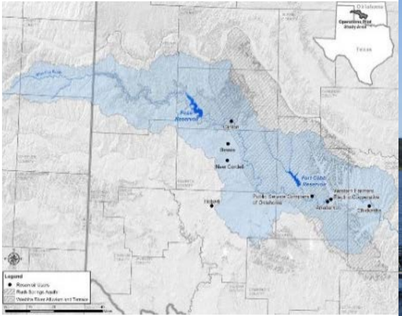
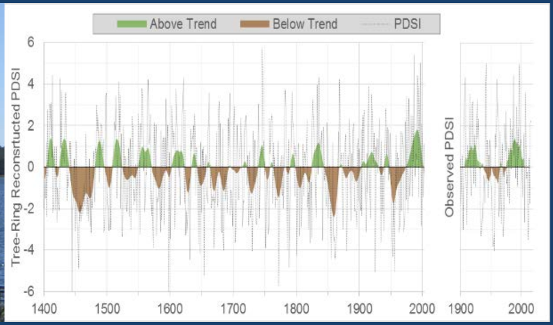
RECLAMATION

Managing Water in the West

RESERVOIR OPERATIONS PILOT STUDY

Final Report: Washita Basin Project, Oklahoma





Oklahoma-Texas Area Office
Great Plains Region

U.S. Department of the Interior
Bureau of Reclamation

May 2018

Mission Statements

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

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

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Reservoir Operations Pilot Study, Great Plains Region

Washita Basin Project, Oklahoma

Peer Review Plan and Documentation

Date: May 08, 2018

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Subject and Purpose: A Reservoir Operations Pilot Study on the Washita Basin Project, Oklahoma was conducted under Reclamation's Reservoir Operations Pilot Initiative (Initiative). The Initiative aims to identify innovative approaches to improve water management strategies in the western United States. Under the Initiative, Reclamation selected five "pilot" studies for implementation, one in each of Reclamation's five regions. The Upper Washita Pilot Study (Pilot Study) was selected to represent the Great Plains Region. The Pilot Study was led by Reclamation's Oklahoma-Texas Area Office (OTAO). The ultimate goal of these pilots is to develop guidance for identifying and implementing changes that increase flexibility in reservoir operations in response to future variability in water supplies, floods, and droughts.

The purpose of this peer review document is to document compliance with the Office of Management and Budget Final Information Quality Bulletin for Peer Review (70 FR 2664-2677) and Reclamation's Policy on Peer Review of Scientific Information and Assessments (CMP P14). These were established to ensure quality of scientific information disseminated by Reclamation and increase credibility of decisions to which scientific information contributes.

Impact of Dissemination: The Pilot Study report is *not* determined to be influential or highly influential as defined by the Office of Management and Budget Final Information Quality Bulletin for Peer Review (70 FR 2664-2677) and the Reclamation Manual Peer Review of Scientific Information and Assessments (CMP P14)

Peer Review Scope: The purpose of the peer review was to ensure that the technical information, data, models, analyses, and conclusions resulting from the Pilot Study are technically supported and defensible, and that the results and findings are technically sound and consistent with current professional practice.

Manner of Review/Selection of Reviewers: The peer review was conducted by reviewers who were not directly involved with conducting the component of the study they are reviewing and who have scientific and technical expertise that is relevant to the content under review.

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Reservoir Operations Pilot Study, Great Plains Region

Washita Basin Project, Oklahoma

Peer Review Plan and Documentation

Component I: Conversion of Tree Ring Data into New Inflow Sequences/Stochastic Resampling Methodology

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Component II: Impacts of Paleo Droughts on Reservoir Yield/Firm Yield Model Development
Component III: Standardization of Drought Scenarios
Component IV: Development and Operation of the Enhanced Drought Response Reservoir Operations (EDRRO) Model

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List of Acronyms and Abbreviations

%	Percent
acre-ft	Acre-feet
acre-ft/yr	Acre-feet per year
CD	Current demand
WFEC	Western Farmers Electric Cooperation
DCP	Drought Contingency Plan
DD	Dry to dry
DPR	Definite Planning Report
DW	Dry to wet
EDRRO	Enhanced Drought Response Reservoir Operations
ft	Feet
HI/SD	High intensity/short duration
K-NN	K-nearest neighbor
LI/LD	Low intensity/long duration
LSCV	Least squares cross-validation
M&I	Municipal and Industrial
MaxD	Maximum projected demand
MC	Markov Chain
MCD	Master Conservancy District
MinD	Minimum Contract Demand
N/A	Not Applicable
NA	No Action
PDSI	Palmer Drought Severity Index
Pilot	Upper Washita Reservoir Operations Pilot Study
PSO	Public Service of Oklahoma
Reclamation	Bureau of Reclamation
USGS	United States Geologic Survey
UWBS	Upper Washita Basin Study
VBA	Excel's Visual Basic Analysis
VIC	Variable Infiltration Capacity
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WD	Wet to dry
WFEC	Western Farmers Electric Cooperative
WW	Wet to wet

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EXECUTIVE SUMMARY

Purpose and Need

A significant challenge facing water resource managers in the arid western U.S. is preparing for and responding to drought. The need to meet Municipal and Industrial (M&I) demands during times of drought can be particularly challenging. M&I demands include needs for domestic and residential purposes, including water for human consumption, public health/sanitation, as well as for commercial and industrial processes. As such, an interruption in water supply could have detrimental impacts on public health and sanitation. Additional challenges exist when M&I needs are supplied by a reservoir because drought conditions reduce rainfall and runoff that are necessary to fill the reservoir, while at the same time increasing storage losses due to evaporation. Reduced reservoir storage is often further exacerbated by increases in upstream demands that reduce flow in tributaries contributing to reservoir inflows.

Furthermore, no two droughts are the same; they vary in intensity, duration, and severity. This causes vulnerabilities in reservoir supplies to manifest differently every time. Water resource managers are charged with considering these and other variables as they make decisions that could determine whether a city runs out of water. Determining how to best manage water to prepare for drought requires assessing risks and having a better understanding of the reservoir's "firm yield," i.e., the amount of M&I water a reservoir can reliably supply during a repeat of the worst drought on record.

What if our firm yield estimates are incorrect? If the estimate is too low, investments could be made in supplemental supplies to withstand a drought that may never come to fruition. If the estimate of firm yield is too high, it could lead to a false sense of security or inaction, meaning that investments that should have been made in order to withstand a critical drought are overlooked. Resource managers planning ahead for drought must determine what assumptions decision-makers are comfortable with, what is an acceptable level of risk, and how these variables inform our willingness to make investments into the future?

This study was conducted as part of Reclamation's Reservoir Operations Pilot Initiative (Initiative) which aims to identify innovative approaches to improve water management strategies in the western United States. The Initiative began in 2014 to help meet priorities identified in the Department of the Interior's WaterSMART program and is a key component of Reclamation's implementation of the SECURE Water Act of 2009 (Act). The overarching goal of the Act and the WaterSMART program is to help secure reliable water supplies to meet the Nation's current and future water needs. Under the Initiative, Reclamation selected five "pilot" studies for implementation, one in each of Reclamation's five regions. The Upper Washita Pilot Study (Pilot Study) was selected to represent the Great Plains Region. The Pilot Study was led by Reclamation's Oklahoma-Texas Area Office (OTAO). Pilot studies in other regions are currently underway and are expected to be completed in 2018. The ultimate goal of these pilots is to develop guidance for identifying and implementing changes that increase flexibility in reservoir operations in response to future variability in water supplies, floods, and droughts.

In Part I of this report, we set the stage by describing in more detail the challenges faced by local water districts charged with managing a reservoir through a critical drought for the purposes of providing reliable water supplies to cities and communities. Our analysis is focused on Reclamation's Washita Basin Project, administered by Reclamation's OTAO, which is comprised of Foss and Fort Cobb Reservoirs, and the vulnerabilities these reservoirs experienced during a recent catastrophic drought. Foss and Fort Cobb Reservoirs provide numerous benefits, including drinking water and power generation to several communities throughout west-central Oklahoma.

We also highlight Reclamation's interest in addressing these issues. In addition to the broad interest Reclamation has in fulfilling its mission to manage and develop water supplies, Reclamation maintains an interest in preserving federally authorized benefits of our Projects. Preserving these benefits provide value to the region while also helping the managing entities fulfill their contractual requirements to operate the reservoirs and repay Project construction costs associated with single-purpose delivery of water for M&I purposes. One of the purposes of this Initiative is to help achieve these goals through increased flexibility in reservoir operations.

Part I of this report further describes recent and ongoing efforts by Reclamation and local stakeholders to address drought-related vulnerabilities at Foss and Fort Cobb Reservoirs. This includes investments in the Upper Washita Basin Study (UWBS), which is evaluating (among other things) impacts and solutions associated with competing upstream demands that are reducing streamflows into the reservoirs. The UWBS also is evaluating how potential changes in future climate conditions could impact reservoir firm yield. The analysis compares simulated changes in runoff over a 30-year future period (2045-2074) with simulated run-off over a 50-year historical period (1950-1999). While the results are expected to provide water resource managers with a fairly robust range of reservoir yields that might be expected under a wide range of future conditions, an opportunity exists to extend the 50-year historical reference period even further, thus providing more insight into the variability of historical climate conditions and associated impacts on reservoir supplies.

It also includes drought contingency planning efforts, which recently resulted in the establishment of reservoir elevation thresholds that would trigger demand reductions by reservoir users. An outcome of this effort included a request by the local drought task force for Reclamation to use an existing "Firm Yield" model to predict what the reservoir yield would be under various severe drought scenarios – *beyond* the 1970s and 2011 droughts, along with the necessary demand curtailments that could prolong reservoir storage under these various future drought scenarios. Furthermore, while in the midst of a drought, the task force wanted a tool that could make near-term reservoir storage predictions based on observed climate conditions and real-time adjustments in demands on the reservoir.

From a long-range planning perspective, one of the key limitations of the Firm Yield model is that it assumes that the future emulates the past. Making matters worse, we only have about 90 years of historical data by which to base our assumptions about the future. Another key limitation is its weakness at combining near-term streamflow predictions with real-time demand changes to make informed predictions on reservoir yield. During the 2011 drought, officials were forced to make fairly simplistic and arbitrary assumptions about reservoir storage. Further complicating the issue was that the Firm Yield model lacks the ability to account for actual changes in water demand that could or would be occurring over those same time periods. Indeed, knowing what water is leaving the reservoir is every bit as important as knowing what is flowing in.

Despite the positive steps being taken in the examples cited above, opportunities exist to build upon the science and further improve the tools available to predict reservoir yield, both in the near term and long term. For example, a reconstruction of PDSI[1] shows us how the duration and intensity of droughts observed in west-central Oklahoma during the 90-year period of record *are far less variable* than so called “mega-droughts” (i.e., “paleo-droughts”) *that are known to have occurred* (but not directly observed) over centuries based on data collected from tree rings. An opportunity exists therefore to improve our understanding of how variations in climate can affect reservoir yield by extending the length we can look backwards in time; doing so will provide water managers a better glimpse into how the future may unfold both in the near term and long term.

Study Objectives

Recognizing the benefits that could come out of such an analysis, the Reservoir Operations Pilot (ROP) Study sought to do the following:

1. Develop a method of converting tree ring data into new inflow datasets that can be incorporated into Reclamation’s Firm Yield model. By extending the historical period, we would capture a greater range of variation (i.e., cycles of wet and dry periods; duration and intensity of droughts) than that which we currently captured using existing practices, thereby providing us with a more robust calculation of the range of reservoir firm yields that reflect impacts from paleo droughts. This would help inform long-term planning efforts and better prepare for the next drought (i.e., *enhanced drought preparedness*).
2. Develop a method of using the new Firm Yield model supply calculations created under No. 1 to make enhanced near-term projections, while also accounting for actual water use.
3. Use the “Enhanced” Firm Yield model to evaluate “what if” demand management scenarios and identify the associated risks of a M&I reservoir going dry based on the type of drought you may (or may not) be experiencing (i.e., *enhanced drought response*).

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[1] The Palmer Drought Severity Index (PDSI) uses temperature and precipitation data to estimate relative dryness on a ten point scale {-10 (dry) to +10 (wet)}, and it has been reasonably successful at quantifying long-term drought.

Methods

In Part II, we introduce “dendroclimatology”, the science of using tree rings to provide information about climate conditions that existed centuries ago, along with the promising implications of using tree ring data in water resources management. However, a key challenge is converting historical tree ring data into future predictions of reservoir yield. We developed and utilized published methodologies to translate tree ring-based hydroclimate data into new reservoir inflow datasets for Foss and Fort Cobb Reservoirs. We then evaluated the impacts of a large number (1,000+) “paleo” droughts on reservoir firm yield.

In Part III, in addition to the two most severe droughts observed since record keeping, we selected five of the 1,000+ paleo drought scenarios which, if properly planned for and responded to, provide a low risk window of Foss and Fort Cobb Reservoirs going dry. We selected a risk window of 5.0 to 0.1 percent, meaning that we wanted to be 95 to 99.9 percent “sure” that the paleo drought we plan for would not be surpassed by a potentially worse drought, statistically speaking. For comparison purposes, the observed droughts of record at Foss and Fort Cobb Reservoirs appear to provide risk windows of approximately 30 and 10 percent, respectively, meaning that the risk of those reservoirs going dry under a drought worse than the observed drought of record is higher.

In Part IV, we introduce and describe step-by-step instructions on the development and use of the Enhanced Drought Response Reservoir Operations (EDRRO) Model, a tool that can be used to plan for and respond to these drought scenarios using real-time water use data. In Part V, we perform several test runs of the EDRRO model at Foss and Fort Cobb Reservoirs. Results from seven modeling scenarios are presented, beginning with “No Action” scenarios which reflect the extent to which supply shortages would exist if no measures are taken to curtail demands of reservoir users during any of the seven drought scenarios. We then use the EDRRO model to evaluate the effectiveness of reservoir customer demand curtailments that can be triggered at different reservoir elevation thresholds to prevent supply shortages.

Results

As expected, the EDRRO model showed that the paleo droughts evaluated in this study would have catastrophic impacts on reservoir yield, much more so than the observed droughts of record. Also, as expected, significant demand curtailments would be necessary in order to prevent the reservoirs from going dry. For Foss Reservoir, the firm yield, as determined by the observed 1970s drought of record, is 19,700 acre-feet per year (acre-ft/yr), whereas the EDRRO model predicts reservoir firm yield under the five paleo droughts to range between 14,000 acre-ft/yr and 7,400 acre-ft/yr. If maximum projected (year 2060) demands are being placed on the reservoir, those demands would need to be curtailed by between 32 and 66 percent, respectively, in order to prevent the reservoir from going dry. For Fort Cobb Reservoir, the firm yield ,as determined by the observed 1950s drought of record, is 19,200 acre-ft/yr, whereas the EDRRO model predicts reservoir firm yield under the five paleo droughts to range between 18,700 acre-ft/yr and 15,300 acre-ft/yr. If maximum projected (year 2060) demands are being placed on the reservoir, those demands would need to be curtailed by between 36 and 53 percent, respectively, in order to prevent the reservoir from going dry. Overall, EDRRO modeling results showed that implementing demand curtailments earlier (i.e., at a higher reservoir elevation) rather than later provided only minimal benefits in terms of offsetting the overall magnitude of demand curtailments. With that said, when demand curtailments of a significant magnitude are expected, steps should be taken as early as practical to identify demand management strategies in advance of the next drought, as well as legal, institutional, and administrative procedures involved with implementing and enforcing those curtailments during a drought.

Conclusions and Guidance

The EDRRO modeling results for Foss and Fort Cobb Reservoirs reveal important information that can help the managers and users of these reservoirs better understand risk and make more informed decisions about how to ensure that secure water supplies are available for M&I use.

1. No two droughts are the same; they each vary in intensity, duration, and severity. Our hydroclimate record keeping encompasses only a relatively narrow period of time, so the trends we have observed may not be an accurate predictor of future conditions.
2. If one compares observed PDSI alongside PDSI calculated over a 600-year period using tree ring data, it becomes evident that the droughts observed over the relatively short 90-year period are far less severe than the so called “mega droughts” that have occurred throughout the last millennium. Therefore, the assumption that future droughts will mimic those that we have experienced in the past appears to be fundamentally flawed. In fact, tree ring data show us the next drought could be much worse than anything we have experienced.
3. Water resource managers should take careful consideration of their risk tolerance and risk exposure when planning for drought. We believe risk tolerance to a reservoir going dry should be very low, and if a reservoir serves as the sole supply source of M&I water, then arguably, the risk tolerance should be zero. The safety and sanitation of the public depends on it, as does industry – and ultimately, a city’s economic prosperity, or even their existence, depends on it.
4. This Pilot Study details a credible, replicable approach which allows risk exposure to be calculated using tree ring data. When comparing known reservoir yields that occurred during the worst observed historical droughts to the calculated reservoir yields resulting from “mega droughts”, we found that risk exposure (i.e., risk of the reservoirs going dry) ranged from 10 to 30 percent at Fort Cobb and Foss Reservoirs, respectively.
5. For drought planning purposes, any gap between risk exposure and risk tolerance should provide a signal for actions to be taken to mitigate those risks.
6. This Pilot Study developed the EDRRO model for this very purpose. In our case, we sought to narrow the risk gap through one type of action in particular: reducing reservoir user demands (e.g., via water conservation). In planning for the next drought, we selected a risk tolerance of 5.0 to 0.1 percent.

7. Improved operational flexibility is key. The future cannot be known with any degree of certainty. While a key strength of the EDRRO model lies with its capabilities of making more informed predictions about future long-term reservoir supplies, the reality is, when the next drought comes, the real power of the EDRRO model will truly reveal its ability to be used to manage demands and prevent supply shortages real time while in the midst of the drought. Thanks to this effort, when the next drought hits Foss and Fort Cobb Reservoirs, the managing entities will have improved operational flexibility and be better prepared. Our staff stand ready to provide details and assistance for any interested party wishing to do the same.

8. Even though the EDRRO model has demonstrated itself as a powerful and promising tool to enhance drought planning and response, it is important to stress that the EDRRO model should not be used in a vacuum. Complimentary efforts should be undertaken to address other risks to reservoir supply, such as those associated with land development, permitting, and water use that may occur upstream of a reservoir. These uses may reduce inflows into the reservoir and require the development of models and tools in their own right. For example, in the study area evaluated here, efforts are currently underway as part of the UWBS to analyze how upstream permits and water use affect base flows of streams entering Foss and Fort Cobb Reservoirs. In coordination with state and local officials, we are currently exploring how the EDRRO model could be used to inform decision-making regarding demand curtailments of junior water right holders upstream of Foss and Fort Cobb Reservoirs in conjunction with demand reductions of reservoir customers.

PART I:
PURPOSE AND NEED

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PART I: PURPOSE AND NEED

Authority and Purpose

This study was conducted as part of Reclamation's Reservoir Operations Pilot Initiative (Initiative) which aims to identify innovative approaches to improve water management strategies in the western United States. The Initiative began in 2014 to help meet priorities identified in the Department of the Interior's WaterSMART program and is a key component of Reclamation's implementation of the SECURE Water Act of 2009 (Act). The overarching goal of the Act and the WaterSMART program is to help secure reliable water supplies to meet the Nation's current and future water needs.

Under the Initiative, Reclamation selected five "pilot" studies for implementation, one in each of Reclamation's five regions. The Upper Washita Pilot Study (Pilot Study) was selected to represent the Great Plains Region. The Pilot Study was led by Reclamation's Oklahoma-Texas Area Office (OTAO). Pilot studies in other regions are currently underway and are expected to be completed in 2018. The ultimate goal of these pilots is to develop guidance for identifying and implementing changes that increase flexibility in reservoir operations in response to future variability in water supplies, floods, and droughts.

Description of the Study Area and Federal Features

The Upper Washita Basin is comprised of over 5,000 square miles of drainage area in west-central Oklahoma and the Texas panhandle, and includes two Reclamation reservoirs: Foss and Fort Cobb (Figure 1). Important groundwater resources within the study area include the Rush Springs aquifer and Washita River alluvium and terrace, which serve as significant water supply sources for agricultural irrigation. The aquifers also contribute to the base flows of surface water streams and tributaries that flow into Foss and Fort Cobb Reservoirs.

Foss and Fort Cobb Reservoirs were constructed in 1961 and 1959, respectively as part of the Washita Basin Project. Although Reclamation still maintains ownership responsibility of the dam and conveyance infrastructure, operations and maintenance responsibilities have been transferred to the two respective water districts, Foss and Fort Cobb Reservoir Master Conservancy Districts (MCDs). Both MCDs are under contract with Reclamation to operate and maintain the project facilities and to repay the portion of the original construction costs associated with single purpose M&I water supply. Foss MCD holds a 17,634 acre-foot per year (acre-ft/yr) water right, of which 17,634 acre-ft/yr is contractually allocated to the member cities of Clinton, New Cordell, Hobart, and Bessie. Fort Cobb MCD holds an 18,000 acre-ft/yr water right, of which 15,211 acre-ft/yr is contractually allocated to the cities of Anadarko and Chickasha, and the Western Farmers Electric Cooperative (WFEC) and Public Service of Oklahoma (PSO) power plants. Together, Foss and Fort Cobb Reservoirs provide 90 percent of the surface water supply source in the study area, including municipal water for about 40,000 people.

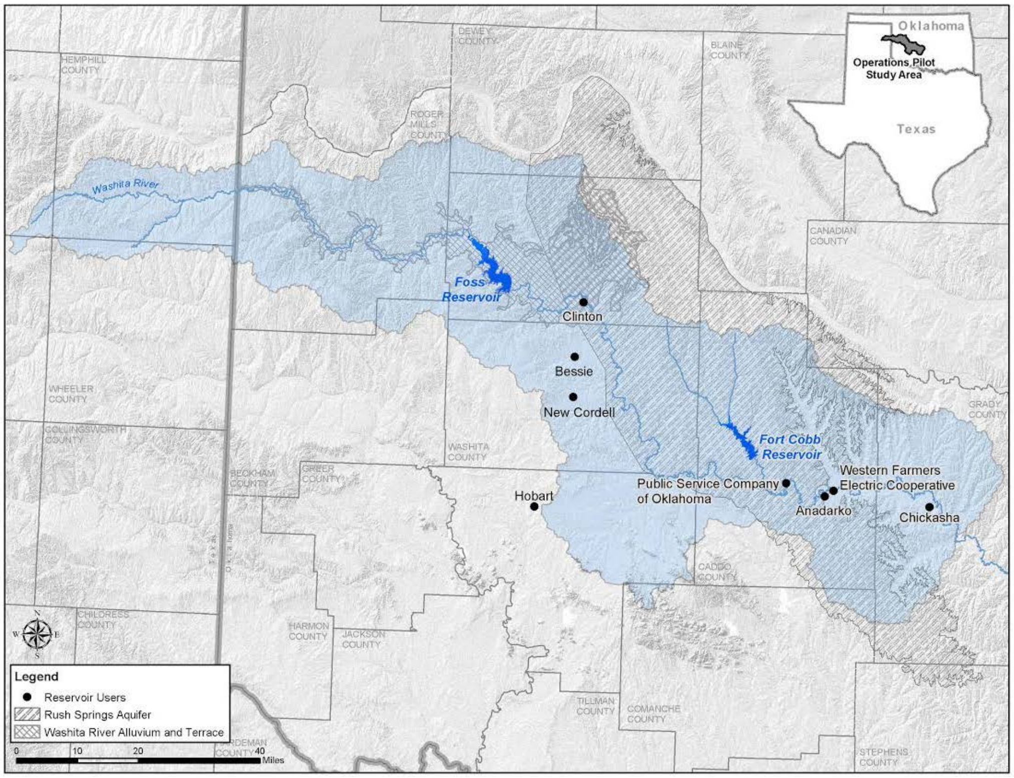

Figure 1: Reservoir Operations Pilot Study Area, Great Plains Region

Problems, Needs, and Opportunities

A significant challenge facing water resource managers in the arid western U.S. is preparing for and responding to drought. The need to meet Municipal and Industrial (M&I) demands during times of drought can be particularly challenging. M&I demands include needs for domestic and residential purposes, including water for human consumption, public health/sanitation, as well as for commercial and industrial processes. As such, an interruption in water supply could have detrimental impacts on public health and sanitation. Additional challenges exist when M&I needs are supplied by a reservoir because drought conditions reduce rainfall and runoff that are necessary to fill the reservoir, while at the same time increasing storage losses due to evaporation. Reduced reservoir storage is often further exacerbated by increases in upstream demands that reduce flow in tributaries contributing to reservoir inflows.

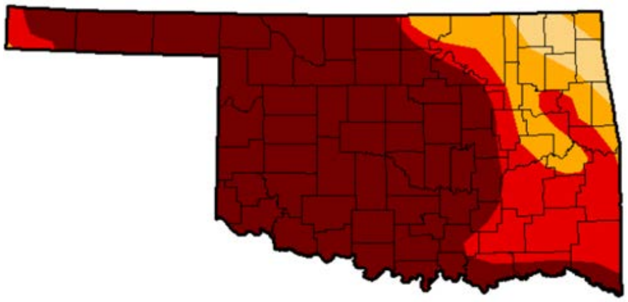

Figure 2: Oklahoma, U.S. Drought Monitor 2014

Figure 3: Low lake levels at Foss Reservoir during the 2011 drought

These types of challenges have long faced water resource managers of Foss and Fort Cobb Reservoirs in southwest Oklahoma. Most recently, the area experienced a catastrophic drought from 2011 to 2015 (Figures 2-4). Foss and Fort Cobb Reservoir levels reached record lows, which had major impacts both on tourism and the environment. As the crisis unfolded, officials turned to alternative supplies, but in some cases, those supplies also dried up. The MCDs and municipalities reacted by significantly curtailing demands, but it was impossible to assess what level of curtailment could be considered reasonable or how it would preserve reservoir supplies - because no one knew just how severe and prolonged the drought would be. In some areas, unbeknownst at the time, they were experiencing a new drought of record.

Figure 4: Courtesy dock at Foss Reservoir during the 2011 drought

Finally, due to record rainfall in the late summer of 2015, the drought in Oklahoma ended as quickly and intensely as it had begun. With it, came a renewed interest by federal, state, and local officials to make sure they were better prepared for the next drought. The cornerstone of this effort entailed a close reexamination of the different assumptions that go into understanding how to predict the reliability of reservoir supplies. This started with revisiting one of the most critical assumptions in this equation: *that future droughts will mimic those that we have experienced in the past*.

Understanding Drought

The southern Great Plains region, including southwest Oklahoma, is particularly vulnerable to drought because, aside from climatic patterns, many areas lack the topography and climate needed to generate snowmelt that can feed streams that flow into reservoirs where it is stored for beneficial use. Rather, the reservoirs depend almost entirely on rainfall, as well as runoff and base flows generated by connecting aquifers. Once water is in storage, temperature becomes a big factor because it contributes to evaporation which reduces the amount of water in storage. Thus, the combined impact of temperature and precipitation provides a good indication in southwest Oklahoma of not only the severity of a drought, but how that impacts reservoir supplies. One method of measuring the combined effect of these variables on the relative dryness of an area is through the Palmer Drought Severity Index (PDSI). The PDSI uses temperature and precipitation data to estimate relative dryness on a ten point scale {-10 (dry) to +10 (wet)}, and it has been reasonably successful at quantifying long-term drought[2]. In Figure 5 below, measurements of temperature, precipitation, and PDSI show that west-central Oklahoma has experience four major droughts on record: mid-1930s, mid-1950s, late-1960s/early-1970s, and 2011-2015.

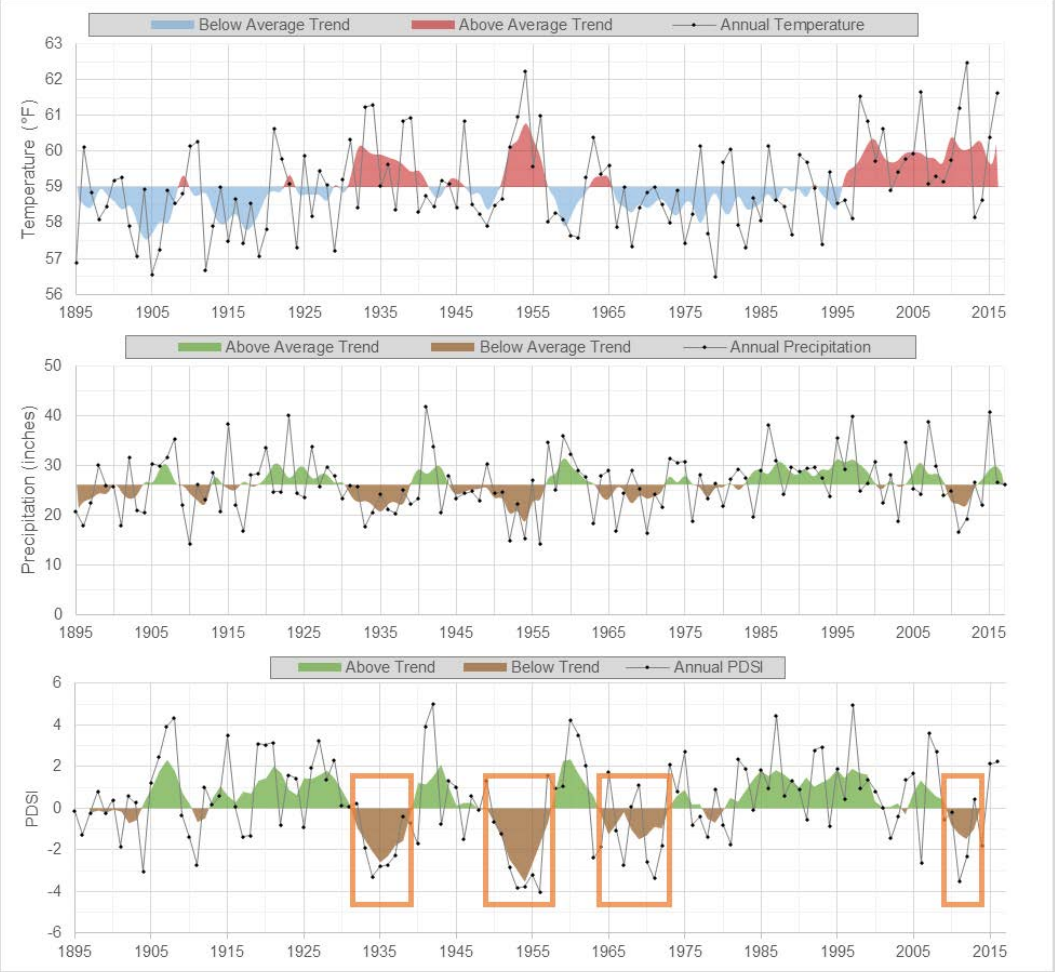

Figure 5: Annual and 5-year running averages for temperature, precipitation, and PDSI (West Central Oklahoma Climate Division 04, http://charts.srcc.lsu.edu/trends. Orange boxes illustrate major droughts on record.

The U.S. Geological Survey (USGS) recently performed a comparison of the 2011 drought with previous drought periods which is useful for putting the extent and severity of the 2011 drought into context (USGS 2013). The drought of the 1930s, known as the “Dust Bowl” in the Great Plains, was particularly severe in western Oklahoma, which led to development of nationwide soil conservation measures. Despite the widely known effects of the “Dust Bowl” of the 1930s, the lesser-known 1950s drought was more wide spread and severe. And while the late 1960s/early 1970s drought lasted even longer than the 1950s drought, it

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[2] National Center for Atmospheric Research

was not as severe. The 2011 drought lasted only a relatively short period of time, but it was as severe (if fact, worse in some areas) than any of the three previously recorded droughts.

However, if one compares the observed PDSI presented in Figure 5 alongside PDSI calculated over a 600-year period using tree ring data, it becomes evident that the droughts observed over the relatively short 90-year period are *far less severe* than the so called “mega droughts” that have occurred throughout the last millennium (Figure 6). Therefore, the key assumption stated earlier, that *future droughts will mimic those that we have experienced in the past*, appears to be fundamentally flawed. In fact, the tree ring data show us the next drought could be much worse than anything we have experienced.

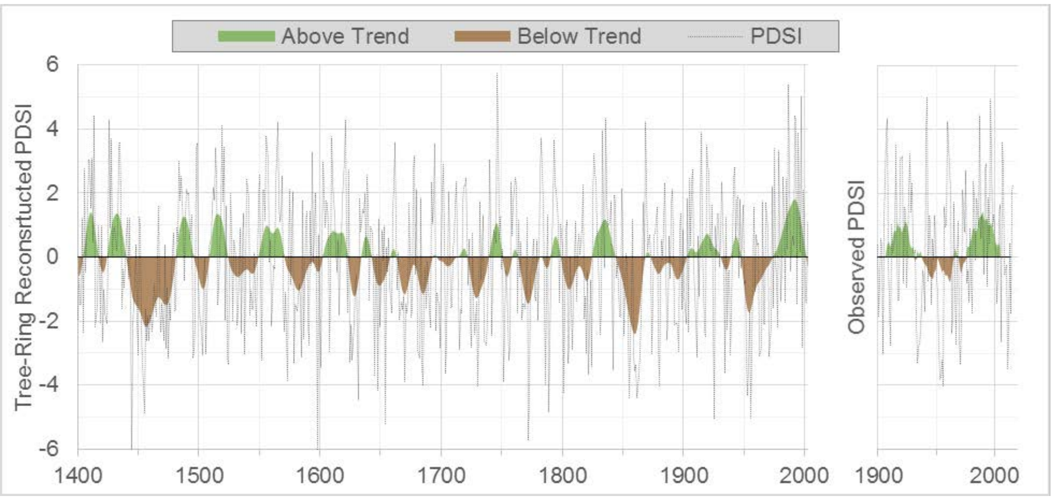

Figure 6: Reconstructed (left side) versus observed[3] (right side) PDSI data over a 600-year period near the study area (Cook et al. 2004).

Understanding Reservoir Yield

As we have demonstrated, it is clear that no two droughts are the same – and such is the case on their subsequent impacts on a reservoir. A droughts duration and intensity will affect reservoirs differently depending on a number of factors including the size and topography of the reservoir and contributing watershed, upstream land use/development, and the influence of groundwater on base flows that contribute to streams flowing into reservoirs. Like many Reclamation reservoirs constructed to deliver M&I water supplies, when Foss and Fort Cobb were designed, the reservoir storage and “firm yield” volumes were calculated as part of a Reclamation Definite Planning Report (DPR). For M&I purposes, a reservoir’s “firm yield” is defined as the volume of M&I water that the reservoir can reliably deliver on an annual basis (at some future date) during a worst case drought scenario based the observed historical record. The term “future” accounts for storage lost to sedimentation; Reclamation’s DPRs typically assumed a 100-year sedimentation period into its firm yield estimates. From a historical context, the firm yield is important because it represented the amount of water rights the MCDs could secure from the State prior to reservoir construction and prior to entering into a repayment contract with the United

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[3] Observed PDSI in this graphic does not capture the 2011 drought

States. Looking today and towards the future, the firm yield is important because it represents the amount of water that is “*supposed”* to be dependable during the most critical drought, and thus should theoretically provide a foundation by which local officials may react during a drought or plan the development of alternative water resources to supplement or augment reservoir supplies in order to prolong and secure M&I water supplies. After all, M&I supplies are considered critical to public health and sanitation, and to local economies that may depend entirely on a reservoir for their growth and prosperity, let alone their existence.

However, a reservoir’s firm yield cannot be known with certainty. The firm yield calculation is just that: a “calculation”. At Reclamation’s OTAO, the calculation is performed using a mass balance excel-based computer model (i.e., Firm Yield model). The Firm Yield model includes different variables, discussed in detail below, that are based on a set of assumptions on *future* conditions. The future conditions are based, in large part, on observed historical data collected over time - so the firm yield is neither absolute nor fixed - it is an *assumed* volume based on *assumed* future conditions. These assumptions are important because they determine our understanding of risks and vulnerabilities, and ultimately guide decisions and investments in water management strategies that aim to reduce risks and improve overall supply reliability.

But what if our firm yield estimates are incorrect? If the estimate is too low, investments could be made in supplemental supplies to withstand a drought that may never come to fruition; but if the estimate is too high, it could lead to a false sense of security or inaction – and investments are avoided that otherwise should have been made in order to withstand a critical drought. The questions are, what assumptions are decision-makers comfortable with, what is an acceptable level of risk, and how does this inform ones willingness to make investments into the future? This requires a closer examination of the strengths and weaknesses of tools and data we currently have and whether opportunities exist to improve our assumptions.

Existing Data and Tools

Reclamation’s Firm Yield Model

As previously stated, standard practice has been to define a reservoir’s firm yield as the maximum amount of M&I water that can be consistently withdrawn annually from the reservoir without completely depleting the reservoir through the historical observed drought of record. The firm yield is calculated using an excel-based model that simulates monthly reservoir volume based on inputs into and losses from the reservoir (Figure 7). The details of how these data are collected and the assumptions that go into calculating firm yield are described below.

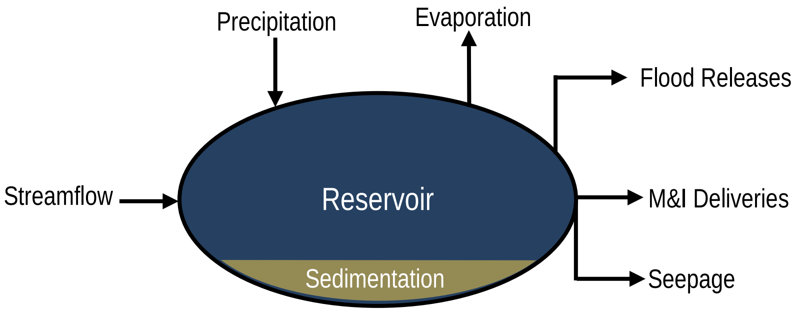

Figure 7: Schematic of Reservoir Firm Yield model

Firm Yield Mass Balance Equation:

[**Starting Reservoir Volume** (includes sedimentation)] + [**Inflow** (Streamflow + Precipitation)] – [**Losses/Uses** (Evaporation + Seepage + Flood Releases + Downstream Releases + M&I Deliveries)] = **Ending Reservoir Volume**

Starting Reservoir Volume

The initial reservoir starting volume is arbitrary as long as the modeled reservoir fills before the modeled drought-period begins.

Sedimentation

The accumulation of sediment is a significant factor that can reduce the volume of a reservoir. The amount of sediment accumulated is estimated using field data collected during a sediment survey. The observed sediment conditions over time are used to project a rate of future sediment accumulation. These data are used to generate an "area-capacity curve" which is built into the Firm Yield model and correlates the future sediment condition to an assumed future reservoir volume and surface area. In the case of the current Firm Yield model for Foss and Fort Cobb Reservoirs, the projections are made out to year 2060. Thus, it is important to stress that the reservoir firm yield is calculated under *future sediment conditions* (i.e., it is a *future* yield that accounts for accumulations of sediment over time).

Inflow

Inflow to the reservoir is comprised of streamflow and precipitation. As previously stated, current practice is to use observed (or extrapolated) inflows as the primary predictor of future inflows into the reservoir. In the case of Foss and Fort Cobb Reservoirs, as indicated in the projects' DPRs, inflow data are considered reliable for the purposes of calculating reservoir yield beginning in 1926. For the purposes of this report, the inflow record is extended through 2015, resulting in 90 years of inflow data for both reservoirs.

Streamflow

Streamflow, which comprises the most significant contribution of inflow into the reservoir, is accounted for differently depending on whether the record exists before or after the reservoir was constructed. For pre-construction periods, streamflows into the reservoir are extrapolated and reported in the project DPRs using gage data within the subject river basin, if available, although the data are adjusted depending on the location of the gage relative to the reservoir. If gage data are not available within the basin, streamflow may be generated using correlations developed based on gage data from an adjacent river basin. In either case, the DPR data are entered directly into the Firm Yield model. For post-construction periods, streamflows into the reservoir are back calculated as “computed inflows” using actual observed end-of-month reservoir conditions as reported in Reclamation’s monthly Water Supply Reports. These conditions are based on known reservoir levels and on assumed losses from reservoir releases, and assumed evaporation, seepage, etc. which are described below in the “Losses” section.

Precipitation
Rainfall on the reservoir surface is another source of inflow to the reservoir. Rainfall rates are taken from the recorded values in the Water Supply Report. Missing precipitation data in the monthly Water Supply Report are extrapolated using data available from the nearest Oklahoma “Mesonet” monitoring station[4]. Precipitation data are not accounted for separately by the Firm Yield model; rather, they are added into the “net evaporation” calculation described below.

Uncertainty - Future Changes in Inflow
It is recognized that neither streamflow nor precipitation are static, and that historical trends may not be an accurate predictor of future inflows into the reservoirs. However, predicting these future changes is complicated. We know that streamflow can be affected by a variety of factors including changes in upstream land use and water demands, and that precipitation can be affected by changes in future climate patterns. The challenge is identifying appropriate methods to account for these changes using best available data and tools - which is one of the reasons this Pilot Study is being undertaken. It is worth noting here again, that this Pilot Study is focusing on influences on inflow associated with climate patterns; impacts associated with upstream land use and water demands are being evaluated as part of the Upper Washita Basin Study.

Losses/Uses

Losses from the reservoir include evaporation, seepage, flood releases, required downstream releases (if applicable), and M&I deliveries.

Reservoir Evaporation
Evaporation rates are calculated as “net” rates, beginning in 1926, that account for inputs generated by precipitation. The net evaporation rate is applied to the running reservoir surface area calculated in the model to generate a volume of reservoir evaporation (net evaporation has an inverse relationship with reservoir surface area). The storage calculations are based on the original surface area versus elevation capacity data provided from the DPR, not the future sediment-reduced area capacity in order to account for reservoir fringe losses and evapotranspiration.

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[4] The Oklahoma Mesonet is a network of monitoring stations that measure various weather conditions throughout the state: https://www.mesonet.org/

Reservoir Seepage

Seepage occurs when stored reservoir water is lost through percolation into the ground and/or underneath the dam. Seepage is difficult to quantify, although some measurements can be made at a dam's toe drain outfall (for example). In the case of Fort Cobb Reservoir, the toe drain measurements are included in Reclamation's Water Supply Report. These measurements can then be used to reduce pre-construction stream flow data (reported in the Project DPRs) to ensure that pre-construction stream flows are consistent with post-construction computed stream flows, which inherently include seepage losses based on end-of-month reservoir conditions. In the case of Foss and Fort Cobb Reservoirs, seepage was assumed as negligible in the Project DPRs.

Reservoir Flood Releases/Spills

When net inflow into the reservoir exceeds storage limits within the top of the reservoir conservation pool, the "excess" volume above the conservation pool is "spilled" (i.e., released) from the reservoir. These losses are calculated directly by the Firm Yield model. In any month when a spill occurs, the end-of-month reservoir content will be equal to the content at the top of the conservation pool. In a month where no spilling occurs, the model will show the spill to be zero.

Downstream Releases

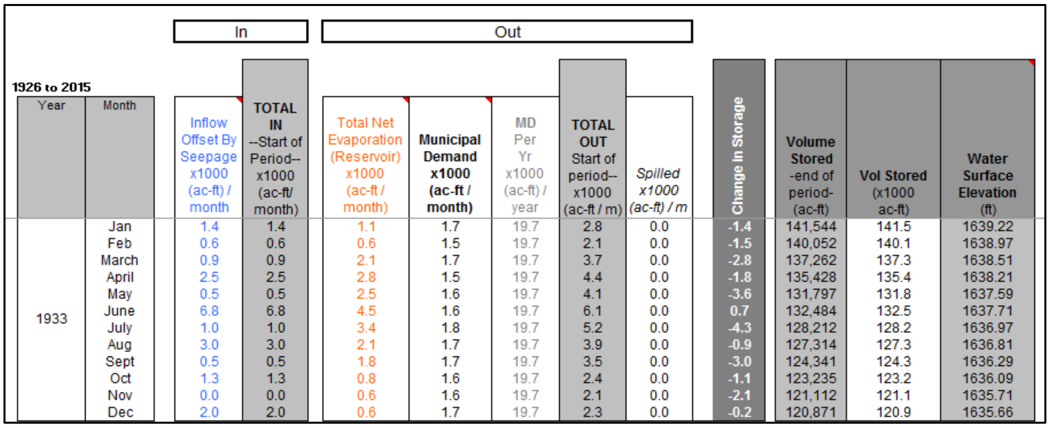
A reservoir may be required to release a specified amount of water over certain periods of time to fulfill legal or institutional requirements/agreements. Typically, releases would be associated with meeting minimum flow requirements for a specific purpose (water rights, ecosystem needs, etc.). In such cases, the Firm Yield model will account for these losses. No downstream releases are required for Fort Cobb Reservoir. Foss Reservoir has a variable downstream release requirement associated with discharge of waste brine generated by their desalination plant.

M&I Deliveries

The Firm Yield model reduces reservoir volume by the amount of M&I water assumed to be delivered over the period of record. The amount of annual M&I water delivered may be equal to the water right or to the projected water demand in, for example 2060, which is the year used for the projection of future sediment conditions. In either case, the model assumes a constant annual M&I water delivery rate for the entire period of record. However, monthly M&I deliveries are adjusted to account for varying demands that may change throughout the year (i.e., peaking during the summer).

Ending Reservoir Volume and Firm Yield

For each monthly time step, the Firm Yield model uses the data described above to calculate the ending reservoir volume. The ending volume for each month then becomes the starting volume for the subsequent month. Repeating this process for a chosen study period results in simulated monthly reservoir storage over that period. Figure 8 illustrates a portion of the Firm Yield model platform.



1926 to 2015		In		Out								
Year	Month	Inflow Offset By Seepage x1000 (ac-ft) / month	TOTAL IN --Start of Period-- x1000 (ac-ft/ month)	Total Net Evaporation (Reservoir) x1000 (ac-ft / month)	Municipal Demand x1000 (ac-ft / month)	MD Per Yr x1000 (ac-ft) / year	TOTAL OUT Start of period-- x1000 (ac-ft / m)	*Spilled x1000 (ac-ft) / m*	Change in Storage	Volume Stored -end of period- (ac-ft)	Vol Stored (x1000 ac-ft)	Water Surface Elevation (ft)
1933	Jan	1.4	1.4	1.1	1.7	19.7	2.8	0.0	-1.4	141,544	141.5	1639.22
	Feb	0.6	0.6	0.6	1.5	19.7	2.1	0.0	-1.5	140,052	140.1	1638.97
	March	0.9	0.9	2.1	1.7	19.7	3.7	0.0	-2.8	137,262	137.3	1638.51
	April	2.5	2.5	2.8	1.5	19.7	4.4	0.0	-1.8	135,428	135.4	1638.21
	May	0.5	0.5	2.5	1.6	19.7	4.1	0.0	-3.6	131,797	131.8	1637.59
	June	6.8	6.8	4.5	1.6	19.7	6.1	0.0	0.7	132,484	132.5	1637.71
	July	1.0	1.0	3.4	1.8	19.7	5.2	0.0	-4.3	128,212	128.2	1636.97
	Aug	3.0	3.0	2.1	1.7	19.7	3.9	0.0	-0.9	127,314	127.3	1636.81
	Sept	0.5	0.5	1.8	1.7	19.7	3.5	0.0	-3.0	124,341	124.3	1636.29
	Oct	1.3	1.3	0.8	1.6	19.7	2.4	0.0	-1.1	123,235	123.2	1636.09
	Nov	0.0	0.0	0.6	1.6	19.7	2.1	0.0	-2.1	121,112	121.1	1635.71
	Dec	2.0	2.0	0.6	1.7	19.7	2.3	0.0	-0.2	120,871	120.9	1635.66

Figure 8: Sample of a portion the Firm Yield model platform, Foss Reservoir

The modeled storage simulation can then be run to determine the reservoir firm yield by increasing the annual M&I water delivery rate until reservoir storage is depleted to a point where it almost reaches the dead storage pool elevation but does not actually enter the dead storage pool (i.e., does not go dry). Figures 9 and 10 illustrate this process for Foss and Fort Cobb Reservoir over the 90-year period of record. The graph reveals firm yields of 19,700 acre-ft/yr for Foss Reservoir and 19,200 acre-ft/yr for Fort Cobb Reservoir. These values represent the maximum amount of M&I water that can be delivered on an annual basis through the critical drought period without the reservoir going dry assuming 2060 sediment conditions.

Figure 9: Firm Yield model simulation of Foss Reservoir storage during a repeat of the 1970s drought of record, revealing a firm yield of 19,700 acre-ft/yr.

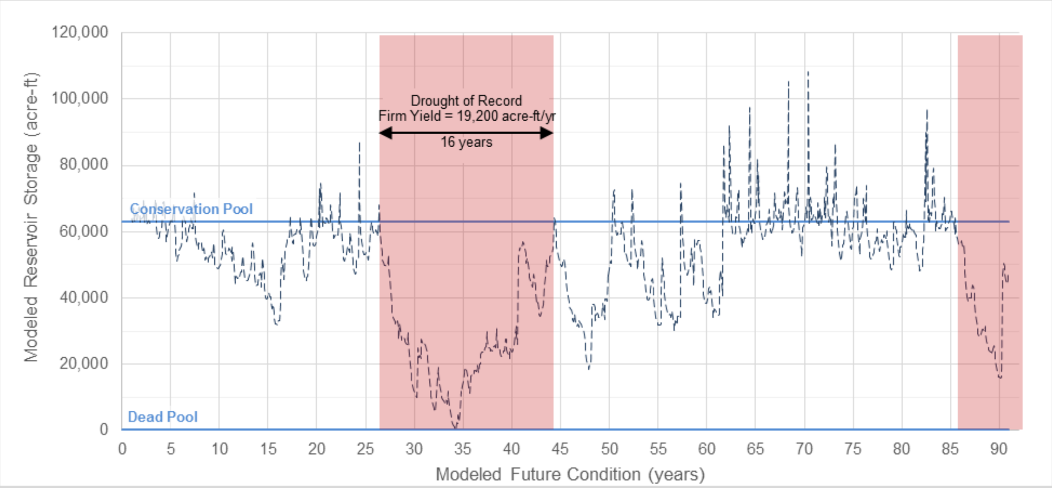


Figure 10: Firm Yield model simulation of Fort Cobb Reservoir storage during a repeat of the 1950s/1960s drought or record, revealing a firm yield of 19,200 acre-ft/yr.

The benefits of the Firm Yield model become apparent when one compares the modeled future storage to actual observed reservoir conditions. For example, the observed historical reservoir conditions displayed in the top of Figure 11 show Foss Reservoir filling with water between 1961 (date of dam construction) and 1977. However, the modeled future storage of Foss Reservoir displayed in the bottom of Figure 11 reveals that the most critical "drought of record" affecting the reservoir actually occurred between 1961 and 1987, which coincided with the time that the reservoir was filling. The observed condition, therefore, masks the true impacts of the drought of record on reservoir yield; the observed condition also could be (falsely) interpreted as showing the 2011-2015 drought as the drought of record rather than the period between 1961 and 1987.

Similar conclusions can be seen at Fort Cobb Reservoir. Observed historical reservoir conditions displayed in the top of Figure 12 show Fort Cobb Reservoir filling with water between 1959 (date of dam construction) and 1962. However, the modeled future storage of Fort Cobb Reservoir displayed in the bottom of Figure 12 reveals that the most critical "drought of record" affecting the reservoir began before the dam was constructed in the early 1950s and extended into the late 1960s. Similar to Foss Reservoir, the observed condition of Fort Cobb Reservoir masks the true impacts of the drought of record on reservoir yield and does not accurately portray the magnitude/duration of the 2011-2015 drought relative to the drought of record between 1952 and 1968.

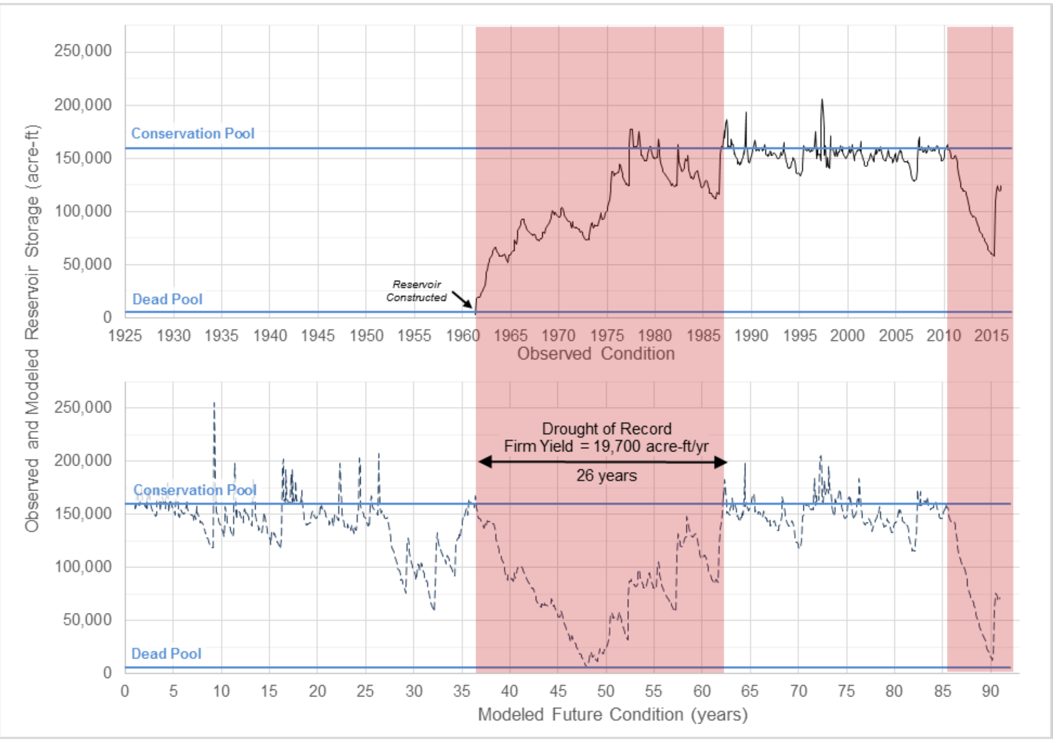


Figure 11: Top: observed historical reservoir conditions of Foss Reservoir. Bottom: modeled future storage of Foss Reservoir.

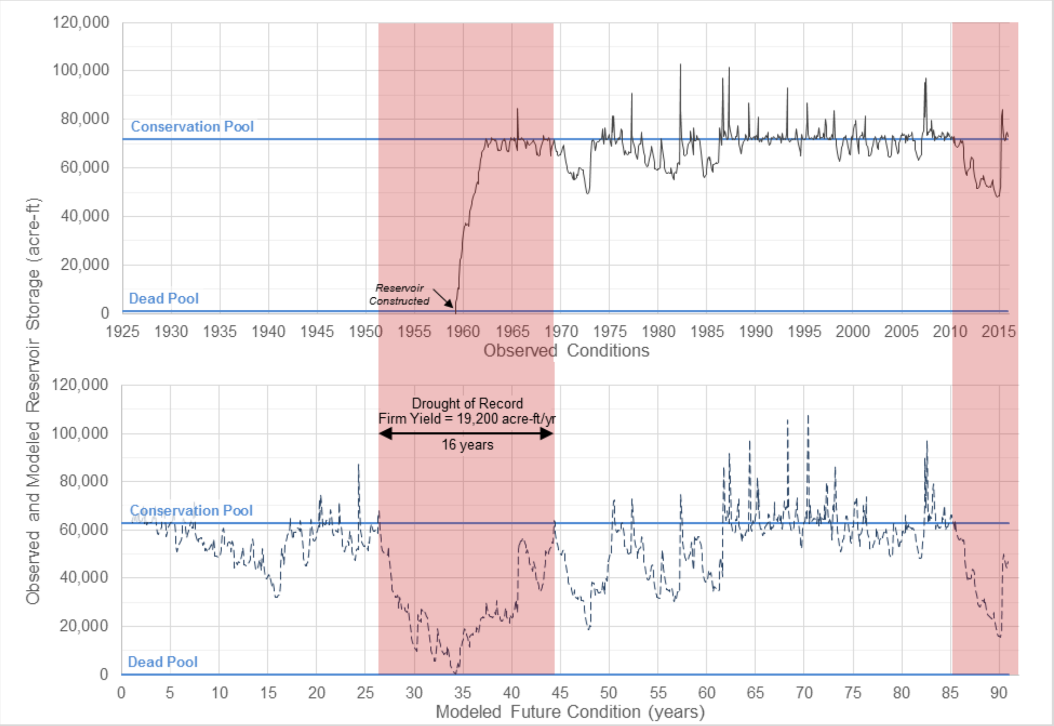


Figure 12: Top: observed historical reservoir conditions of Fort Cobb Reservoir. Bottom: modeled future storage of Foss Reservoir.

Constraints and Opportunities

Firm Yield model and Data Limitations

The model simulations clearly demonstrate the Firm Yield model's usefulness as a risk management tool to better predict how much M&I water a reservoir could deliver during a critical drought scenario. However, like any risk assessment, it is important to not only recognize the limitations of the tool being used to manage risk, but also to identify the extent to which those limitations can actually be addressed. For example, predicting future sediment losses based on an assumed reservoir area-capacity curve can be challenging because local conditions may change sedimentation rates over time; as well, the frequency and science of collecting sedimentation data may change over time. Seepage losses also are difficult to quantify and predict, namely because we lack technologies to detect and measure seepage in a meaningful way at large reservoirs.

By far the biggest contributing variable to the firm yield equation is streamflow. As such, it generates the greatest source of uncertainty in the Firm Yield model. Stream flows themselves are comprised of a complex set of inputs and losses that change over time. Inputs are primarily comprised of runoff from precipitation, as well as from base flows generated from underground aquifers that connect to the stream. Losses in streamflow are comprised of evaporation and seepage, and from diversions from the stream itself or from the pumping of an aquifer that contributes base flows to the stream. For the most part, the observed end-of-month reservoir conditions already account for these inputs/losses because they are included within the post-construction computed streamflows performed by the Firm Yield model. As previously discussed, computed pre-construction streamflows typically involve using adjustments made in the Project DPRs. In either case, the past is used as an indicator of the future.

In terms of predicting the future, one major challenge lies with identifying historical trends and differentiating between those impacts on streamflow that are human-induced versus those that are climate-induced. Identifying trends in human-induced impacts is relatively easier than identifying trends in climate-induced impacts because (1) human-induced impacts have occurred over a shorter, more recent historical time period, making them less variable; for instance, the vast majority of development and water use upstream of Foss and Fort Cobb Reservoirs began after their respective droughts of record in the 1970s and 1950s; and (2) human water use can generally be either directly reported, measured or otherwise estimated based on the amount and volume of permits, or in the case of domestic use, the amount of non-permitted groundwater wells. Human use also can be estimated via tools such as satellite imagery. Furthermore, predicting future human water use is fairly straightforward and comprised of standard approaches involving the use of data/trends associated with land use and development, population growth, amount and types of water use, etc. In the case of Foss Reservoir, the DPR assumed that computed historical streamflows repeat themselves into the future, but applied a 12 percent reduction in future flows attributable to future human-induced upstream impacts (i.e., diversions, flood retention structures, etc.), while for Fort Cobb Reservoir, the DPR applied a 32 percent reduction to streamflows due to upstream water use and changes in land use. These reductions were based on numerous assumptions given the limited amount of data that were available at the time. They did not take into account the reality that historical trends often change over time, nor did they account for actual differences between those impacts on streamflow that are human-induced versus those that are climate-induced.

On the other hand, predicting future climate-induced impacts is more difficult because (1) the period after which record keeping began provides only a snapshot of historical climate conditions, meaning that the variation in climate that has occurred over centuries may not be captured; (2) it requires measuring and/or accounting for an abundance of variables that can be difficult to understand and predict. In the case of Foss and Fort Cobb Reservoirs, neither of the DPRs accounted for or made predictions about future climate-induced changes in streamflow – they simply assumed that the future would replicate the past.

Recognizing limits of the Firm Yield model and associated data, efforts are currently underway (discussed below) within the study area to develop tools that improve how we quantify and predict gains and losses in streamflow as well as evaluate strategies to help improve water supply reliability. In some cases, these tools and data will directly enhance the prediction capabilities of the Firm Yield model; in other cases, new approaches are being developed that could compliment the Firm Yield model or are filling a niche that the Firm Yield model cannot provide.

Existing and Ongoing Studies

To quantify impacts from upstream development/water use on reservoir yield, the ongoing WaterSMART Upper Washita Basin Study (UWBS) is combining results from a USGS MODFLOW groundwater model with results from an Excel-Central Resources Surface Water Allocation Model to generate new inflow data sets that will be input into the Firm Yield model to simulate impacts on reservoir yield. Similarly, to quantify changes in future runoff, as part of the UWBS' climate risk assessment, a Variable Infiltration Capacity (VIC) Model is being developed to simulate changes in runoff over a 30-year future period (2045-2074) in comparison to a 50-year historical period (1950-1999); again, the VIC outputs will serve as new inflow data sets and will be incorporated into the Firm Yield model. The combined results from these models can provide a fairly robust range of reservoir yields that might be expected under a wide range of future conditions, but importantly, these analyses also have limitations. Namely, the UWBS climate risk assessment still incorporates a relatively recent and short period of record as a reference period by which to compare future changes in climate.

Another recently completed effort is the Foss Reservoir Drought Contingency Plan (DCP). Using federal cost-share funds provided under Reclamation's Drought Response Program, a task force comprised of various stakeholders evaluated a range of mitigation strategies that help build long-term resiliency to drought; the task force also evaluated response strategies that would be implemented during the midst of a drought. In either case, the supply reliability of Foss Reservoir is a key aspect of the DCP. When weighing different mitigation strategies that build long-term resiliency, one local official exclaimed at a drought task force meeting, “before we go spend our hard earned tax-payers money on pursuing alternative supplies to our bucket (i.e., Foss Reservoir), we need to have a better idea how much water we have in the bucket!” This comment was made during a discussion about the severity of the 2011 drought, which caused Foss Reservoir to drop to a record low within inches of the water supply intake. One of the primary questions asked by the task force was whether the 2011 drought was worse than the 1970s drought of record. Reclamation subsequently used the Firm Yield model to determine that the 2011 drought, while very intense, was relatively short and was therefore *not* worse than the 1970s drought. Nevertheless, it was too close for comfort, and stakeholders expressed serious concerns about what storage levels would have looked like had the drought continued. To address these concerns, in addition to identifying long-term strategies to potentially augment Foss Reservoir supplies, the task force established reservoir elevation levels under the DCP that would trigger different response actions (i.e., demand curtailments/conservation measures). Three response triggers were established: “Watch”, “Warning”, and “Emergency”. Furthermore, the task force asked Reclamation to use the Firm Yield model to predict what the reservoir yield would be under various severe drought scenarios – beyond the 1970s and 2011 droughts. They also want to know the extent to which demand curtailments could prolong reservoir storage under these various drought scenarios.

The 2011 experience that was felt by users of Foss Reservoir was shared by users of another Reclamation reservoir in the adjacent river basin: Tom Steed Reservoir. Like Foss Reservoir, Tom Steed provides M&I water to several communities in southwest Oklahoma. As the 2011 drought unfolded, Reclamation collaborated with local officials in using the Firm Yield model to make near-term predictions on how the drought could continue to affect reservoir levels under a combination of near-term climate, inflow, and demand scenarios. The model was then used to evaluate how demand curtailments could prolong reservoir supplies; ultimately, results were used by local officials as a basis for implementing water conservation measures that proved critical towards withstanding the severe drought. Indeed, the Firm Yield model proved itself as a user-friendly tool that can quickly generate results, despite having to process a variety of complex variables.

However, one of the key limitations of the Firm Yield model that was revealed during the Tom Steed Reservoir 2011 drought experience was the model’s weakness at combining near-term climate and streamflow forecasts with real-time demand changes to make informed predictions on reservoir yield. During the 2011 drought, local officials were “flying blind” because near-term climate and stream forecasting in the southern Great Plains is particularly difficult. Officials were left to make fairly simplistic and arbitrary assumptions about what reservoir storage would be if, for example, the last nine months of streamflow repeat themselves versus the last six months and so on. Further complicating the issue was that the Model lacked the ability to account for actual changes in water demand that could or would be occurring over those same time periods. Indeed, knowing what water is leaving the reservoir is every bit as important as knowing what is flowing in.

Opportunities for a Pilot Study

Despite the positive steps already being taken in the examples cited above, opportunities exist to build upon the science and further improve the tools available that can predict reservoir yield, both in the near term and long term. It was previously stated that standard practice has been to assume future inflows into the reservoir mimic historical inflows which have been collected over a relatively short 90-year period. A similarly narrow time period also is being used by the UWBS' climate risk assessment. However, Figure 6 previously showed how the duration and intensity of droughts observed in southwest Oklahoma during the 90-year period of record *are far less variable* than so called "mega-droughts" (i.e., "paleo-droughts") *that are known to have occurred* (but were not directly observed) over centuries based on data collected from tree rings. An opportunity exists therefore to improve our understanding of how variations in climate can affect reservoir yield by extending the length we can look backwards in time; doing so will provide water managers a better glimpse into how the future may unfold both in the near term and long term. The question now is, how can we use the tree ring data in a meaningful way to make assumptions about future droughts and their impacts on M&I reservoir supplies?

Furthermore, in the midst of a drought, given the lack of forecasting tools available in the area, standard practice has been to make fairly simplistic and arbitrary assumptions about inflow and losses. An opportunity exists therefore to improve our understanding of how we can make more informed near-term projections, while also taking into consideration losses in storage caused by actual water use.

Study Objectives

Recognizing the benefits that could come out of such an analysis, the Reservoir Operations Pilot (ROP) Study sought to do the following:

1. Develop a method of converting tree ring data into new inflow datasets that can be incorporated into Reclamation's Firm Yield model. By extending the historical period, we would capture a greater range of variation (i.e., cycles of wet and dry periods; duration and intensity of droughts) than that which we currently capture using existing practices, thereby providing us with a more robust calculation of the range of reservoir firm yields that reflect impacts from paleo droughts. This would help inform long-term planning efforts and better prepare for the next drought (i.e., *enhanced drought preparedness*).
2. Develop a method of using the new Firm Yield model supply calculations created under No. 1 to make enhanced near-term projections, while also accounting for actual water use.
3. Use the "Enhanced" Firm Yield model to evaluate "what if" demand management scenarios and identify the associated risks of a M&I reservoir going dry based on the type of drought you may (or may not) be experiencing (i.e., *enhanced drought response*).

PART II:

IMPACTS OF PALEO DROUGHTS ON RESERVOIR YIELD

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PART II: IMPACTS OF PALEO DROUGHTS ON RESERVOIR YIELD

Methods: Conversion of Tree Ring Data into New Inflow Sequences

The data and methodology used to generate inflow sequences from tree ring data for the firm yield analysis of Foss and Fort Cobb Reservoirs are presented here. This entailed using existing tree ring data and reconstructed annual summer PDSI data over a 616-year historical period (year 1400-2015). Next, the PDSI data were evaluated following a "stochastic resampling methodology" to determine the annual wet-dry "transition probabilities" over the 616-year period. This PDSI time-series in conjunction with the existing inflow time-series for each reservoir was then used in a stochastic resampling framework to develop new inflow sequences. These generated inflow sequences were subsequently used in the Firm Yield model to evaluate impacts on reservoir yield.

Overview of "Dendrochronology" and "Dendroclimatology"

Trees are known to provide compelling evidence about the past. Appearing as rings in the cross section of a tree trunk (Figure 13), tree rings can provide evidence of floods, droughts, insect infestations, fires, and even earthquakes. The number of rings generally represents how long the tree has lived, with each year giving rise to a new ring of growth. However, this growth for a given species depends on local conditions such as water availability, with wetter, cooler years generally resulting in more growth, as indicated by thicker rings relative to dryer, hotter years, which result in thinner rings. The term "dendrochronology" refers to the general science of analyzing data from tree ring growth. The more specific application of using dendrochronology to reconstruct the climate of the past using trees is called "dendroclimatology". The method generally entails: (1) comparing modern meteorological records with the widths of tree rings produced during the same period of time; (2) establishing a statistical equation for the relationship between the two and accounting for the biological growth; and (3) substituting the widths of the dated rings in the equation to obtain a statistical estimate of the climate for previous years (Fritts, 1976). Thus, the estimates of

Figure 13: Cross section of a tree trunk, illustrating wet years (thicker rings) versus dry years (thinner rings)

climate from tree rings can substitute for meteorological records and provide valuable information for periods and area where no other meteorological information exists.

Over the last decades, a vast network of tree-ring chronologies has been created, and continues to be created, by scientists across North America and Europe. Called the “International Tree-Ring Data Bank” (http://www.ncdc.noaa.gov/paleo/treering.html), this network has been enabling the reconstruction of large-scale climate patterns over much of North America going back several centuries.

Reconstruction of Summer PDSI Data

Using the existing network of tree ring chronologies previously discussed, Cook et al. (2004) reconstructed summer (June-July-August [JJA]) average PDSI (Palmer, 1965) for most of North America using a 2.5° latitude by 2.5° longitude grid (a total of 286 grid points). The maximum temporal coverage for the reconstructed gridded PDSI data developed by Cook et al. (2004) is 0-2003 AD. As previously stated in Part I, PDSI is a measure of meteorological drought where negative PDSI values indicate dry conditions, while positive values indicate wet conditions. PDSI values generally fall between the range, -6 and +6. Reconstructed PDSI provides a means to assess regional drought variability over an extended time period (Cook et al., 1999; Cook et al., 2004). Figure 14 shows the reconstructed PDSI grid points in the vicinity of the Upper Washita River Basin (UWRB).

As shown in Figure 14, a total of nine reconstructed PDSI grid points are in the vicinity of the UWRB. To select a grid point that best represents drought variability of the UWRB from the nine grid points, a correlation analysis was conducted using observed Foss and Fort Cobb inflows and reconstructed PDSI for each of the nine grid points over the period 1926-2003 (78 years). Table 1 lists the grid points and corresponding correlation results. The correlation analysis showed that grid point 164 had the highest correlation between reconstructed PDSI data and observed inflows and was thus selected for this analysis.

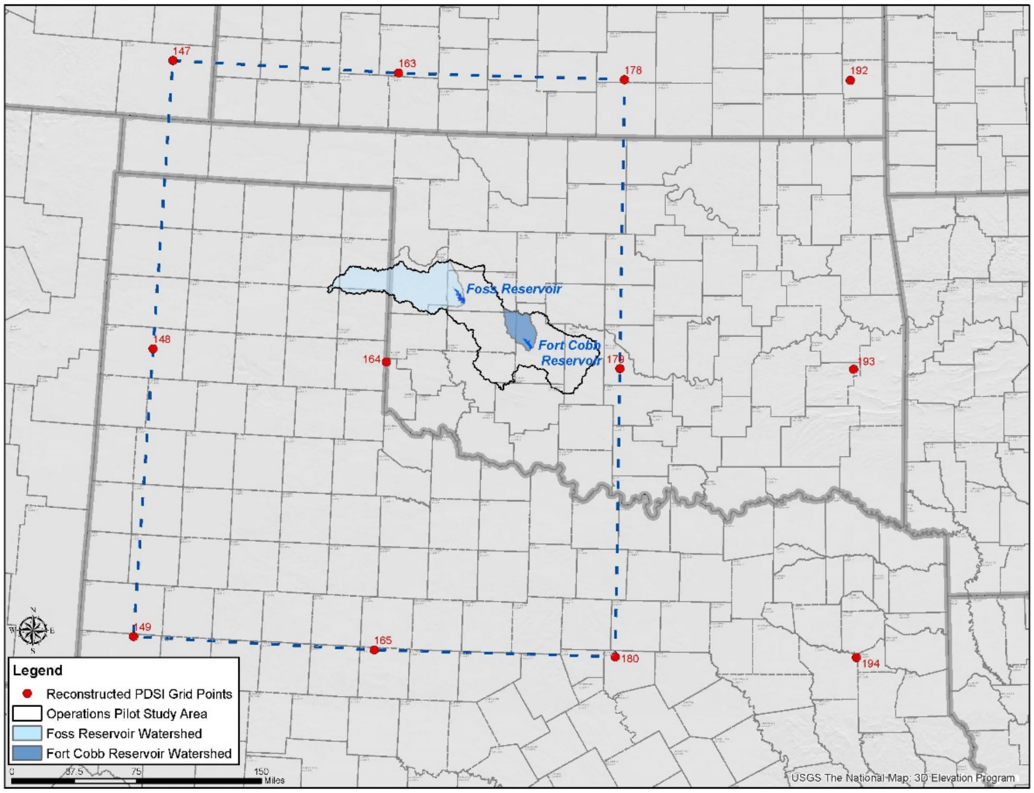

Figure 14: Reconstructed PDSI grid points in the vicinity of the Upper Washita River Basin (blue boundary).

Table 1: Coordinates (latitude in degrees [°] north [N]; longitude in degrees west [°W]) of the nine reconstructed PDSI grid points along with the state, climate division, and PDSI correlation with Foss and Fort Cobb Reservoir inflows.

Reconstructed PDSI Grid Number	Latitude (°N)	Longitude (°W)	State	Climate Division	Correlation With Foss Inflow	Correlation With Fort Cobb Inflow
178	37.50	97.50	KS	8	0.2454	0.5663
163	37.50	100.00	KS	7	0.2880	0.4238
147	37.50	102.50	CO	1	0.2893	0.4910
148	35.00	102.50	TX	1	0.2904	0.3865
149	32.50	102.50	TX	1	0.2249	0.2504
165	32.50	100.00	TX	2	0.2377	0.4442
180	32.50	97.50	TX	3	0.2013	0.5107
179	35.00	97.50	OK	5	0.2013	0.5290
164	35.00	100.00	OK	4	0.3058	0.5563

As illustrated in Figure 15, a total of 136 tree ring chronologies were available within an 800-kilometer radius for the PDSI reconstruction at grid point 164. Within this radius, which was selected based on a “radius-screening probability optimum”, only 33 of the 136 chronologies yielded acceptable statistical calibration and verification results for this grid-point (Cook et al., 2004). Figure 16 illustrates the number of tree-ring chronologies and corresponding reconstructed tree-ring PDSI for grid point 164, along with calibration and verification statistics. Although the PDSI reconstruction data for grid point 164 begins in 837 AD (Cook et al., 2004), the number of chronologies used in each reconstruction are typically quite small in the early years of the reconstruction period. For example, only two chronologies were used in the PDSI reconstruction for this grid point for the years 837-1034 AD. This small sample size (number of chronologies) results in low calibration and verification statistics (e.g., the coefficient of determination [R^2]) in the early years of the reconstruction development process. For grid point 164, the calibration and verification statistical correlations become acceptable beginning in the year 1400, which was based on seven tree-ring chronologies. This time frame, starting year 1400, has also been used in paleohydrologic studies in the western U.S. that used stochastic resampling methodology concepts (e.g., Gangopadhyay et al., 2009).

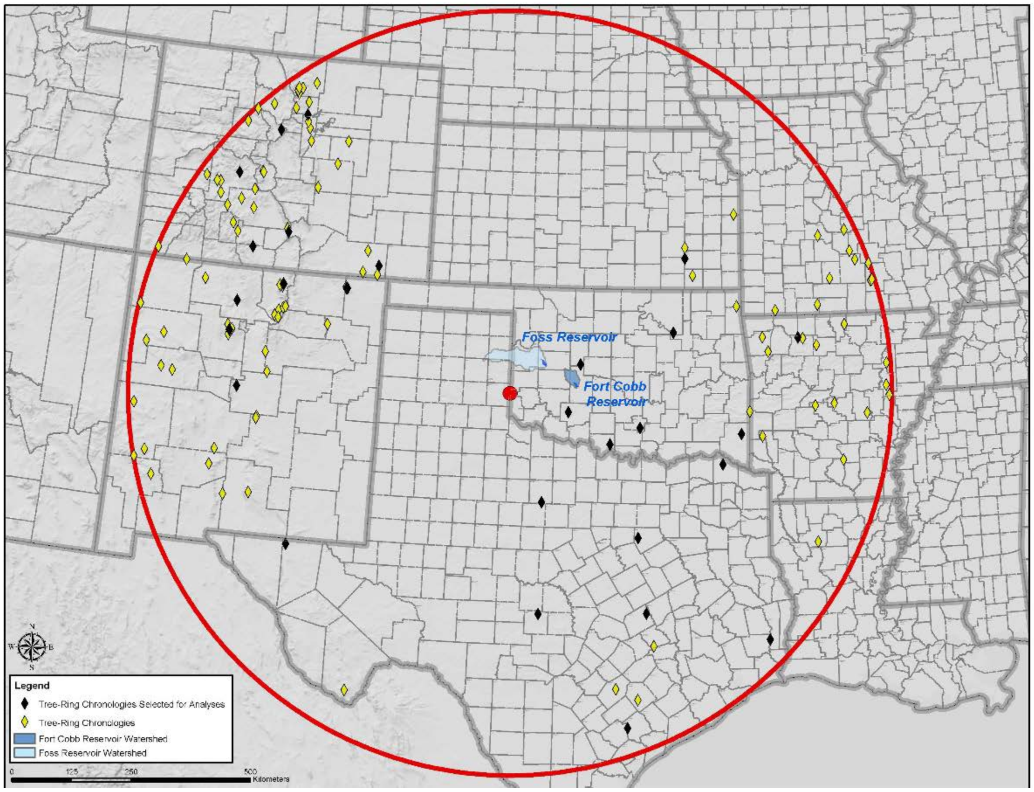

Figure 15: Location of tree-ring chronologies within an 800-km radius of grid point 164.

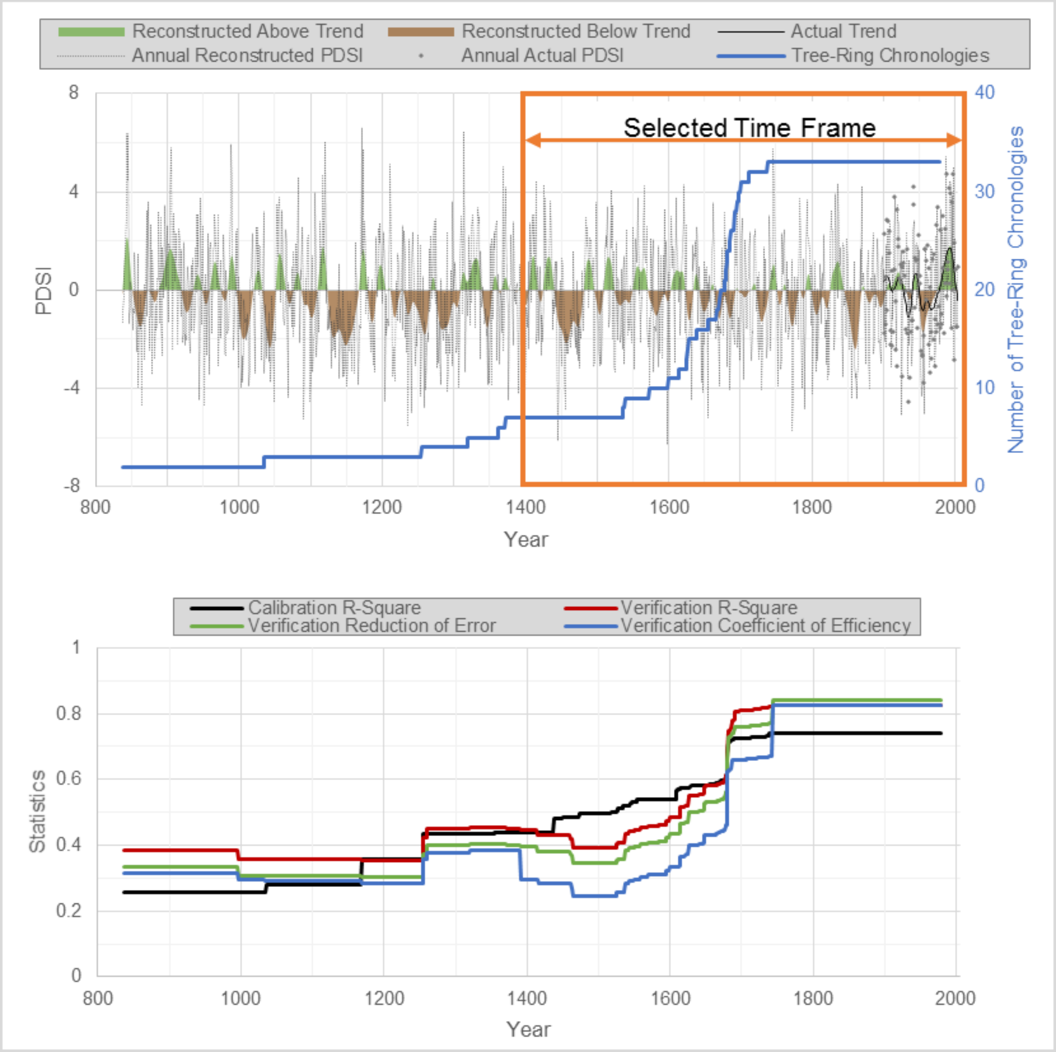

Figure 16: Top: The number of statistically acceptable tree-ring chronologies and corresponding PDSI reconstruction between the years 800 and 2004. The orange box illustrates the time frame used for this analysis. Bottom: statistical calibration and verification results for selected tree-ring chronologies.

Furthermore, the period of analysis for reservoir yield was selected to be 1926-2015 (90 years), and to account for the recent period of drought variability, the PDSI data needed to be extended from 2004 to 2015. Because grid point 164 (Table 1) is located in Oklahoma climate division 4 (see Table 1), PDSI values from this climate division for June, July, and August (JJA) (National Climatic Data Center, 2017) were averaged for the period 2004-2015 and used to extend the period of record to end in 2015. Thus, the PDSI time-series used in this analysis is 616 years and covers the period 1400-2015. The stochastic resampling methodology used to develop the inflow sequences is described in the next section.

Stochastic Resampling Methodology

The stochastic resampling methodology used to develop inflow sequences follows the algorithm described in Prairie et al. (2008). The Prairie et al. (2008) algorithm is a conditional Markov Chain (MC; Haan, 1977) simulation framework that uses time varying (i.e., transient) transition probabilities and nonparametric K-nearest neighbor (K-NN) resampling to develop inflow sequences. In summary, this framework consists of three steps: (1) develop the transient transition probabilities from the reconstructed PDSI data; (2) generate a hydrologic state to initialize (i.e., starting point) along with the selection of the transient transition probabilities for use in MC simulation; and (3) MC simulation to generate flows conditionally using K-NN resampling. A more detailed description of this method is provided in Prairie et al. (2008), where it is referred to as "nonparametric paleo-conditioning". A brief description of these steps follows.

Step 1: To develop the transient transition probabilities, the first operation is to convert the PDSI magnitudes into a state of either wet versus dry information. PDSI values greater than zero (PDSI > 0) were assigned as "wet" (represented by 1), and PDSI values less than and equal to zero (PDSI ≤ 0) were assigned as "dry" (represented by 0). This transforms the original PDSI data into a binary time-series consisting of either 0 or 1. Four states are possible: (i) dry to dry (DD); (ii) dry to wet (DW); (iii) wet to dry (WD); and (iv) wet to wet (WW). Figure 17 illustrates the transient transition probabilities derived from the PDSI data. Transient transition probabilities are derived using the concept of a moving window, where the width of this window is optimally estimated through least squares cross-validation (LSCV) procedure (Scott, 1992). The estimation of the transition probability at any given time centered on the optimal window is a weighted average of the state transitions within this optimal window width. Prairie et al. (2008) used the discrete quadratic kernel function developed by Rajagopalan and Lall (1995) as the weighting function. The optimal window width for the study area was estimated to be 52 years using the LSCV criterion. Thus, accounting for this 52-year window for the overall time series of 1400-2015, the transient transition probabilities (Figure 17) broadly represent dry or wet transitions over the period 1452-1963 (512 years).

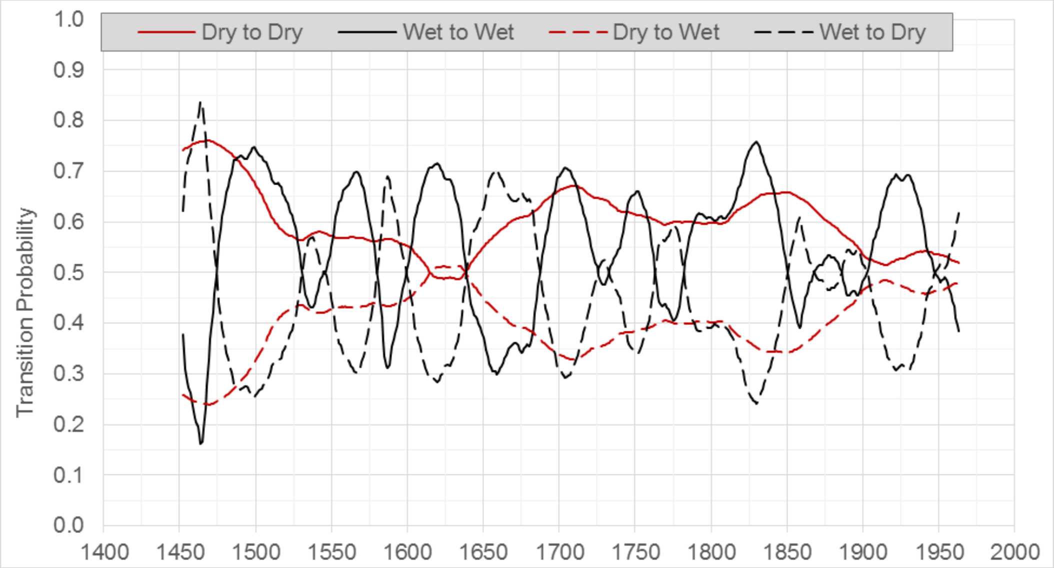

Figure 17: Two state transient transition probability with four transitions – Dry to Dry; Wet to Wet; Dry to Wet; Wet to Dry; derived from the PDSI data.

Step 2: Before beginning the MC simulation, a simulation horizon of *T* years first needs to be selected. In this case, *T*=90 years was used; this corresponds to the length of the historical period used (1926-2015; 90 years). This 90-year time window is then selected at a random starting point over the 512-year period. Whether starting with a randomly selected dry or wet year, the transition probabilities over this 90-year window can be used to develop subsequent states of the hydrologic system over that 90-year period. Note that, until now, all calculations involved information derived only from the PDSI data. In the next part of the calculation, the respective historical observed (1926-2015; 90 years) inflows of Foss and Fort Cobb Reservoirs are used. The median inflows over the historical period for Foss and Fort Cobb Reservoirs were, 48,694 acre-feet and 38,924 acre-feet, respectively. Similar to the PDSI data, for a given reservoir, a historical year was assigned to be either "dry" state (represented by 0), if the magnitude of inflow for the year was less than or equal to the median inflow value, or it was assigned as "wet" state (represented by 1) if the magnitude of inflow for the year exceeded the median inflow value. This step then results in a binary time-series depicting inflow states for the reservoirs. Recall, a two-state (dry or wet) hydrologic system results in four state-transitions (DD; DW; WD; WW). Thus, each year in the historical period can be assigned to one of the four state transition categories.

Step 3: Informed by the states generated from the transient transition probabilities in conjunction with the flow magnitudes, 1,000 randomly selected starting points were used to traverse the transient transition probabilities. These transition probabilities in conjunction with the inflow data were used in the K-NN resampling process (Prairie et al., 2008) to select the sequence of proceeding years (and subsequently their corresponding inflows for the selected year). A total of three sets of inflow data were used in the generation of inflow sequences; these were Foss Reservoir inflow, Fort Cobb Reservoir inflow, and a indexed inflow record (a summation of Foss and Fort Cobb Reservoir inflows). Each generated inflow sequence was 90-years in length resulting in an ensemble of 1,000 realizations (i.e., shuffles) each of length 90-years. Each ensemble member

(3,000 in total, 1,000 for each set of inflow data) was used as an input in Reclamation's Firm Yield model as described in the next section.

Results - Impacts of Tree Ring Inflow Sequences on Reservoir Firm Yield

Reclamation modified its Firm Yield model using Excel's Visual Basic Analysis (VBA) and relied on the preset "goalseek" function that is built into the software to solve for the reservoir firm yield for each shuffle. By utilizing VBA, the model was automated to repeat the previous steps (shuffle and goalseek) for each inflow sequence to provide an output of reservoir firm yield. It is important to note that this process does not use any synthetic or generated data; rather, it utilizes only the PDSI-informed shuffling of the observed records for the two reservoirs. Table 2 below shows a sample of tree ring (paleo) inflow sequences generated using the methods described above, along with the corresponding reservoir firm yield calculations using the inflow data from Foss Reservoir, one of the three sets of inflow data. Overall, a total of 3,000 firm yields were calculated, 1,000 for each of the three sets of inflow data used.

Table 3 provides summary statistics for the 3,000 firm yield calculations generated for this analysis. Figures 18 and 19 plot all 3,000 firm yield calculations for Foss and Fort Cobb Reservoirs, respectively. The reservoirs' respective firm yields as determined by the observed drought of record are plotted for reference.

Table 2: A sample of shuffled paleo inflow sequences and corresponding reservoir firm yield calculations using the paleo inflow sequence based on Foss Reservoir.

Sequence Position	Observed Record	Shuffled Sequence 0001	Shuffled Sequence 0002	Shuffled Sequence 0003	…	Shuffled Sequence 1,000
1	1926	1962	1972	1978	…	1986
2	1927	1976	1973	1941	…	1961
3	1928	1974	1974	2008	…	1928
4	1929	1941	1992	2001	…	1948
5	1930	1943	1974	2009	…	1941
…	…	…	…	…	…	…
89	2014	2011	2005	1942	…	1948
90	2015	1982	2006	1952	…	1949
Foss Reservoir Firm Yield (acre-ft/yr)	19,700	31,000	19,600	24,800	…	21,000
Fort Cobb Reservoir Firm Yield (acre-ft/yr)	19,200	25,100	20,000	23,200	…	24,100

Table 3: Summary statistics for the 3,000 reservoir firm yield calculations generated for Foss and Fort Cobb Reservoirs based on the three sets of paleo-informed inflow sequences. The “observed” firm yields of Fort Cobb and Foss Reservoirs (based on the historical drought of record) are 19,200 acre-ft/yr and 19,700 acre-ft/yr, respectively.

	Paleo Inflow Sequence Based on Foss Reservoir Inflows		Paleo Inflow Sequence Based on Fort Cobb Reservoir Inflows		Palo Inflow Sequence Based on Combined Foss and Fort Cobb Reservoir Inflows	
Reservoir Firm Yield Results (acre-ft/yr)	Fort Cobb Reservoir	Foss Reservoir	Fort Cobb Reservoir	Foss Reservoir	Fort Cobb Reservoir	Foss Reservoir
Maximum	31,200	41,400	30,400	41,900	31,800	43,000
Minimum	15,800	7,400	16,000	9,200	15,300	7,700
Mean	23,000	23,600	22,400	25,000	23,000	24,000
Median	23,000	23,300	22,200	25,000	23,000	24,000
Standard Deviation	2,700	6,000	2,400	5,300	2,700	5,600

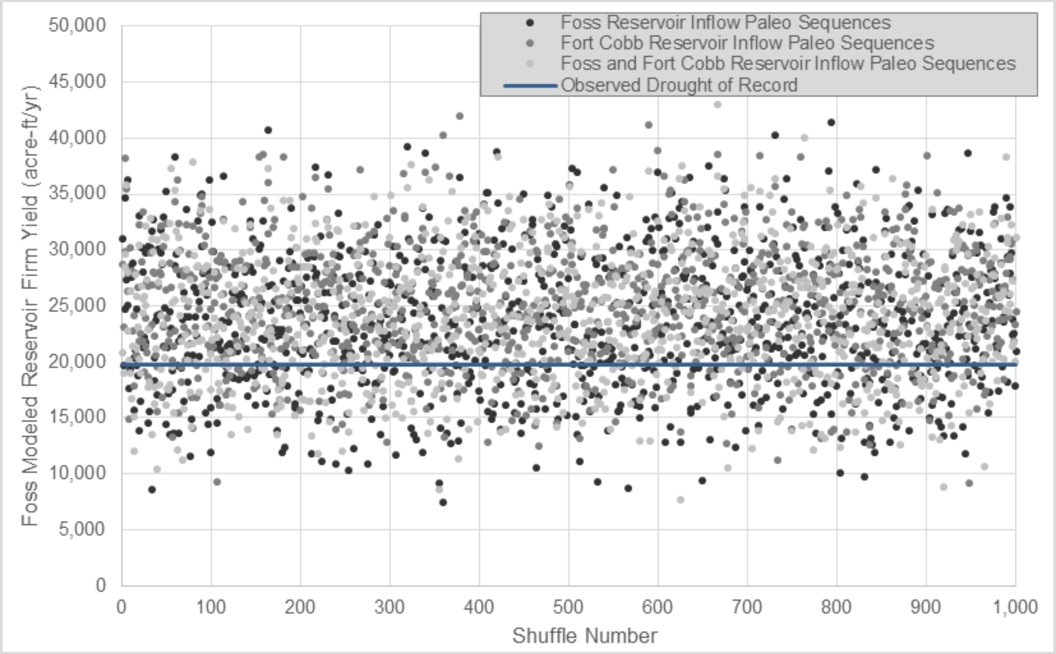

Figure 18: Foss Reservoir firm yield results based on three sets of paleo-informed inflow sequences generated using Foss Reservoir inflow, Fort Cobb Reservoir inflows, and a combination of Foss/Fort Cobb Reservoir inflows. The blue line represents the firm yield based on the observed drought of record.

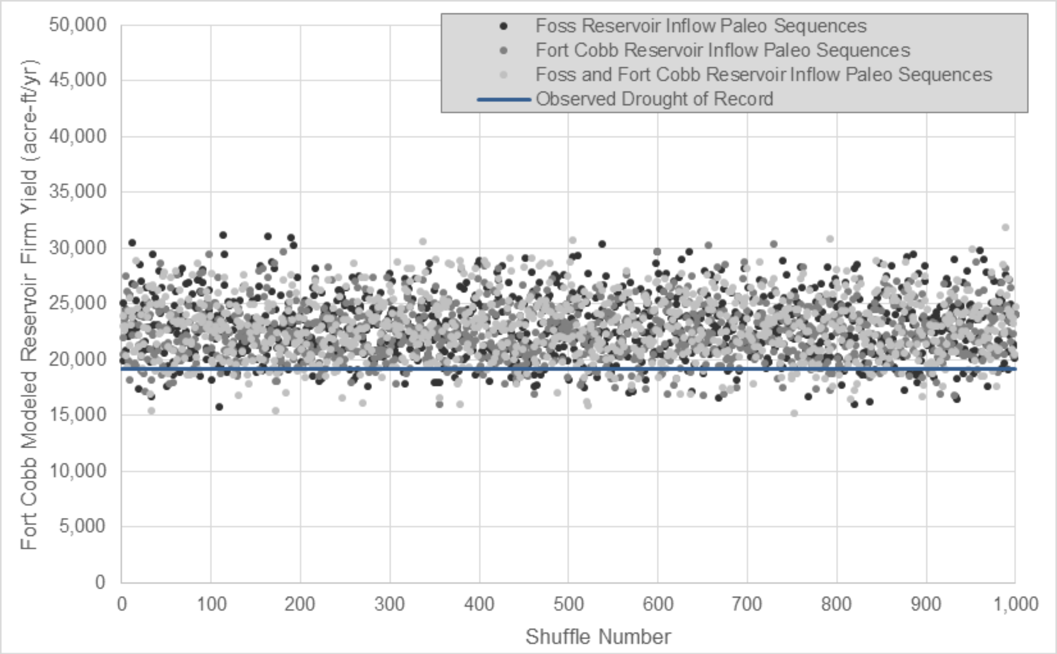

Figure 19: Fort Cobb Reservoir firm yield results based on three sets of paleo-informed inflow sequences generated using Foss Reservoir inflow, Fort Cobb Reservoir inflows, and a combination of Foss/Fort Cobb Reservoir inflows. The blue line represents the firm yield based on the observed drought of record.

Discussion

Returning to our original study objectives previously described, we have accomplished Objective No. 1, which was to develop a method of converting tree ring data into new inflow datasets that can be incorporated into Reclamation's Firm Yield model. By extending the historical period, we have captured a greater range of variation (i.e., cycles of wet and dry periods; duration and intensity of droughts) than that which we currently capture using existing practices, thereby providing us with a more robust calculation of reservoir firm yield that includes impacts from paleo droughts. This would help inform long-term planning efforts and better prepare for the next drought (i.e., *enhanced drought preparedness*). Below, we briefly discuss some of the implications with the results observed thus far and set the stage for accomplishing study Objectives No's 2 and 3.

As expected, the paleo-informed inflow sequences generated a broad range of firm yield calculations for both Foss and Fort Cobb Reservoirs. Foss Reservoir's firm yield estimates range from 7,400 acre-ft/yr to 43,000 acre-ft/yr with an average of approximately 23,000 - 25,000 acre-ft/yr depending on which of the three inflow datasets were used to generate the paleo sequence. For reference, Foss Reservoir's firm yield, as determined by the observed 1970s drought of record, is 19,700 acre-ft/yr – this corresponds to a drought that ranks in the approximate 70th percentile when one considers the full range of 3,000 paleo-informed yields. In other words, about 30 percent of the paleo-informed firm yield values were *worse* than the firm yield that is based on the observed drought of record, with a good number of those *far worse* than the firm yield which could be expected based on 90 years of observed hydrology.

For Fort Cobb Reservoir, paleo-informed firm yield values ranged from 15,300 acre-ft/yr to 42,000 acre-ft/yr with an average of about 23,000 acre-ft/yr. For reference, Fort Cobb Reservoir's firm yield, as determined by the observed 1950s drought of record, is 19,200 acre-ft/yr – this corresponds to a drought that ranks in the approximate 90th percentile when one considers the full range of 3,000 paleo-informed yields. In other words, about 10 percent of the paleo-informed firm yield values were *worse* than the firm yield that is based on the observed drought of record. Unlike Foss Reservoir, the lowest paleo-informed firm yield values obtained were relatively closer to the firm yield expected based on 90 years of observed hydrology.

It appears that Foss and Fort Cobb Reservoirs vary somewhat in terms of the extent to which the observed 90-year hydrology captures the potential severity of dry periods that could be expected when considering tree ring data. For example, Fort Cobb Reservoir's firm yield value falls within the 90th percentile of all 3,000 paleo-informed yields calculated while Foss Reservoir's falls only within the 70th percentile. A couple of reasons may exist for this difference. Although both Foss and Fort Cobb Reservoirs are located in close proximately to one another within the Washita River Basin and essentially have the same reservoir yield (based on observed hydrology), their size and geology likely contribute to how much hydrologic variation may be expected. The smaller number of extreme dry periods predicted at Fort Cobb Reservoir relative to Foss Reservoir is likely attributable to the fact that Fort Cobb Reservoir is smaller in size and drainage area, and under a relatively strong influence of aquifer base flows that help maintain reservoir levels during extreme dry periods simulated in this analysis. Whatever the case may be, it is still worth noting that the statistical analysis performed here demonstrates that the observed 90-year record does not sufficiently account for the severity of droughts that could be expected when one draws on over 600 years of tree ring data. In fact, the analysis shows that about 10 to 30 percent of the droughts could be worse depending on the reservoir in question.

It is worth asking, in terms of whether a reservoir will go dry, is 10 to 30 percent an acceptable risk when it comes to providing much-needed M&I water supplies to the cities and industries which depend on these reservoirs? Likely not. Assuming the answer is "no", then what methods could be employed to reduce this risk given the firm yield results we have seen from the tree ring analyses? In the case of Foss Reservoir, which has an extreme low-end firm yield estimate of 7,400 acre-ft/yr, the risk becomes even more pronounced if one considers just how bad it could get. The next section describes how Reclamation's Firm Yield model was modified even further to utilize paleo-informed inflow sequences and to account for actual water use, thus transforming the Model into a real-time operations tool that can allow us to evaluate "what if" demand management scenarios and subsequent risks of a reservoir going dry under these extreme paleo droughts. The question is, out of the 3,000 paleo-informed firm yield estimates, which of these paleo droughts do we plan for?

PART III:

REDUCING RISK TO RESERVOIR SUPPLIES - PLANNING FOR THE NEXT PALEO DROUGHT

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PART III: REDUCING RISK TO RESERVOIR SUPPLIES - PLANNING FOR THE NEXT PALEO DROUGHT

Whether one is making decisions for long-term planning purposes or strategizing on drought contingency/response measures, a central question one should ask is: which drought do we plan for?

Using Foss and Fort Cobb Reservoirs as an example, we have already proven our uncertainties correct in Part II of this report by demonstrating that the drought of record we have observed within the last 100 years is *not* the worst drought; in fact, if we extend the period of record back 600 years, we showed that about 10 to 30 percent of the droughts over this extended period are worse in terms of their effect on reservoir yield. Again, this percentage will vary from region to region depending on factors such as local climate patterns, size of the reservoir and drainage basin, and local hydrogeology. Whatever the case may be, this percentage is important because it *quantifies the risk*. It is worth again stressing the important point that in the case here, we are focusing on providing water for M&I demands. These demands include requirements for domestic/residential purposes (i.e., human consumption), as well as commercial and industrial processes. M&I demands require a more reliable water supply relative to other types of demands such as agricultural irrigation which can be curtailed or discontinued altogether during critical drought periods without having detrimental impacts on public health and sanitation. As such, the risk of not having enough water to meet these needs should be very low, particularly if the city wishes to continue to grow, attract business, and prosper. As one stakeholder exclaimed during a recent public meeting, “we want southwest Oklahoma to be open for business!”

Selection of Drought Scenarios

Returning to the question of “which drought do we plan for”, it is first important to revisit a point stressed earlier in this report that “no two droughts are the same”. Again, here we are focused on a “hydrologic” drought in terms of its severity and impact on reservoir supplies. The severity of a drought depends on both its intensity and duration, but even two droughts of equal severity may have different intensities and duration. For instance, a high intensity/short duration drought may have the same severity as a lower intensity/higher duration drought. By equal severity, we mean that the reservoir firm yield under ether drought would be the same. Figure 20 illustrates this example with two hypothetical droughts that results in the same reservoir firm yield. As expected, the most severe droughts are those that are of high intensity/long duration. To put this into context, as referenced earlier in this report, despite the widely known effects of the “Dust Bowl” of the 1930s, the 1950s drought was actually more intense and of longer duration, and was thus more severe. And while the late 1960s/early 1970s drought lasted even longer than the 1950s drought, it was less intense and overall, it was less severe. The 2011 drought lasted only a relatively short period of time, but it was as severe (if not worse in some areas) than any of the three previously recorded droughts. Whatever the case may be, for the analysis included here, three types of droughts are considered: high intensity/short duration; low intensity/long duration; and high intensity/long duration.

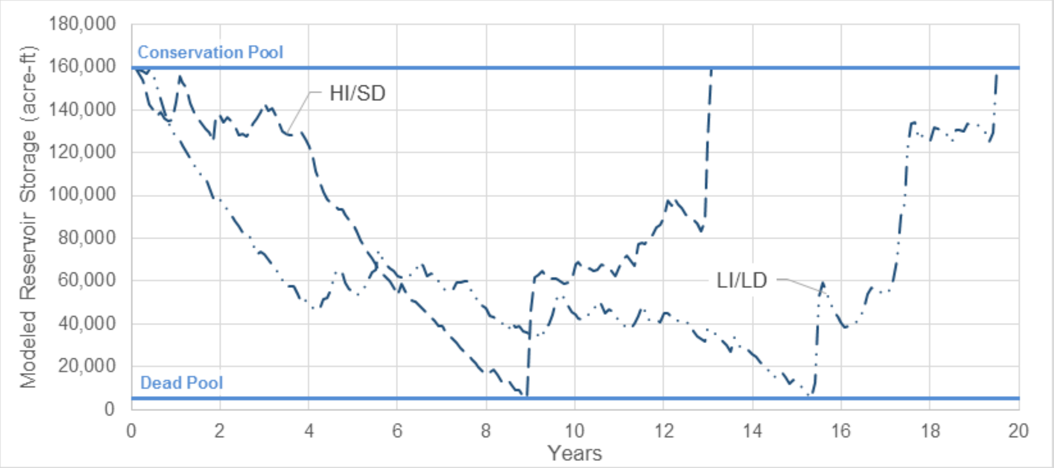

Figure 20: Under two hypothetical droughts, the firm yield is the same (i.e., 18,100 acre-ft/yr) for both a high intensity/short duration (HI/SD) and a low intensity/long duration (LI/LD).

Standardizing Drought Duration

In Part II, we ran 3,000 model simulations for each reservoir resulting in paleo-informed firm yield estimates that were illustrated in Figures 18 and 19. These firm yield values represented the various levels of drought "severity" over the 600-year time series, but revealed little about the intensity and duration of these droughts. We know that a severe drought of short duration must be intense by default and an equally severe drought of longer duration would naturally be less intense. Therefore, by solving for drought duration, we have a default understanding of drought intensity. The primary challenge for this analysis, however, was being able to standardize the datasets so we could calculate the duration of each of these paleo droughts relative to other paleo droughts, as well as the observed drought of record. The following steps were taken to accomplish this:

1. VBA was used to identify the controlling drought of record for each of the 3,000 reservoir storage/firm yield simulations.
2. The years of the controlling drought were clipped using VBA.
3. The controlling droughts were "standardized" by applying a fixed water demand (use) on the reservoir for each simulation. For Foss Reservoir, a fixed demand of 7,400 acre-ft/yr was applied because this is the maximum amount of water the reservoir could deliver under the most severe paleo-informed controlling drought of record. For Fort Cobb Reservoir, a fixed demand of 15,300 acre-ft/yr was applied for the same reason.
4. VBA was used to calculate the duration of all 3,000 droughts on an "apples to apples" basis.
5. The calculated drought durations were plotted against reservoir firm yield.

Figures 21 and 22 illustrate the importance of standardizing the controlling droughts by applying a fixed demand on the reservoirs. According to Figure 21, a simulation of the observed 90-year record reveals that Foss Reservoir's controlling drought of the 1960s/1970s lasted 309 months (26 years) and results in the reservoir almost going completely dry to deliver the firm yield of 19,700 acre-ft/yr. However, when the fixed water demand of 7,400 acre-ft/yr is applied to this simulation, the "standardized" drought duration is reduced to 173 months (14 years), and reservoir storage increases from close to zero to about 70,000 acre-ft/yr at its lowest point. This highlights just how severe the worst paleo drought was relative to the observed drought of record at Foss Reservoir. Similarly, according to Figure 22, a simulation of the observed 90-year record reveals that Fort Cobb Reservoir's controlling drought of the 1950s lasted 215 months (18 years) and resulted in a reservoir firm yield of 19,200 acre-ft/yr. However, when the fixed water demand of 15,300 acre-ft/yr is applied to this simulation, the "standardized" drought duration is reduced to 171 months (14 years), and reservoir storage increases from close to zero to about 12,000 acre-ft/yr at its lowest point. This also highlights the severity of the worst paleo drought relative to the observed drought of record at Fort Cobb Reservoir.

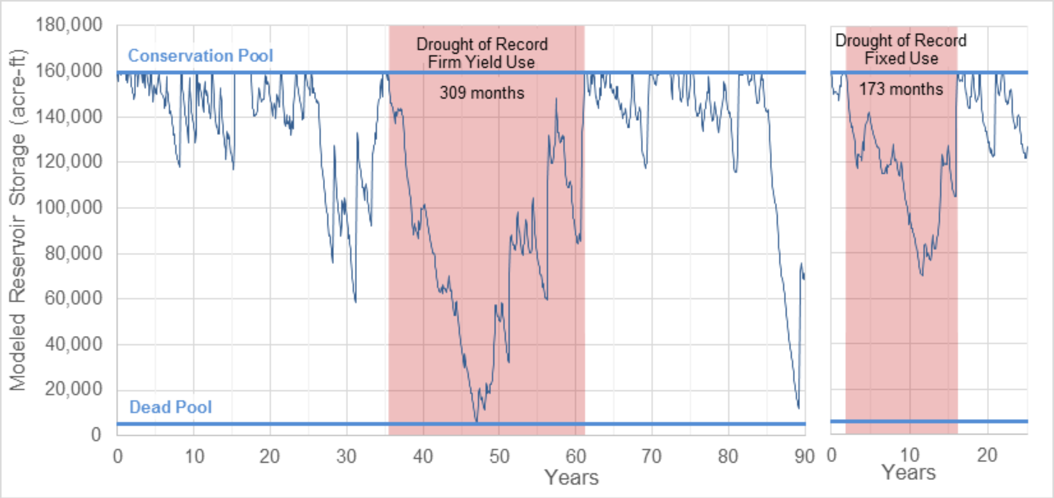

Figure 21: Simulated storage of Foss Reservoir during the controlling drought of record based on the 90-years of observed hydrology under two demand scenarios.

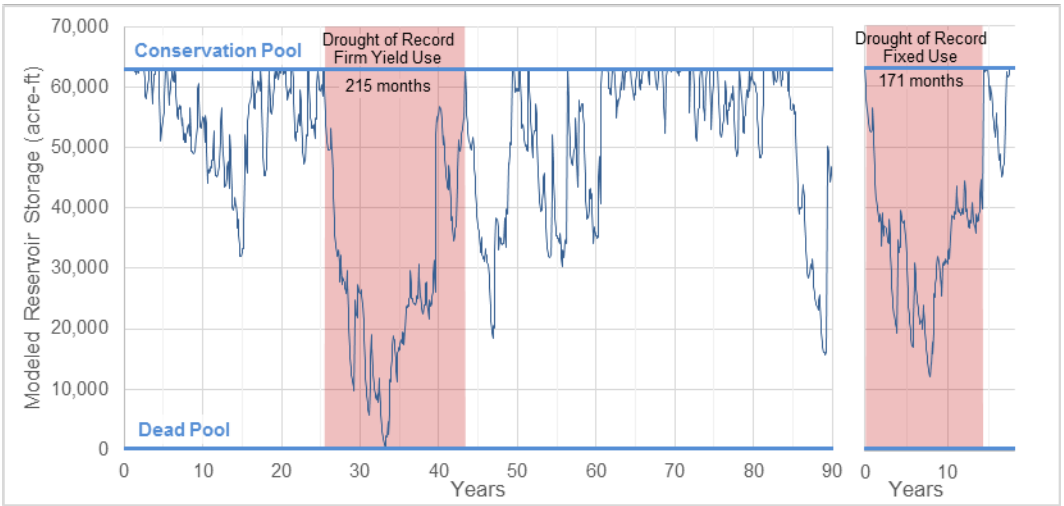

Figure 22: Simulated storage of Fort Cobb Reservoir during the controlling drought of record based on the 90-year record of observed hydrology under two demand scenarios.

Standardizes drought durations (based on fixed demands) were then plotted against their respective firm yield values in Figures 23 and 24. Recall that three paleo inflow sequences were used to develop the 3,000 simulations for each reservoir: Foss Reservoir (1,000 simulations); Fort Cobb Reservoir (1,000 simulations); and a combination of Foss/Fort Cobb Reservoir (1,000 simulations). We noted earlier that the paleo-informed firm yield values of Foss Reservoir exhibited a broader range of variation than those at Fort Cobb Reservoir; this variation was mostly attributable to only one of the three inflow datasets: the Foss Reservoir inflow record – this was evident because it resulted in the highest standard deviation (as noted in Table 3, Part II). Therefore, for Foss Reservoir, we plotted only the paleo droughts resulting from this one inflow record. Because Fort Cobb Reservoir exhibited less variation, we plotted the paleo droughts calculated from all three inflow datasets.

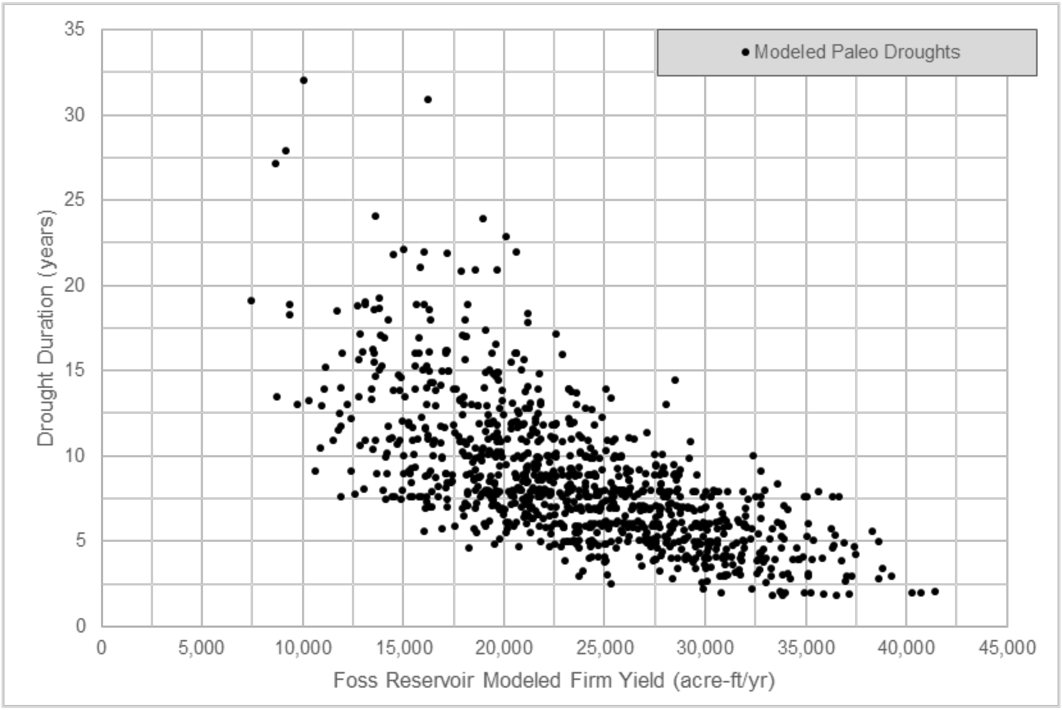

Figure 23: Standardized duration of paleo droughts relative to Foss Reservoir firm yield resulting from 1,000 model simulations using inflow sequences informed by tree ring data.

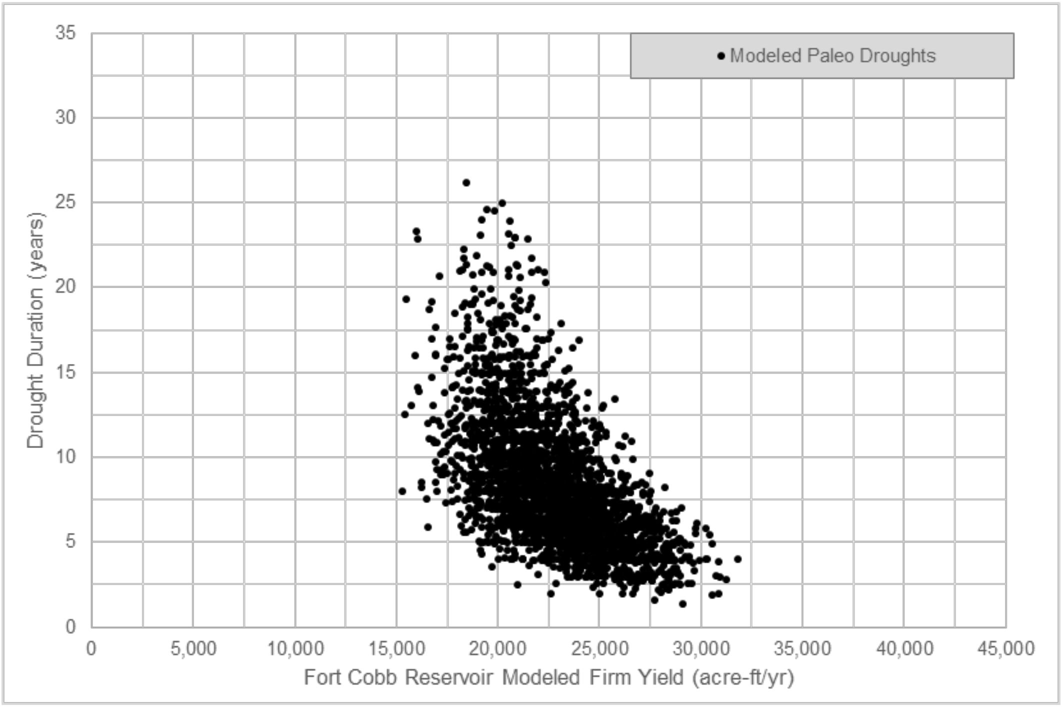

Figure 24: Standardized duration of paleo droughts relative to Fort Cobb Reservoir firm yield resulting from 3,000 model simulations using inflow sequences informed by tree ring data.

Selection of Drought Scenarios

Once we have an "apples to apples" comparison of the paleo droughts, the next step was to select which of these droughts we wanted to plan for and include in the operations modeling phase of this analysis. Recall that the observed droughts of record for Foss and Fort Cobb Reservoir fall within the 70th (rounded from 72nd) and 90th (rounded from 92nd) percentiles, respectively. For comparison purposes, it is important to point out that the 2011-2015 drought falls within the 61st and 21st percentiles for Foss and Fort Cobb, respectively. These droughts, which were standardized using methods previously described, are plotted on Figures 25 and 26 and provide context into their severity relative to the modeled paleo droughts. Both of these droughts were used as reference scenarios and incorporated into the next phase of this analysis using the operations model.

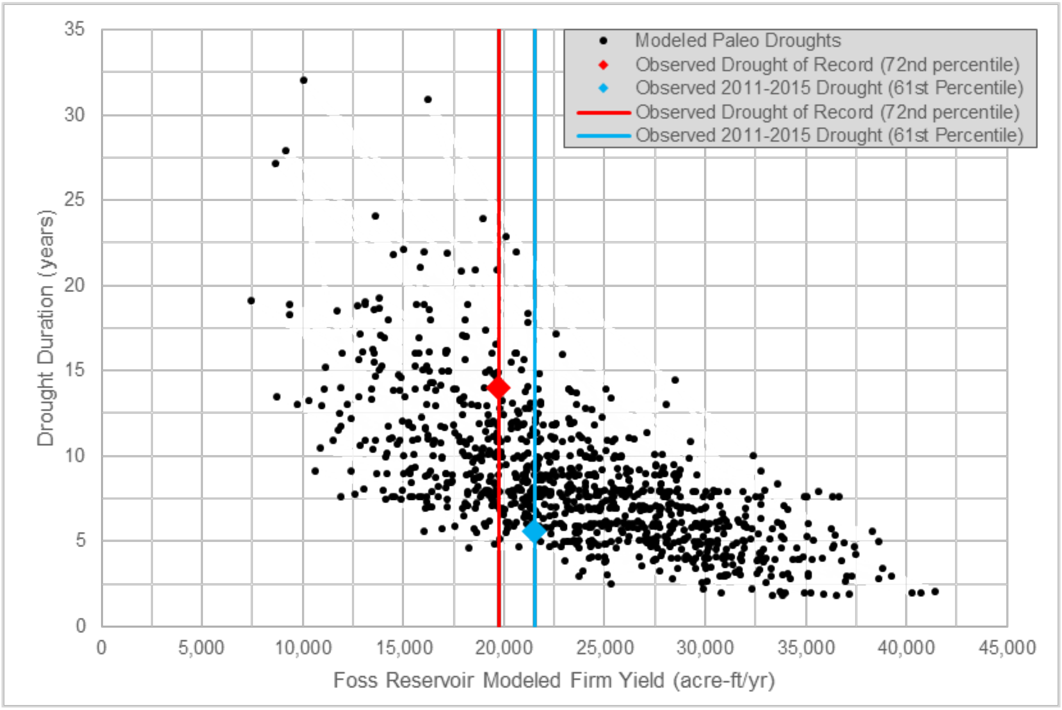

Figure 25: Standardized duration and severity of the 2011-2015 drought and the observed drought of record at Foss Reservoir relative to modeled paleo droughts resulting from 1,000 model simulations using inflow sequences informed by tree ring data.

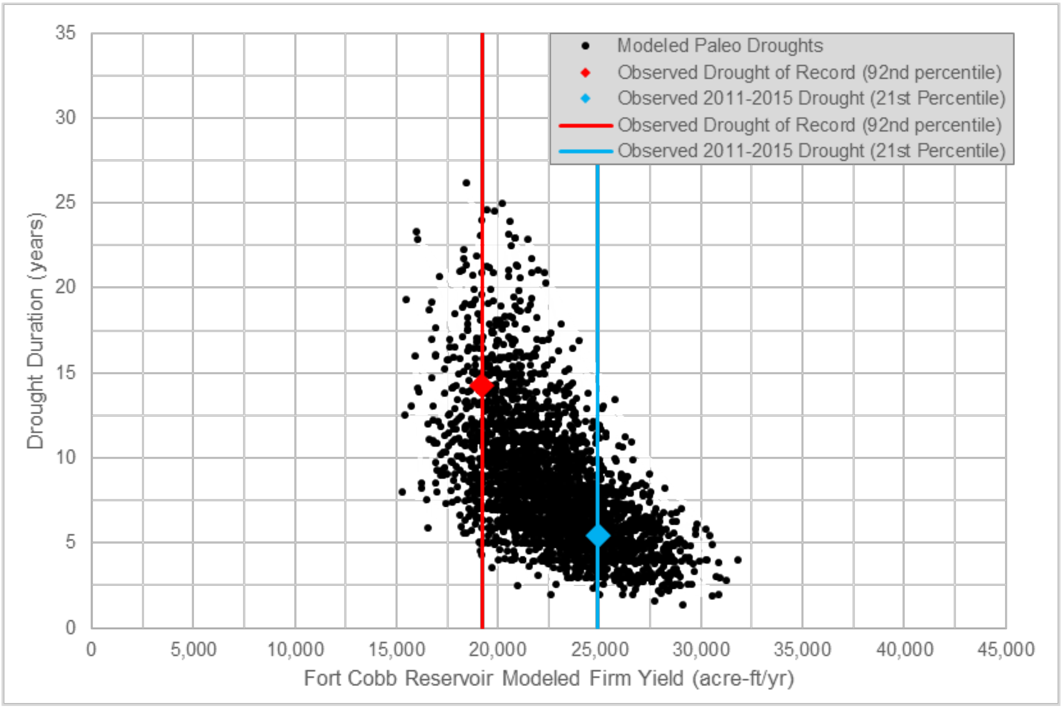

Figure 26: Standardized duration and severity of the 2011-2015 drought and the observed drought of record at Fort Cobb Reservoir relative to modeled paleo droughts resulting from 3,000 model simulations using inflow sequences informed by tree ring data.

Regarding the selection of paleo drought scenarios, the question again is: how much risk is a water manager willing to take on when delivering M&I water supplies? The answer to this question can entail a multitude of factors including but not limited to stakeholder preference and the extent to which the reservoir in question is either a sole supply or can be augmented or supplemented with other water supplies (such as groundwater). Here, we assume that the reservoir is the sole supply source of M&I water and that the risk threshold should be very low.

In deciding which paleo drought scenarios to include in the model, we begin with the understanding that 27 and 8 percent of the firm yield calculations for Foss and Fort Cobb Reservoirs, respectively, fell below the firm yield based on the observed hydrologic record. These percentages correspond to 270 droughts (based on 1,000 simulations) for Foss Reservoir and 540 for Fort Cobb Reservoir (based on 3,000 simulations). Out of this subset of droughts, the first step was to decide on a "risk window". In this case, we selected a risk window of 5.0 to 0.1 percent, meaning that we want to be 95 to 99.9 percent "sure" that the paleo drought we plan for would not be surpassed by a potentially worse drought, statistically speaking (Figures 27 and 28). This risk window is discretionary and will vary depending on the needs and priorities of local officials and stakeholders.

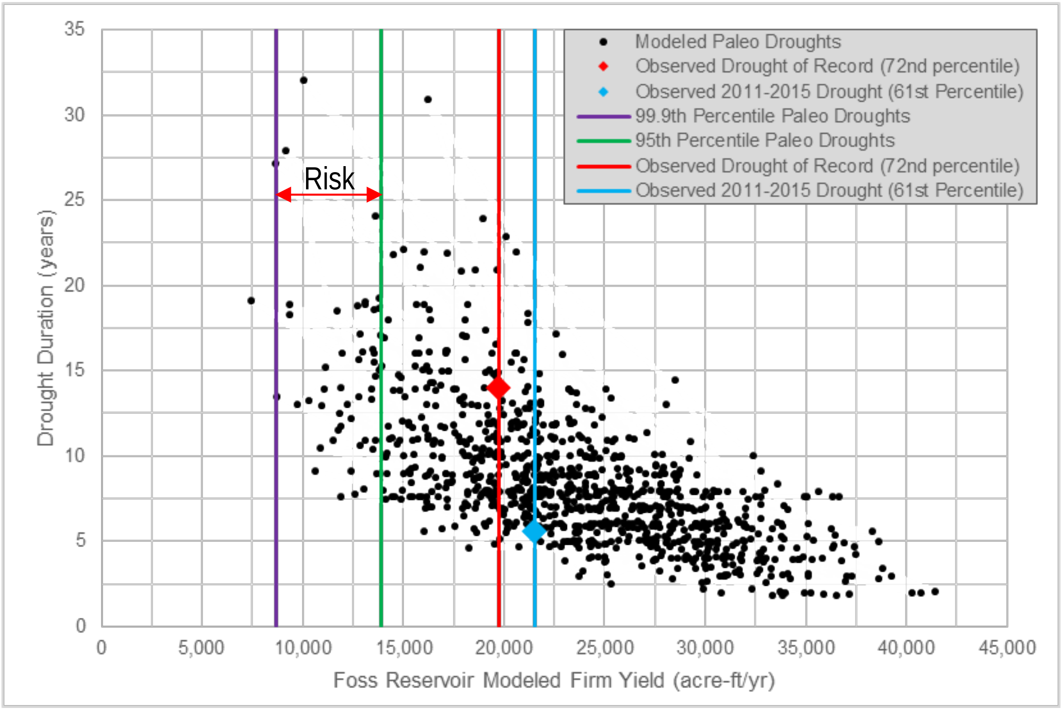

Figure 27: Risk window selected for Foss Reservoir encompassing the 95th and 99.9th percentile paleo droughts. The 2011-2015 drought and observed drought of record are provided as reference points.

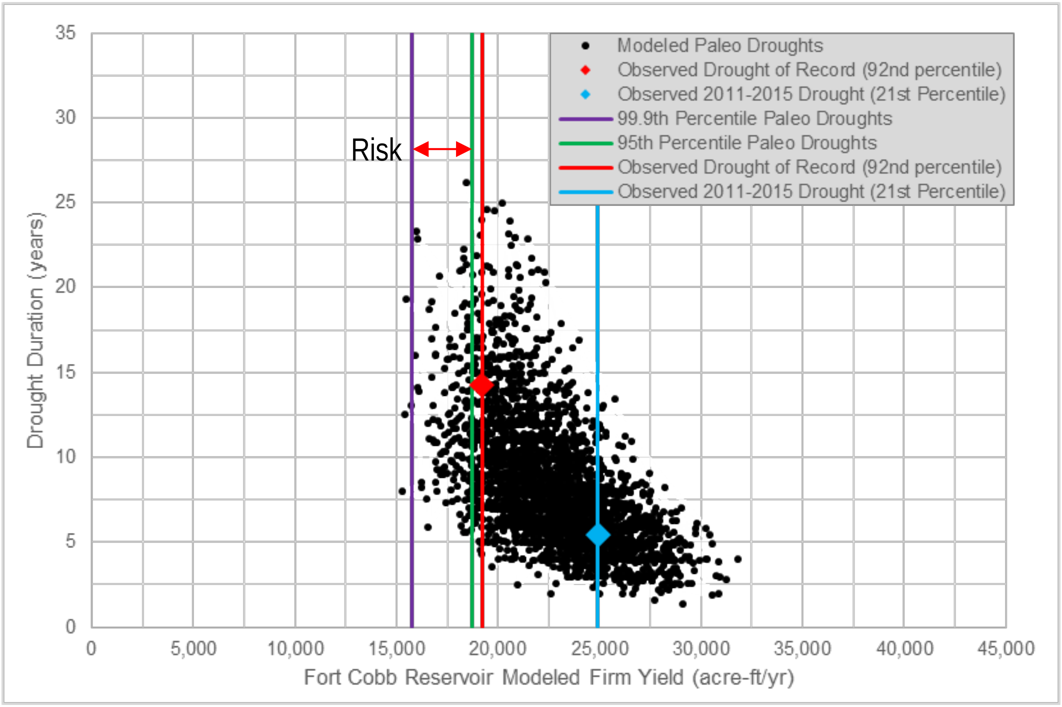

Figure 28: Risk window selected for Fort Cobb Reservoir encompassing the 95th and 99.9th percentile paleo droughts. The 2011-2015 drought and observed drought of record are provided as reference points.

The risk window selected here provides a conservative range of only the most severe paleo drought scenarios, which if properly planned for using the operations model (discussed in next section), would pose only the most minimal risks to the reservoirs going dry. By minimal, we mean a 5.0 percent to 0.1 percent probability of going dry. At the same time, we wanted to select scenarios that capture the variability in duration and intensity of the paleo droughts that fall within this risk window. In addition to scenarios representing the two most severe observed droughts, a total of five paleo drought scenarios were selected for each reservoir. Tables 4 and 5 below summarize the drought scenarios selected for input into the operations model. The scenarios are illustrated in Figures 29 and 30.

Table 4: Drought scenarios selected for Foss Reservoir

Foss Reservoir Selected Drought Scenarios	Modeled Reservoir Firm Yield (acre-ft/yr)	Drought Duration (Years)
Observed 2011-2015 Drought (61st Percentile)	21,600	5
Observed Drought of Record (72nd Percentile)	19,700	14
95th Percentile Paleo Droughts (High Intensity/Short Duration)	14,000	8
95th Percentile Paleo Droughts (Low Intensity/Long Duration)	13,600	24
99.9th Percentile Paleo Droughts (High Intensity/Short Duration)	8,700	13
99.9th Percentile Paleo Droughts (Low Intensity/Long Duration)	8,700	27
Most Severe Paleo Drought Scenario	7,400	19

Table 5: Drought scenarios selected for Foss Reservoir

Fort Cobb Reservoir Selected Droughts	Modeled Reservoir Firm Yield (acre-ft/yr)	Drought Duration (years)
Observed 2011-2015 Drought (21st Percentile)	24,900	5
Observed Drought of Record (92nd Percentile)	19,200	14
95th Percentile Paleo Droughts (High Intensity/Short Duration)	18,700	5
95th Percentile Paleo Droughts (Low Intensity/Long Duration)	18,400	26
99.9th Percentile Paleo Droughts (High Intensity/Short Duration)	15,300	8
99.9th Percentile Paleo Droughts (Low Intensity/Long Duration)	16,000	13
Most Severe Paleo Drought Scenario	15,300	23

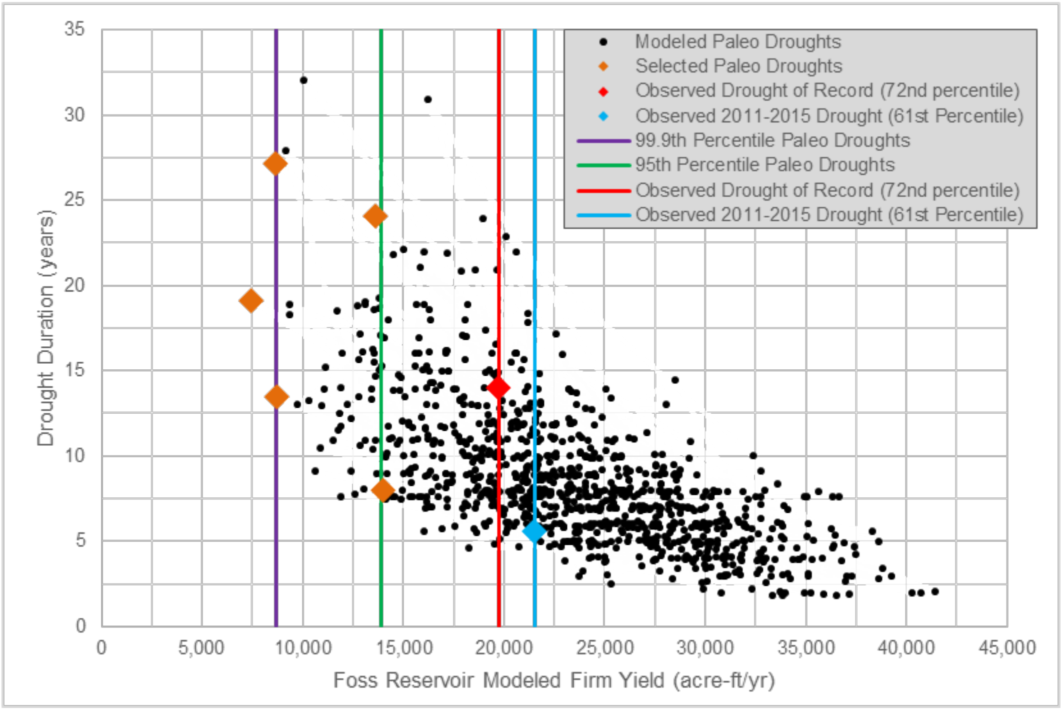

Figure 29: Paleo drought scenarios selected for Foss Reservoir.

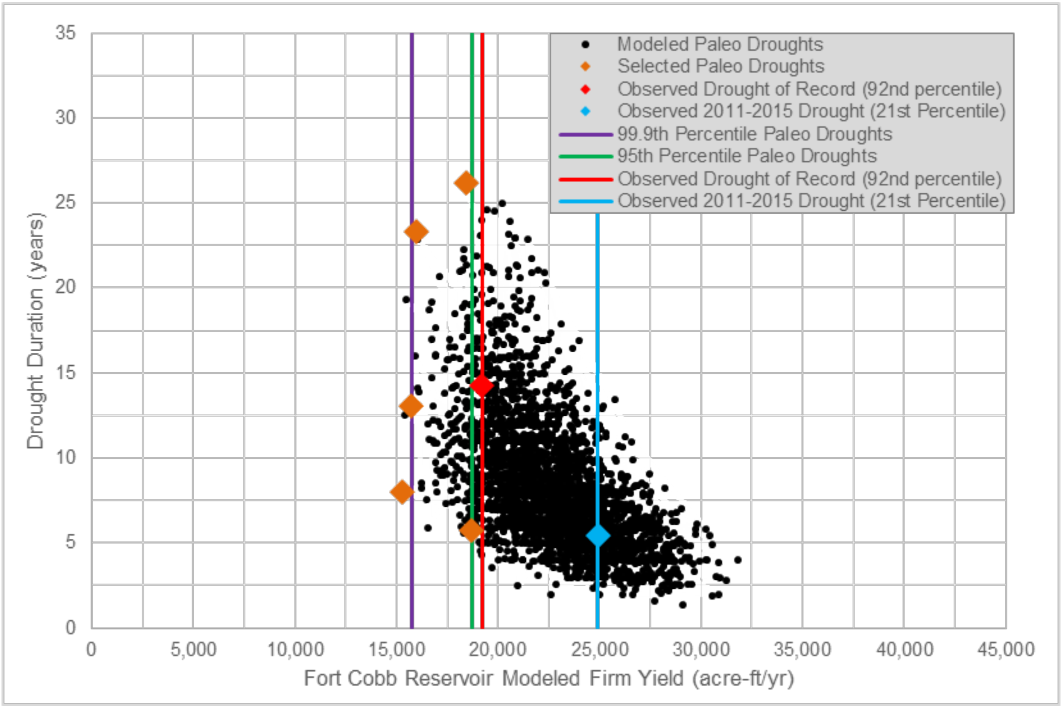

Figure 30: Paleo drought scenarios selected for Fort Cobb Reservoir.

PART IV:

AN OPERATIONS MODEL FOR ENHANCED DROUGHT RESPONSE

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PART IV: AN OPERATIONS MODEL FOR ENHANCED DROUGHT RESPONSE

Recall the story that was described in Part I regarding the 2011 drought's impact on southwest Oklahoma. As the drought unfolded, local officials were "flying blind" for a couple of key reasons. First, near-term climate forecasting is difficult, particularly in the southern Great Plains. Second, decision-making used a set of fairly simplistic and arbitrary assumptions because a viable tool was not available to evaluate impacts of the drought on reservoir yield. Among these was that (1) historical inflows would just repeat themselves on some arbitrary timescale and (2) that over these timescales, reservoir demands would remain static. We noted the opportunity that exists to improve our understanding of how we can make more informed near-term projections, while also taking into consideration losses in storage caused by actual water use. From a long-range planning standpoint, given what we now know about tree ring data and the magnitude of paleo droughts, we noted another fundamentally flawed assumption: that inflows into the reservoir will mimic historical inflows which have been collected over a relatively short 90-year period.

This section presents a "new and improved Firm Yield model", developed by Reclamation staff, which integrates the analyses and results presented in Part II (impacts of paleo droughts on reservoir firm yield) and Part III (selection of paleo drought scenarios) into a real-time drought response tool that can be used to evaluate how demand management scenarios can prolong reservoir yield. The tool also can actively be used during a drought or it can be used for long-range drought resiliency planning, thus providing greater flexibility to reservoir operators.

Enhanced Drought Response Reservoir Operations (EDRRO) Model:

The EDRRO model was developed as a modified "enhanced" version of Reclamation's existing Firm Yield model previously discussed in Part I; the original Firm Yield model still exists, but a new platform was added for real-time operations and planning to improve the model's value and robustness. Appendix A displays a screenshot of the Model interface for Fort Cobb Reservoir. Details of the EDRRO model platform are described below.

Model Interface

The model platform is comprised of multiple interfaces, some of which require manual data entry, denoted in green, while others fill in automatically using formulas built into the interface, denoted in gray. For the sake of brevity, we focus this section on the EDRRO platform for Fort Cobb Reservoir as an example because the interfaces are less complex than Foss Reservoir, which experiences additional uses associated with advanced water treatment. With that said, we cite the Foss Reservoir interfaces where appropriate to highlight the versatility of the EDRRO model and provide clarity to results that are presented in the next chapter. Details are provided below.

1. Instructions for Using this Model

This section provides step by step instructions for operating the model as follows:

- The first entry in Column Q is the end-of-month date (ex: 01/31/17) for the month when the reservoir elevation was last at or above the top of the conservation storage pool (i.e., the drought begins when the reservoir drops below the top of conservation storage). Next, enter the water use data for each of the proceeding months, ending with the current month. A minimum of 12 months of water use data is needed, so if the drought started less than 12 months ago, then enter water use data for months prior to the drought (i.e., prior to 01/31/17) such that at least 12 months of water use data has been entered.
- In Column R thru V, enter the monthly total water use, water use for each customer, and reservoir elevation from the Corrected Water Supply Spreadsheet.
- In Cell N46, enter the elevation of the lowest operable intake for water delivery.
- In Cells N53 and N54, enter a percent reduction and a base flow amount that contributes inflows into the reservoir, if applicable.
- In Cells G41, H41, and I41, enter the reservoir elevations corresponding to the desired proposed drought response levels.
- In Cells G43, H43, and I43, enter the desired portion of the contractual water allocation (percentage) to be delivered at each drought response level (i.e., the inverse of the desired demand curtailment).

2. Modeled Reservoir Storage

The Modeled Reservoir Storage interface of the EDRRO model platform serves as the primary visual tool of the platform and combines data and analyses that are either manually entered and/or automatically populated from all of the other interfaces of the Model platform (Figure 31). Observed Reservoir Storage, denoted as a heavy line, is plotted using real-time water use and reservoir elevation data. Future reservoir storage is projected based on the seven drought scenarios selected in Part III of this report. Predetermined reservoir elevation triggers, denoted as Watch, Warning, and Emergency Levels, provide thresholds by which the user can test how various demand curtailments can affect reservoir storage and prevent shortages. These interfaces are described in detail below.

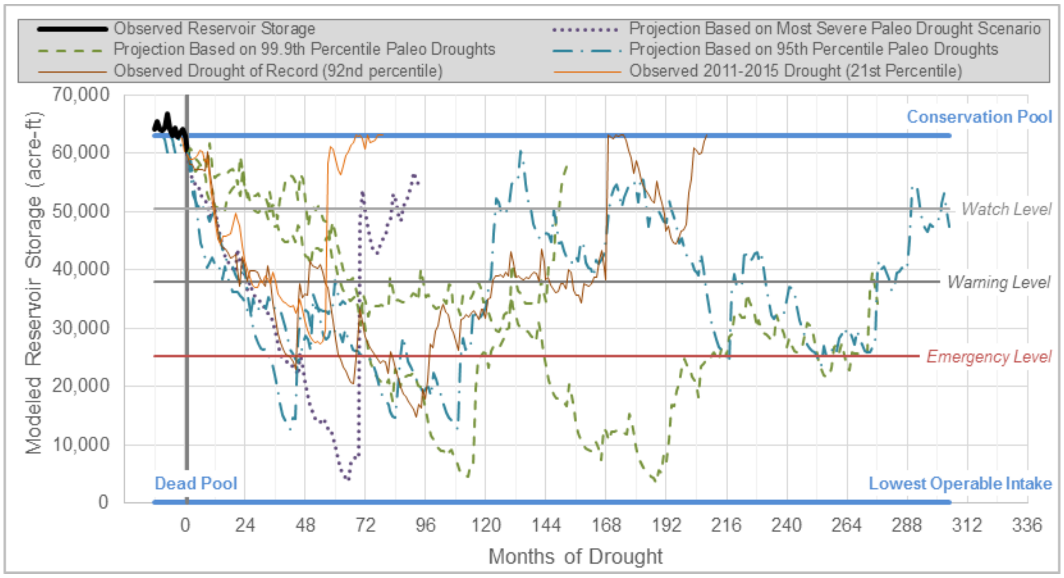


Figure 31: Modeled Reservoir Storage interface of the EDRRO model for Fort Cobb Reservoir. This interface illustrates Watch, Warning, and Emergency thresholds which can be used to curtail demands based on reservoir elevation triggers in order to prevent these shortages.

3. Water Use and Reservoir Data

Water use and reservoir elevation data are manually entered into this interface (Table 6); the former is collected directly from water customers while the latter is obtained from monthly water supply reports or from hydromet, U.S. Geological Survey, and/or U.S. Army Corps of Engineers websites. Total water use for each customer is entered separately to account for other losses that may occur in distribution. In this example, water use data for the three customers that have contracts with the Fort Cobb Reservoir Master Conservancy District are entered (i.e., for WFEC, Anadarko, and Chickasha). The first step is to enter the last full month when the reservoir was full, say January 2016 (for example below). This marks the beginning of the drought. Next, enter water use data for each proceeding month up to and including the last full month of available water use data, say February 2017 (for example below). If less than 12 months has passed since the reservoir elevation dropped below the top of the conservation storage pool, then enter water use data for months prior to the drought such that at least 12 months of water use data has been entered.

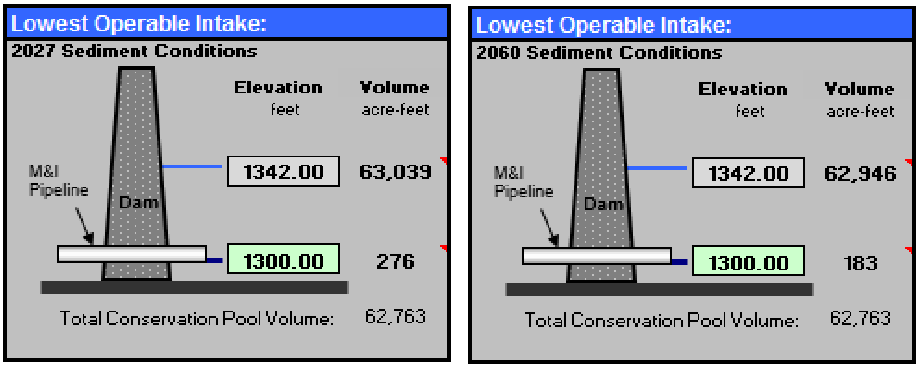
Observed reservoir storage is automatically generated and is based on a previously developed area-capacity curve. The storage boundaries are denoted as blue lines in the “Modeled Reservoir Storage” interface of the EDRRO model, with the upper boundary defined as Conservation Pool elevation and the lower bound defined as the elevation of the Lowest Operable Intake. In this case, a ten-year sediment condition (2027) is assumed which corresponds to an assumed drought length of ten years as displayed in Figure 32 below.

Table 6. Water Use/Reservoir Data Interface of the EDRRO model where known water use and reservoir elevation data are manually entered and used to plot monthly reservoir storage (sediment adjusted), as illustrated in the Modeled Reservoir Storage Interface.

Water Use					Reservoir Data	
Date	Total Water Use (1,000 x acre-feet)	WFEC (1,000 x acre-feet)	Anadarko (&PSO) (1,000 x acre-feet)	Chickasha (1,000 x acre-feet)	Reservoir Elevation (ft)	Observed Reservoir Storage (acre-feet)
1/31/2016	0.848	0.109	0.397	0.323	1,342.35	64,182
2/29/2016	0.820	0.072	0.382	0.346	1,342.74	65,478
3/31/2016	0.871	0.073	0.422	0.355	1,342.30	64,017
4/30/2016	0.915	0.124	0.401	0.374	1,342.27	63,919
5/31/2016	0.905	0.135	0.400	0.348	1,342.42	64,412
6/30/2016	1.040	0.184	0.393	0.451	1,343.08	66,628
7/31/2016	1.164	0.268	0.413	0.461	1,342.33	64,116
8/31/2016	1.283	0.270	0.412	0.584	1,341.98	62,974
9/30/2016	1.106	0.198	0.404	0.482	1,342.36	64,215
10/31/2016	1.034	0.140	0.443	0.426	1,341.95	62,877
11/30/2016	0.959	0.129	0.413	0.394	1,342.14	63,494
12/31/2016	0.873	0.112	0.372	0.370	1,342.31	64,050
1/31/2017	0.848	0.109	0.397	0.323	1,342.00	63,039
2/28/2017	0.820	0.072	0.382	0.346	1,341.00	59,883

4. Lowest Operable Intake

The lowest operable intake is entered as a means of defining when the reservoir is fully depleted and can no longer supply water. The term “operable” is stressed because in some cases, an intake may exist but no longer be operable, at least without some modification. For example, during the 2011 drought, the lowest intake at Foss Reservoir was buried in sediment and rendered inoperable and unrepairable during the drought, in which case the elevation of the next operable intake would be entered here. It is recognized that measures could be taken during a drought to access stored water below the intake (i.e., through temporary pumps); however, for the purposes of the EDRRO model, we assume that a shortage occurs when storage falls below the intake. Whatever the case may be, a user can enter any elevation value to represent the lower bound of the reservoir. Figure 32 displays the component interface with two different sediment conditions.


Lowest Operable Intake:
2027 Sediment Conditions
Elevation feet: 1342.00 — Volume acre-feet: 63,039
Elevation feet: 1300.00 — Volume acre-feet: 276
Total Conservation Pool Volume: 62,763

Lowest Operable Intake:
2060 Sediment Conditions
Elevation feet: 1342.00 — Volume acre-feet: 62,946
Elevation feet: 1300.00 — Volume acre-feet: 183
Total Conservation Pool Volume: 62,763

Figure 32: Lowest Operable Intake interface of the EDRRO model where the lowest operable intake is defined. The figure on the left displays 2027 sediment conditions (assumes drought begins in 2017); the figure on the right displays 2060 sediment conditions (assumes drought begins in 2050).

5. Inflow Depletions

The EDRRO model contains an Inflow Depletions interface which allows the user to manually assign a percent reduction (Appendix A, Cell N53) to a base flow amount (Appendix A, Cell N54) that contributes inflow into the reservoir. Here, we focus on base flow because during a critical drought, it is the largest contributor to reservoir firm yield. Depletions could be caused by upstream uses during a drought such as surface water diversions and/or from groundwater pumping from an aquifer that contributes base flows to a stream that flows into the reservoir. The base flow amount and the percent reduction thereof may be informed by separate studies and/or models which quantify these, or otherwise by assumptions based on best available data.

For example, the firm yield of Fort Cobb Reservoir is known to rely on base flows originating from the Rush Springs aquifer which is the source of ground water for extensive agricultural irrigation use throughout the area. Models are currently being developed as part of the Upper Washita Basin Study to quantify groundwater pumping impacts, as well as impacts from surface water diversions upstream by junior water right holders. The results will help inform how we account for the depletion of inflows into the reservoir.

6. Drought Response Levels

Three reservoir elevation triggers are integrated into the EDRRO model and can be used during a drought to evaluate how drought contingency/response measures such as staged water use restrictions affect reservoir storage (Table 7). They are denoted as Level 1, Level 2, and Level 3. As part of the Foss Reservoir Drought Contingency Plan (funded under Reclamation's Drought Response Program), a drought task force established three reservoir elevation triggers that were built into the EDRRO model for Foss Reservoir. Generally speaking, these levels are discretionary and should be selected by the user based on local needs and stakeholder involvement. For the purposes of this example, we used the triggers selected by the Foss Reservoir task force as follows, and which are denoted as light gray, dark gray, and red lines on the "Modeled Reservoir Storage" interface:

- Watch Level: 80 percent of conservation pool (light gray line)
- Warning Level: 60 percent of conservation pool (dark gray line)
- Emergency Level: 40 percent of conservation pool (red line)

The green “Reservoir Elevation” cells in this interface must be manually adjusted to achieve the desired “Reservoir Storage” percentage (sediment adjusted) corresponding to each of the three drought response levels. As previously discussed, storage volumes assume “Conservation Pool” as the top boundary and the “Lowest Operable Intake” as the bottom boundary, but can be adjusted to meet the user’s needs. Once the reservoir elevations that correspond to drought response levels are known, demand curtailments can then be adjusted at each drought level (elevation) to evaluate impacts on storage and identify whether shortages may occur.

The demand curtailments are manually entered as the “Percent of Contract Allocation” in Cells G43-I43. This is because these percentages take into account the full water supply volume allocated to each customer pursuant to their water supply contract (see “Water Allocation” in Cells E49-E51), as well as how much of that contracted amount is actually being used (see “Previous 12-Months” in Cell F43). The “Percent of Contractual Allocation” is calculated by dividing the “Previous 12-Months” use (Cell F43) by the “Total Contract Allocation” (Cell E52). The latter provides a reference point by which you can base preferred demand curtailments under each drought response level. In this example, customers have used a combined total of 64 percent of the water allocation over the last 12 months, and it remains unadjusted for all three drought levels. In the case of Foss Reservoir, customers have used a combined total of 17 percent of their water allocation over the last 12 months (Table 8 below). In the next section of this report, we revisit this interface and begin adjusting demands and evaluating impacts on modeled reservoir storage.

7. Water Use and Contractual Allocations

Contract Uses: Using the manual inputs tabulated in the “Water Use” and “Drought Response Levels” interfaces, this interface automatically populates water supply allocations under each of the drought response levels pursuant to stipulations of the individual water supply contracts, again using the total water supply allocations (Cell E52) as the reference point (Table 7). Cells D49-51 are reserved for cases where a water supply contract allocates water by percentage rather than volume, as in the case of Foss Reservoir (Table 8). Water allocations will be site specific and vary depending on locale, but in the case of Foss and Fort Cobb Reservoirs, the water supply contracts include “shared shortage” clauses that require each entity to reduce water use by an equal proportionate share during drought periods. For instance, if the total water supply allocation is reduced from 64 percent to, say, 52 percent, each of the three customers would be required to reduce water use by twelve percent. Again, this will be illustrated further in the next section of the report. This interface also automatically populates the water usage totals per customer (“Previous 12-Months) that are manually entered in the Water Use Interface (Table 6 above)

Noncontract and Other Uses. In this part of the interface, other noncontract water uses are accounted for. In the case of Fort Cobb Reservoir (Table 7), the difference between actual water usage reported by the customers versus water usage reported by the MCD is calculated as a loss (i.e., 238 acre-ft/yr). For Foss Reservoir (Table 8), the other uses are known and therefore manually entered into the Water Use Interface previously described. These uses are associated with a water treatment plant which employs an advanced treatment process that generates a waste brine that requires additional raw water to manage.

Table 7: Fort Cobb Reservoir Interface for Drought Response Levels and Reservoir Uses that automatically adjust water supply allocations for each drought level for each customer based on stipulations included in their water supply contracts.

Drought Response Levels	Previous 12-Months	Drought Response Level 1	Drought Response Level 2	Drought Response Level 3
Reservoir Elevation (ft)	N/A	1337.8	1332.8	1326.5
Percent Storage (Sediment Adjusted)	N/A	80%	60%	40%
Percent of Contractual Allocation	64%	64%	64%	64%

Water Use and Contractual Allocations	Contract Water Allocation		Previous 12-Months	Level 1 Annual Allocation	Level 2 Annual Allocation	Level 3 Annual Allocation
	Percent	acre-ft/yr	acre-ft/yr	acre-ft/yr	acre-ft/yr	acre-ft/yr
Contract Uses						
WFEC	-	4,543	1,813	2,923	2,923	2,923
Anadarko (includes PSO)	-	6,061	4,853	3,899	3,899	3,899
Chickasha	-	7,396	4,915	4,758	4,758	4,758
Subtotal	-	18,000	11,580	11,580	11,580	11,580
Noncontract and Other Uses						
Calculated Losses	-	-	238	238	238	238
Subtotal	-	-	238	238	238	238
TOTAL	-	18,000	11,818	11,818	11,818	11,818

*The total volume of water contracted Fort Cobb Reservoir is actually 15,211 acre-ft/yr, but the MCD holds a water right for 18,000 acre-ft/yr so this is what was used for planning purposes in the model. The contracted uses for each customer were adjusted proportionally so total use equals the 18,000 acre-ft/yr water right. The Percent of Contractual Allocation (Previous 12 months) underrepresents that actual percentage based on 15,211 acre-ft/yr.

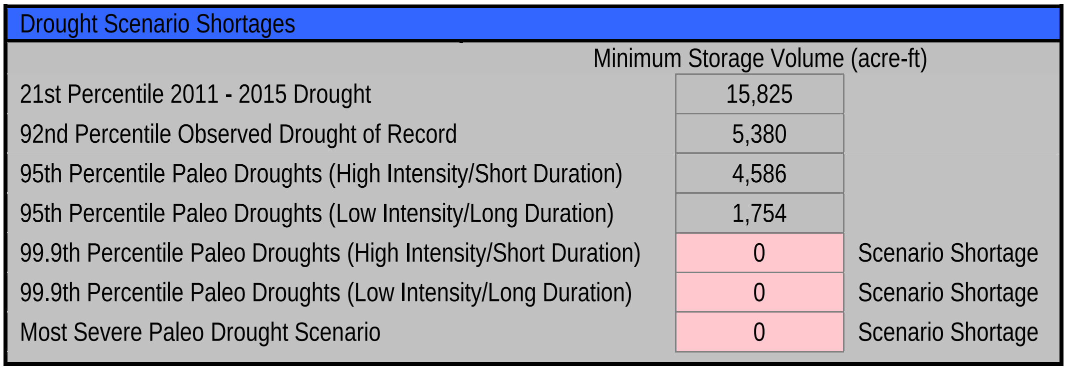
Table 8: Foss Reservoir Interface for Drought Response Levels and Reservoir Uses that automatically adjust water supply allocations for each drought level for each customer based on stipulations included in the water supply contracts.

Drought Response Levels						
			Previous 12-Months	Drought Response Level 1	Drought Response Level 2	Drought Response Level 3
Reservoir Elevation (ft)			N/A	1637.0	1631.0	1623.7
Percent Sediment Adjusted Active Storage			N/A	80%	60%	40%
Percent of Contractual Allocation			17%	17%	17%	17%
Water Use and Contractual Allocations						
	Contract Water Allocation		Previous 12-Months	Level 1 Annual Allocation	Level 2 Annual Allocation	Level 3 Annual Allocation
	Percent	acre-ft/yr	acre-ft/yr	acre-ft/yr	acre-ft/yr	acre-ft/yr
Contract Uses						
Clinton	48.63249	8,430	1,833	1,407	1,407	1,407
Hobart (*includes Butler and Frontier Development Authority*)	35.75129	6,197	820	1,034	1,034	1,034
Bessie	1.58138	274	28	46	46	46
New Cordell	14.03484	2,433	212	406	406	406
Subtotal	*100*	*17,334*	*2,894*	*2,894*	*2,894*	*2,894*
Noncontract and Other Uses						
Wholesale Customers	N/A	N/A	0	0	0	0
Treatment Plant Use	N/A	N/A	25	25	25	25
Brine Plant Effluent	N/A	N/A	807	807	807	807
Effluent Dilution (Plant)	N/A	N/A	993	993	993	993
Effluent Dilution (River)	N/A	N/A	6,666	6,666	6,666	6,666
Subtotal	-	-	*8,490*	*8,490*	*8,490*	*8,490*
TOTAL	100	17,334	11,383	11,383	11,383	11,383

8. Drought Scenario Shortages

This interface automatically populates the minimum reservoir storage under each of the seven drought scenarios. By minimum, we mean the lowest storage volume that the reservoir reaches over the forward looking model period. The interface is programmed to highlight supply shortages in red. For the purposes of this study, a shortage occurs when storage drops below the elevation of the lowest operable intake. Again, the user can assign any desired elevation as the lower bound of storage. Table 9 shows that if the three customers are using 64 percent of their water supply allocation, as previously discussed, then shortages would exist under both of the 99th percentile paleo droughts and under the most severe paleo drought. This interface demonstrates the EDRRO model's utility at combining real-time water use data with an array of drought scenarios to determine whether shortages occur and if so, by how much.

Table 9: Example for Fort Cobb of results table in model. This scenario shows shortages for three paleo drought scenarios, indicated by storage values less than the lowest operable intake.



Drought Scenario Shortages		
	Minimum Storage Volume (acre-ft)	
21st Percentile 2011 - 2015 Drought	15,825	
92nd Percentile Observed Drought of Record	5,380	
95th Percentile Paleo Droughts (High Intensity/Short Duration)	4,586	
95th Percentile Paleo Droughts (Low Intensity/Long Duration)	1,754	
99.9th Percentile Paleo Droughts (High Intensity/Short Duration)	0	Scenario Shortage
99.9th Percentile Paleo Droughts (Low Intensity/Long Duration)	0	Scenario Shortage
Most Severe Paleo Drought Scenario	0	Scenario Shortage

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PART V:
EDRRO MODELING RESULTS

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PART V: EDRRO MODELING RESULTS

Recall that in Part II, we converted tree ring data into new inflow datasets and evaluated the impacts of a large number (1,000+) paleo droughts on reservoir firm yield using Reclamation's Firm Yield model. In Part III, in addition to the two most severe droughts observed since record keeping, we selected five of the 1,000+ paleo drought scenarios which, if properly planned for and responded to, provide the lowest risk of the reservoirs going dry. In Part IV, we introduced the Enhanced Drought Response Reservoir Operations (EDRRO) Model, a tool that can be used to plan for and respond to these drought scenarios using real-time water use data. In this section, we perform several test runs of the EDRRO model. Results of a wide range of modeling scenarios are presented, beginning with "No Action" scenarios which reflect the extent to which supply shortages would exist if *no measures are taken to curtail demands* during any of the seven drought scenarios. Next, we present how various "Demand Curtailment" scenarios that are triggered at different reservoir elevation thresholds could prevent supply shortages[5].

No Action Scenarios

Selection of No Action Scenarios

The first step here is to define what is meant by "No Action". By "action", we mean demand curtailments. Therefore, No Action means that "status quo uses" would occur without any demand curtailments during the droughts that are modeled. But the term "status quo uses" needs further refinement because it can depend on different factors, such as contractual agreements, and will change as the demands for water either increase or decrease over time. As stated previously, one of the key strengths of the EDRRO model is its ability to incorporate real-time water use data. However, for the purposes of demonstrating the utility of the EDRRO model for this report, some basic assumptions are made about status quo water use. This will not only provide us with a baseline by which to compare the demand curtailment scenarios, but also simplify the modeling analyses and results. It should be noted that these scenarios and associated assumptions will vary at each locale and are at the discretion of the EDRRO model user.

For Foss and Fort Cobb Reservoirs, three No Action water use scenarios were selected: (1) Minimum Contract Demand [MinD]; (2) Current demand [CD]; and (3) Maximum projected demand [MaxD]. The MinD equals the minimum volume of water that customers are required to take pursuant to their water supply contracts with the MCDs, if applicable. For CD, we selected the highest three-year running average water use over the last ten years[6]. The MaxD equals the maximum projected water demand in 2060[7]. The No Action scenarios and corresponding use volumes are provided in Table 10.

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[5] As discussed in Part IV, a "shortage" occurs when the reservoir drops below the elevation of the lowest operable intake.

[6] Because demands depend on a number of factors and can fluctuate from year to year, we chose a ten-year period to compare maximum three-year running averages. For Foss Reservoir, water use associated with advanced water treatment plant's brine is included.

[7] This corresponds to the Foss and Fort Cobb Reservoir MCD water rights of 17,334 acre-feetY and 18,000 acre-feetY, respectively.

Table 10: Three No Action water use scenarios for Foss and Fort Cobb Reservoirs.

Water Use Scenario	Foss Reservoir	Fort Cobb Reservoir
Minimum Contract Demand (acre-ft/yr)	8,028	N/A*
Current Demand (acre-ft/yr)	11,383	11,580
Maximum Projected Demand (acre-ft/yr)	17,334	18,000

*A minimum contract demand does not exist for customers of the Fort Cobb Master Conservancy District

EDRRO model Instructions

- The three water use scenarios are entered into the Water Use Interface of the EDRRO model as follows: for CD, enter the actual maximum three-year running average of water use over the last ten years and distribute that volume over a 12-month period based on the actual monthly distribution for that period. For MinD and MaxD, distribute the annual volume over the same 12-month period based on the proportion of actual use by month that was calculated for current demands.
- It should be noted that while MaxD at Fort Cobb Reservoir corresponds to 100 percent use of their contracted water allocation, MaxD at Foss Reservoir corresponds to *only 25 percent* use of their contractual allocation because the remaining 75 percent of their water right is being used to manage waste brine associated with the advanced water treatment plant.
- For Fort Cobb Reservoir, the Inflow Depletions Interface is adjusted to account for both a 25 percent and a 50 percent reduction in base flow for the CD and MaxD scenarios. Either of these base flow reductions are possible under these demand scenarios which is why they are both modeled. The base flow at Fort Cobb Reservoir is 17,316 acre-ft/yr. These reductions are assumed based on the best available data.

Results

Tables 11 and 12 provide a summary of modeling results for Foss and Fort Cobb Reservoirs, respectively. A supply shortage is denoted as an “X” in the Tables. The Modeled Reservoir Storage results for Foss Reservoir, as depicted from the EDRRO model Interface, are illustrated in Figures 40-47 in Appendix B. The Modeled Reservoir Storage results for Fort Cobb Reservoir are illustrated in Figures 48-57 in Appendix B. To allow the reader to more easily discern impacts of droughts on reservoir storage, figures present impacts in a progression from the least severe observed droughts to the most severe paleo droughts under all three demand scenarios.

For Foss Reservoir, under the MinD scenario, a shortage is observed during the most severe paleo drought; under the CD scenario, a shortage is observed under the most severe paleo drought and under both the 99th percentile droughts; under the MaxD scenario, a shortage is observed under the most severe and under both of the 95th and 99th percentile droughts. Under all three demand scenarios, no shortages would occur under either of the observed critical droughts.

For Fort Cobb Reservoir, two different base flow depletion scenarios were evaluated in addition to two demand scenarios. Under the CD/25 percent base flow reduction scenario, no shortages are observed. Under the CD/50 percent base flow reduction scenario, a shortage is observed under both 99th percentile droughts, as well as under the most severe paleo drought. Under the MaxD/25 percent base flow reduction scenario, shortages are observed under all droughts except the 2011-2015 drought. Under the MaxD/50 percent base flow reduction scenario, shortages are observed across all seven drought scenarios.

Table 11: EDRRO "No Action" Modeling Results at Foss Reservoir showing whether shortages exist under three water use scenarios and seven drought scenarios.

Observed and Paleo Droughts	Water Use Scenario	Volume (acre-feet)	Contract Water Allocation (%)	Shortage
Observed 2011-2015 Drought (61st Percentile)	MinD	8,028	13	-
Observed Drought of Record (72nd Percentile)	MinD	8,028	13	-
95th Percentile Paleo Droughts (HI/SD)	MinD	8,028	13	-
95th Percentile Paleo Droughts (LI/LD)	MinD	8,028	13	-
99.9th Percentile Paleo Droughts (HI/SD)	MinD	8,028	13	-
99.9th Percentile Paleo Droughts (LI/LD)	MinD	8,028	13	-
Most Severe Paleo Drought	MinD	8,028	13	X
Observed 2011-2015 Drought (61st Percentile)	CD	11,383	17	-
Observed Drought of Record (72nd Percentile)	CD	11,383	17	-
95th Percentile Paleo Droughts (HI/SD)	CD	11,383	17	-
95th Percentile Paleo Droughts (LI/LD)	CD	11,383	17	-
99.9th Percentile Paleo Droughts (HI/SD)	CD	11,383	17	X
99.9th Percentile Paleo Droughts (LI/LD)	CD	11,383	17	X
Most Severe Paleo Drought	CD	11,383	17	X
Observed 2011-2015 Drought (61st Percentile)	MaxD	17,334	25	-
Observed Drought of Record (72nd Percentile)	MaxD	17,334	25	-
95th Percentile Paleo Droughts (HI/SD)	MaxD	17,334	25	X
95th Percentile Paleo Droughts (LI/LD)	MaxD	17,334	25	X
99.9th Percentile Paleo Droughts (HI/SD)	MaxD	17,334	25	X
99.9th Percentile Paleo Droughts (LI/LD)	MaxD	17,334	25	X
Most Severe Paleo Drought	MaxD	17,334	25	X

* MinD = Minimum Demand, CD = Current Demand, MaxD = Maximum Demand (full permitted amount).

** MaxD contract allocation is capped at 25 percent because the remaining 75 percent of MCD water right is allocated towards managing waste brine associated with an advanced water treatment plant. In effect, 100 percent of the water right is being utilized under MaxD.

*** An "X" denotes a shortage.

Table 12: EDRRO “No Action” Modeling Results at Fort Cobb Reservoir showing whether shortages exist under two water use scenarios, two base flow depletion scenarios, and seven drought scenarios.

Observed and Paleo Droughts	Water Use Scenario	Volume (acre-feet)	Base Flow Depletion (%)	Contract Water Allocation (%)	Shortage
Observed 2011-2015 Drought (21st Percentile)	CD	11,580	25	76	-
Observed Drought of Record (92nd Percentile)	CD	11,580	25	76	-
95th Percentile Paleo Droughts (HI/SD)	CD	11,580	25	76	-
95th Percentile Paleo Droughts (LI/LD)	CD	11,580	25	76	-
99.9th Percentile Paleo Droughts (HI/SD)	CD	11,580	25	76	-
99.9th Percentile Paleo Droughts (LI/LD)	CD	11,580	25	76	-
Most Severe Paleo Drought	CD	11,580	25	76	-
Observed 2011-2015 Drought (21st Percentile)	CD	11,580	50	76	-
Observed Drought of Record (92nd Percentile)	CD	11,580	50	76	-
95th Percentile Paleo Droughts (HI/SD)	CD	11,580	50	76	-
95th Percentile Paleo Droughts (LI/LD)	CD	11,580	50	76	-
99.9th Percentile Paleo Droughts (HI/SD)	CD	11,580	50	76	X
99.9th Percentile Paleo Droughts (LI/LD)	CD	11,580	50	76	X
Most Severe Paleo Drought	CD	11,580	50	76	X
Observed 2011-2015 Drought (21st Percentile)	MaxD	18,000	25	100	-
Observed Drought of Record (92nd Percentile)	MaxD	18,000	25	100	X
95th Percentile Paleo Droughts (HI/SD)	MaxD	18,000	25	100	X
95th Percentile Paleo Droughts (LI/LD)	MaxD	18,000	25	100	X
99.9th Percentile Paleo Droughts (HI/SD)	MaxD	18,000	25	100	X
99.9th Percentile Paleo Droughts (LI/LD)	MaxD	18,000	25	100	X
Most Severe Paleo Drought	MaxD	18,000	25	100	X
Observed 2011-2015 Drought (21st Percentile)	MaxD	18,000	50	100	X
Observed Drought of Record (92nd Percentile)	MaxD	18,000	50	100	X
95th Percentile Paleo Droughts (HI/SD)	MaxD	18,000	50	100	X
95th Percentile Paleo Droughts (LI/LD)	MaxD	18,000	50	100	X
99.9th Percentile Paleo Droughts (HI/SD)	MaxD	18,000	50	100	X
99.9th Percentile Paleo Droughts (LI/LD)	MaxD	18,000	50	100	X
Most Severe Paleo Drought	MaxD	18,000	50	100	X

* MinD = Minimum Demand, CD = Current Demand, MaxD = Maximum Demand (full permitted amount).

** An “X” denotes a shortage.

Demand Curtailment Scenarios

Selection of Scenarios

Now that we have an idea how much we are at risk of running short on supplies if nothing is done to curtail demands under various drought scenarios, the focus here is on how to prevent shortages in the event that one of these droughts actually occur. In this section, we answer the following:

1. How much would demands need to be curtailed in order to ensure that there is enough water stored in the reservoir to make it through various droughts?
2. How would the severity of the drought affect the extent to which demands need to be curtailed?
3. To what extent does the timing of demand curtailments affect their ability to prevent shortages? In other words, is it more effective to curtail demands when earlier when reservoir levels reach the "Warning Level" or can we wait until reservoir levels drop even lower to the "Emergency Level"?

Demand curtailment scenarios were identified based on their ability to prevent water supply shortages relative to the No Action under the various drought scenarios. In terms of timing, we chose Drought Response Level 3 (Emergency) as the reservoir level threshold that would trigger a demand curtailment. Next, we adjusted demands at Drought Response Level 2 (Warning) to evaluate the benefits of initiating demand curtailments earlier rather than waiting until reservoir levels drop to Emergency Levels.

EDRRO Model Instructions

- Begin with simulating reservoir storage under the No Action Scenario as described in the previous section. Recall that under the No Action Scenarios, the "Percent of Contractual Allocation" remains unchanged under all three drought response levels.
- In the Drought Response Levels Interface, under Drought Response Level 3, reduce the "Percent of Contractual Allocation" until the Drought Scenario Shortage Interface indicates that no shortages exist (i.e, no red highlight as shown in Table 9). Recall that this interface automatically populates the minimum reservoir storage under each of the seven drought scenarios. By minimum, we mean the lowest storage volume that the reservoir reaches over the modeled period. The Interface is programmed to highlight supply shortages in red. For the purposes here, a shortage occurs when storage drops below the elevation of the lowest operable intake. Table 9 discussed earlier illustrates this Interface.
- As we will demonstrate in the next section, the user can select any of the three drought response levels to initiate demand curtailments.

Results

Tables 13 and 14 provide a summary of the "Action" versus "No Action (NA)" modeling results for Foss and Fort Cobb Reservoirs, respectively. The drought scenarios, expected reservoir yield, and the corresponding percent demand curtailment that would be required under the CD and MaxD scenarios for Foss Reservoir, are illustrated in Figures 33 and 34, respectively. Similar results for Fort Cobb Reservoir are illustrated in Figures 35 and 36, respectively.

For Foss Reservoir, under both the CD and MaxD scenarios, demand curtailments would *not* be necessary under a repeat of either the 1970s drought of record or the 2011 drought. However, demands would need to be curtailed by 15.2; 44.8; and 66.0 percent under the MinD, CD, and MaxD scenarios, respectively in order to prevent a water supply shortage under all five paleo drought scenarios, including the most severe paleo drought simulated by the EDRRO model.

For Fort Cobb Reservoir, the results vary depending not only on the water use scenario, but by the percent base flow depletion. Under the CD scenario/50 percent base flow depletion scenario, demand curtailments would not be necessary under either the 1950s drought of record, the 2011 drought, or the 95th percentile paleo droughts. However, under the MaxD/50 percent base flow depletion scenario, a demand curtailment of 36 percent would be necessary to withstand the same droughts. In order to prevent a water supply shortage under all five paleo droughts, including the most severe paleo drought, demands would need to be curtailed by 20.3; 35.7; and 53.0 percent under the CD/50 percent base flow depletion, MaxD/25 percent base flow depletion, and MaxD/50 percent base flow depletion, respectively.

The Timing of Curtailments – Impacts of Triggers at Different Drought Response Levels

As previously discussed, the EDRRO Model can be used to evaluate impacts of demand curtailments at three different drought response levels. Although the user can set the response levels to any elevation, for our test, we chose: Level 1 "Watch" = 80 percent full; Level 2 "Warning" = 60 percent full; and Level 3 "Emergency" = 40 percent full. In the previous section, we evaluated how demand curtailments would prevent shortages if they were triggered when the reservoir reached the Emergency Level. Results show that significant demand curtailments would be necessary to prevent shortages under the most extreme drought scenarios evaluated by the EDRRO Model. In this section, we briefly evaluate whether any of these Emergency curtailments could be offset/reduced by curtailing demands earlier when the reservoirs reach the Warning Level[8].

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[8] An analysis was not performed on demand curtailments at a Level 1 "Watch" due to the frequent occurrence of the reservoirs reaching this threshold.

Table 13: EDRRO modeling Results at Foss Reservoir showing the percent demand curtailment needed to prevent shortages under three water use scenarios and seven drought scenarios.

Scenario Number	Water Use Scenario	Contract Water Allocation (%)	Emergency Drought Level		Scenarios with Shortages	Most Severe Paleo Drought	99.9th Percentile Paleo Droughts		95th Percentile Paleo Droughts		72nd Percentile Observed Drought of Record	61st Percentile 2011-2015 Drought
			Curtailment (%)	Use (acre-feet)			HI/SD	LI/LD	HI/SD	LI/LD		
1 (NA)	MinD	13	0	8,028	1	X	-	-	-	-	-	-
2	MinD	13	15.2	6,804	0	-	-	-	-	-	-	-
3 (NA)	CD	17	0	11,383	3	X	X	X	-	-	-	-
4	CD	17	30.4	7,918	2	X	X	-	-	-	-	-
5	CD	17	37.0	7,169	1	X	-	-	-	-	-	-
6	CD	17	44.8	6,285	0	-	-	-	-	-	-	-
7 (NA)	MaxD	25	0	17,334	5	X	X	X	X	X	-	-
8	MaxD	25	31.5	11,877	4	X	X	X	-	X	-	-
9	MaxD	25	32.7	11,673	3	X	X	X	-	-	-	-
10	MaxD	25	52.3	8,271	2	X	X	-	-	-	-	-
11	MaxD	25	64.8	6,094	1	-	X	-	-	-	-	-
12	MaxD	25	66.0	5,889	0	-	-	-	-	-	-	-

NA = No Action; MinD = Minimum Demand; CD = Current Demand; MaxD = Maximum Demand; X denotes which droughts had shortages for each scenario; HI/SD = High Intensity/Short Duration; LI/LD Low Intensity/Long Duration

Table 14: EDRRO modeling Results at Fort Cobb Reservoir showing the percent demand curtailment needed to prevent shortages under two water use scenarios, two base flow reduction scenarios, and seven drought scenarios.

Scenario Number	Water Use Scenario	Contract Water Allocation (%)	Base Flow Depletion (%)	Emergency Drought Level		Scenarios with Shortages	Most Severe Paleo Drought	99.9th Percentile Paleo Droughts		95th Percentile Paleo Droughts		92nd Percentile Observed Drought of Record	21st Percentile 2010-2015 Drought
				Curtailment (%)	Use (acre-feet)			HI/SD	LI/LD	HI/SD	LI/LD		
1 (NA)	CD	76	50	0	11,818	3	X	X	X	-	-	-	-
2	CD	76	50	16.2	9,904	2	-	X	X	-	-	-	-
3	CD	76	50	19.1	9,563	1	-	X	-	-	-	-	-
4	CD	76	50	20.3	9,423	0	-	-	-	-	-	-	-
5 (NA)	MaxD	100	25	0	18,000	6	X	X	X	X	X	X	-
6	MaxD	100	25	11.0	16,020	5	X	X	X	X	X	-	-
7	MaxD	100	25	15.4	15,228	4	X	X	X	X	-	-	-
8	MaxD	100	25	16.0	15,120	3	X	X	X	-	-	-	-
9	MaxD	100	25	31.5	12,330	2	X	X	-	-	-	-	
10	MaxD	100	25	35.3	11,646	1	-	X	-	-	-	-	-
11	MaxD	100	25	35.7	11,574	0	-	-	-	-	-	-	-
12 (NA)	MaxD	100	50	0	18,000	7	X	X	X	X	X	X	X
13	MaxD	100	50	3.9	17,298	6	X	X	X	X	X	X	-
14	MaxD	100	50	29.3	12,726	5	X	X	X	X	X	-	-
15	MaxD	100	50	33.5	11,970	4	X	X	X	-	X	-	-
16	MaxD	100	50	35.9	11,538	3	X	X	X	-	-	-	-
17	MaxD	100	50	47.5	9,450	2	X	X	-	-	-	-	-
18	MaxD	100	50	52.4	8,568	1	-	X	-	-	-	-	-
19	MaxD	100	50	53.0	8,460	0	-	-	-	-	-	-	-

NA = No Action; MinD = Minimum Demand; CD = Current Demand; MaxD = Maximum Demand; X denotes which drought had shortages for each scenario; HI/SD = High Intensity/Short Duration; LI/LD Low Intensity/Long Duration

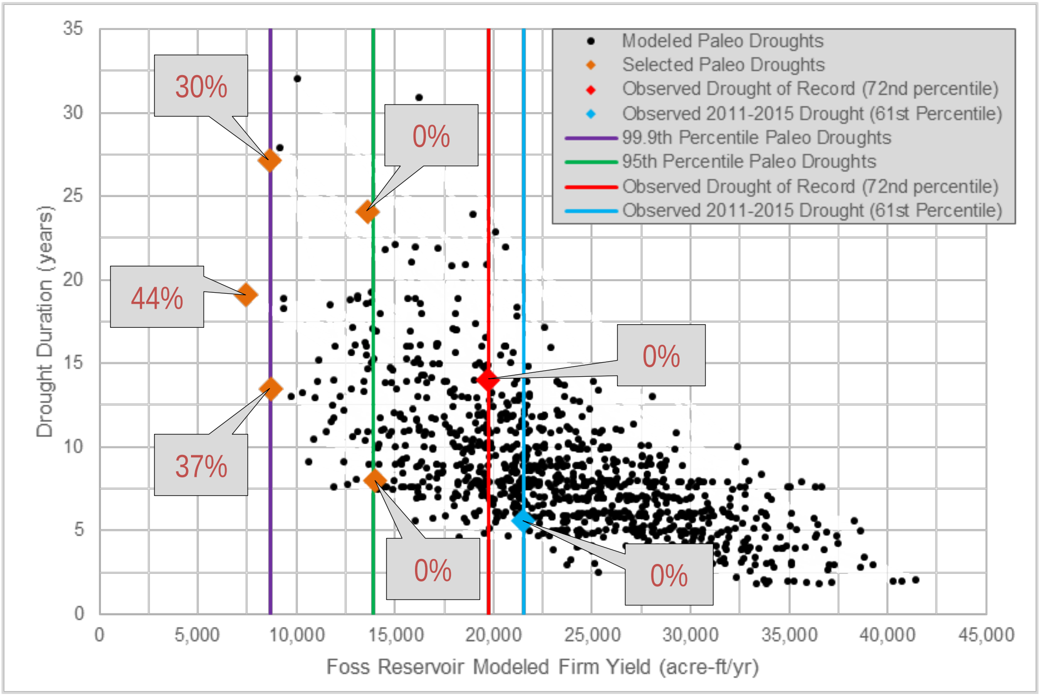

Figure 33: Percent demand curtailments needed under the Current Demand (CD) scenario to prevent water shortages at Foss Reservoir under seven drought scenarios simulated using the EDRRO model.

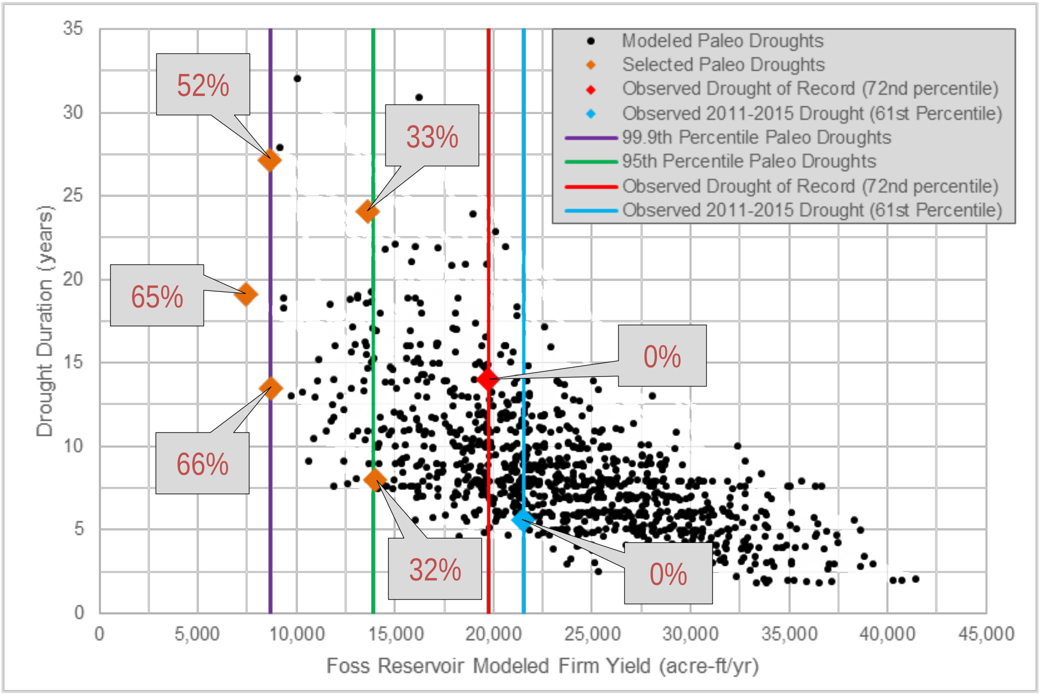

Figure 34: Percent demand curtailments needed under the Maximum Demand (MaxD) scenario to prevent water shortages at Foss Reservoir under seven drought scenarios simulated using the EDRRO model.

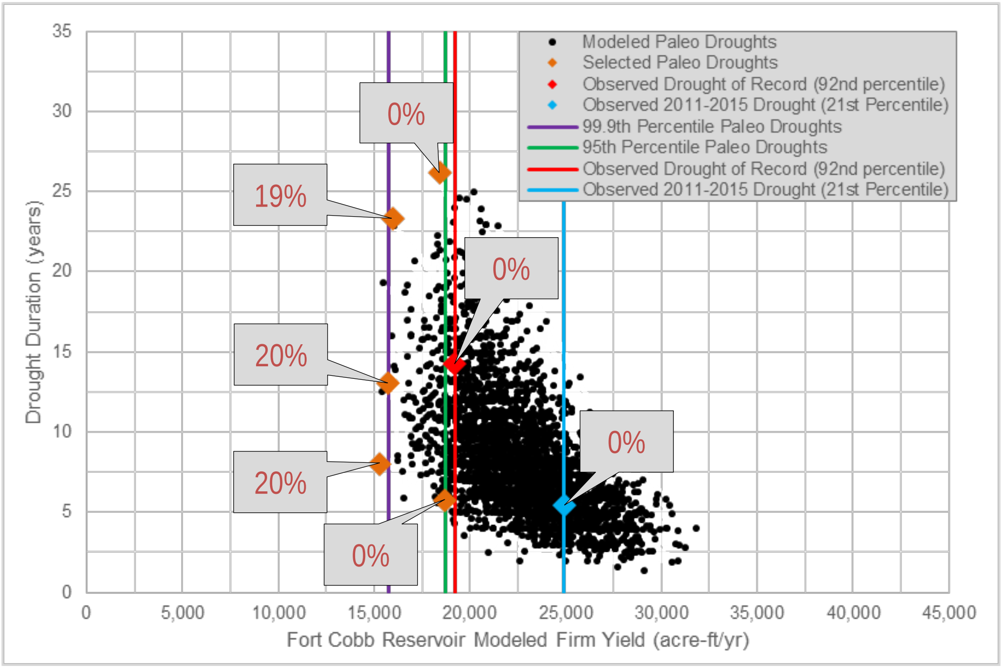

Figure 35: Percent demand curtailments needed under the Current Demand (CD)/50 percent base flow reduction scenario to prevent water shortages at Fort Cobb Reservoir under seven drought scenarios simulated using the EDRRO model.

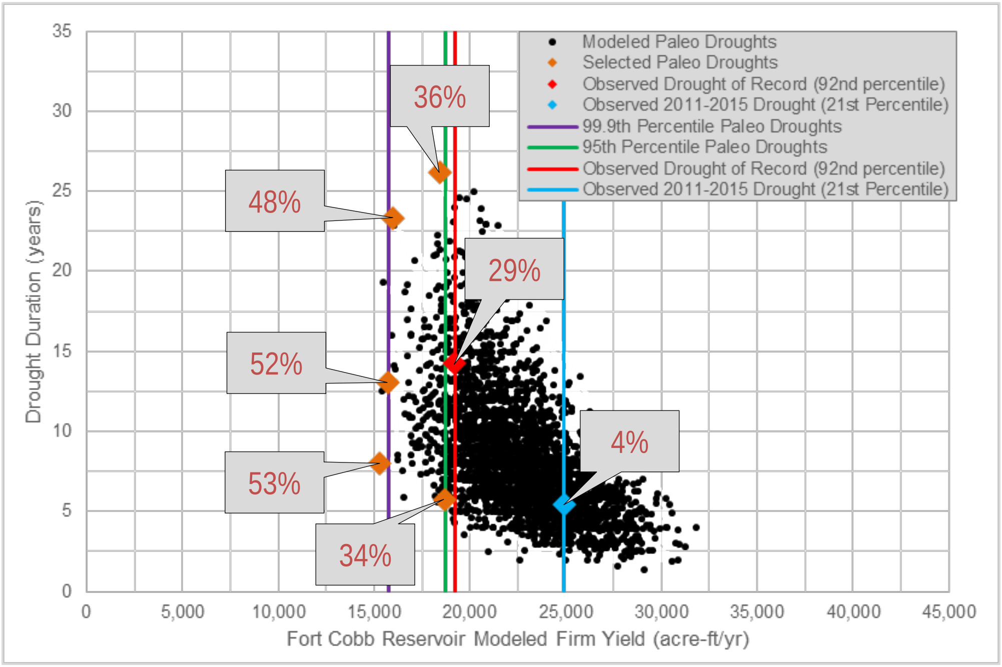

Figure 36: Percent demand curtailments needed under the Maximum Demand (MaxD)/50 percent base flow reduction scenario to prevent water shortages at Fort Cobb Reservoir under seven drought scenarios simulated using the EDRRO model.

Figures 37 and 38 display the results for Foss and Fort Cobb Reservoirs, respectively. For Foss Reservoir, for every ten percent demand curtailment that occurs at the Warning Level, the percent demand curtailment at the Emergency Level is reduced by zero to 3.2 percent. For Fort Cobb Reservoir, for every ten percent demand curtailment that occurs at the Warning Level, the percent demand curtailment at the Emergency Level is reduced by zero to 2.9 percent. These values vary depending on the intensity of the drought and amount of water use. Overall, the benefit of implementing demand curtailments at the Warning Level relative to the Emergency Level are relatively small. With that said, there is likely a psychological benefit of implementing demand curtailments earlier rather than later, especially in cases where significant demand curtailments are expected and may take time to implement.

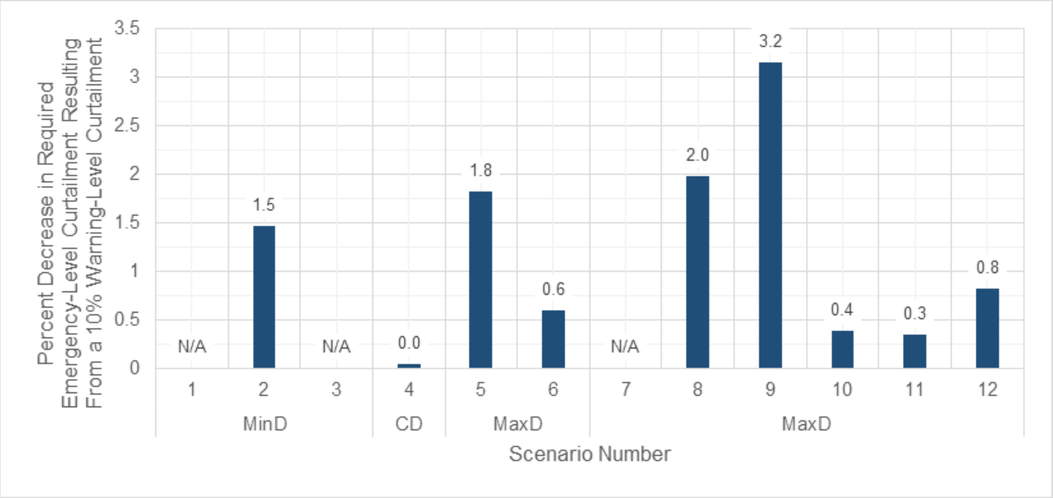

Figure 37: EDRRO Modeling Results for Foss Reservoir showing how a ten percent demand curtailment at the Warning Level offsets demand curtailments at the Emergency Level. N/A = Not Applicable; MinD = Minimum Demand; CD = Current Demand; MaxD = Maximum Demand.

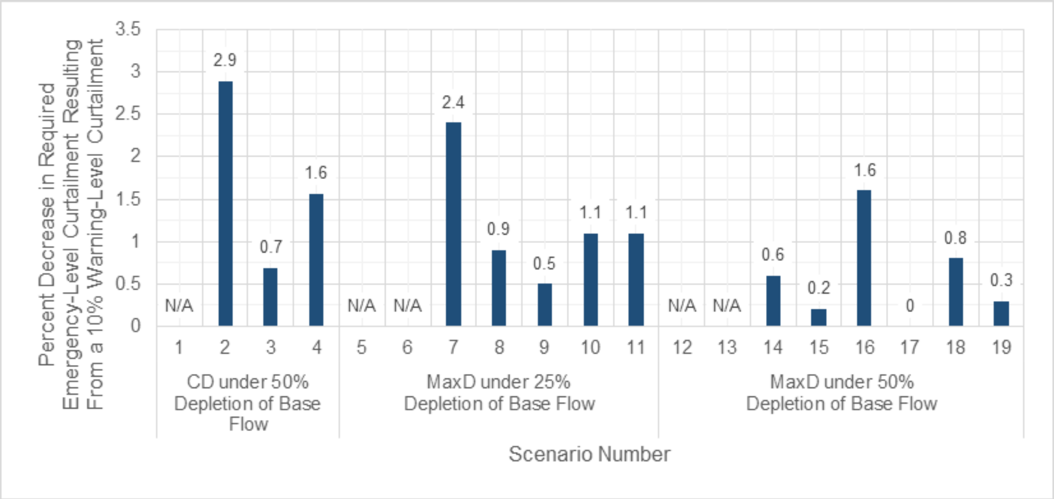

Figure 38: EDRRO modeling results for Fort Cobb Reservoir showing how a ten percent demand curtailment at the Warning Level offsets demand curtailments at the Emergency Level. N/A = Not Applicable; MinD = Minimum Demand; CD = Current Demand; MaxD = Maximum Demand.

Discussion

The EDRRO modeling results for Foss and Fort Cobb Reservoir reveal important information that can help the managers and users of these reservoirs better understand risk and make more informed decisions to ensure that secure water supplies are available for M&I use. Earlier, we posed the question: how much risk is a water manager willing to take on when delivering M&I water supplies? Indeed, the risk should be very low, and if a reservoir serves as the sole source of M&I water, then arguably, the risk tolerance should be zero. In deciding which paleo drought scenarios to include in the EDRRO model, we began with the understanding that 27 and 8 percent of the firm yield calculations for Foss and Fort Cobb Reservoirs, respectively, fell *below* the firm yield that is based on the observed record. Out of this subset of droughts, we selected a risk window of 5.0 to 0.1 percent, meaning that we wanted to be 95 to 99.9 percent "sure" that the paleo drought we plan for would not be surpassed by a potentially even worse drought. The risk window we selected provided a conservative range of only the most severe paleo drought scenarios, which if properly planned for, would pose only the most minimal chance of the reservoirs going dry. In addition to scenarios representing the two most severe observed droughts, a total of five paleo drought scenarios were selected, and using the EDRRO model, we simulated the percentage of demands that would need to be curtailed in order to withstand the selected drought scenarios.

As expected, to withstand these paleo droughts, significant demand curtailments would be required; curtailments that will increase as water use increases into the future and approaches the MaxD levels simulated by the EDRRO model. In terms of the timing of demand curtailments, it was unexpected to find that curtailing demands earlier when the reservoir reaches the Warning Level has such a negligible effect on demand curtailments needed when the reservoir reaches the Emergency Level. Regardless, these results provide valuable information that stakeholders can use as they plan towards the future; however, it should be recognized that the results are still based on a fundamental set of assumptions about how the future will unfold. We believe the assumptions and methods described herein are more robust than standard practice, but no one can predict the future with certainty. If the next critical drought comes sooner rather than later, then the CD use scenario may be a good indicator of demand curtailments, if any, that may be in store for customers; and if the next critical drought unfolds decades from now, then the MaxD use scenario may, in turn, be a good indicator of future expected demand curtailments. But what if a severe paleo-type drought occurs in the year 2100? Considering water demands at that time would likely surpass those in 2060, curtailments would become even more severe. Regardless, this information could be used by decision makers now to identify what steps could be taken to actually implement and enforce demand curtailments before the next drought hits.

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PART VI:

CONCLUSIONS AND GUIDANCE

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PART VI: CONCLUSIONS AND GUIDANCE

The EDRRO model appears to be a valuable tool that can help water resource managers address significant challenges associated with preparing for and responding to drought, particularly when managing a reservoir that provides water for M&I purposes. Through this study, we have improved our understanding of how variations in climate can affect reservoir yield by developing a method of converting tree ring data into new inflow datasets. We improved upon our existing Firm Yield model and developed the EDRRO model that calculates reservoir firm yield based on these tree ring inflow datasets. By extending the historical period, we have captured a greater range of variation than that which we currently capture using existing practices. This has provided us with a robust range of reservoir firm yield calculations under various drought scenarios, along with the corresponding risks of the reservoir going dry depending on the type of drought you may experience. Along with those risks, water resource managers can use the EDRRO model to look toward the future and evaluate when and how much the water demand from reservoir users may need to be curtailed in order to prevent supply shortages that could prove catastrophic to communities that depend on a reservoir for their water supply. This can improve risk-based decision-making, inform long-term demand management strategies, including operational flexibility, and/or guide investments in alternative water supplies. Recognizing that no tool can predict the future with absolute certainty, we also developed an interface within the EDRRO model that adjusts these reservoir supply predictions in real-time based on actual water use of reservoir customers, and on “what if” demand curtailment scenarios aimed at preventing a supply shortage while in the midst of a severe drought.

The EDRRO modeling results for Foss and Fort Cobb Reservoir reveal important information that can help the managers and users of these reservoirs better understand risk and make more informed decisions about how to ensure that secure water supplies are available for M&I use.

1. No two droughts are the same; they each vary in intensity, duration, and severity. Our hydroclimate record keeping encompasses only a relatively narrow period of time, so the trends we have observed may not be an accurate predictor of future conditions.
2. If one compares observed PDSI alongside PDSI calculated over a 600-year period using tree ring data, it becomes evident that the droughts observed over the relatively short 90-year period are far less severe than the so called “mega droughts” that have occurred throughout the last millennium. Therefore, the assumption that future droughts will mimic those that we have experienced in the past appears to be fundamentally flawed. In fact, tree ring data show us the next drought could be much worse than anything we have experienced.

3. Water resource managers should carefully consider their risk tolerance and risk exposure when planning for drought. We believe risk tolerance to a reservoir going dry should be very low, and if a reservoir serves as the sole supply source of M&I water, then arguably, the risk tolerance should be zero. The safety and sanitation of the public depends on it, as does industry – and ultimately, a city's economic prosperity, or even their existence, depends on it.
4. This Pilot Study details a credible, replicable approach which allows risk exposure to be calculated using tree ring data. When comparing known reservoir yields that occurred during the worst observed historical droughts to the calculated reservoir yields resulting from "mega droughts", we found that risk exposure (i.e., risk of the reservoirs going dry) ranged from 10 to 30 percent at Fort Cobb and Foss Reservoirs, respectively.
5. For drought planning purposes, any gap between risk exposure and risk tolerance should provide a signal for actions to be taken to mitigate those risks.
6. This Pilot Study developed the EDRRO model for this very purpose. In our case, we sought to narrow the risk gap through one type of action in particular: reducing reservoir user demands (e.g., via water conservation). In planning for the next drought, we selected a risk tolerance of 5.0 to 0.1 percent.
7. Improved operational flexibility is key. The future cannot be known with any degree of certainty. While a key strength of the EDRRO model lies with its capabilities of making more informed predictions about future long-term reservoir supplies, the reality is, when the next drought comes, the real power of the EDRRO model will truly reveal its ability to be used to manage demands and prevent supply shortages real time while in the midst of the drought. Thanks to this effort, when the next drought hits Foss and Fort Cobb Reservoirs, the managing entities will have improved operational flexibility and be better prepared. Our staff stand ready to provide details and assistance for any interested party wishing to do the same.
8. Even though the EDRRO model has demonstrated itself as a powerful and promising tool to enhance drought planning and response, it is important to stress that the EDRRO model should not be used in a vacuum. Complimentary efforts should be undertaken to address other risks to reservoir supply, such as those associated with land development, permitting, and water use that may occur upstream of a reservoir. These uses may reduce inflows into the reservoir and require the development of models and tools in their own right. For example, in the study area evaluated here, efforts are currently underway as part of the UWBS to analyze how upstream permits and water use affect base flows of streams entering Foss and Fort Cobb Reservoirs. In coordination with state and local officials, we are currently exploring how the EDRRO model could be used to

inform decision-making regarding demand curtailments of junior water right holders upstream of Foss and Fort Cobb Reservoirs in conjunction with demand reductions of reservoir customers.

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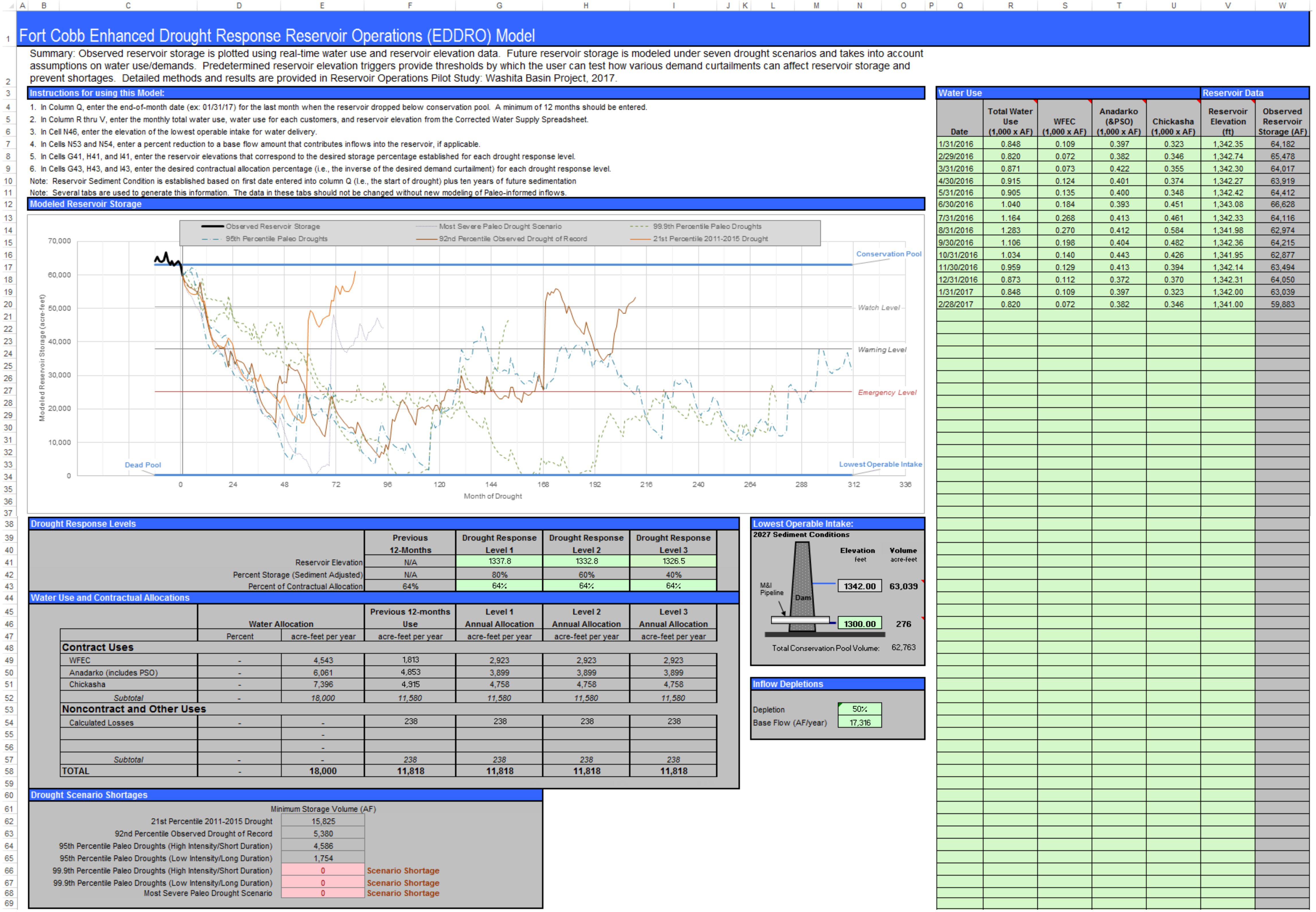
APPENDIX A: MODEL INTERFACE



Fort Cobb Enhanced Drought Response Reservoir Operations (EDDRO) Model

Summary: Observed reservoir storage is plotted using real-time water use and reservoir elevation data. Future reservoir storage is modeled under seven drought scenarios and takes into account assumptions on water use/demands. Predetermined reservoir elevation triggers provide thresholds by which the user can test how various demand curtailments can affect reservoir storage and prevent shortages. Detailed methods and results are provided in Reservoir Operations Pilot Study: Washita Basin Project, 2017.

Instructions for using this Model:

1. In Column Q, enter the end-of-month date (ex: 01/31/17) for the last month when the reservoir dropped below conservation pool. A minimum of 12 months should be entered.
2. In Column R thru V, enter the monthly total water use, water use for each customers, and reservoir elevation from the Corrected Water Supply Spreadsheet.
3. In Cell N46, enter the elevation of the lowest operable intake for water delivery.
4. In Cells N53 and N54, enter a percent reduction to a base flow amount that contributes inflows into the reservoir, if applicable.
5. In Cells G41, H41, and I41, enter the reservoir elevations that correspond to the desired storage percentage established for each drought response level.
6. In Cells G43, H43, and I43, enter the desired contractual allocation percentage (i.e., the inverse of the desired demand curtailment) for each drought response level.

Note: Reservoir Sediment Condition is established based on first date entered into column Q (I.e., the start of drought) plus ten years of future sedimentation

Note: Several tabs are used to generate this information. The data in these tabs should not be changed without new modeling of Paleo-informed inflows.

Modeled Reservoir Storage

Water Use / **Reservoir Data**

Date	Total Water Use (1,000 x AF)	WFEC (1,000 x AF)	Anadarko (&PSO) (1,000 x AF)	Chickasha (1,000 x AF)	Reservoir Elevation (ft)	Observed Reservoir Storage (AF)
1/31/2016	0.848	0.109	0.397	0.323	1,342.35	64,182
2/29/2016	0.820	0.072	0.382	0.346	1,342.74	65,478
3/31/2016	0.871	0.073	0.422	0.355	1,342.30	64,017
4/30/2016	0.915	0.124	0.401	0.374	1,342.27	63,919
5/31/2016	0.905	0.135	0.400	0.348	1,342.42	64,412
6/30/2016	1.040	0.184	0.393	0.451	1,343.08	66,628
7/31/2016	1.164	0.268	0.413	0.461	1,342.33	64,116
8/31/2016	1.283	0.270	0.412	0.584	1,341.98	62,974
9/30/2016	1.106	0.198	0.404	0.482	1,342.36	64,215
10/31/2016	1.034	0.140	0.443	0.426	1,341.95	62,877
11/30/2016	0.959	0.129	0.413	0.394	1,342.14	63,494
12/31/2016	0.873	0.112	0.372	0.370	1,342.31	64,050
1/31/2017	0.848	0.109	0.397	0.323	1,342.00	63,039
2/28/2017	0.820	0.072	0.382	0.346	1,341.00	59,883

Drought Response Levels

	Previous 12-Months	Drought Response Level 1	Drought Response Level 2	Drought Response Level 3
Reservoir Elevation	N/A	1337.8	1332.8	1326.5
Percent Storage (Sediment Adjusted)	N/A	80%	60%	40%
Percent of Contractual Allocation	64%	64%	64%	64%

Water Use and Contractual Allocations

	Water Allocation		Previous 12-months Use	Level 1 Annual Allocation	Level 2 Annual Allocation	Level 3 Annual Allocation
	Percent	acre-feet per year	acre-feet per year	acre-feet per year	acre-feet per year	acre-feet per year
Contract Uses						
WFEC	-	4,543	1,813	2,923	2,923	2,923
Anadarko (includes PSO)	-	6,061	4,853	3,899	3,899	3,899
Chickasha	-	7,396	4,915	4,758	4,758	4,758
Subtotal	-	*18,000*	*11,580*	*11,580*	*11,580*	*11,580*
Noncontract and Other Uses						
Calculated Losses	-	-	238	238	238	238
		-				
		-				
Subtotal	-	-	*238*	*238*	*238*	*238*
TOTAL	-	**18,000**	**11,818**	**11,818**	**11,818**	**11,818**

Lowest Operable Intake:

2027 Sediment Conditions

Elevation feet	**Volume** acre-feet
1342.00	63,039
1300.00	276

Total Conservation Pool Volume: 62,763

Inflow Depletions

Depletion	50%
Base Flow (AF/year)	17,316

Drought Scenario Shortages

	Minimum Storage Volume (AF)	
21st Percentile 2011-2015 Drought	15,825	
92nd Percentile Observed Drought of Record	5,380	
95th Percentile Paleo Droughts (High Intensity/Short Duration)	4,586	
95th Percentile Paleo Droughts (Low Intensity/Long Duration)	1,754	
99.9th Percentile Paleo Droughts (High Intensity/Short Duration)	0	Scenario Shortage
99.9th Percentile Paleo Droughts (Low Intensity/Long Duration)	0	Scenario Shortage
Most Severe Paleo Drought Scenario	0	Scenario Shortage

Figure 39: Screenshot of Fort Cobb Reservoir Drought Operations Model. Cells that are green are to be input for specific drought situations. All other cells are either fixed or functions of the input data.

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APPENDIX B: NO ACTION RESULTS

Foss Reservoir "No Action" Results

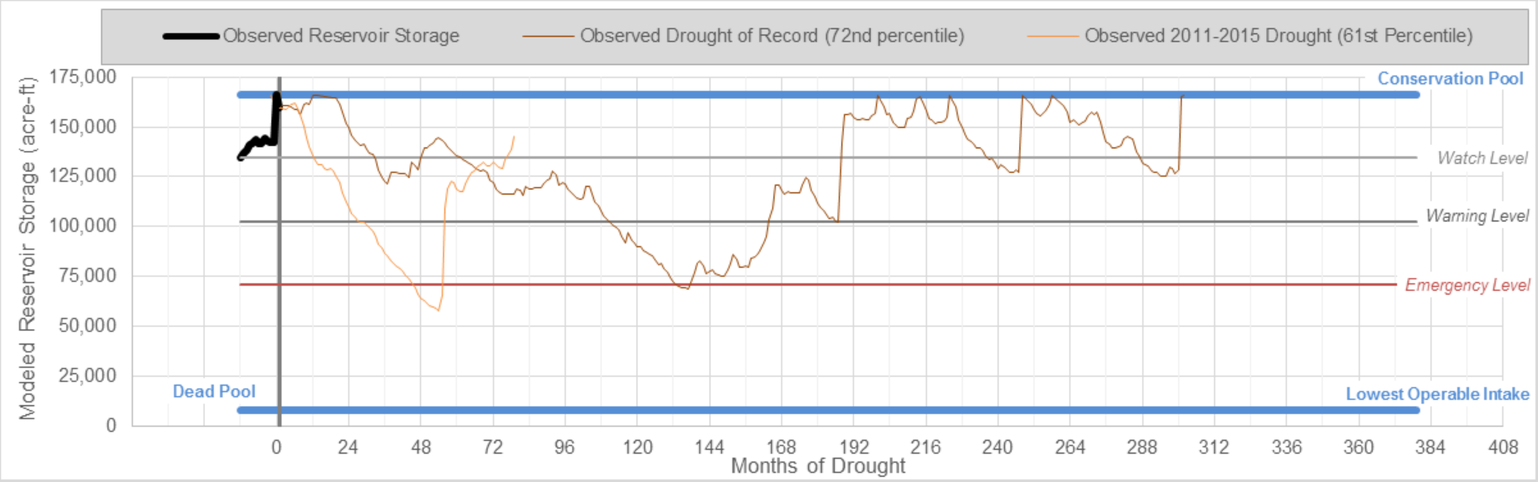

Figure 40: Modeled storage of Foss Reservoir under two observed critical droughts. Under a minimum demand scenario. No shortages are observed.

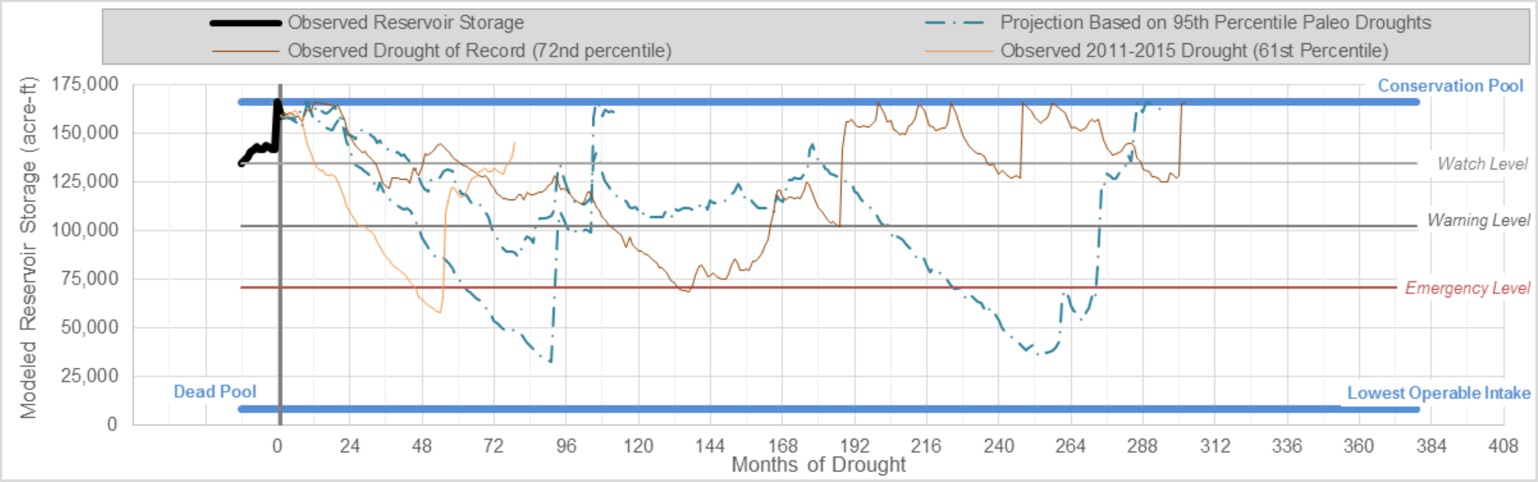

Figure 41: Modeled storage of Foss Reservoir under (a) two observed critical drought scenarios; and (b) 95th percentile paleo droughts [HI/SD; LI/LD]. Under a minimum demand scenario. No shortages are observed.

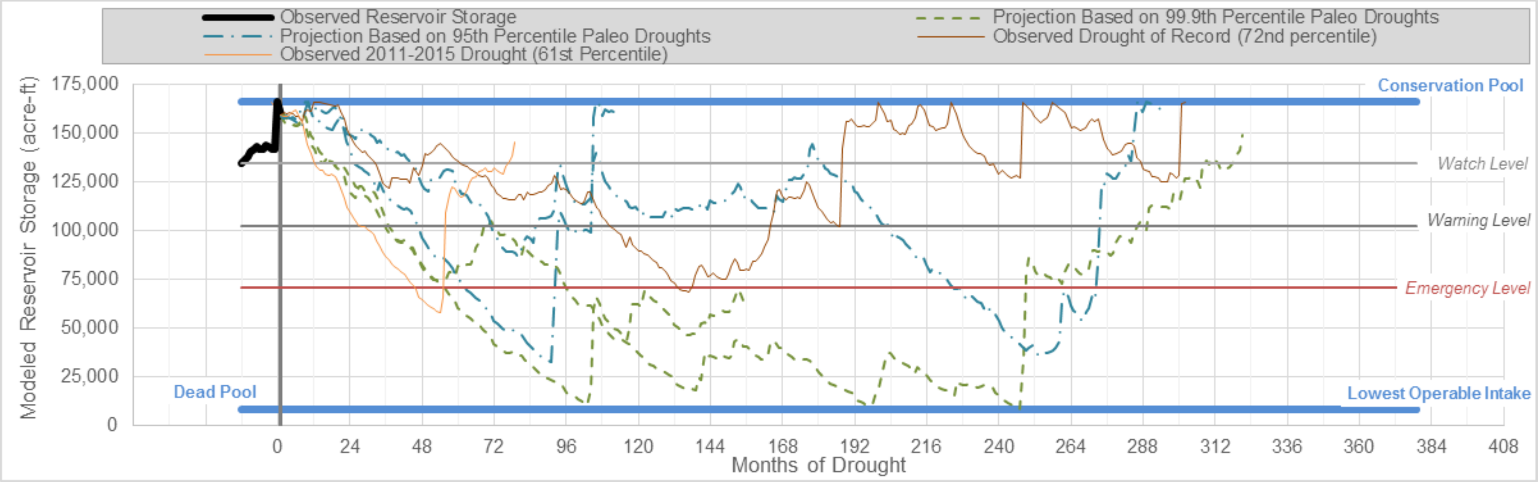

Figure 42: Modeled storage of Foss Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; and (c) 99.9th percentile paleo droughts [HI/SD; LI/LD]. Under a minimum demand scenario. No shortages are observed.

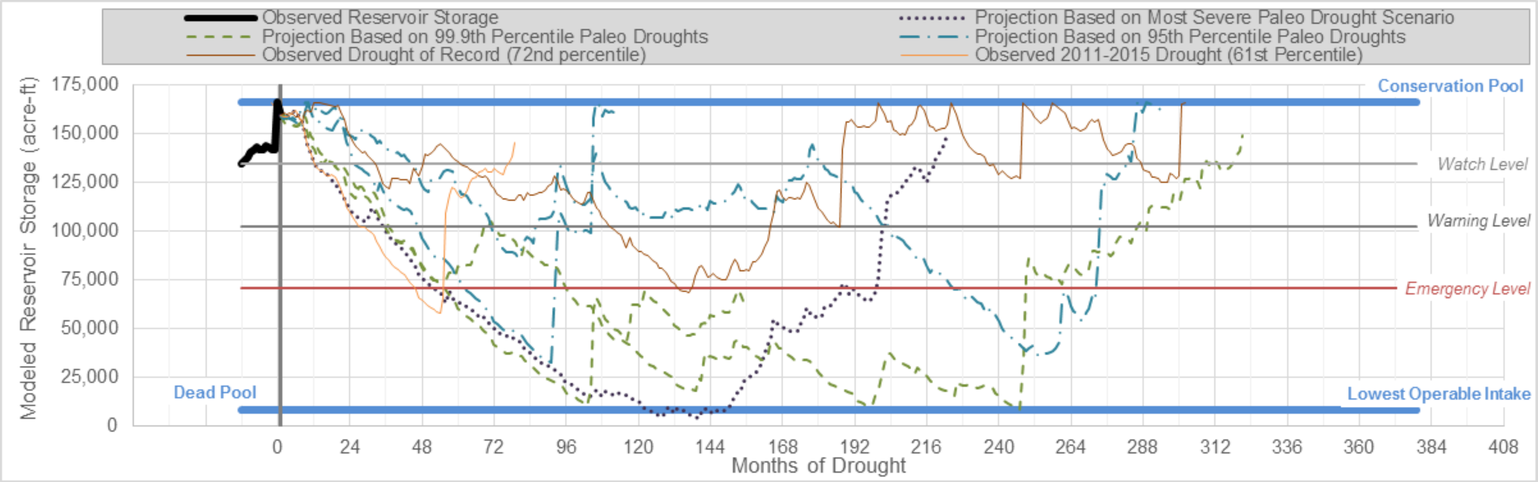

Figure 43: Modeled storage of Foss Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; (c) 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. Under a minimum demand scenario. One shortage observed.

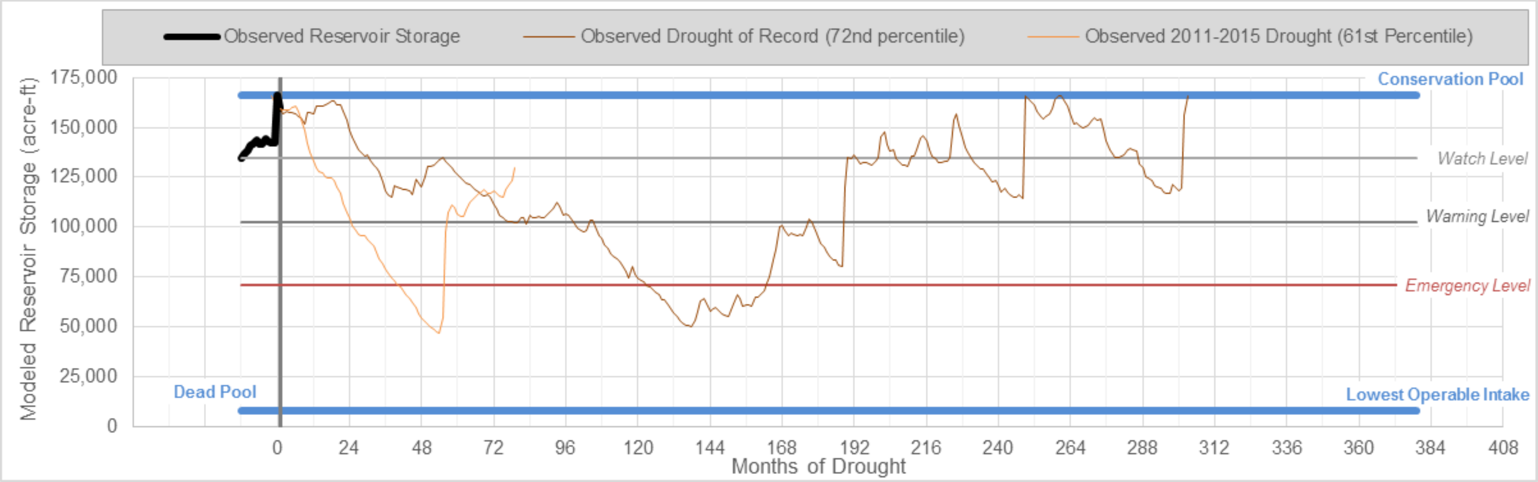

Figure 44: Modeled storage of Foss Reservoir under two observed critical droughts. Under a current demand scenario. No shortages are observed.

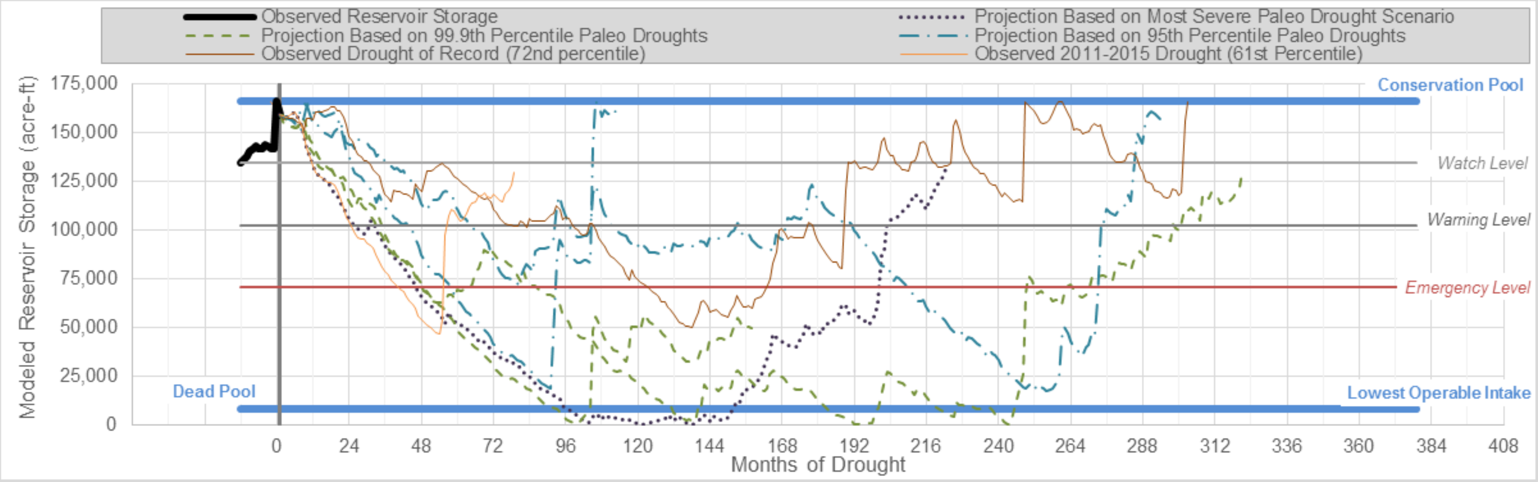

Figure 45: Modeled storage of Foss Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; (c) 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. Under a current demand scenario. Three shortages observed.

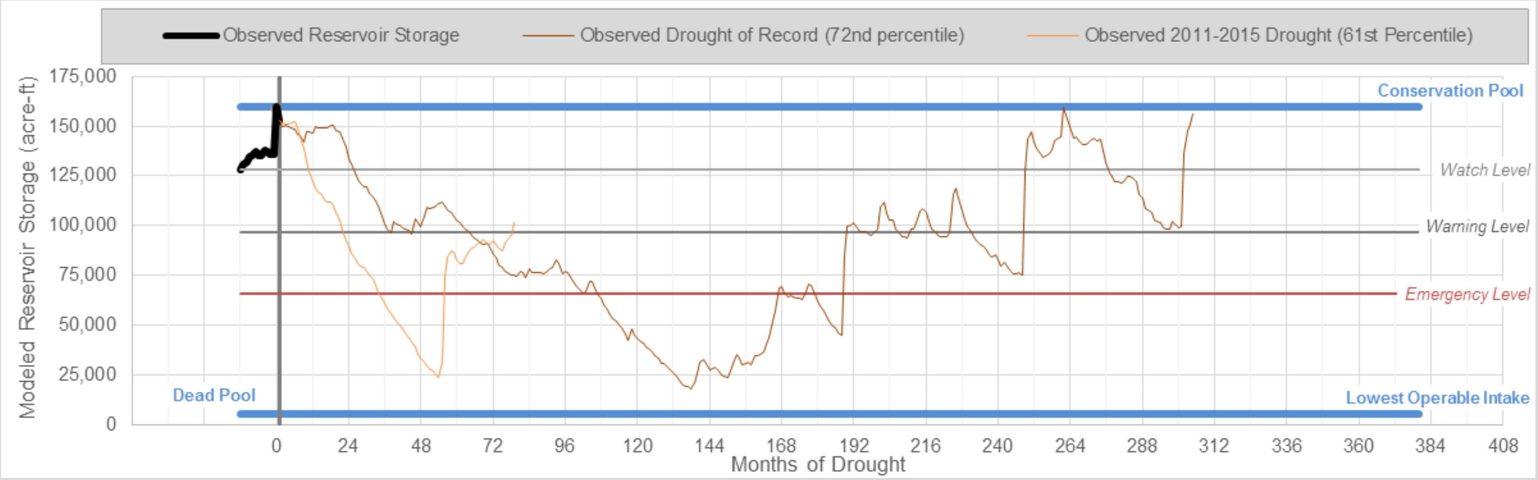

Figure 46: Modeled storage of Foss Reservoir under two observed critical droughts. Under a maximum demand scenario. No shortages are observed.

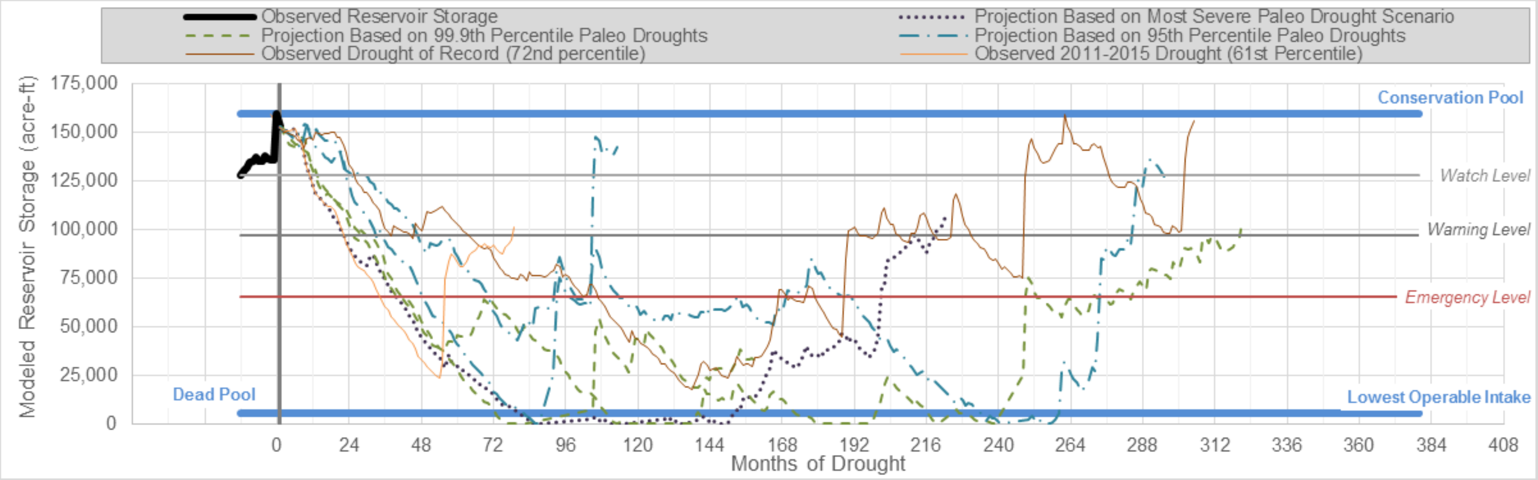

Figure 47: Modeled storage of Foss Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; (c) 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. Under a maximum demand scenario. Five shortages observed.

Fort Cobb Reservoir “No Action” Results

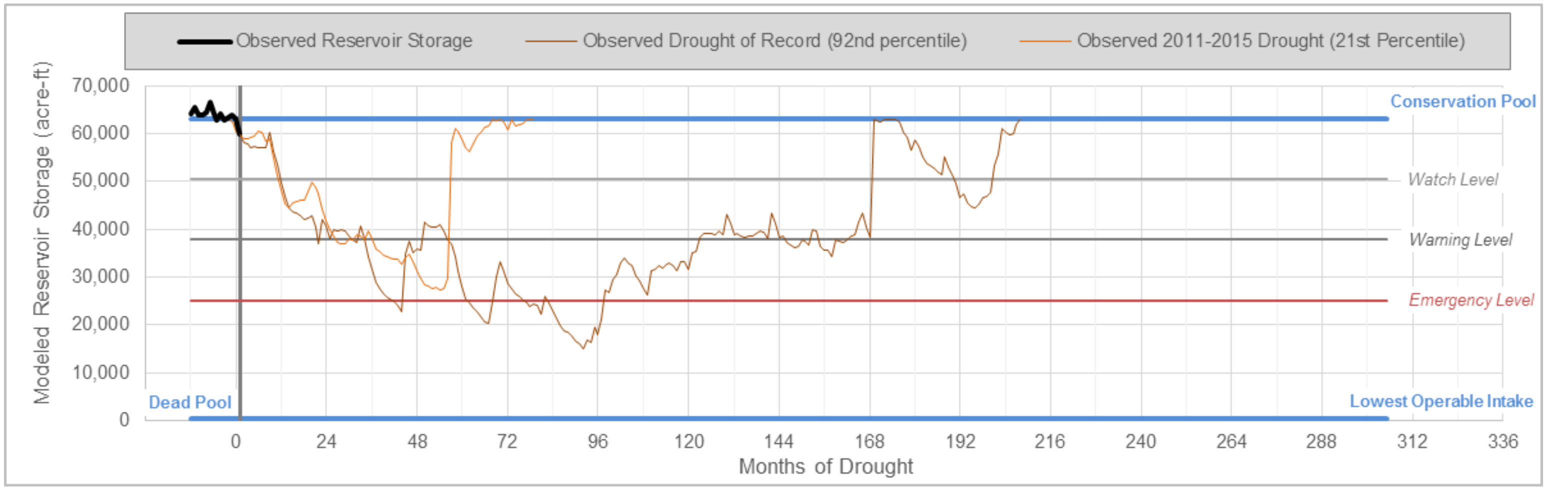

Figure 48: Modeled storage of Fort Cobb Reservoir under two observed critical droughts. A 25 percent base flow depletion. Under a current demand scenario. No shortages are observed.

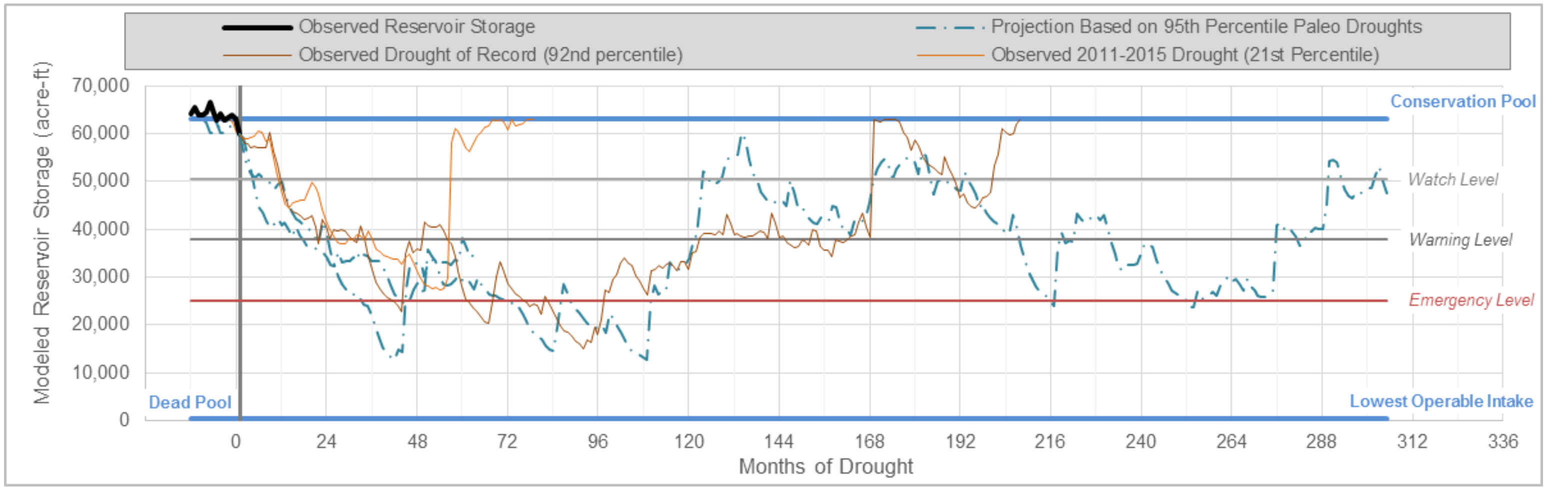

Figure 49: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; and (b) 95th percentile paleo droughts [HI/SD; LI/LD]. A 25 percent base flow depletion. Under a current demand scenario. No shortages are observed.

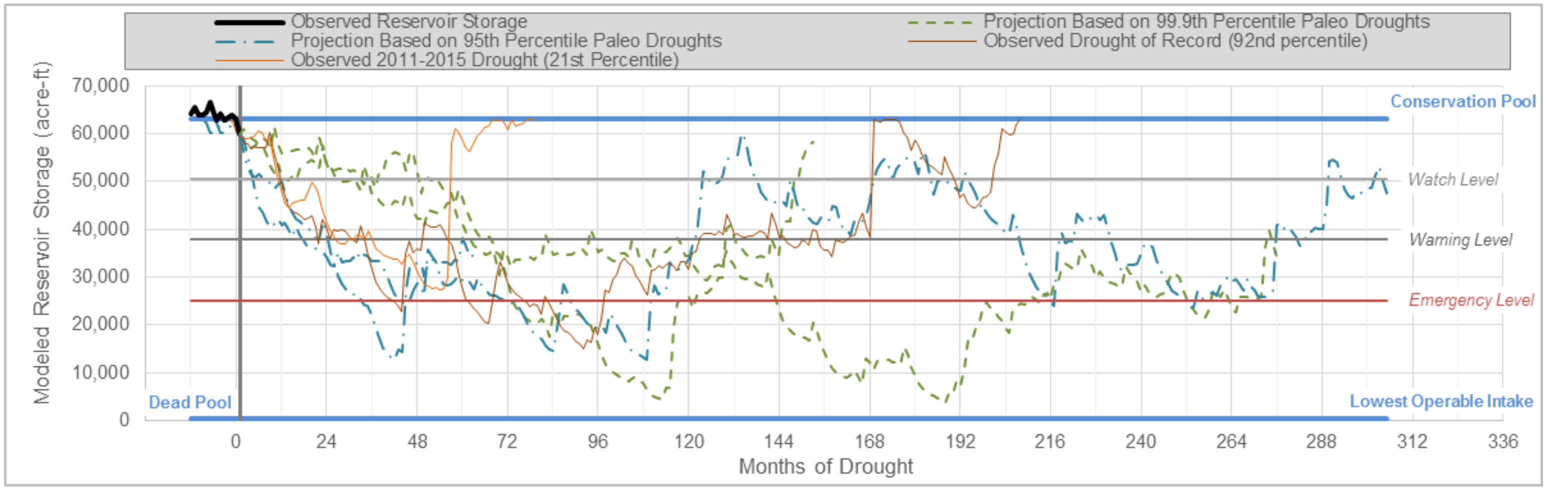

Figure 50: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; and (c) 99.9th percentile paleo droughts [HI/SD; LI/LD]. A 25 percent base flow depletion. Under a current demand scenario. No shortages observed.

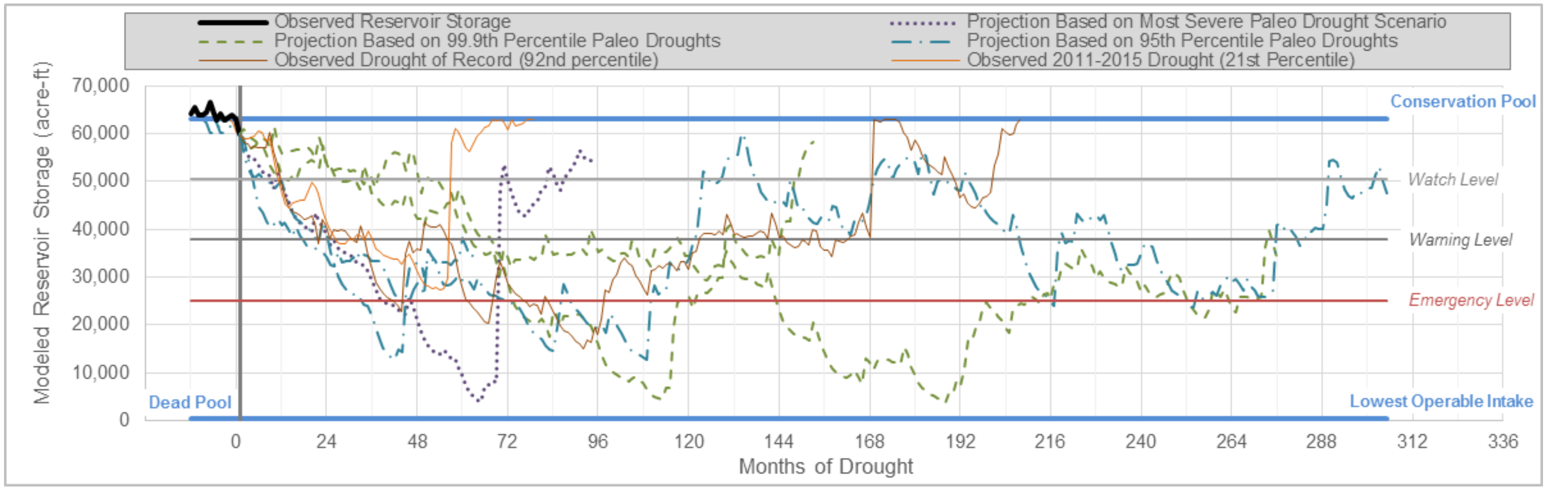

Figure 51: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. A 25 percent base flow depletion. Under a current demand scenario. No shortages observed.

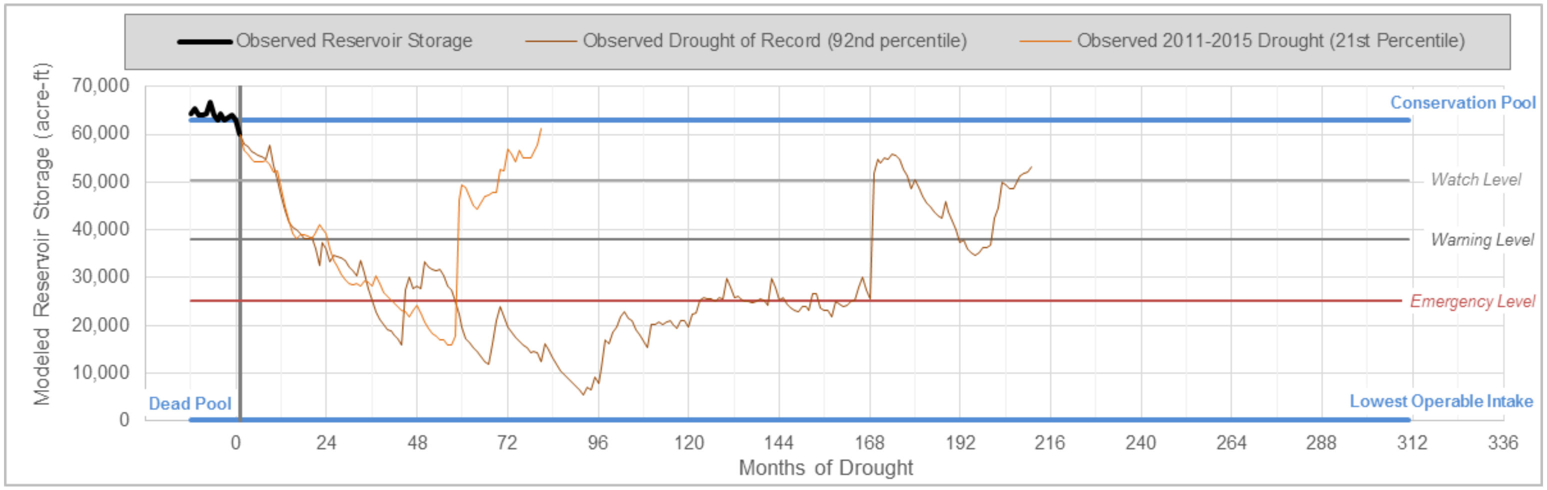

Figure 52: Modeled storage of Fort Cobb Reservoir under two observed critical droughts. A 50 percent base flow depletion. Under a current demand scenario. No shortages are observed.

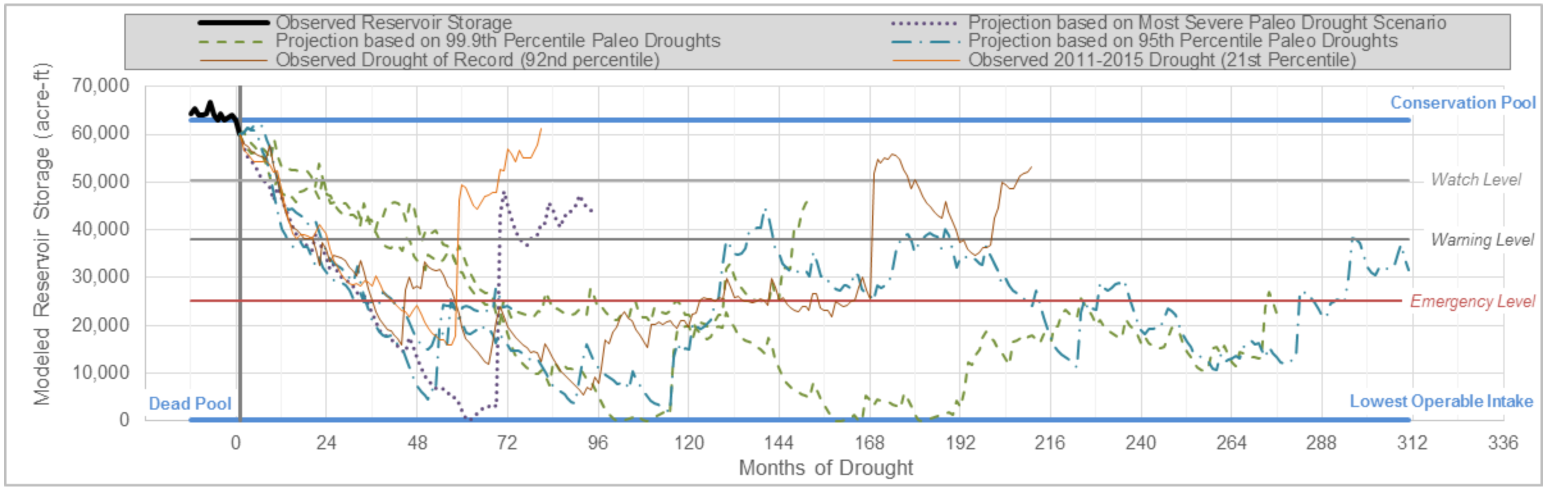

Figure 53: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. A 50 percent base flow depletion. Under a current demand scenario. Three shortages observed.

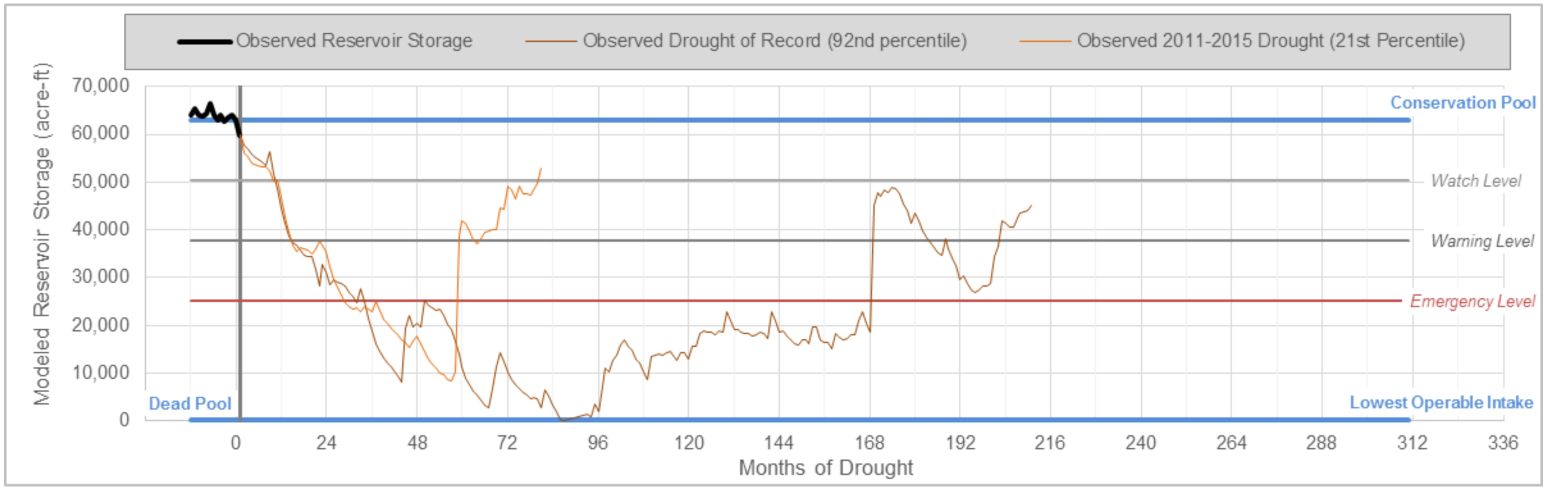

Figure 54: Modeled storage of Fort Cobb Reservoir under two observed critical droughts. A 25 percent base flow depletion. Under a maximum demand scenario. One shortage observed.

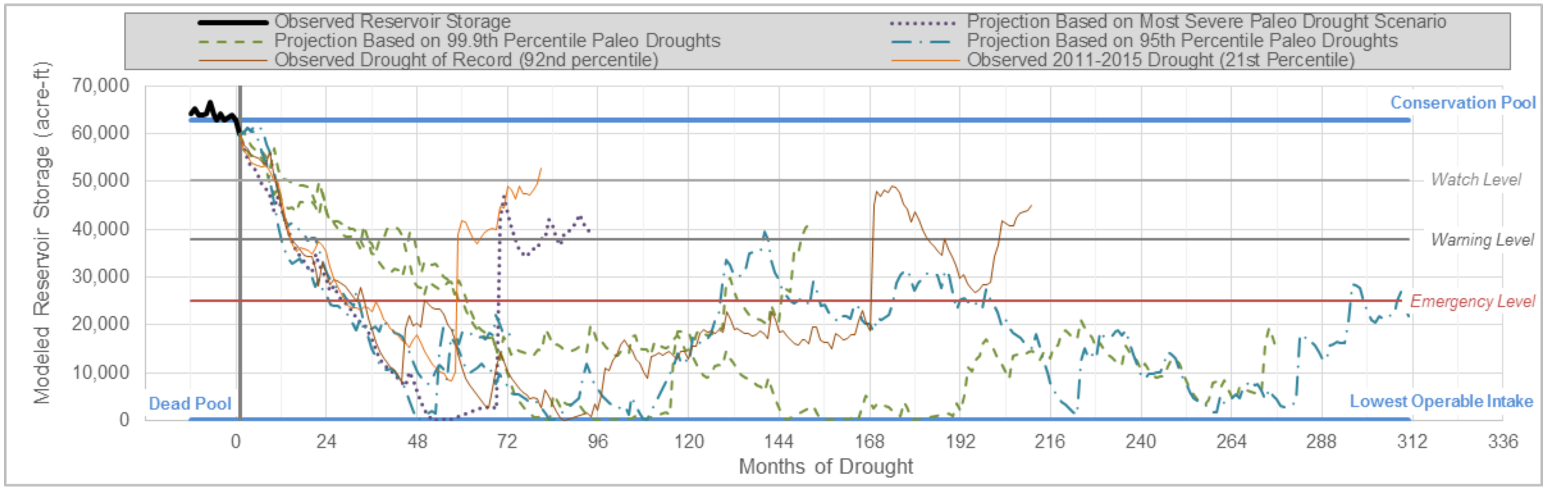

Figure 55: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. A 25 percent base flow depletion. Under a maximum demand scenario. Six shortages observed.

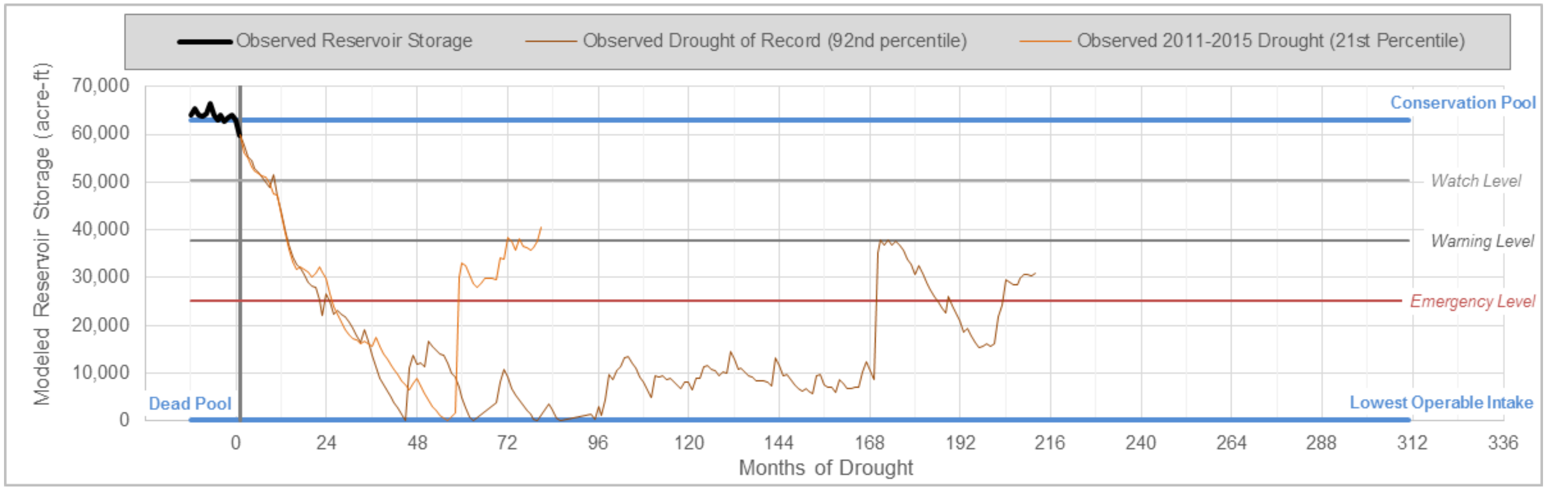

Figure 56: Modeled storage of Fort Cobb Reservoir under two observed critical droughts. A 50 percent base flow depletion. Under a maximum demand scenario. Two shortage observed.

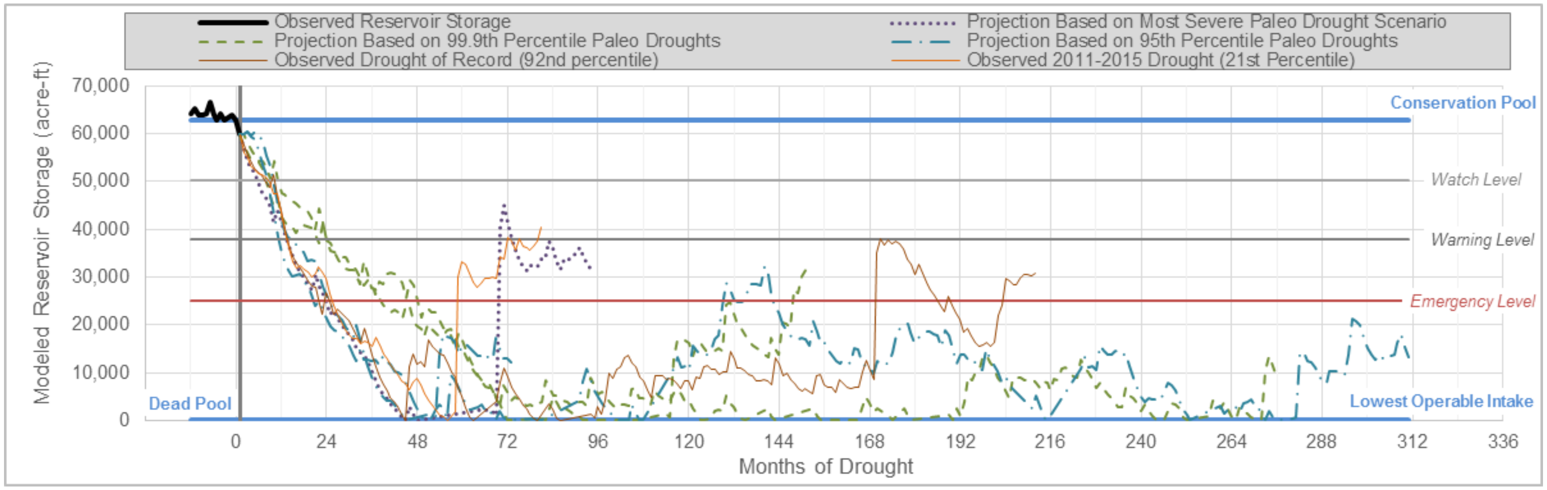

Figure 57: Modeled storage of Fort Cobb Reservoir under (a) two observed critical drought scenarios; (b) 95th percentile paleo droughts [HI/SD; LI/LD]; 99.9th percentile paleo droughts [HI/SD; LI/LD]; and (d) most severe paleo drought. A 50 percent base flow depletion. Under a maximum demand scenario. Seven shortages observed.