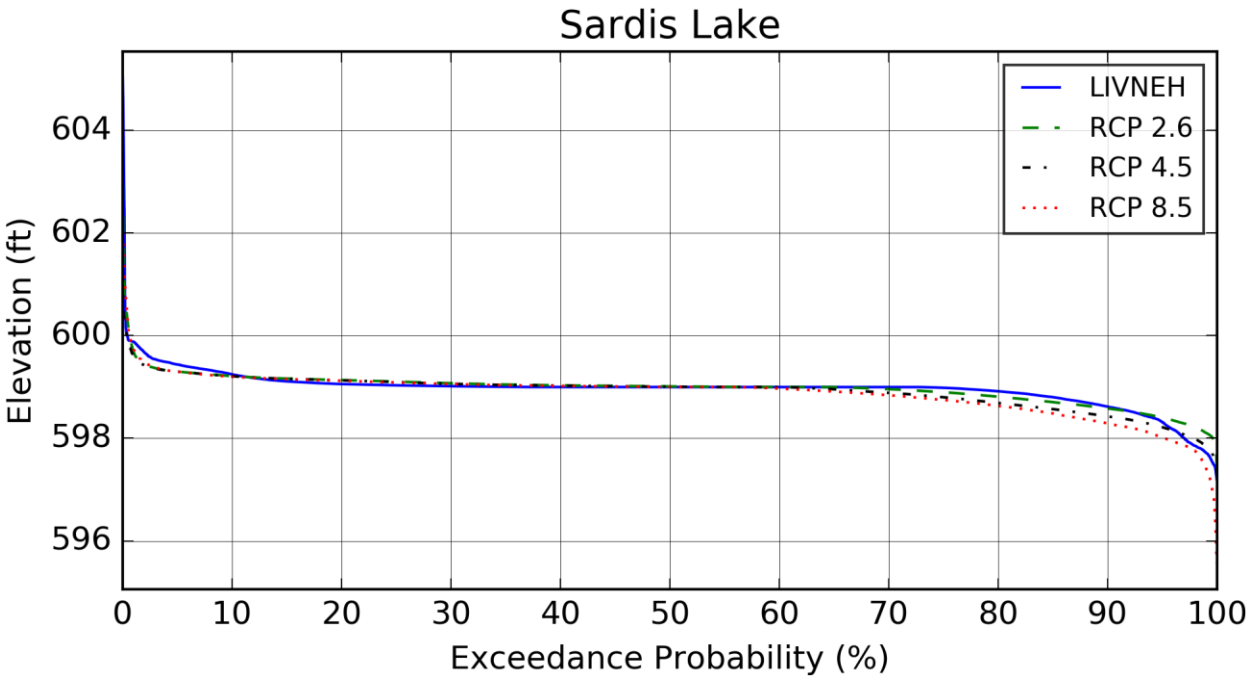

R.C. Longmire Lake
Storage (AF)
14,000
13,000
12,000
11,000
10,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

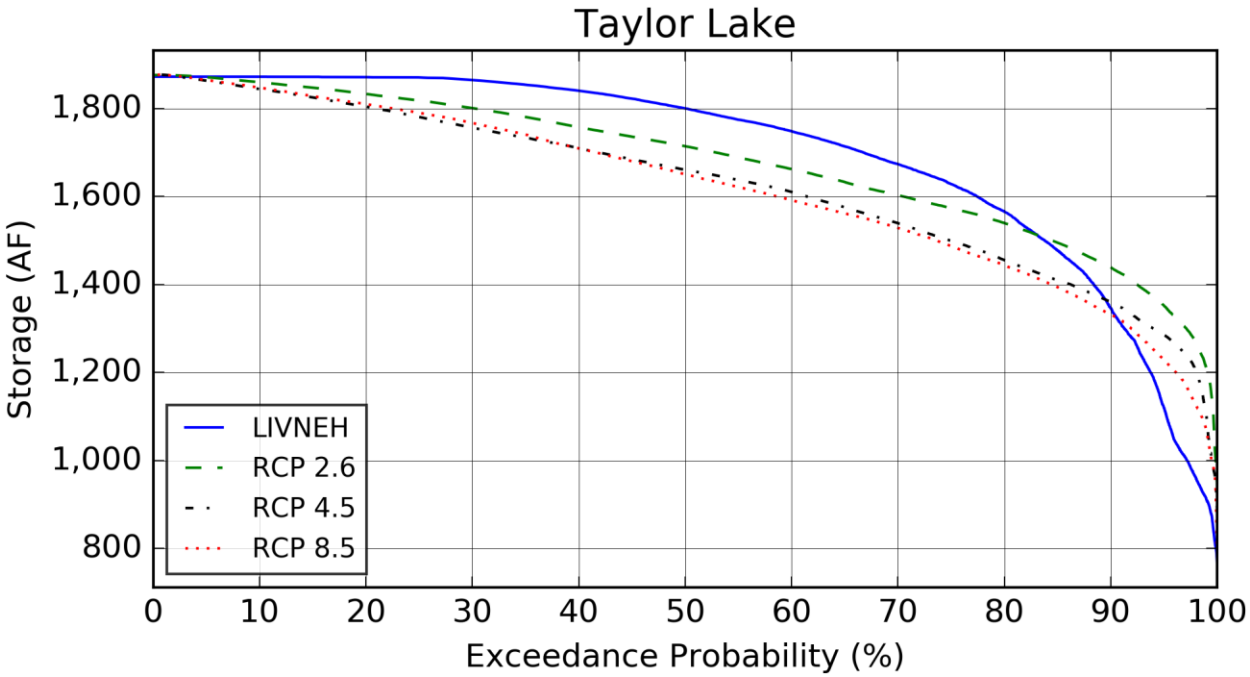

Rex Smith Lake
Storage (AF)
4,000
3,000
2,000
1,000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

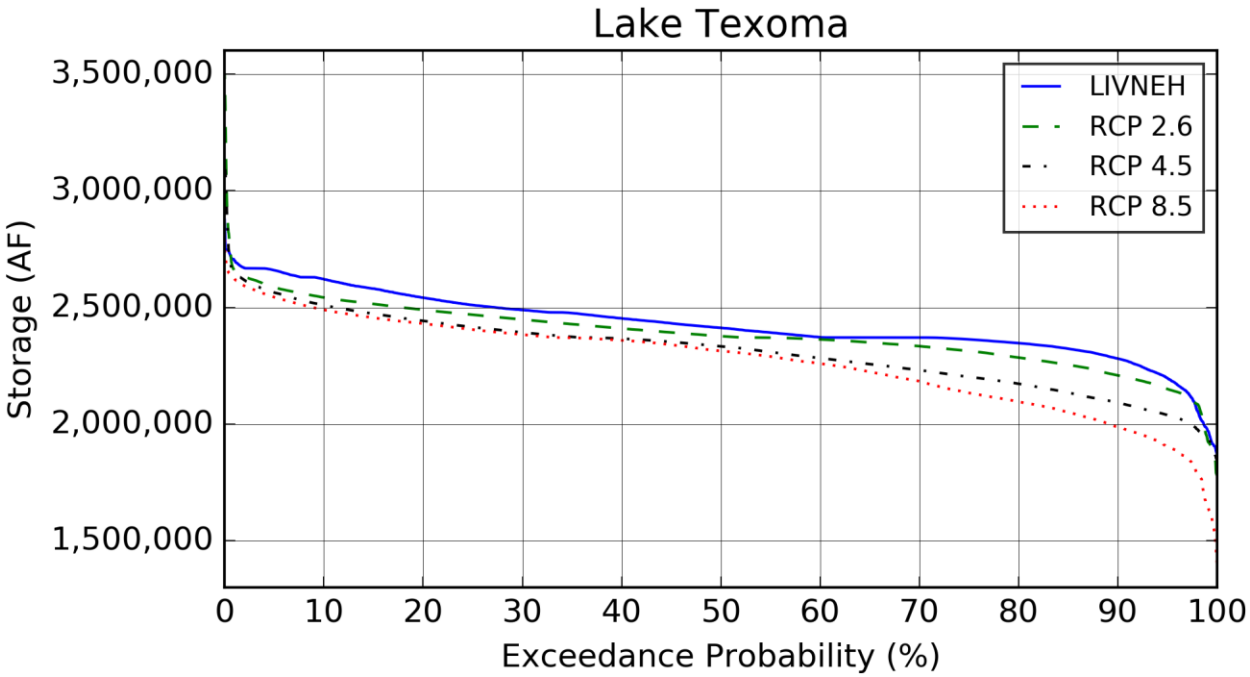

Rock Creek Reservoir (Lake Scott King)
Storage (AF)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

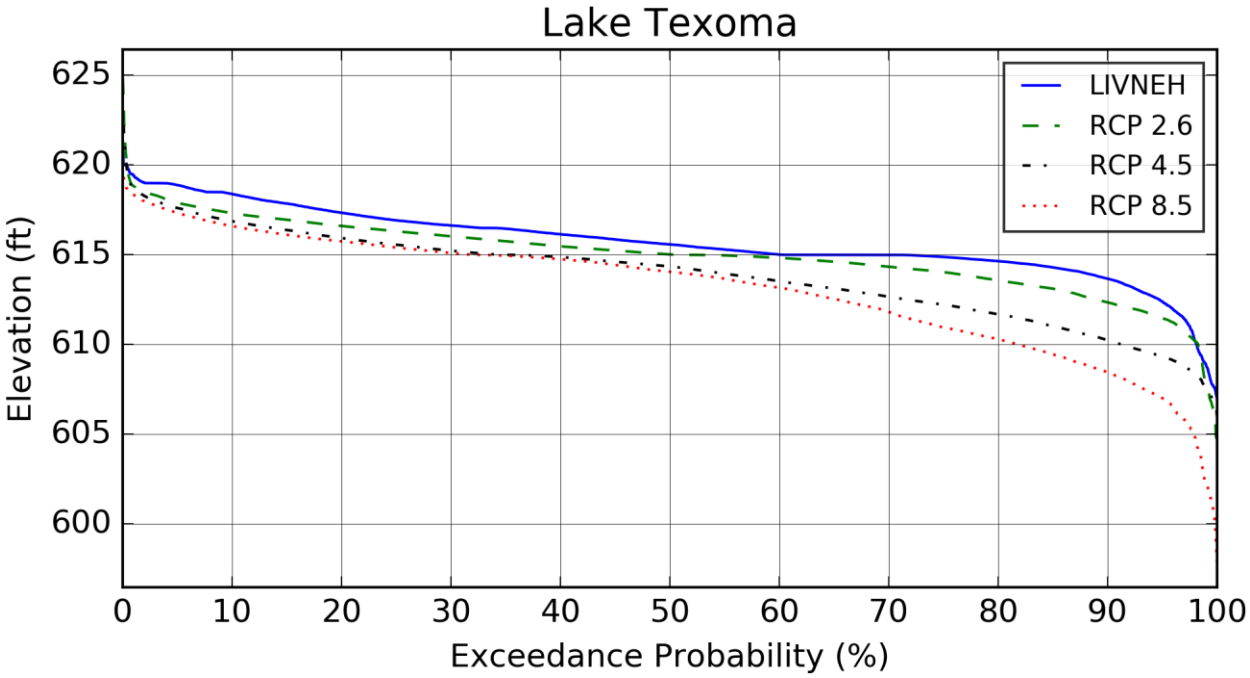

Rock Creek Reservoir (Lake Scott King)
Elevation (ft)
805
800
795
790
785
780
775
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

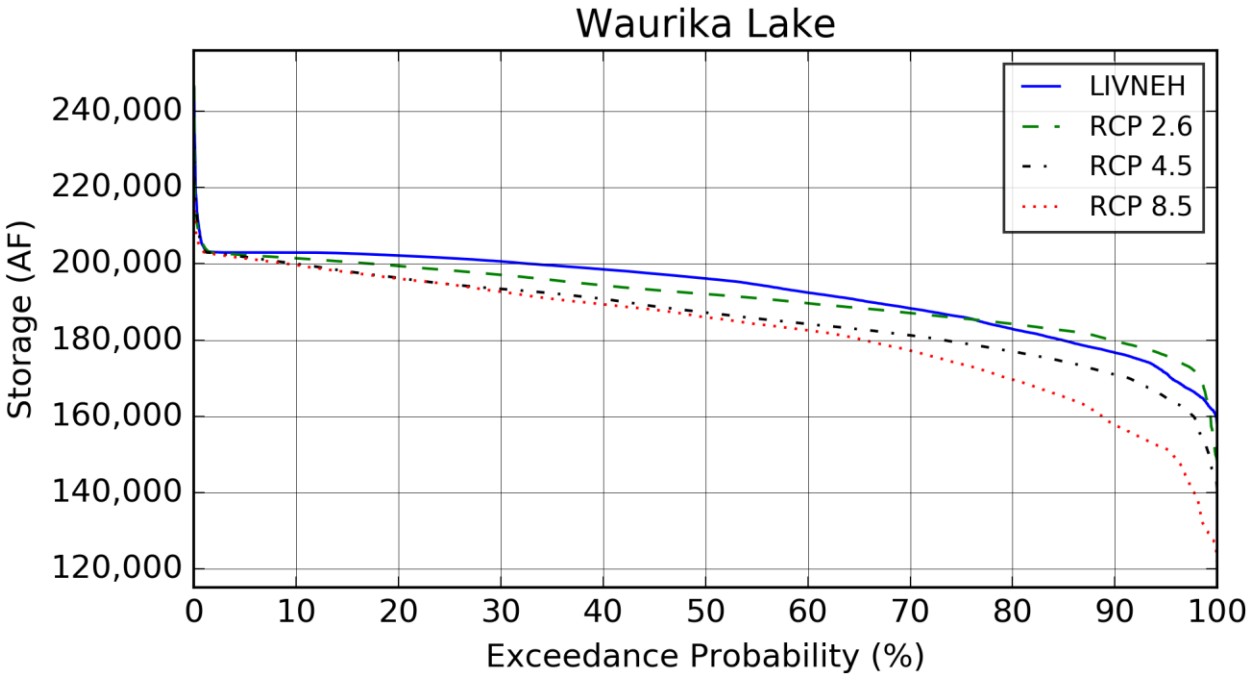

Sardis Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
360,000
340,000
320,000
300,000
280,000
260,000
240,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

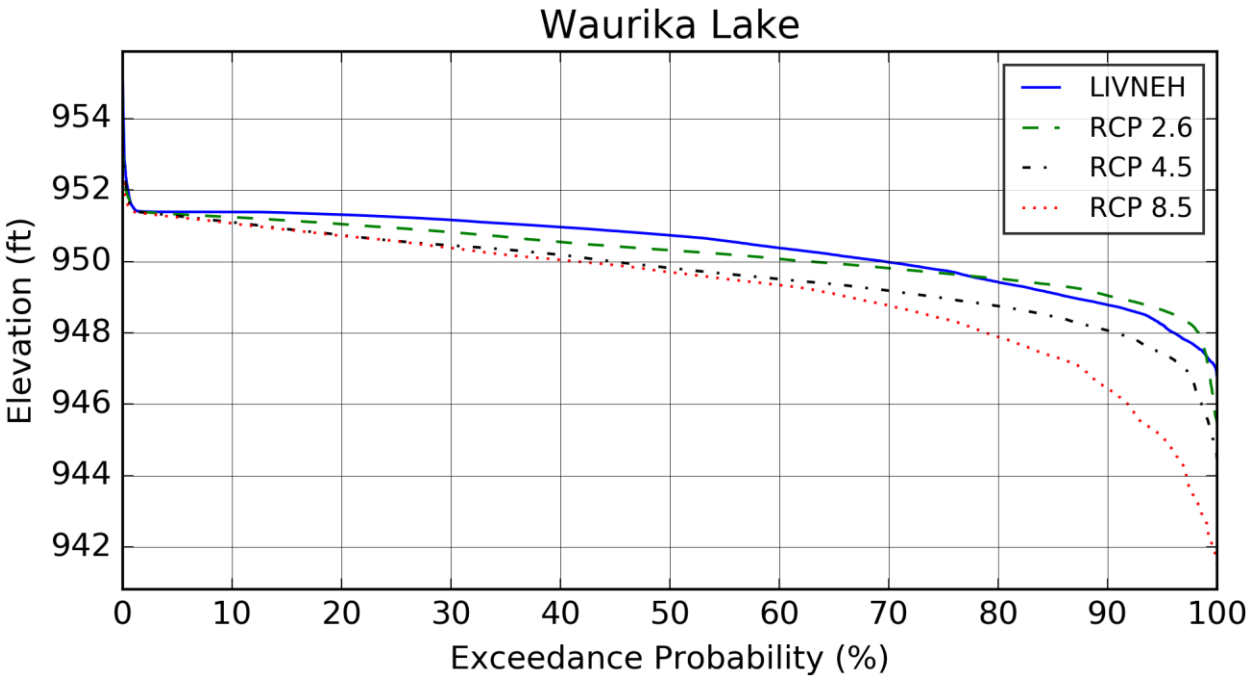

Sardis Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Elevation (ft)
604
602
600
598
596
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)

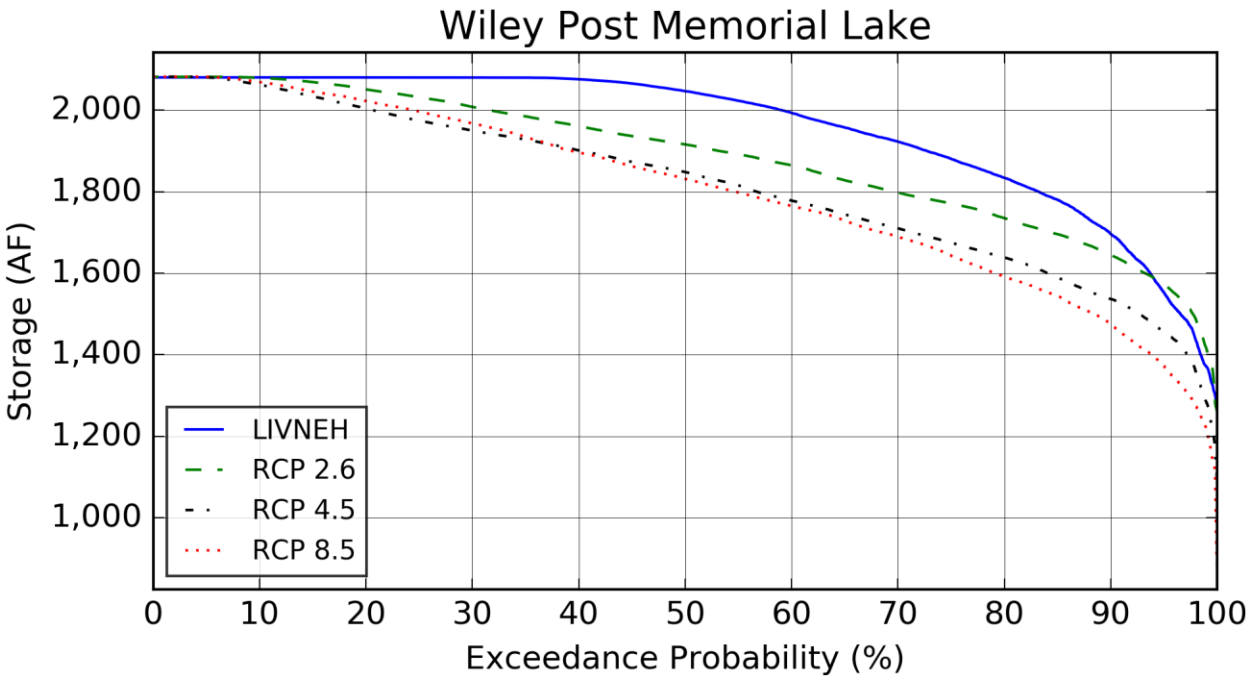

Taylor Lake
Storage (AF)
1,800
1,600
1,400
1,200
1,000
800
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5


Lake Texoma
Storage (AF)
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5


Lake Texoma
Elevation (ft)
625
620
615
610
605
600
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5


Waurika Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Storage (AF)
240,000
220,000
200,000
180,000
160,000
140,000
120,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)


Waurika Lake
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5
Elevation (ft)
954
952
950
948
946
944
942
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)


Wiley Post Memorial Lake
Storage (AF)
2,000
1,800
1,600
1,400
1,200
1,000
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability (%)
LIVNEH
RCP 2.6
RCP 4.5
RCP 8.5

Appendix E – Supplemental Information

Table 4. Small modeled tributaries not clearly shown in Figure 3.

Reach Name	OCWP Planning Basin Number	Corresponding Inflow Location Name
Little Beaver Creek	25	Little Beaver
Beaver Creek	25	Beaver
Cow Creek	26	Cow
Little Washita River	16	Little Wash
Mill Creek	21	Mill Creek
Honey Creek	14	Honey
Unnamed	14	Baptist
Unnamed	14	Gene
Island Bayou	13	Island
Muddy Boggy Creek North of Confluence with Caney Boggy Creek	8	Muddy Boggy North
Byrds Mill Creek	9	Byrds Mill
Sandy Creek	9	Sandy Creek
North Boggy Creek north of Atoka Lake	8	Atoka US
Cedar Creek	6	Cedar Creek
Little River upstream of Pine Creek Lake	3	Pine Creek US
Mountain Fork River upstream of Broken Bow Lake	4	Broken Bow US

Table 5. Municipal entities' respective surface water permits and associated reservoirs. Only permits that have a primary purpose of municipal supply are included. Additionally, only permits within the spatially refined model region are included.

Entity Name	Oklahoma Surface Water Permit Number	Priority Date	Permit Amount (AFY)	Model Results Grouped	OCWP Planning Basin Number	Associated Lake or Reservoir	Latitude[1]	Longi-tude[1]
Ada, City of	19590157	5/19/1959	3,360	Yes	9		34.595	-96.666
Ada, City of	19800107	8/21/1980	5,340		9		34.595	-96.666
Antlers Public Works Authority	19540874	10/21/1954	235	Yes	6		34.249	-95.595
Antlers Public Works Authority	19720060	2/23/1972	523		6	Hugo Lake	34.202	-95.487
Arbuckle Area Council	19820061	4/12/1982	457	No	9	Delaware Creek Lake	34.413	-96.545
Arbuckle Master Conservancy Dist	19570516	5/14/1957	3,127	Yes	14	Lake of the Arbuckles	34.443	-97.021
Arbuckle Master Conservancy Dist	19820009	1/21/1982	20,873		14	Lake of the Arbuckles	34.435	-97.031
Ardmore, City of	19030002	10/6/1903	2,668	Yes	14	Mountain Lake	34.367	-97.285
Ardmore, City of	19650046	1/18/1965	1,267		14	Rock Creek Reservoir	34.256	-97.182
Ardmore, City of	19650047	1/18/1965	1,267		14	Lake Jean Neustadt	34.282	-97.169
Atoka, City of	19730282A	7/19/1973	8,000	Yes	8	McGee Creek Reservoir	34.308	-95.882
Atoka, City of	19910049	9/3/1991	2,000		8	Atoka Reservoir	34.516	-96.056
Baptist General Convention of OK	20090017	7/13/2009	1,008	No	14		34.423	-97.113
Bridgeview Camp A Corp	19570284	3/28/1957	3	No	21	Lake Texoma	34.029	-96.633
Broken Bow Public Works Authority	19820105	8/4/1982	940	Yes	4	Broken Bow Lake	34.156	-94.703
Broken Bow Public Works Authority	19860015	3/27/1986	9,720		4	Broken Bow Lake	34.155	-94.700
Bryan County RWS & SWM #2	20040019	6/14/2004	921	Yes	12		34.089	-96.370
Bryan County RWS & SWM #2 / Rural Water, Sewer & SW Mgmt Dist#2 [2]	19770025	2/2/1977	639		12		34.089	-96.370
Bryan County RWS & SWM #2 / Rural Water, Sewer & SW Mgmt Dist#2 [2]	19790054	4/12/1979	300		12		34.051	-96.381
Buncombe Creek View	19810164	8/21/1981	1	No	21	Lake Texoma	33.890	-96.799
Chickasaw National Recreation Area	19560823	10/26/1956	100	No	14	Lake of the Arbuckles	34.449	-97.009
Chickasha, City of	19060002	4/1/1906	74	Yes	16		35.070	-97.925
Chickasha, City of	19551469	9/23/1955	5,200		16	Lake Chickasha	35.131	-98.135

Entity Name	Oklahoma Surface Water Permit Number	Priority Date	Permit Amount (AFY)	Model Results Grouped	OCWP Planning Basin Number	Associated Lake or Reservoir	Latitude[1]	Longi-tude[1]
Coalgate Public Works Authority	19630174	6/26/1963	224	Yes	8	Coalgate Reservoir	34.572	-96.232
Coalgate Public Works Authority	19800078	6/20/1980	3,000		8	Coalgate Reservoir	34.572	-96.233
Coalgate, City of [3]	20040009	4/19/2004	4,608		8	McGee Creek Reservoir	34.313	-95.876
Comanche Public Works Authority	19660531	7/29/1966	300	No	23	Comanche Lake	34.369	-97.886
Davis, City of	19720076	3/10/1972	25	No	14		34.429	-97.149
Duncan, City of	19550061	1/7/1955	2,168	Yes	14	Lake Humphreys	34.584	-97.885
Duncan, City of	19620028	2/2/1962	1,245		14	Lake Fuqua	34.600	-97.672
Duncan, City of	19890003	12/23/1988	3,240		14	Lake Humphreys	34.584	-97.885
Duncan, City of	20140076	12/16/2014	1,600		14	Clear Creek Lake	34.585	-97.843
Durant, City of	19400050	6/3/1940	1,842	Yes	12		34.053	-96.341
Durant, City of	19710554	12/31/1971	4,500		12		34.053	-96.341
Durant, City of	19780140	10/6/1978	6,000		12	Durant Lake	34.085	-96.379
Elmore City, City of	19650648	12/27/1965	238	No	14	Elmore City Lake	34.628	-97.390
Healdton, City of	19740481	12/5/1974	1,473	No	22	Healdton Lake	34.237	-97.449
Hughes Co Rural Water District #2	19940025	4/28/1994	300	No	8	Ashland Lake	34.766	-96.163
Hugo Municipal Authority	19540795	10/7/1954	1,700	Yes	5	Hugo Lake	34.010	-95.383
Hugo Municipal Authority	19720048	2/28/1972	28,800		5	Hugo Lake	34.010	-95.383
Idabel Public Works Authority	19550764	3/8/1955	1,000	Yes	3		33.935	-94.827
Idabel Public Works Authority	19820137	12/22/1982	3,929		3		33.936	-94.829
Kiowa, Town of	19250005	1/1/1925	70	Yes	8	Country Club Lake	34.683	-95.907
Kiowa, Town of	19830053	9/1/1983	232		8	Country Club Lake	34.670	-95.895
Latimer Co Rural Water District #2	19880022	7/14/1988	1,000	No	6	Sardis Lake	34.680	-95.328
Lindsay, City of	19040007	11/15/1904	31	No	15		34.821	-97.603
Little, Dan and Prudence [4]	19630317	10/1/1963	942	Yes	21	Oteka Lake	34.169	-96.859
Little, Dan and Prudence [4]	19710306	5/19/1971	568		21	Oteka Lake	34.171	-96.861
Mack Alford Correctional Center	19860011	2/24/1986	180	No	8	Atoka Reservoir	34.521	-96.031
Madill Public Works Authority	19070001	11/15/1907	342	Yes	21	Carter Lake	34.124	-96.796

Entity Name	Oklahoma Surface Water Permit Number	Priority Date	Permit Amount (AFY)	Model Results Grouped	OCWP Planning Basin Number	Associated Lake or Reservoir	Latitude[1]	Longi-tude[1]
Madill Public Works Authority	19780143	10/16/1978	600		21	Carter Lake	34.121	-96.797
Madill Public Works Authority	19790114	9/17/1979	2,500		21	Hauani Lake	34.057	-96.877
Marlow, City of	19690101	2/17/1969	1,877	No	14	Taylor Lake	34.751	-97.921
Marshall County Water Corporation [4]	19970004	2/26/1997	1,616	Yes	21	Rex Smith Lake	33.983	-96.780
Maysville, Town of	19660701	12/8/1966	540	Yes	15	Wiley Post Memorial Lake	34.866	-97.376
Maysville, Town of	19700156	5/12/1970	160		15	Wiley Post Memorial Lake	34.866	-97.376
McCurtain Co Rural Water Dist #1	19660337	6/22/1966	2,000	No	2		33.948	-94.647
Mountain Fork Water Supply Corp	19710083	3/5/1971	538	Yes	4		34.043	-94.621
Mountain Fork Water Supply Corp	19800098	8/7/1980	1,173		4		34.043	-94.621
Murray State College	19860005	1/27/1986	300	No	21		34.253	-96.681
Oklahoma City, City of	19540613	9/11/1954	31,367	Yes	8	Atoka Reservoir	34.446	-96.084
Oklahoma City, City of	19730282D	7/19/1973	40,000		8	McGee Creek Reservoir	34.308	-95.883
Oklahoma City, City of	19800048	3/27/1980	60,300		8	Atoka Reservoir	34.446	-96.084
Pauls Valley, City of	19840064	10/5/1984	3,361	No	14	R.C. Longmire Lake	34.745	-97.056
Pushmataha Co Rural Water Dist #3	19920022	7/31/1992	400	Yes	6	Hugo Lake	34.201	-95.487
Pushmataha Co Rural Water Dist #3	19930017	4/14/1993	300		6	Hugo Lake	34.201	-95.487
Sardis Lake Water Authority	19910054	9/26/1991	6,000	No	6	Sardis Lake	34.669	-95.330
Smith, Bryant & Mavis	20020016	3/26/2002	1,900	No	3		34.149	-94.920
Southern Oklahoma Water Corporation	19730375	9/13/1973	192	No	14		34.323	-97.036
Talihina Public Works Authority	19620079	5/28/1962	300	Yes	6	Carl Albert Lake	34.783	-95.075
Talihina Public Works Authority	19680415	11/15/1968	1,500		6	Carl Albert Lake	34.768	-95.068
Tishomingo, City of	19030004	11/15/1903	23	Yes	21		34.266	-96.693
Tishomingo, City of	19710516	11/1/1971	497		21		34.287	-96.696
Tishomingo, City of	20160023	10/11/2016	7,000		21		34.245	-96.683
Tourism & Recreation, Dept of	19560078A	1/31/1956	78	No	21	Lake Texoma	33.987	-96.631
University of Oklahoma	19860010	2/5/1986	7	No	21	Lake Texoma	33.881	-96.797
Valliant, City of	19800132	9/15/1980	614	No	3		34.058	-95.042
Wapanucka Public Works Authority	19930003	1/29/1993	320	No	9		34.364	-96.477

Entity Name	Oklahoma Surface Water Permit Number	Priority Date	Permit Amount (AFY)	Model Results Grouped	OCWP Planning Basin Number	Associated Lake or Reservoir	Latitude[1]	Longi-tude[1]
Waurika Project Master Cnsrvncy Dst	50363	6/7/1965	44,022	Yes	25	Waurika Lake	34.246	-98.048
Waurika Project Master Cnsrvncy Dst	19830041	6/29/1983	784		25	Waurika Lake	34.253	-98.051
[1] Latitudes and longitudes are estimated because a surface water permit can have multiple diversion locations								
[2] It was assumed that Bryan County RWS & SWM #2 and Rural Water, Sewer & SW Mgmt Dist#2 were the same entities								
[3] The City of Coalgate was grouped with the Coalgate Public Works Authority								
[4] Little, Dan and Prudence were grouped with the Marshall County Water Corporation								

Table 6. Modeled reservoirs and corresponding information.

Lake or Reservoir Name	Year Built	Owner / Operator[1]	OCWP Planning Basin Number	State	Lati-tude[2]	Longi-tude[2]	Spatially Refined Model Region	Normal Capacity (acre-ft)	Normal Surface Area (acres)	EAC Source[3]
Altus Reservoir	1945	BOR	36	OK	34.887	-99.297	No	132,832	6,260	Exist
Lake of the Arbuckles	1967	BOR	14	OK	34.434	-97.029	Yes	72,399	2,349	Exist
Ardmore City Lake	1910	City of Ardmore	14	OK	34.227	-97.153	Yes	1,993	153	Exist
Lake Arrowhead	1966	City of Wichita Falls	-	TX	33.764	-98.372	No	230,359	14,506	Exist
Ashland Lake[4]	1988	HCCD	8	OK	34.766	-96.162	Yes	644	102	Est
Atoka Reservoir	1964	OKC	8	OK	34.449	-96.081	Yes	110,708	5,408	Exist
Broken Bow Lake	1970	USACE	4	OK	34.145	-94.684	Yes	918,244*	14,183*	Exist
Buffalo Lake	1938	USFWS	-	TX	34.921	-102.101	No	24,970	1,913	Exist
Carl Albert Lake	1964	City of Talihina	6	OK	34.768	-95.069	Yes	2,738	161	Exist
Carter Lake	1960	City of Madill	21	OK	34.123	-96.794	Yes	950	85	Est
Lake Chickasha	1958	City of Chickasha	16	OK	35.132	-98.129	Yes	16,321	1,354	Exist
Clear Creek Lake	1948	City of Duncan	14	OK	34.580	-97.839	Yes	7,710	722	Est
Coalgate Reservoir	1965	City of Coalgate	8	OK	34.571	-96.232	Yes	3,466	346	Est
Comanche Lake	1960	City of Comanche	23	OK	34.367	-97.889	Yes	2,500	184	Est
Country Club Lake	1950	Unknown	8	OK	34.670	-95.895	Yes	1,020**	133	Est

Lake or Reservoir Name	Year Built	Owner / Operator[1]	OCWP Planning Basin Number	State	Lati-tude[2]	Longi-tude[2]	Spatially Refined Model Region	Normal Capacity (acre-ft)	Normal Surface Area (acres)	EAC Source[3]
Delaware Creek Lake[4]	1966	Unknown	9	OK	34.411	-96.543	Yes	674	67	Est
Lake Diversion	1924	City of Wichita Falls, WCWID	-	TX	33.814	-98.933	No	35,324	3,397	Exist
Durant Lake	1994	City of Durant	12	OK	34.083	-96.385	Yes	4,176	265	Exist
Lake Ellsworth	1962	City of Lawton	28	OK	34.794	-98.368	No	81,126	4,903	Exist
Elmore City Lake	1966	Elmore City	14	OK	34.628	-97.389	Yes	606	69	Est
Fort Cobb Reservoir	1959	BOR	18	OK	35.164	-98.450	No	73,833	3,806	Exist
Foss Reservoir	1961	BOR	20	OK	35.538	-99.186	No	177,900	6,801	Exist
Lake Fuqua	1962	City of Duncan	14	OK	34.599	-97.672	Yes	21,100	1,500	Est
Greenbelt Lake	1968	GMIWA	-	TX	35.003	-100.892	No	60,400	2,025	Exist
Hauani Lake[4]	1985	City of Madill	21	OK	34.057	-96.878	Yes	3,000	218	Est
Healdton Lake	1979	City of Healdton	22	OK	34.236	-97.449	Yes	3,038	319	Exist
Hugo Lake	1974	USACE	5	OK	34.010	-95.383	Yes	141,040*	12,338*	Exist
Lake Humphreys	1958	City of Duncan	14	OK	34.583	-97.882	Yes	14,041	882	Est
Lake Jean Neustadt	1969	City of Ardmore	14	OK	34.282	-97.169	Yes	6,400	459	Exist
Lake Kemp	1923	City of Wichita Falls, WCWID#2, USACE	-	TX	33.755	-99.145	No	268,095	15,590	Exist
Laka Kickapoo	1945	City of Wichita Falls	-	TX	33.663	-98.779	No	86,345	5,864	Exist
McGee Creek Reservoir	1987	BOR	8	OK	34.314	-95.875	Yes	113,965	3,808	Exist
Mountain Lake	1956	City of Ardmore	14	OK	34.366	-97.286	Yes	3,474	212	Exist
Lake Murray	1937	OK	21	OK	34.034	-97.071	Yes	161,642	5,877	Exist
Oteka Lake	1978	MCWC	21	OK	34.173	-96.860	Yes	720	54	Est
Pat Mayse Lake	1967	USACE	-	TX	33.853	-95.545	No	117,844	5,638	Exist
Pine Creek Lake	1969	USACE	3	OK	34.113	-95.079	Yes	51,924*	3,867*	Exist
R.C. Longmire Lake	1989	City of Pauls Valley	14	OK	34.745	-97.059	Yes	14,424	745	Est
Rex Smith Lake	1998	MCWC	21	OK	33.979	-96.780	Yes	4,600	230	Est
Rock Creek Reservoir[4]	1979	City of Ardmore	14	OK	34.258	-97.180	Yes	3,551	232	Exist
Sardis Lake	1982	USACE	6	OK	34.631	-95.350	Yes	274,192	13,528	Exist
Taylor Lake	1960	City of Marlow (leased)	14	OK	34.750	-97.920	Yes	1,877	227	Est

Lake or Reservoir Name	Year Built	Owner / Operator[1]	OCWP Planning Basin Number	State	Lati-tude[2]	Longi-tude[2]	Spatially Refined Model Region	Normal Capacity (acre-ft)	Normal Surface Area (acres)	EAC Source[3]
Lake Texoma	1944	USACE	21	OK / TX	33.819	-96.572	Yes	2371,383*	69,854*	Exist
Tom Steed Reservoir	1975	BOR	35	OK	34.739	-98.988	No	97,520	6,402	Exist
Waurika Lake	1977	USACE	25	OK	34.235	-98.053	Yes	203,060	10,533	Exist
Wiley Post Memorial Lake	1971	City of Maysville	15	OK	34.863	-97.384	Yes	2,082	302	Est

[1] BOR = US Bureau of Reclamation, HCCD = Hughes County Conservation District, OKC = City of Oklahoma City, USACE = US Army Corps of Engineers, USFWS = US Fish and Wildlife Service, WCWID = Wichita County Water Improvement District, GMIWA = Greenbelt Municipal and Industrial Water Authority, WCWID#2 = Wichita County Water Improvement District No.2, OK = State of Oklahoma, MCWC = Marshall County Water Corps,

[2] Locations are estimated at the reservoir's dam

[3] Exist = Existing, Est = Estimated

[4] Alternative name: Ashland Lake = SCS – Upper Muddy Boggy Creek Site 20, Delaware Creek Lake = SCS - Delaware Creek Site – 9, Huani Lake = Madill Reservoir, Rock Creek Reservoir = Lake Scott King

* Conservation pool elevation varies based on season; minimum value is shown

** Capacity was estimated based on OWRB surface area estimates and maximum depth estimates from elevation data.