Salt and Verde River Reservoir System SECURE Reservoir Operations Pilot Study

Study Report

U.S. Department of the Interior
Bureau of Reclamation

Salt River Project
Arizona

Mission Statements

Department of the Interior
The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

Reclamation

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.

Salt River Project

As a community-based not-for-profit water and energy company, SRP provides reliable, affordable water and power to more than 2 million people living in central Arizona.

BUREAU OF RECLAMATION

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Study Report

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EXECUTIVE SUMMARY

Introduction

The Salt and Verde River Reservoir System Pilot Study (Study) was conducted as part of U.S. Bureau of Reclamation's (Reclamation) reservoir operations pilot initiative (Initiative), focused on identifying 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.

This Study was selected to represent the Lower Colorado Region and was led by Reclamation's Phoenix Area Office (PXAO). Pilot studies in other regions listed on the Pilot Study website at https://www.usbr.gov/watersmart/pilots/index.html. The goal of the pilots is to develop guidance for identifying and implementing changes that increase flexibility in reservoir operations in response to variability in water supplies, floods, and droughts.

Salt River Project Overview

The Salt River Project (SRP) was founded in 1903 and became one of the founding participants under the National Reclamation Act signed into law in 1902. This enabled SRP to receive the much needed financing to build Theodore Roosevelt Dam and provide a reliable source of water in a semiarid, highly variable climate. Roosevelt Dam was completed in 1911, with five other dams on the Salt and Verde rivers completed between the 1920s and 1940s. These six dams on the Salt and Verde rivers make up the Salt and Verde Reservoir System (System). Then in the 1990s, Roosevelt Dam was modified to increase storage capacity and add flood-control space, making the combined storage capacity of the System approximately 2.3 million acre-feet (AF) of water.

The Salt and Verde rivers' (Salt-Verde) watershed upstream of the System stretches across central Arizona encompassing an area of approximately 12,500 square miles. The northern border of the watershed is defined by the southern end of the Colorado Plateau, and the southern end of the watershed lies in the low Sonoran Desert. With elevations stretching from over 12,600 feet at the top of Humphreys Peak to a low of approximately 1,500 feet at Stewart Mountain Dam, the watershed is affected by a wide range of climates.

SRP manages the System first for safety of the dams and the public at risk downstream in the Phoenix metropolitan area. Except for Roosevelt Dam and

Lake, which now has a flood control zone (modified from 1989 - 1996), all other dams' purpose has remained the same: water conservation. In addition to flood control capacity at Roosevelt Dam, since 2008, SRP manages the Verde River reservoir system as stipulated by the Habitat Conservation Plan (HCP) which provides measures to minimize and mitigate incidental take of 16 species.

While management strategies have changed over the history of the System, its primary objective - to protect the safety of the public and the dams – has not. Additional to management of the System for the safety of the dams and public, SRP manages the reservoirs to assure a reliable supply of water protecting and supporting downstream water users in the Phoenix metropolitan area.

Study Objectives and Methods

To ensure a reliable water supply, SRP has invested considerable efforts in understanding the past and future hydro-climatology and sustainability of the watershed-reservoir system. However, those efforts did not provide a complete understanding of the entire surface water process from meteorology to reservoir operations. It is readily accepted that seasonal inflows could be at risk in a future climate. The potential of increased hydrologic variability and sedimentation could lead to a decrease in storage that reduces reliability of surface water delivery. In addition, potential extreme weather events could challenge functionality of the System. These possibilities were not completely quantified in past work for specific guidance that would change system operations, and the fundamental purpose of this Study is to address those gaps.

Therefore, this SECURE reservoir operations pilot study of the System had two main objectives: (1) identify and evaluate observed and projected changes to surface water availability, and discern implications to System operation to the end of this century arising from climate change, and (2) use climate change projections and hydrology simulations to understand any effect on the Probable Maximum Flood (PMF) for the System. These objectives were examined using two accepted methodologies in the field of climate science, the Period Change method and the Transient method.

Management Challenges in the Salt-Verde Watershed

The Salt-Verde watershed has demonstrated high hydroclimate variability over more than a century posing a challenge to analyses of the System's performance and establishing its sustainability for the future. The large range of elevations lends itself to a diverse hydro-climatology, with precipitation falling in a bimodal pattern during the winter and summer seasons. Winter precipitation is highly variable and falls as rain in lower elevations and snow in higher elevations. Summers are hot but not dry, as rains from convective thunderstorms occur frequently due to the North American monsoon. However, the majority of surface water inflows to the System occur during the winter and spring from rain and snowmelt when low temperatures keep evapotranspiration at a minimum.

The length of time between replenishment of the System and storage volume of surface water in the System on target dates are key statistics for management and important to understanding system sensitivity to key variables. Surface water storage volumes can affect other operational decisions such as the amount of groundwater to be pumped or recharged. Moreover, the volume of water delivered can be as important as surface water supply that is vulnerable to climate change. Because of the great variability, SRP currently plans for the identified worst case water supply scenarios based on the historical record. Therefore, there is a need to quantify performance uncertainties and identify system risk probabilities to inform decision making on strategic and operational alternatives that may be different than what is in place today.

Reservoirs in the Sonoran desert provide side benefits, including opportunities for recreation (boating, fishing, etc.). All reservoir operation objectives and side benefits may be at risk because of a change in climate.

How the Study Addressed Management Challenges

This study used two separate methodological approaches to analyze the two key research questions, surface water availability in a future climate and the effects of a future climate on the PMF. These two approaches, the transient method and the period change method, are commonly used in climate research and are the two approved methodological approaches for climate science studies under the Reclamation. The robust two-method approach supported the desired outcome of the study by providing a complete understanding of the surface water process related to the System in a future climate.

Transient methods develop continuous climate and hydrology scenarios from a past reference date out through a planning time horizon to the end of the 21st century (the study's planning horizon). These scenarios are generated from physics based global climate models (GCM) that are driven by projected forcing such as greenhouse gases, aerosol concentrations, and land use, among others.

Period change methods develop climate change scenarios that reflect what the impact of climate change would be by shifting the historical reference time period to future time period (the study's planning horizon) by an agreed upon understanding of a future hydro-climatology.

Findings

Transient Method Findings

The transient analysis considered 64 GCM projections using two future pathways for greenhouse gas emissions. The resulting 64 projections were input into a hydrology model, producing 64 continuous streamflow simulations.

Results from the 64 climate model and hydrology simulations indicate significant challenges in their interpretation. Many of the simulations display precipitation and streamflow behavior for both the reference (1950 - 2005) and projected (2006 - 2099) periods that is significantly different than the historic record. The summer season exhibits the greatest biases with precipitation which are amplified in streamflow results. In turn, this produces anomalous reservoir spills during the summer and confuses the interpretation of winter season effects on reservoir operations. To mitigate this issue, typical historical monthly summer inflows were used in place of the simulated summer inflows. In addition, both upward and downward trends in future simulated precipitation patterns are present in several of the 64 downscaled GCMs. In view of these challenges the application of all 64 simulations and their representations of potential differences in the future climate on SRP operations are not prudent. However, to meet the objectives for this study, the three wettest and three driest simulations were identified to analyze for future water supply and flood implications.

Results from the detailed analysis did not indicate any significant differences from historical data that would alter current operating protocols of the System. Inflows from the wet simulations fell well short of the Probable Maximum Flood (PMF), but resulted in greater reservoir water spill. Two of the dry simulations did indicate at least one period of reduced water allocation to users but never came close to depleting the System, similar to reservoir modeling of the observed period. However, System inflow biases during the winter season for the reference period (dry winters have too much inflow and wet winters have too little inflow) lead to some questions about the relevance of the results.

Period Change Method Findings

The period change analysis considered the historical record, a paleo climate reconstruction, and a stochastic simulation of the Net Basin Supply (NBS) developed from detailed statistical characterization of the watershed.

A dozen representative 10,000 year time series were stochastically generated to reflect the full range of temporal variability in NBS for the current system, sufficient for detailed probabilistic risk assessments of relevant management variables over 120,000 years of simulated data. Results from this period change analysis indicate that reductions of approximately 10% in typical net basin supply (NBS) are possible with a future average temperature increase of 3.1°C.

However, the decrease in NBS as it relates to temperature are not linear. It was found that sensitivity to temperature is greatest when temperature is highest and inflows are lowest, making the summer season inflows most vulnerable to temperature change. However, the summer season contributes a small portion of annual NBS. Roughly half of the summer temperature sensitivity is related to evaporative losses from the reservoirs themselves. Winter season NBS, which is relied upon to replenish reservoirs, is less temperature sensitive; and, wet years drown out much - if not all - of the climate change temperature signal.

In summary, results from the period change methodology indicate that surface water delivery from the reservoirs with supplemented groundwater is reliable through the end of this century with anticipated climate change and water demand volumes. However, if demand increases and/or temperatures increase beyond current projections, marginal risks to water supply reliability could develop.

Conclusions and Next Steps

An exhaustive and complete study using two accepted research approaches were employed to understand vulnerabilities of SRP's water supply reliability and ability to manage extreme events in the future. Both methodologies suggest that SRP's current operational strategies are sufficient to maintain a secure and reliable water supply to its downstream shareholders. In addition, the transient method indicates that the System's current infrastructure will be more than capable of handling future flood events.

Knowing that the system is reliable against a range of future conditions gives SRP confidence that operating the reservoir system under its current procedures will ensure a sustainable water supply for its shareholders. These findings can give confidence to SRP's municipal, industrial and agricultural users that future water availability and infrastructure is secure. In addition, results from this study can inform water managers participating in similar hydroclimate studies of the strengths and weakness of study methodologies and approaches

However, this study also identified significant biases with the transient method that limits confidence in its application of projected reservoir operations. The identified uncertainties create a need for potential future work related to improving hydro-climate simulations which would improve the usefulness of those results. In addition, this study also identified the need for future sedimentation and demand studies to further increase this confidence or inform SRP on potential operational changes due to an increase in reservoir sedimentation or system demand. Some of the key next steps and future research are:

- Sedimentation and demand studies to further increase the confidence on potential operational and infrastructure changes due to an increase in sedimentation and system demand.

- Development of new GCM precipitation downscaling methodologies that perform better for lower mid-latitude mountainous environments and convective precipitation (e.g., better representation of summer precipitation).
- Improved hydrologic modeling (e.g. VIC and/or SAC-SMA) to reduce biases for lower mid-latitude environments such that the hydrologic models represent the full range of hydrologies (e.g. realistic representation of the precipitation/hydrology response).

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APPENDIX A - SNOW WATER EQUIVALENT ANALYSIS A-1

List of Acronyms

AF	Acre-Feet
AF/Year	Acre-Feet/Year
AR5	5th Assessment Report
CAP	Central Arizona Project
cfs	Cubic Feet per Second
CMIP5	Coupled Model Intercomparison Project Phase 5
Ft	Feet
GCM	Global Climate Model or General Circulation Model
HCP	Habitat Conservation Plan
IPCC	Intergovernmental Panel on Climate Change
KAF	Thousand (kilo) Acre-Feet
LOCA	Locally Constructed Analogues
Max.	Maximum
Min.	Minimum
NBS	Net Basin Supply
NCS	New Conservation Storage
OASIS	Operational Analysis and Simulation of Integrated Systems
PMF	Probable Maximum Flood
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PROP	Project Reservoir Operations Plan or Planning
R/P	Runoff/Precipitation
Reclamation	U.S. Bureau of Reclamation
ResSim	Reservoir Simulation Model (Seasonal)
RPM	Reservoir Planning Model (monthly)
Sac-SMA	Sacramento – Soil Moisture Accounting
SNOW-17	Snow accumulation and ablation model, a component of the National Weather Service River Forecast System

SPD	Storage Planning Diagram
SRP	Salt River Project
SRPSIM	Salt River Project Simulation Model (monthly)
SWE	Snow Water Equivalent
SWR	SRP Surface Water Resources Department
System	Salt River and Verde River Reservoir System
U.S.	United States
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WCM	Water Control Manual Modified Roosevelt Dam

Note: Downscaled model names are used in the text both in all upper or lower case letters. For example, ipsl-cm5a-mr_rcp85 is the same as IPSL-CM5A-MR_RCP85

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1. INTRODUCTION

SRP has effectively managed the System using sophisticated and up-to-date models and forecasting, and has introduced the results of the tree-ring research (Hirschboeck and Meko, 2005) into its water resource planning strategy. In addition, SRP has funded and participated in studies researching the potential effects of climate change and hydrologic variability on its operations. However, a comprehensive result analysis and translation for operational decision making has not been performed.

There are two objectives of this Study:

- Identify and evaluate observed and projected changes to surface water availability and attempt to discern which year-to-year changes are occurring due to climate change or are within normal variability. This is expected to assist in identifying trends that can be used in forecasting possible impacts of climate change to the System.
- Use observed and projected climate information to understand if climate change or projected hydrologic variability affects the Probable Maximum Precipitation and Probable Maximum Flood (PMF) used for the 1980s and 1990s Safety of Dams[1] improvements.

This report of this Study is organized as follows:

Section 1 – Introduction: includes Study objectives and description of report organization.

Section 2 – Salt-Verde Watershed, Arizona: describes the Salt River and Verde River watershed, location, water course and hydrology.

Section 3 – Reservoir System: summarizes the system's location, description and characteristics, reservoir allocations, historic and current operations, operating plans, simulation models, and flood control objectives.

Section 4 – Uncertainties with Climate Change Research: some qualifiers for the audience to understand the uncertainties related to climate change research.

Section 5 – Transient methodology: explains transient method GCM downscaling, precipitation analysis, developed inflow data series and reservoir simulation results.

[1] Public Law 95-578, November 2, 1978, as amended by Public Law 98-404 (August 28, 1984), Public Law 106-377 (October 27, 2000), Public Law 107-117 (January 10, 2002), and Public Law 108-439 (December 3, 2004)

Section 6 – Period change methodology: builds upon a full system characterization from the entirety of its historical record, stochastic times series are developed and used as input to the seasonal reservoir simulation model.

Section 7 – Conclusions and Recommendations

2. SALT-VERDE WATERSHED, ARIZONA

The Salt River watershed contributes to Roosevelt Lake, Apache Lake, Canyon Lake, and Saguaro Lake. The Verde River watershed contributes to Horseshoe Reservoir and Bartlett Reservoir. Combined, the Salt-Verde watershed covers about 12,500 square miles in central and eastern Arizona. (See Figure 2-1.)

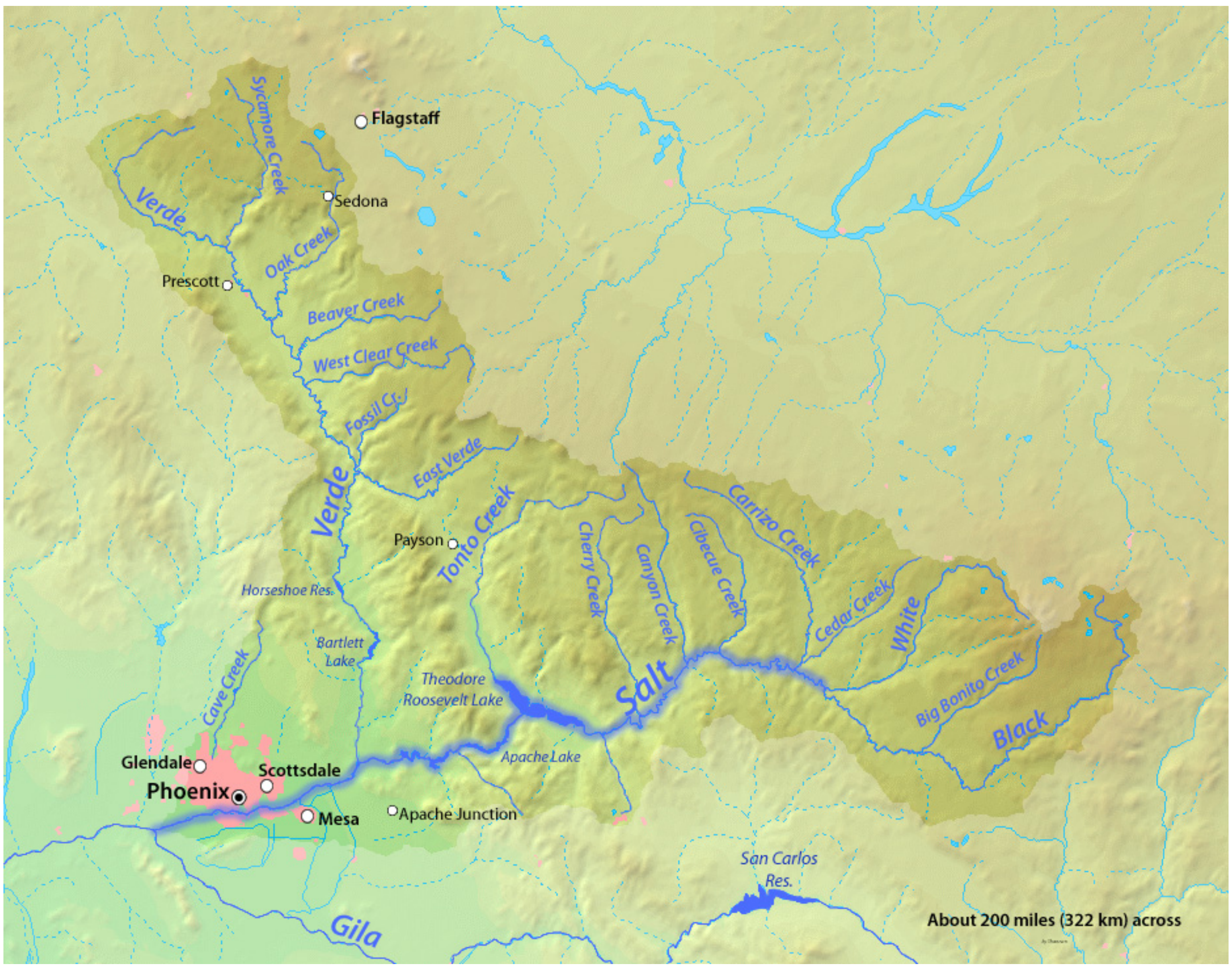

Figure 2-1: Salt and Verde watershed in central Arizona (https://commons.wikimedia.org/w/index.php?curid=14995781)

2.1 Geographic Location and Water Course

The Salt River watershed has an area of about 6,250 square miles and ranges in elevation from 11,400 feet in the White Mountains on the eastern portion of the watershed to as low as 1,300 feet in the Sonoran Desert on the western portion of the watershed. From the confluence of the White and Black rivers, the Salt River roughly follows a 140-mile course southwesterly to its confluence with the Gila River at an elevation of about 900 feet above mean sea level. The Salt River is perennial from its headwaters to Granite Reef Diversion Dam near Mesa, Arizona. Numerous streams that start as springs and seeps along the Mogollon Rim and in the White Mountains feed the tributaries of the Salt River. The perennial flows in these areas are primarily a result of geologic barriers discharging groundwater to streams. Volcanic rocks are exposed along the east-central portion of the state in the Central Highlands. Water is forced through this volcanic material through joints and fractures and discharges as springs where these fractures intersect the ground surface.

The Verde River drains an area of approximately 6,250 square miles and ranges in elevation from 12,600 feet in the San Francisco Peaks near Flagstaff, Arizona, to 7,000 feet along the Mogollon Rim, to as low as 1,300 feet in the Sonoran Desert. From the Verde River's headwaters near Paulden, Arizona, to its confluence with the Salt River, the Verde River follows a course about 140 miles long. This course drains eastward from its beginnings near Sullivan Lake Dam to Perkinsville, Arizona, then southeastward to its confluence with Fossil Creek where it continues southward until it joins with the Salt River.

Both watersheds consist of mixed coniferous and ponderosa pine forests in the higher elevations, pinon juniper ecosystems in the mid-level elevations, and Sonoran desert in the lower elevations.

The water stored in the System provides approximately 40 percent of the municipal, industrial, and agricultural water supply to the Phoenix metropolitan area, the fifth largest city and the 12th largest metropolitan area in the United States.

2.2 Hydrology

The majority of the water supply that SRP manages comes from winter precipitation and snowpack in the headwaters of the Salt-Verde watershed of Arizona. The water supply is extremely variable.

Two distinct precipitation seasons are recognized over the Salt-Verde watershed: the winter precipitation season from December through March and the summer precipitation season, July through September (monsoon season). Figure 2-2 depicts the monthly and seasonal precipitation totals and average runoff produced by those two seasons. It is clear from this figure the importance of the winter season precipitation for the total water supply. However, the high degree of variability that exists during the winter season is not depicted in Figure 2-2. In comparison, summer precipitation is similar to winter precipitation but far less variable. This is a direct result of the North American monsoon with the wet phase consistently starting in early July and then slowly transitioning to a drier fall pattern in mid- to late- September. In addition, an important source of precipitation during this transition from summer to fall can be from tropical storms that form off the west coast of Mexico and travel northward into the southwest United States (Southwest). In fact, the wettest 24-hour precipitation record on the Salt-Verde watershed occurred with such an event when the Workman Creek precipitation gauge recorded 10.99 inches on September 4, 1970 from Tropical Storm Norma (Roeske et al., 1978).

The mean monthly inflow into SRP-operated reservoirs shown in Figure 2-2 indicates that most of the runoff that results in streamflow occurs from February to April and very little occurs on average in the summer months of July, August, and September. If the summer monsoon is active and productive, an increase in runoff during August and September can occur. The increase from runoff during the monsoon season is generally not significant enough to change operations or planning. The exception to this would be related to tropical storms and their resultant precipitation and streamflow on the Salt-Verde watershed. One such event, hurricane Lester (Tropical Storm Lester when it arrived in Arizona in August 1992), produced an average of three inches of rainfall over the Salt and Verde watersheds and an inflow volume of approximately 150,000 AF. With the Verde system nearly full prior to Lester, all of the inflows into the Verde system could not be captured, with a little over 60,000 AF of water spilled from Bartlett Reservoir.

However, one storm can produce one-third or half of the total inflow for the winter runoff season (January through May) as is shown in Figure 2-3 for January/February 2013. This highlights the existing variability in inflow in the Desert Southwest.

Timing of winter storms, quantity and timing of snowpack, and forest health conditions affect quantity and quality of water supply. Changes in the timing and frequency of the storms can affect the formation of the snowpack and thus the available surface water supply.

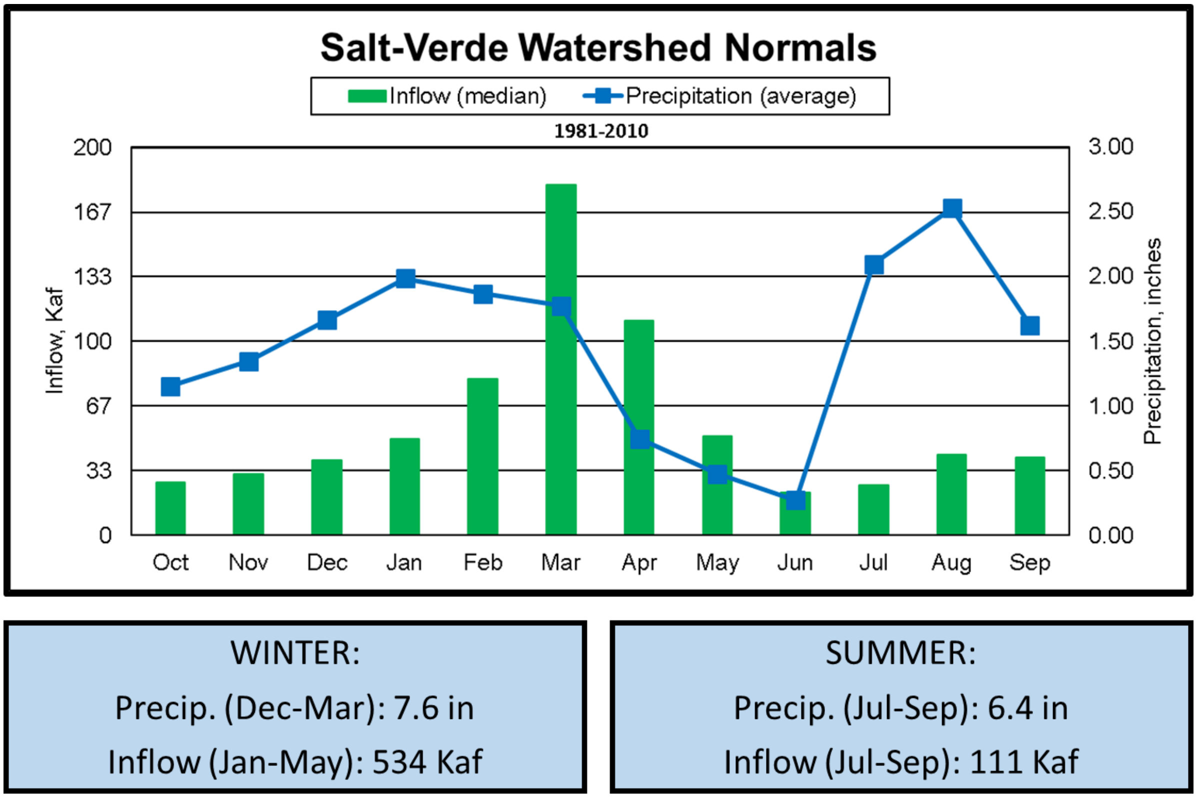

Figure 2-2: Salt-Verde watershed normals: average precipitation and median inflow (1981-2010)

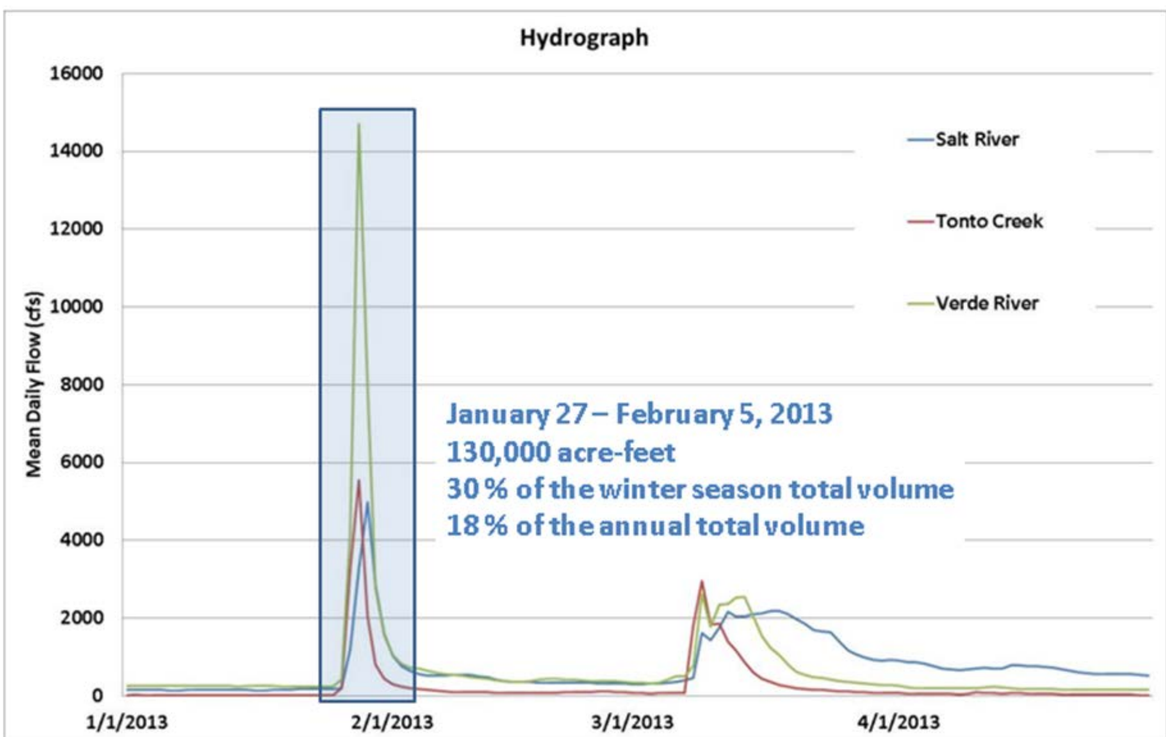

Figure 2-3: Reservoir inflow hydrograph for the winter runoff season 2013

The highly varying precipitation during the fall and winter season results in large year to year variability in SRP's reservoir inflows and falls as both rain and snow. For most elevations the snow is ephemeral, but even the high elevations lack of snowfall during the dry years can result in runoff season inflows that show no signs of a diurnal snowmelt pattern. This makes the Southwest US, especially the Salt and Verde watersheds unique in the Western US when considering winter snowpack dynamics during the accumulations and melt cycle. For example, a comparison of streamflows and snow conditions for the Verde River Basin, Salt River Basin, and the Dolores River Basin are shown in Figures 2-4 and 2-5. One can see in Figures 2-4 how the more ephemeral snow conditions over the Verde River Basin produce a highly variable hydrograph when compared to the Dolores River.

In Figure 2-5 the maximum snow conditions are similar between the Dolores River Basin and the Salt River Basin, but median and minimum snowpack are different with the highly variable nature snow conditions over the Salt River Basin clearly seen through timing and quantity of snow water equivalent (SWE).

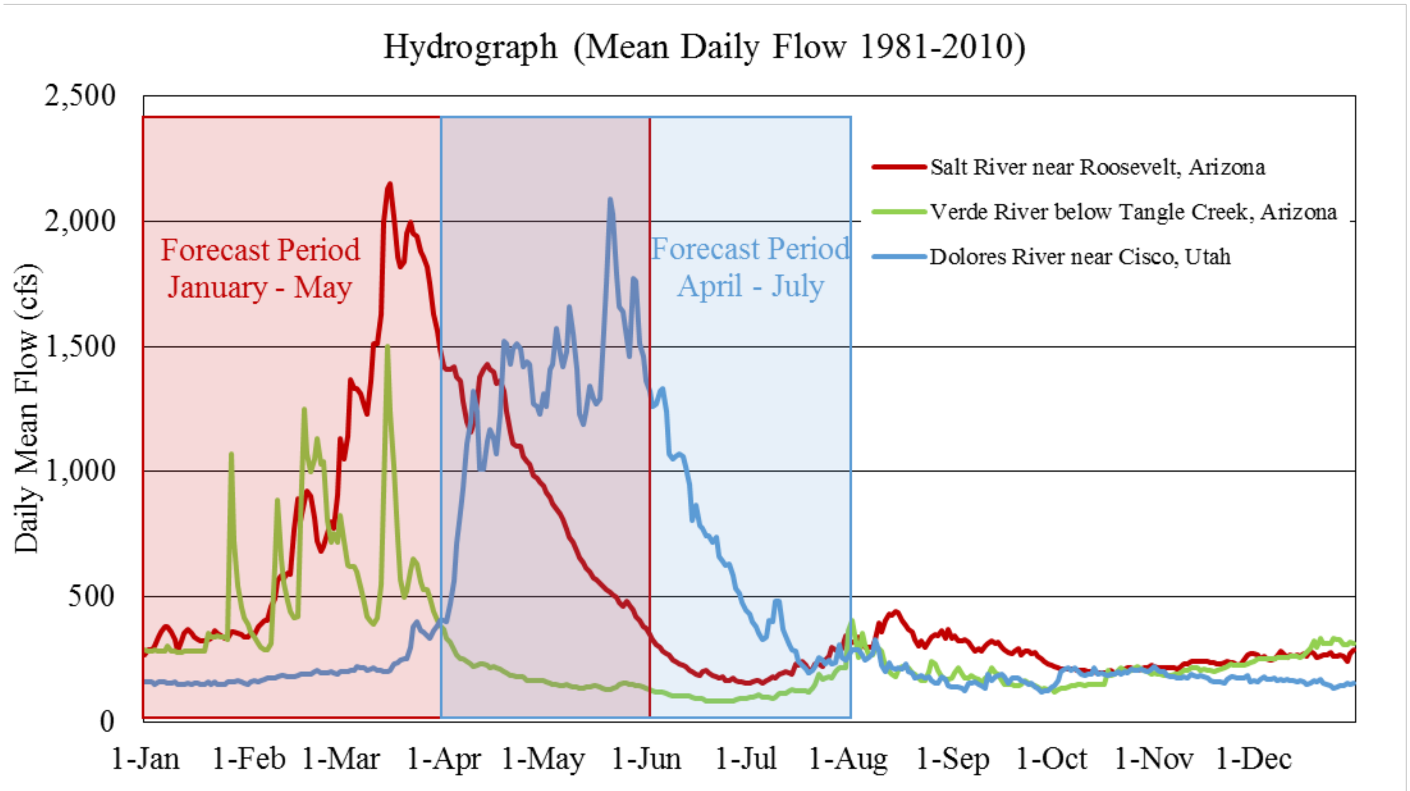

Figure 2-4: Water supply forecast periods in the Salt-Verde Watershed in Arizona compared with the Dolores River Basin in Colorado

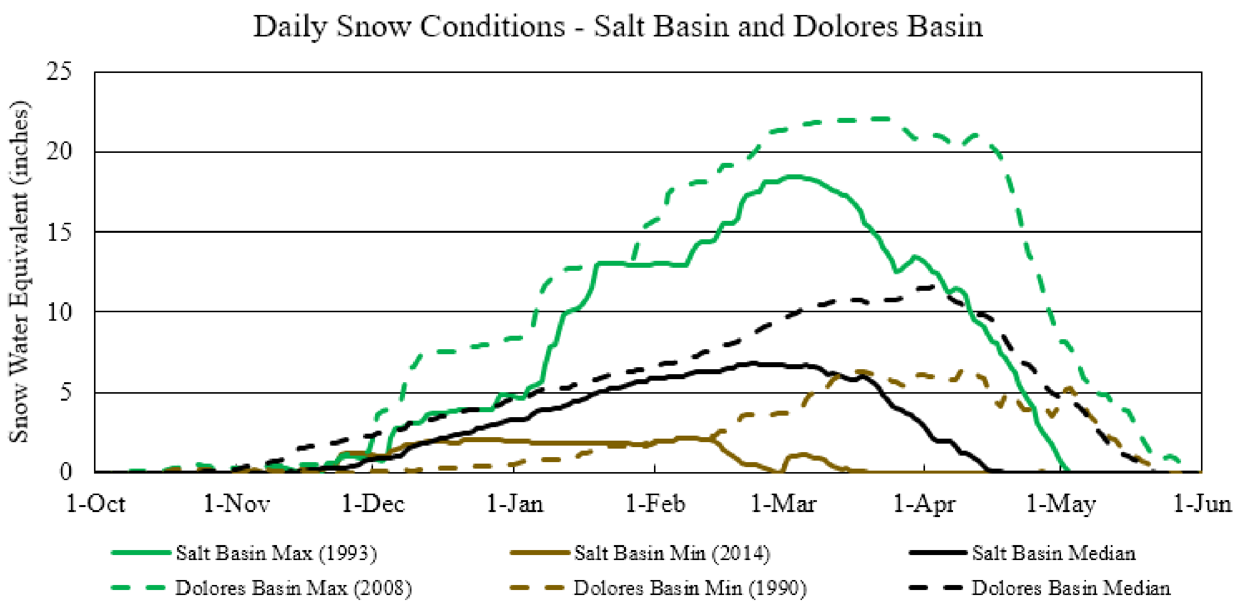

Figure 2-5: For the Salt Basin in Arizona and the Dolores River Basin in Colorado, the minimum, maximum, and median daily snow water equivalent derived from the averaging of snowpack telemetry sites in each basin

Most of the analysis in this report are from U.S. Geological Survey (USGS) gauged data which provide detailed data for inflows into the reservoirs (Table 2-1).

Table 2-1: Gauged data available at major inflow locations in the Salt-Verde watershed

			Gauge ID	Data Record
USGS Gauge, above reservoirs (inflow)				
	Salt River	near Roosevelt	09498500	Oct-1913 to present
	Tonto Creek	near Roosevelt	09499500	Oct-1913 to Dec-1940
	Tonto Creek	above Gun Creek	09499000	Jan-1941 to present
	Verde River	at Bartlett Reservoir	0950900	Oct-1938 to Dec-1945
	Verde River	below Tangle Creek	09508500	Sep-1945 to present
USGS Gauge, below reservoirs (release)				
	Salt River	below Stewart Mountain Dam	09502000	Oct-1934 to present
	Verde River	below Bartlett Dam	09510000	Oct-1913 to present

The winter, summer, and annual percentages of total annual precipitation for each watershed is shown in Table 2-2. The winter proportion of precipitation for the Salt-Verde watershed is practically the same. In the summer the Salt River watershed receives on average about three percent more precipitation. As is shown in Table 2-3, winter precipitation results in higher inflows with the Salt River watershed receiving about 43 percent of the inflows and the Verde River watershed about 32 percent. The summer proportions of inflow show a different story. Most of the precipitation is used by the vegetation (high evapotranspiration). Since the Verde River watershed is on average at a lower elevation, it loses proportionally more of the inflow.

Table 2-2: Average proportions of annual precipitation for winter/summer seasons

	Winter	Summer	Total Annual Percentage Precipitation for Each Watershed
Salt River Watershed	29%	23%	52%
Verde River Watershed	28%	20%	48%
Total for Each Season	57%	43%	

Table 2-3: Typical proportions of annual system inflow for winter/summer seasons

	Winte r	Summer	Total Annual Percentage Inflow for Each Watershed
Salt River Watershed	43%	17%	60%
Verde River Watershed	32%	8%	40%
Total for Each Season	75%	25%	

3. RESERVOIR SYSTEM

3.1 Location, Description, and Characteristics of the System

While owned by Reclamation, the System is operated and managed by SRP. SRP operates six dams and reservoirs on the Salt and Verde rivers, as well as one on East Clear Creek. (See Figure 3-1.)

There are two reservoirs on the Verde River: 1) Horseshoe Reservoir, which is formed by Horseshoe Dam; and 2) Bartlett Reservoir, which is formed by Bartlett Dam. There are four reservoirs on the Salt River: 1) Roosevelt Lake, which is formed by the Modified Theodore Roosevelt Dam (Roosevelt Dam); 2) Apache Lake, which is formed by Horse Mesa Dam; 3) Canyon Lake, which is formed by Mormon Flat Dam; and 4) Saguaro Lake, which is formed by Stewart Mountain

Dam. All four dams on the Salt River have hydropower-generation capabilities. Apache Lake, Canyon Lake, and Saguaro Lake are operated at relatively full levels year-round to maximize power generation. Roosevelt Lake levels fluctuate depending on Salt-Verde watershed runoff and water demand. It is the only dam operated by SRP with flood-control space which is managed by SRP following the guidance of the Water Control Manual Modified Roosevelt Dam (WCM), Salt and Gila Rivers, Arizona developed by the U.S. Army Corps of Engineers, Los Angeles District (1997). Bartlett and Horseshoe Dams do not have hydropower-generation capabilities. The reservoir water levels can fluctuate from almost full to empty depending on Verde watershed runoff and water demand.

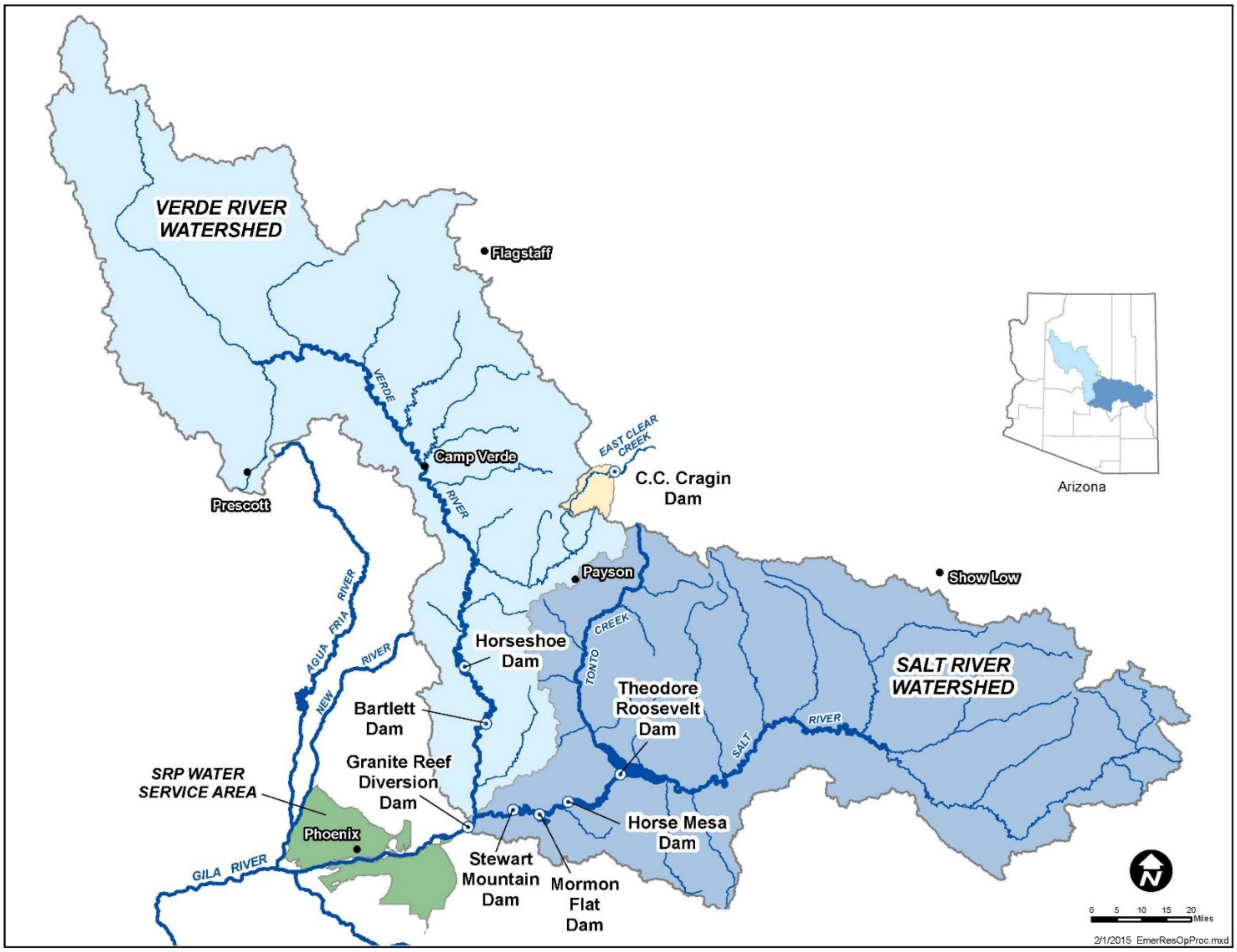

Figure 3-1: **Salt-Verde watershed and dams operated by SRP**

Granite Reef Diversion Dam is located northeast of Phoenix downstream of the confluence of the Salt and Verde rivers. Granite Reef Diversion Dam diverts water from the Salt River into the canals north and south of the Salt River for delivery to SRP water users. No water is stored and no power is generated at

Granite Reef Diversion Dam. SRP also operates and maintains C.C. Cragin Dam, which is located on East Clear Creek forming C.C. Cragin Reservoir (formerly known as Blue Ridge Reservoir). The C.C. Cragin Reservoir on East Clear Creek (Little Colorado River Watershed) is not included in this Study. Table 3-1 and Figure 3-2 provide a summary of each reservoir, including storage capacities.

Table 3-1: Reservoir storage capacities

Reservoir & Dam Name	Capacity (AF)*	Year Last Silt Survey	Notes
Roosevelt Lake, Roosevelt Dam (includes 17,026 AF Dead Pool Storage)	1,631,532	2013	1905-1911, expanded 1996
Apache Lake, Horse Mesa Dam	245,138	-	1924-1927
Canyon Lake, Mormon Flat Dam	57,852	-	1923-1925
Saguaro Lake, Stewart Mountain Dam	69,765	-	1928-1930
Salt Sub-Total	**2,004,287**		
Horseshoe Reservoir, Horseshoe Dam	109,217	2001	1944-1946, spillway added 1949
Bartlett Reservoir, Bartlett Dam	178,186	1977	1936-1939
Verde Sub-Total	**287,403**		
Total Salt-Verde Reservoir System	2,291,690		
* Based on most recent silt survey			
C.C. Cragin Reservoir	15,000		On East Clear Creek (See Figure 3-1.)

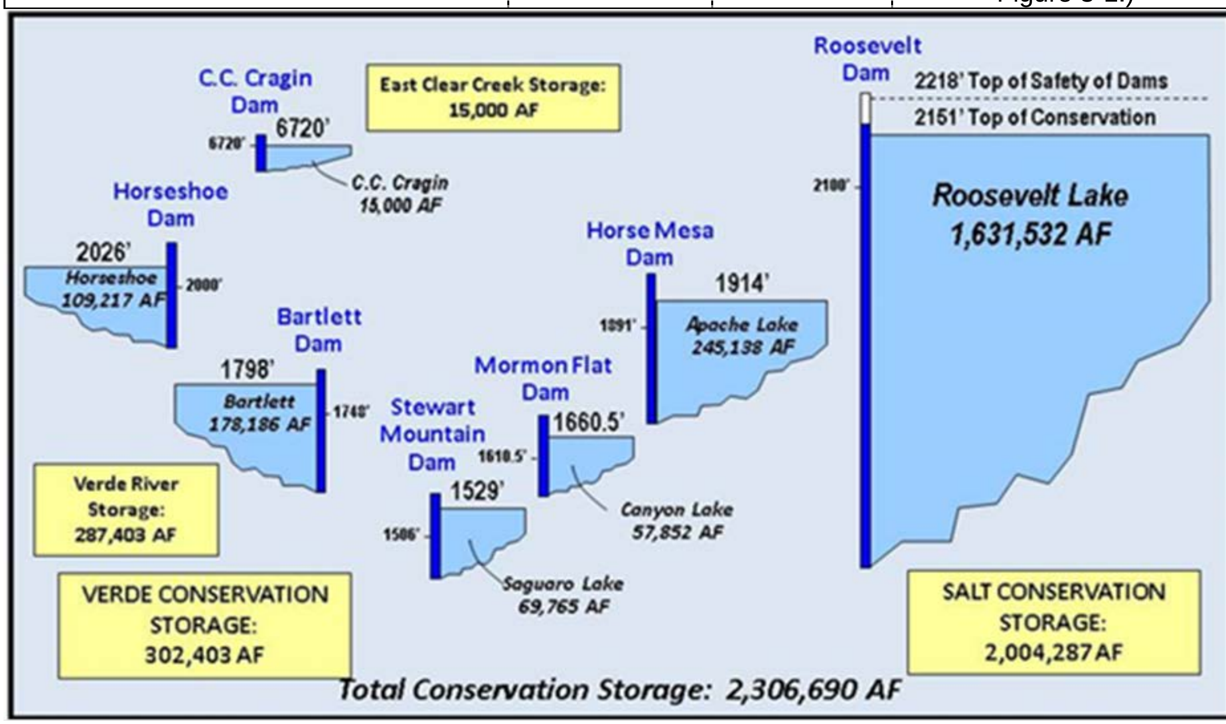

Figure 3-2: Storage capacity for SRP operated reservoirs

A timeline of the completion of each dam in the System is shown in Figure 3-3. In 1996, safety of dams' modifications were completed at Roosevelt Dam, raising it by 77 feet. The raise extended the design life of the dam by 100 years by creating storage space for 100 years of sediment as well as creating flood control space to handle the probable maximum flood and downstream constraints. The oldest dam with its original structure on the System is now Mormon Flat Dam, almost 92 years old. Bartlett Dam is the oldest dam on the Verde River and is 80 years old.

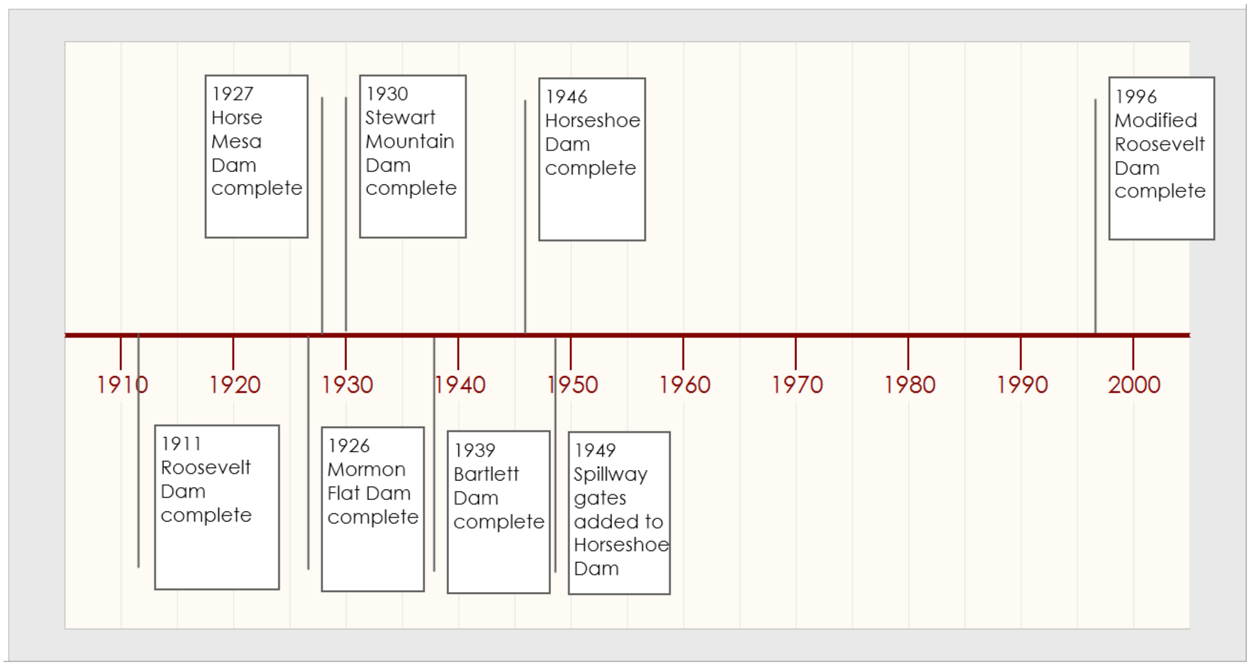

Figure 3-3: Completion/modification timeline of dams on the Salt and Verde rivers

3.2. General Reservoir Storage Allocations

The other reservoirs' main purpose is water supply, and they do not have storage allocations like the ones in Roosevelt Lake.

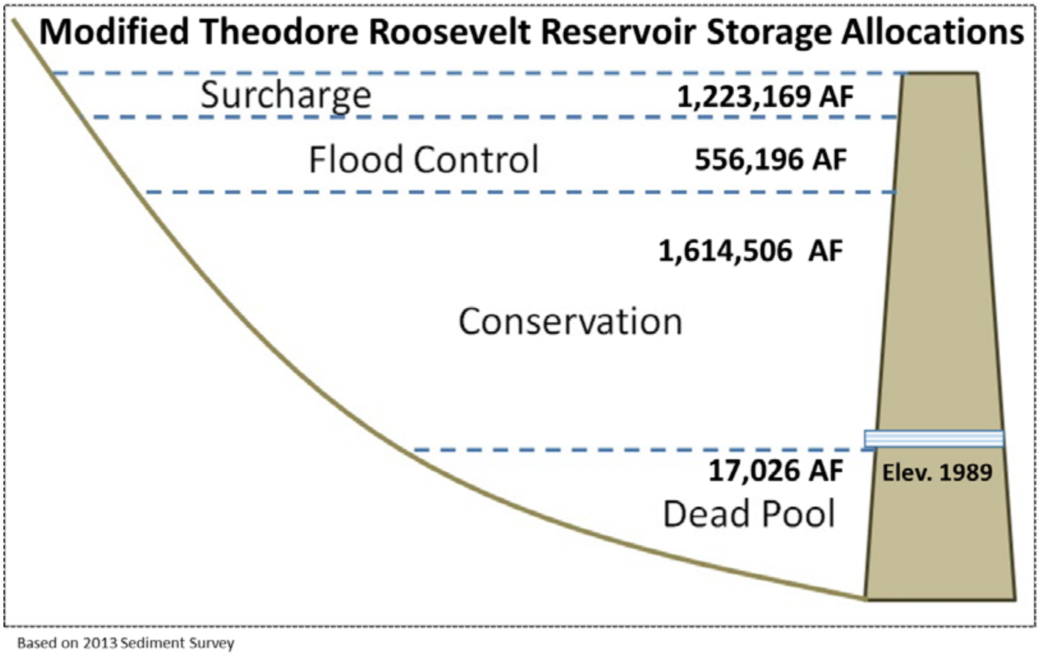

Figure 3-4: Roosevelt lake storage allocations based on the 2013 sediment survey

3.3 Historic and Current Operations

The conjunctive management of surface and groundwater resources at SRP has historically created a very reliable and steady supply of water for SRP's shareholders and customers. Figure 3-5 shows a 37-year snapshot of the variable surface water inflow and the steady year-to-year total deliveries to SRP's shareholders and customers. Surface water stored in the reservoirs and the availability of groundwater to augment surface water is key to maintaining this steady reliable and consistent water supply vital to sustain life and the economic vitality in the Phoenix metropolitan area.

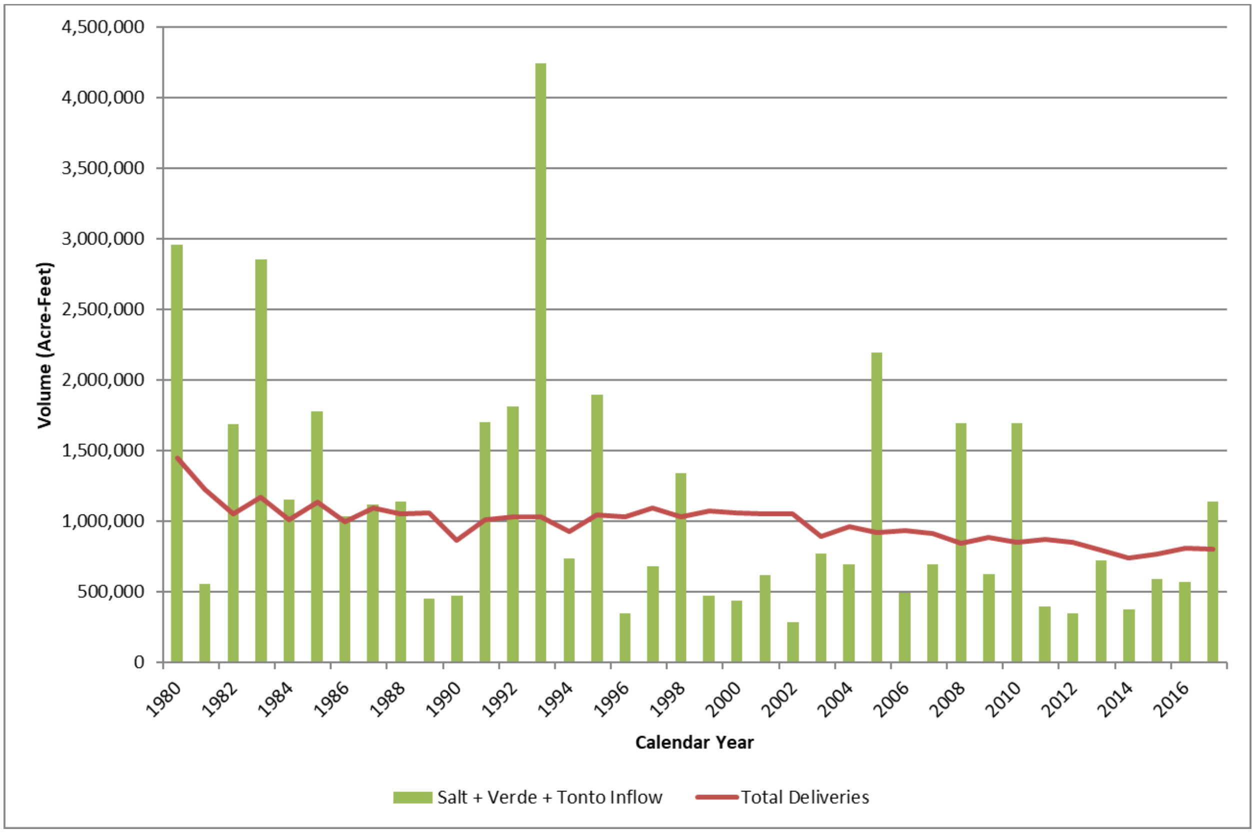

Figure 3-5: Total annual inflow into SRP reservoirs versus total annual water deliveries from 1980-2016

The System has periods of high and low seasonal inflows from snowpack and precipitation. Seasonal inflow and groundwater levels could be at risk from climate change and increased hydrologic variability, potentially resulting in a water supply drought, sedimentation, and water quality issues, and thus a less reliable water supply. Less surface water supply will result in increased groundwater pumping. As an example, low inflow years cause the reservoirs' storage to drop considerably (see Figure 3-6). To slow the decline in storage as a result of low inflows, SRP increased groundwater pumping in recent years. It is not known how long high levels of groundwater pumping can be maintained. Climate change impacts resulting in extreme weather events could result in volume or timing changes to inflow during the winter snowmelt and other parts of the year. The current operating limits of the System could be stretched such that it would be difficult to provide a reliable water supply.

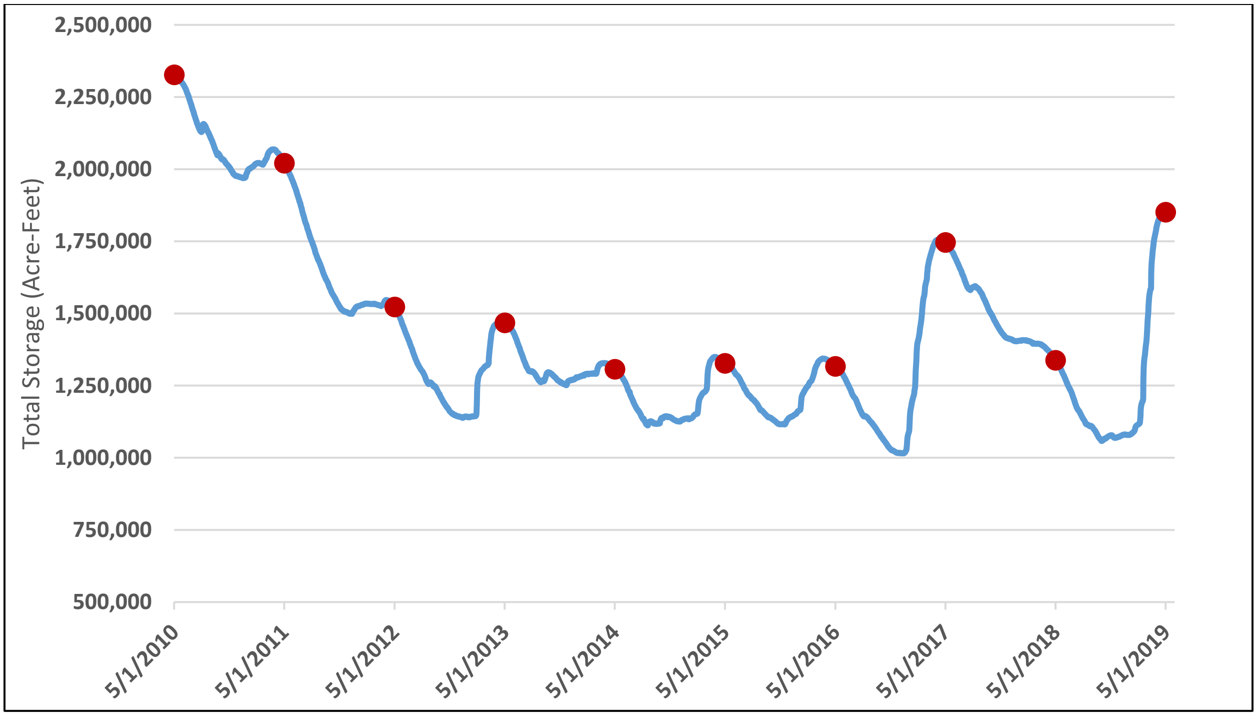

Figure 3-6: Total SRP reservoir storage from 2010 (full system) - 2017 (red dot represents May 1 storage)

SRP manages the System first for safety of the dams and the downstream public at risk in the Phoenix metropolitan area. Except for Roosevelt Dam and reservoir, which now has a flood-control zone (modified from 1989-1996), all other dams' purpose has remained the same, water conservation. In addition to flood-control capacity at Roosevelt Dam, since 2008, SRP manages the Verde River reservoir system as stipulated by the HCP which provides measures to minimize and mitigate incidental take of 16 species. *"The HCP provides measures: 1) to minimize and mitigate, to the maximum extent practicable the impacts of continued reservoir operations on covered species and the habitat they use or occupy; and 2) to ensure that any incidental take of listed species will not appreciably reduce the likelihood of the survival and recovery of the species in the wild."*[2]

SRP's reservoir operations (surface water) objectives are: safety of dams, maximizing storage, and minimizing spill. SRP conjunctively manages its surface water and groundwater resources to provide a water supply in perpetuity to its shareholders.

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[2] U.S. Fish and Wildlife Service, Department of the Interior, Final Environmental Take Permit for the Operation of Horseshoe and Bartlett Reservoirs, March 2008. http://www.fws.gov/southwest/es/arizona/Documents/HCPs/Horseshoe/Horseshoe-Bartlett%20FEIS%202008.pdf

3.3.1 Annual Operating Plans

SRP's Surface Water Resources (SWR) Department is responsible for the development of conjunctive water resource management planning for reservoir and groundwater pumping operations, for the coordination of emergency reservoir operations and for weather forecasting in support of SRP's water and power business needs.

Water resource planning assures an adequate and reliable source of water for SRP's shareholders. Emergency reservoir operations are vital to maintain the safety and integrity of the dams and the downstream public at risk. Weather forecasting provides support for routine and emergency operation of SRP's reservoir and electric distribution systems which increase system reliability and safety as well as augments energy resource planning.

To accomplish these objectives, SRP's hydrologists, meteorologists, and engineers monitor pertinent water and weather data. SWR manages SRP's water resources to sustain life and economic viability in SRP's service area (covering a large part of the Phoenix metropolitan area) integrating its expertise in weather forecasting, hydrology, water operations, management, and planning.

The primary operational objective of SRP's water resources management is using the conjunctive management of multiple sources of water to ensure an adequate supply of water to satisfy SRP's shareholders water demand in perpetuity. SRP uses a Project Reservoir Operations Planning (PROP) spreadsheet for short- to medium-term planning (1-3 years) for guidance in meeting SRP's primary objective. The PROP uses reservoir conditions at the end of the winter runoff season (May 1) to forecast monthly storage levels, surface water releases, groundwater pumping, and other sources of water (such as Central Arizona Project water, reclaimed water, etc.) for the remainder of the current year (May-December) and the following two calendar years. This is accomplished by using the Storage Planning Diagram (SPD), (see Figure 3-7). The SPD gives the relationship between total reservoir storage, groundwater pumping production, and water allocation to manage water supplies based on the tree-ring drought of record for Salt River, Tonto Creek, and Verde River combined inflow.

For longer term planning (30-50 years), SRP used the Salt River Project Simulation Model (SRPSIM) until about 2016. SRPSIM was a program which simulated operation of the reservoirs operated by SRP. The SRPSIM was a subprogram of Central Arizona Project Simulation Model which was developed by Reclamation in the late 1970s. The program was originally written in 1979 (and updated in 1982) by Mr. Randy Chandler of Reclamation. The purpose of the model was to simulate the changes to the System resulting from Plan 6 (Safety of Dams) improvements to the dams, including flood-control storage at Roosevelt Lake. In 1985, SRP modified SRPSIM to add flexibility in changing reservoir characteristics. SRPSIM was a simulation model run on the mainframe computers until the early 1990s. The user interface was also on the mainframe. Once transferred to the PC environment, only experienced engineers could run the program, make changes, and manage the input and output files. Many contracts and settlements were negotiated in the 1990s and SRP's service area changed from mainly agricultural to mainly urban or municipal/industrial customers over the last 20 years. Hence, in 2015, SRP hired a consultant to develop a new Reservoir Planning Model (RPM).

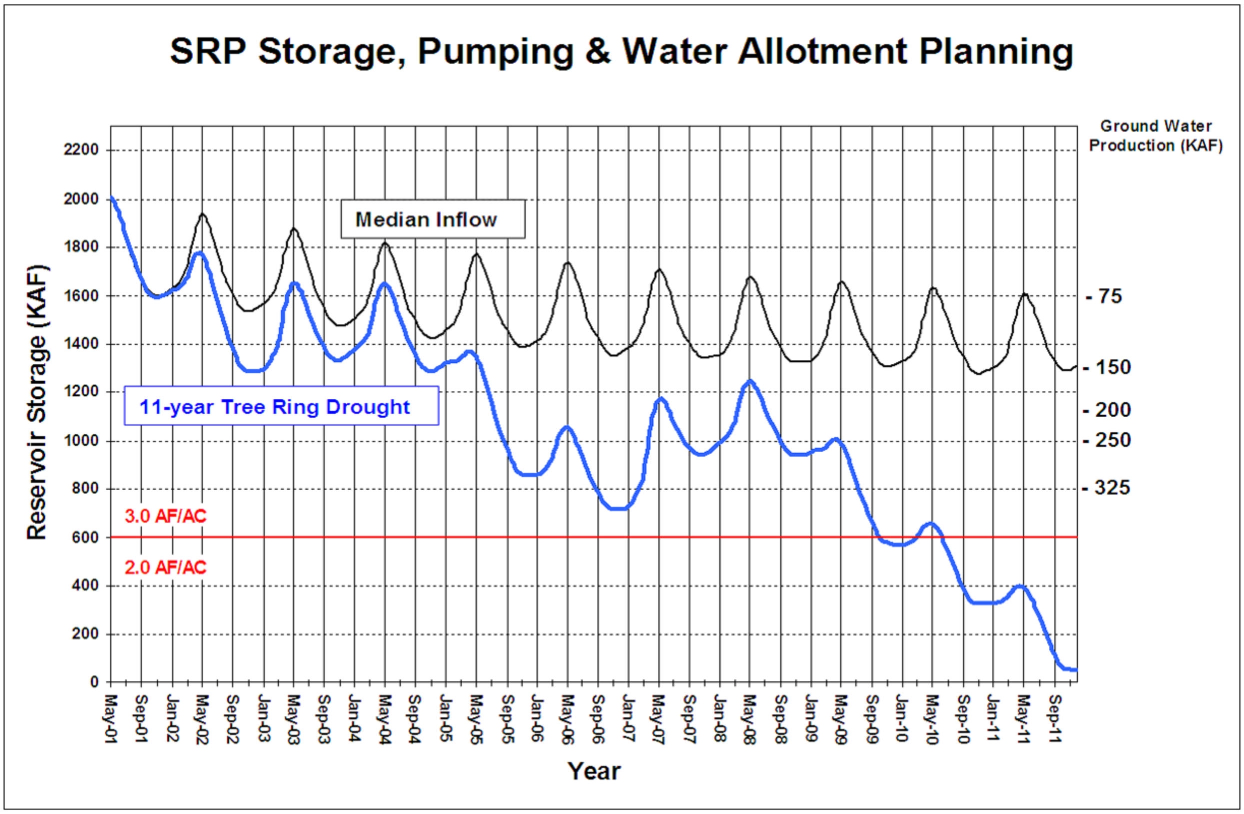

Figure 3-7: Storage planning diagram (Phillips et al. 2009)

Groundwater supplements surface water delivery from the System to the Phoenix metropolitan area. Managing the amount of groundwater pumping is critical for SRP reservoir storage planning. When storage is above 1.5 million AF, groundwater pumping is at its minimum value of 65,000 acre-feet per year (AF/yr). As storage levels decrease, groundwater pumping increases. For reservoir operations planning, the maximum groundwater pumping capacity is set at 325,000 AF/year.

SWR prepares seasonal runoff forecasts from January 1st through May 1st each year. SWR seasonal runoff forecasts are prepared using statistical correlations to current snow conditions, antecedent moisture conditions, and weather patterns. The USDA Natural Resources Conservation Service (NRCS) and Colorado Basin River Forecasting Center (CBRFC) conjunctively issue seasonal forecasts for the

Salt and Verde Watersheds. SWR collaborates with these two agencies before issuing its official seasonal runoff forecast. These forecasts can result in early changes of the operating plan (in case of far below normal runoff). Most of the time a new short to medium term PROP will be prepared after the runoff season ends (end of May).

PROPs are coordinated within SRP between the five operating groups which include hydrogeneration planning groups and canal operations. If groundwater savings facility water is available then the cities are asked if they want to make use of this water. "*A Groundwater Savings Facility (GSF) Permit allows the permit holder to deliver a renewable water supply, called "in-lieu" water, to a recipient who agrees to replace groundwater pumping with in lieu water, thus creating a groundwater savings. The recipient must agree in writing that for every gallon of in lieu water received, the recipient will reduce groundwater withdrawals from within an Active Management Area (AMA) or Irrigation Non-expansion Area (INA) by one gallon. Information regarding the criteria a facility must meet to be permitted as a GSF is included in A.R.S. § 45-812.01.*"[3]

3.3.2 Reservoir Operations Simulation Models

3.3.2.1 Monthly Time Step Reservoir Planning Model and Input

SRP used the RPM to assess the impacts on the System of the hydrology derived from the 64 GCMs used in the transient method of this study. The RPM is an application of OASIS (Operational Analysis and Simulation of Integrated Systems), a generalized water resources modeling platform that simulates the routing of water by solving a linear program. OASIS is a mass balance model. Water cannot be created or removed artificially from the System. It was created to evaluate System performance for a given set of demands, operating policies, and facilities over the historic inflow record and future predicted inflow.

RPM uses a map-based schematic that includes nodes for reservoirs, demands, water contracts, and other points of interest in the System, and arcs that represent means of water conveyance between nodes. The model schematic is shown in Figure 3-8.

[3] See:
https://www.azleg.gov/viewdocument/?docName=http%3A%2F%2Fwww.azleg.gov%2Fars%2F45%2F00812-01.htm

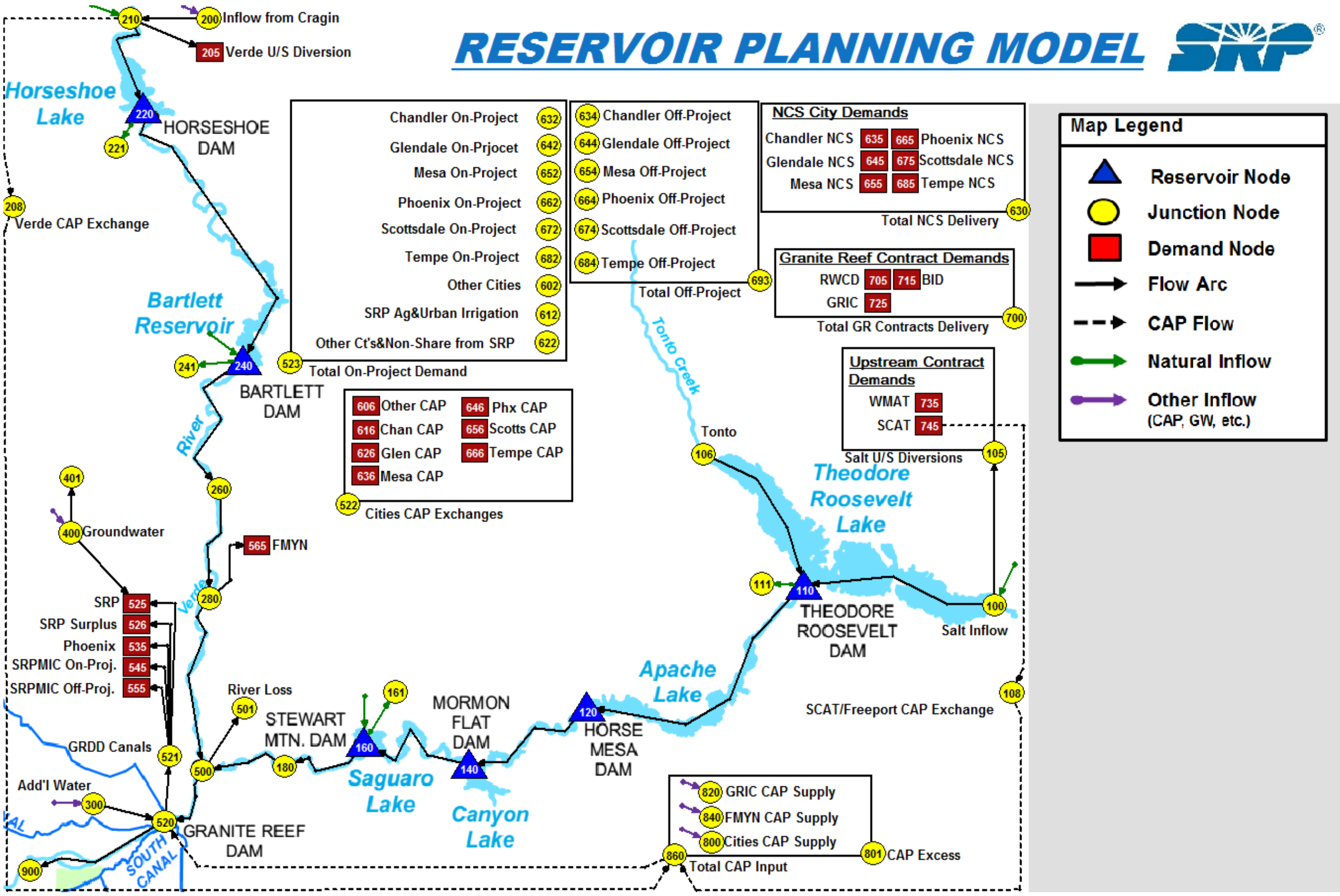

Figure 3-8: Diagram of the Reservoir Planning Model interface

In total, the model has approximately 80 nodes and 90 connecting arcs. There are six reservoir nodes, 25 withdrawal nodes, 15 on- and off-project demand nodes, and other miscellaneous nodes to account for inflows, minimum flow requirements, reservoir evaporation and seepage, and other points of interest. The three lower Salt River reservoirs are operated as one because they are maintained around 95 percent capacity year around due to hydrogeneration operations. Using mass balance and continuity, RPM routes water through the System using goals and constraints based on reservoir operations policies and demands on a monthly time-step.

Monthly streamflows for a reference period and future period for the USGS stream gauges, Salt River near Roosevelt, Tonto Creek above Gun Creek, and Verde River below Tangle Creek were input to RPM at nodes 100, 106, and 210, respectively. Using a relationship with flows at these nodes, local inflows for each simulation were determined for Roosevelt Lake, the lower Salt River system, Horseshoe Lake, and Bartlett Reservoir. These local inflows were input to RPM at nodes 110, 160, 220, and 240 respectively. After inflows were determined and input to the RPM, the model was run for each climate scenario, and output was analyzed (Sections 5.5.4: Analysis of Reservoir Planning Model Output for the Historic Record and 5.5.5: More Detailed RPM Analysis for the Six Selected Simulations for the future Period).

Demand

As the SRP service area has transitioned from agriculture lands to urbanized lands, deliveries from the System have decreased from 1.4 million AF/year in 1980 to 800,000 AF/ year in 2016. Similar demands to 2016 are expected in the foreseeable future, and 800,000 AF/year was used as the demand in the RPM model. The RPM consolidates most of the demands for SRP’s service area (excluding the New Conservation Storage, Fort McDowell Yavapai Nation, and upstream demands) into one demand node. Future demand may not significantly increase in the next 85 years as the service area becomes more urbanized. But to analyze potential future increases in demand, the RPM simulations were also conducted with 950,000 AF per year. However, the analysis conducted for this Study primarily focused on the RPM simulations with 800,000 AF of demand per year.

Demand Distribution

The current monthly demand over the year is not constant and is modeled as a pattern in the RPM model. Table 3-2 shows how annual demand is distributed over 12 months in the System. This demand pattern is used in the RPM model for all simulations and future years.

Table 3-2: Monthly distribution of annual demand

Month	Percentage of Annual Demand
January	3.9%
February	4.4%
March	6.5%
April	9.5%
May	11.1%
June	13.1%
July	13.5%
August	12.9%
September	8.8%
October	7.3%
November	6.3%
December	2.9%

Demand Year and Sedimentation

Reservoir elevation-storage-area curves vary with demand year due to sedimentation. In the RPM model, a demand year is chosen to dictate reservoir elevation-storage-area curves used for all years of a simulation. In this study, reservoir elevation-storage-area-curves for demand year 2013 were used for all simulations. In the future, sedimentation will affect reservoir capacity and potentially impact operations. At this point, future sedimentation simulations were not considered with the global climate simulations. However, as improved hydrology is developed for the global climate simulations, future water supply studies should analyze and consider how sedimentation affects reservoir operations.

Reservoir and River Operations

River and reservoir operating rules in the RPM follow current operations. Much of the reservoir operations are handled by model weighting. Figure 3-9 shows the priority of weighting in the model as described below. Storage (above dead storage) in the reservoirs is weighted lower than the demands at Granite Reef Diversion Dam; therefore, water will be released to meet demands before storage needs are evaluated. Demands upstream of the reservoirs have higher weights than storage to prevent shortages upstream to fill storage downstream. Evaporation, seepage, and river loss are all weighted higher than storage and downstream demands to prioritize counting those physical losses before any operational decisions are made.

For individual reservoir operations on the Salt River, the weight on the C-Zone (defined as storage between the upper and lower rules – shown in Figure 3-10) in Roosevelt Lake is slightly higher than the equivalent weight in the Lower Salt River, but lower than the B-Zone (storage below the lower rule and above dead storage) weight in the Lower Salt River reservoirs. This incentivizes the model to hold the Lower Salt River reservoir system at the lower rule of ~354 thousand acre feet (KAF), and to keep the balance in Roosevelt Lake above the lower rule.

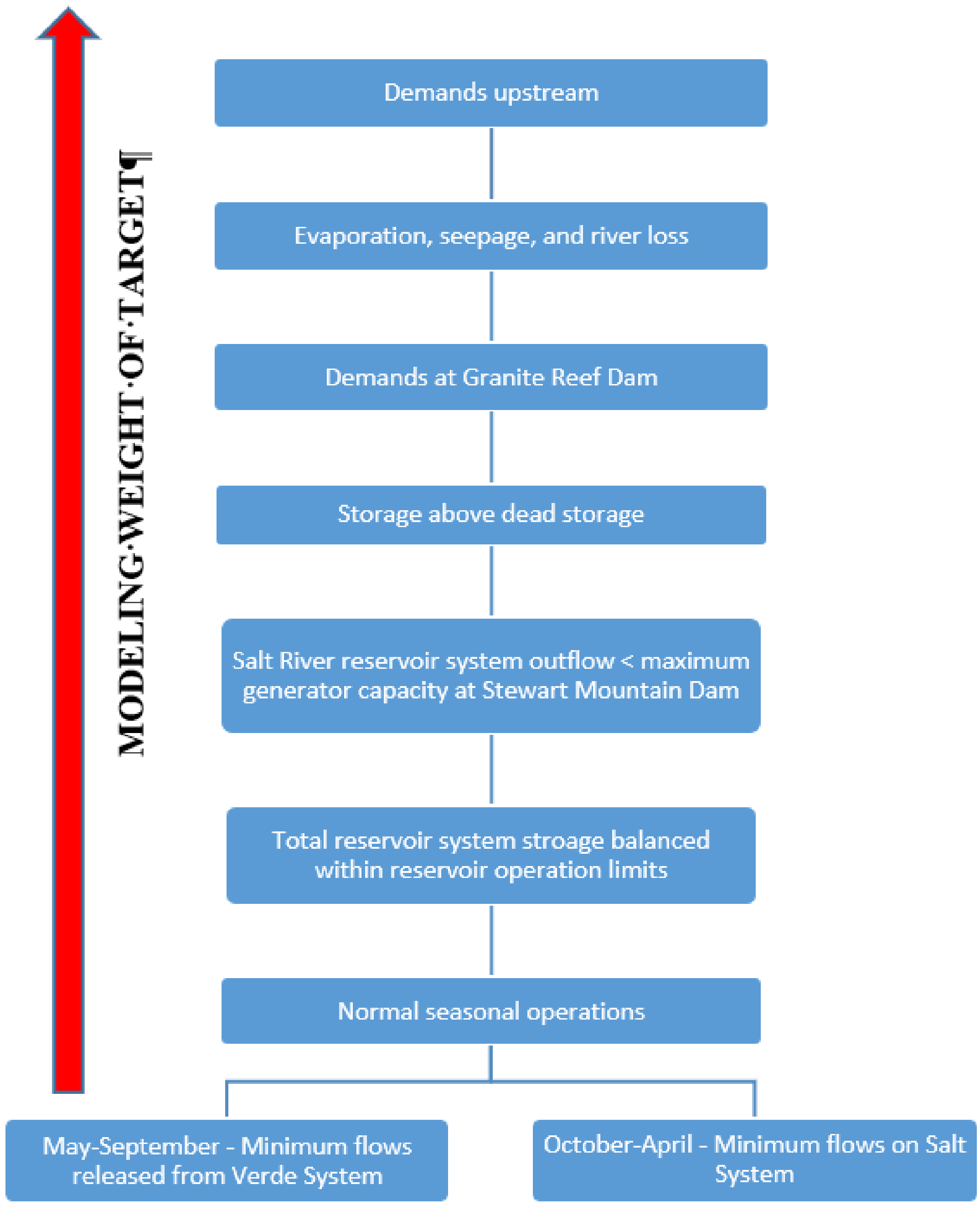

Figure 3-9: Operations order of modeling target weights

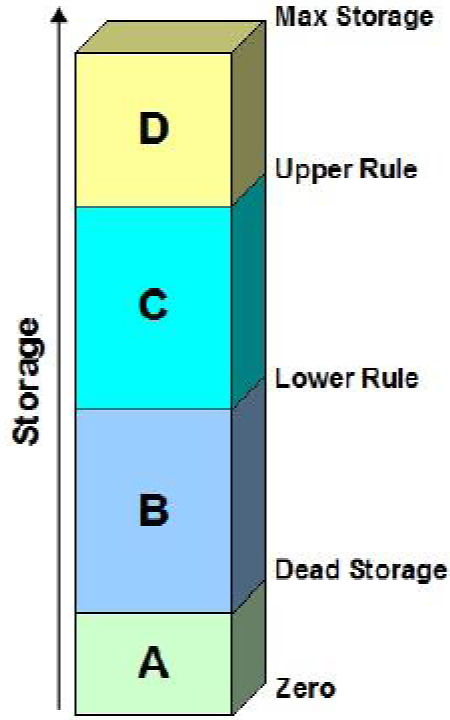

Figure 3-10: Reservoir operations in RPM

The Verde River is handled similarly: the storage weight in Horseshoe Reservoir is slightly higher than the C-Zone weight in Bartlett Reservoir, but lower than the B-Zone weight for Bartlett Reservoir. This incentivizes the model to hold Bartlett Reservoir at the lower rule (defined by a seasonal pattern), and to keep the balance in Horseshoe Reservoir. Figure 3-11 shows the modeling weight of individual reservoir operations.

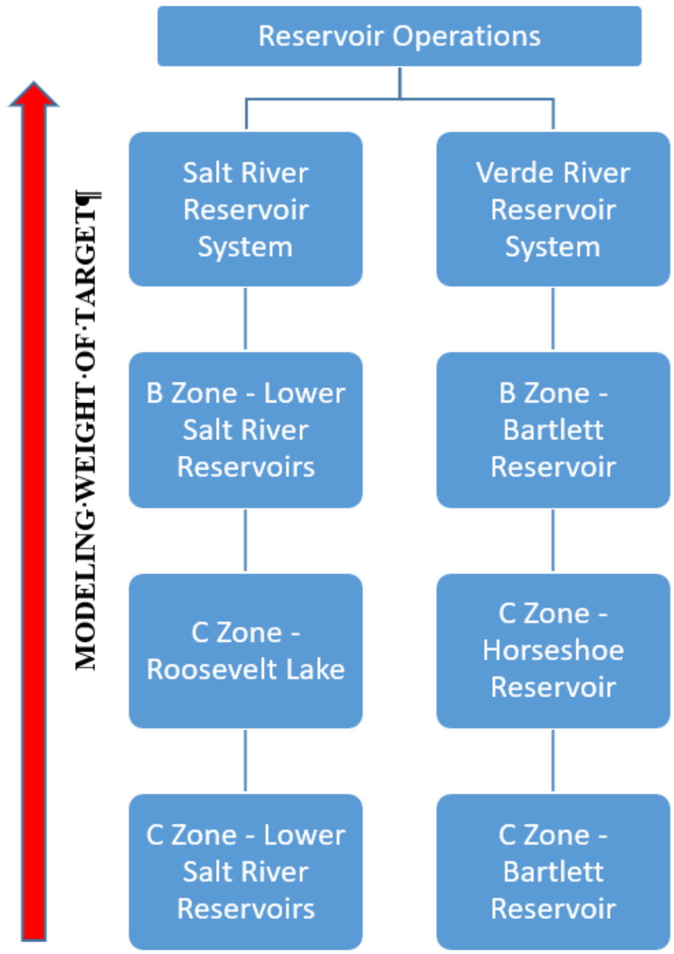

Figure 3-11: Individual reservoir operations modeling weights

The river system used to meet demands is then determined. First, targets for normal seasonal operations are set. From May through September, a target is set on the Verde River reservoir system to limit flows to the minimum release, so the model will try to make demand releases from the Salt River reservoir system. From October through April, the inverse is targeted (minimize Salt River outflows, making demand releases from the Verde River reservoir system). Once the normal targets are set, some additional qualifiers are defined. A target is set for the Salt River reservoir system outflow not to exceed the maximum generator capacity at Stewart Mountain Dam. The weight on this target is higher than the seasonal norms, so if a demand release would cause Lower Salt River outflows to exceed the generator capacity, the balance above the maximum would be attempted to be released from the Verde River reservoir system.

Additionally, targets are defined to keep a balance between the total storage in each reservoir system, defined by operating limit rule curves. Each system has a target that discourages storing water above the operating limit, so if one system is above the operating limit and one is at or below it, the demand release from the System will be adjusted appropriately to try to operate to the curves. The weight for these targets is slightly higher than the normal seasonal targets, but much lower than the weight for actual storage in the reservoirs, so the effect will be to shift demand releases between the two reservoir systems when needed, but not to release water in excess of demand from storage.

Minimum Flow Requirement
For the Verde system, the minimum outflow from Bartlett Dam is set as 100 cubic feet per second (cfs) plus Fort McDowell Yavapai Nation demands. For the Lower Salt River, the minimum outflow is set to 8 cfs.

Groundwater Pumping
The maximum pumping capacity is 325,000 AF/year. Minimum and maximum groundwater pumping values keep pumping within certain limits.

Groundwater supplements surface water delivery from the System to satisfy the demand in the Phoenix metropolitan area. Managing the amount of groundwater pumping is critical for SRP reservoir storage planning. Part of SRP's service area cannot be served by the gravity canal and lateral system. Hence, a minimum amount of pumping is always necessary. Historically, annual minimum pumping ranged between 50,000 and 55,000 AF.

However, around 2010 contractual deliveries, groundwater pump tests and maintenance, and power plant requirements have increased the minimum pumping requirement to approximately 65,000 AF. Therefore, it is assumed for the RPM analysis that minimum pumping will be about 65,000 AF. As storage levels decrease, groundwater pumping increases. When storage levels are high, spill events are more likely to occur. Spill is basin supply that cannot be captured (stored) in the System (see SPD Figure 3-7 for the relationship between reservoir storage levels, groundwater pumping and water allotment).

Groundwater is a more expensive water source than surface water. Hence, use of groundwater will be held to the minimum required for the given storage level. Typically, the water allotment is set in September for the next calendar year to assist the cities with their water planning. The January 1st estimated storage level is used as a guide. Groundwater pumping levels can be adjusted after review of the end of the runoff season reservoir storage level on
May 1st.

New Conservation Storage (NCS)
The NCS is additional storage built at Roosevelt after its safety of dams modification in 1996. It is owned by six cities. NCS credits accrue when SRP operational space is full and the Salt River system storage is increasing. The RPM accounts for NCS in a separate demand node.

Central Arizona Project (CAP) Exchanges
CAP exchanges and inflows have been removed from the RPM for the model runs performed in simulations conducted for this Study. Although the SRP system can exchange water with the CAP system, it is very rare and is avoided except in unusual circumstances. Also, in times of drought, CAP water is not guaranteed to be available for SRP use.

Demands and Diversions Upstream
Several demands upstream of Roosevelt Lake are accounted for in the RPM model. A node upstream of the reservoirs on the Verde River also accounts for upstream diversions on the Verde River.

River and Reservoir Loss
River loss is computed by multiplying a constant for annual loss by the monthly fraction of evaporation for both rivers. This volume is forced into a designated loss node at the confluence of the Salt and Verde rivers. Reservoir seepage is computed by multiplying the beginning of month storage (since the wetted area does not change significantly month to month) by a seepage constant that is specific to each river system. Reservoir evaporation is computed by multiplying a monthly pattern (in inches) developed by SRP by the surface area of the reservoir. Evaporation is based on long-term monthly averages.

3.3.2.2 Seasonal Time Step Reservoir Simulation Model and Input

The cumulative interaction of runoff variability with reservoir design and operation will greatly affect the status of the System at any point in time. The interplay is essential to understanding impacts on ability to deliver water over the short and long term. The RPM that is applied for this purpose operates on a monthly time step. The 10,000-year simulation data sets were developed based upon seasonal characteristics and analysis with the monthly RPM is cumbersome for such long series. So, for System assessments on a seasonal basis a reservoir operations simulation model (ResSim) was developed in consultation with SWR staff to confirm its accuracy, completeness, and consistency with the essential operating rules in RPM. The model incorporates customer water demand partitioned per a representative seasonal demand schedule, System replenishments by NBS, and the web of decision rules used to manage the System with groundwater backup and operating protocols. Although the System is managed day-to-day, key operational protocols can be represented in modeling on a seasonal basis, simplifying calculations while maintaining the seasonal schedule of management decisions.

ResSim was built according to system configuration and operational information as of 2010, and main features of the model can be summarized as:

- Water year start date of October 1st, with May 1st winter-to-summer transition
- Six Salt and Verde reservoirs, rated per current storage capacities (no sedimentation considered)
- Representative seasonal water demand schedule, modifiable from 900,000 AF/year
- Groundwater pumping per SRP SPD (Figure 3-7)
- Priority to water supply for the Salt River reservoirs' hydroelectric generation
- Seasonal depletion and replenishment sequences per balance of surface water demand versus NBS
- Seasonal reservoir positioning rules, with attention to winter runoff
- Defined depletion/replenishment sequences within and between the Salt and Verde sides of the System
- Spillage monitoring and correction between the Salt and Verde sides of the System
- Reduced water allocation rules (2/3 of season demand) implemented below 600,000 AF of total remaining reservoir storage
- System total depletion shutdown at 50,000 AF remaining storage
- No water sourcing from outside the System

The ResSim model outputs 28 characteristics of the System for each season, including all volumes of surface water in and out of the System, water stored in each of the six reservoirs, excess Salt or Verde surface water spillage, the customer water demand and the amount of demand that is delivered, the amount of groundwater pumped to supplement surface water, and coded messages associated with significant thresholds (e.g., reduced allocation, System depletion).

3.3.3 Flood Control Objectives and Requirements for the Reservoirs

Roosevelt Dam is the only facility in the SRP-operated System designed to provide downstream flood-control protection. The other six facilities primary purpose is to provide municipal and irrigation water supply, and hydropower to the Phoenix metropolitan area. Modification of Roosevelt Dam in the early 1990s added 77 feet of height to the dam with a portion of the increased reservoir capacity resulting in 556,196 AF of flood-control space. The overall objective of the flood-control space is to minimize downstream flood damages along the Salt and Gila rivers, including the System, the Phoenix metropolitan area, and other downstream communities. One of the main flood-control objectives for Roosevelt Dam is to limit the combined release of the Salt and Verde rivers to 180,000 cfs at the confluence of those rivers (U.S. Army Corps of Engineers, 1997).

Large inflows from general winter storms and rain on snow events create the highest susceptibility of entering the flood-control space of Roosevelt Dam. With the extra storage capacity at Roosevelt Dam, most of the large inflows can be stored and released from the flood-control zone following the guidance of the Water Control Manual, (U.S. Army Corps of Engineers, 1997).

Water enters the flood-control space at Roosevelt Dam when the water surface elevation of 2,151 ft is reached. SRP will operate the reservoir then as prescribed by the water control diagram developed by the U.S. Army Corps of Engineers (1997). (See Figure 3-12.)

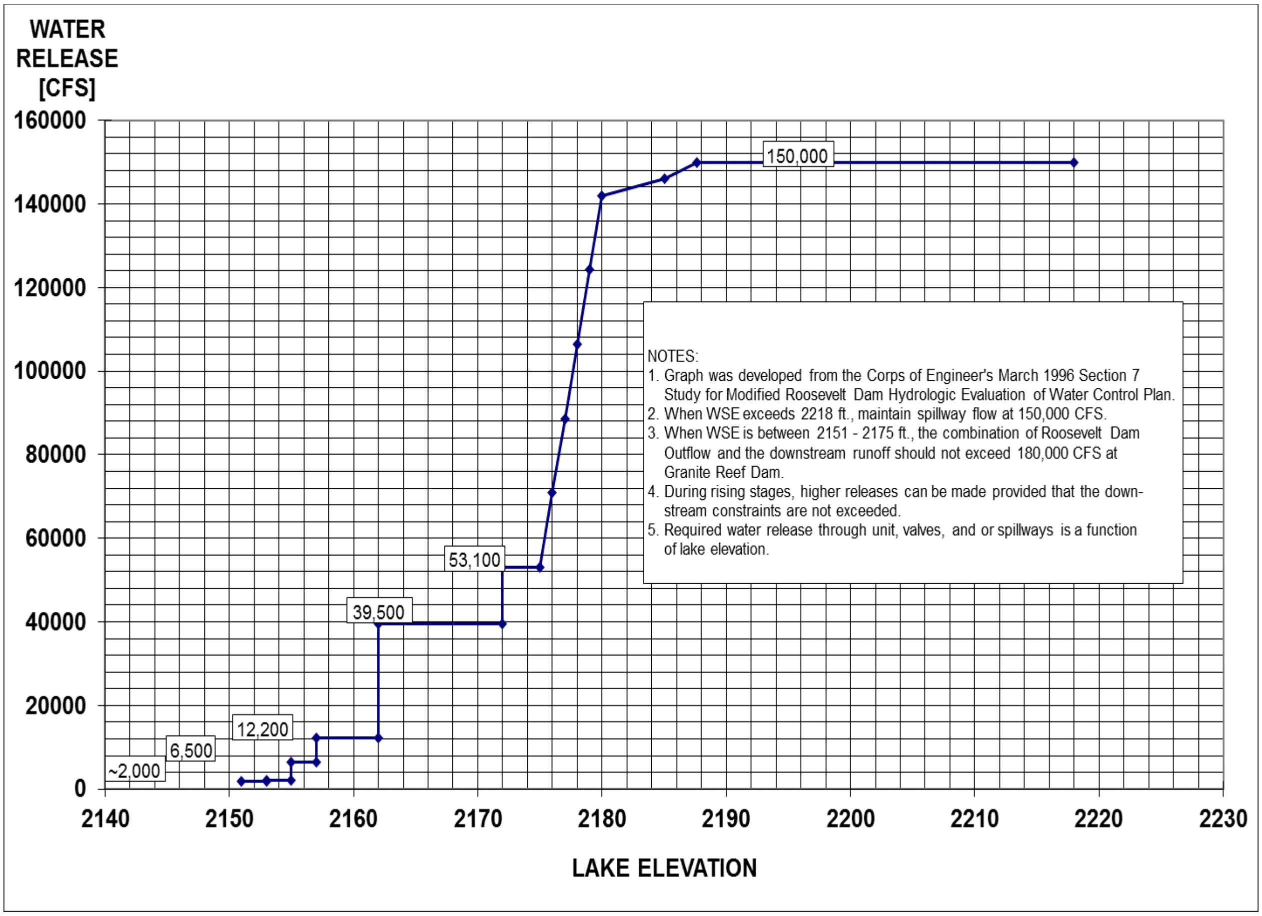

Figure 3-12: Releases from Roosevelt Lake's flood-control space for rising stages

However, the downstream requirement of having less than 180,000 cfs in the Salt River before it enters the Phoenix metropolitan area is more rigid. Releases from the flood-control space can be held back to avoid exceeding the 180,000 cfs at the confluence of the Salt and Verde rivers. As soon as the flows drop below this threshold, the releases required by the water control diagram at the given elevation of Roosevelt Lake must be resumed to a level such that the flood-control space can be emptied within 20 days (environmental requirement). Any deviations from the water control diagram need to be communicated with Reclamation and the U.S. Army Corps of Engineers, Los Angeles District. For any other reason than flood operations, minor deviations from this diagram may be made with prior approval from the U.S. Army Corps of Engineers. Major deviations would require a new review of the WCM with all other federal requirements such as a National Environmental Policy Act review. Roosevelt Dam is a Section 7 project (SRP, 2002 and U.S. Fish and Wildlife 2002).

3.3.4 Water and Related Resource Operations

While water supply is the primary purpose of the Salt and Verde Reservoirs, hydropower is generated at all four dams on the Salt River reservoir system. Six cities (Chandler, Glendale, Mesa, Phoenix, Scottsdale, and Tempe) have storage rights in Roosevelt Lake since they bought into the raising of the dam during the Safety of Dams Program improvements. The additional conservation storage (304 KAF) was to extend the life of the dam by about 100 years. The six cities have a right to store 272 KAF in the Additional Active Conservation Capacity (aka New Conservation Storage, NCS) at Roosevelt Dam[4].

The operating agreement of the NCS stipulates in Section 13 the hydrogeneration benefits the six cities receive for storing water in the Additional Active Conservation Capacity at Roosevelt Dam[5]. Additional hydrogeneration benefits are calculated for the delivery of NCS water and for the additional hydraulic head when there are NCS credits stored at Roosevelt Lake. Additional hydrogeneration benefits are only calculated at Roosevelt Dam.

Minimum flow requirements are in existence both on the Salt River below the Stewart Mountain Dam as well as the Verde River below Bartlett Dam. After safety of dam improvements to Stewart Mountain Dam, less leakage was entering the river. It was estimated that the leakage was about 8 cfs before the improvements were made. Hence, now when the water order moves to the Verde River reservoir system in the fall, a minimum release from Stewart Mountain Dam of 8 cfs is required (Salt River Project, 1987).

The Fort McDowell Indian Community Water Rights Settlement Act of 1990, P.L. 101-628, 104 Stat, 4480 (1990) includes a minimum flow provision in the Verde River. The settlement states that SRP shall maintain a minimum flow in the Verde River below Bartlett Dam by releasing no less than "*100 cubic feet per second of water (measured at the U.S.G.S. gauging station immediately below Bartlett Dam) from Bartlett Dam at all times, plus the amount of water necessary to satisfy any diversion between Bartlett Dam and the confluence of the Salt and Verde Rivers,*" including diversions by Rio Verde,and the Fort McDowell Indian Community (now called the Fort McDowell Yavapai Nation. This minimum flow provision is not absolute. Section 16.2 of the Settlement continues to explain that

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[4] Agreement among the United States, The Central Arizona Water Conservation District, The Flood Control District of Maricopa County, The Salt River Agricultural Improvement and Power District and Salt River Valley Water Users' Association, The Arizona Cities of Chandler, Glendale, Mesa, Phoenix, Scottsdale, and Tempe, The State of Arizona, and The City of Tucson for Funding of Plan Six Facilities of the Central Arizona Project, Arizona, and for Other Purposes, 15 April 1986.

[5] Operating Agreement for Additional Active Conservation Capacity at Modified Theodore Roosevelt Dam among the Salt River Project Agricultural Improvement and Power District, Salt River Valley Water Users' Association, United States Bureau of Reclamation, Flood Control District of Maricopa County, and the Arizona Cities of Chandler, Glendale, Mesa, Phoenix, Scottsdale and Tempe, 14 December 1993.

the minimum flow may be interrupted because of drought, compliance with other user agreements, and necessary repairs for maintenance, accidents, or emergencies.

There are no required releases for water quality management.

Recreation at the reservoirs is incidental to the reservoirs' function of water conservation. Recreation includes boating, fishing, water skiing, swimming, camping, hiking, wildlife viewing, etc. Five of the lakes have marinas which are managed by concessionaires with contracts with the U.S. Forest Service (USFS). Horseshoe Reservoir does not have a marina. Safety on the lakes is provided by the Maricopa County Sherriff's Department which patrols the lakes and the rivers downstream of the dams. All listed reservoir operations, objectives, and additional benefits may be at risk because of climate change impacts to hydrologic variability.

The reservoirs are not managed for recreation. However, safety of the public is of utmost concern to SRP. And sometimes, operations are changed to make sure no hazards are created. For example, flows are increased on the holiday weekends of heavy use of the Salt River downstream of Stewart Mountain Dam for tubing. Also, SRP's operational staff communicates with marina concessionaires, the USFS, and the Maricopa County Sherriff's Department among others if changes in operation will affect any of the uses of the lakes. An example would be lake drawdowns for maintenance of the appurtenant structures to the dams.

In the early 2000s, SRP worked with the Federal government on developing two HCPs aimed at helping SRP provide a reliable water supply to the Phoenix metropolitan area while minimizing the impact to native species and their breeding habitats. The HCPs are the Roosevelt HCP (SRP, 2002 and U.S. Fish and Wildlife, 2002) and the Horseshoe-Bartlett HCP (U.S. Fish and Wildlife, 2008).

The HCPs are the foundations of 50-year renewable federal "*incidental take permits*" that allow SRP to continue storing water in and releasing water from Roosevelt Lake and Horseshoe and Bartlett reservoirs.

The Roosevelt HCP did not require any operational changes at Roosevelt. The Horseshoe-Bartlett HCP required SRP to change its operations at Horseshoe Reservoir. SRP agreed to modify its operation of Horseshoe Dam to help protect native aquatic species in the Verde River and enhance native fish populations within the Verde River watershed.

3.4 Past Studies Looking at Reservoir Operations

Throughout most of the 1930s, SRP only had to manage the releases from the reservoirs on the Salt River supplemented with the deep well pumps in the Salt River Valley Water Users' Association Service area, to satisfy the mainly agricultural water demand. The flows from the Verde River were unregulated until the completion of Bartlett Dam in 1939. Spill releases, although closing off the at-grade crossings of the Salt River, were not as disruptive before the area started to urbanize. Drought was dealt with by increasing groundwater pumping or if severe, by reducing the allocation. A reduction in allocation resulted in the farmers cultivating less acreage. The main uncertainty in setting the allocation was the estimation of reservoir inflow from the winter snowpack. SRP was very much interested in the regular snow survey (started in 1935) conducted by the US Department of Agriculture, Soil Conservation Service (now Natural Resources Conservation Service) and also itself started performing regular snow surveys (at a later date). The cooperative program started in Arizona with the USFS and the National Park Service (Helms et al., 2008).

In 1944, the president of the Salt River Valley Water Users' Association received a letter from the USFS informing SRP that USFS was working on the possibility of forecasting the flow of the Salt River into Roosevelt Lake by use of the records that the USFS had obtained from Parker Creek, as part of the Sierra Ancha Experimental Forest. The USFS researcher had discussed this with J.A. West, SRP's Chief Hydrographer. The USFS presented its methodology and results for the years 1935 through 1943. The average difference between actual and forecasted flow over those years was 20 percent, with the largest percent differences in low inflow years. For 1944, using the Parker Creek data, the forecasted flow was within 2.2 percent of actual flow (Letter Price to Orme, 1944). 1941 was a high inflow year, but a 26-year dry spell started for SRP, with no spillway releases. The first spillway releases since the beginning of the 1940s were reported in 1966. Wilson and Kirdar (1970) describe how the runoff forecasting developed at SRP in the 1960s and highlight the releases from 1966. Moore (1962) at the Western Snow Conference in 1962 presented a paper about the economic considerations of water yield forecasting for the Salt River Valley, Arizona. Moore mentions that in 1960 the estimated damage of uncontrolled flow in the Salt River below Granite Reef Diversion Dam was estimated at $600,000 for a flow of 30,000 cfs. No flood damage occurred. However, the agricultural value of this quantity of uncontrolled water was $201,000, and the municipal and industrial value was just short of $6 million. Information from the snow surveys enabled SRP not to spill water but use it beneficially.

As the service area urbanized, flooding and shortages became more of a problem. Hence, the forecasting of water supply became important.

The first more formal PROP Program (later Plan or Planning) was started during the 1966 high inflow and release year. A five-year PROP analysis was performed and criteria for reservoir operations to maximize water storage and minimize spill were developed. The snow survey program received a lot of attention and new technologies were applied (satellite snow mapping) to be able to improve the water supply forecasting (Kirdar et al., 1977). Not until the devastating floods from the late 1970s and the beginning 1980s, which caused a lot of damage and disruption of economic activity in the growing Phoenix metropolitan area, were those criteria written down in SRP internal documents. First in 1979, later more documented with the analysis of the 1978 flood (Salt River Project, 1981) and 1983 for the Verde River Reservoirs (Salt River Project, 1982).

During the 1980s, many important studies related to reservoir operations were performed. The main drivers were the construction of the CAP canal which would bring Colorado River to Central Arizona (of which the design started in the 1970s), the Arizona 1974 Water Rights Registration Act resulting in the Gila River Basin Adjudication, and the Central Arizona Water Control Study (CAWCS) initiated by the Bureau of Reclamation in 1978 and finished in 1983. A changing climate was not a consideration at that time.

The CAP canal presented the possibility to have a connection (bi-directional or as a turnout) to the SRP canal system. Another source of water could be introduced. The Gila River Basin Adjudication brought initially a lot of uncertainty about the Indian water rights (the oldest rights) and SRP Shareholders water rights. Negotiations were started in the mid-1980s. The CAWCS was initiated to help resolve more than a decade of controversy over a project proposed to control flooding and provide regulatory storage in the Phoenix, Arizona, area. Studies were required on how this would affect SRP reservoir operations.

SRP developed the SRPSIM simulation model for water resources long-term planning. Before SRP could take a negotiating position, it needed to know what its Shareholders water resources picture would be like 50 years ahead. The Water Demand and Water Supply studies were completed in 1984 and 1985, respectively. Both Water Demand and Water Supply studies assess how the reliability situation would change if water rights claims on Shareholders' water were realized (analysis was performed using SRPSIM). SRPSIM was used through the water rights negotiations, for the determination of the water rights claim to the NCS at Roosevelt Lake, and for the development of the Water Control Manual (U.S. Army Corps of Engineers, 1997).

Reclamation performed the PMF studies during the 1980s required to size the flood control and surcharge capacity at Roosevelt Dam. There were controversies on the methodologies used. The U.S. Army Corps of Engineers and a water resources consultant (hired by the Arizona Public Service) also performed PMF studies.

SRP hired consultants to determine the largest flood flows (which historically occurred on the Salt and Verde rivers) to develop reference points for the theoretical PMF determined by Reclamation. Three studies were conducted under supervision of Dr. Victor Baker from the University of Arizona and one by Dr. Jerry Stedinger of Cornell University. Partridge (1985) and Ely (1985) published the results of the paleoflood studies for the Salt River and Verde River, respectively. The Verde River study reported that the largest flood detected by geological evidence on the Verde River above Horseshoe Reservoir had a peak streamflow of 176,600 cfs and occurred about 1,000 years ago (reference year 1985). The Salt River study concluded that the largest flood detected by geological evidence on the Salt River above Roosevelt Lake had a peak streamflow of 145,000 cfs and occurred between 1,000 and 2,000 years ago. The studies were expanded in 1985 to three sites, one each on the Salt River, Verde River and Tonto Creek (Ely, 1985; Partridge, 1985). This study confirmed the findings of the first studies cited above and found that the largest peak flow on Tonto Creek was between 28,000 and 35,000 cfs and occurred in 1980 (slackwater analysis). A subsequent paleoflood study, after the 1993 floods, reported considerably higher flood peaks on Tonto Creek (Fuller et al., 1996).

In 1987, a paleoflood study was conducted in the Phoenix metropolitan area in the vicinity of the Mill Avenue Bridge and the Hohokam Canals. The geological flood record in the Hohokam Canals spanned 1,100 years. The largest flood detected by geological evidence at SRP's Crosscut Facility had a peak streamflow of 420,000 cfs and occurred about 1,000 years ago. This correlates with the paleoflood findings on the Verde and Salt rivers. The 1891 flood was measured at 260,000 cfs and was exceeded twice during the last 1,100 years (Fuller, 1987).

The Cornell University study (Stedinger et al., 1986) determined that the million-year flood on the Salt River is less than 250,000 cfs and on the Verde River less than 300,000 cfs. However, extrapolation of statistically developed flood frequency curves with only a 2,000-year flood record may not be justified beyond the 10,000-year event.

After the 1993 flood event, the studies were refreshed and published by the Arizona Geological Survey (House et al., 1995).

The flooding of the 1970s and 1980s resulted in SRP's desire to develop more extensive expertise in the weather, short- and long-term forecasting to better be able to manage the water supply. Considerable moneys were expended on studies and models for the long-term weather functions as well as the improvement of the data collection network and computing environment. More advance notice would enable SRP to react swiftly if high inflows were expected. The improvement of precipitation estimates (precipitation mosaic algorithm from multiple radars) was the focus during the 1990s.

In the beginning 2000s, when it was clear the watershed and Southwest was experiencing an extended drought, numerous studies were initiated to update the tree-ring research. Results were used in this study for the period-change methodology.

Over the past 20 years, extended drought comparable to the worst historical drought in recorded history has raised concerns regarding SRP's traditional method of water planning and management. Phillips et al (2009) discusses SRP's historic and current strategy with water resources management, showing how and why the strategy has evolved since the 1980s. In 2008, University of Arizona researchers took annual flows reconstructed from tree rings for water years 1361-2005 (Hirschboeck and Meko, 2005, 2008) and converted them into monthly flow volumes. This method used analog years and statistical aggregation (Meko 2008) to achieve this. SRP now uses the monthly flows of the 11-year mega-drought identified by tree ring records to plan out water supply in the short and long term. Phillips et al (2009) also suggest that the usual approach to water management and planning may no longer be appropriate with a changing climate due to global warming.

Many studies have been conducted on the Salt-Verde watershed to identify how future climate change will affect temperature and streamflow. These studies have informed SRP that future climate change simulation may affect water supply and operations of the System.

Ellis et al (2008) developed a water budget runoff model for the Salt-Verde watershed and input six GCMs to estimate runoff in the future using statistical downscaled Intergovernmental Panel on Climate Change (IPCC) data with 2050 greenhouse gas concentrations. They found that all 6 model-simulation combinations simulate a mean temperature rise between 2.4℃ and 5.6℃, but runoff varied from 50% to 127% of historical levels. This study concluded that the large variability among predictions of precipitation trends create substantial uncertainty.

Another study (Rajagopal et al. 2009) calibrated the Variable Infiltration Capacity (VIC) model for the Salt-Verde watershed, and then used five statistically downscaled IPCC3 GCMs as input into the VIC model through the end of the 21st century. The multi-model ensemble predicted that streamflow in the basins will decrease by 25% by the end of the 21st century. This decrease in streamflow is mainly caused by a significant decrease in storage of snow within the basin and decreased winter precipitation.

Hawkins et al. (2015) applied a distributed hydrologic model to the Beaver Creek watershed of central Arizona to explore its potential for climate change assessments. They investigated its response during historical (1990-2000) and future (2031-2040) projections derived for a GCM with a higher emission scenario. Results showed a 1.2℃ increase in temperature, a 2.4 fold increase in amount and threefold increase in variability in precipitation, and a 3.1 fold increase in amount and 5.1 fold increase in variability in streamflow.

Realizing the complexities variabilities in the surface water runoff models, Murphy et al. (2014) identified two efficient heuristics, temperature sensitivity of streamflow and precipitation elasticity to runoff, that are readily interpretable and easily applied to assess water resource sustainability to long term climate change simulations.

Woodhouse et al. (2016) studied water streamflow on the Upper Colorado River Basin over the past century. Their research showed that while cool season precipitation explains most of the variability in annual flows, temperature appears to be highly influential under certain conditions. Recent droughts have been made more severe by warmer temperatures that increase the effects of relatively small precipitation deficits.

Singh et al. (2018) projected that Atmospheric River (AR) Events would become more intense in a warmer climate. This study selected five AR events based on the ones with largest impact on streamflow. The fractional increase in vapor transport (IVT) over the basin varies from about 41% to about 50%. The fractional increase in perceptible water (PW) over the basin varies from 34.2% to 40%. However the changes in PW and IVT do not translate linearly into changes in precipitation.

These previous studies demonstrate that the changing climate may have a significant impact on temperatures and flows in the Salt-Verde watershed. However, studies so far have not determined the magnitude of impact on the System. The goal of this Study is to fill the missing gaps related to increasing temperature and Reservoir inflow relationships that have not been fully understood in past research and identify how the changing climate may (if at all) affect the System.

3.5 Collaboration and Outreach

Both Reclamation and SRP were partners in this study. Reclamation had the role of financial oversight and control. SRP was the collaborator. Both entities contributed expertise and direction to the Study from their unique perspectives.

Reclamation contributed the climate change data and modeling using the transient method (and also evaporation, snow water equivalent). SRP enlisted outside expertise to develop the period change methodology. Reclamation coordinated with SRP in all aspects of the Study.

Stakeholders include water users (including cities as agents of the shareholders) and power users. Power users include residential, municipal and industrial users, including mines. Water users are the SRP shareholders (or cities as their agents) and water contract storage holders. Other stakeholders include recreation users, USFS, the Arizona Game and Fish Department, and other environmental organizations.

4. UNCERTAINTIES WITH CLIMATE CHANGE RESEARCH

The information presented in this report was developed in collaboration with basin stakeholders and was peer reviewed in accordance with Reclamation and Department of the Interior policies. This report is intended to inform and support planning for the future by identifying potential future scenarios. The analyses provided in this report reflect the use of best available datasets and methodologies at the time of the Study.

Water resources studies are developed in collaboration with basin stakeholders to evaluate potential future scenarios to assess risks and potential actions that can be taken to minimize impacts, including supply and demand imbalances. These types of studies support a proactive approach to water resources management, using the best available science and information to develop simulations of future conditions within the watershed. This positions communities to take steps now to mitigate the impacts of future water supply management issues, including water shortages, impacts of droughts and floods, variations in water supply, and changing water demands for water for new or different uses.

Because every water resources planning study requires the study partners to make assumptions about future conditions, addressing the uncertainties in those assumptions is an essential component of the planning process. For example, there are uncertainties associated with the characterization of future water supply and demand, demographics, environmental and other policies, economic projections, climate conditions, and land use, among others. Moreover, projections are often developed using modeling techniques that themselves are only potential representations of a particular process or variable, and therefore, introduce additional uncertainties into characterizations of the future. The cumulative effect of these interacting uncertainties is not yet well known in the scientific community and are not presented within this Study. However, by recognizing this at each process step, uncertainties are adjusted for and reduced when possible, to allow Reclamation and its stakeholders to use the best available science to create a range of possible future risks. Those future risks can be used to help identify appropriate adaptation strategies fundamental to the planning process. It should be noted that simulations of future conditions should not be interpreted as a prediction of the future, nor is the goal of any water resources planning study to focus on a singular future. Rather the goal is to plan for a range of possible conditions, thereby providing decision support tools for water managers.

Of significant interest are projections of future climate, which ultimately drive many assumptions of water supplies and demands through their influence on the hydrologic cycle. Projections of future climate are developed using the scientific community's best assessment of potential future conditions as characterized by GCMs. GCM projections are based upon initial model states, assumptions of future greenhouse gases in the atmosphere, and internal as well as external forcings, such as solar radiation and volcanic activity. Changes in land surface, atmosphere, and ocean dynamics, as well as how such changes are best modeled in GCMs continue to be areas of active research. Depending on these and other uncertainties, projected future conditions, such as the magnitude of temperature and precipitation changes, may vary.

Observed climatic data and GCM simulations show warming trends over recent decades. However, the degree to which the magnitude of GCM simulated warming agrees with historic observations varies based on the data, methods, and time periods used for making such comparisons. Some recent studies have found that models have simulated higher rates of temperature increases relative to observations (Santer et al., 2017a/2017b); another study has shown that current warming is within a range of model simulations (Lin and Huybers, 2016); and yet other studies, have shown the observed and projected warming rates to be similar (Richardson, et al. 2016). In addition, precipitation from GCM simulations show substantial biases and temporal inconsistencies when compared with observed data, even at the climatic time scales and large spatial scales. The disagreements between observations and GCM simulation are generally more severe for precipitation than temperature (Anagnostopoulos et al., 2010). Furthermore, there is disagreement between GCM simulations on the direction of projected changes in precipitation, although there is stronger consensus in certain climates (e.g. Mediterranean climates) than others (Kundzewicz et al., 2008). The evaluation and refinement of GCM performance is an ongoing area of research and includes methods to characterize model outputs and observations, and how measurement errors, internal variability, and model forcings can be improved to enhance future performance (Santer et al., 2017b).

Further, it is important to recognize that these models perform better at global rather than regional or watershed level scales. Accordingly, techniques must be employed to localize or "downscale" GCM output for applications such as basin-specific water resources planning studies. These downscaled projections of climate are used as inputs to hydrologic models to produce projected streamflow, which is then used to assess impacts to the water resource system being studied. Uncertainties at each of the steps necessary to translate GCM output to water resources impacts can be characterized and adjusted for, yet uncertainties remain in the downscaling process that can result in variations depending on the modeling technique used.

Ultimately, future conditions at any particular time or place cannot be known exactly, given the current state of scientific understanding of potential future conditions. It is important to recognize that the risks and impacts are the result of collective changes at a given location. Warming and increased carbon dioxide may increase plant water use efficiency, lengthen the agricultural growing season, but may also have adverse effects on snowpack and water availability. These complex interactions underscore the importance of using a planning approach that identifies future risks to water resources systems based on a range of plausible future conditions, and working with stakeholders to evaluate options that mitigate potential impacts in ways most suitable for all stakeholders involved.

5. STUDY METHODOLOGIES AND RESULTS

5.1 Climate Change Research Methodologies

The study objectives of evaluating observed and projected changes to surface water availability in a future climate lends itself to multiple methods to quantify the potential for change. As outlined in Reclamation's (2014) technical memorandum, *Technical Guidance for Incorporating Climate Change Information into Water Resources Planning Studies (Chapter5)*, quantitative effects analysis for evaluating climate change impacts may be pursued with a wide range of methods typically drawn from two categories that have been used in past studies: (a) period change methods and (b) transient methods. For completeness and best representation of a future period the Salt River Project SECURE Reservoir Operations Study employed both of these approaches.

Period change methods develop climate change simulations that reflect what the impact of climate change would be between a historical reference time period and a future time period. This is accomplished by shifting the historical dataset to create a new dataset reflecting how the particular record (temperature and precipitation) would have appeared under future climate conditions according to understandings of the hydroclimate and water resource system response. These change simulations are used to generate new hydrology information and new system change simulations using system operation models.

Transient methods develop climate, hydrology, and system projections using future simulations generated from GCMs, (aka general circulation models) that are a continuous dataset from present-day out through the study's planning time horizon to the end of the 21st century. They are driven by known forcings such as greenhouse gas and aerosol concentrations, solar irradiance and land use, among others, following a prescribed rate of change. The method establishes a reference period with statistical distributions similar to the historic period but absent specific timing of historical events. To capture an appropriate range of future climate uncertainty, transient methods feature a large number of projections to adequately characterize the possible range of future hydrology and system conditions at any stage in time during the planning horizon.

The Salt-Verde watershed has demonstrated high hydroclimate variability over more than a century of instrumental data, posing a challenge to analyses of the System's performance envelope and establishing its sustainability for the future. Rigorous assessments are needed to quantify performance uncertainties and identify system risk probabilities to inform decision making on strategic and operational alternatives that may be different than what is in place today.

If management is to act upon the information it must be clear, interpretable within their base of experience, establish their confidence in its reliability, be directly relevant to system operations, be practical to implementation of considerations, apply the best science available, and quantitatively relate to the historical evidence. These points are described in further detail in the Reclamation (2014) technical guidance memorandum, Chapter 5. Both research methodologies have been employed in this study to meet those objectives.

Below are two criteria to judge the credibility of the downscaled data sets and the hydrologic modeling results: stationarity of precipitation and runoff efficiency of precipitation.

5.2 Stationarity of Precipitation - Historical Period

Murphy and Ellis (2014) reported that historical precipitation on the Salt-Verde watershed has been stationary over the long-term instrumental record for both the winter and summer seasons, although with periods of drier or wetter conditions than average. No long-term trend is present, and research to date has not provided an indication whether one will emerge. Udall and Overpeck (2017) evaluated trends in the Colorado River Basin, encompassing the Salt and Verde watersheds, and summarized "*Whereas it is virtually certain that warming will continue with additional emissions of greenhouse gases to the atmosphere, there has been no observed trend towards greater precipitation in the Colorado basin, nor are climate models in agreement that there should be a trend*."

Stationarity tests of historical Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation for each watershed-season provide a basis of comparison and are illustrated in Figures 5-1, 5-2, 5-3, and 5-4. 31-year interval sample means are tested to a 95% confidence level against means of earlier years in the record. Interval samples that rejected the null hypothesis of stationarity are indicated by a marker above the graph axis at its center. Three of the watershed-seasons are clearly stationary across their record while the Salt watershed in winter reveals a couple decades of high precipitation which then cycles back to the long-term mean and into a drought period. Such natural variability does not result in an overall conclusion of non-stationarity since it is the long-term trend which is of interest.

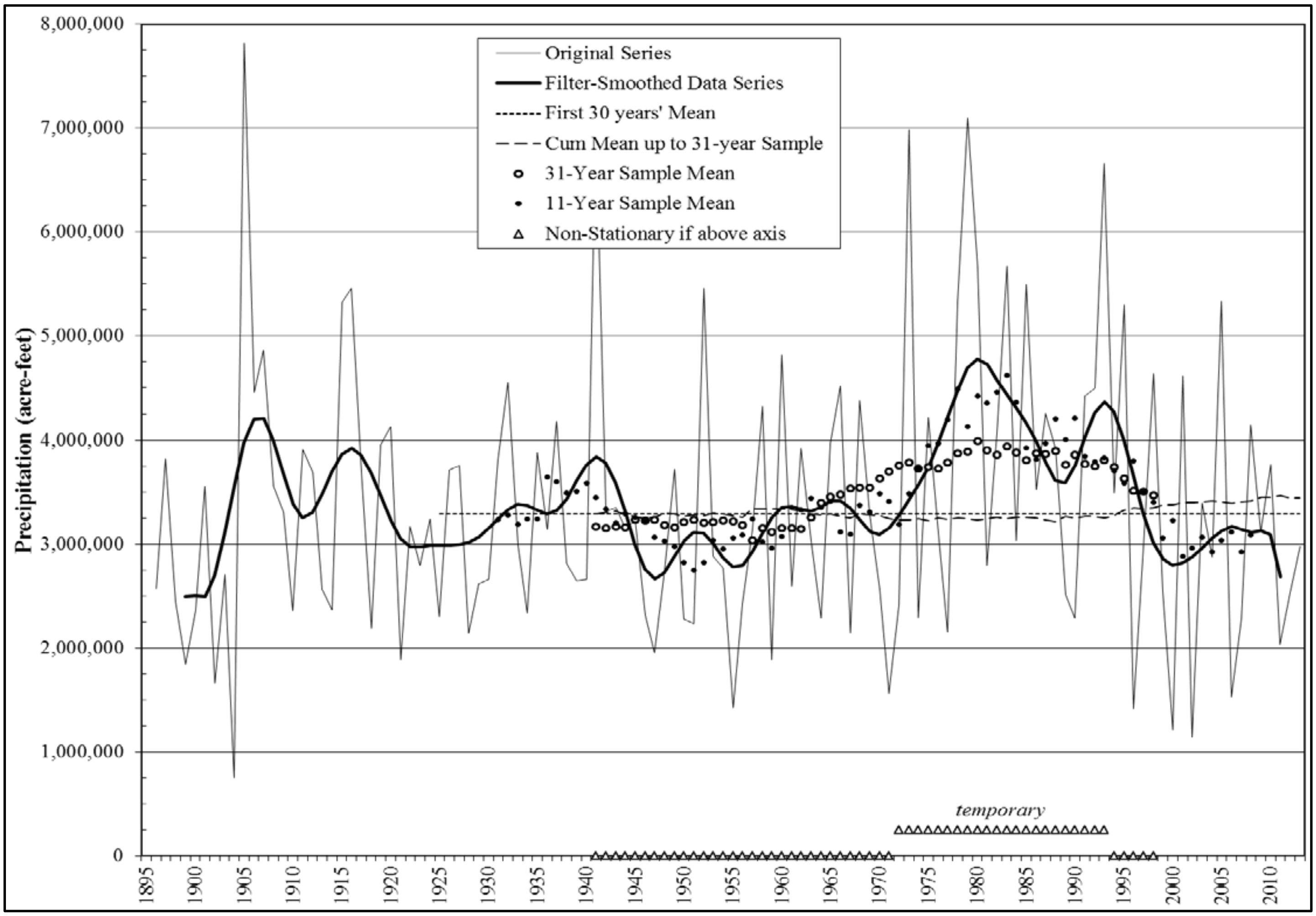

Figure 5-1: Stationarity testing of historical (PRISM) Salt winter precipitation relative to cumulative mean

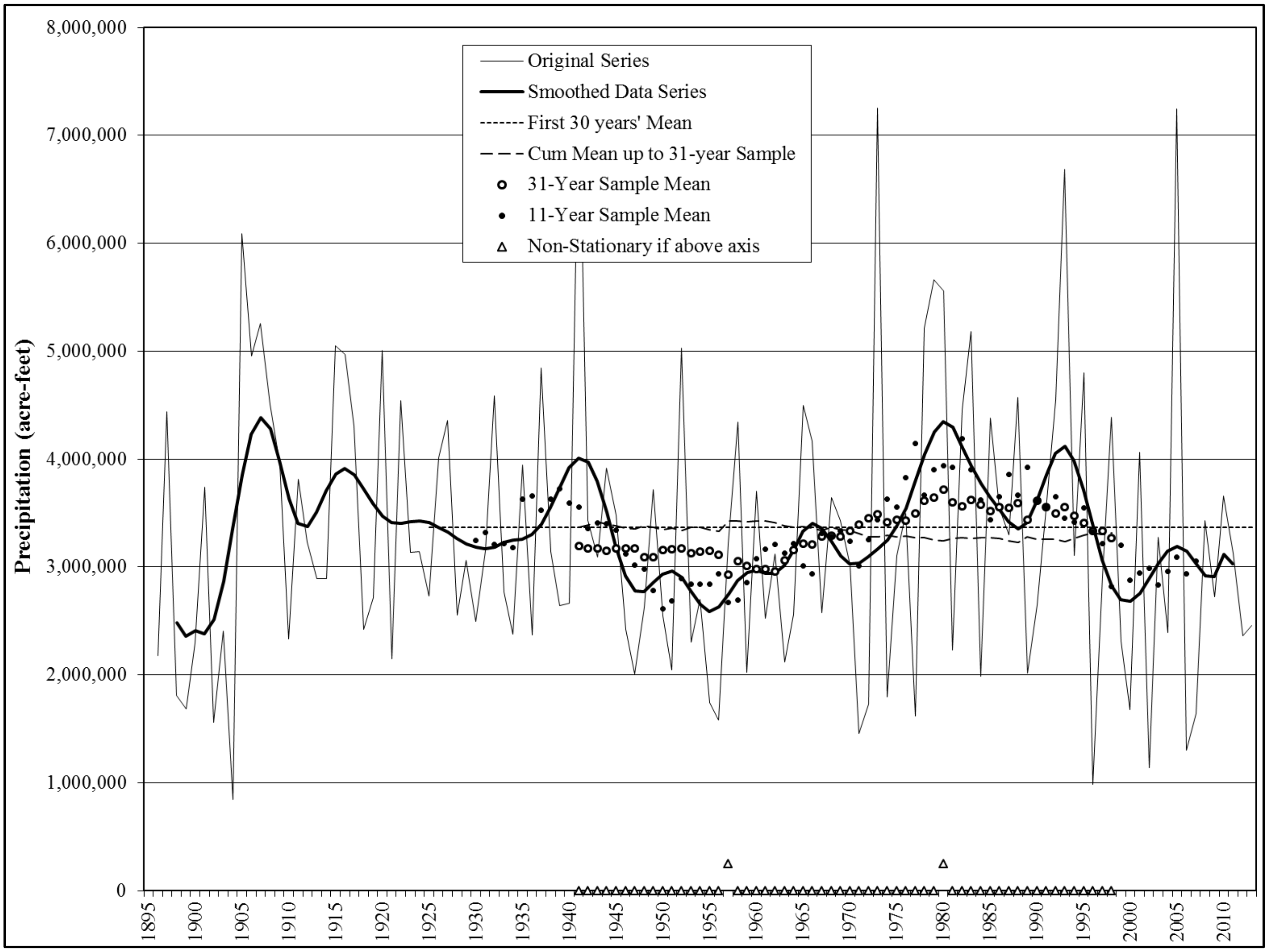

Figure 5-2: Stationarity testing of historical (PRISM) Verde winter precipitation relative to cumulative mean

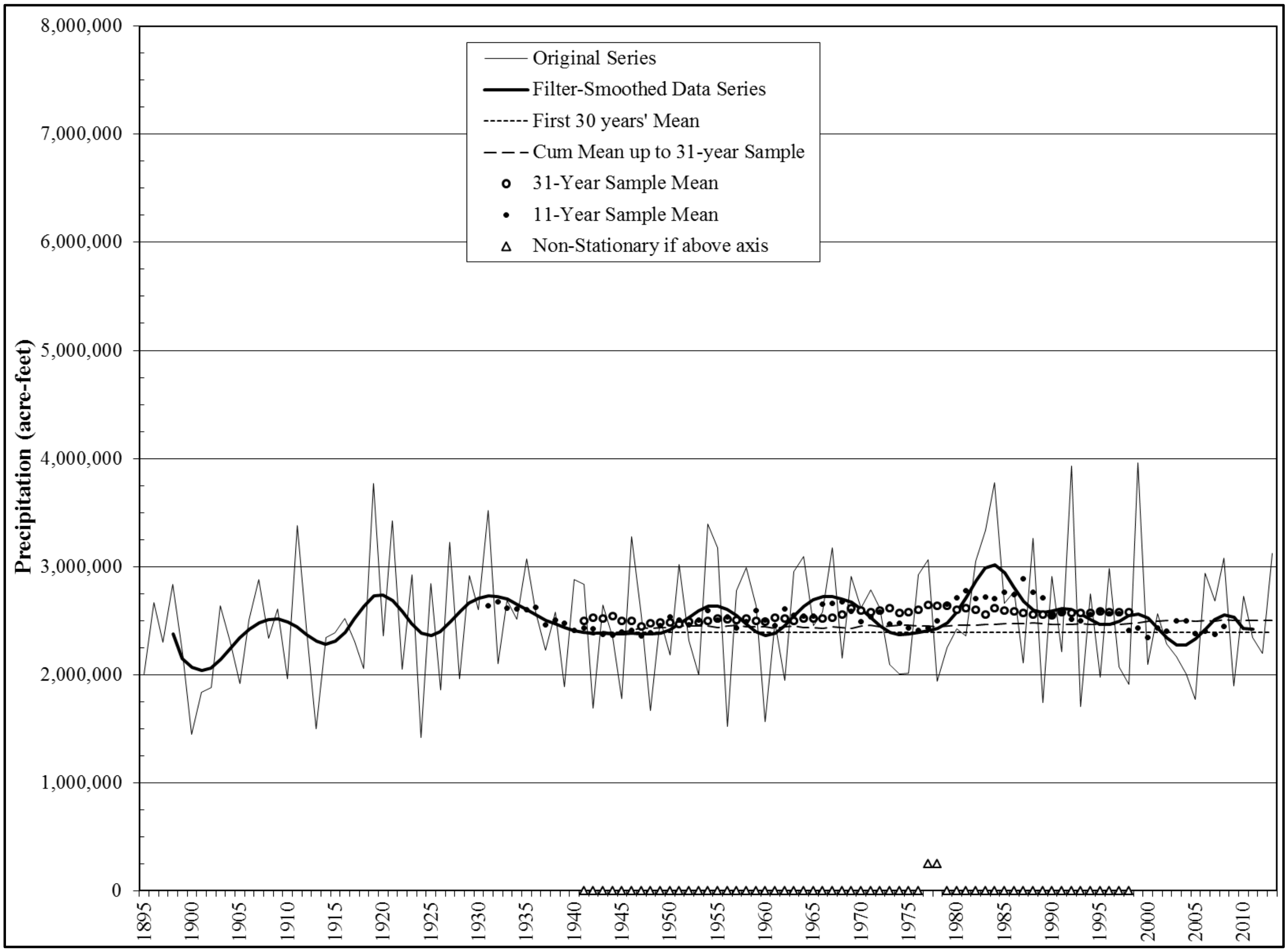

Figure 5-3: Stationarity testing of historical (PRISM) Salt summer precipitation relative to cumulative mean

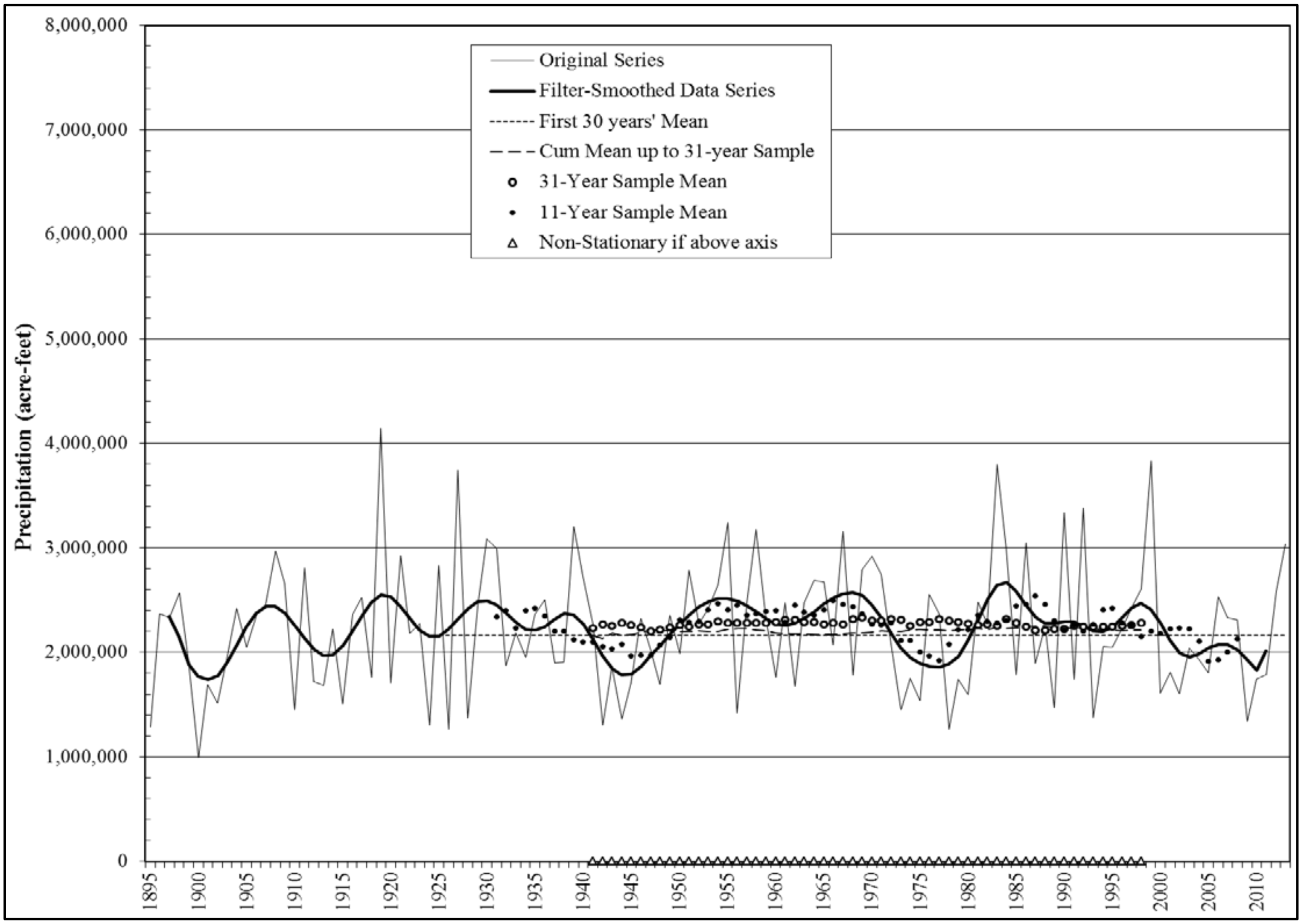

Figure 5-4: Stationarity testing of historical (PRISM) Verde summer precipitation relative to cumulative mean

5.3 Runoff Efficiency of Precipitation - Historical Period

Hydrologic response of streamflow to causal precipitation is a critical watershed behavior, and it provides insight to the characteristic precipitation elasticity of runoff unique to a watershed-season. The efficiency with which precipitation on the watershed is converted to runoff is a fractional value simply expressed as the ratio runoff/precipitation (R/P). Figures 5-5 and 5-6 show the historical behavior of winter runoff efficiency in the Salt-Verde watershed per the instrumental (historical) record. From a theoretical basis and as seen in practice, winter efficiencies are typically small at low precipitation levels and increase with higher precipitation towards an asymptotic value, although with some variability due to a mix of various hydrologic influences. This general behavior provides a way to examine the chain of simulation model results for consistency with observed historical response.

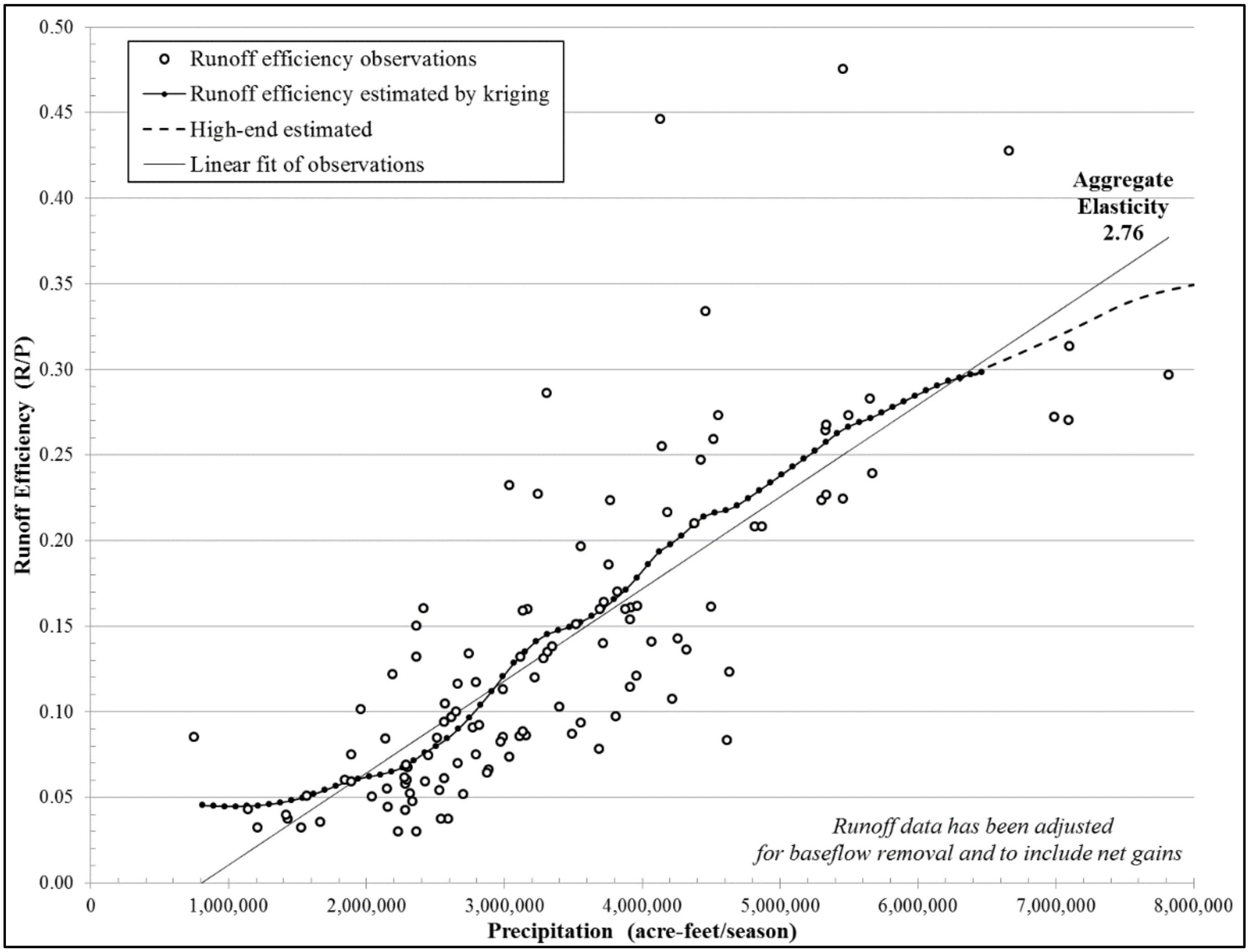

Figure 5-5: Runoff efficiency by precipitation level, Salt in winter, per instrumental (historical) record

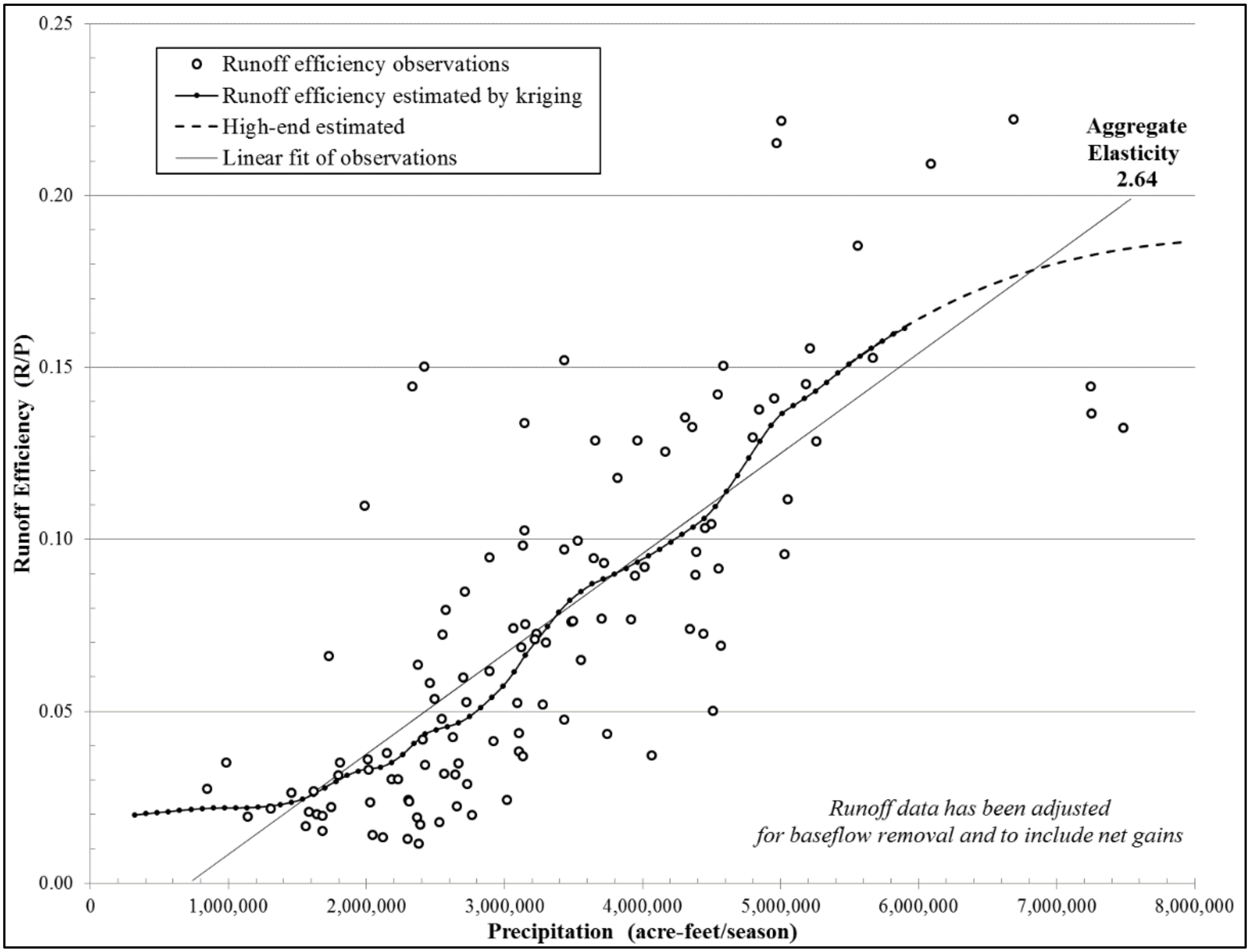

Figure 5-6: Runoff efficiency by precipitation level, Verde in winter, per instrumental (historical) record

5.4 Transient Method

5.4.1 Climate Change Projections

Evaluating future hydrologic conditions requires an understanding of future climate conditions. GCMs provide a tool for developing projections of future climate conditions including temperature and precipitation. The international climate community has coordinated efforts to develop sets of GCM projections reflecting a range of future conditions. The World Climate Research Programme, through the Coupled Model Intercomparison Project Phase 5 (CMIP5), (Taylor et al. 2012) developed the set of projections serving as the basis for the IPCC Fifth Assessment Report (AR5) (IPCC 2013). Over the historical period, CMIP5 GCM simulations are constrained by observations of atmospheric and ocean states. For the future period, simulations use a set of Representative Concentration Pathways (RCP) (van Vuuren et al. 2011), developed to reflect different future simulations of greenhouse gas emissions. In correspondence with the Fourth National Climate Assessment (USGCRP 2017), this Study considered two RCPs: (i) RCP4.5 which reflects emissions that peak in 2040 and then decline, and (ii) RCP8.5 which reflects emissions that continue to rise throughout the 21st century. CMIP5 GCM projections were produced on a coarse spatial scale (e.g. ~100km); finer spatial scales are required to evaluate local hydrologic conditions. Downscaling approaches, through statistical and/or physically-based models, provide a way of resolving coarse GCM projections to spatial scales relevant for local-scale analyses. An archive of downscaled GCM projections[6] was developed through a collaborative effort between Federal and non-Federal agencies (U.S. Bureau of Reclamation et al., 2013, 2016b). For this analysis we used a set of 32 GCM projections (Table 5-1). These projections provided time series of daily temperature and precipitation which could then be used with a hydrology model to develop projections of future streamflow.

Table 5-1: GCMs included in the downscaled LOCA archive

Model	Model	Model
access1-0	miroc-esm	giss-e2-r
csiro-mk3-6-0	canesm2	mpi-esm-mr
inmcm4	gfdl-esm2g	cmcc-cm
access1-3	miroc-esm-chem	hadgem2-ao
ec-earth	ccsm4	mri-cgcm3
ipsl-cm5a-lr	gfdl-esm2m	cmcc-cms
bcc-csm1-1	miroc5	hadgem2-cc
fgoals-g2	cesm1-bgc	noresm1-m
ipsl-cm5a-mr	giss-e2-h	cnrm-cm5
bcc-csm1-1-m	mpi-esm-lr	hadgem2-es
gfdl-cm3	cesm1-cam5	

[6] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

A total of 64 projections were considered, 32 each for RCP4.5 and RCP8.5. These 64 projections were downscaled using the locally constructed analogues (LOCA) method (Pierce et al. 2014) to a 1/16° latitude by 1/16° longitude. (~14 square miles) resolution for the period 1950 - 2099. The LOCA method spatially downscales each GCM simulated day by searching a finer scale reference dataset for a similar day, and then optimally combining them to produce GCM simulations at a fine scale. The Livneh et al. dataset[7] (Livneh et al. 2015), over the period 1950-2005, served as the reference dataset for downscaling.

5.4.2 Hydrology Modeling

The SRP requires monthly streamflow as input to its RPM long-term planning model. These streamflow values were needed at five locations, Figure 5-7, corresponding to USGS gauge locations and listed in Table 5-2. The Variable Infiltration Capacity (VIC) model (Liang et al. 1994, Liang et al. 1996; Nijssen et al. 1997) was used to simulate daily streamflow and these simulations were then aggregated to monthly streamflow. VIC is a grid-based hydrology model that solves the full water and energy budget. VIC simulates physical hydrologic processes and produces time series of hydrological variables including infiltration, surface runoff, soil moisture, evapotranspiration, base flow, and snow.

VIC model version 4.1.2 was used to correspond with hydrology developed to support Reclamation's 2016 SECURE Water Act Report to Congress (U.S. Bureau of Reclamation, 2016a).

[7] ftp://livnehpublicstorage.colorado.edu/public/Livneh.2013.CONUS.Dataset/

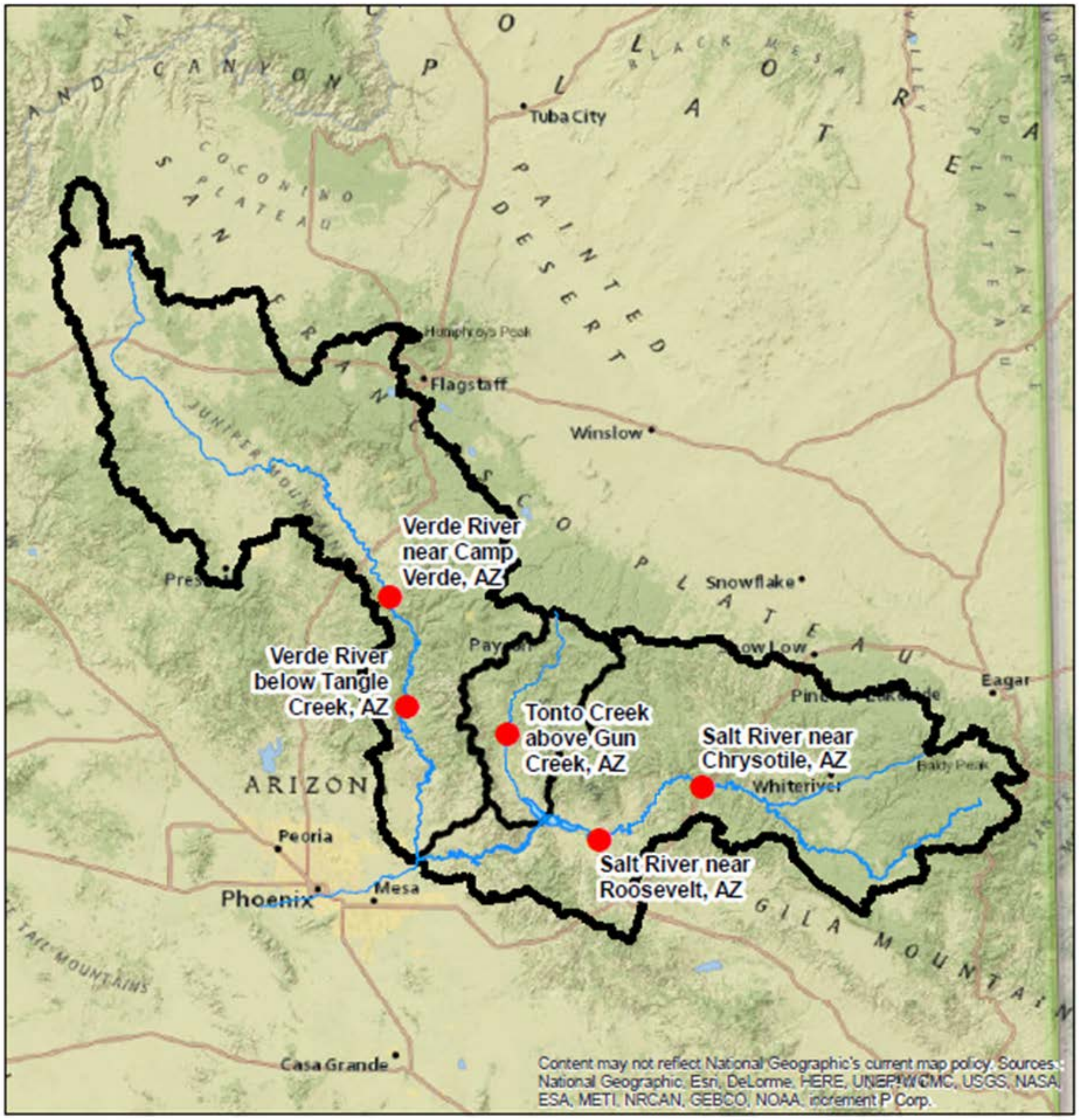

Figure 5-7: Five streamflow gauge locations used for VIC output

The model was configured to run on a 1/16° latitude by 1/16° longitude grid at a daily time step. Required gridded model parameters including elevation, land cover, soil and hydrologic characteristics were obtained from the Livneh et al. dataset[8] (Maurer et al. 2002; Livneh et al. 2013). Selected model parameters were adjusted during calibration and this is discussed further in Section 5.4.2.1: VIC Model Calibration. VIC requires gridded minimum and maximum temperature, precipitation, and wind speed as forcings. Historical hydrology simulations were made using the Livneh et al. dataset. Future hydrology simulation were made

[8] ftp://livnehpublicstorage.colorado.edu/public/Livneh.2015.NAmer.Dataset/nldas.vic.params/

using projections of precipitation and temperature from the LOCA downscaled CMIP5 climate projections and day-of-year mean wind speed from the Livneh et al. dataset.

VIC model output includes surface runoff, base flow, and snow water equivalent (SWE) at each grid cell. Streamflow simulations are produced by routing the gridded surface runoff and base flow through a defined channel network using the approach defined by Lohmann et al. (1996). VIC streamflow simulations reflect natural conditions and do not account for any water management operations. Additionally, representation of groundwater dynamics is limited to a depth of approximately ten feet and consists of recharge that entirely emerges as lagged base flow.

5.4.2.1 VIC Model Calibration

VIC contains model parameters that can be calibrated to better reflect local conditions and simulate streamflow that more accurately reflects a target dataset. SRP developed for calibration and bias correction a historical dataset using USGS gauge records (Table 5-2) for five locations within the Salt-Verde watershed over the period 1914 to 2016. These gauge records reflect largely unimpaired flows, with some minimal diversions above the Verde River near Camp Verde, AZ gauge and the Salt River near Chrysotile, AZ gauge (SRP personal communication, 2017). For the Verde River near Camp Verde, Verde River below Tangle Creek, and Tonto Creek above Gun Creek, near Roosevelt locations, multiple gauge records were combined, with the contributing area method used to adjust for differences in gauge location.

Table 5-2: Historical streamflow records used in VIC calibration

USGS ID	VIC ID	Name	Contributing Stations
09506000	VRNCV	Verde River near Camp Verde, AZ	USGS 09505000 (1/1/1914-3/31/1920) USGS 09506000 (4/1/1934-9/29/1945 and 10/1/1988-12/5/2016) USGS 09505550 (11/5/1971-12/31/1978 and 7/23/1981-11/19/1981)
09508500	VRBTC	Verde River below Tangle Creek, above Horseshoe Dam, AZ	USGS 09510000 (1/1/1914-9/30/1938) USGS 09509000 (10/1/1938-8/21/1945) USGS 09508500 (8/22/1945-12/31/2016)
09499000	TONTO	Tonto Creek above Gun Creek, near Roosevelt, AZ	USGS 09499500 (1/1/1914-12/20/1940) USGS 09499000 (12/21/1940-12/31/2016)
09497500	SLTCH	Salt River near Chrysotile, AZ	USGS 09497500 (9/18/1924-12/31/2016)
09498500	SLTRO	Salt River near Roosevelt, AZ	USGS 09500500 (1/1/1914-12/31/2016)

The optimizer described in Yapo et al. (1998) was used to identify the optimal parameter set for each of the model parameters listed in Table 5-3. Calibrations were run independently for each of the locations listed in Table 5-2 to identify optimal parameter sets. The final calibrated parameter set combined together the optimal parameter sets for each location.

Table 5-3: Summary of VIC model parameters used in calibration

Model Calibration Parameter	Parameter units	Description	Parameter Range
Ds	fraction	Fraction of where nonlinear base flow occurs	0.00001-1.0
Ds_{max}	mm day^{-1}	Max velocity of base flow	0.1-30.0
Ws	fraction	Fraction of max soil moisture where nonlinear base flow occurs	0.05-1.0
D2	mm	Middle soil depth	0.1-1.0
D3	mm	Lowest soil depth	0.5-2..5

5.4.2.2 Bias Correction

Model calibration greatly improved simulations of streamflow over the historical period, however, biases remained which made it difficult to evaluate reservoir operations and management. A post-processing bias-correction approach was used to further adjust the streamflow simulations. The bias-correction approach employed, bmorph[9], developed by the University of Washington to support the River Management Joint Operating Committee Planning Study II. The bias-correction approach bmorph uses a quantile-mapping approach based on methods described in Pierce et al. (2015) and uses a reference dataset to statistically adjust streamflow. The same historical streamflow dataset (Table 5-2) used for calibration is also used for bias-correction. Once bias-corrected, the streamflow simulations were aggregated to a monthly time step for use in the RPM.

5.4.3 Hydrology Model Results Discussion

The National Weather Service (NWS) through the Colorado River Basin Forecast Center develops and issues streamflow forecasts for locations throughout the Salt-Verde watershed. These forecasts use calibrated hydrologic and snow accumulation models developed using the Sacramento-Soil Moisture Accounting (Sac-SMA) hydrology model and the Snow accumulation and ablation model (SNOW-17) snow accumulation model. These models have been calibrated to observed local conditions and potentially provide an improvement over streamflows produced by other hydrology models through this calibration. This study explored the use of developing streamflow using the VIC hydrology model. As a follow-on to this Study, the coupled Sac SMA/SNOW-17 model will be used to simulate streamflow and results will be compared to results from this study.

[9] https://github.com/UW-Hydro/bmorph

5.5 Discussion of Results of the Downscaled Data Sets

5.5.1 Stationarity of Precipitation in the Downscaled CMIP5 Models

An important area of interest for this Study was whether downscaled CMIP5 models provide any clear indication of either increasing or decreasing mean precipitation in the future. If not, then anticipated climate change effects for the System would instead arise from increasing temperatures.

The methodology used for stationarity testing was documented by Murphy and Ellis (2014). Monthly data were aggregated for each watershed's winter (Oct-1 to Apr-30) and summer (May-1 to Sept-30) seasons. Simple t-tests for a statistically significant difference of sample means across time series were employed. While a time series is usually examined for stationarity of both its mean and variance, a study of variance was not conducted due to time constraints and complexity. However, some observations on summer precipitation variance are reported in Section 5.5.2: Stationarity of Precipitation—Historical Period.

Model projection (2006 - 2099) time series were tested against their reference period precipitation data (1950 - 2005) for each of the 32 RCP4.5 scenario models and 32 RCP8.5 models. A wide variety of time series patterns were found in test results, and many of them were concluded to be non-stationary (summarized in Table 5-4). Samples of those series are given in Figures 5-8 through 5-11 where projections are higher or lower than the reference period. Just 12 (37%) of the RCP4.5 models and eight (25%) of the RCP8.5 models were stationary in all four watershed seasons. For the winter season, 28% of RCP4.5 models and 50% of RCP8.5 models were non-stationary. For the summer season 50% of RCP4.5 models and 66% of RCP8.5 models are non-stationary. As shown in Table 5-4 there is a mix of increasing and decreasing non-stationary behavior among models. The results indicate that a consistent finding for mean precipitation change in the future is not present. The extent to which many models display projection patterns very different than the historical record and unrepresentative of their reference period places into question whether realistic precipitation projections for the Salt and Verde watersheds are presented by the models.

Table 5-4: Mean precipitation stationarity test results for the projection period of each model-simulation, winter and summer

	RCP4.5		RCP8.5	
MODEL	**Winter**	**Summer**	**Winter**	**Summer**
ACCESS1-0_1	NS↓		NS↓	NS↓
ACCESS1-3_1				NS↑
BCC-CSM1-1_1		NS↕		NS↓
BCC-CSM1-1-M_1				
CANESM2-1		NS↑		NS↑
CCSM4_6				
CESM1-BGC_1				
CESM1-CAM5_1				
CMCC-CM_1	NS↓		NS↓	
CMCC-CMS_1		NS↓	NS↓	NS↓
CNRM-CM5_1		NS↑	NS↕	NS↑
CSIRO-MK3-6-0_1				
EC-EARTH_8				
EC-EARTH_2				NS↕
FGOALS-G2_1		NS↕		NS↑
GFDL-CM3_1				NS↓
GFDL-ESM2G_1	NS↕	NS↕		
GFDL-ESM2M_1				
GISS-E2-H_2			NS↑	NS↓
GISS-E2-H_6	NS↑			
GISS-E2-R_2			NS↑	NS↓
GISSE2R6		NS↕		
HADGEM2-AO_1	NS↓	NS↓		NS↓
HADGEM2-CC_1			NS↕	NS↕
HADGEM2-ES_1		NS↕	NS↕	NS↕
INMCM4_1				
IPSL-CM5A-LR_1	NS↓	NS↓	NS↓	NS↓
IPSL-CM5A-MR_1		NS↕	NS↕	NS↓
MIROC5_1	NS↓	NS↕	NS↓	
MIROC-ESM_1		NS↑	NS↕	NS↑
MIROC-ESM-CHEM_1	NS↕	NS↑	NS↓	NS↑
MPI-ESM-LR_1		NS↕	NS↓	NS↓
MPI-ESM-MR_1		NS↓		NS↓
MRI-CGCM3_1			NS↑	
NORESM1-M_1	NS↓		NS↓	NS↕

NS↑	projection higher than reference period
NS↓	projection lower than reference period
NS↕	inconsistencies in projection period

The null hypothesis of stationarity is rejected if either or both watersheds test non-stationary. A finding of non-stationarity with increase, decrease, or inconsistencies in times series is denoted by NS↑, NS↓, or NS↕. A blank indicates the projection was stationary relative to its reference period.

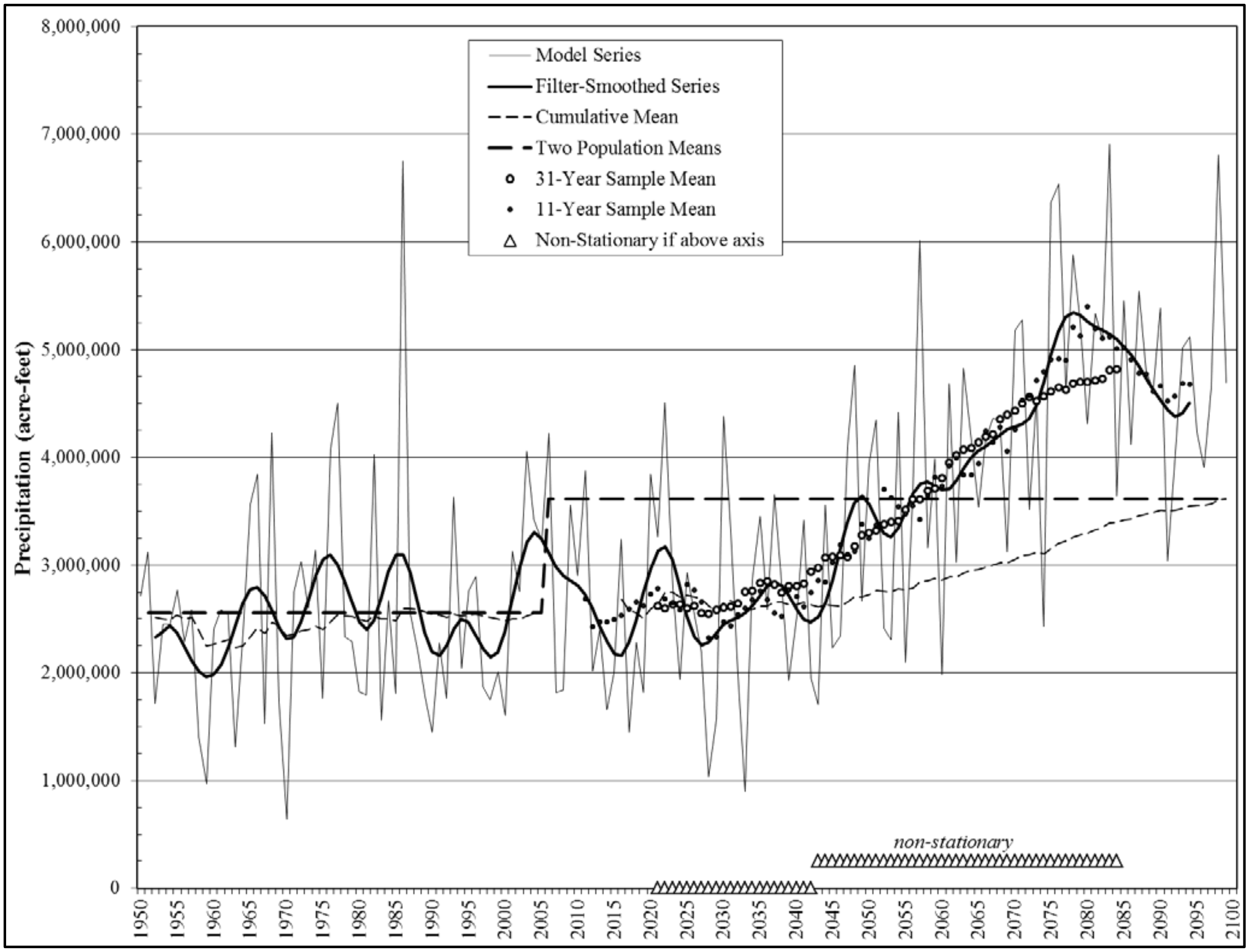

Figure 5-8: Stationarity testing of CANESM2_1_RCP85, Verde summer precipitation. Interval tests of 2006 - 2099 compared to 1950 – 2005

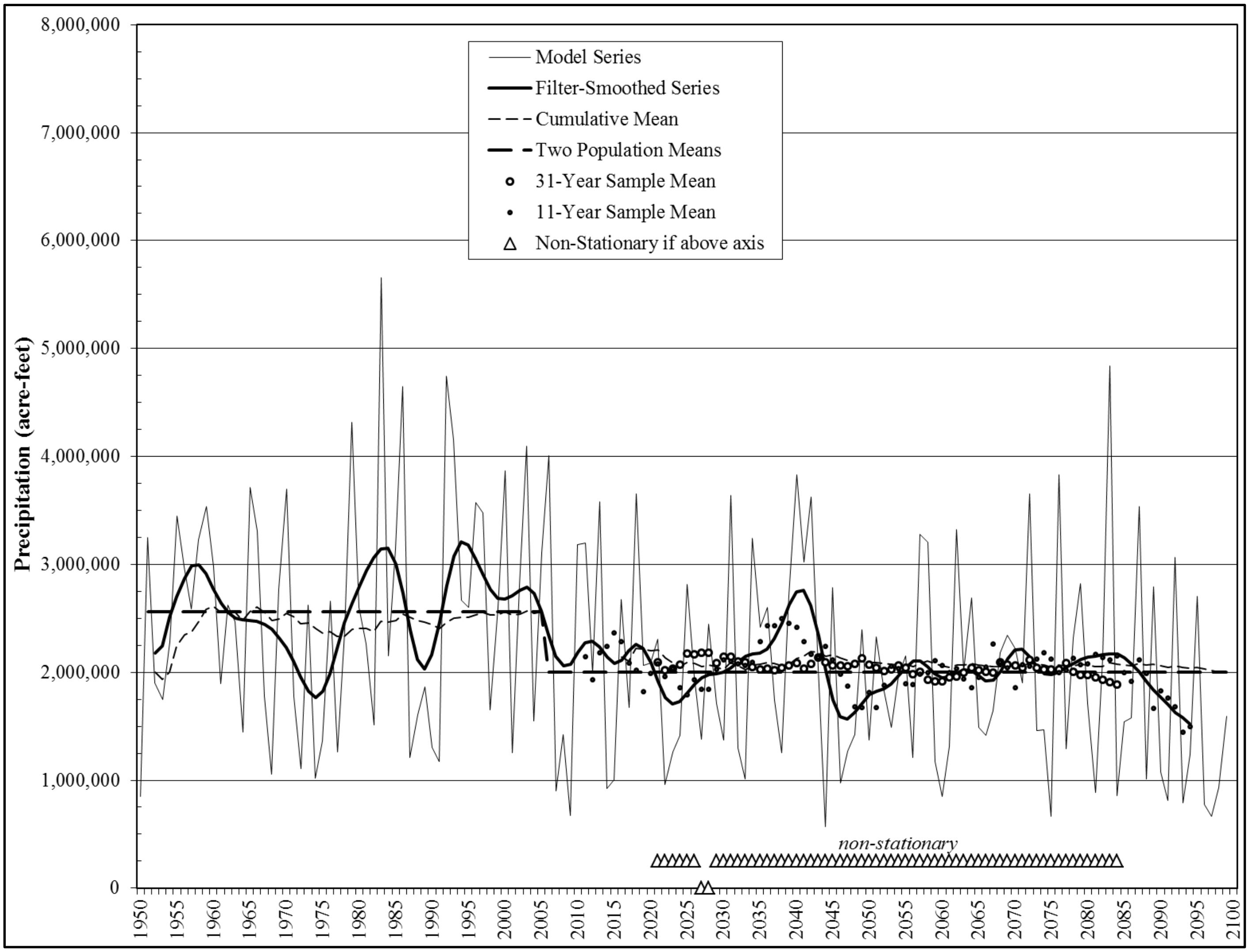

Figure 5-9: Stationarity testing of HADGEM2_AO_1_RCP45, Verde summer precipitation. Interval tests of 2006 - 2099 compared to 1950 – 2005

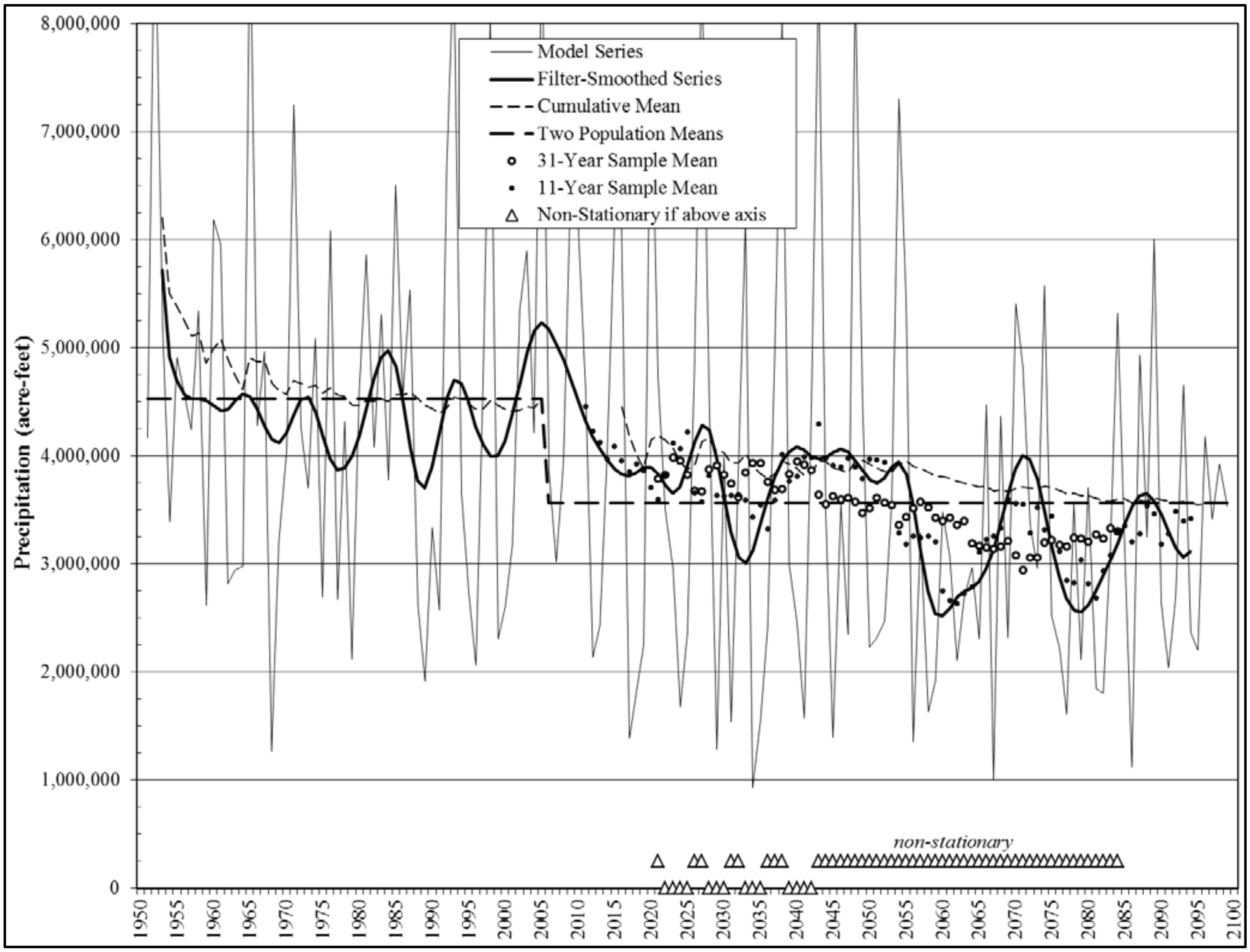

Figure 5-10: Stationarity testing of MIROC5_1_RCP45, Salt winter precipitation. Interval tests of 2006 - 2099 compared to 1950 – 2005

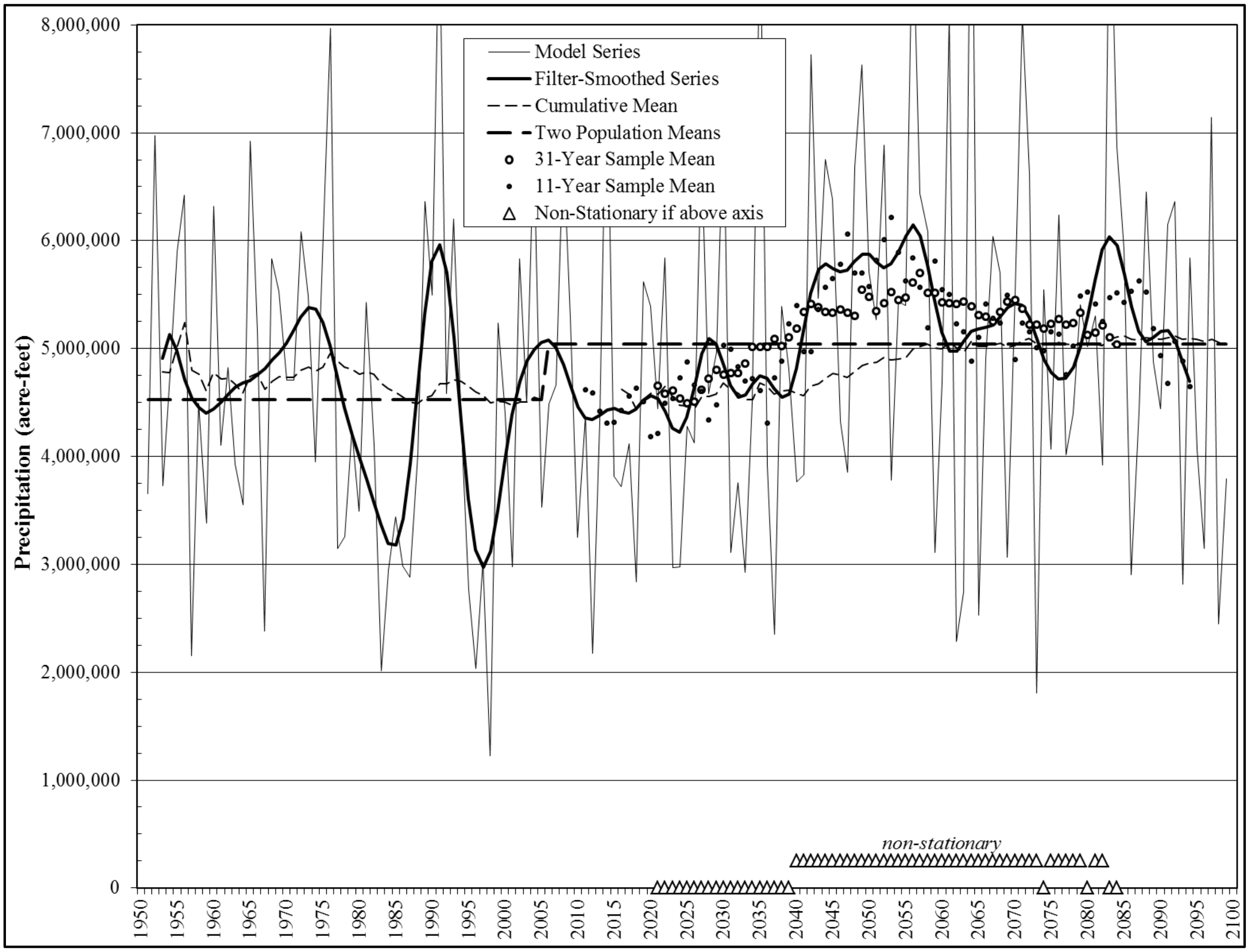

Figure 5-11: Stationarity testing of MRI-CGCM3_1_RCP85, Salt winter precipitation. Interval tests of 2006 - 2099 vs 1950 – 2005

5.5.2 Summer Precipitation and Resultant Streamflow

Modeled streamflows are the result of complex relationships represented in land surface hydrology models. Precipitation is necessarily the primary starting input. The distributions of precipitation have consequent effects on runoff time series, from which sequences of low years imply drought while sequences of high precipitation provide replenishment of surface water resources. If precipitation is understated or overstated, differentials may be amplified in streamflow results.

It was noted during review of the 64 CMIP5 models that many summer precipitation values (sum of May 1 to Sept 30) were higher or lower than the range of actual historical values for the watersheds. Model data reductions had been performed for each watershed to the Granite Reef Diversion Dam while comparative historical PRISM data are per watershed area to the last gauge above reservoirs. The geographic difference, while small, results in offset distributions. PRISM data were therefore upshifted by the median differential between distributions in the comparisons shown below. As shown in Figures 5-12 and 5-13, the distributions of model summer precipitation are wider than what is in the historical record of the Salt-Verde watershed. This is the case for both the model reference periods' data (1950 - 2005) and projection periods' data (2006 - 2099). The projection distributions are slightly broader than the reference periods.

Since the higher variance of model distributions will have implications to streamflow sequences, the PRISM data and the reference period values were questioned in comparison to each other. This can be done through implications to runoff efficiency (R/P) expectations. Salt and Verde efficiencies have been low in summer (low single-digit %). And while there is a logical expectation of increasing hydrologic efficiency with increasing precipitation (as there is in winter), it is a weak relationship in the summer season. Summer runoff data in the historical period is known and can be held fixed with substitution of alternative precipitation assumptions. If precipitation in low portions of the distribution was less as model reference period data suggests then runoff efficiency would be larger.

If precipitation in upper portions of the distribution was higher as the models suggest then efficiency would be smaller. The implication is that runoff efficiency declines with increasing precipitation, which is inconsistent with hydrologic expectations. This implication was evaluated for the Salt watershed history, and a weak increasing relationship with PRISM data switched to a statistically significant declining relationship with model data. This implies that distributions of reference (and projection) model precipitation data are not representative of the watersheds in summer. This is not unexpected since other researchers have reported challenges modeling the dynamics of summer monsoon precipitation in these watersheds. They report that the monsoon precipitation in the Southwest can only be reasonably represented with convection permitting models at no more than 5 km resolution using temporal regional forcing conditions as inputs. This is a modeling complexity beyond the scope of this study.

The standard deviations of the summer precipitation time series for each model are given in Figures 5-14 and 5-15 in comparison to the standard deviation of the historical PRISM record. All models' standard deviations are higher than the historical record, and these deviations are typically double what they should be. As discussed above, on a cumulative basis the wider distribution of summer precipitation contributes to a wet bias in modeled streamflows. The wet bias is sufficiently prevalent to cause frequent spillage of excess water from the reservoirs in summer as rendered by reservoir operations modeling. In actual experience summer spillage is very unusual, having historically occurred only as a consequence of a longer winter runoff season (full reservoirs) and not caused by summer precipitation events. The probability of summer spillage is considered to be negligibly small, and other analyses (see Section 6.3.2.6: Reservoir Water Spill) confirm this expectation.

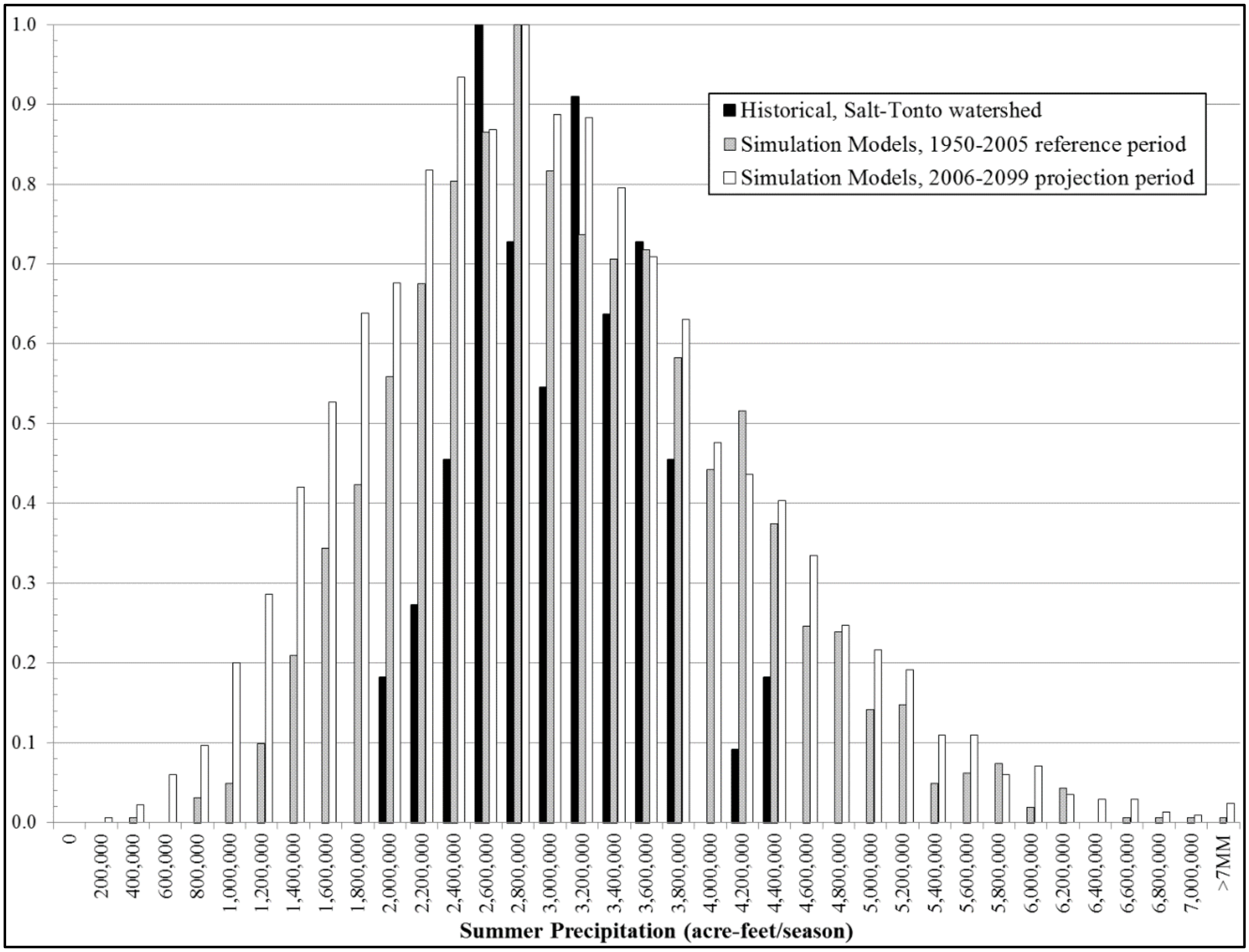

Figure 5-12: Distributions of Salt summer precipitation – historical data in comparison to model results

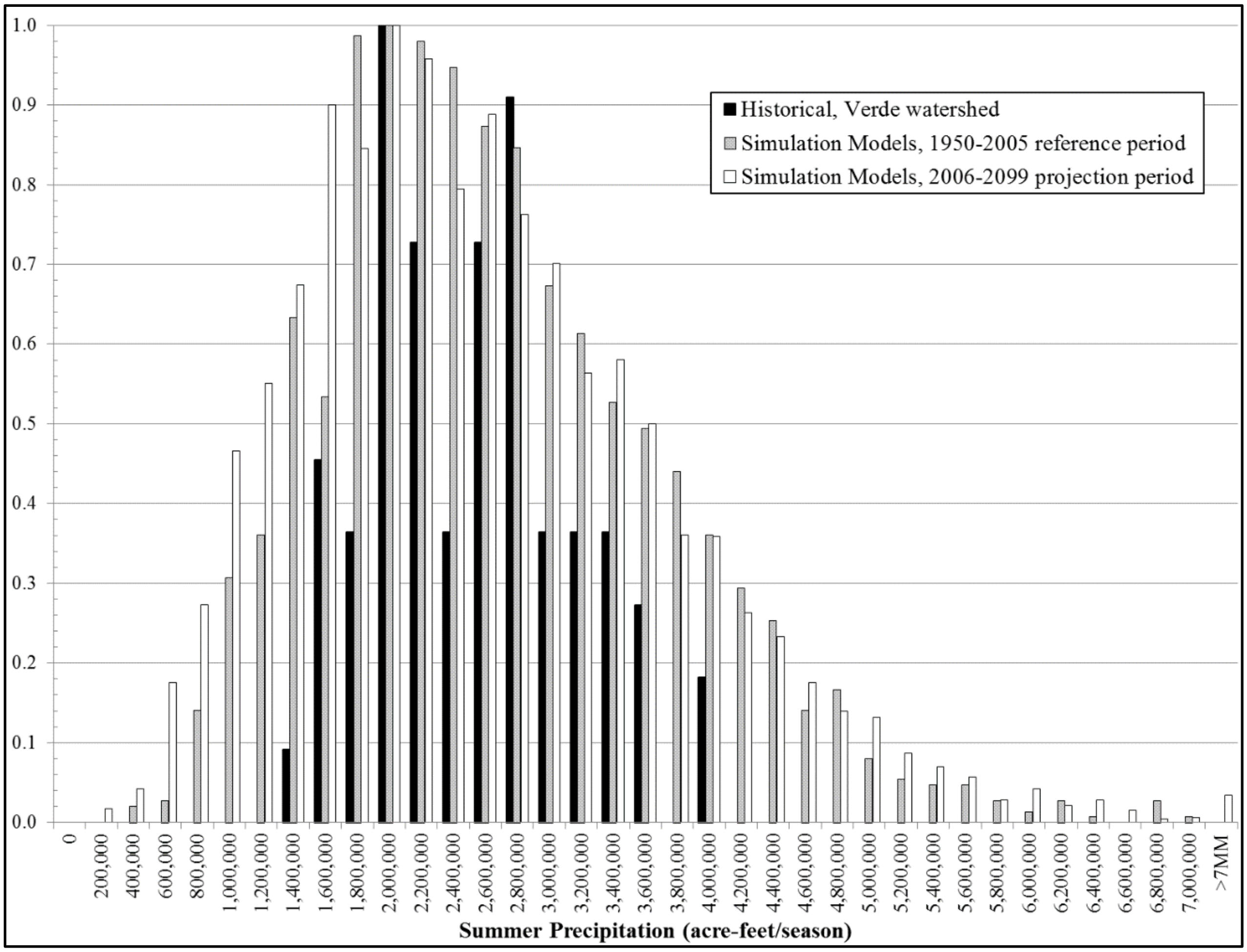

Figure 5-13: Distributions of Verde summer precipitation – historical data in comparison to model results

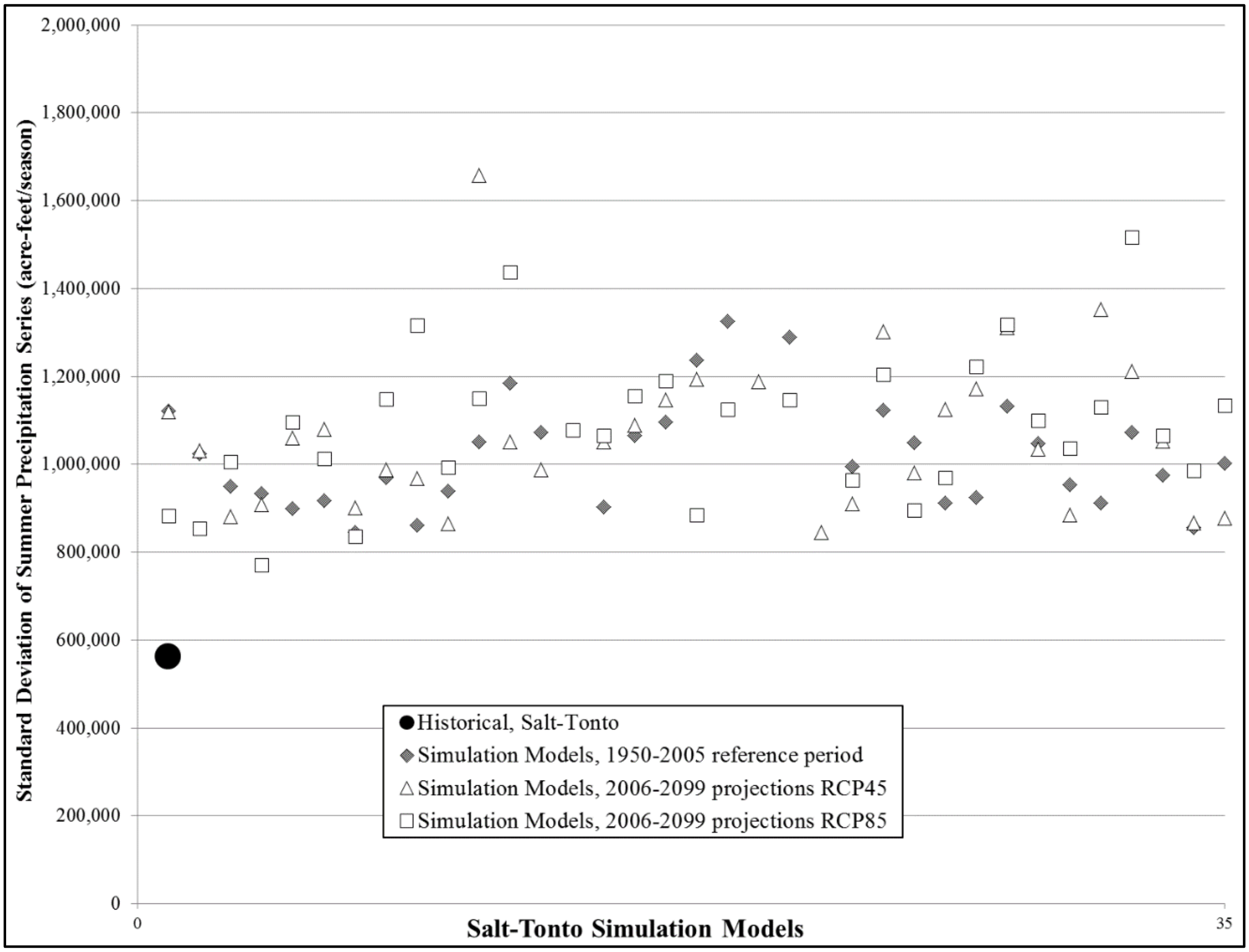

Figure 5-14: Standard deviations of Salt summer precipitation series, models compared to historical record

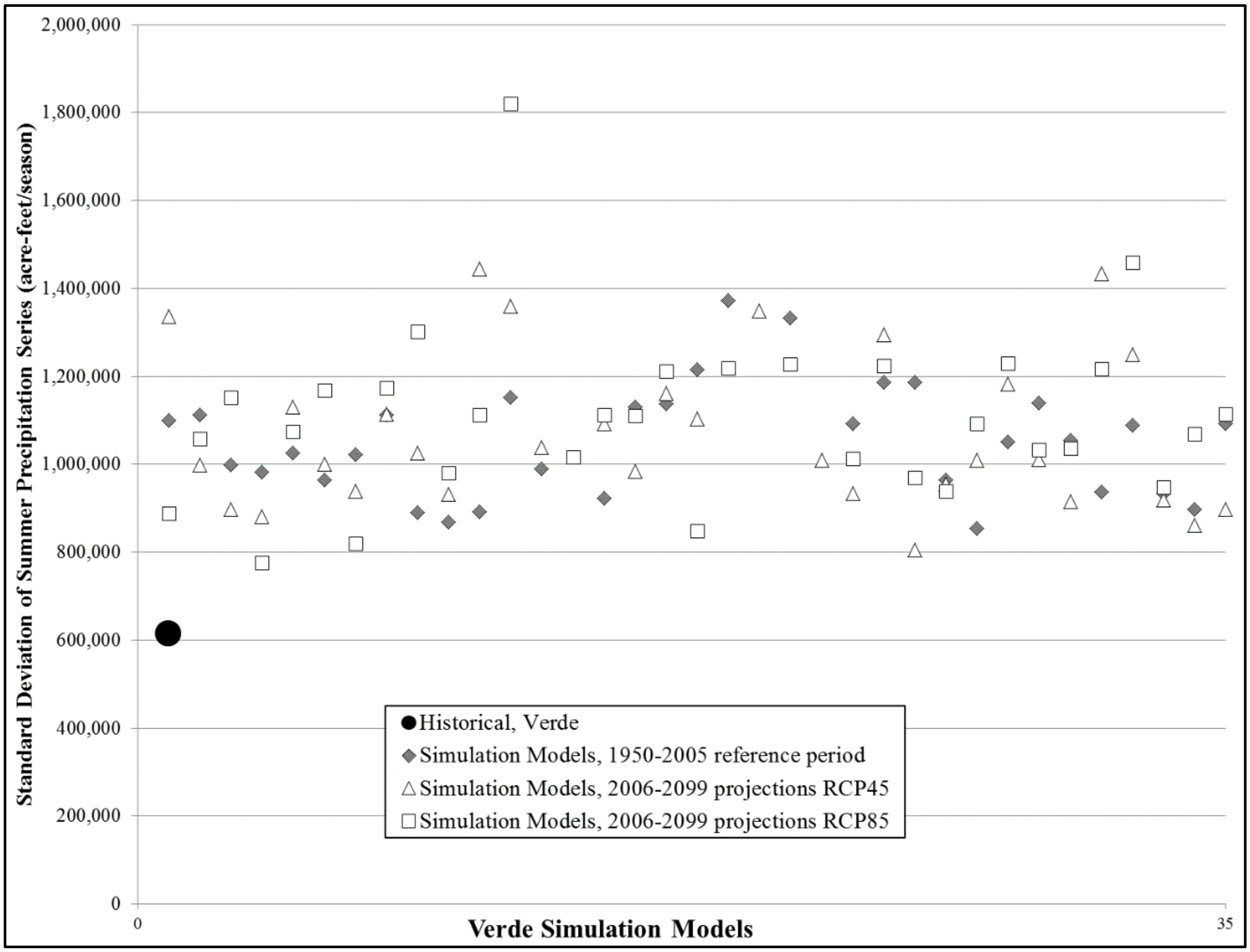

Figure 5-15: Standard deviations of Verde summer precipitation series, models compared to historical record

Total System inflow is the sum of streamflow at Verde River below Tangle Creek, Salt River near Roosevelt, and Tonto Creek above Gun Creek. During the historical period (1951-2016), comparisons of May-September total System inflow between the 64 simulated streamflow time series and the USGS record indicate striking differences in the distribution of flows. The empirical cumulative distribution functions for the 64 simulations display a substantial positive bias at all percentiles (Figure 5-16). The simulation ipsl-cm5a-mr_rcp85 displayed in Figure 5-16 is the "driest" of the 64 simulations in that it has the lowest median (i.e., 50th percentile). This simulation also displays a notable positive bias at all percentiles (Figure 5-16). For example, the bias is +78,433 AF (+67%) at the 10th percentile, +85,144 AF (+41%) at the 50th percentile, and +319,622 AF (+96%) at the 90th percentile. Additionally, the 99th percentile value in the observed distribution (578,232 AF) is below the 80th percentile of the simulation mean distribution (Figure 5-16). Furthermore, the highest percentiles of the mean of the 64 simulations are ~1,200,000 AF (Figure 5-16), more than half of the total reservoir storage on the System. This suggests that many of the simulations have enough May-September inflow to create summer spill events. In the historical record, only ~21% of the annual flow occurs between May and September and spill events typically only occur in the winter and early spring.

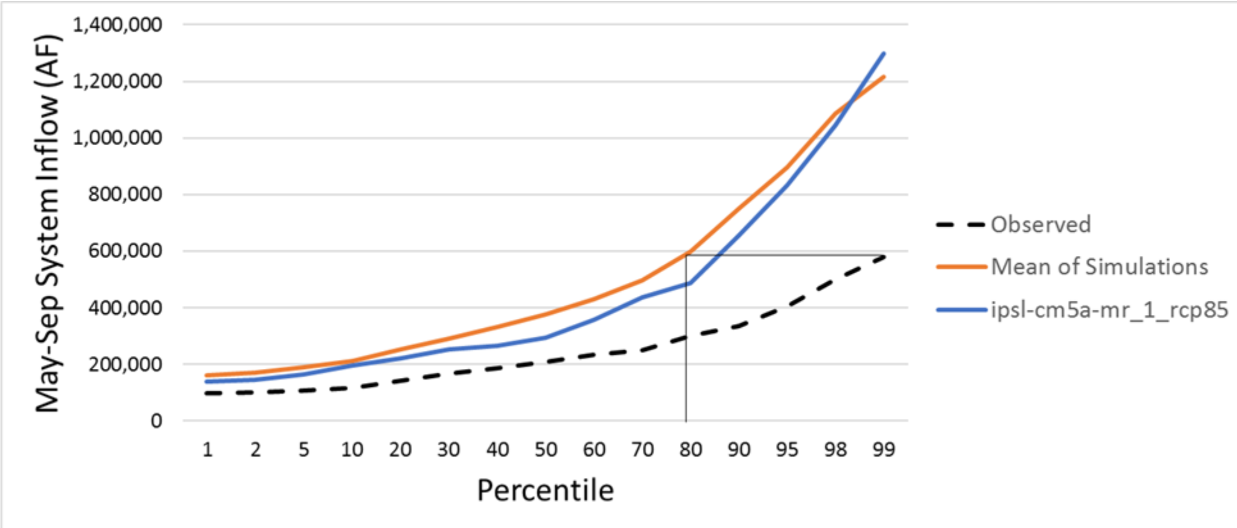

Figure 5-16: **For the historical period (1951 - 2016), May-September total system inflow empirical CDFs for the USGS record, the mean of the 64 simulations, and the simulation with the lowest median**

An example mapping of the percentiles between observed distribution and simulation mean distribution is displayed in the graph with thin black lines.

This problematic positive bias in the summer flows likely stems from a similar positive bias in summer precipitation in the 64 downscaled climate simulations (analysis shown above). Historical experience has established that winter rains and late winter/early spring snowmelt are the critical inflow resource for SRP water resource management. Potential future changes affecting this season are of greatest concern to SWR staff. The summer wet-bias confuses the interpretation of winter season effects on reservoir operations. Therefore the summer bias was removed from all 64 simulations. This was achieved through replacing May-September flows with median historical values. For the remainder of this report, analysis is performed on the 64 simulation time series with this modification.

Whiskers represent the ranges and boxes represent the interquartile ranges and medians. The values from the historical observations are given by x.

With the summer bias removed, comparisons of water year total System inflow between the 64 simulated streamflow time series and the USGS record during the historical period (1951-2016) indicate important differences in the distribution of flows.

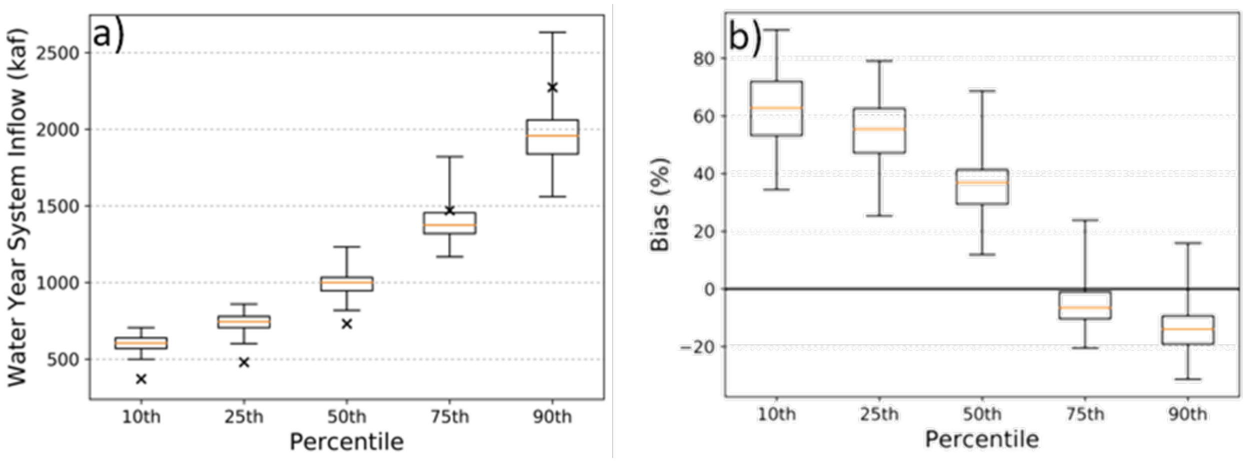

Figure 5-17: **(a) For the 64 modeled streamflow time series, selected percentile values for water year system inflow during the historical period (1951 - 2016) and (b) the corresponding bias of the 64 streamflow time series**

For all 64 simulations, there is a positive (or wet) bias in the median water year flow, and at the 10th and 25th percentiles (Figure 5-17a). This bias is most substantial at the 10th percentile, where the bias ranges from +34% to +90% (Figure 5-17b). For median water year flow, the bias ranges from +87,000 AF (12%) to +502,000 AF (+69%). This wet bias is not evident at the higher percentiles, with nearly 50 of the 64 simulations displaying less water year release at the 75th percentile than the USGS record (Figure 5-17a). The biases at the 90th percentile range from –714,000 AF (-31%) to +358,000 AF (+16%).

There are many definitions of drought, however, inflow less than the lower quartile is important for SRP storage planning (Phillips et al., 2009). With respect to each modeled inflow time series' water year lower quartile during the historical period (1951 - 2016), the number of occurrences of at least two consecutive years of lower quartile inflow ranged from one to five out of all 64 simulations. The median number of occurrences out of the 64 simulations was three, which is equal to the number of occurrences in the USGS record. Twenty-three of the 64 simulations and the USGS record displayed zero occurrences of three or more consecutive years below their respective lower quartile values during the historical period.

In summary, there is little agreement between the 64 simulations and the USGS record in the extremes of water year inflow. Furthermore, all 64 simulations display a substantial wet bias in the middle percentiles. Regarding drought as defined by consecutive years of inflow below each time series' respective lower quartile, there does not appear to be substantial differences between the USGS record and the 64 simulations.

Due to the notable biases in all 64 simulations in the middle and lower streamflow percentiles (Figure 5-17), useful information about projected changes (e.g., future relative to historical) in drought within all simulations is likely unattainable. Therefore, a detailed analysis of the projected changes in all 64 simulations, and the potential impacts on SRP operations is not prudent. For this reason, the three "driest" simulations in the future period (i.e., 2050-2099) were chosen for further detailed analysis (Table 5-5). These simulations consistently displayed 5 year to 30 year periods in the future that had less total System inflow than the USGS record. Similarly, the three "wettest" simulations were selected for further detailed analysis (Table 5-5).

Table 5-5: The inflow totals for the wettest and driest consecutive year periods in the past (1914-2016) and future (2050-2099) for the USGS record and simulations, respectively

	Observed Dry (KAF)	Simulated Dry Future (KAF)	Simulation	Observed Wet (KAF)	Simulated Wet Future (KAF)	Simulation
1yr	287	311	ipsl-cm5a-lr_1_rcp85	4,238	7,434	***cesm1-bgc_1_rcp45***
3yr	1,344	1,153	ipsl-cm5a-lr_1_rcp85	8,674	10,614	mpi-esm-mr_1_rcp85
5yr	2,425	2,332	ipsl-cm5a-lr_1_rcp85	10,919	14,266	cnrm_cm5_1_rcp85
10yr	7,474	5,562	***cmcc-cms_1_rcp45***	18,865	21,564	giss-e2-h_6_rcp45
20yr	15,458	13,505	***ipsl-cm5a-lr_1_rcp85***	32,501	36,513	***csiro-mk3-6-0_1_rcp85***
30yr	26,132	20,381	***miroc5_1_rcp45***	43,831	53,681	***mri-cgcm3_1_rcp85***

Selected periods are displayed, although all periods from one to thirty consecutive years were examined. The simulations chosen for detailed analysis are in bold italic font.

5.5.3 Runoff Efficiency of Precipitation Simulations

From the 64 model simulations used for this study, three of the driest and three of the wettest in the winter season were identified and examined in detail for streamflows and implications to reservoir operations. Their summer flows were replaced by historical medians to suppress the summer season wet bias and allow winter behavior to be analyzed. Winter runoff efficiencies of the six models were calculated for the reference (1950 - 2005) and projection (2006 - 2099) periods.

Four of the models (cmcc-cms_1_rcp45, ispl-cm5a-lr_1_rcp85, miroc5_1_rcp45, mri-cgcm3_1_rcp85) display the expected increase of efficiency with increasing precipitation in the Salt watershed in both their reference and projection periods. However, their modeling results for the Verde display a weak or negligible form of the anticipated *f(P)* relationship.

Two models (cesm1-bgc_1_rcp45, csiro-mk3-6-0_1_rcp85) display anomalous behavior. Model cesm1-bgc_1_rcp45 for the Salt behaves as expected for reference period data as shown in Figure 5-18, although the *f(P)* relationship is absent for the Verde in Figure 5-19. The relationship is reversed for the projection period (Figures 5-20, 5-21) where many efficiency values are unrealistically high for low precipitation. Results for model csiro-mk3-6-0_1_rcp85 in Figures 5-22 to 5-25 show declining *f(P)* for both watersheds in both reference and projection period data, and there is a scattering of unrealistically high efficiency values in the low precipitation range.

Hydrologic response appears to be inconsistent among the six models. While these sample 10 percent of the model population, they are indicative of behavior that is likely present amidst other simulation model results. The models examined display varying degrees of consistency or inconsistency in hydrologic response that should, at minimum, be roughly similar to the observational record. It is not possible to a-priori identify which models will be well-behaved, and the characteristics seen in this sample tend to undermine confidence in their linkage of precipitation to streamflow projections.

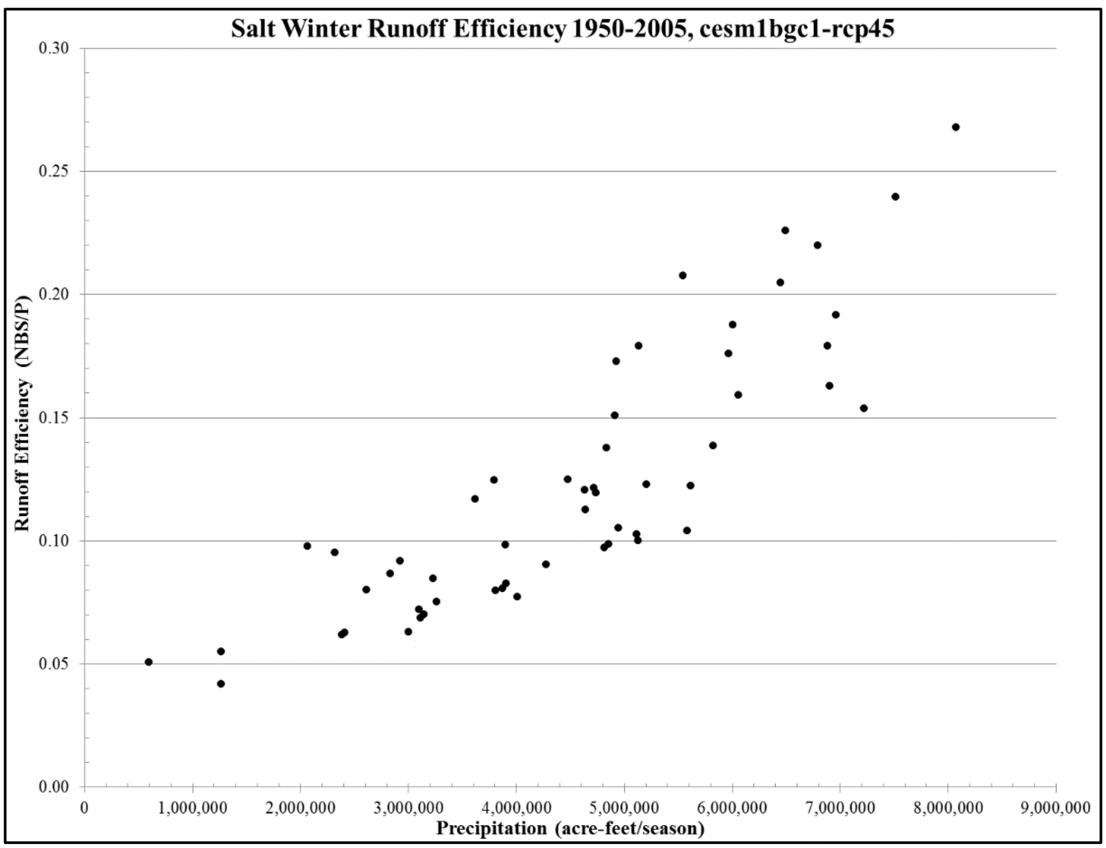

Figure 5-18: Model cesm1bgc1-rcp45, reference period, Salt winter runoff efficiency

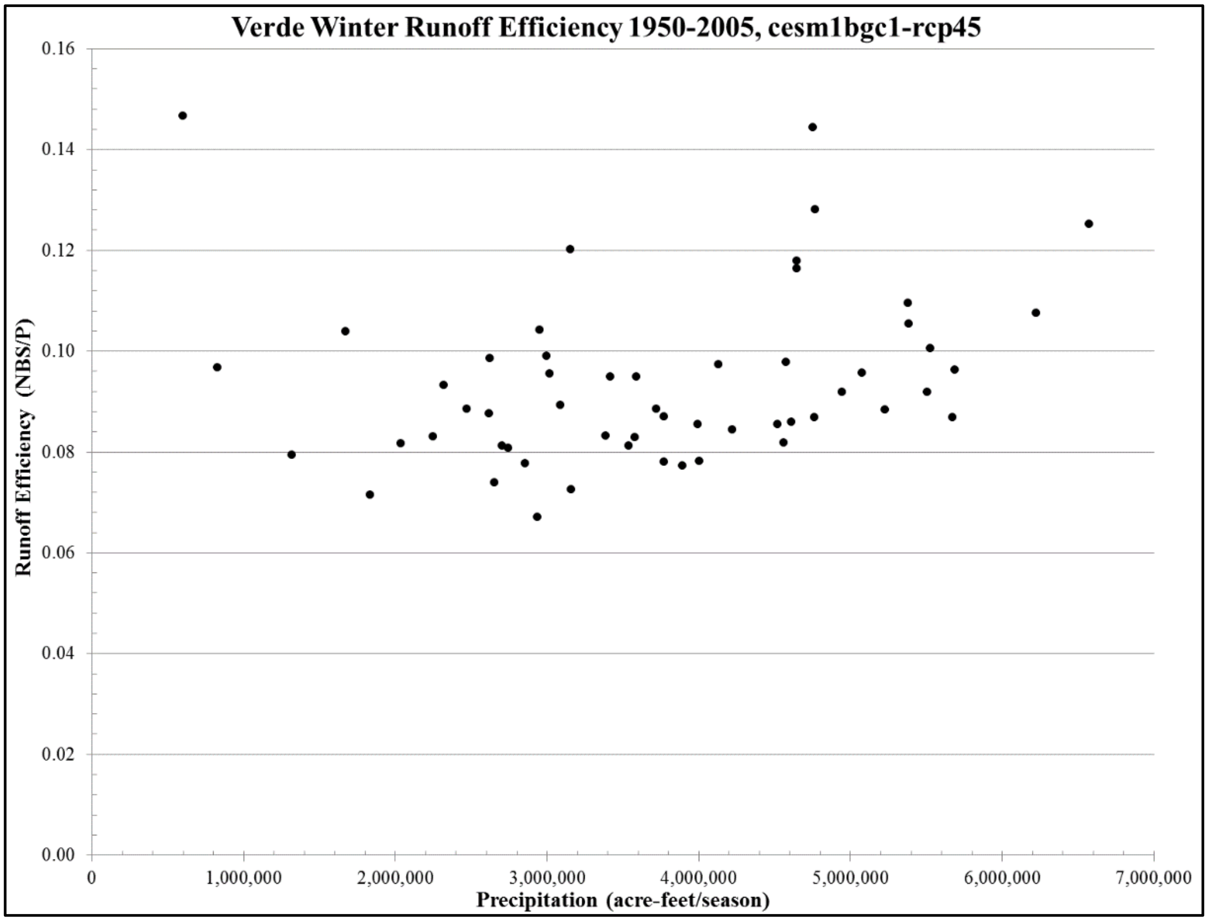

Figure 5-19: Model cesm1bgc1-rcp45, reference period, Verde winter runoff efficiency

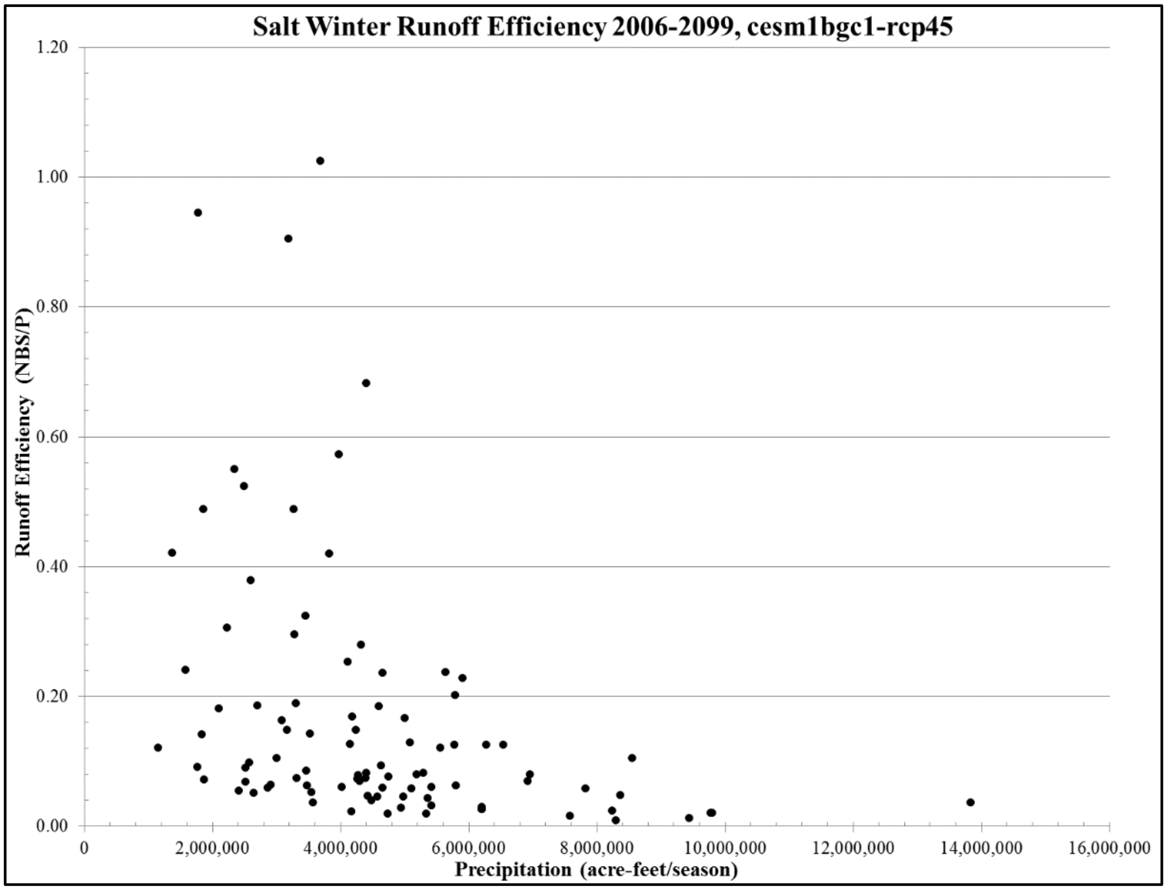

Figure 5-20: Model cesm1bgc1-rcp45, projection period, Salt winter runoff efficiency

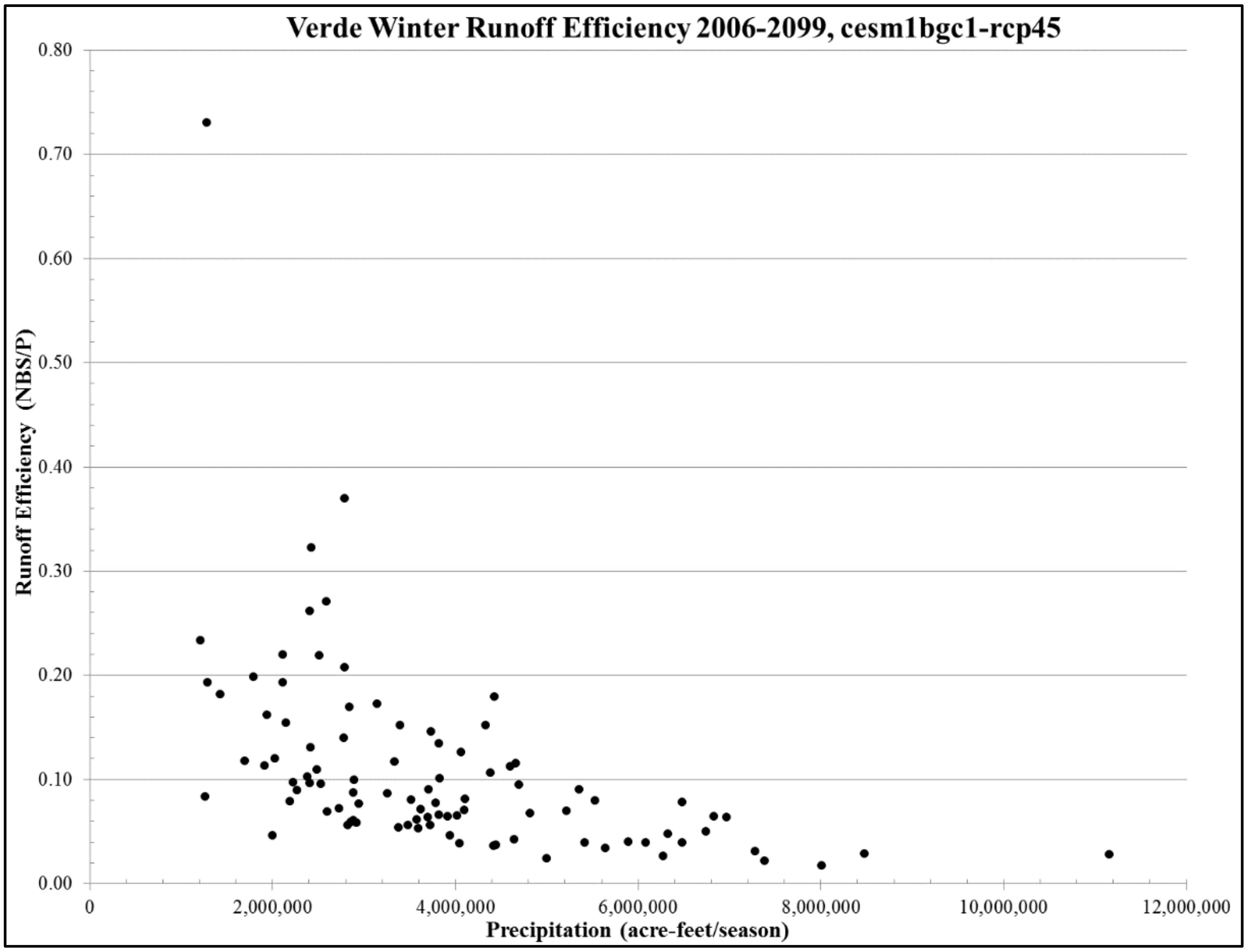

Figure 5-21: Model cesm1bgc1-rcp45, projection period, Verde winter runoff efficiency

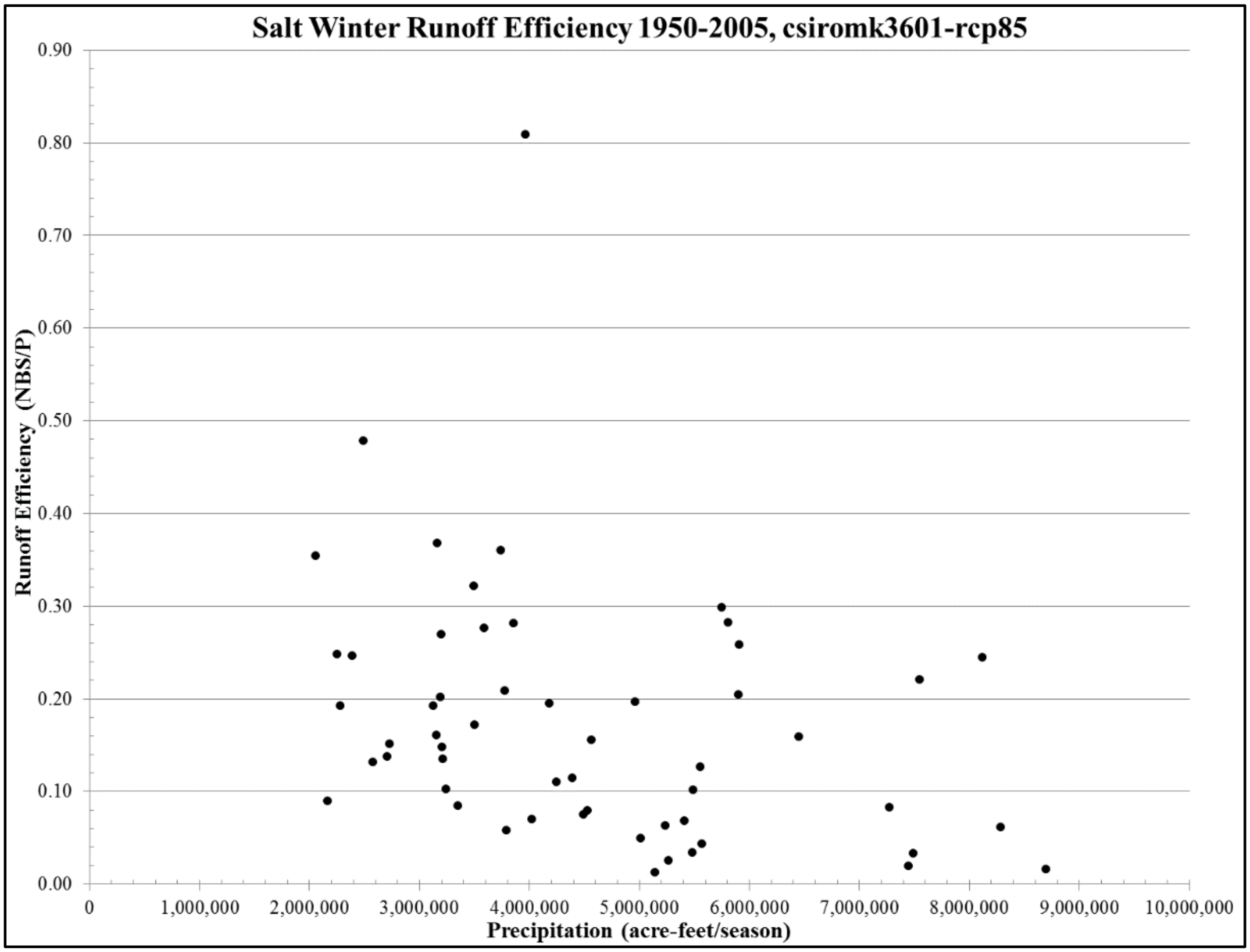

Figure 5-22: Model csiromk3601-rcp85, reference period, Salt winter runoff efficiency

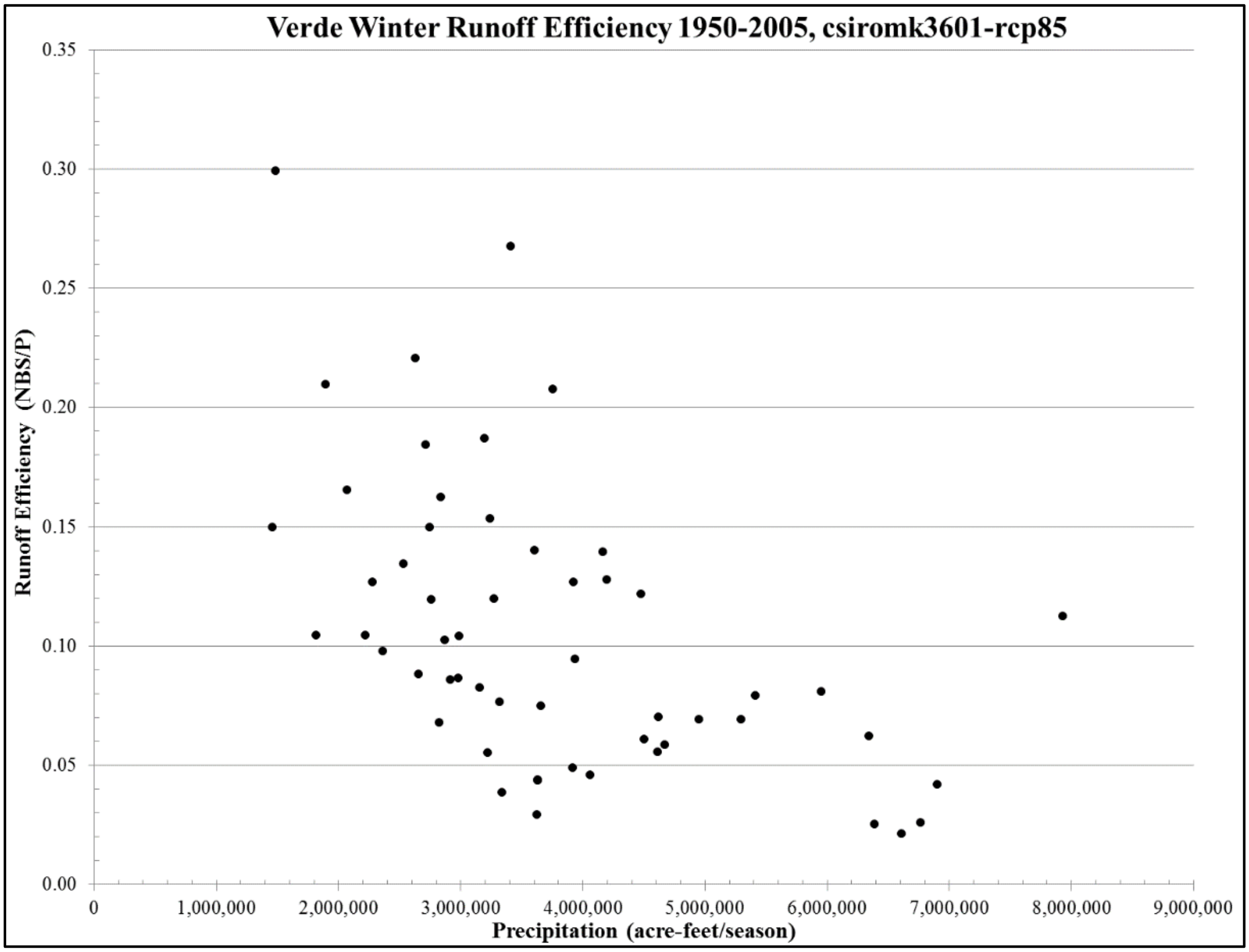

Figure 5-23: Model csiromk3601-rcp85, reference period, Verde runoff efficiency

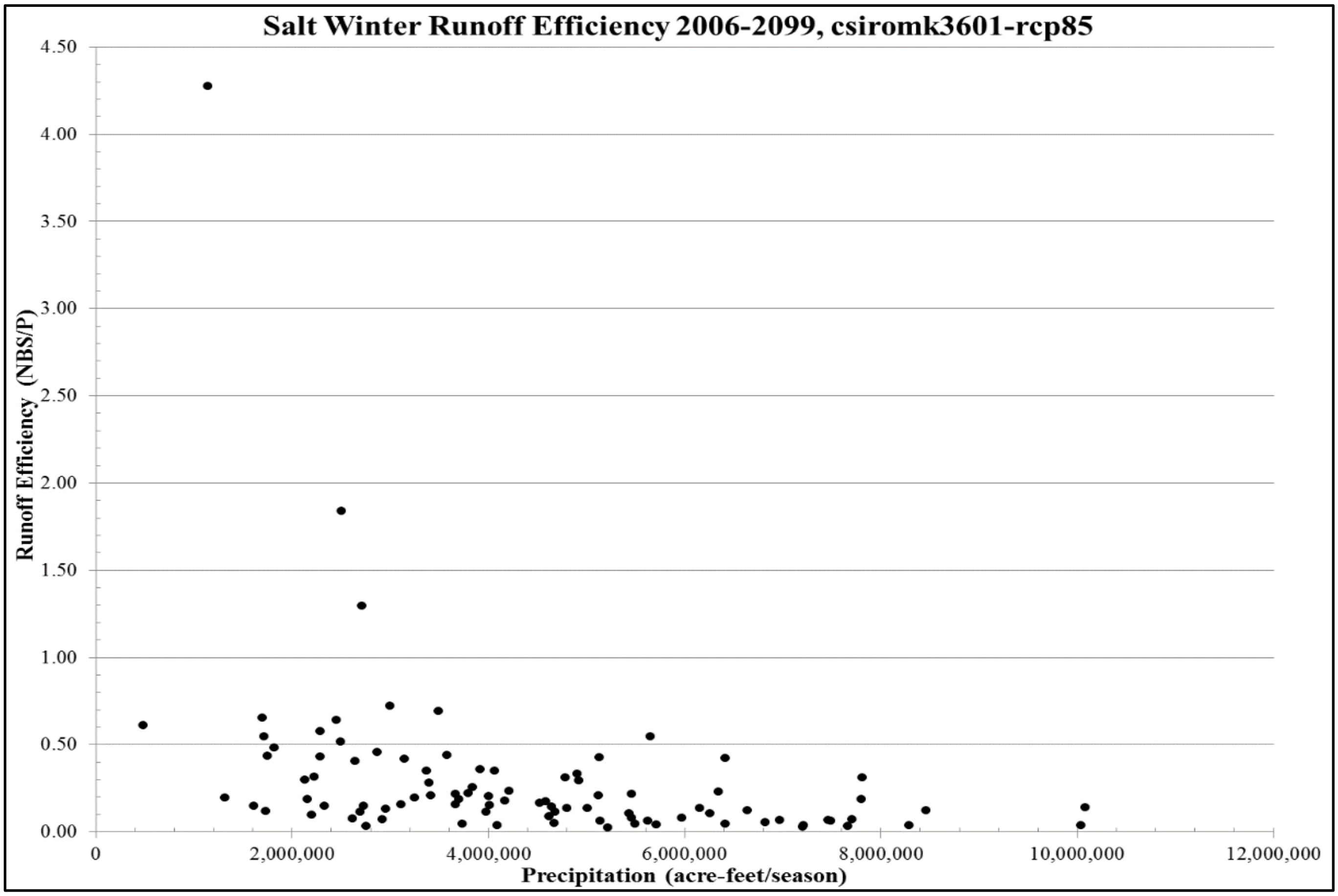

Figure 5-24: Model csiromk3601-rcp85, projection period, Salt runoff efficiency

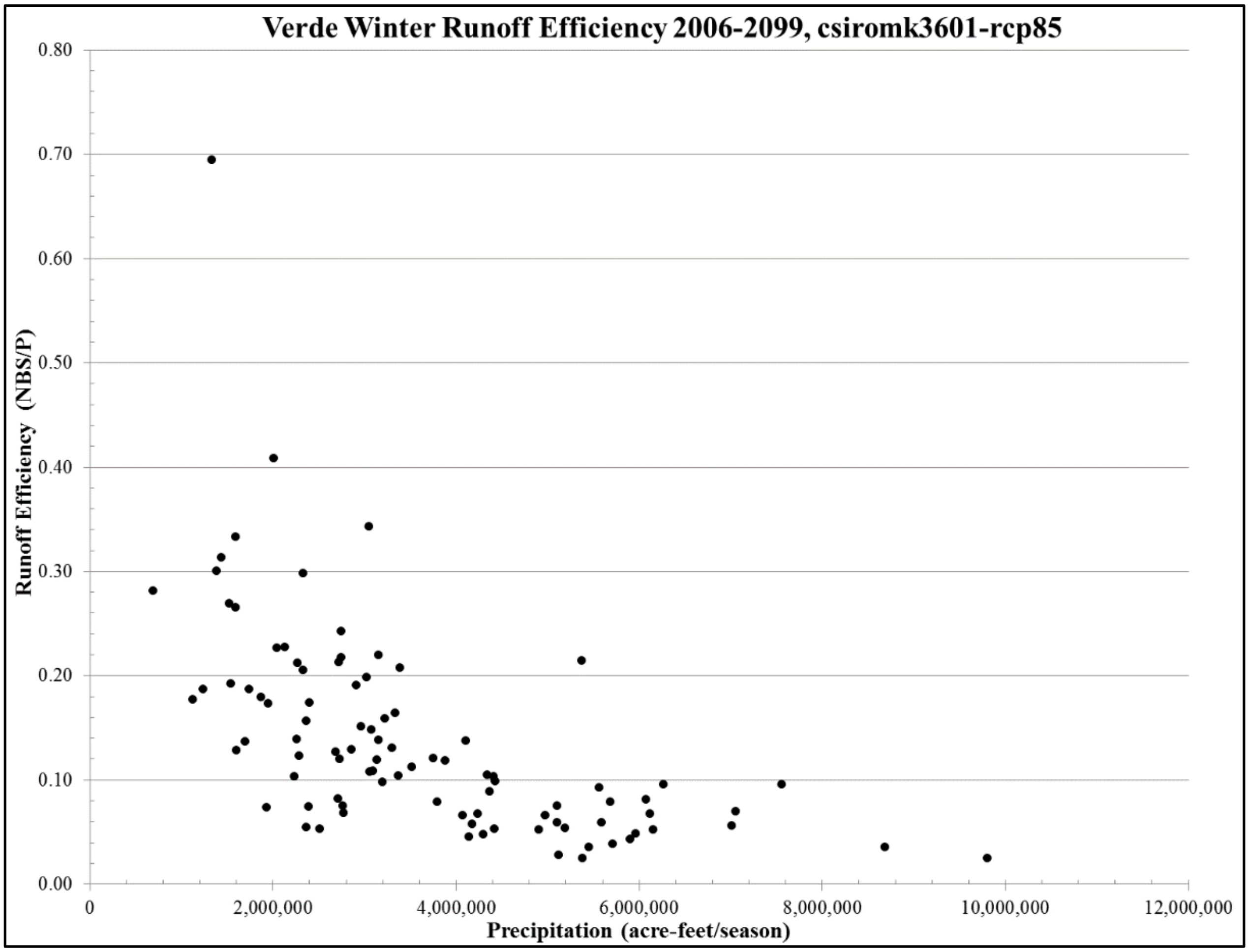

Figure 5-25: Model csiromk3601-rcp85, projection period, Verde winter runoff efficiency

5.5.4 Analysis of Reservoir Planning Model Output for Historic Period

All inflow time series from the 64 downscaled models and VIC hydrology were run through the RPM with the input as described in Section 3.3.2.1: Monthly Time Step Reservoir Planning Model. The results of those 64 RPM runs were compared against the results from the historical period defined as the inflow from 1951 through 2016 (Table 5-6). The variables which were chosen for this comparison were: median inflow from October 1 through April 30, System spill years, Verde River reservoir system spill years only (no spill from the Salt River reservoir system), years of minimum pumping, accumulated spill volume, median December 31 total storage (before runoff season starts) and median April 30 total storage (end of the runoff season). Also included in the table (first row) is the observed record as recorded by SRP. However, during this period SRP's service area transitioned from mainly agricultural (until the late 1980s) to almost totally urban. When the service area was mainly agricultural, water resources planning was different from planning with a more urban use demand pattern (Phillips et al., 2009).

The winter season period from October 1 through April 30 was used rather than the water year or calendar year to compare historical with modeled inflow. It was found that the VIC-modeled summer inflow was erroneously high. To work around this problem the median historical inflow was used for the period from May 1 through September 30. Hence, for all models the inflow is the same from May 1 through September 30. As is shown in Table 5-6, the median inflow from October 1 through April 30 for all 64 models was higher than the historical median for that same period (ranging from 65 to 479 KAF higher). Higher inflows will result in higher total reservoir storage. Two measures of median reservoir storage are included in Table 5-6: December 31 and April 30. As can be seen, the median storage for all 64 models for those two dates is higher than the modeled median storage using the historical (instrumental) record. This has consequences for the amount of groundwater pumping which is required to satisfy the SRP demand. Total storage higher than 1,500 KAF results in the model determining that only minimum pumping is required (refer to Figure 3-7, the Storage Planning Diagram).

All 64 modeled inflow time series produce more than 33 years of minimum pumping in the historical 65 years. Thus, in 50 percent or more of years, minimum pumping is required. The baseline historical results show 25 out of the 65 years, or 38 percent of the years require minimum pumping.

As expected, higher median inflow results in higher reservoir storage which may result in more spill years. As found, 60 out of the 64 models showed a higher number of System spill years (either from the Salt or Verde River or both). However, the cumulative amount of spill (cumulative over the 65 years of simulation) is a mixed bag. Spill amounts can be higher or lower than the spill amount from the historical (baseline) run. Despite the collective bias in the 64 simulations toward more frequent spill events and higher storage, 39 of 64 simulations (61 percent) display less total spill during the historical period than the historical (baseline) run, which resulted in a cumulative spill amount of 18,217 KAF.

Years that only the Verde River reservoir system spills are also included in Table 5-6. While the Verde River watershed produces about 40 percent of the inflow to the System, there is an imbalance in storage between the Verde River and Salt River reservoirs. The Verde River reservoir system is about 12 percent of the total conservation storage capacity. The historical (baseline) record showed six years with spill only from the Verde River reservoir system. The 64 models showed the number of Verde River reservoir system spill years ranging from three to 16 years, with 47 models (73 percent) showing more Verde-only spill years than the historical (baseline) record.

Table 5-6: RPM results for the USGS record and the 64 inflow simulations for the historical period (1951 - 2016) (rows are in ascending order based on the number of years with minimum pumping.)

Model	Median Inflow (Oct 31-Apr 30) [KAF]	System Spill Years	Verde Only Spill Years	Min. Pumping Years	Accumulated Spill Volume [KAF]	Median Dec 31 Storage [KAF]	Median April 30 Storage [KAF]
Observed	589	24	5	16	16,284	1,133	1,467
Historic USGS RPM (baseline)	589	25	6	25	18,217	1,535	1,894
CANESM2_1_RCP45	745	27	7	33	13,533	1,691	2,047
CANESM2_1_RCP85	770	26	6	34	14,549	1,691	2,057
BCC-CSM1-1_1_RCP85	654	25	4	35	13,480	1,642	1,962
MIROC5_1_RCP45	779	28	6	35	20,304	1,748	2,189
CESM1-CAM5_1_RCP45	868	32	7	36	18,806	1,753	2,239
CESM1-CAM5_1_RCP85	855	27	5	37	13,279	1,753	2,198
ACCESS1-3_1_RCP85	781	25	7	38	12,602	1,738	2,140
BCC-CSM1-1-M_1_RCP85	897	35	16	38	14,686	1,739	2,191
BCC-CSM1-1_1_RCP45	782	29	5	38	14,945	1,730	2,061
BCC-CSM1-1-M_1_RCP45	858	36	15	39	17,785	1,739	2,160
CMCC-CMS_1_RCP85	833	29	3	39	12,424	1,751	2,150
GFDL-ESM2G_1_RCP85	816	29	11	40	13,435	1,758	2,060
GFDL-ESM2M_1_RCP45	750	27	5	40	10,237	1,755	2,075
MIROC5_1_RCP85	771	30	7	40	22,947	1,770	2,194
MRI-CGCM3_1_RCP45	781	31	4	40	18,771	1,772	2,203
MRI-CGCM3_1_RCP85	881	33	5	40	18,761	1,784	2,256
ACCESS1-3_1_RCP45	830	29	9	41	13,915	1,758	2,164
CESM1-BGC_1_RCP85	820	28	6	41	12,599	1,752	2,100
CESM1-BGC_1_RCP45	829	30	8	42	16,245	1,775	2,100
HADGEM2-AO_1_RCP85	861	32	8	42	15,248	1,786	2,169
HADGEM2-ES_1_RCP45	914	34	10	42	16,264	1,770	2,141
HADGEM2-ES_1_RCP85	898	34	10	42	16,264	1,770	2,141
GFDL-ESM2G_1_RCP45	838	32	12	43	13,661	1,769	2,123
GFDL-ESM2M_1_RCP85	764	30	5	44	10,865	1,764	2,122
MIROC-ESM-CHEM_1_RCP85	846	36	9	44	18,834	1,794	2,235
NORESM1-M_1_RCP85	837	33	10	44	19,897	1,808	2,185
ACCESS1-0_1_RCP45	733	25	4	45	17,730	1,728	2,022
ACCESS1-0_1_RCP85	760	25	4	45	17,730	1,743	2,083
CMCC-CMS_1_RCP45	819	29	5	45	12,124	1,762	2,182
CNRM-CM5_1_RCP85	757	32	7	45	14,819	1,759	2,161
CSIRO-MK3-6-0_1_RCP85	776	34	4	45	23,924	1,802	2,182

Model	Median Inflow (Oct 31-Apr 30) [KAF]	System Spill Years	Verde Only Spill Years	Min. Pumping Years	Accumulated Spill Volume [KAF]	Median Dec 31 Storage [KAF]	Median April 30 Storage [KAF]
FGOALS-G2_1_RCP45	864	27	7	45	11,726	1,754	2,118
FGOALS-G2_1_RCP85	863	30	8	45	15,324	1,749	2,119
GFDL-CM3_1_RCP85	791	34	8	45	21,359	1,795	2,201
GISS-E2-H_2_RCP85	844	28	4	45	12,023	1,757	2,149
GISS-E2-R_6_RCP45	761	29	8	45	12,622	1,764	2,164
IPSL-CM5A-MR_1_RCP45	835	32	11	45	15,416	1,777	2,099
MPI-ESM-LR_1_RCP85	836	34	11	45	19,127	1,780	2,206
CNRM-CM5_1_RCP45	824	33	5	46	20,256	1,766	2,157
GISS-E2-R_2_RCP85	733	30	8	46	11,667	1,767	2,157
HADGEM2-AO_1_RCP45	873	33	10	46	15,080	1,811	2,234
MIROC-ESM-CHEM_1_RCP45	851	36	10	46	21,062	1,786	2,242
MPI-ESM-MR_1_RCP85	897	33	5	46	20,785	1,767	2,153
NORESM1-M_1_RCP45	838	35	10	46	18,212	1,813	2,191
GFDL-CM3_1_RCP45	816	35	9	47	20,688	1,796	2,201
GISS-E2-H_6_RCP45	837	29	3	47	14,116	1,755	2,151
MPI-ESM-LR_1_RCP45	836	35	10	47	18,541	1,798	2,221
CSIRO-MK3-6-0_1_RCP45	847	34	4	48	22,778	1,820	2,209
IPSL-CM5A-MR_1_RCP85	828	35	12	48	16,955	1,794	2,130
CCSM4_6_RCP45	900	36	7	49	21,944	1,794	2,253
CCSM4_6_RCP85	891	32	6	49	24,187	1,784	2,210
HADGEM2-CC_1_RCP45	862	40	12	49	17,772	1,789	2,223
INMCM4_1_RCP45	868	37	10	49	14,967	1,821	2,226
INMCM4_1_RCP85	889	42	11	49	19,685	1,811	2,231
MPI-ESM-MR_1_RCP45	954	37	6	49	24,092	1,822	2,276
CMCC-CM_1_RCP85	775	36	10	50	16,771	1,756	2,118
EC-EARTH_2_RCP85	976	36	6	50	26,171	1,814	2,264
IPSL-CM5A-LR_1_RCP85	979	38	7	51	29,956	1,810	2,258
MIROC-ESM_1_RCP45	792	28	11	51	12,974	1,730	2,122
MIROC-ESM_1_RCP85	826	28	11	51	12,974	1,730	2,122
CMCC-CM_1_RCP45	826	37	8	52	16,502	1,779	2,199
EC-EARTH_8_RCP45	1,068	39	6	53	29,133	1,814	2,274
HADGEM2-CC_1_RCP85	886	45	16	53	18,633	1,803	2,249
IPSL-CM5A-LR_1_RCP45	907	39	8	53	33,873	1,818	2,247

Blue cells are wet future simulations
Orange cells are dry future simulations

The bias toward higher storage in the simulations is likely the result of the substantial wet bias in the middle and lower percentiles in all 64 simulations (Figure 5-17). This higher storage bias results in substantially more frequent minimum pumping years and more spill events in the 64 simulations relative to the historical (baseline) record, but not in a cumulative higher spill volume (Table 5-6). This can be explained by the bias in most of the 64 simulations toward less inflow in the upper percentiles (Figure 5-17).

Six models from the 64 downscaled models were chosen for additional research. They are highlighted in Table 5-6 (blue cells are future wettest simulations and red cells are future driest simulations). The driest simulations consistently displayed 5-year to 30-year periods in the future that had less total System inflow than the USGS record. Similarly, the three wettest simulations displayed 5-year and 30-year periods in the future that had more total inflow than the USGS record (Table 5-5, models listed in *Italics*).

The total reservoir storage for dry simulations and wet simulations for the historical period are shown in Figures 5-26 and 5-27, respectively. There is only one month during the historical period out of all six simulations when storage is below 700 KAF, 100 KAF above the reduced allocation threshold of 600 KAF. In contrast, there are 18 months when storage is below 700 KAF for the historical (baseline) record, and five months when the storage is below 600 KAF. In general, storage appears to remain above 800 KAF even for periods of drought for the six simulations.

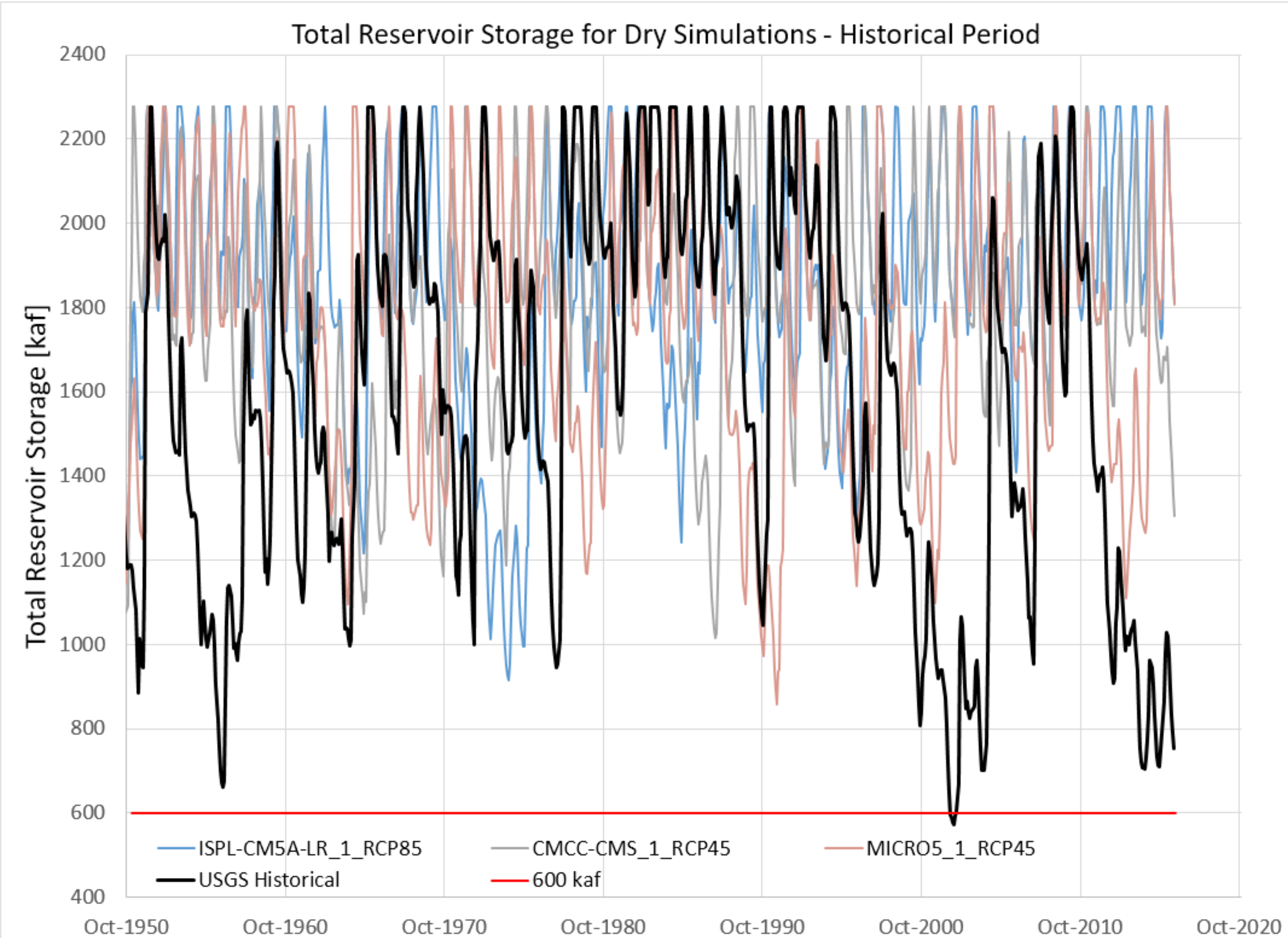

Figure 5-26: Total system storage for the three driest simulations from 1951 – 2016

In summary, observed streamflow records and modeled streamflow time series were input into the same model for reservoir operations (i.e., the RPM). With operational procedures held constant in the comparison of RPM output, it is evident that the biases in the streamflow distributions displayed in Figure 5-17, are also seen in the RPM results. The simulation wet biases in the middle and lower percentiles result in higher storage and more years of minimum groundwater pumping. Spill events are also frequent but total spill volumes are not greater, a result of the low bias for the upper streamflow percentiles.

5.5.5 More Detailed RPM Analysis for Six Selected Simulations – for the Future Period

Results of the RPM simulations using the inflow from the six selected models (see Table 5-6) for the future period, 2035-2099, are shown in Tables 5-7 and 5-8 for two demand simulations, 800 KAF and 950 KAF, respectively. Also included in the tables for comparison are the baseline RPM results using the historic inflow (USGS) from 1951-2016 as well as the SRP reported observed operations for that period.

An average demand of 800 KAF is the current and expected future demand on the System. This discussion will focus on the RPM results of the 800 KAF demand simulation compared with the historical (USGS) inflows, unless stated otherwise. It is important to note that operations as recorded by SRP during the historical time period, especially from 1951 through the 1980s, were drastically different than reservoir operations today. RPM using the historical inflows, with the current reservoir configuration, could be one simulation on how the System would behave in the future. Hence, it is used in this discussion to compare against the simulations from the six downscaled models. Given that demand is kept the same, the four important metrics of inflow, total storage, spill, and groundwater pumping, are considered when comparing results of the six simulations.

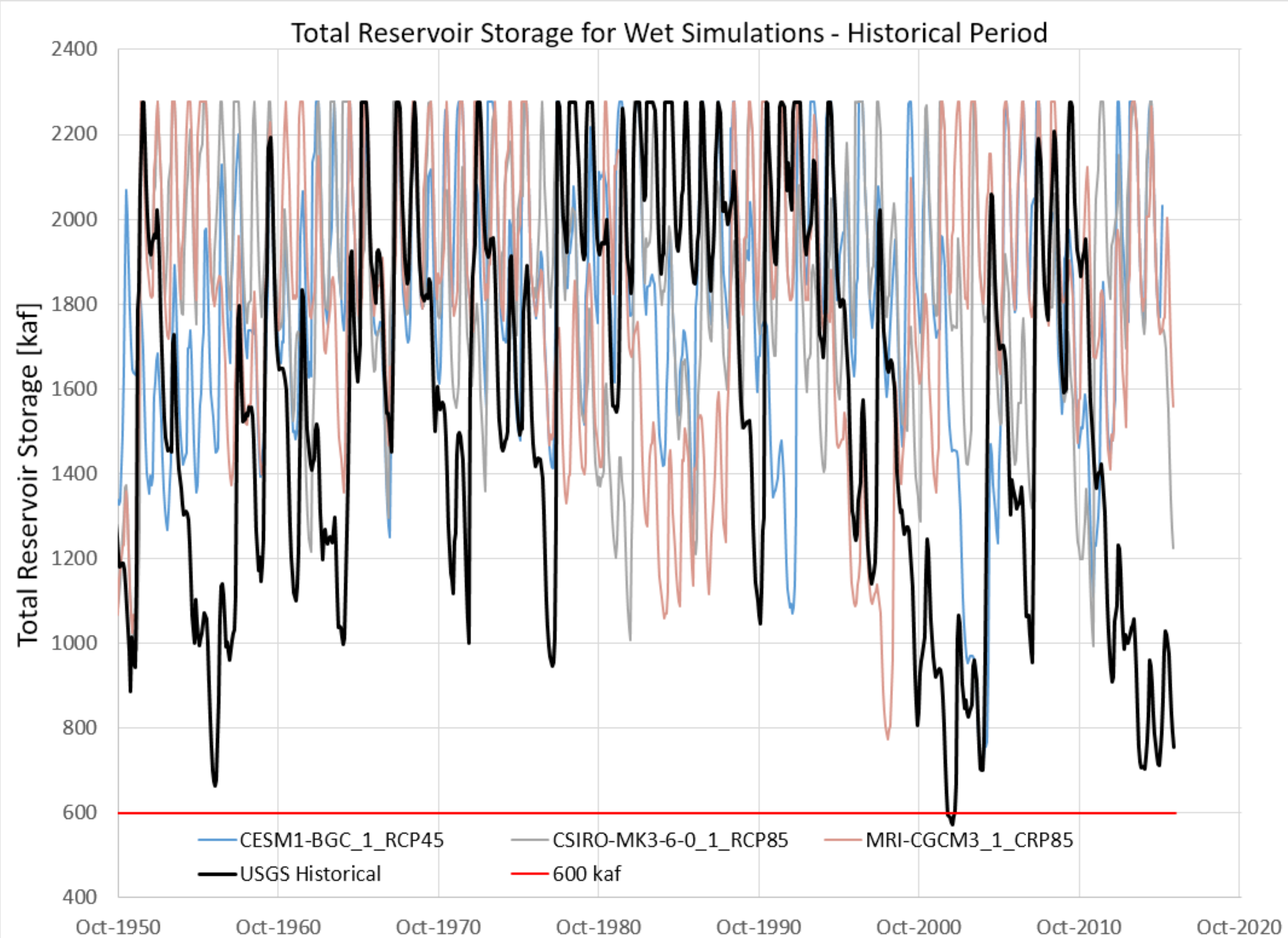

Figure 5-27: Total system storage for the three wettest simulations from 1951 – 2016

5.5.5.1 Wet Simulations

As shown in Tables 5-5 and 5-6, the three wet simulations (cesm1-bgc_1_rcp45, csiro-mk3-6-0_1_rcp85, mri-cgcm3_1_rcp85) have significantly more future inflow when compared to the historical inflow. The January 1 median storage for the wettest simulation (mri-cgcm3_1_rcp85) is 1,796 KAF, compared to 1,535 KAF for modeled historical inflows (Table 5-7). All three wet simulations have higher median storage than observed and modeled historical USGS inflows. Figure 5-28 shows the monthly storage for each wet future simulation and the historical (baseline USGS). SRP sets the water allotment in August/September each year based on estimated storage on January 1. If total reservoir storage is less than 600 KAF on January 1, allocation will be reduced, indicating a severe shortage in water supply. The RPM results using historical (USGS) inflows and observed operations (1951-2016) have at least one year with January 1 storage less than 600 KAF. However, none of the future modeled wet simulations have a year with January 1 storage less than 600 KAF.

While there is a noticeable difference between median storage using the historical (USGS) inflows and future wet simulations, the most obvious differences in the three wet simulations are shown in spilling and pumping metrics. One wet simulation (cesm1-bgc_1_rcp45) has a similar number of spill years on the System compared to modeled historical USGS inflows.

Results from the 'wet' simulations show that the number of Salt spill events range from 11 to 18 more years of spill. One 'wet' simulation resulted in one less year of spill on the Salt River side of the System, but three more on the Verde River side.

The model which resulted in the most spill years on the Salt River and on the Verde River was mri-cgcm3_1_rcp85. It did not show the highest median storage on January 1st nor the greatest average 11-year spill volume (Table 5-7). But another indication in the future of the three wet models was that in 58 out of the 64 years (91 percent of the time) groundwater pumping was at a minimum (Table 5-8). This means that 47 (Verde spill years) out of 64 years (73 percent of the time) there was water spilled in the river. Such a wet future for such a long time does not seem credible.

The most credible wet simulation was cesm1-bgc_1_rcp45, which is still considerably wetter than the historic model, but is more in line with the high variability expected in the Arizona arid climate of the southwest U.S. (Also see the blue line in Figure 5-28.)

Table 5-7: Storage and spill historical observations (1951-2016), RPM results from the historical inflow record (1951-2016) with different demands, and the six inflow simulations during the future period (2035-2099)

Model	Regime	Average Demand [KAF]	Median Storage [KAF]	Jan 1 Storage ≤ 600 KAF [years]	Consecutive Years of Jan 1 Storage ≤ 600 KAF [years]	Salt Spill [years]	Verde Spill [years]	Greatest Average 11-year Spill Volume [KAF]
Observed Operations (1951-2016)	n/a	-	1133	5	2	19	22	717
Historic Inflows with 800 KAF demand (1951-2016)	n/a	844	1535	1	0	19	25	757
Historic Inflows with 950 KAF demand (1951-2016)	n/a	960	1389	4	0	14	22	652
CESM1-BGC_1_RCP45 (2035-2099)	wet	838	1699	0	0	18	25	1153
CSIRO-MK3-6-0_1_RCP85 (2035-2099)	wet	842	1811	0	0	30	37	1102
MRI-CGCM3_1_RCP85 (2035-2099)	wet	852	1796	0	0	37	47	1049
IPSL-CM5A-LR_1_RCP85 (2035-2099)	dry	824	1512	1	0	17	24	572
CMCC-CMS_1_RCP45 (2035-2099)	dry	829	1471	1	0	14	20	716
MIROC5_1_RCP45 (2035-2099)	dry	816	1219	0	0	7	10	515

Table 5-8: **Pumping historical observations (1951-2016), RPM results from the historical inflow record (1951-2016) with different demands, and the six inflow simulations during the future period (2035-2099)**

Model	Regime	Min. Pumping [years]	Average Pumping [KAF]	Max. Pumping [years]	Most Consecutive Years of Maximum Pumping [years]	Pumping ≥250 [years]	Most Consecutive Years of Pumping ≥ 250 [years]	Greatest Average 11-year Pumping Volume [KAF]
Observed Operations (1951-2016)	n/a	16	284	17	9	30	15	468
Historic Inflows with 800 KAF demand (1951-2016)	n/a	25	129	4	2	8	4	196
Historic Inflows with 950 KAF demand (1951-2016)	n/a	15	173	14	5	22	6	262
CESM1-BGC_1_RCP45 (2035-2099)	wet	31	98	0	0	2	2	155
CSIRO-MK3-6-0_1_RCP85 (2035-2099)	wet	49	87	1	1	1	1	157
MRI-CGCM3_1_RCP85 (2035-2099)	wet	58	67	0	0	0	0	70
IPSL-CM5A-LR_1_RCP85 (2035-2099)	dry	31	128	4	3	10	7	259
CMCC-CMS_1_RCP45 (2035-2099)	dry	25	127	5	5	8	7	252
MIROC5_1_RCP45 (2035-2099)	dry	10	171	8	3	17	7	260

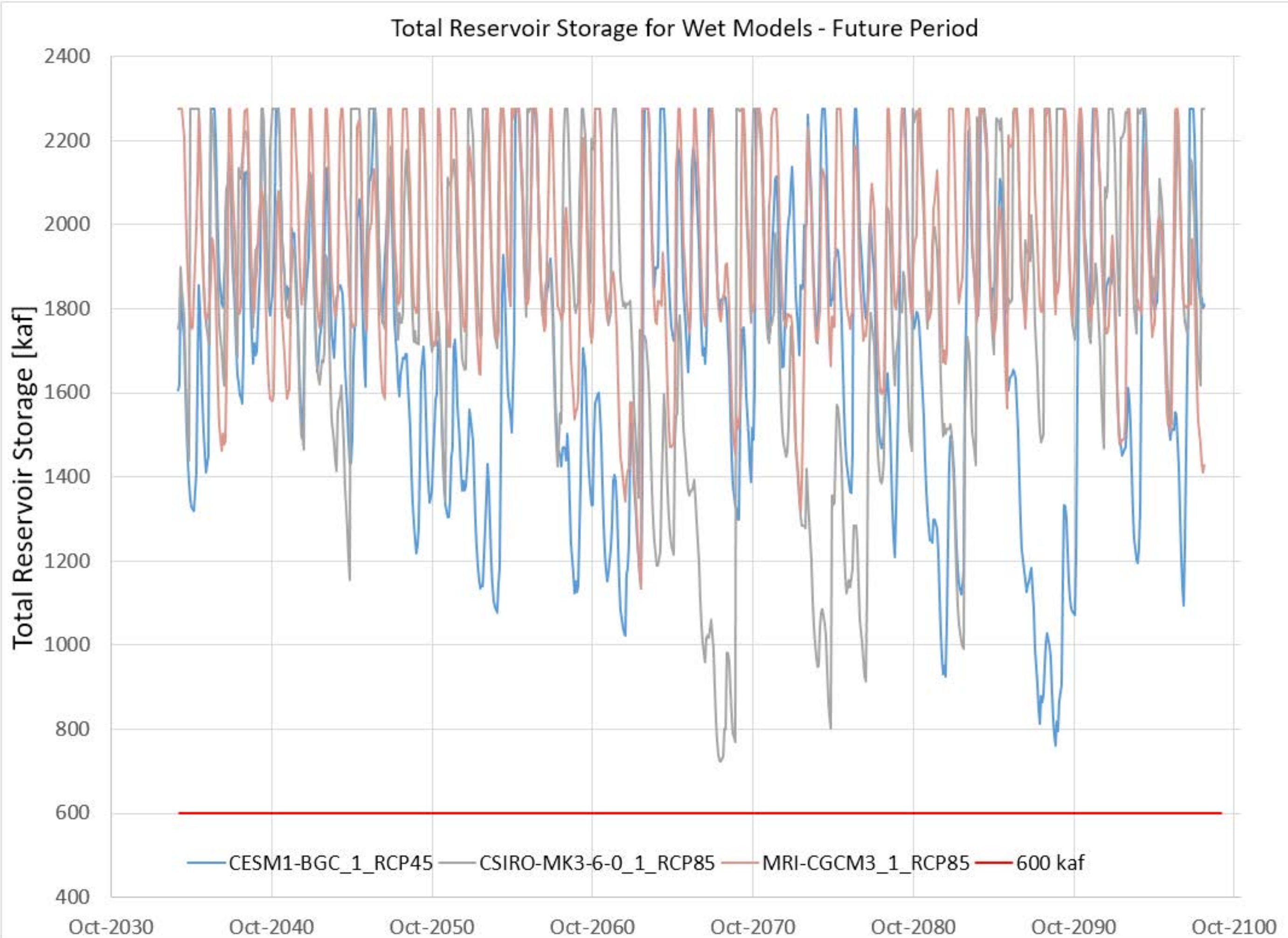

Figure 5-28: Total system storage for the three wettest simulations displayed from 2035 – 2099

5.5.5.2 Probable Maximum Flood

The PMF is the largest hypothetical flood based on the most severe theoretical meteorological and hydrological event/s for a given basin. A key aspect of reservoir operations under wet conditions is being able to manage flood events without compromising the reservoir infrastructure. In the early-mid 1990s the Salt and Verde rivers reservoirs infrastructure received upgrades to manage the PMF. These upgrades included flood control storage on the Salt River system and the addition of auxiliary spillways on the Verde River system. With these modifications, the Salt and Verde systems are currently designed to safely manage their PMFs. The PMF for Roosevelt Lake (Salt River plus Tonto Creek) has a peak release of 654,000 cfs with a 16-day volume of 3,020,000 AF (U.S. Army Corps of Engineers, Water Control Manual, 1997). The PMF for the Horseshoe

Reservoir has a peak release of 562,000 cfs and a 15-day volume of 2,410,000 AF[10]

For this Study, the single wettest event for each of the three climate simulations were calculated and compared against the PMF. For the volumetric portion of the analysis, a ratio of the volumetric period to the winter (Oct-Apr) volumes for the top five flood events in the historic USGS dataset (Table 5-9) was calculated. This ratio was then applied to the largest one year winter volume for the three wet climate simulations. The peak release was then calculated using a ratio derived from the PMF, peak release divided by volumetric period and applied to the calculated volumetric period.

Table 5-9: The five wettest flood events (Instrumental Record) for the Salt and Verde systems

	Verde River	
Date	10-day Volume (AF)	Winter Volume (AF)
3/9/1978	523,000	875,000
2/24/1980	517,000	1,090,000
1/17/1993	502,000	1,550,000
2/24/1927	312,000	571,000
2/21/2005	301,000	1,110,000

	Roosevelt (Salt + Tonto)	
Date	16-day Volume (AF)	Winter Volume (AF)
1/31/1916	1,080,000	2,240,000
1/22/1993	970,000	2,480,000
3/15/1978	768,000	1,320,000
2/29/1980	707,000	1,460,000
2/25/1920	498,000	1,620,000

The results from this analysis indicate that the three wettest climate simulations fall below the PMF and therefore are managed safely through the System (Table 5-10). However, without a knowledge of constraints on downstream infrastructure, it is out of the scope of this study to postulate the effects of a larger PMF on non-SRP agencies and entities downstream of the System. This may be a topic for future research.

[10] Memorandum from Chief, Hydrology Branch to Chief, Concrete Dams Branch (Reclamation) with as subject "*PMF (Probable Maximum Flood) Studies, Verde River Dams, Salt River Project, Arizona.*" May 17, 1988.

Table 5-10: Estimated largest flood events for the three wet climate simulations

		Verde River	
Model	Year	10-day Volume (AF)	Peak Inflow (cfs)
CESM1-BGC_1_RCP45	2071	943,000	220,000
CSIRO-MK3-6-0_1RCP85	2099	823,000	192,000
MRI-CGCM3_1_RCP85	2071	484,000	113,000

		Roosevelt (Salt + Tonto)	
	Year	16-day Volume (AF)	Peak Inflow (cfs)
CESM1-BGC_1_RCP45	2071	2,410,000	531,000
CSIRO-MK3-6-0_1RCP85	2057	1,790,000	394,000
MRI-CGCM3_1_RCP85	2083	1,940,000	427,000

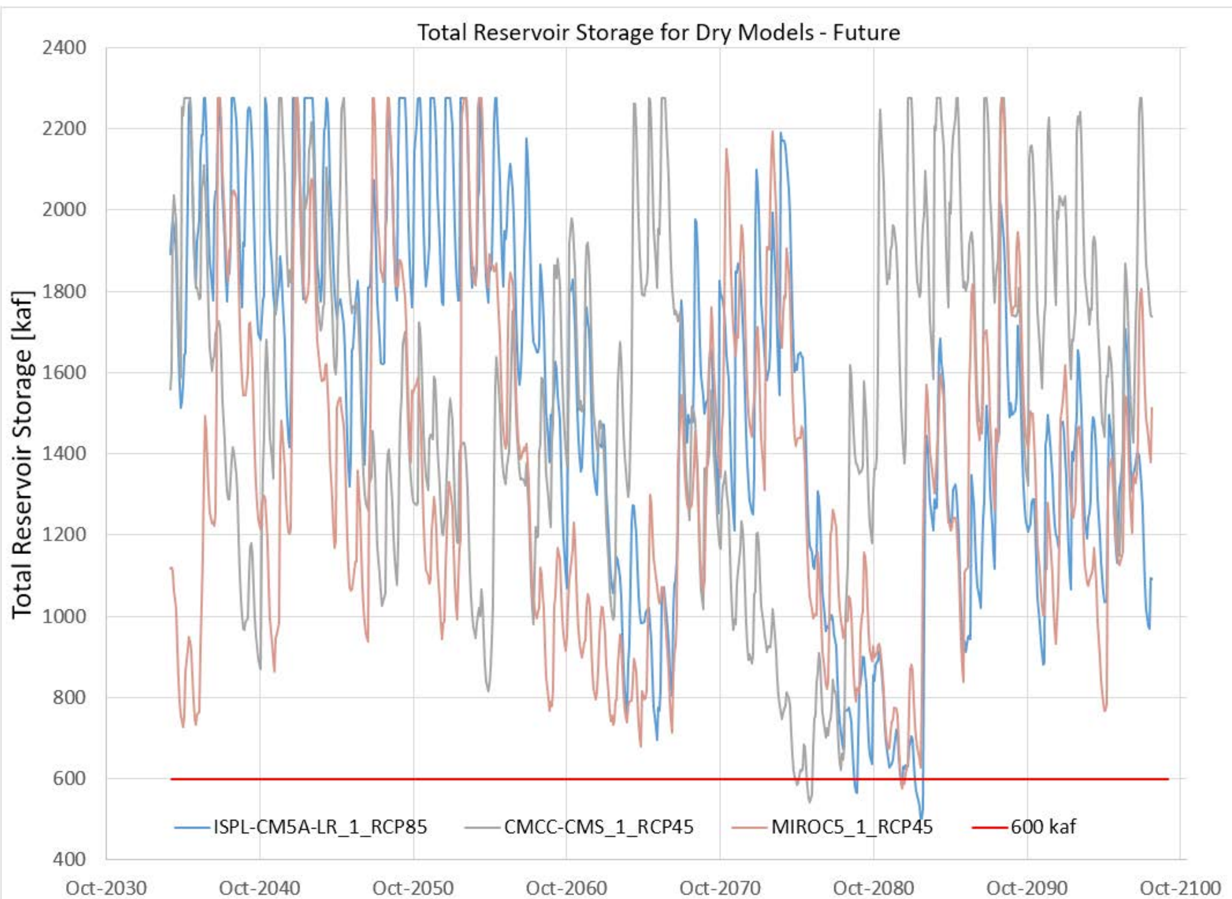

Figure 5-29: Total system storage for the three driest simulations from 2035-2099

5.5.5.3 Dry Simulations

The three dry simulations (ipsl-cm5a-lr_1_rcp85, cmcc-cms_1_rcp45, miroc5_1_rcp45) have less future inflow when compared to the historical (USGS) inflow (Table 5-5 and 5-6). The median storage for the driest simulation (mri-cgcm3_1_rcp85) is 1,219 KAF compared to 1,535 KAF for modeled historical inflows. The third driest simulation, ipsl-cm5a-lr_1_rcp85**,** has similar median storage to modeled historical flows. The monthly total reservoir storage for each dry future simulations show that the lowest total reservoir storage for all three dry model runs occur around year 2080 (Figure 5-29). The duration and magnitude of the lows in reservoir storage are similar to the modeled historical flows in data year 2002 shown in Figure 5-26. Similar to modeled historical inflows, two of the three dry runs also have one year with total January 1 reservoir storage below 600 KAF. All three dry simulations are on average able to deliver the requested demand for water. The dry simulations all show expected variability in reservoir storage because of variability on inflows (see Figure 5-29).

One dry simulation (ipsl-cm5a-lr_1_rcp85) has a similar number of spill years on the Salt and Verde system when compared to modeled historical inflows. Simulation cmcc-cms_1_rcp45 has five fewer years with spill on the Salt and Verde system than the modeled historical USGS inflows. Simulation ipsl-cm5a-lr_1_rcp85 has more than half as many spill years on both the Salt (7 spills) and the Verde (10 spills). Average annual pumping volumes are similar to modeled historical inflows for two of the three dry simulations. However, one simulation (miroc5_1_rcp45) has over 40 KAF/year more average annual pumping than modeled historical inflows. The same trend holds true for this simulation in most consecutive years of maximum pumping, pumping years greater than 250 KAF, and greatest average 11-year pumping volume. These trends indicate that the model miroc5_1_rcp45 is the most credible of a dry future and could put a greater stress on the System than the model which used the historical (USGS) inflows.

5.5.5.4 Discussion

As will be discussed in Section 6.2.3: Definition of Hydrologic Drought for the System, the number of continuous years with NBS below median is an appropriate definition of hydrologic drought applicable to this System, with a drought ended by a year of NBS above median. For this study that criterion is 850,000 AF/year.

Continuous years of hydrologic droughts were determined for the observational record, historical modeled and future modeled inflows for the three wet and three dry simulations. Table 5-11 shows the results of this analysis. The maximum drought period increased in miroc5_1_rcp45 between the historical (4 years maximum) and projection period (10 years maximum) because the precipitation series is nonstationary with a down-trend is shown in Figure 5-10. Conversely, model mri-cgcm31_rcp85 has the maximum drought period decreasing between the historical (maximum 6 years) and projection period (maximum 3 years) because the precipitation series is nonstationary with an up-trend shown in Figure 5-11. Due to the biases in the simulations (Figure 5-17), it is uncertain whether the hydrologic drought analysis from the models are a reliable expectation of the future. However, the baseline analysis does represent expected system reliability from the USGS historical record. The system has sustained two periods of 6-year hydrologic drought in the recent past: 1999 - 2004 and 2011 - 2016.

Table 5-11: Comparison of hydrologic drought in baseline and six downscaled models

Inflow Series	Historical (1951-2005) Maximum Continuous years in Drought*	Future (2006-2099) Maximum Continuous years in Drought*
USGS (Baseline)	6	n/a
IPSL-CM5A-LR_1_RCP85 (Dry)	5	8
CMCC-CMS_1_RCP45 (Dry)	3	8
MIROC5_1_RCP45 (Dry)	4	10
CESM1-BGC_1_RCP45 (Wet)	3	7
CSIRO-MK3-6-0_1_RCP85 (Wet)	4	5
MRI-CGCM3_1_RCP85 (Wet)	6	3

*Hydrologic drought defined as inflow < 850 KAF/WY

RPM results indicate that the System will on average not experience water shortages from the three wet future simulations. More spill and less pumping would result in less stress on the system for these wet simulations. This will not pose any problems to the operation of the System (except for not having enough storage to capture most of the runoff), but more spill and less pumping may present different problems downstream. Typically infrastructure in the desert is built to handle drier conditions. Less groundwater pumping in a wetter future may also be more challenging for the downstream users.

RPM results indicate there is only one dry simulation (miroc5_1_rcp45) that may stress the operation of the System more than modeled historical inflows. However, total monthly reservoir storage for this simulation is very comparable to storage for modeled historical inflows, and the lowest storage found is just below the 600 KAF, occurring only once. SRP’s current reservoir operations methodology as described in Philips et al. (2009) adequately manages the driest future simulations modeled.

While it appears the System adequately handles the driest future model simulations, the wet bias in the lower percentiles (Figure 5-17) identified in the models for the historical time period is concerning and must be considered. The presence of a wet bias in the simulations' historical inflows suggests that the driest future simulations should actually be drier than modeled. Drier simulations could greatly stress the System. To further analyze how the system could be more stressed, the downscaled data sets and derived hydrology must be improved. The dry bias in the upper percentiles of inflows (Figure 5-17) must also be considered when interpreting results from the three wet simulations. The wettest years and months may actually be wetter than modeled and spill volumes in the future may be underestimated with the current data set. The monthly resolution of the RPM also makes it challenging to quantify changes in spill events. Spill volumes on the Verde River side of the System, with its much lower capacity, are sensitive to daily events. The work presented in Appendix A suggests that the March 1 water equivalent of the snowpack declines in the future over nearly the entire basin, with the most notable declines occurring in the East Verde, Oak, and Sycamore Creek sub-basins of the Verde River. Given that this decrease was present in both the wet and dry future simulations, it is likely that snowfall to rainfall ratios will decrease in the future, contributing to larger daily runoff totals during precipitation events. The likely underestimation of future spill volumes is problematic because spill operations have substantial impacts on systems downstream of the Granite Reef Diversion Dam. In summary, the bias in the inflows of all the simulations must be corrected if they are to adequately analyze and form the basis from which to recommend future adaptations to operations of the System.

Simulating hydrology in arid regions like the Salt-Verde watershed present challenges given the often intermittent flows experienced by some streams, and the sensitivity of streamflow to small, intense precipitation events. Hydrology models like VIC often struggle to accurately represent these dynamics, even when the model is calibrated, and this also makes the models sensitive to the quality of the input data (precipitation and temperature).

An issue facing gridded datasets (Livneh et al., 2015) is the tendency to distribute what would otherwise be an intense and local rain event over a larger area, which then produces a different hydrologic response from what was observed. In arid regions, which may see little precipitation otherwise, spreading this precipitation across a larger area can result a majority of it being lost to infiltration or evaporation in a hydrology model rather than generating runoff that subsequently turns into streamflow.

A challenge facing hydrology models stems from the methods used to estimate the additional required meteorological inputs when only minimum temperature, maximum temperature, precipitation, and wind speed are provided. These additional meteorological inputs include shortwave and longwave radiation, relative humidity, and vapor pressure. Bohn et al. (2013) have shown that the Mountain Climate Simulator scheme used by VIC for estimating these impacts have large biases in arid regions. The calibration and bias-correction approaches used in the study seek to address these challenges and produce streamflow relevant for examining future impacts to water management, but still did not yield satisfactory results. Future efforts should focus on developing more adequately downscaled precipitation datasets with a particular focus on reducing the positive bias in summer precipitation. Precipitation datasets with the reduced bias should be used as input into a given hydrologic model (e.g., VIC) prior to calibration. Bias-correction of hydrologic model output independent of the bias-correction of precipitation data input should be avoided.

6. PERIOD CHANGE METHODOLOGY

6.1 Description

This section outlines the period change methodology that has been utilized in study of the SRP System with its current configuration and operating guidelines, and reports results for the System's ability to deliver water to its service area for the balance of this century. The following schematic outlines how key elements of the period change methodology were employed for the study.

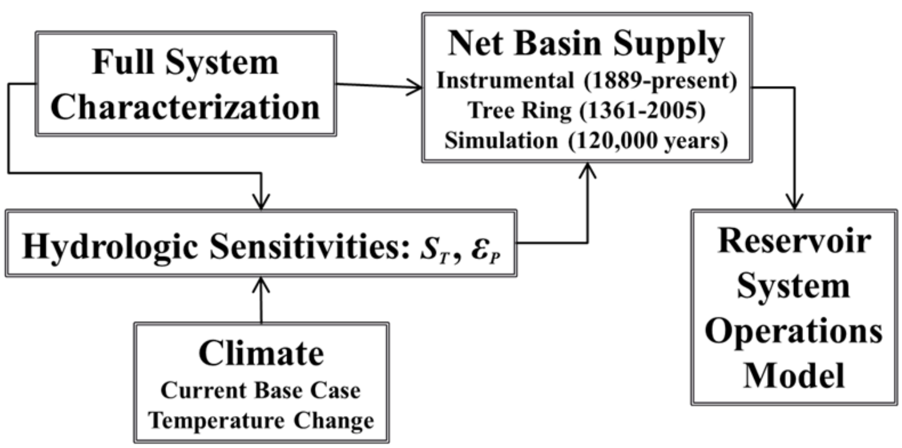

Figure 6-1: Elements of the period change research methodology

The methodology builds upon a full system characterization from the entirety of its historical record which dates from the late 19th century. The SRP System is fortunate in having one of the longest instrumental records available for watersheds in the western United States for that purpose. Some characteristics of the System are provided in the historical performance section of this report.

Three data sets of seasonal NBS of surface water have been established and employed for study:

(i) The observed record of instrumental data since 1889
(ii) A paleoclimate reconstruction from tree ring records since the mid-14th century
(iii) A stochastic simulation developed from detailed statistical characterization of the watersheds

Each of the NBS time series were passed through a reservoir system operations model to establish the current System's cumulative response with probabilistic characterizations serving as the base case against which climate change impacts are measured.

Evidence of historical hydrologic response in the observational record was utilized to establish hydrologic sensitivity algorithms for each watershed-season. Climate change projections of temperature and precipitation to a future time period are translated through the algorithms to generate modified NBS time series. Those are also passed through the reservoir operations model to arrive at measures of impact on operational metrics in comparison to the current system. Detailed probabilistic assessments of the future state in comparison to the current system identify the drivers of resource vulnerability, differentiate natural variability from the impacts of climate change, and support risk-based decision making. All elements of the methodology have been employed in previous research and are grounded in observational evidence.

6.2 Net Basin Surface Water Supply

Runoff volume data for the Verde and Salt rivers and Tonto Creek were sourced from the archive of the USGS daily streamflow data (USGS-NWIS). The measuring gauges are located just above the first point of interception in each river as an input to a reservoir, capturing the flow originating upstream. Data acquisition began in 1913 for each location. Additionally, SRP produced a reconstruction of monthly streamflow back to 1889 (Sands, 1979). That record includes the drought of 1898-1904 on the Salt-Verde watershed and therefore has been included in characterization of the range of hydrologic conditions on the basins. The reconstructed data from 1889 together with gauge data since 1913 are considered to be the instrumental record for study purposes.

There are important miscellaneous losses and gains of water at the reservoirs which affect water storage and supply. Losses can be due to evaporation and interactions between surface and sub-surface water in the proximity of the reservoirs. As well, during some periods of high precipitation and runoff the reservoirs can experience gains larger than the loss mechanisms due to combinations of direct precipitation on reservoirs, ungauged ephemeral streams, overland flow bypassing a stream gauge, streambed modifications, or gauge calibration performance. The net loss or gain of water is quantified by the difference between reservoir inflows and releases compared to storage changes over a time period.

NBS of available surface water is equivalent to runoff measured at the reservoir input gauges less miscellaneous loss at the reservoirs and provides the measure of water that can be made available to the service area's distribution system.

6.2.1 Net Basin Supply per Tree Ring Data Records

A set of tree-ring cores were collected in 2005 by researchers at the University of Arizona's Laboratory of Tree-Ring Research to supplement an existing archive and develop an annual streamflow reconstruction of the Salt-Verde watershed supplying the SRP System from the mid-14th century to 2005 (Hirschboeck and Meko, 2005, 2008). This provided a comparison to the drought of the late-1990s and early 2000s, placing it in the long-term historical context linked to climate variability. The tree ring data set in comparison to the instrumental record was analyzed to obtain adjustments correcting effects of tree ring data transformations during streamflow reconstruction and establish a 645-year (1361 to 2005) runoff time series (see Murphy and Ellis, 2019). While 2002 was found to be a single-year low-flow extreme in the reconstructed record (ring absent in 60% of tree cores), several droughts more severe than that one were found in the long-term record. Hirschboeck and Meko also examined the degree to which variations in seasonal precipitation could be identified by examination of partial-ring-width measurements in tree ring earlywood and latewood to provide information on seasonality of the streamflows. Estimates of System losses were then applied to obtain a NBS reconstruction of surface water availability.

6.2.2 Simulated Time Series of Net Basin Supply

The streamflow record of the Salt-Verde watershed dating from 1889 is one of the longest for rivers in the western United States and provides a useful data set for several research questions. However, it is only one rendition of flow sequences which could have occurred and which may develop in the future. Detailed risk assessments of system performance can require much longer time series for probabilistic analyses and even the tree-ring data set is too limited a time series for those purposes.

A solution lies in generating long synthetic runoff time series by Monte Carlo simulation (Salas et al. 2006; Zagona et al. 2001) to render the full range of flow representations which capture all possible outcome sequences with associated probabilities. A methodology was developed for the Salt-Verde watershed based in the 127-year record and that represents covariance of flow contributions from the dual watersheds with joint probability distributions and highly skewed discrete density functions characteristic of their unique seasonal behaviors and season-to-season correlations. A dozen representative 10,000 year time series were stochastically generated with the methodology that reflect the full range of temporal variability in NBS of the current System, sufficient for detailed probabilistic risk assessments of relevant management variables over 120,000 years of simulated data.

Each watershed-season's probability distribution is shown in Figure 6-2. All are highly skewed, and it is readily apparent that water supply during the winter season is of primary importance to system sustainability. An occurrence of a wet winter from the upper tail of distributions can readily replenish a significant amount of the System's 2,300,000 AF reservoir storage capacity.

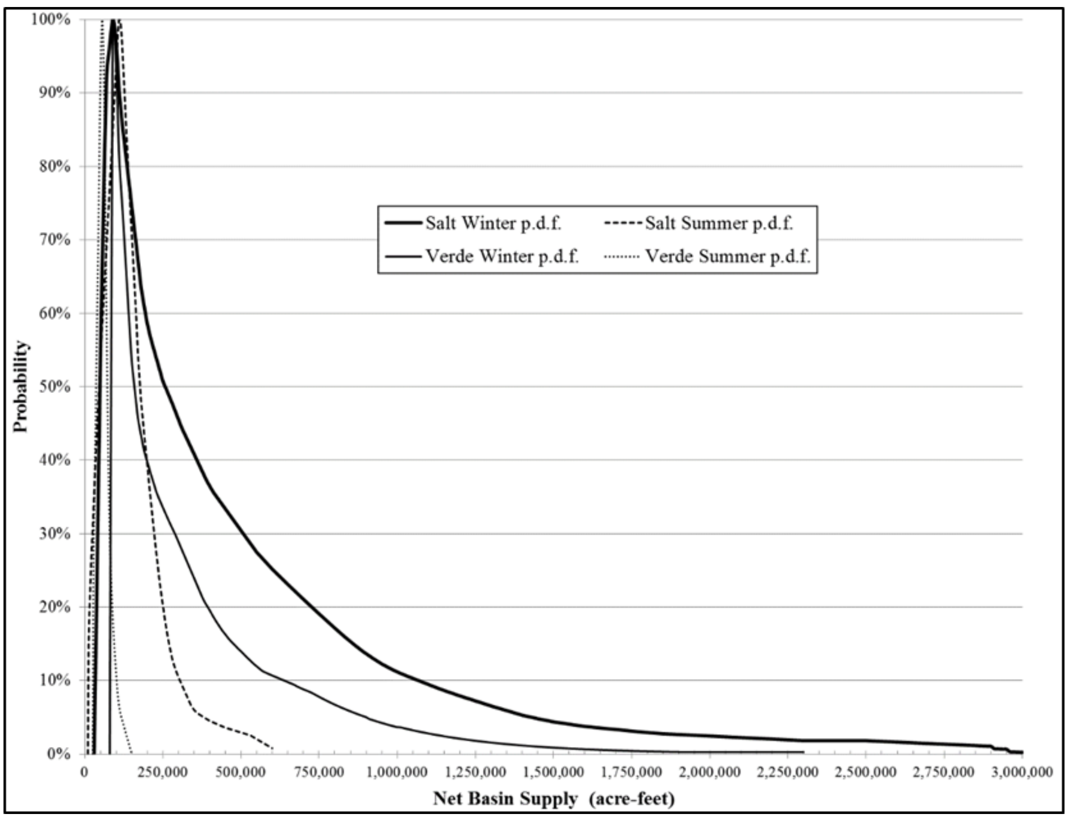

Figure 6-2: Probability density functions of each watershed-season

6.2.3 Definition of Hydrologic Drought for the System

The total annual NBS probability distribution is given in Figure 6-4. While average annual NBS approaches 1.2 million AF/year, the median of the current System is lower in the skewed distribution at approximately 850,000 AF/year. Additionally, the SRP groundwater delivery system operates at a minimum pumping rate of 50,000 AF/year (and is self-limited at 325,000 AF/year; Phillips et al. 2009). So, median surface water NBS supplemented by minimum pumped groundwater can therefore sustain 900,000 AF of annual water deliveries from the System over the long term based upon the statistical character of surface water supply. That value is also the average annual water delivered for the years 2003-2011 (Figure 6-3). In this regard the watersheds are well-matched to the demands placed on the System. Any delivery reductions from that level readily benefit reservoir storage because the probability of reservoir inflows sufficient to sustain the System is enhanced when withdrawal volumes are below the median of the skewed NBS probability distribution. The primary demand level analyzed in this study is therefore 900,000 AF/year, along with the more recent (2012-2017) average demand of 800,000 AF/year (Figure 6-3).

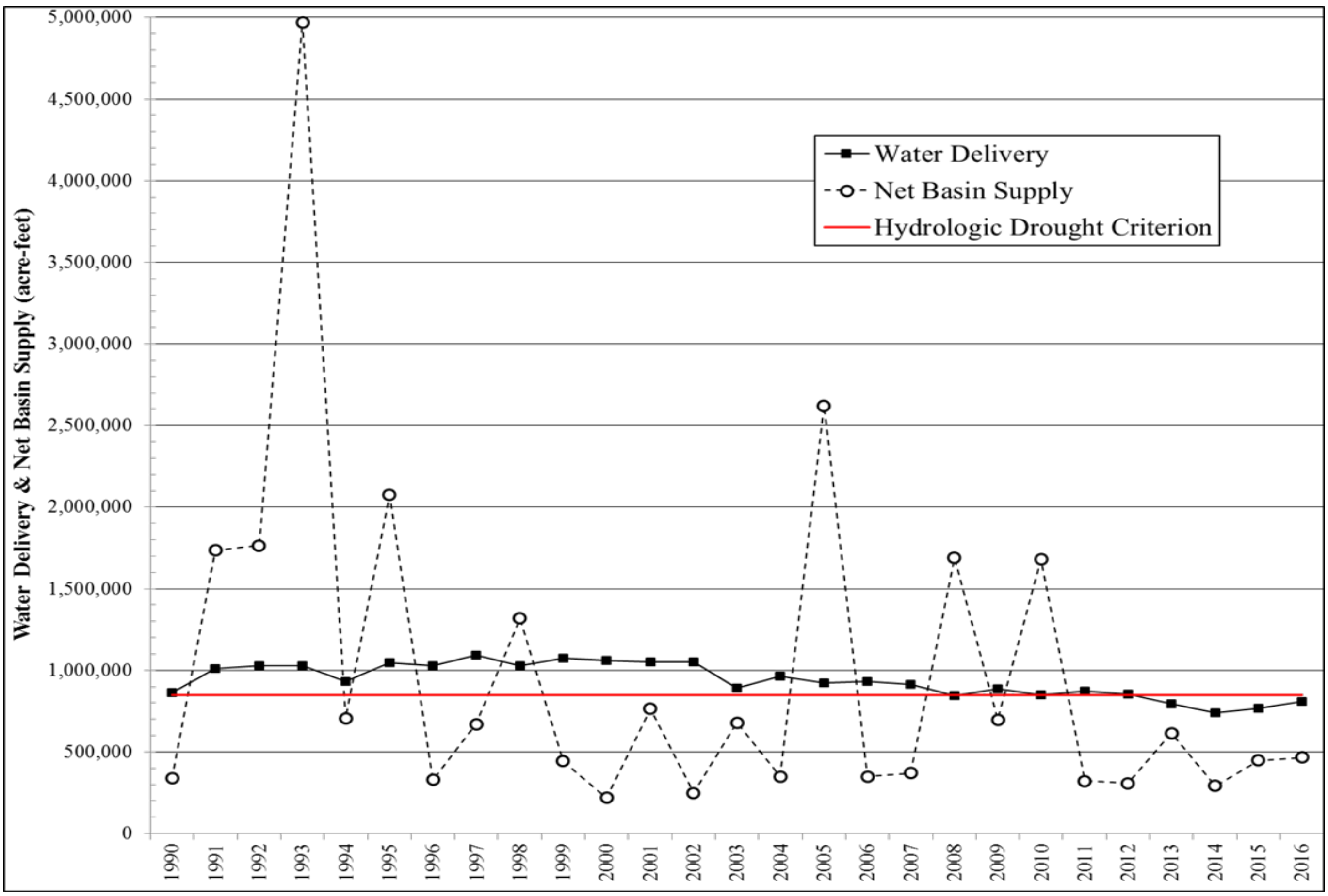

Figure 6-3: Hydrologic drought criterion, annual water deliveries and NBS from the Salt-Verde watershed, 1990-2016

A continuing sequence of years with NBS below median will lead to reservoir storage reductions which will eventually require an increase in groundwater pumping until a wet year occurs. The skewed tail of the NBS distribution represents high flow years that provide sufficient surface water to replenish the System when a wet winter does occur, as can be seen in Figure 6-9 for years of abrupt storage recovery. Since it can take just one wet winter to replenish the System, drought is alleviated by those fast-refresh events, and that year is a demarcation point for the drought's duration. Therefore, a run of continuous years with NBS below median is an appropriate definition of hydrologic drought applicable to the System, with a drought ended by a year of NBS above median. For this study that criterion is taken to be 850,000 AF/year.

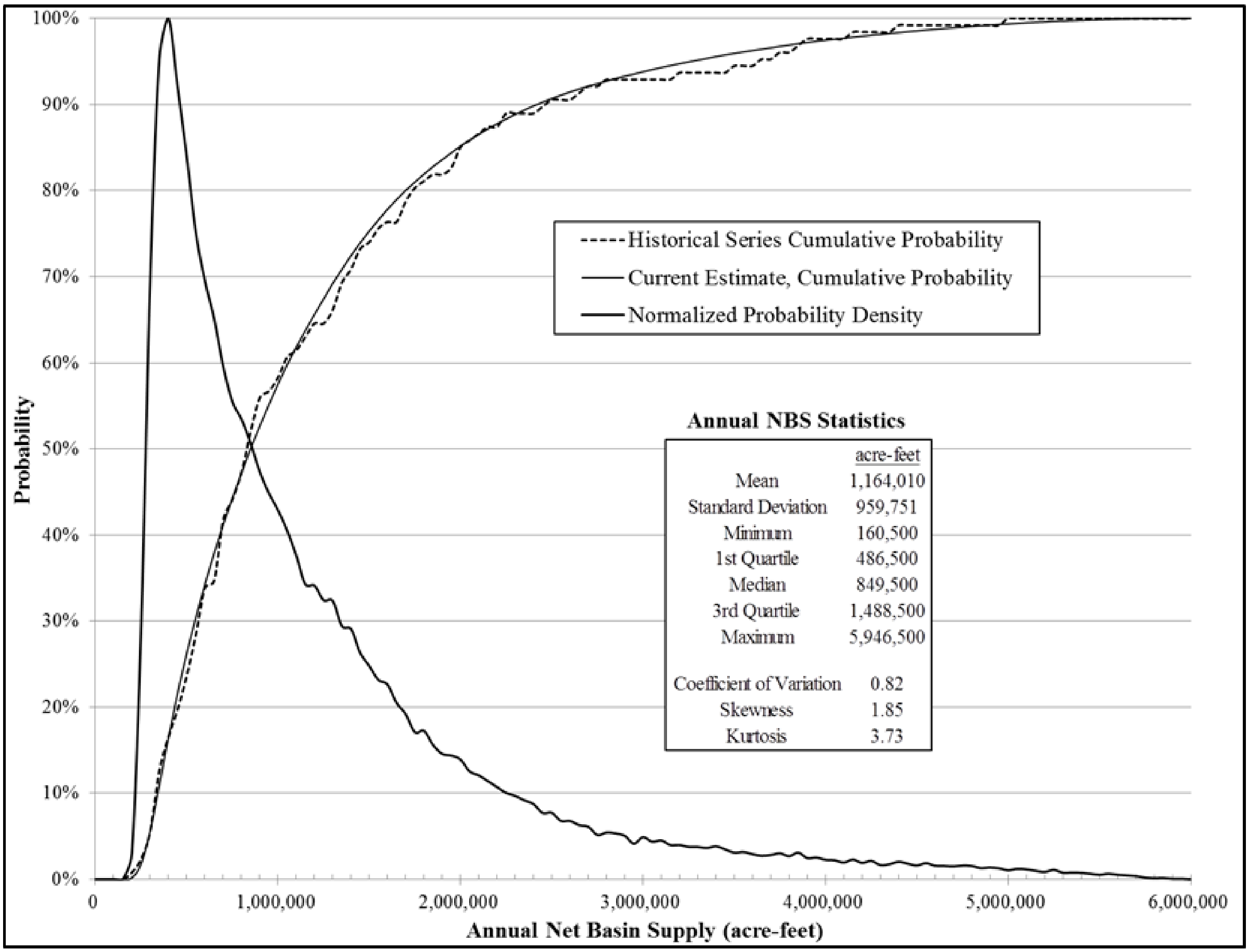

Figure 6-4: Probability distribution of annual NBS in the SRP System derived from the instrumental data record

6.2.4 Hydrologic Sensitivities to Climate

As stated in Reclamation Technical Memorandum No. 86-68210-2016-01 (U.S. Bureau of Reclamation 2016c), Revealing Uncertainties, Hydrologic Modeling, p.126-127:

"*An important result in research on the hydrologic impacts of climate change is that the portrayal of climate change impacts depends on the decisions made on the selection, configuration, and calibration of hydrologic models (Wilby 2005; Miller et al. 2012; Vano et al. 2014; Mendoza et al. 2015). In one of the earliest studies, Wilby (2005) demonstrated that parameter uncertainties have a large impact on the portrayal of climate change impacts. Subsequent work has demonstrated that the portrayal of climate change impacts also depends on the choice of hydrologic models and on specific decisions made in model calibration (Miller et al. 2012; Vano et al. 2014; Mendoza et al., 2015). For a variety of reasons, hydrologic model calibration often receives inadequate attention in climate change impact assessments, with potential first-order effects on the estimation of future hydrologic responses*."

Sec. 5.2.3 of the technical memorandum suggests a number of opportunities to reduce uncertainty in hydrologic modeling relating to selection, configuration, and calibration of hydrologic models, emphasizing that they should represent important processes and realistically represent the uniqueness of individual basins. The complexities of hydrologic process representations have long been acknowledged (Schaake 1990; Rogers & Fiering 1990) and that they are potentially nonlinear and unique to the character of each watershed. These issues have been explored for western watersheds, including the Colorado River Basin (Risbey & Entekhabi 1996; Sankarasubramanian et al. 2001; Fu et al. 2007b; Vano et al. 2012). From that research a pair of hydrologic sensitivity functions were introduced and recommended: precipitation elasticity and temperature sensitivity of runoff (Fu et al. 2007a; Vano & Lettenmaier 2014). Vano & Lettenmaier reported on applicability of the sensitivity functions to the UCRB compared to variable infiltration capacity (VIC) land surface hydrology modeling, demonstrating viability of their use for bounding future streamflow uncertainties for water resource applications.

Fu et al. (2007a) explored how to reflect the complicated nonlinear relationships among runoff, precipitation, and temperature. They evaluated various interpolation methods for deriving the runoff response surface in comparison to observational data records and found that ordinary kriging methods were best at providing multivariate interpolations from which functional expressions of elasticity and sensitivity can be calculated. Kriging is an optimal interpolation method that gives the best linear unbiased estimate of intermediate values within a domain of irregularly sampled data, and some explanation of the technique is provided by Cressie (1990) and by Press et al. (2007). Once the response surface has been developed, slope features can be examined and temperature sensitivity and precipitation elasticity functions can be calculated per their definitions –

Temperature sensitivity of runoff, the % change of runoff for 1°C *temperature change:*

$$S_T = (\Delta R/R) / \Delta T \qquad (\%/^{o}C)$$

Precipitation elasticity of runoff, the % change of runoff for % change in precipitation:

$$\varepsilon_P = (\Delta R/R) / (\Delta P/P) \quad \text{(unitless)}$$

Applying these dual heuristics provides some valuable benefits, including that they are derivable from the observational record, they capture the entirety of historical watershed response, they can be assessed across the full probability distributions of potential outcomes, complex nonlinear behavior can be revealed, and Vano & Lettenmaier (2014) demonstrated that temperature sensitivity and precipitation elasticity may be applied additively to render joint hydrologic response of both parameters.

The hydrologic sensitivity surfaces for the Salt-Verde watershed were calculated by kriging for each of the winter and summer seasons using historical observations of temperature, precipitation, and runoff which are available since 1895. The record contains a sequence of temperature increases over the past ~120 years (Figure 6-7), which together with annual variability provides a sufficient range over which to assess temperature sensitivity and its extrapolations. Similarly, large natural variability in the stationary precipitation record (Murphy and Ellis 2014) spans the wide range of hydrologic outcomes (Figures 5-1, 5-2, 5-3, 5-4). Kriging solutions of various data subsets were evaluated and seasonal algorithmic solutions developed for the Salt-Verde watersheds. Results were previously reported (Murphy et al. 2014, 2015) and are summarized below.

A review of precipitation elasticity is complex and not central to the analyses performed for this study. In general, elasticity values over 2.0 were found for central portions of the NBS distribution, similar to the Vano & Lettenmaier (2014) study which was conducted only at average UCRB streamflows. But, elasticity declines towards 1.0 at low and high precipitation where runoff efficiencies (R/P) tend towards asymptotic values.

Temperature sensitivity was found to be small in the winter season (Vano & Lettenmaier 2014 identified similar seasonal dependency). While average winter sensitivity for the Salt watershed was found to be slightly positive (incremental surface flow volume induced by earlier runoff when conditions still cool), statistical significance was inconclusive. Temperature sensitivity for the Verde winter was also found to be indistinguishable from zero, except at low flows

(NBS<182,000 AF/season) where an average sensitivity of -3%/ ^{o}C was found. Little temperature impairment of flows in these watersheds is therefore evidenced during the winter season.

However, the finding is different for the summer season where flow impairments can be large. Temperature sensitivity plays its largest role in the center of the runoff distribution. As can be seen in Figures 6-5 and 6-6, summer temperature sensitivities in excess of -10%/^{o}C were found for the mid-range of flows, and details are unique by watershed. The inverse-triangular functions are fit to analytic results across the range. Very high evapotranspiration in the semi-arid watersheds during summer months results in large runoff impairments for central portions of runoff distributions. At low runoff levels temperature sensitivity is present but small. That end of the distribution represents temperature effects on base flow within limited stream channels. It is also low for high runoff events in the summer monsoon season, where heterogeneous overland flows are flashy and often accompanied by transient temperature reductions.

In addition to summer temperature effect on reservoir inflows, miscellaneous loss at the reservoirs has a temperature sensitivity. On the Salt side of the System a sensitivity of approximately 10,000 AF/^{o}C for the summer season was identified. On the Verde side of the System temperature sensitivity is 15% to 30% of that, and is inversely proportional to NBS as shown in Figure 6-6. The Salt's larger number is attributable to reservoir size where Roosevelt Lake's surface area is vulnerable to enhanced evaporation with higher temperatures.

The results of joint interactions of temperature sensitivity and precipitation elasticity with both in combination are complex due to how they apply in different portions of the NBS distribution (a full discussion is beyond the scope of this report). As expected, precipitation changes can offset temperature changes, with a finding that a 5% precipitation increase can offset a 3^{o}C temperature increase at median NBS, but differently at other values. Temperature change has more influence in lower parts of the distribution, and precipitation change has more influence in upper portions of the distribution. But, specific outcomes depend on the relative mix of watershed-season contributions to total annual surface water yield. It can be noted that low frequency modes of natural variability in the historical record have temporarily shifted decadal average precipitation more than 5% in the past (Figures 5-1, 5-2, 5-3, and 5-4), and it can be expected to do so in the future. The combined result with future temperature change may make the extraction of temperature's influence on NBS difficult to identify in long-term future records.

To develop a clear sensitivity assessment to temperature change, the analyses reported below have assumed persistence of demonstrated historical precipitation variability without any long-term increasing or decreasing trend in the future consistent with other current research assumptions (e.g. Udall and Overpeck, 2017). The derived temperature sensitivity functions described above have been used for the analyses reported herein for period change methods, and they are applied multiplicatively with increasing temperature.

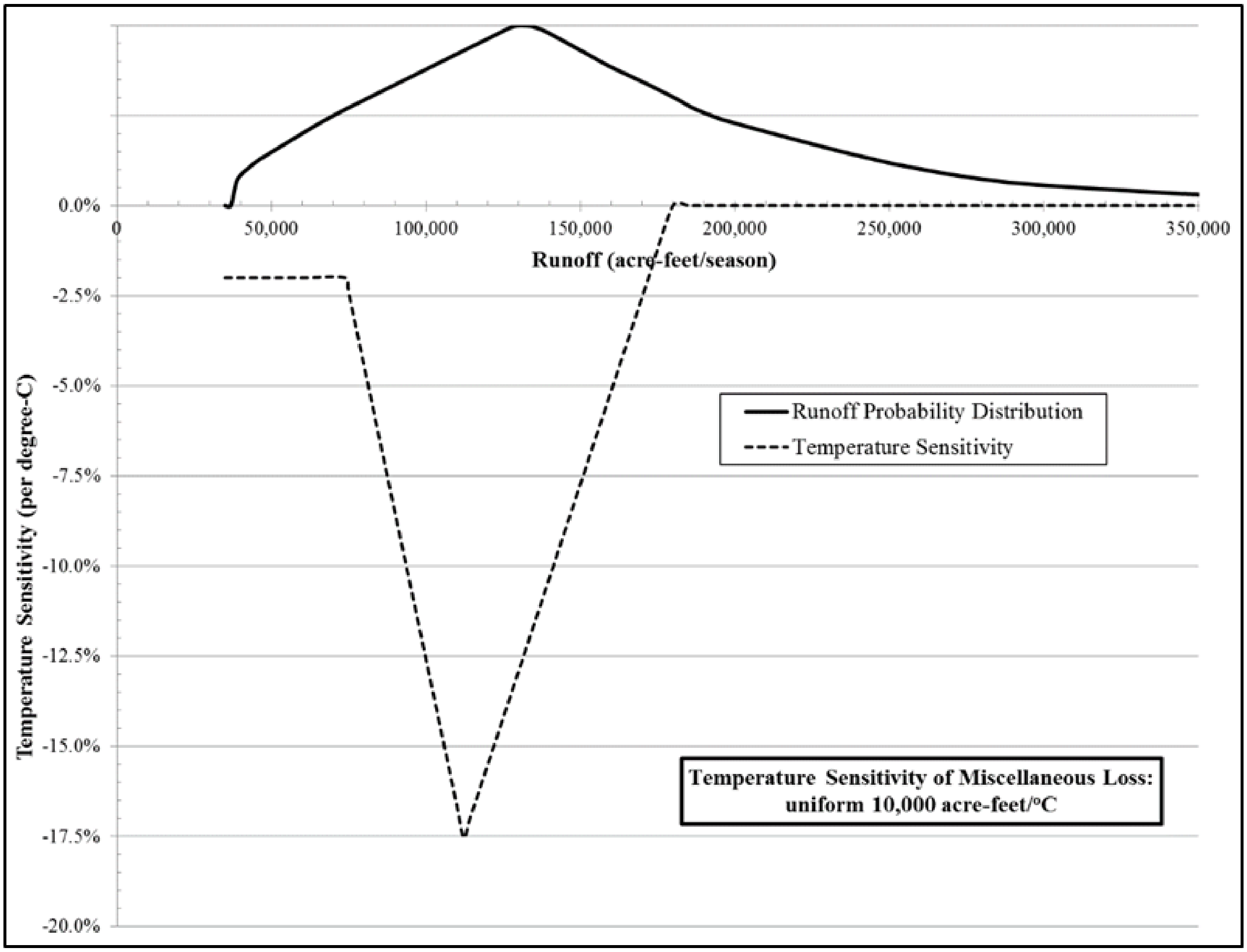

Figure 6-5: Temperature sensitivity of the Salt watershed and reservoirs in the summer season

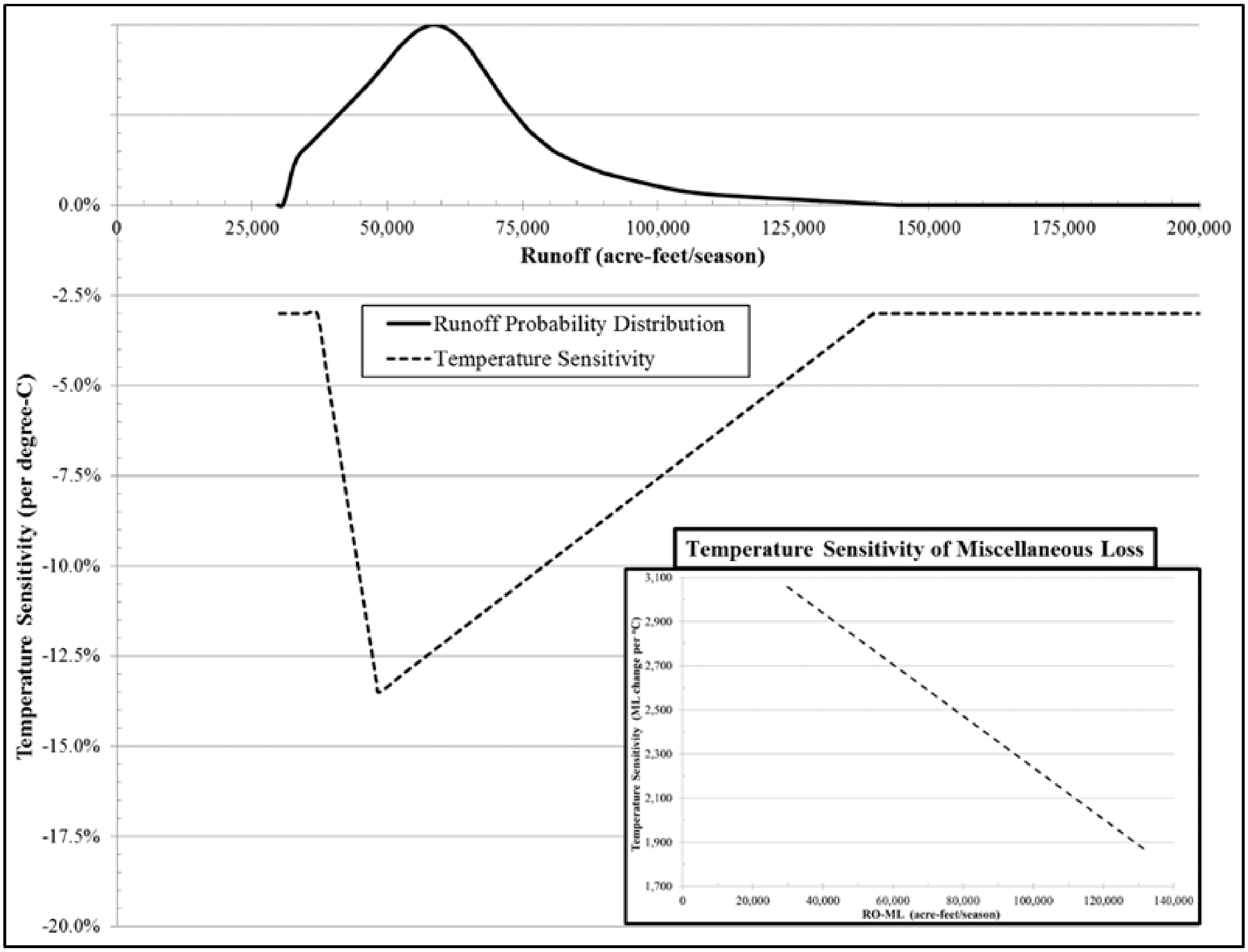

Figure 6-6: Temperature sensitivity of the Verde watershed and reservoirs in the summer season

6.2.5 Climate Change Assumptions

The effect of any future changes of temperature and/or precipitation on NBS of surface water can be calculated using the temperature sensitivity and precipitation elasticity functions derived above with the specific change assumption. As was reported by Murphy and Ellis (2014), examination of the historical record of the Salt-Verde watershed reveals that temperature has been persistently non-stationary (Figure 6-7) while precipitation has been stationary (Figures 5-1, 5-2, 5-3, and 5-4). Watershed temperatures have displayed periodic increases and decreases which have accumulated to an overall average increase of approximately 1.8^{o}C above late 19th century levels. While highly variable over the data record, precipitation does not yet display any long-term trend. These findings are consistent with other research, such as reported by Udall and Overpeck (2017): "*Whereas it is virtually certain that warming will continue with additional emissions of greenhouse gases to the atmosphere, there has been no* *observed trend towards greater precipitation in the Colorado basin, nor are climate models in agreement that there should be a trend.*"

Borrowing from the transient method results of this study (Sec.5.5), 64 downscaled projections of precipitation and temperature (1950-2099) were obtained from the CMIP5 climate model archive for the Salt-Verde watershed. Half were per the RCP4.5 emissions simulation and half per the RCP8.5 simulation. They were evaluated in detail for projections of future temperature and precipitation. Future temperatures, although spanning a wide range (Figure 6-7), all indicate increasing average levels in the future. However, precipitation results are inconclusive, spanning a range of increasing, decreasing, and no-change outcomes without a clear finding of change in long-term levels.

In such situations of high precipitation uncertainty where there is no clear and supportable basis from which to apply a trend, guidance from forecasting research (Armstrong 2001) recommends that none should be used. That is not to say that sensitivity analyses should be set aside, but that research investigations find minimum forecast errors with persistence assumptions until a clear basis for including trends can be established. If temperature change is clearer than for precipitation, then first steps in sensitivity analysis should study temperature effects to establish a basis of understanding of the watersheds and system response to likely simulations. The analyses reported below therefore focus on temperature change results while maintaining the established precipitation hydrology.

Before obtaining the 64 model-RCP temperature results the historical response of Salt-Verde watershed to increasing greenhouse gases was studied and compared to global temperature response. Climate sensitivity of the watersheds to increasing CO_2 since 1957 (beginning of instrumental record) was found to reflect approximately 3^{o}C of temperature change per a doubling of CO_2 concentration. Salt-Verde surface temperature increase has been slightly more than twice the global surface air temperature increase. With these observations, a couple temperature projections were made. The mean global temperature changes projected by IPCC AR5 (IPCC 2013, Table TS.1) were scaled per the higher Salt-Verde sensitivity, and a temperature change from recent levels to late-century (last 30 years) was estimated at +3.1 ^{o}C using mid-range RCP assumptions. Additionally, the empirical climate sensitivity was used with mid-range RCP assumptions to project a late-century change about half that value. These findings are shown in Figure 6-7 in comparison to the envelope of projections from the RCP4.5 and RCP8.5 CMIP5 model simulations.

The average temperature changes from 2005 (last year of the reference period) to 2085 in the CMIP5 models examined in the transient study method study are given in Table 6-1. Change values for the Salt side of the System are essentially the same as on the Verde. Summer increases are slightly larger than for winter.

The wide range of projections for each RCP simulation are shown in Figure 6-7. The +3.1°C change estimate based in AR5 is about 1°C higher than was found for the average RCP4.5 model projection and within lower portions of the RCP8.5 envelope. The +3.1°C change value had already been employed for the analyses reported below, and CMIP5 results do not refute its applicability.

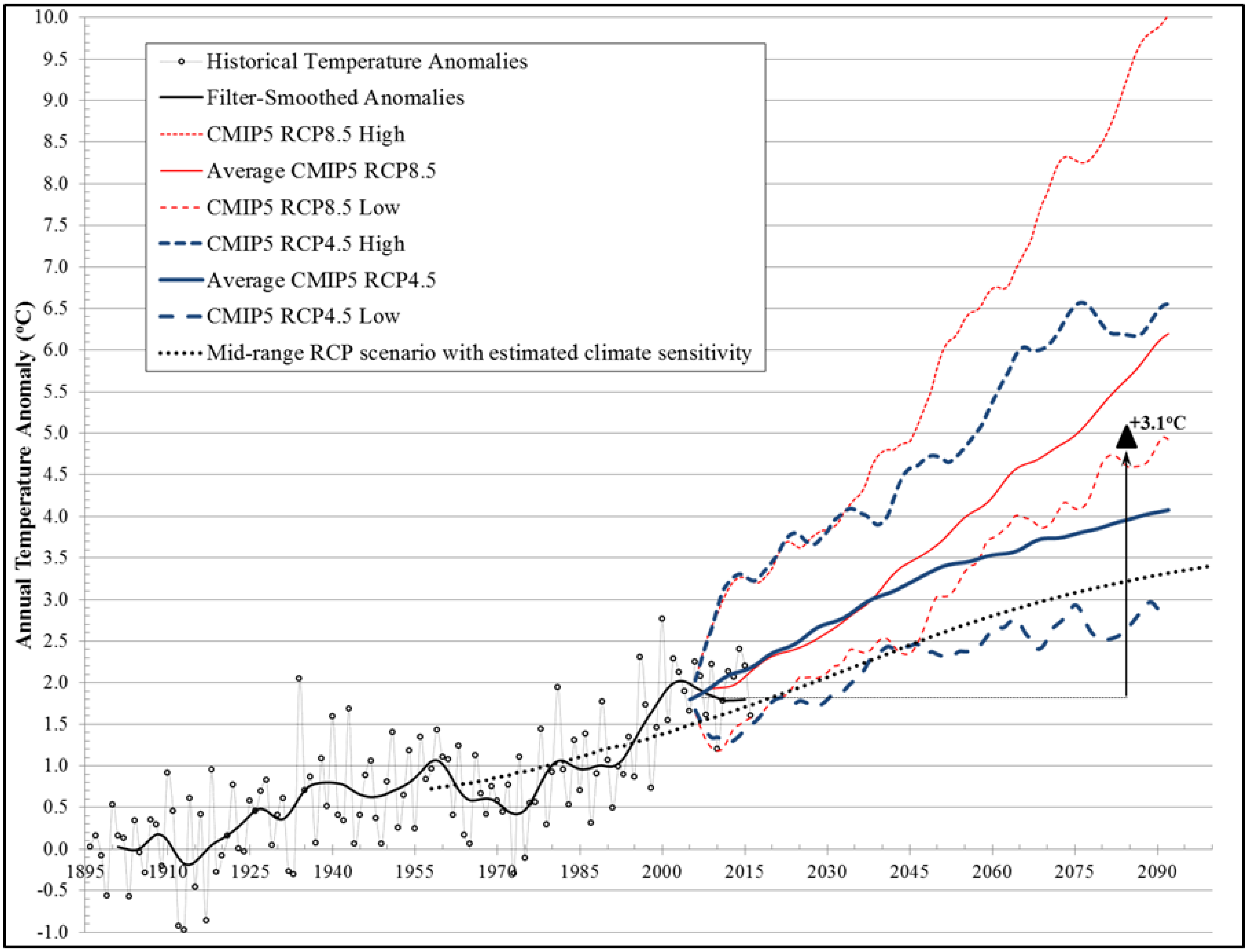

Figure 6-7: History and projections of annual temperature anomaly of average surface air temperature in the Salt-Verde watershed

Table 6-1: Average temperature change projections to 2085 per CMIP5 models and relative to IPCC AR5

Average Temperature Increases, 2005 to 2085 (°C)				
	CMIP5 Models			estimate per global
	RCP4.5	**RCP6.0**	**RCP8.5**	**IPCC AR5**
	(interpolated RCP6.0)			mid-range RCP
Winter	2.1	2.8	3.8	---
Summer	2.4	3.1	4.2	---
Annual	2.2	2.9	4.0	3.1

6.3. Reservoir Operations Simulation Model (ResSim) Results

6.3.1 Analysis Results - Historical Period

While there are several system variables of interest, total remaining water storage at season transitions is the one most relevant to system sustainability. Therefore, it is a primary one reported in analyses. Reservoir response to the NBS instrumental record if the System had been in place with current operating rules is instructive. Figure 6-8 shows the historical time series of annual NBS since 1889, and Figure 6-9 provides the modeled reservoir storage response to that record for two levels of water demand (800,000 and 900,000 AF/year). Most recently, a wet winter in 2010 refilled the reservoirs as can be seen in Figure 6-9. Water demand from the System averaged 900,000 AF/year from 2003-2011, and modeling with that value would place the System near the reduced allocation threshold during the most recent 6-year drought. But since 2012 actual water deliveries declined to around 800,000 AF/year as part of the long-term trend in declining customer demand (Figure 6-3). The cumulative differential has amounted to about a half million acre-feet of water remaining in the reservoirs relative to what would be expected with the old demand level. This illustrates that it is not only the water supply volume that determines the condition of the resource system at a point in time. Water demand, system design, and management protocols also play an important role in setting system conditions. Reservoir simulation models provide the important toolset by which to represent those factors and assess cumulative impacts of the highly variable seasonal inflows from the dual watersheds.

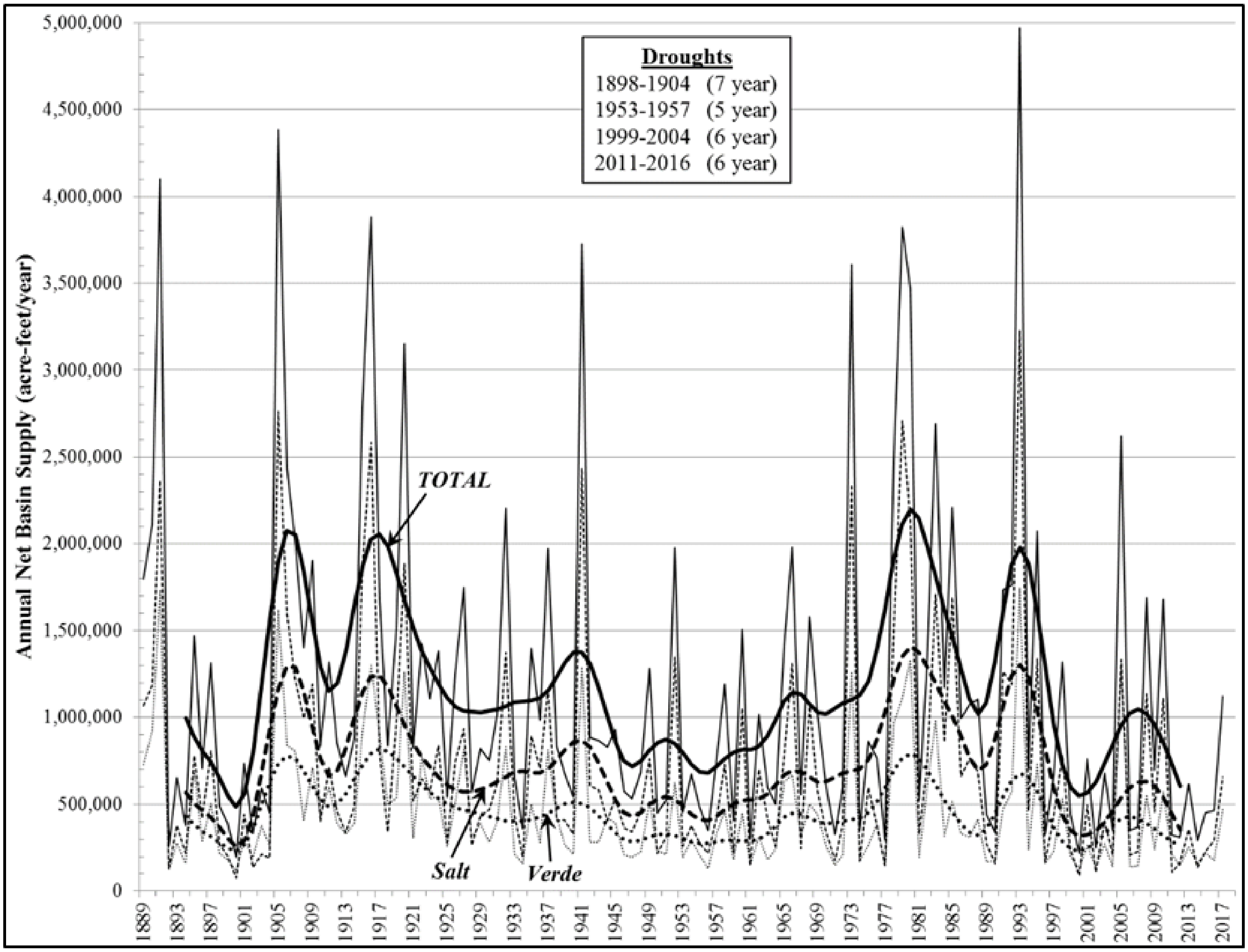

Figure 6-8: Historical time series of NBS by Water Year. A hydrologic drought period for the System is defined by runs of years with annual NBS below median (850,000 AF/year)

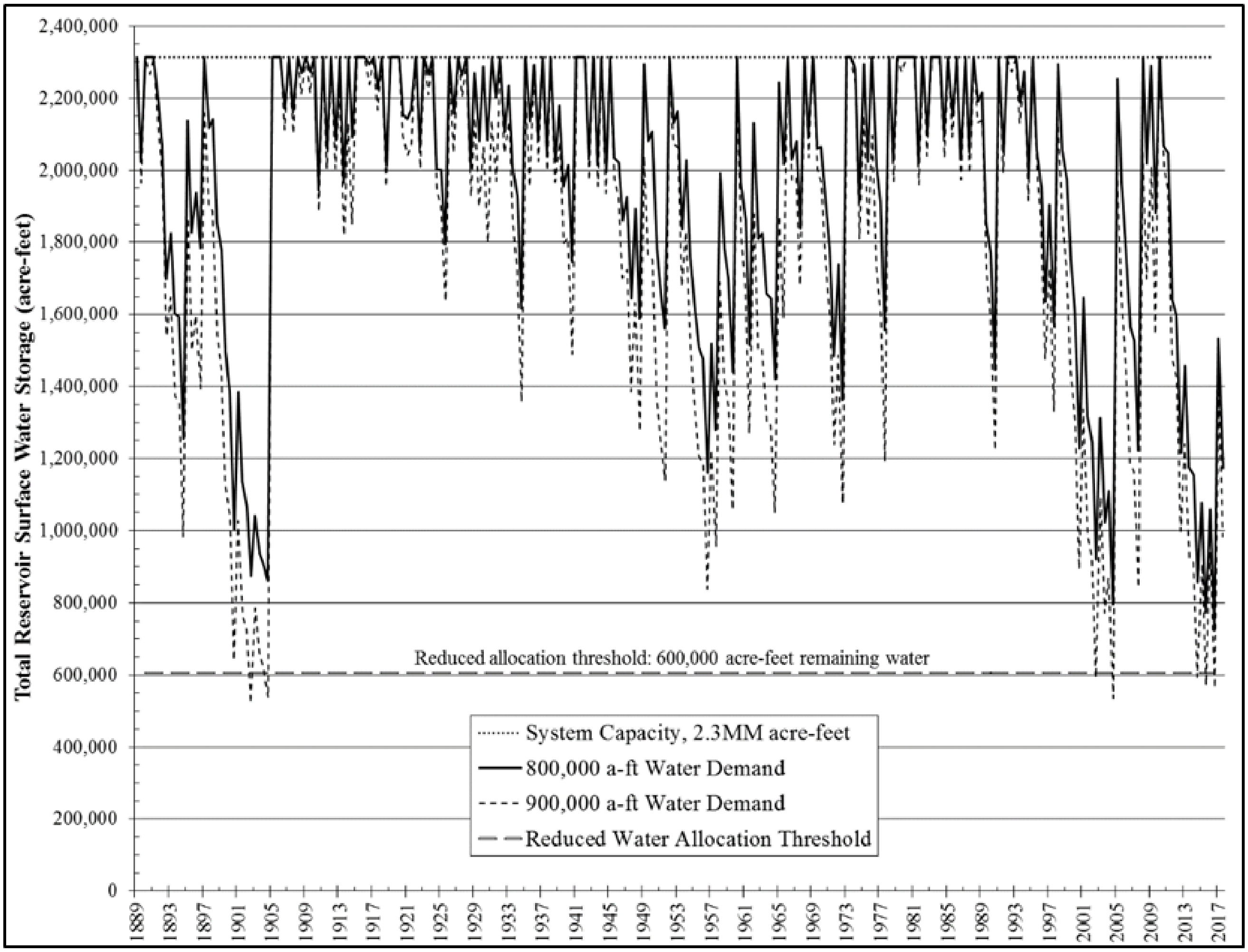

Figure 6-9: Total reservoir storage at the end of the winter and summer seasons, 1889 to present, as modeled by ResSim

6.3.2 Analysis Results - Tree Ring Record and Simulated Time Series

6.3.2.1 Implications of Temperature Change to Net Basin Supply

The NBS probability distribution resulting from a +3.1^{o}C average temperature change is given in Figure 6-10 compared to the current system base case from Figure 6-4. The effect of temperature increase is a downward shift of the distribution. The changes in NBS distribution parameters are all statistically significant to >95% confidence, as the number of simulated years is very large (120,000). The degree of NBS change is nonlinear and a function of position examined within the distribution and some quantification is provided in the table insert. The 3.1^{o}C temperature increase results in a 7% to 10% reduction in the vicinity of the mean and median NBS.

Even more illuminating is what occurs in very low and high flow regimes. Previous research (Fu et al. 2007b; Vano and Lettenmaier 2014) identified seasonal dependence of temperature sensitivity and hinted at nonlinear response. This investigation utilizes a specific quantification of those based in observational evidence, and it reveals a more detailed expectation of streamflow impairment. Temperature sensitivity was found to be minimal in winter but with discernable summer effects upon flows from the watersheds and losses at the reservoirs. The System primarily depends on winter precipitation for reservoir inflow. Therefore, if winter precipitation is absent in a year, annual NBS is comprised more of the summer flows and losses that are temperature sensitive. Annual NBS impairment can be expected in the range of -6% to -10%/^{o}C when summer effects are a greater proportion of the total. If instead winter runoff is the dominant portion of annual NBS and subject to minimal temperature sensitivity, summer effects are diluted within the annual impairment. Productive El Niño winters can result in upper-quartile NBS, and their annualized temperature sensitivity is only ~1% to -2%/^{o}C. Drought periods comprised of multiple years from the lower NBS range will be exacerbated by increasing temperatures. But, temporary drought relief contributed by wet winters from upper portions of the distribution will be minimally affected. The overall effect on a drought from a temperature increase is the cumulative sum of the complex temperature sensitivities over duration of the drought, and examples are shown in results reported below.

The NBS differentials to the future +3.1^{o}C average temperature change were examined to identify the origin of annual NBS reductions. Their average apportionment is shown in the insert of Figure 6-10. A small percentage of the NBS reduction is due to winter runoff impairment, which might be unresolvable amidst high year-to-year precipitation variability. Future temperature changes will primarily have an effect during the summer season. Of those NBS impairments at the margin, roughly half occurs during runoff to streamflow and half as additional miscellaneous loss at the reservoirs. So, evaporative water loss from the reservoirs is as important as what happens on the watersheds. This finding might be expected, and it is difficult to envision a manner in which to suppress such natural loss.

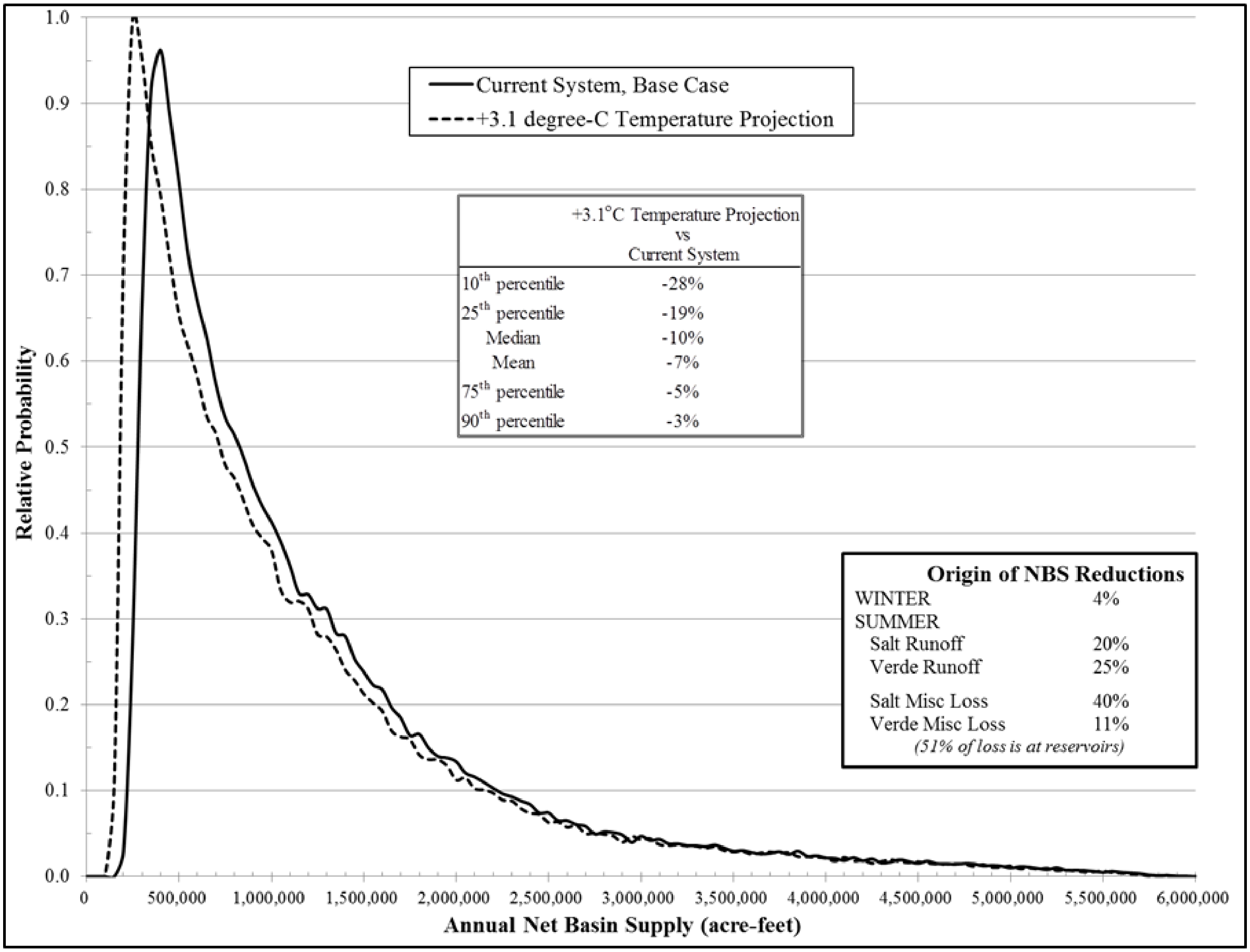

Figure 6-10: Annual NBS probability distributions for the current system and with a 3.1ºC temperature increase (NBS changes as a function of position within the distribution and origin of the reductions are tabulated)

6.3.2.2 Drought of Record

Paleoclimate research has provided evidence of droughts in past centuries more severe than those in the instrumental record, including a megadrought in the late 16th century (Woodhouse and Overpeck 1998). That drought and others are revealed in the Salt and Verde tree ring data set developed by researchers at the University of Arizona's Laboratory of Tree-Ring Research (Hirschboeck and Meko, 2005, 2008). Drought periods are readily evident in Figure 6-11 after application of a decadal filter to suppress high frequency variability. The late 16th century event from 1566 to 1594 is the most severe and is considered the most challenging drought of record for the SRP System. It contains a series of low multi-year periods embedded across three decades with occasional high-flow years. The three embedded droughts are summarized in Table 6-2.

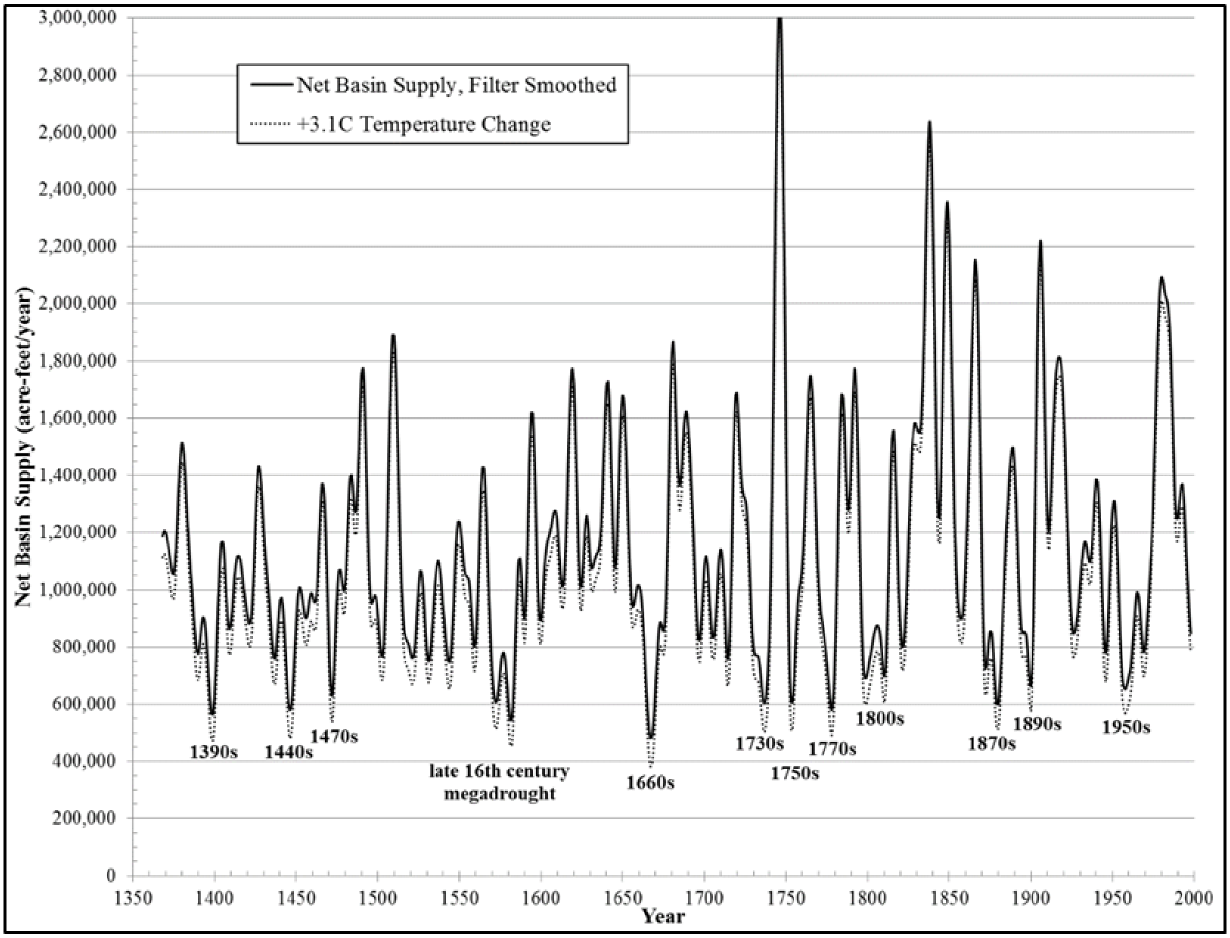

Figure 6-11: Tree ring time series of NBS by Water Year, 1361 to 2005 (The data have been smoothed with a decadal cutoff filter. Drought eras are identified as-labeled)

The full tree ring NBS series was passed through the reservoir operations simulation model to assess expected response of the System to 800,000 and 900,000 AF/year demand, and modeled storage at the end of all summer seasons is shown in Figure 6-12 for a water demand of 800,000 AF/year.

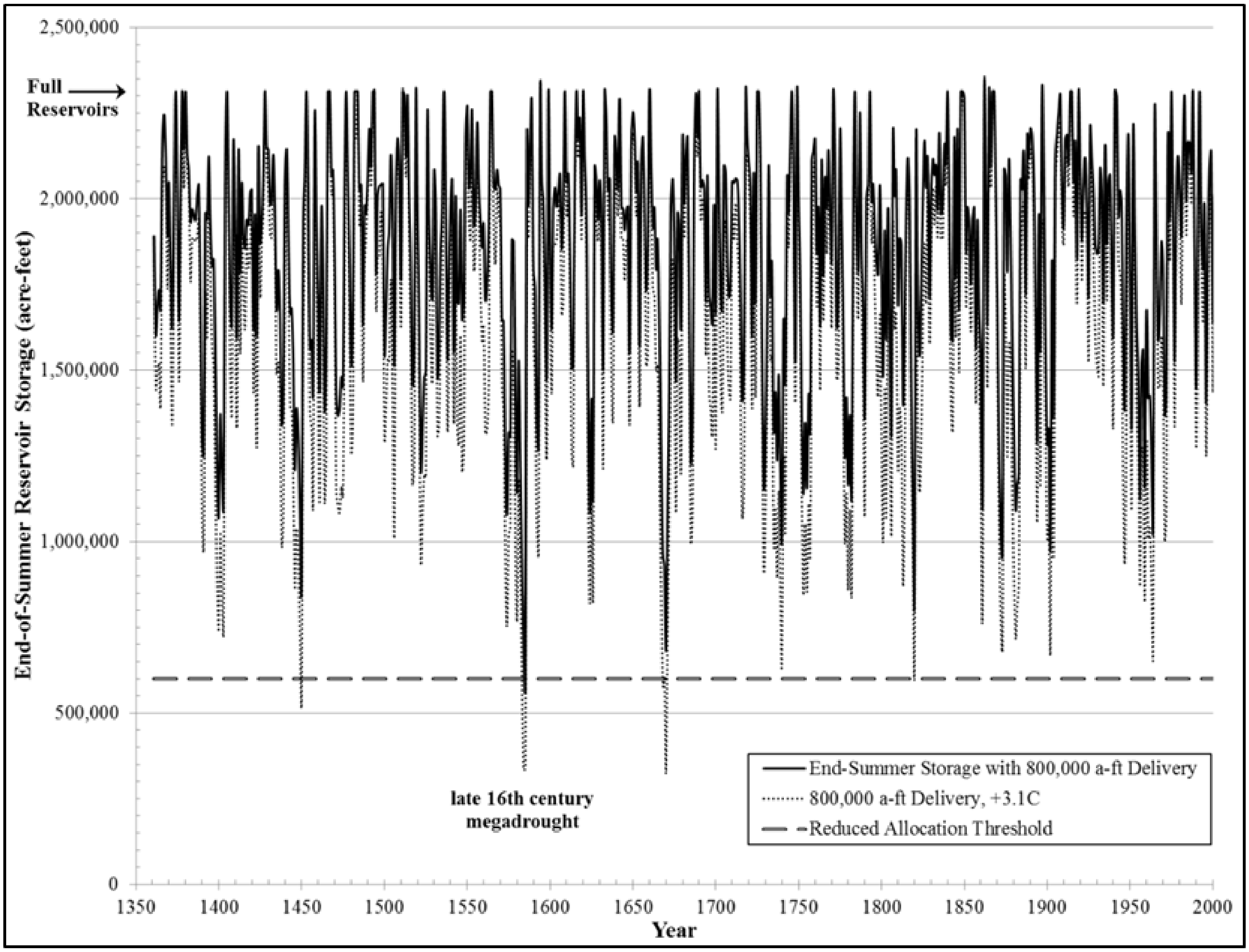

Figure 6-12: End-of-summer reservoir storage in ResSim-modeled tree ring time series, modeled water demand = 800,000 AF/year

Table 6-2: Details of the severe late 16th century drought of record

Runs of drought years within late 16th century megadrought (1566-1594)					With +3.1°C	
Droughts	Duration (years)	Average Annual NBS (AF)	Lowest Year	Lowest Annual NBS (AF)	Droughts	Duration (years)
1570-1574	5	544,624	1571	371,739	1569-1576	8
1582-1585	4	352,211	1584	307,517	1582-1585	4
1590-1593	4	480,991	1590	272,835	1589-1593	5

Details of NBS and storage response for the 16th century megadrought are provided in Figures 6-13 and 6-14. The megadrought began after a very wet 1565 that would have filled the reservoirs, followed by two years below median NBS in 1566-1567. Reservoir storage would stay high, maintained by a modestly wet 1568. Then followed several years of low NBS, and 1571, 1573, and 1574 were particularly dry and would have depleted about half of reservoir storage. A wet 1577 provided some storage recovery, followed by three dry years reducing stored water, and then a modest recovery in 1581. Four sequential dry years, 1582-1585, would have reduced reservoir storage to the 600,000 AF threshold that triggers conservation measures. But such actions would have been brief, as high runoff in 1586 would have replenished the System to nearly full reservoirs. The System would have topped off in 1588 with a couple modestly wet years. Then a four-year drought with notably low NBS in 1590 would have reduced storage by half. High runoff in 1594 would have been sufficient to fully refill the System and spill water for an end to that drought era. So, although the megadrought period was particularly long, occasional wet winters provide reservoir refills sufficient to keep the System at manageable water storage levels. During this megadrought average winter storage changes (no warming versus +3.1 °C warming) were -15% and -14% for 900,000 AF and 800,000 AF demand respectively.

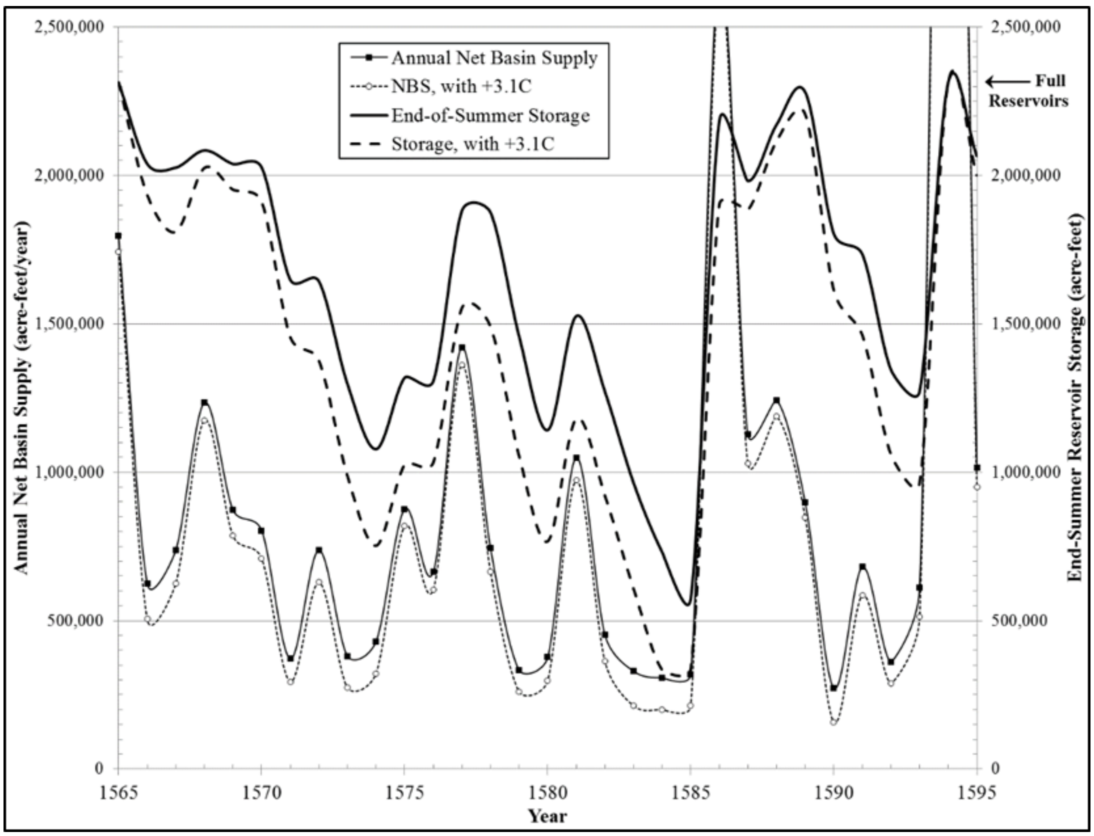

Figure 6-13: Late 16th century NBS and reservoir storage response with 800,000 AF/year demand

The +3.1°C average temperature change was applied with hydrologic temperature sensitivities to modify the NBS reconstruction and reassess storage response. Two of the three embedded droughts would have marginally extended to longer duration (Table 6-2). Annual NBS reductions are greatest when there is a dry winter and a greater proportion of summer flows. Consequently, lower portions of the NBS curves in Figure 6-13 are the most affected by large hydrologic sensitivities in summer. When a consecutive sequence of low NBS years occurs, the cumulative reduction in storage becomes evident (like that seen from 1578 to 1585). This results in an increasing number of years below the reduced allocation threshold. When periods of storage below the reduced allocation threshold are limited to a few years, implementing conservation measures to reduce deliveries is feasible. However, managing the customer base through such times obviously becomes more challenging if conservation measures are extended to multiple years. Results indicate that during droughts more multiyear sequences near the threshold will occur with a combination of high water demand and simultaneously elevated temperatures. This emerges in the rightmost column of Table 6-3 where more years below 600,000 AF were found to occur. System management considerations can balance risks of those conditions based upon envisioned conditions in the future.

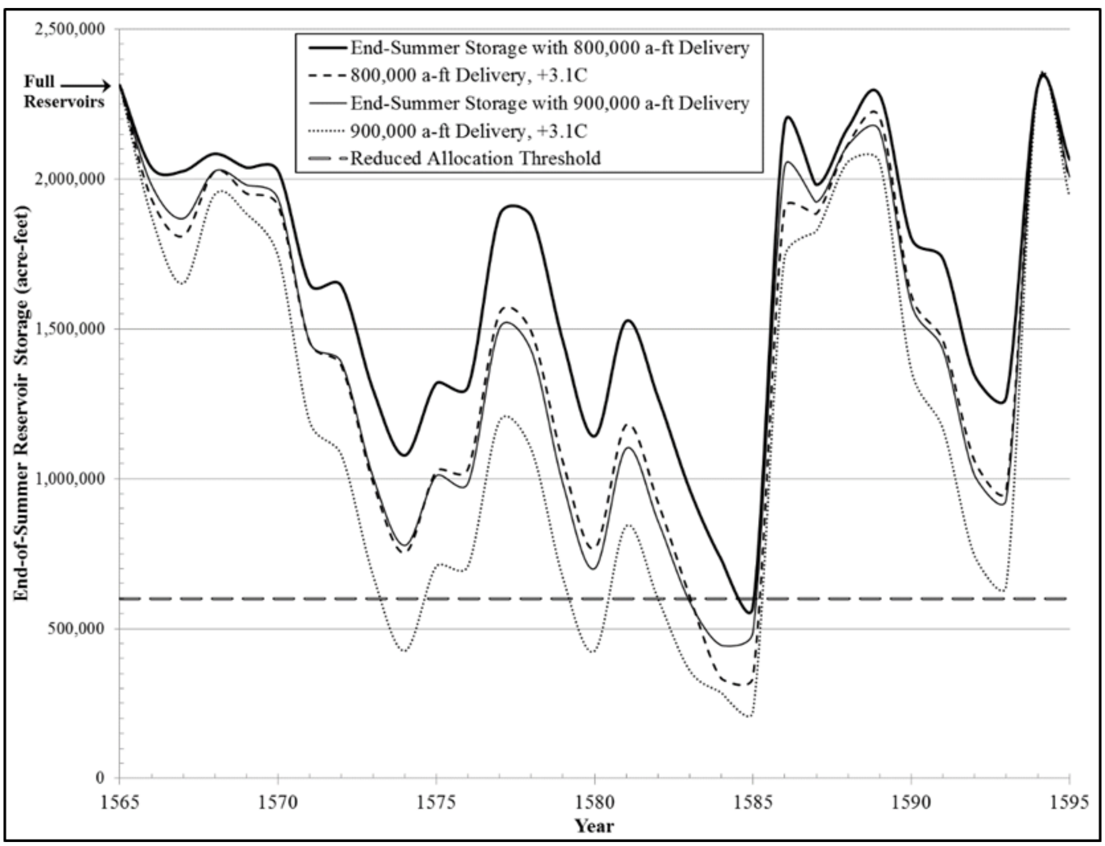

Figure 6-14: Late 16th century storage response with demand and temperature changes

Judging by response of the curves in Figure 6-14, a +3.1°C change is approximately offset by a 100,000 AF/year water demand reduction. This provides a first-order estimate of system sensitivity tradeoffs. Since a water demand reduction of that amount has already occurred over the last five years but temperature increases are projected some decades into the future, the system is essentially already positioned for the climate change impacts that have been modeled with the megadrought. Alternatively, although it does not appear to be needed at this time, larger water deliveries could be considered when called for if the risk of low storage conditions is acceptable over short time periods.

There was no total system depletion for the range of conditions analyzed with the tree ring data set, present and future. This finding is robust even when tree ring NBS errors are considered, assisted by the observation that even during extended drought there is shown to be intermittent wet years sufficient to provide some system recovery and maintain sustainability of the system (Figure 6-13).

Depletion risk is thoroughly analyzed in the '*System Reliability*' section (Sec.6.3.2.3) of this report, which indicates those risks lie above one million acre-feet of annual demand and higher temperatures than analyzed. With the temperature trends presently in evidence and declining water requirements (to ~800,000 AF/year and potentially lower), such a combination appears unlikely in the foreseeable future. If another megadrought similar to the one in the late 16th century tree ring record reoccurred in a warmer future this analysis indicates the System is sustainable under current operating guidelines. It should be noted that evidence of this drought of record was incorporated into the revision of operating protocols in 2006 for improving System resilience for just such an eventuality.

Table 6-3: Effect upon reservoir storage from demand and temperature changes in the tree ring data record

		WATER DEMAND 800,000 AF/year				**WATER DEMAND 900,000 AF/year**			
		Base Case		+3.1°C Temperature		Base Case		+3.1°C Temperature	
DROUGHT		# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year
1390s	Tree Ring		1400		1403		1400	4	1400
1440s	Tree Ring		1450	1	1450	1	1450	3	1450
1470s	Tree Ring		1472		1473		1473		1473
1580s	Tree Ring	1	1585	2	1584	3	1584	6	1585
1660s	Tree Ring		1670	2	1670	2	1670	4	1668
1730s	Tree Ring		1740		1740		1740	4	1740
1750s	Tree Ring		1755		1753		1755	1	1753
1770s	Tree Ring		1782		1782		1782	3	1780
1800s	Tree Ring		1806		1801		1806		1806
1870s	Tree Ring		1881		1881		1881	5	1881

		WATER DEMAND **800,000 AF/year**				**WATER DEMAND** **900,000 AF/year**			
		Base Case		+3.1°C Temperature		Base Case		+3.1°C Temperature	
DROUGHT		# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year	# Years < 600,000	Minimum Year
1890s	Tree Ring		1902		1902		1902	2	1902
	Instrumental		1904	2	1902	2	1902	7	1900
1950s	Tree Ring		1964		1964		1964	4	1964
	Instrumental		1956		1956		1956	1	1956
2000s	Tree Ring		2004		2004		2004	1	2004
	Instrumental		2004	1	2004	2	2004	5	2004
			2016	2	2015	3	2016	3	2016

6.3.2.3 System Reliability

This analysis is an evaluation of the System reliability under various water delivery levels and future temperature conditions with the current system configuration and operating guidelines. Quantification of system reliability, as it can be currently understood, is fundamentally important for understanding potential limitations under future climate simulations and a range of different water demands.

Various measures of system reliability can be quantitatively assessed by the methodology employed for this analysis. Based upon discussions with SRP water operations staff, the System could conceivably continue to deliver water and generate hydroelectric power down to total remaining water storage of 50,000 AF (which would largely remain in the Salt side of the System). That criterion was therefore used as the threshold for total depletion of surface water in the System and System reliability defined as the probability of maintaining greater than 50,000 AF of remaining storage when delivering a given annual water volume on an ongoing basis. Reliability can be expected to diminish at larger water delivery levels and/or by increasing future temperatures. Higher reliability is expected with decreasing water demand and a more benign climate.

Complete System depletion is clearly a threat to be avoided with an ample safety margin. Attention to low risk values is therefore appropriate considering its importance and a condition to be managed to a very low probability of occurrence – such as to a risk of 1% or less in a century. System risks are typically expressed as the probability of a given number of events occurring within a timeframe, such as over one century for the System. Statistically, the Poisson probability distribution is applicable to characterization of situations when events are infrequent and independently distributed in time. At very low probabilities

Poisson statistics simplify to the risk of one occurrence, while the risk of two or more occurrences is vanishingly small. This study examined demand-climate combinations to identify those with high system reliability as measured by a low risk (<1%) of one depletion occurrence in a century.

Risks were assessed for the current, base case climate as of the present time and also for an average future temperature level 3.1^{o}C higher than present temperatures. Additionally, an intermediate temperature change of +1.5^{o}C was assessed that provides further differentiation within the test matrices below.

The dozen 10,000-year simulated NBS time series for the three temperature cases were used in development of the matrix for a total of 120,000 years of operation for each demand-temperature, enabling risk assessments to low probabilities. The analysis focused where reliability was found to be at the margin of 99-100% starting with 900,000 AF/year demand and exercised through the matrix of water demand and temperature levels. Each reservoir simulation run was conducted at a fixed annual water demand partitioned per seasonal delivery expectations that approximate 41% in winter and 59% in summer.

Table 6-4 tabulates the number of storage depletion instances found in 120,000 years of analysis for each tested demand-temperature combination. Table 6-5 provides the calculation of depletion risk in a century, and the expression of System reliability.

With a 900,000 AF/year demand total reservoir storage was not depleted to less than 50,000 AF across all 120,000 years in the current system simulation nor for the +1.5^{o}C temperature change case. There were two depletion instances for the +3.1^{o}C case, which calculates to a 0.17% probability of depletion in a century. Six or more depletions in 120,000 years of analysis calculate to more than a 0.5% risk of depletion/century, and Table 6-5 delineates where those occur. The boundary lines provide guidance to where system reliability can confidently be considered to be high.

The System is 100% reliable under current climate conditions and operating guidelines up to annual delivery volumes of one million AF/year. A future temperature change of +1.5^{o}C later in this century introduces a 1% risk of depletions; but, this can be readily addressed by a 50,000 AF/year reduction in water delivery to 950,000 AF/year. Similarly, the larger temperature change of +3.1^{o}C can be remedied by another 50,000 AF/year delivery reduction. Those delivery levels are higher than actual demand for the past 15 years, and recent declines provide another risk reduction. Even higher temperature changes could be assessed by the methodology, but results can be anticipated by extrapolations from Table 6-5. A general sensitivity finding indicates that a 3^{o}C temperature increase can be offset by approximately 100,000 AF/year of demand reduction.

Table 6-4: Number of reservoir storage depletions found for cases tested (each cell was evaluated with a 120,000 year simulation)

Annual Demand	Number of Depletions		
	Base Case	+1.5ºC	+3.1ºC
600,000			
650,000			
700,000			
750,000			
800,000			
850,000			0
900,000	0	0	2
950,000	*	1	19
1,000,000	0	12	
1,050,000	6		
1,100,000			

* = no depletions based on adjacent cells

Table 6-5: Probability of total storage depletion in a century and system reliability

Annual Demand	Probability of a Depletion/Century			System Reliability		
	Base Case	+1.5ºC	+3.1ºC	Base Case	+1.5ºC	+3.1ºC
600,000	0.0%	0.0%	0.0%	100%	100%	100%
650,000	0.0%	0.0%	0.0%	100%	100%	100%
700,000	0.0%	0.0%	0.0%	100%	100%	100%
750,000	0.0%	0.0%	0.0%	100%	100%	100%
800,000	0.0%	0.0%	0.0%	100%	100%	100%
850,000	0.0%	0.0%	0.0%	100%	100%	100%
900,000	0.0%	0.0%	0.2%	100%	100%	99.8%
950,000	0.0%	0.1%	1.6%	100%	99.9%	98.4%
1,000,000	0.0%	1.0%		100%	99.0%	
1,050,000	0.5%	8.0%		99.5%	92.0%	
1,100,000	5.0%			95.0%		

Base Case at 1,100,000 and 1.5ºC at 1,050,000 are estimated from 20,000-year simulations.

The long-term downward trend in actual water deliveries towards 800,000 AF/year is now well below demand where finite risks were found by this analysis. In the 2016 calendar year 809,000 AF was delivered, and that volume can be sustained under the temperature simulations examined. The System can therefore be considered 100% reliable at the present time and for the rest of this century to the stipulated reliability criterion.

6.3.2.4 Refill Reliability

The distribution of time between replenishment of surface water in reservoirs is an instructive statistic for management and important to understanding system sensitivity to key variables. Refills of surface water storage can affect other operational decisions such as the amount of groundwater to be pumped or recharged. And, volume of water delivered can be as important as surface water supply that is vulnerable to climate change. Sensitivity of the System to the effects of water demand and temperature change on refilling events was therefore studied in this analysis.

The System typically attains its maximum storage in a water year with the conclusion of winter runoff, usually around the May 1st transition from winter to summer operations, although wet winters on the Salt can sometimes extend high flows into May. For this analysis total reservoir storage at each year's winter-summer transition was evaluated for whether it attained 100% of capacity, ≥90% of capacity, and ≥80% of capacity. Times between occurrences were tabulated for analysis. This was done for (1) the actual storage record (1931-2017), (2) the historical NBS record (1889-2017) evaluated with the ResSim reservoir operations model, (3) the tree ring NBS record (1361-2005) tested with ResSim, and (4) a 10,000 year simulation of NBS modeled with ResSim.

Temperature changes were applied with the hydrologic sensitivity functions to the tree ring and the 10,000 year simulation data, and two demand levels were tested: 800,000 AF/year and 900,000 AF/year. Average time between refills to the three capacity levels are given in Table 6-6.

The actual storage data record began with the Salt side of the System in 1931 and increments of reservoir capacity were added over time, the latest being the Roosevelt Lake expansion completed in 1996. Capacity used in calculations was what was available on the System at the time of storage measurement. Times between refills in the actual storage record were influenced by multiple factors which are not typical today. Water releases in earlier decades were significantly larger then, in part due to sizeable delivery system losses. The storage record prior to the 1970s indicates release protocols inconsistent with today's practice and unclear drought management guidelines.

Table 6-6: Average time between refills of reservoirs to the levels indicated

	Refill to 100% of Capacity (years)			**Refill to ≥90% of Capacity (years)**			**Refill to ≥80% of Capacity (years)**		
	Base Case	+1.5ºC	+3.1ºC	Base Case	+1.5ºC	+3.1ºC	Base Case	+1.5ºC	+3.1ºC
Actual 1931-2017	9.9			3.8			2.5		
Modeled 1889-2017 Historical NBS									
Demand: 800,000 AF/year	2.1			1.5			1.3		
Demand: 900,000 AF/year	2.5			1.8			1.4		
Modeled 1361-2005 Tree Ring NBS									
Demand: 800,000 AF/year	2.4	2.6	2.9	1.7	1.8	2.0	1.3	1.4	1.5
Demand: 900,000 AF/year	3.0	3.4	3.8	2.1	2.4	2.7	1.6	1.8	1.9
Modeled 10,000-Year NBS Simulation									
Demand: 800,000 AF/year	2.3	2.5	2.8	1.6	1.7	1.9	1.2	1.4	1.5
Demand: 900,000 AF/year	2.9	3.2	3.5	2.0	2.2	2.4	1.5	1.7	1.8

All modeled results employ the current system configuration and management guidelines which have been significantly updated over the past two decades. Precision of estimates for average time between refills can be expected to improve when longer records are analyzed, and this can be seen comparing Figure 6-15 with Figure 6-16 which contains more years of analyzed data. The 645-year tree ring results are similar to those from the 10,000 year simulation, confirming consistency of the findings.

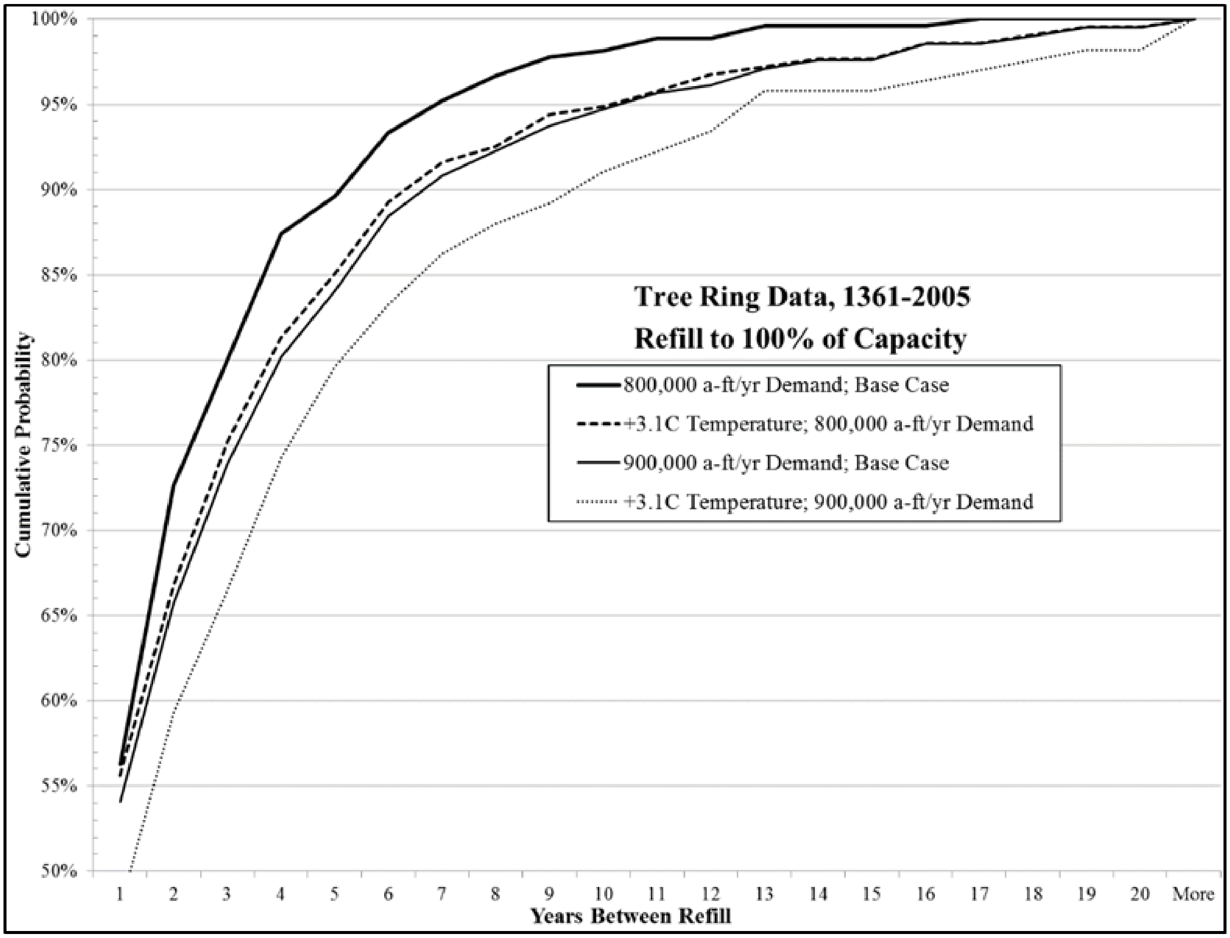

Figure 6-15: Probability distribution of time between system refills for the tree ring NBS data

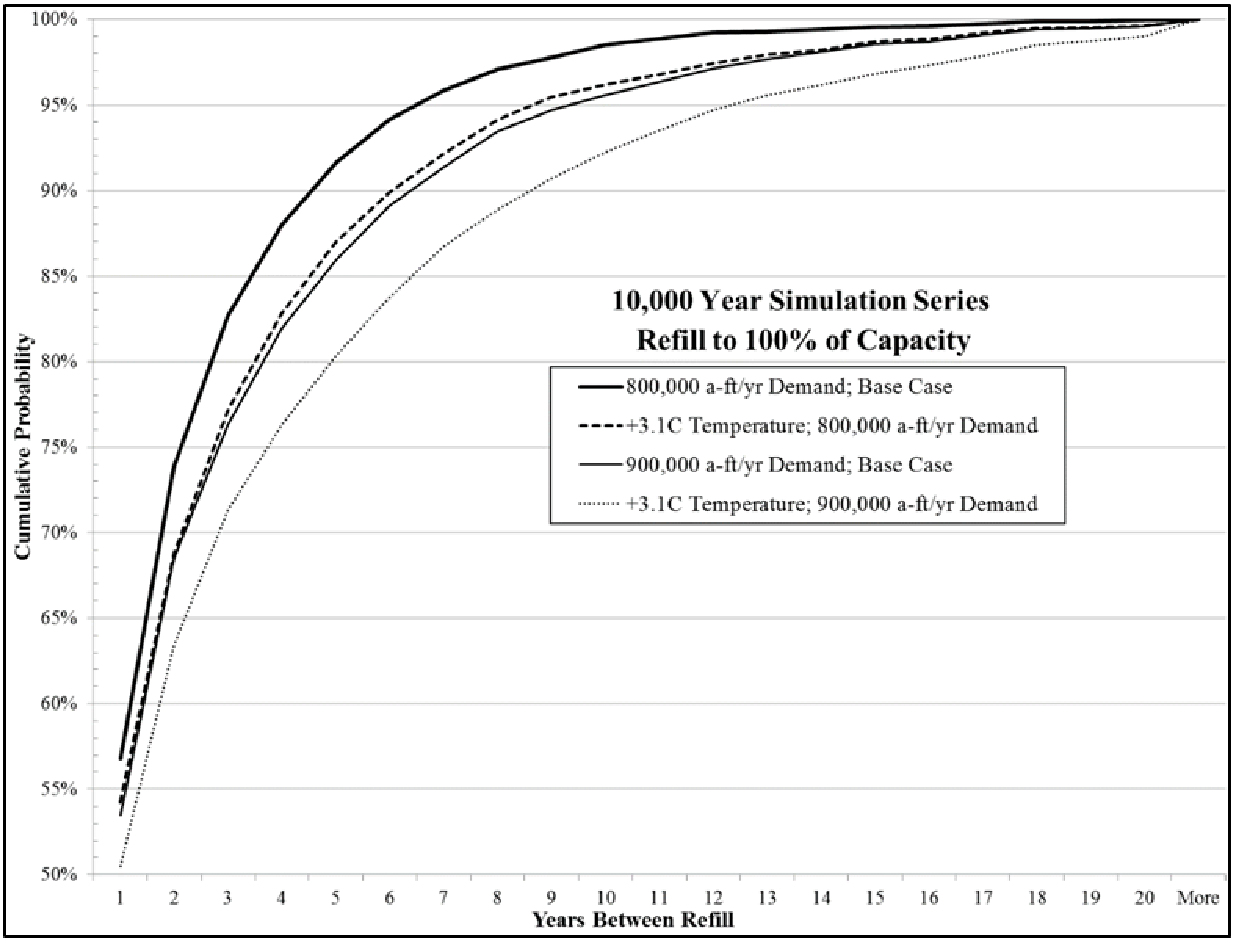

Figure 6-16: Probability distribution of time between system refills for a 10,000 year NBS simulation data series

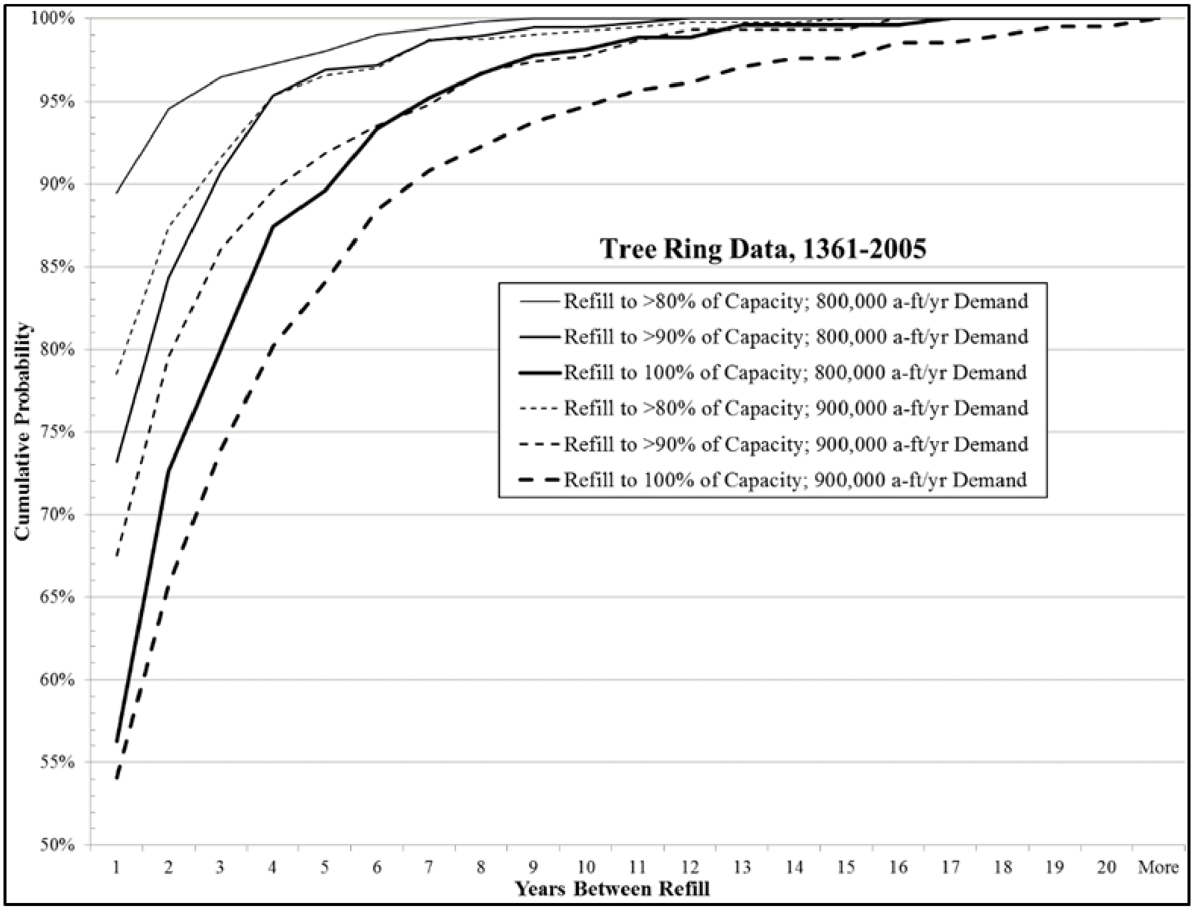

Figure 6-17: Probability distribution of time between reservoir refill levels, base case current system for the tree ring NBS data

Average times between refills are now all less than a few years, although it is important to note those values are averages over multiple centuries of data. More informative are the probability distributions of time (Figures 6-15, 6-16, 6-17), which shows there are finite probabilities of several years between a refill. The demand and temperature sensitivities are evident in the characteristic curves. The 3.1^{o}C temperature increase shifts the curves from a negligible amount to as much as 2 years. The 900,000 AF/year curve shifts to longer refill times with the imposition of a +3.1^{o}C temperature change; but, when demand is then reduced to 800,000 AF/year the curve returns to a similar position with the same temperature change. So, there is an approximate 100,000 AF/year demand offset for +3^{o}C temperature change, which is similar to the finding for System reliability at low storage levels. This sensitivity tradeoff therefore is present across the range of reservoir response, from near-depletion to nearly full conditions.

6.3.2.5 Groundwater Pumping

The SRP System supplements surface water deliveries with groundwater pumped within the service area, and the pumping rate is a function of remaining reservoir storage that ranges from 50,000 AF/year to a self-imposed limit of 325,000 AF/year (Phillips et al. 2009). To the extent that reservoir storage is a function of demand and temperature change then groundwater pumping will be as well. This was analyzed with the 120,000 year NBS time series simulation. The probability distribution of water pumped as a percentage of what is delivered is given in Figure 6-18.

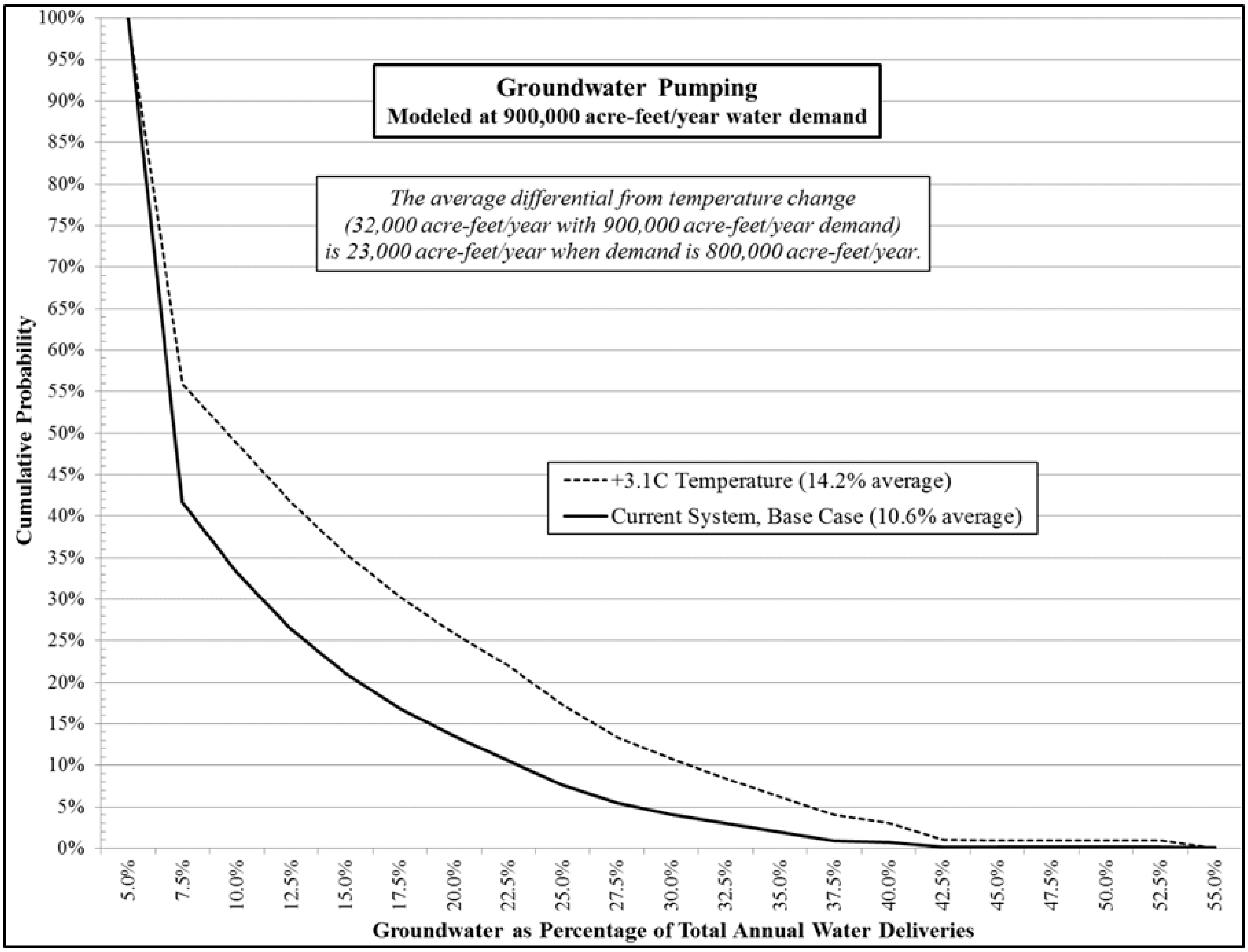

Figure 6-18: Probability distribution of groundwater as percentage of total water delivered by the current System and with a temperature increase

More groundwater is required with a +3.1oC average temperature and the distribution shifts upward; but, it returns to a similar position when demand is reduced by 100,000 AF/year at the +3.1oC temperature (not shown). This offset is similarly found in the other sensitivity analyses. The long-term average incremental amount of groundwater pumped is 32,400 AF/year when demand is 900,000 AF/year. That amount is lower (~23,000 AF/year) when demand is 800,000 AF/year. This finding can inform preparatory groundwater recharge plans with a quantitative expectation that marginally more pumping might occur in the future.

6.3.2.6 Reservoir Water Spill

When storage capacity of reservoirs is exceeded during wet periods, excess water is spilled and passes through the Salt River Valley in the Phoenix metropolitan area, Arizona and on to the Gila River while providing some recharge of groundwater from the streambed. A full condition of the reservoirs is a function of cumulative water deliveries and can be affected by temperature change. Using the 120,000 year NBS time series simulation, the probability of spillage during the summer season is negligibly small. However, there is a finite probability distribution of spillage during the winter season over the long term, which can amount to a significant surface water resource passing through the system. The probability distribution is given in Figure 6-19 for the 900,000 AF/year demand, and the effect of a +3.1^{o}C average temperature increase is shown. On average, 12% less water is spilled with that temperature increase. The curve shift with 3.1^{o}C higher temperature can be offset by 100,000 AF/year of reduced water demand. Spillage is on average 20% larger with the lower 800,000 AF/year demand for the base case and the higher temperature case. This demand-temperature tradeoff is similarly found in the other sensitivity analyses.

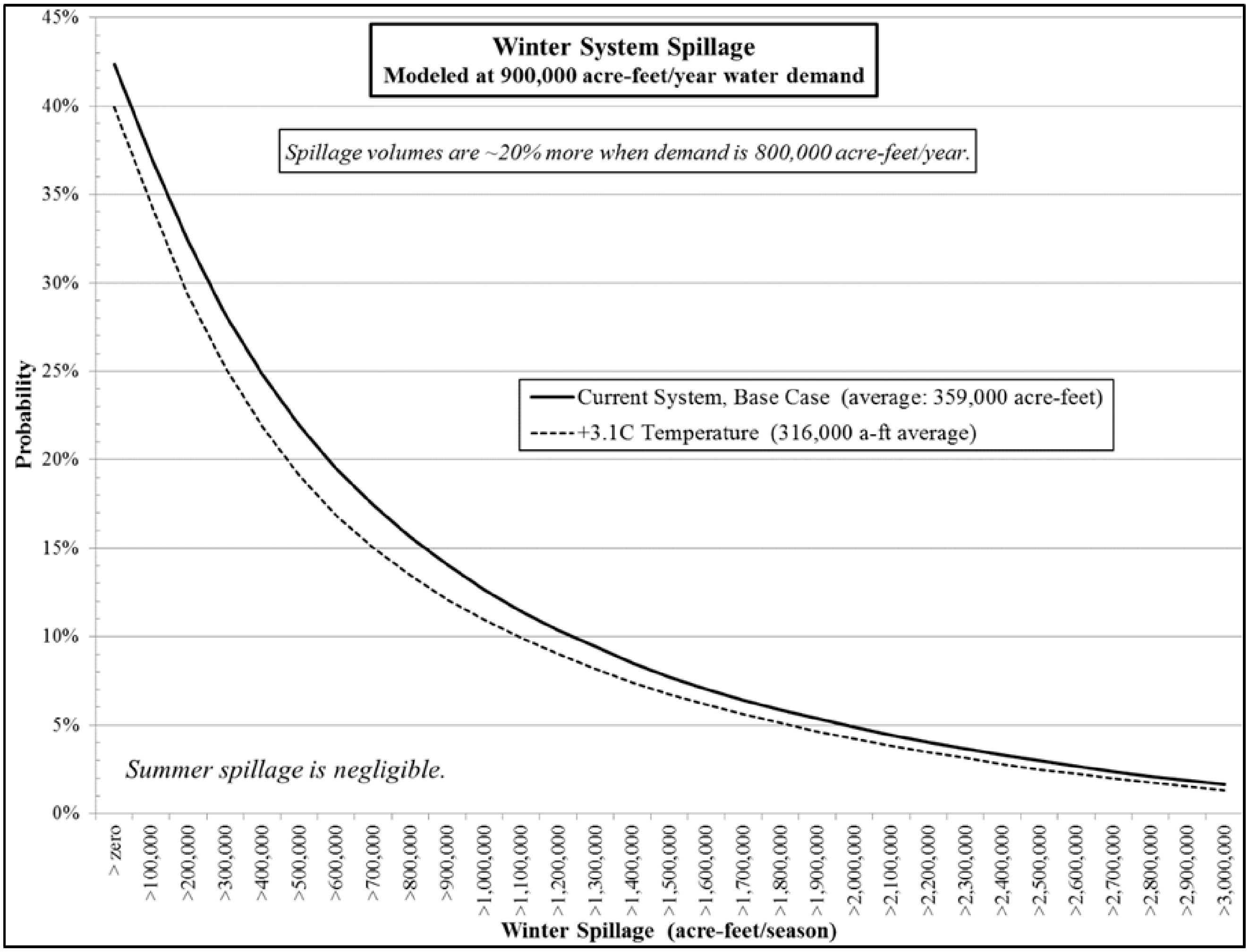

Figure 6-19: Probability distribution of water spillage from the System for the current System and with a temperature increase

6.4 Conclusions

Since temperatures have increased above levels of natural background variability in historical records there are expectations of persistent temperature change in the Salt-Verde watersheds. The exact amount of future change remains uncertain, but estimates can be made and the effects from a bounded range of temperature increase assessed.

Despite demonstrated high variability, no persistent change of precipitation, either increasing or decreasing, is evident in the historical record of the watersheds. And, there are no conclusive findings from research to date whether there will be any trend in the future. Results of climate model analyses for this study are consistent with that observation. Whether a persistent precipitation change will emerge remains highly uncertain.

Therefore, climate impacts and recommendations based upon evidentiary findings for temperature change alone can provide guidance to water management with some degree of confidence. If any specific actions are advised, then consideration of speculative future precipitation consequences can be incorporated to those deliberations although without specific quantitative expectations beyond the demonstrated envelope of natural variability until future research clarifies.

Findings from the period change analyses indicate that the SRP System is reliable for the balance of this century within the range of anticipated water demand and temperature change. There are finite but small probabilities of low reservoir storage conditions that might necessitate implementing conservation measures, but recent experience (such as 2002-2004) has informed adaptive water management for such threatening periods. Although demand trends are declining, it appears feasible to service higher demand than is being currently delivered, although with marginally higher attendant operating risks. If such a need arises in the future a reassessment of temperature changes should be undertaken at that time for risk updates. At the present time analyses indicate a System performance tradeoff of approximately 100,000 AF/year of deliveries for a +3^{o}C average temperature change to maintain similar operating performance. The recent decline in deliveries has accordingly positioned the System for a warmer future.

The System's response to drought has been clarified in this study and provides instructive guidance to drought management practice. It is appropriate to consider every year as the start (or continuation of) a drought with the objective of slowing reservoir storage reduction towards the level at which actions are necessary to reduce water allocation to the service area. The cumulative effect of low NBS on storage revealed in drought examples such as Figure 6-13 is similar to studies of other more severe ones from time series simulations and in what was actually experienced during the 1999-2004 drought. Results demonstrate that the strategy and tactics managing the progression towards low storage levels must be an essential focus of decision makers in sustaining the System. Slowing the storage reduction can be accomplished by any combination of the following options: (a) diversification of water supply with sources from outside the current System configuration, (b) modification of operating protocols, or (c) increasing reservoir storage capacity to a higher starting level to catch runoff when it is available and provide a larger operating storage range.

The findings of this study indicate no need at the present time to act upon option (a). Current operating protocols appear to address and minimize system risks, and no actions on option (b) are indicated at the present time. However, the finding of effects on groundwater requirements due to elevated temperatures can inform groundwater recharge programs in anticipation of future needs. Based upon the finding of finite probabilities of significant winter spillage from the System in wet periods there is a potential to address option (c) through capture of that water resource for further risk reduction. The capacity expansion of Roosevelt Lake in 1996 provided an important System risk reduction, and natural variability provides an opportunity for more should management strategy align with that objective.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Transient Method

Results from the 64 climate model simulations indicate significant challenges in their interpretation. Many of the simulations display precipitation and streamflow behavior for both the reference (1950-2005) and projected (2006-2099) periods that is significantly different than the historic record. The summer season exhibits the greatest biases with precipitation which are amplified in streamflow results. In turn, this produces anomalous reservoir releases during the summer and confuses the interpretation of winter season effects on reservoir operations. To mitigate this issue, historical monthly summer inflows were used in place of the simulated summer inflows.

In addition to the summer season precipitation and streamflow biases, winter season results indicate a wet bias of inflows in the low to middle portions of the inflow distribution while exhibiting a dry bias at the upper end of the distribution. This results in drought years having too much inflow into the reservoir system and in comparison, the replenishing wet years having too little inflow. In turn, reservoir release is greater and groundwater pumping is less for the majority of the simulations during both the reference and future periods in comparison to equivalent modeling with the observed record. However, total spill volume is less than the modeled observed period while system storage is greater.

To gain an interpretation of hydrology behavior, runoff efficiency of the 64 GCM-hydrology simulations was analyzed. In general, a watershed will display low efficiencies at low precipitation levels and increasing efficiency with higher precipitation values, which provides a way to examine simulation model results for consistency with observed historic behavior. Declining runoff efficiency with increasing precipitation occurs with some of the simulations, which is inconsistent with hydrologic expectations. These occurrences create another challenge when analyzing simulated reservoir inflows.

Several of the 64 downscaled GCMs displayed upward and downward trends in future simulated precipitation patterns. Other research for this region concludes that although there is certainty of continued warming in the future, no trend in precipitation can yet be identified nor can it be concluded whether one will emerge in the future. Any trends in future precipitation from the models should therefore be scrutinized. The non-stationarity of projected GCM precipitation data becomes a concern since the downscaled GCM projections used in this study are inconsistent, unexplained, and creates a lack of confidence in the data.

In view of these challenges, applying all 64 simulations and their representations of potential differences in the future climate on SRP operations are not prudent. However, to meet the objectives for the Study, the three wettest and three driest simulations were identified to analyze for future water supply and flood implications. Results from the detailed analysis did not indicate any significant differences from historical data that would alter current operating protocols of the SRP system. Inflows from the wet simulations fell well short of the PMF, but resulted in greater reservoir release. Two of the dry simulations did indicate at least one period of reduced water allocation to users but never came close to depleting the System, similar to reservoir modeling of the observed period.

However, confidence is low in the representativeness of the 64 simulations (including the three wet and three dry ones), and the identified wet bias may hint at the possibility that the driest future simulations are not dry enough. Similarly, the low bias in the upper percentiles does not lend confidence to any simulated changes in the PMF. The PMF analysis here was an attempt to overcome this low bias and quantify the largest projected floods in the 64 climate simulations. A more complex PMF analysis would not be prudent and the underlying assumptions in the PMF analysis (i.e., the largest floods occur in the wettest winters and the wettest simulations produce the largest floods) provided a simple and efficient way to quantify the largest projected floods in the 64 simulations. An improved climate data set and hydrology model would be needed before management could have confidence in simulations of the future that would indicate changes to reservoir operations and strategies using the transient method results.

Developing a GCM precipitation downscaling methodology that performs better for lower mid-latitude mountainous terrain (e.g., better representation of summer precipitation) would be an important next step for future study.

7.2 Period Change Method

Results for the period change methodology using 120,000 simulated years of inflows indicate that reductions of approximately 10% in typical NBS are possible with a future average temperature increase of 3.1°C. However, decreases in NBS relating to temperature are not linear. It was found that sensitivity to temperature is greatest when temperature is high and inflows are lowest, making the summer season inflows most vulnerable to temperature change. However, the summer season contributes a small portion of annual NBS. Roughly half of the summer temperature sensitivity is related to evaporative losses from the reservoirs themselves. Winter season NBS, which is relied upon to replenish reservoirs, is less temperature sensitive; and, wet years drown out much, if not all, of the climate change temperature signal.

A similar analysis was performed for the paleoclimatology developed by researchers at the Laboratory of Tree-Ring Research. In particular, a three decade mega-drought in the late 16th century was analyzed in detail. Results suggest that this drought presented in the same future temperature climate as the simulated years would result in a couple years where surface water supply allocation would need to be reduced, but reservoir storage was never fully depleted. These results are similar to the recent actual drought years of the early 21st century (1995 to present) when demand has been declining from 900,000 to 800,000 AF/yr. If future demand returned to 900,000 AF/year, then a mega-drought (past or present) could entail a few years of reduced water allocation deliveries; but once again, the system is never depleted.

In summary, results from the period change methodology indicate that surface water delivery from the reservoirs with supplemented groundwater is reliable through the end of this century with anticipated climate change and water demand volumes. However, if demand increases and/or temperatures increase beyond current projections, marginal risks to water supply reliability could develop.

7.3 Recommendations

An exhaustive and complete study using two accepted research approaches were employed to understand vulnerabilities of SRP's water supply reliability and ability to manage extreme events in the future. Both methodologies suggest that SRP's current operational strategies are sufficient to maintain a secure and reliable water supply to its downstream shareholders.

The wet biases identified in the transient method limits confidence in its application to simulation of projected reservoir operations. The identified uncertainties create a need for potential future work related to improving hydro-climate simulations which would improve the usefulness of those results.

The period change method suggests minor reductions in system reliability in the unlikely simulation of water demand increases beyond current expectations or future temperature increases exceeding the range explored in this Study. The projected reliability reductions can most likely be addressed through appropriately timed conservation measures and adaptive management policies.

The results for this Study indicate that current operational strategies adequately address future water supply reliability. However, if new knowledge is presented related to the future hydro-climate of the Salt-Verde watershed, future strategies to address water supply reliability could involve any combination of securing additional water sources from outside the current System, changes to current reservoir operations, and increasing storage capacity within the System, although no specific actions in those areas are indicated at the present time.

Knowing that the system is reliable against a range of future conditions gives SRP confidence that operating the reservoir system under its current procedures will ensure a sustainable water supply for its shareholders. These findings can inform other water managers of the importance of system design, and how research performed for the Storage Planning Diagram can help water managers guide water system operations.

However, this study also identified the need for next steps and future research listed below:

- Sedimentation and demand studies to further increase the confidence on potential operational and infrastructure changes due to an increase in sedimentation and system demand.
- Development of new GCM precipitation downscaling methodologies that perform better for lower mid-latitude mountainous environments and convective precipitation (e.g., better representation of summer precipitation).
- Improved hydrologic modeling (e.g. VIC and/or SAC-SMA) to reduce biases for lower mid-latitude environments such that the hydrologic models represent the full range of hydrologies (e.g. realistic representation of the precipitation/hydrology response).

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Definitions

Basin	Used interchangeably with the term watershed.
Customer	Any person or entity to whom/which SRP delivers water.
Downscaling	Any procedure to infer high-resolution information from low-resolution variables.
future time period	For this study the period from 2006 - 2099.
incidental take	To harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct that results from, but is not the purpose of, carrying out an otherwise lawful activity.
Inflow	That part of the streamflow that enters the reservoir (see Runoff).
precipitation elasticity of runoff	The percentage change of runoff for the percentage change in precipitation.
Release	Controlled release of excess water from the reservoir outlet works including valves, turbines, river outlet works and spillways.
Roosevelt Dam	Includes the original Theodore Roosevelt Dam and the Modified Theodore Roosevelt Dam.
Roosevelt Lake	Reservoir formed by Roosevelt Dam.
Runoff	That part of the precipitation, snow melt, or irrigation water that appears in uncontrolled (not regulated by a dam upstream) surface streams, rivers, drains or sewers. Runoff is used interchangeably with inflow.
runoff efficiency	A coefficient relating the amount of runoff to the amount of precipitation received.
service area	Land within the boundaries of the Salt River Reservoir District.
shareholders	Owners of land within the Salt River Reservoir District governed by the Association Articles of Incorporation as amended and Federal reclamation laws who are entitled to water delivery from the Salt River Valley Water Users Association upon payment to the Association of the assessment, fees or other charges fixed by the Board of Governors of the Association.
spill or spillage	Excess inflow to the reservoir which cannot be stored for future use and which is released through the dam's outlet works downstream. Used interchangeably with the term release.
Streamflow	The water discharge that occurs in a natural channel. A more general term than runoff, streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

System	Salt River and Verde River Reservoir System (operated by SRP).
total annual inflow	The total system inflow from October 1 through September 30.
total system inflow	The sum of streamflow at Verde River below Tangle Creek, Salt River near Roosevelt and Tonto Creek above Gum Creek.
water delivery requirements	Water delivered to shareholders, contract holders and other customers.
water demand	Water to be released from the reservoirs to meet the water delivery requirements (includes river and canal losses).
water year	Period from October 1 through September 30
Watershed	A watershed is an area of land that drains all the streams and rainfall to a common outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel. The word watershed is sometimes used interchangeably with drainage basin or catchment.

APPENDIX A - SNOW WATER EQUIVALENT ANALYSIS

VIC provides simulations of SWE, or the depth of liquid water if a column of snow was melted, at each grid cell. While these simulations of SWE are not bias-corrected to observed records, we present change results which compare historical simulated SWE to future simulated SWE. The assumption in examining changes is that biases are consistent between the historical and future simulations. Mean first-of-month SWE was calculated for each grid cell for the historical period (1950-1999) using VIC simulations forced with the Livneh et al. dataset, and for three future periods, the 2020s (2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099), using the set of dry and wet GCM projections shown in Table A-1.

From the set of 64 downscaled GCM projections, a set of three dry projections and a set of three wet projections were identified and are listed in Table A-1.

Table A-1: Wet and dry GCMs and simulations (RCPs)

Dry GCMs and Simulations	Wet GCMs and Simulations
cmcc-cms_1 RCP4.5	cesm1-bgc_1 RCP4.5
ipsl-cm5a-lr_1 RCP8.5	csiro-mk3-6-0_1 RCP8.5
miroc5_1 RCP4.5	mri-cgcm3_1 RCP8.5

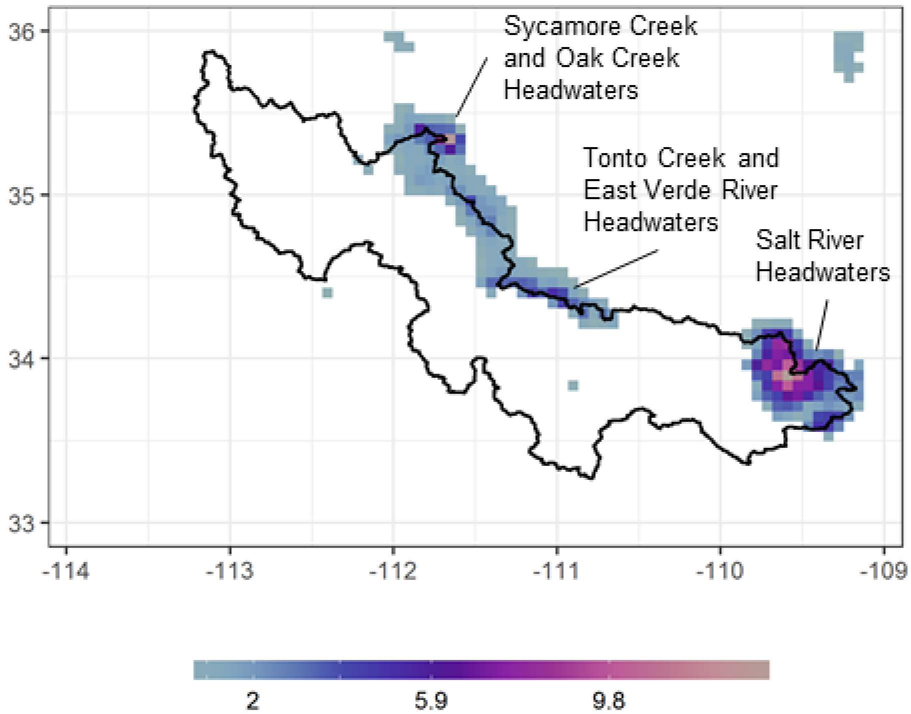

Figure A-1: Mean March 1 SWE for the 1950-1999 historical period in inches. SWE extents are from VIC simulations with SWE less than half an inch masked

The black line delineates the Salt-Verde watershed above Roosevelt Dam**.**

Figure A-1 shows VIC simulated SWE for the historical period, with SWE values less than half an inch masked. Regions of significant SWE include the headwaters of the Salt River, the headwaters of Tonto Creek and the East Verde River, and the headwaters of Sycamore Creek and Oak Creek. SWE in these headwaters areas range from 4 inches to 13.25 inches.

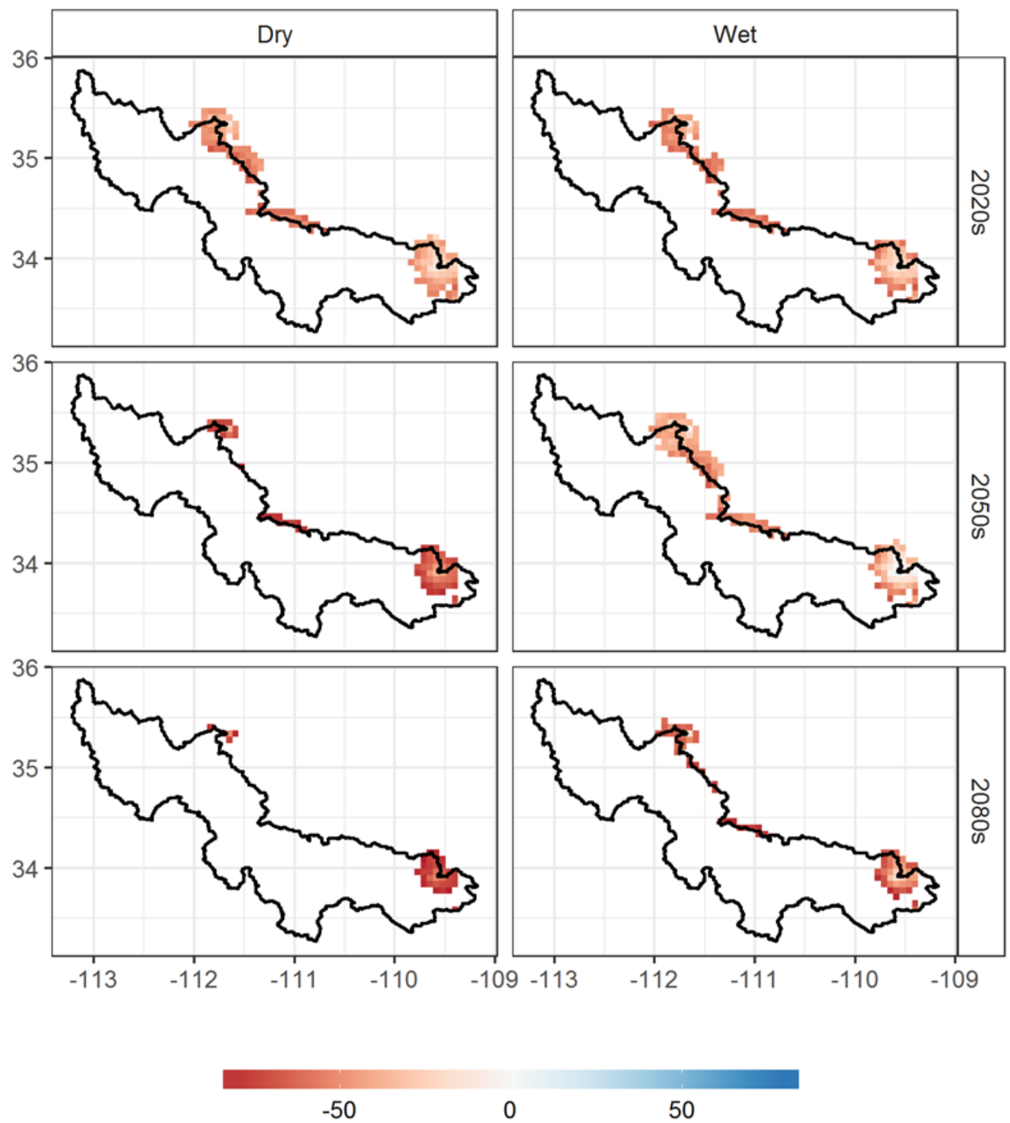

Figure A-2: Mean March 1 SWE change in percent for the dry GCM projections (left) and wet GCM projections (right) and for the three future periods, 2020s (top), 2050s (middle), and 2080s (bottom). Changes are shown relative to the 1950-1999 historical period. SWE extents are from VIC simulations with SWE less than ½'' masked

The black line delineates the Salt-Verde watershed above Roosevelt Dam.

Figure A-2 shows the change in mean March 1 SWE for the dry and wet GCM projections in the three future periods. In the 2020s SWE is still present in all three regions seen in the historical simulation, however the spatial extent of SWE greater than half an inch has shrunk for both the dry and wet projections. This decrease in extent is even more apparent in the 2050s, with Sycamore and Oak Creek headwaters region and the Tonto Creek and East Verde River headwaters region greatly reduced in the dry projections. By the 2080s, in the dry projections

SWE has completely disappeared in the Tonto Creek and East Verde River headwaters region and has almost disappeared in the Sycamore and Oak Creek headwaters region. The minimum and maximum SWE changes for each of the headwaters regions are shown in Table A-2. These changes correspond to the changes seen in Figure A-2.

Table A-2: Mean March 1 SWE changes

Salt River Headwaters						
	2020s		2050s		2080s	
Change	Dry	Wet	Dry	Wet	Dry	Wet
Maximum	-64%	-70%	-83%	-70%	-88%	-86%
Minimum	-12%	-12%	-38%	5%	-54%	-18%

Tonto Creek and East Verde River Headwaters						
	2020s		2050s		2080s	
Change	Dry	Wet	Dry	Wet	Dry	Wet
Maximum	-72%	-68%	-83%	-70%	-	-85%
Minimum	-49%	-51%	-77%	-43%	-	-78%

Sycamore Creek and Oak Creek Headwaters						
	2020s		2050s		2080s	
Change	Dry	Wet	Dry	Wet	Dry	Wet
Maximum	-69%	-67%	-79%	-61%	-85%	-77%
Minimum	-14%	-13%	-37%	-6%	-52%	-17%

With the exception of a slight increase in SWE for some grid cells in the Salt River headwaters region in the 2050s wet projections, decreases are seen across all three regions, for all three future periods, and for both the dry and wet projections. The Tonto Creek and East Verde River headwaters region sees the greatest decreases in SWE. 2020s decreases for both the dry and wet projections are comparable and range from ~50 to 70%. By the 2050s, dry projections show decreases of 77 to 83% while wet projections show decreases of 43 to 70%, similar to the 2020s. By the 2080s, there is no SWE left in the dry projections, while there are decreases of 78 to 85% in the wet projections. Changes in SWE for the both the Salt River headwaters and Sycamore Creek and Oak Creek headwaters regions are similar. In the 2020s, both dry and wet projections show decreases of ~10 to 70%. In the 2050s, there is some distinction between projections, with the dry projections showing decreases of ~40 to 80% and the wet simulations decreases of ~0 to 70%. The 2080s show a similar distinction, with dry projections showing decreases of ~50 to 85% and the wet projections showing decreases of ~20 to 85%. It is important to note that these changes in SWE are found using only cells with simulated SWE greater than half an inch. As seen in Figure A-2, throughout the future period there are decreases in the extent of SWE across all three regions.