Appendix G

US Bureau of Reclamation Mojave River Watershed Climate Change Assessment

RECLAMATION
Managing Water in the West

Technical Memorandum No. 86-68210-2013-04

Mojave River Watershed Climate Change Assessment

Mojave Watershed, California
Lower Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
Lower Colorado Region
Technical Service Center
Denver, Colorado

Mojave Water Agency

September 2013

Mission Statements

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

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

Cover Photo: Mojave River Forks Dam with the San Bernardino Mountains in the background.

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Mojave River Watershed Climate Change Assessment

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U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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Acronyms and Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
AB 32	Assembly Bill 32: The Global Warming Solutions Act
AF	acre feet
AFY	acre feet per year
BAP	Base Annual Production
BCSD	Bias-Correction Spatial Disaggregation
CAT	Climate Action Team
CBO	Congressional Budget Office
CDF	Cumulative Distribution Function
cfs	cubic feet per second
CMIP3	Coupled Model Intercomparison Project Phase 3
CO_2e	carbon dioxide equivalent
Delta	Sacramento-San Joaquin Delta
DOE	U.S. Department of Energy
EO	Executive Order
EVA	Extreme value analysis
FPA	Free Production Allowance
GCM	Global Circulation Models
GEV	generalized extreme value
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IRWM	Integrated Regional Water Management
HDWD	Hi-Desert Water District
km	kilometer
km^2	square kilometers
MAF	million acre-feet
MGD	million gallons per day
mi^2	square miles
msl	mean sea level
MWA	Mojave Water Agency
MWD	Metropolitan Water District of Southern California
NLLH	negative log likelihood
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
Reclamation	Bureau of Reclamation
SWE	Snow Water Equivalent
SWP	California State Water Project
TAF	thousand acre feet
TDS	total dissolved solids
UK	United Kingdom
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WET-CAT	Water-Energy group
VIC	Variable Infiltration Capacity

Executive Summary

This report details a climate change assessment of the Mojave River watershed completed by the Bureau of Reclamation (Reclamation) in cooperation with the Mojave Water Agency (MWA). The analysis consists of three tasks:

1) Assess future surface water supplies, including native flows and imports (see Chapter 2)

2) Project potential changes in flood frequency (see Chapter 3)

3) Conduct a greenhouse gas emissions (GHG) inventory for the water sector (See Chapter 4)

An introduction chapter (Chapter 1) provides background of the MWA study area along with water supply and demand settings.

The MWA service area spans 4,900 square miles in San Bernardino County in Southern California, shown in Figure ES-1. The area has very limited water supplies. It is classified as High Desert, and precipitation and runoff throughout the basin are highly variable. Most of the native surface water originates from ephemeral streams draining from the San Bernardino and San Gabriel Mountains. Significant surface water is also imported from the California State Water Project (SWP) through contracts held by MWA.

Groundwater resources are vitally important to water management within the agency boundary. Since groundwater production started in the 1900s, extraction has greatly expanded, and groundwater supplies are currently used to meet the vast majority of demand. However, since the 1950s, groundwater overdraft has been a recognized problem within the basin. As a result, in recent years an adjudication system has been put into place in an effort to curb overdraft.

Future Water Supply Assessment

The first task of this project was to quantitatively assess the impact of climate change on total surface water supply for the MWA—both natural surface water flows within MWA service area and projected changes in availability of SWP water supply.

Overall, increasing annual flows are projected for all three locations analyzed by 2020; however, seasonal results vary, for example, April to July runoff is expected to decrease. Furthermore, SWP deliveries are projected to be slightly lower than the estimates used in previous planning studies.

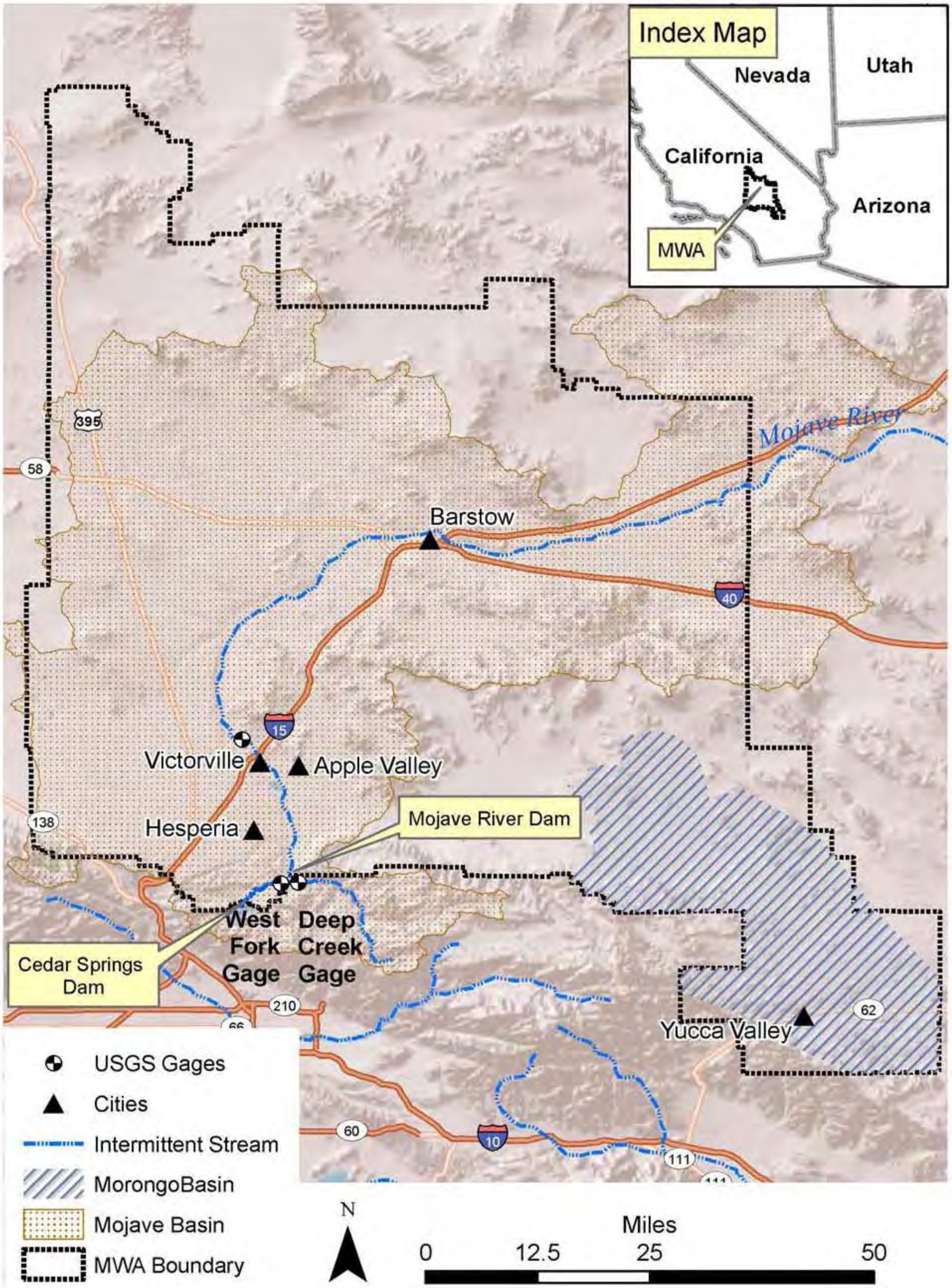

Figure ES-1. Map of the study area.

Climate change analysis of natural flows within MWA follows the methodology established for the West-wide Climate Risk Assessment (Reclamation 2011). Downscaled climate variables were extracted from 112 Global Circulation Model (GCM) projections and used to force hydrologic simulations of the basin from 1950 through 2099 using the macro-scale Variable Infiltration Capacity (VIC) model.

Native Flow

Simulated flows were analyzed at three locations corresponding to USGS gaging stations (gages): the Deep Creek, West Fork, and Lower Narrows.

The first two locations capture the two primary tributaries to the Mojave River just before their confluence at the Forks. The third location is on the main stem of the Mojave River, downstream of where it emerges from the mountains.

Analysis of climate forcings (i.e., precipitation and temperature) in the basin shows slight declines in precipitation with large variability and clear increases in temperature with increasing uncertainty moving further into the future.

Projections of native flow within the Mojave Basin show significant variability at the three gages analyzed for the 2020 time period. The median projected change in annual flows for all three stations over this time period is positive; however, seasonal results vary (e.g., the median trend in April to July runoff is expected to be negative). Furthermore, there is significant variability between climate projections and the range of future predictions includes both increases and decreases in annual flow.

Natural flows were also projected out to the 2050s and 2070s. Results show greater decreases in flows moving further into the future, especially in the spring/summer runoff season (April through July).

Imported Flow

Future SWP imports were analyzed using the most recent SWP Reliability Report from the State of California (2012a). Previous regional climate change studies have projected increased temperatures and winter precipitation, and declines in snowpack resulting from the warming trend. By mid-century, it is predicted that Sierra Nevada snowpack will reduce by 25 to 40 percent from the historical average. Decreased snowpack is projected to be greater in the northern Sierra Nevada, closer to the origin of SWP water, than in the southern Sierra Nevada. Furthermore, an increase in “rain on snow” events may lead to earlier runoff. Results from the SWP Reliability Report for the 2020 time period indicate a slight increase in annual natural flows (less than 5 percent), and SWP deliveries slightly lower than the estimates used in previous planning studies (the 2010 MWA Urban Water Management Plan estimated deliveries of 54 TAF [MWA 2011b]).

Flood Frequency

The second task of this project was to use climate projections to analyze future flood frequency.

Overall, results do not indicate a clear increase in flood risk for either location. These finding are consistent with the water supply analysis.

Although many reaches of the Mojave River remain dry for the greater part of the year, the Mojave River can experience large flood events. The majority of flooding takes place during the cool season from December to March, when multi-day, widespread storms saturate the headwaters.

Flood frequency was analyzed at two locations along the Mojave River: the Lower Narrows near Victorville (at the same location as the water supply analysis) and at the Forks (where Deep Creek and West Fork converge) just upstream of the Mojave River Dam. Non-stationary generalized extreme value (GEV) functions were used analyze how changing climate conditions may influence flood frequency at both locations. Models were fit to historical streamflow and climate data such that the parameters of the function vary with precipitation and temperature. Future estimates of precipitation and temperature generated from 112 global climate model projections were then used to fit GEV distributions for future periods and to estimate potential changes in flood frequency.

Analysis focused on two flood rates: 7,250 cubic feet per second (cfs) (when the Mojave River Dam starts to attenuate flows) and 23,500 cfs, (the maximum flow rate through the dam). The 112 GCM projections vary in precipitation and temperature projections. The GEV model results for both locations correspondingly show variability between projections that spans both increased and decreased flood frequency. However, there are no clear trends.

Greenhouse Gases

The third task was to determine GHG emissions from 1990 through 2050 for the MWA service area. To do this, a GHG Emissions Calculator was developed to evaluate emissions from the water sector. We used this calculator to determine GHG emissions from 1990 to 2050 for the MWA service area.

Overall, reducing water demand or lowering volumes of imported water would reduce GHG emissions. However, it is likely that a combination of measures will be required to meet the GHG emission reduction and water conservation targets laid out in California's legislation.

Large amounts of energy are required to develop, treat, and transport water. Also, large amounts of water are needed to produce electrical power. The interdependence of water and energy has long been referred to as the water-energy nexus." Energy production results in GHG emissions, thus, conserving water lowers GHG emissions.

Recognizing the need for action, California has put in place ambitious GHG emission reduction and water conservation goals:

- **GHG Emission.** California Assembly Bill 32 (AB 32) requires that every major financial sector in California, including water (i.e., developing, treating. and delivering water), reduce its GHG emissions to the 1990 levels by 2020, and to 80 percent below the 1990 levels by 2050.

- **Water Conservation.** In February 2008, California directed State agencies to develop a plan to reduce statewide per capita urban water use by 20 percent by the year 2020.

Reclamation developed the GHG Emissions Calculator—an important tool for decision makers to evaluating impacts to GHG emissions when developing water supply plans. The GHG Emissions Calculator can be used to evaluate a variety of measures to reduce GHG emissions, including changes to water supply portfolio, gray water reuse, and rainwater harvesting (Reclamation 2013).

While other energy reducing methods are possible (e.g., using renewable energy, graywater reuse, and adjusting the water supply portfolio), this study analyzed whether water conservation measures alone would be enough to meet AB 32 GHG emission reduction targets in the MWA service area. Results from the GHG Emissions Calculator show that a 20 percent reduction in water use by 2020 will not be sufficient to meet these goals. Rather, water use would have to be reduced further to meet the AB 32 targets for GHG emissions by:

- **AB 32 Year 2020 Target (i.e., 1990 GHG emission levels)**. Lowering GHG emissions using water conservation only would require reducing water use by 44 percent from the No Action baseline scenario[1].

- **AB 32 Year 2050 Target (i.e., 80 percent below 1990 GHG emission levels).** Meeting these requirements would necessitate a 44 percent reduction in water use by 2020, followed by an additional 50 percent each decade.

[1] The GHG Emissions Calculator was used to develop this baseline water use based on future population, water demands, and other factors.

1. Introduction

1.1 Background and Introduction

1.1.1 Study Area

The Mojave Water Agency (MWA) in Southern California spans 4,900 square miles in San Bernardino County. The agency encompasses two major drainage areas: the Mojave River area and the Morongo Basin/Johnson Valley area. This study focuses on the adjudicated boundary of the Mojave Basin area shown in Figure 1, which includes roughly 3,800 square miles (mi^2).

1.1.2 Physical Setting

The study area is classified as High Desert, part of the Mojave Desert. Elevations within the area range from 5,500 feet mean sea level (msl) in the mountains in the south to 1,500 feet msl in the east.

Surface Water

Precipitation and runoff throughout the basin are highly variable; most of the surface water originates from ephemeral streams draining from the San Bernardino and San Gabriel mountain ranges.

Originating in the San Bernardino Mountains, the Mojave River is the largest drainage system in the Mojave Desert (Feller 2013). The Mojave River has been referred to as an "upside-down" and "backwards" river (Feller 2013). "Upside-down," because water flows underground in large portions of the river and "backwards," because it flows north away from the coast rather than draining to the coast.

Fed by rainfall and snowpack in the San Bernardino Mountains, Deep Creek and the West Fork of the Mojave River converge at the Forks (also the location of Mojave River Dam); and the Mojave River drains to the north and then east and terminates in the Soda and East Cronese Lakes (in California but outside of the study area). These two terminal lakes are dry and only pond water after large storms. Most of the river is also ephemeral—only flowing immediately after storms. The river is perennial upstream of the Forks and downstream near Upper and Lower Narrows, Afton Canyon and downstream of the Victor Valley Wastewater Treatment Plant.

The Morongo Basin/Johnson Valley Area is in the southeastern portion of the agency area. It has no sizeable rivers—only small, ephemeral streams fed by mountain runoff. Runoff from these streams either percolates into the stream beds or flows to dry lake beds where it evaporates.

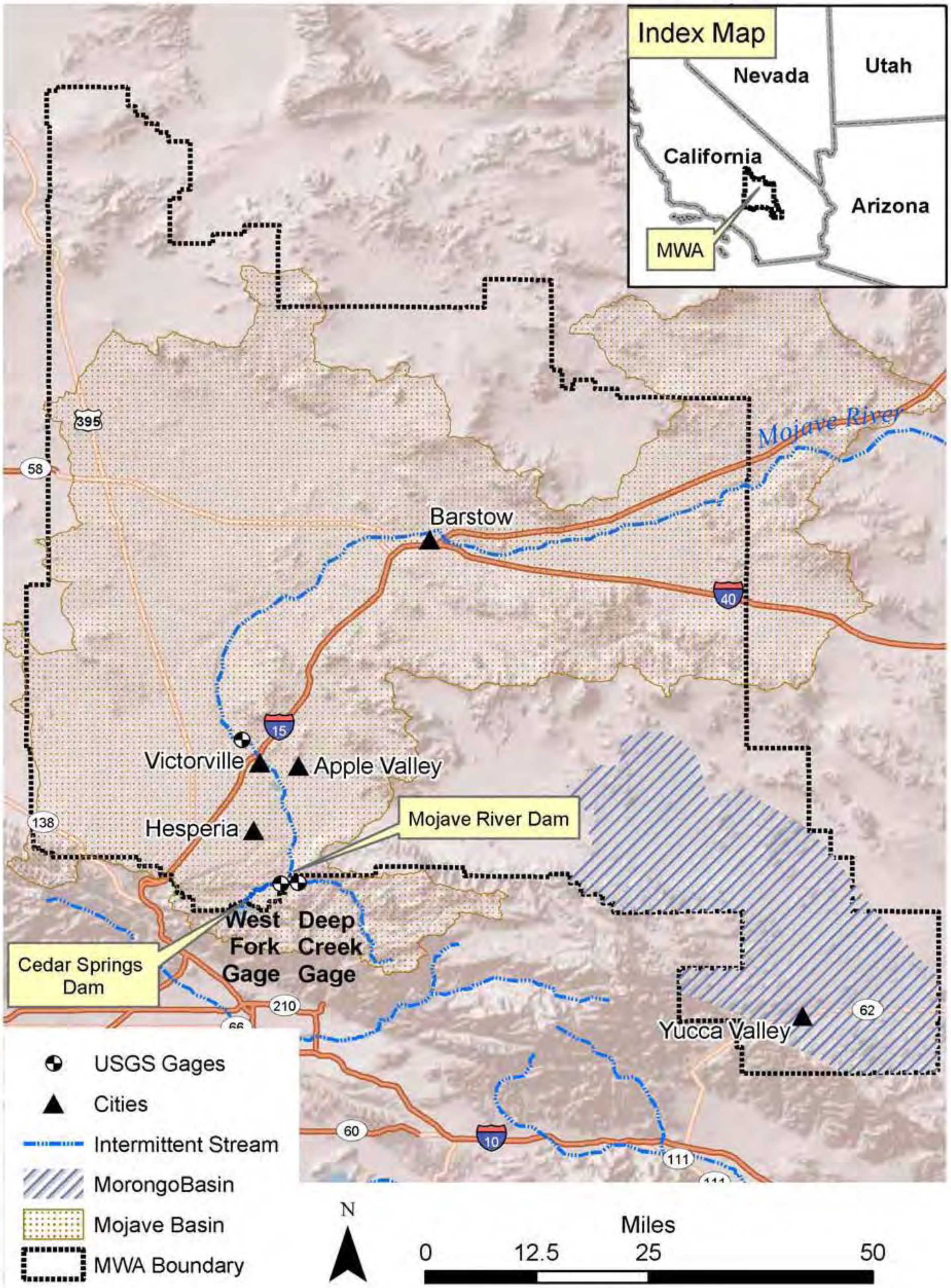

Figure 1: Mojave Water Agency service area map.

This analysis used data from three U.S. Geological Survey (USGS) gages, shown on Figure 1, and listed in Table 1.

Table 1: Streamflow Gages Used for Analysis

Location	USGS Gage Name	USGS Gage Number
Mojave River Dam	Deep Creek Near Hesperia	10260500
	West Fork Near Hesperia	10261000, 10260950[1]
Lower Narrows	Lower Narrows Near Victorville	10261500

[1] The 10261000 gage has data up to 1971 and the 1026950 gage has data from 1974 to present. From 1972 to 1974 there are no data for the West Fork and the total flow data consist only of Deep Creek flows.

Groundwater

While this report focuses on surface water sources, groundwater resources are vitally important to water management in the area. Characterized by alluvial plains and valleys with closed basins, the area consists of water-bearing unconsolidated sediment separated by hills and low mountains with non-water bearing bedrock. Groundwater flow is generally constrained by a series of northwest trending geologic faults.

Although there are many sub-basin designations, groundwater resources can generally be divided into two basins: the Mojave and Morongo groundwater basins.

As with surface water, the predominant groundwater basin is the Mojave. The Mojave groundwater basin is essentially a closed basin, covering roughly 1,400 square miles, with nearly five million acre feet of storage capacity. It is comprised of a younger, higher-permeability alluvial aquifer on top of older, lower-permeability regional aquifer. Water used to flow from the regional aquifer to the floodplain aquifer; however, the flow has reversed as groundwater production and overdraft have increased.

The Morongo groundwater basin covers roughly 1,000 square miles, with 60 percent within the MWA service area. Both basins are fed by infiltration and human induced recharge such as irrigation, wastewater discharge, fish hatcheries, imported water and managed recharge.

1.1.3 The Mojave Water Agency

MWA covers the Mojave Basin area and the Morongo Basin/Johnson Valley Area as shown in Figure 2. The Mojave Basin has been further divided into five sub-basins: Oeste, Este, Alto, Centro, and Baja. The northern part of the Alto subarea has also been divided into its own sub-management unit called the “Alto Transition Zone” to recognize local geology and flows from Alto to Centro. The Morongo Basin also has sub-basins, including Warren Valley.

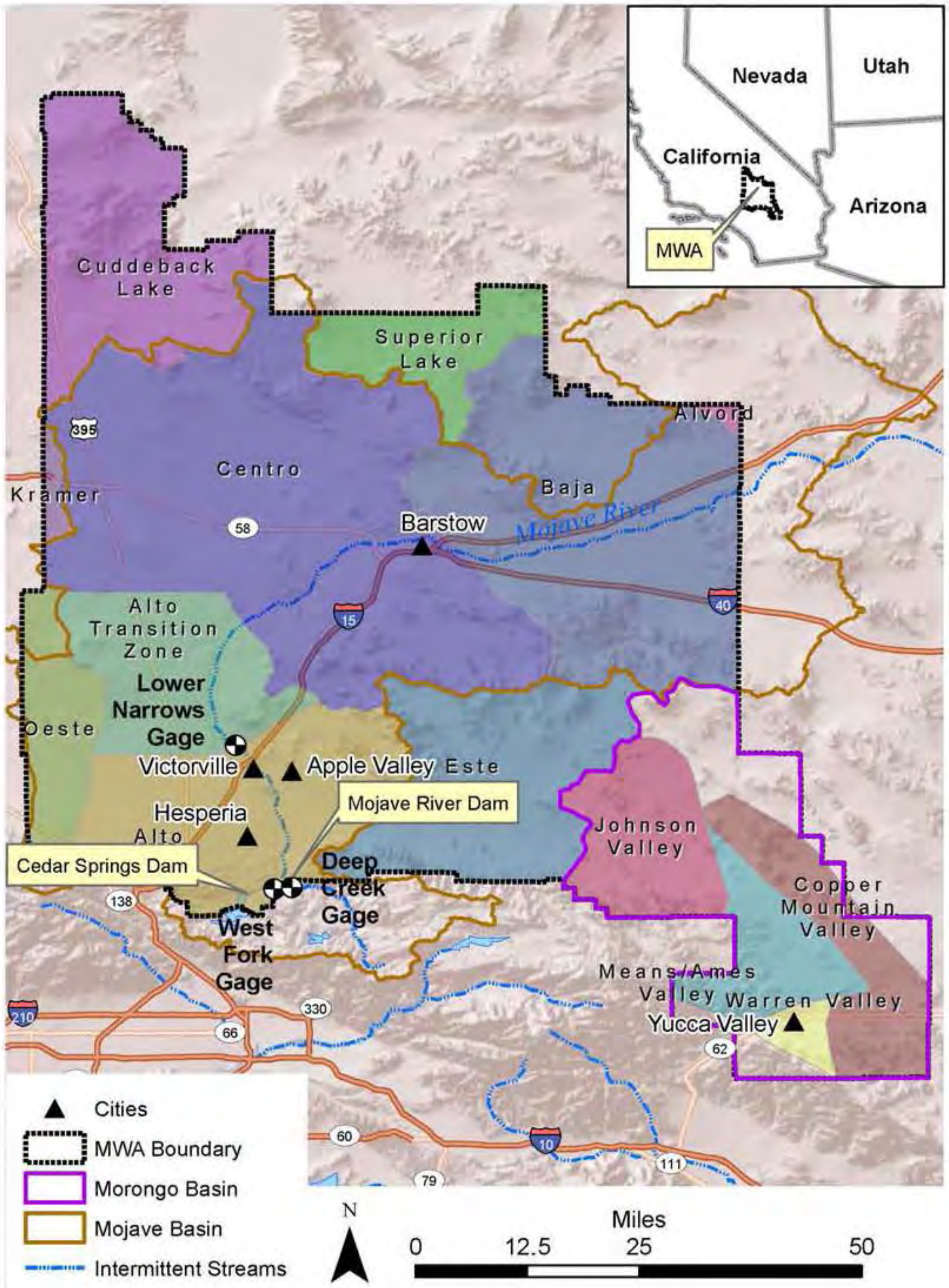

Figure 2: Map of Mojave Water Agency service area with sub-basins.

The MWA area has very limited surface water supplies. Groundwater supplies are currently used to meet the vast majority of demand. Since groundwater production started in the 1900s, groundwater extraction has greatly expanded, and groundwater levels have been declining since the early 1950s. In 1959, the California state legislature created MWA to manage groundwater resources. In 1965, MWA was expanded to include the Johnson Valley and Morongo Basin Areas. MWA works to ensure a reliable water supply for the area that can meet present and future beneficial use requirements by reversing the trend of groundwater overdraft. To this end, MWA:

- Plays an important part in the adjudication of water rights pursuant to several legal judgments.

- Holds a contract for 82,800 acre-feet per year (AFY) of surface water from the California State Water Project (SWP) that it imports to replenish groundwater supplies and meet the Mojave Basin Area and Warrren Valley Judgments (See Section 1.3.3.).

- Works with a wide range of stakeholders through the planning process and with education and outreach. MWA stakeholders consist primarily of water users (e.g., water districts, cities, private water agencies, and agribusiness), environmental groups, regulatory agencies, developers, and community groups. There are roughly 30 local water agencies who are water providers and about 8 municipalities, who are not necessarily water providers. Government agencies like the California Department of Water Resources, California Department of Fish and Game, State Water Resources Control Board, Lahontan Regional Water Quality Control Board, and USGS all have interests in the areas.

- Works with partners like the USGS to collect and assemble data to improve understanding of water supply and water quality and it is responsible for creating regional water management plans.

1.2 Water Resources: Supply and Demand

1.2.1 Groundwater Resources

Groundwater is the primary water source within the basin and supplies virtually all demand. Groundwater production started in the 1900s; by the 1950s production was nearly 190,000 AFY, and overdraft was recognized. Since this time, the overdraft has reduced groundwater storage by an estimated two million acre feet (MAF) (MWA 2004). Significant groundwater pumping along the Mojave River has reversed the alluvial flow from the underlying regional aquifer to the floodplain aquifer. However, in recent years, adjudication has resulted in developing several managed recharge sites and decreasing groundwater withdrawals.

A great deal of work has been completed to characterize the geology of the Mojave Basin.

Mojave Groundwater Basin

Most of the groundwater pumping occurs along the Mojave River. The Mojave groundwater basin is the largest groundwater resource in the MWA service area (with about 5 MAF of storage capacity). Roughly 90 percent of the recharge in this groundwater basin originates in the San Gabriel and San Bernardino Mountains (Hardt 1971). The majority (about 80 percent) of the recharge comes from infiltration from the Mojave River, but infiltration also occurs from storm runoff in the mountains and human-induced recharge from irrigation, wastewater, fish hatcheries, and imported water. Groundwater from the basin is discharged by well pumping, evaporation, transpiration, seepage into dry lakes, and seepage into the Mojave River.

Of the five sub-basins, three (Alto, Centro, and Baja) contain both the overlying unconsolidated alluvial aquifer and the older regional aquifer. The remaining two sub-basins (Oeste and Este) only have the regional aquifer. Deep percolation to the regional aquifer is estimated to be 3,600 AFY—mostly occurring within Alto (3,500 AFY) and Baja (100 AFY) (Mojave Basin Area Watermaster 2012). According to this watermaster report for 2011, roughly 1,175 AFY of groundwater flows from Este and Oeste to Alto; 2,000 AFY from Alto to Centro; and 1,462 AFY from Centro to Baja annually (Mojave Basin Area Watermaster 2012).

Morongo Groundwater Basin

The Morongo groundwater basin is slightly smaller than the Mojave groundwater basin (1,000 square miles [mi^2] versus 1,400 mi^2), and only 60 percent of this area is within the MWA service area. This basin contains a large number of closed and connected sub-basins, and has been divided into as many as 17 sub-basins in past investigations. Similar to the Mojave groundwater basin, groundwater is recharged by infiltration of water from ephemeral streams and human-induced recharge. Groundwater is discharged through well pumping, evaporation through the soil, transpiration by plants, and seepage into dry lakes.

1.2.2 Surface Water Resources

In general, MWA consists of desert plants and animals, but there are some wetland and riparian areas along Mojave River, Harper Dry Lake, Sheep Creek, and other drainages. As a result, there are some locations where mitigation (e.g., hydrologic flow requirements for minimum groundwater or surface water elevations) is enforced. Surface water resources within MWA can be generally divided into three categories: streamflow, imported SWP water, and wastewater discharge imports. Precipitation—and the resulting runoff—are highly variable.

Streamflow

Within the Mojave Basin, a number of sites have been monitored continuously since 1931. Data show that surface water flows vary greatly even within the few perennial reaches. For example, at the Forks (where the Deep Creek and the West Fork of the Mojave River converge in the headwaters of the Mojave Basin) annual flows from 1931 to 1990 range between 6,500 to 360,000 AFY with a median flow of 24,700 AFY (MWA 2004) and a mean flow of 65,540 AFY (Mojave Basin Area Watermaster 2012). About 18 miles downstream of the Forks is the Lower Narrows gage, used to determine compliance with minimum baseflow requirements from Alto to Centro. The average annual flow from 1931 through 2001 at this location was 52,400 AFY, and average baseflow (i.e., the portion of flow fed by groundwater) from 1931 through 1990 was 21,000 AFY. However, in 2001, the baseflow hit its lowest value at 5,345 AFY (MWA 2004).

Imported SWP Water

The SWP is the largest state-built, multi-purpose, user-financed water project in the United States, and nearly two-thirds of all California residents receive at least part of their water from it (State of California 2012a). Originally authorized in 1933 and constructed over several decades, SWP consists of 33 storage facilities, 21 reservoirs and lakes, 20 pumping plants, four pumping-generating plants, 5 hydroelectric plants and 700 miles of canals and pipeline (State of California 2012a). Its purpose is to divert and store water during wet periods in Northern California and deliver water to Northern California, the San Francisco Bay area, the San Joaquin Valley, the central Coast, and Southern California during times of need.

MWA imports significant amounts of surface water from the SWP. Currently, 29 contractors receive annual allocations from the SWP. In return, contractors pay interest and principal on the SWP bonds, all costs to maintain and operate facilities, and a transportation fee based on distance from the Sacramento-San Joaquin Delta (Delta). Each contractor has their own annual allocation contract for “Table A” water that was determined based on the maximum project yield of 4,230 thousand acre feet (TAF) per year. Table A water is given first priority over other SWP water types; however, contractors are not guaranteed their total allocation every year. Rather, once the SWP’s annual supply is determined, contractors’ allocations are determined proportionally based on Table A allocations. MWA is currently contracted for 82,800 AFY of Table A water, but its estimated long-term average annual supply is only 53,880 AFY (MWA 2011b).

Wastewater Discharge Imports

The final source of surface water supply is wastewater—from imported discharge water and from wastewater treatment plants in the area. The Mojave Basin Area imports discharge water from the Lake Arrowhead Community Service District, Big Bear Area Regional Wastewater Agency, and Crestline Sanitation District. For the three years from 2006 through 2009, the average wastewater imports totaled roughly 4,821 acre-feet (AF) (MWA 2011b). Discharges from the Lake Arrowhead Community Services District and the Crestline Sanitation District go to the Alto sub-basin. Together, these flows averaged 2,225 AFY from 2006 through 2009. The remaining 2,596 AFY is discharged to the Este sub-basin from the Big Bear Area Regional Wastewater Agency (MWA 2011b).

Although wastewater discharge imports are small relative to SWP imports, they form an important local supply. The Este subarea has very small natural supply and receives most of its total water supply from wastewater discharge imports (MWA 2004). In addition to wastewater discharge imports, five wastewater treatment agencies are within MWA (the City of Adelanto, the City of Barstow, Helendale Community Services District, Marine Corps Logistics Base, and Victor Valley Wastewater Reclamation Authority), with a combined treatment capacity of about 31.1 million gallons per day (MGD) (MWA 2011b). Currently, there are no users of reclaimed wastewater within the MWA, but there have been several entities identified to receive it in the future.

1.2.3 Artificial Recharge Sites

Artificial recharge sites are an important water management tool in the area. A 2001 USGS study simulated the effect of artificial recharge in the Mojave Basin and found that 20 years of artificial recharge had a strong mitigating impact on groundwater decline (Stamos et al. 2001). However, Stamos et al. (2001) also note that it is difficult to recharge the deeper, underlying regional aquifer in the Mojave Basin using recharge ponds along the Mojave River because water flows much more easily through the upper floodplain aquifer.

1.2.4 Infrastructure

Two primary pipelines transport SWP water from the California Aqueduct to the Mojave Water Agency Area: the Mojave River and Morongo Basin pipelines. The Morongo Basin Pipeline delivers water to the Hi-Desert Water District. The Mojave River Pipeline extends from the California Aqueduct through Barstow to Newberry Springs. Both pipelines deliver water to artificial recharge sites. The Hodge and Lenwood groundwater recharge sites, constructed in 1999, both recharge water to the Centro sub-basin using deliveries from the Mojave River Pipeline. The Daggett and Newberry Springs recharge sites deliver water from the Mojave River Pipeline to the Baja subarea. The Morongo Pipeline recharges water through two recharge sites near the town of Yucca Valley and delivers water to the Alto subarea. It will also soon serve the Reche recharge site (this is currently under construction in Landers), and the pipeline will be extended to deliver water to an additional recharge site in Joshua Basin. MWA recently completed the Oro Grande Wash Pipeline and the Deep Creek recharge site, which also provides water to the Alto subarea.

1.2.5 Historical Supply and Demand

MWA is a water-limited basin (i.e., the natural supply is generally less than demand). As of 2010, there was an annual supply deficit of roughly 19,891 AFY without taking SWP imports into account (MWA 2011b). Historically, agricultural water use dominated demand. However, between 1995 and 2000, the Mojave Basin transitioned from mostly agriculture to mostly urban demands. The Morongo Basin has only urban demands. In 2010, the total demand was 151,884 AF of which 146,090 AF were from the Mojave Basin, and 5,794 AF were from urban demand in the Morongo Basin (MWA 2011b).

In MWA's 2004 Regional Water Management Plan, historical estimates of supply and demand were estimated (using a base period of 1931 through 1990) for hydrologic conditions during an average year, a dry year, and multiple dry years (MWA 2004). Because the streamflow values are skewed by high storm runoffs, the dry year supply was assumed to be equal to the median historical supply for this analysis. The Forks gage has a good record of flows, thus the difference between the average and the median flow (i.e., the ratio of average to the median) was assumed to be the same for ungaged locations (where data are limited).The estimate for multiple dry years was based on the flow from 1988 to1990.

Using this approach, the average annual net supply for the Mojave Basin was estimated to be 63,400 AFY. This decreases dramatically to 22,100 AFY in a dry year and further reduces to only 3,900 AFY for multiple dry years. Annual demand for the Mojave Basin is significantly greater than demand at 105,200 AFY. Of the sub-basins, Alto has the greatest water supply due to its proximity to the headwaters. Centro and Baja depend on infrequent large storm events for recharge and have the next largest supply. Este and Oeste have the smallest supplies and primarily receive water from ungagged surface water, and in the case of Este, wastewater imports. Additional details on supply and demand for the sub-basins are provided in Table 2.

The Morongo Basin had a net annual supply of roughly 4,400 AFY, mostly occurring from precipitation and tributary flows (Table 2). Demands in the Morongo Basin depend highly on SWP imported water delivered through the Morongo Basin Pipeline. The flows in this basin are largely ungaged, so dry year and multiple dry year supply estimates were reduced proportionally from the mean according the reduction in surface water observed at the Forks. Based on this approach, the dry year supply is 1,680 AFY and the multiple dry year supply is 240 AFY (MWA 2004). Overall, the Morongo Basin has an annual deficit of 500 AF before the SWP supply, and the Warren Valley sub-basin accounts for 300 AFY of this deficit.

MWA completed future estimates of supply and demand in the 2010 Urban Water Management (MWA 2011b). MWA estimates that demand will increase by 10 percent in dry years and groundwater banking supply will be 29,284 AFY during single dry years and 6,928 AFY during multiple dry years (MWA 2011b).

Table 2. Year 2000 Average Annual Water Balance (AFY) (adapted from MWA 2004).

Area/Water Year	Net Average Annual Water Supply	Total Demand	Average Annual Surplus/Deficit
Mojave Basin Area			
Alto	34,700	51,500	-16,800
Baja	5,600	28,200	-22,600
Centro	18,500	17,300	+1,200
Este	3,500	5,000	-1,500
Oeste	1,100	3,200	-2,100
Total	***63, 400***	***105,200***	***41,800***
Morongo Basin Area			
Copper Mountain Valley	600	800	-200
Johnson Valley	2,300	30	2,270
Means/Ames Valley	600	600	0
Warren Valley	900	1,200	-300
Sub Total	***4,400***	***2,600***	***-500***
Total (Mojave +Morongo)	***65,500***	***107,800***	***42,300***

The MWA has a contract for 82,800 AFY of Table A SWP water. From 1999 through 2009, MWA has imported an average of 18,718 AFY (MWA 2011b). This water is mainly released from Silverwood Lake and delivered through the Mojave and Morongo Basin Pipelines. On average, about 3,500 AFY is purchased by the Hi-Desert Water District (HDWD) and delivered to the Warren Valley sub-basin using the Morongo Pipeline. In addition to offsetting the water supply deficit, the SWP water delivered through the Morongo Pipeline is used to increase groundwater storage. Analysis of SWP deliveries shows that a total of roughly 332,000 AFY was delivered from 1978 through 2009 (MWA 2011b). Although MWA has not been requesting its entire entitlement, from 1972 through 2001 MWA did receive all of the water it requested 75 percent of the time. On average, the MWA received 88 percent of its total request. However, in the 2001 drought, it only received 39 percent of requested water (MWA 2004). As of 2010, the average year SWP import availability is estimated to be 49,680 AFY for an average year, 5,796 AFY for a dry year and 28,152 AF for multiple dry years (MWA 2011b). Even though it may seem counterintuitive, the most extreme single dry year scenario should be more extreme than the multi-year drought scenario.

1.2.6 Groundwater Adjudication

Adjudication for groundwater users in the MWA was initiated in the 1960s to try to stem groundwater overdraft. However, the adjudication was not completed until the 1990s, when several lawsuits were filed that eventually resulted in the judgments.

Mojave Basin Area Judgment

The 1996 Mojave Basin Area Judgment requires that each water producer's rights to produce water be "ramped down to mitigate the overdraft conditions occurring within the Mojave Basin and provide for a scheduled reduction in pumping with the intent on balancing water production with the available natural supply and the purchase of supplemental water supply" (MWA nd).

The judgment applies to any person or entity producing more than 10 acre-feet of water per year (by well, surface water diversion, or other means) within Mojave River drainage area, who are also within the MWA service area boundaries (MWA nd). About 470 water producers in the MWA service area are bound by this judgment.

Each producer is thus limited to the amount of water they can pump or divert each year, which is calculated as:

- **A base quota.** This judgment assigns Base Annual Groundwater Production (BAP) quotas to these producers. The BAP is the verified maximum year production, in acre-feet, for each water producer for the five year period from 1986 through 1990.

- **A limited amount of that base quota.** Each water producer is assigned a variable Free Production Allowance (FPA), which is the amount of water that producer can pump in a specific subarea in one year without incurring a Replacement Obligation (MWA nd). This is a uniform percentage of the BAP for a sub-basin. The FPA percentage is then decreased uniformly for all users over time until the FPA is balanced with supplies.

- **Carry over and replacement.** If water producers do not use their FPA amount, then they can carry it over to the next year or transfer that water to another producer. If they use water over the FPA amount, they are subject to replacement and make-up water assessments. Thus, under this system if users pump more that their FPA, they must purchase replacement water from MWA equivalent to their excess production.

The 2011 Water Master report recommends that the 2012-2013 FPA be 80 percent of the BAP everywhere (with the exception of Baja, Alto, and Oeste municipal and industrial users), with a recommended FPA of 60 percent (Mojave Basin Area Watermaster 2012). In 2003, this was set to 70 percent for most sub-basins.

Warren Valley Basin Judgment

The Warren Valley Basin was adjudicated in 1977. As the HDWD explains: "[c]oncerned about the prospect of not only continuing but even significantly increasing overdraft, HDWD filed a complaint for adjudication of the groundwater in 1976. The Superior Court for the County of San Bernardino issued its judgment for adjudication. In the adjudication, the Court recognized the need to issue groundwater rights in excess of the Basin's safe yield so that the local economy could support the cost of a solution to the overdraft problem." (HDWD 2012). The judgment issued overlying rights to basin groundwater users and appointed HDWD as Watermaster, charged with stopping overdraft.

To address this problem, a management plan was developed that included importing SWP water from MWA through the Morongo Basin Pipeline.

1.2.7 Projected Supply and Demand from Previous Reports

As part of its regional planning process, MWA has generated several projections of future supply and demand for the basin. Population is projected to increase nearly 25 percent (from about 437,000 to 545,000 people) from 2010 through 2020 (MWA 2011b). Future demands were estimated for 11 economic sectors. Specific assumptions are detailed in the 2010 Urban Water Management Plan. In general, the projected demands reported here assume moderate conservation. Table 3 outlines the projected water budget components for 2020 and 2035. Overall, total demand is projected to increase. For planning purposes, MWA assumes that average natural water supply and agricultural depletion from storage will remain constant from 2020 through 2035. While, wastewater imports and return flows are projected to increase slightly.

Table 3. Projected Supply and Demand for 2020 and 2035 (AFY) (adapted from MWA 2011b).

	2020 Estimates	2035 Estimates
Total demand	170,000	204,000
Natural water supply	54,045	54,045
Agricultural depletion from storage	10,425	10,425
Wastewater imports	5,304	6,385
Return flows	62,220	87,857

However, it is expected that variability of SWP deliveries will increase in the future as contractors start requesting more water. SWP imports are projected to increase from 49,680 AF in 2010 to 54,778 AF per year in 2035 (MWA 2011b). Taking increased supplies into account, the average annual supply deficit, not including SWP imports, will increase from 19,891 AF in 2010 to 45,469 AF per year in 2035 (MWA 2011b). When SWP imports are added in, the projected 2035 surplus is 9,309 AF per year. However, it should be noted that both natural flows and SWP imports are highly variable from year to year and it is projected that by 2030 dry year deliveries will be only 9,878 AF (significantly less than the 54,778 projected average year delivery) (MWA 2011b).

1.3 Water Management and Planning

1.3.1 Water Management Concerns

In their 2004 Regional Water Management Plan, MWA (2004) identified six key water management issues:

1. Water shortages. Currently, demand exceeds supply and this trend is expected to continue in the future.

2. Naturally occurring water quality concerns.

3. Groundwater overdraft.

4. Problems with riparian ecosystem maintenance in all but two sub-basins.

5. Wastewater infrastructure issues in the two subareas with largest demand (i.e., Alto and Baja).

6. Issues with interconnected subareas where actions in one subarea impact management in others.

The focus of the Bureau of Reclamation’s (Reclamation) climate change assessment is primarily water quantity, specifically future water availability, that would impact mainly water shortages, water quality, and riparian ecosystem maintenance. Although water quality will not be addressed with this work, it should be noted that there are a number of contaminants of concern in the basin (e.g., arsenic, nitrates, iron, manganese, chromium VI and total dissolved solids [TDS]). Also, there is growing concern about the accumulation of salt in groundwater. Because the sub-basins within the MWA are essentially closed basins, salt content in imported reclaimed wastewater and SWP water does not get removed and could accumulate over time without some remediation action.

1.3.2 Water Management Strategies

Although the MWA service area has very limited surface water supplies, the area does not have issues with supply reliability (either in quantity or quality) because of its dependence on groundwater. In previous droughts, water providers pumped from groundwater reserves without restricting water use. However, one of MWA’s primary purposes to balance groundwater withdrawals with supplies, and by 2020, it is expected that the aquifers will be in balance. To ensure reliable supply without resorting to unsustainable groundwater use, some changes in water management procedures and improvements to facilities will be needed.

In the coming years, MWA plans to build additional facilities so that they can use their entire SWP allotment and recharge excess supply in wet years. For their regional planning 2004 report, MWA used the Stella model to simulate operations for 18 different development scenarios, using estimated 2020 water demands (WMA 2004). Based on these simulations, MWA's 2004 assessment determined that the 2020 water demand could be met with 10 percent municipal conservation and significant decreases in agricultural production. Because MWA is not actually a water purveyor, it can't implement water shortage plans and municipal water use restrictions for dry years. However, 10 cities within the area have already developed and adopted their own urban water management plans. For its part, the MWA has focused on infrastructure development and water exchange programs.

It is expected that wellhead treatment may be necessary in the future to meet water quality standards for naturally occurring constituents of concern. Although the analysis from the 2004 Regional Water Management Plan didn't conclude with one set of development projects, it did provide a range of potential options including: new recharge facilities, increased recharge efficiency, water treatment or blending, change source of supply, water conservation and storage agreements (MWA 2004).

MWA, in 2004 listed high priority projects to be implemented in 3 to 5 years were:

- **Conservation.** MWA's 2004 goal was to achieve 10 percent municipal conservation in Mojave Basin and 5 percent in Morongo Basin.
- **Wastewater Reclamation.** MWA planned wastewater reclamation in Alto.
- **Wellhead Treatment.** MWA planned wellhead treatment in Alto.
- **Groundwater Recharge.** MWA envisioned recharge in Alto floodplain and the regional Warren Valley aquifer.
- **New water supplies for Pioneertown.**

MWA implemented the Regional Recharge Recovery project (the R^3 Project) as well as recharge projects in the Oro Grande Wash, Ames Valley, Joshua Basin and Antelope Valley Wash.

The MWA also implemented a pilot exchange program with Metropolitan Water District of Southern California (MWD) Basically, MWA gives Metropolitan SWP water in dry years and they get water in wet years to use for recharge. MWD delivered 45,000 AFY of water to MWA in 2003 and 2005, and in years when MWD requested, MWA provided "return" water by exchanging MWA's SWP deliveries. The pilot exchange program ended in 2010. Due to the success of the pilot program, in 2011 MWA and MWD entered into a long-term water storage/exchange agreement that is in effect until 2035. Under the 2011 storage/exchange program, during 2011 and 2012 MWD stored 60,000 acre-feet with MWA. In addition to regional scale exchange programs, individual users can also conduct intra-basin transfers by selling unused BAP.

1.4 Regional Climate Change Analysis

Although there is limited climate change analysis specific to the Mojave River Basin, there is a large body of existing climate change research for the region. This section summarizes findings from relevant studies of historical trends and future projections of climate variables for the region. Much of the information below is summarized from a recent Reclamation report "Literature Synthesis on Climate Change Implications for Water and Environmental Resources" (Spears et al. 2011). The studies referenced here cover a range of geographic extents, but all are relevant to the Mojave Basin (in Reclamation's Lower Colorado Region). For additional details, refer to Spears et al. 2011.

1.4.1 Observed Historical Trends

Given the magnitude of land use changes and development in the Western U.S. over the 20^{th} century, it can be difficult to attribute impacts to climate change. Still, many studies have found statistically significant trends in climate variables over the last 50 years. Studies agree that there has been a clear warming trend. However, precipitation trends are much more uncertain and locally variable.

Many studies have noted a significant warming trend across the Western U.S. over the past century. For example, Cayan et al. (2001) found that spring temperatures in the Western U.S. have increased by 1-3 degrees (°) Celsuis (C) since the 1970s. Mote et al (2005) show increasing trends in winter temperature up to 4 °C at United States Historical Climatology Network gages in the Lower Colorado Region for periods from 1930 through 1997. These findings have important implications for seasonal trends. For example, Easterling (2002) found that the number of winter and spring frost days in the second half of the 20^{th} century (1950 through 1999) decreased, while the last spring frost arrived earlier in the year and the first fall frost arrived later in the year.

Warming trends can have a significant impact on snowpack. One the one hand, many studies have shown increased western snowpack over the last half of the 20^{th} century. From 1930 through 1997, winter precipitation has increased in the Lower Colorado Region. Regonda et al. (2005) found a statistically significant increase in winter precipitation (i.e., the total precipitation from November through March total) for most of the Lower Colorado Region's National Oceanic and Atmospheric Administration (NOAA) Coop Network stations from 1950 through 1999. Still, Hamlet et al. (2005) note that precipitation variability is most strongly associated with decadal variability rather than long-term trends and conclude that "although the precipitation trends from 1916 through 2003 are broadly consistent with many global warming scenarios, it is not clear whether the modestly increasing trends in precipitation that have been observed over the

Western U.S. for the period are primarily an artifact of decadal variability and the time period examined, or are due to longer-term effects such as global warming."

In spite of increased winter precipitation, the Lower Colorado Region has also experienced a general decline in spring snowpack likely due to increased winter precipitation falling as rain (rather than snow), and earlier snowmelt runoff. Knowles et al. (2007) analyzed snowfall liquid water equivalent (SWE) from 1949 through 2004 and precipitation measurements at 207 National Weather Service (NWS) cooperative observation gages in the Western U.S. and found reduced snowpack and snowfall fractions and determined that these declines were strongly related to warming trends. Mote (2006) looked at trends in SWE on April 1 and found that, while trends were both positive and negative, there are primarily negative SWE trends at low elevations where the proportion of precipitation falling as rain rather than snow is most sensitive to small temperature increases. Changes in winter precipitation patterns and snowmelt timing can have significant impacts on streamflow. Regonda et al. (2005) evaluated 1950 through 1999 data from 89 stream gauges in the Western U.S. and reported trends of reduced SWE and peak runoff occurring earlier at most stations during that period (although many of the Lower Colorado stations did not exhibit these trends).

Trends in rainfall patterns are generally more uncertain than changes in snowpack and temperature. Kunkel (2003) noted increased frequency of extreme precipitation events since the 1920s and 1930s in much of the U.S., but trends in Western California were not found to be statistically significant. Drought and precipitation in the Lower Colorado Region is primarily dominated by interannual and multidecadal variations related to ocean-atmosphere interactions and some studies have observed clear trends with longer duration moisture trends. For example, Groisman and Knight (2008) found that the mean duration of prolonged dry spells in the Southwestern U.S. during the last 40 years (1951 through 2005) has increased. Furthermore, MacDonald et al. (2008) note that ongoing radiative forcing (i.e., the difference between the radiation received by earth and radiation released to space) and warming "could be capable of locking much of the southwestern North America into an era of persistent aridity and more prolonged droughts."

1.4.2 Future Projections

In 2009, the Congressional Budget Office (CBO) provided a report summarizing the current understanding of the impacts of climate change in the U.S. (CBO, 2009). They noted that warming will tend to be greater at high latitudes and in interior regions. Warming will lead to more intense and heavy rainfall that will tend to be interspersed with longer relatively dry periods. Future climate conditions will feature less snowfall as well as more rainfall, leading to less snowpack development and earlier snowmelt runoff. These findings are also supported by Lundquist et al. (2009). Similar to conclusions regarding historical trends, there is greater agreement between scenarios and higher confidence in temperature change and less confidence in precipitation changes.

Although there is less confidence in projections for precipitation change for middle latitude regions, Dai (2006), projected that precipitation changes for subtropical latitudes would be generally more consistent and suggested that there would be a tendency toward less annual precipitation, reduced basin-wide runoff decreased soil moisture, and increased evapotranspiration. This is also supported by Milly et al. (2005), Seager et al. (2007), International Panel on Climate Change [IPCC] (2007), Cayan et al. (2010), and Gutzler and Robbins (2010). However, it should be noted that the Global Circulation Models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report have been found to poorly simulate characteristics of the summer monsoon circulation, which is an important source of moisture for the Lower Colorado Region (Lin et al. 2008). Dominguez et al. (2010) selected two GCMs that most realistically captured seasonal precipitation, temperature, and atmospheric circulation, including the summer monsoon and the El Niño Southern Oscillation, and found that future aridity of the Lower Colorado Region will be dramatically amplified during La Niña conditions, which will be much more severe—warmer and drier—than during the historic period. Furthermore, Gutowski et al. (2008) predict that climate change will likely cause precipitation to be less frequent but more intense in many areas and that precipitation extremes are very likely to increase.

Changes in precipitation natural variability, combined with a warming trend, may impact water demand in addition to supply. In general, increases in minimum and maximum temperatures, length of heat waves, and length of frost free season suggest increases in demand for water and electric power. Increased temperatures are predicted to lengthen the growing season for agricultural crops, but crop irrigation water requirements are expected to vary. The average U.S. North American growing season length has already increased by about one week during the 20th century, and Gutowski et al. (2008) project that, by the end of the 21st century, the growing season will be more than two weeks longer than was typical for the late 20th century. This change could increase agricultural water demand if farming practices are able to adapt to the opportunity by planting more crop cycles per growing season.

It is likely that climate change will also influence groundwater resources. While impacts will be basin-specific, Ryan et al. (2008) showed that depletions to natural groundwater recharge are sensitive to climate warming. Reduced mountain snowpack, earlier snowmelt, and reduced spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer wetter winters could also increase the amount of water available for groundwater recharge.

Total effects of climate change on groundwater resources are difficult to predict due to the range of interactions that occur between groundwater and surface water systems. For example, increasing evapotranspiration could lead to declining recharge, which would increase depth-to-water table, which would then decrease riparian area vegetation health. Declining riparian vegetation health could then lead to a cascade of ecosystem impacts related to stream temperatures and species habitats.

This chapter summarized of the state of water resources in the Mojave Basin and relevant findings from previous work. In the subsequent chapters new analysis of projected future water supply (Chapter 2), flood frequency (Chapter 3) and greenhouse gas emissions (Chapter 4) are presented.

2. Climate Change Impacts on Surface Water Supply of the Mojave River Watershed and on Imported State Water Project Supply

The first task of this project is to quantitatively assess the impact of climate change on total surface water supply for the MWA. This includes analyzing natural surface water flows within the MWA service area as well as the projected changes in availability of water from the SWP. Note that the scope of the analysis covers surface water only, and there is no explicit modeling of changes in groundwater recharge and water table depths. In the discussion that follows, we outline the methodology for climate change assessment of both native and SWP imported supplies.

2.1 Methods

2.1.1 Native Flows

Climate change analysis of natural flows within the MWA service area follows the methodology established for the West-wide Climate Risk Assessments. A brief summary is provided here; for more details and verification of the methodology please refer to Gangopadhyay et al. (2011) and Reclamation (2011).

Analysis Methods

To provide a range of flow estimates, we analyzed results from 112 different GCM climate change projections. Each projection provides monthly values of temperature and precipitation, from 1950 through 2099. They cover sixteen different Coupled Model Intercomparison Project Phase 3 (CMIP3[2]) models simulating three different emissions paths (i.e., B1[low], A1b[middle] and A2[high]) and starting from different end of the 20th century climate conditions. The data used for this study was downscaled to 1/8° (about12 kilometers) spatial resolution from GCM outputs using the Bias-Correction Spatial Disaggregation (BCSD) approach demonstrated in Wood et al. (2002). Although there are some drawbacks, the BCSD approach has been shown to perform comparably with other downscaling methods with respect to hydrologic impacts (Wood et al. 2004).

To generate flow estimates, we used climate projections to force hydrologic simulations with the Variable Infiltration Capacity (VIC) model (Liang et al.

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[2] CMIP3 is a compilation of global circulation model outputs from the world’s leading modeling centers.

1994, Liang et al. 1996, and Nijssen et al. 1997). VIC is a spatially distributed hydrologic model that solves the water balance at each model grid cell. It has been widely used in climate change impact and hydrologic variability studies (e.g., Van Rheenen et al. 2004, Maurer et al.2007, Christensen et al 2004, Christensen and Lettenmaier 2007, and Payne et al. 2004). The VIC model contains subgrid-scale parameterizations of infiltration and vegetation. Potential evapotranspiration is calculated using a Penman Monteith type approach and soil moisture is vertically distributed in a three-layer model grid cell.

For this analysis, we ran VIC in water balance mode, driven by daily weather forcings of precipitation, maximum and minimum air temperature, and wind speed. The monthly two-variable climate projections were converted to the necessary daily VIC weather forcings following the historical resampling and scaling technique introduced in Wood et al. (2002). Additional model forcings that drive the water balance (e.g., solar (short-wave) and long-wave radiation, relative humidity, vapor pressure, and vapor pressure deficit) are calculated within the model. To generate streamflow results at a given location, we followed two steps:

1. VIC was run independently for each grid cell in a watershed to produce surface runoff and base flow

2. Runoff from grid cells was routed to river channels and outlets

Flow Locations

For this assessment, we analyzed flow at three locations relatively near the headwaters of the Mojave River. These correspond to USGS gages (Deep Creek, West Fork, and Lower Narrows).

Figure 3 shows the gage locations along with their corresponding upstream area. Downstream gage locations were not used because flow in the lower reaches is ephemeral, thus flows in the lower reaches are not a good indicator of surface water supply. Although the three prediction locations were chosen to correspond to USGS gage locations, the results were not calibrated to historical observations. It is assumed that any biases in the simulations will be carried forward through time and will not impact the differences that are calculated. As this analysis quantifies relative changes from the past to the future, calibrations were deemed unnecessary.

As previously noted, all simulations span from 1950 through 2099. We calculated all future differences relative to a set reference period of calendar years 1990 through 1999. We selected the 1990s as the base historical time period, rather than to a longer historical period, to most adequately capture the clear streamflow trend that has already been occurring in the basin. If, for example, 1950 through 1999 were chosen as the base period instead, projected streamflow changes would likely be larger because they would be including changes that have already occurred.

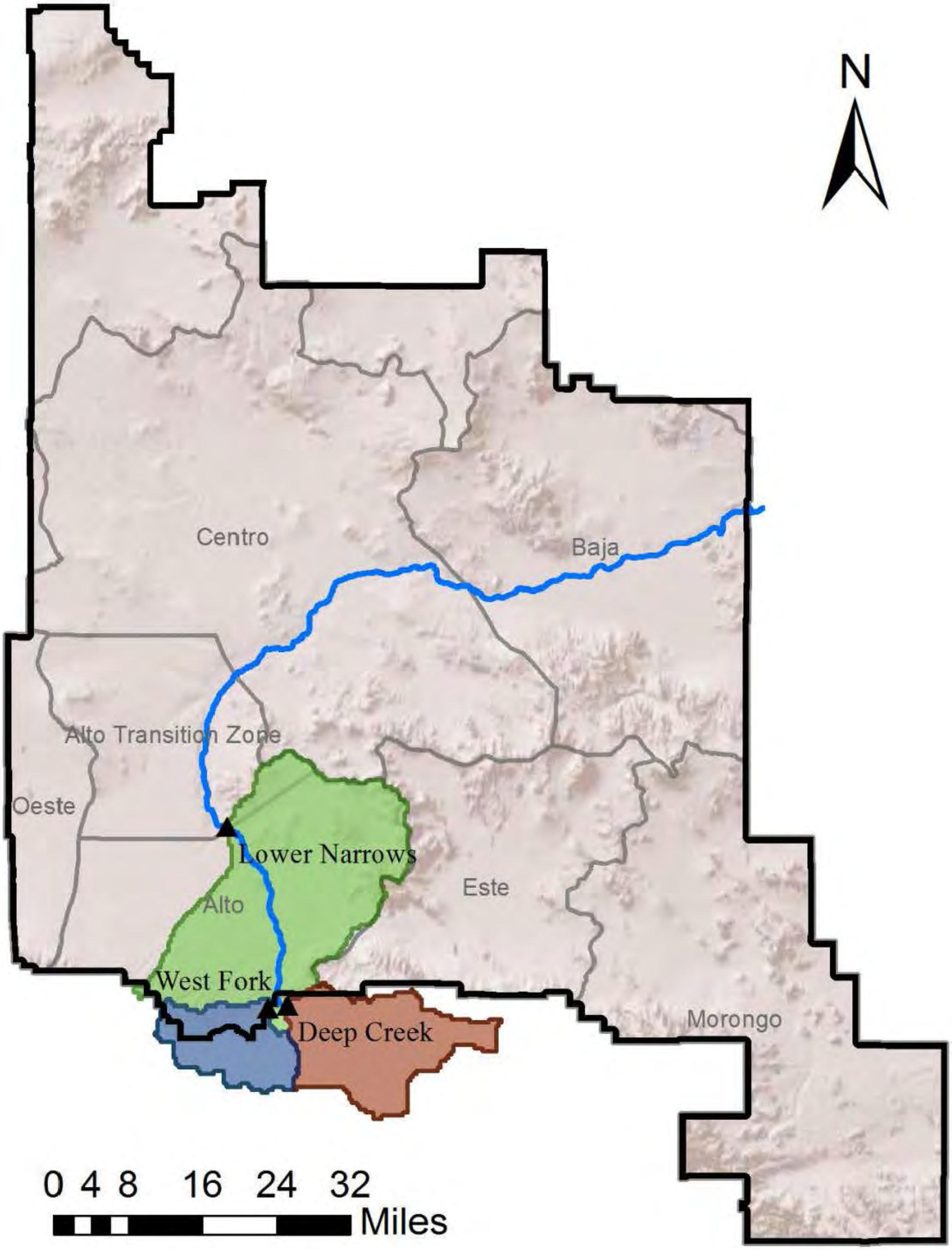

Figure 3: Streamflow assessment locations and upstream areas.

Figure 4 plots the historical observed flow at the Deep Creek gage both as boxplots and a time series of annual flows by decade and for the entire 1950 through 1999 period. A clear increasing trend from the 1950s through the 1990s can be seen through the mean lines plotted on the time-series in Figure 4b (in green). The boxplot also shows a significant increase in variance in the 1990s.

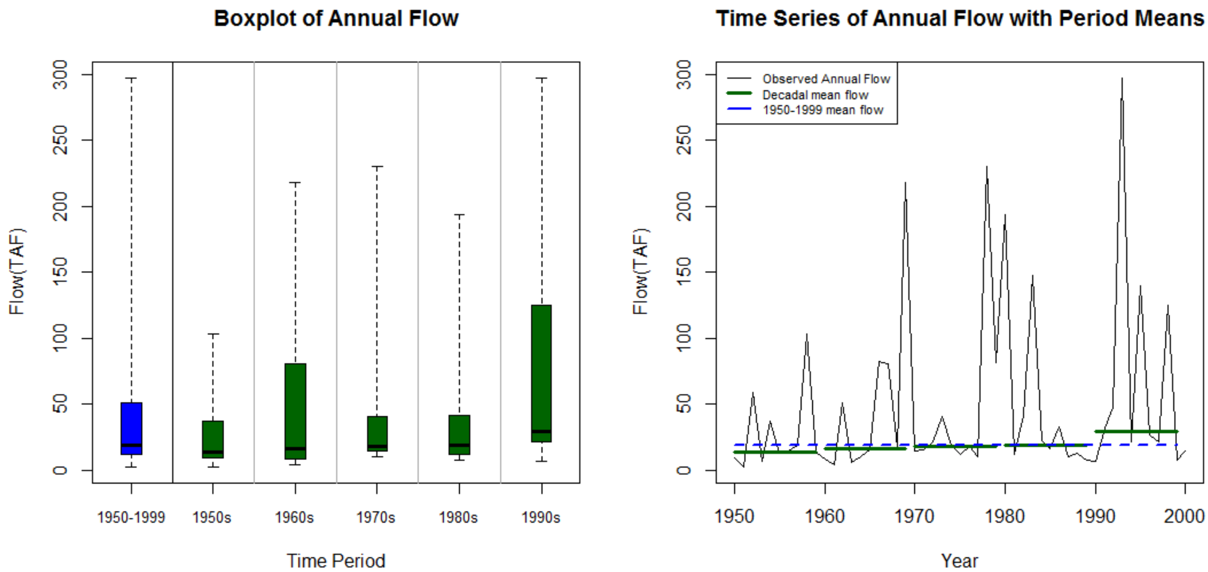

Figure 4: Boxplot (a) and time series (b) of historical gage flow for the Deep Creek gage location.

2.1.2 State Water Project Imports

The SWP is an expansive and complex system consisting of 33 storage facilities, 21 reservoirs and lakes, 20 pumping plants, 4 pumping-generating plants, 5 hydroelectric plants, and 700 miles of canals and pipelines. MWA is one of 29 contractors with contracts for "Table A" water (see Section 1.2.2. for a discussion of these contracts). Each contract defines a maximum delivery but does not guarantee that delivery. Although Table A water holds priority over other SWP water types, actual water delivery is determined annually based on year type and other biological and water quality constraints. Water years are designated as wet, above normal, below normal, dry, or critical based on the amount of precipitation that falls from October 1st to September 30th, snowpack measured on the first of each month January through May, and forecasts of available supply. The SWP has issued reliability reports every two years since 2002, estimating future water supplies for the system as a whole and for deliveries to each water contractor. We used the water supply estimates from the 2011 SWP reliability report directly to quantify expected future SWP imports to MWA.

Extensive modeling work has been done as a part of the SWP Reliability Report. Details of the methodology used to estimate future SWP deliveries can be found in the 2011 reliability report and technical memorandum (State of California 2012 a and b). All estimates of future reliability are projected out to 2031. The CalSim

II model is used to simulate SWP operations. Two future scenarios (extending to 2031) are provided in the SWP Reliability Report. The first scenario assumes that future climate conditions will mirror historical climate records, but applies 2011 land use and operations. The second scenario assumes that demand will be the maximum possible based on contracts, and applies climate change. For the climate change scenario, a single median impact, projection was chosen from the 12 projections for mid-century discussed in "Using Future Climate Projections to Support Water Resources Decision Making in California" (California Climate Change Center 2009).

2.2 Results

2.2.1 Native Flows

Temperature

Figure 5 shows the simulated decadal temperatures for the MWA service area. The top map represents historical condition with:

- Simulated 1990s distribution of ensemble-median (i.e., the median projection of the 112 GCM projections)

- Decadal mean (i.e., the average value for a decade within a single projection)

The four maps in the figure below show changes in the decadal mean conditions for three future periods (2020s, 2050s, and 2070s) from the 1990s conditions at three percentiles within the ensemble (i.e., the 25th, 50th, and 75th percentile projection within the 112 GCM projections). The change in temperature values is scaled from 0° to 6° Farenheit (F). The median change for the 2020s, 2050s, and 2070s from the 1990s shows a spatially consistent increasing temperature trend.

Precipitation

Figure 6 shows the spatial distribution of simulated decadal precipitation for the MWA service area. As with Figure 5, the top map represents historical conditions with the simulated 1990s distribution of ensemble-median decadal mean. The maps below this in the figure show changes in the decadal mean conditions for three future periods (2020s, 2050s, and 2070s) from the 1990s at three change percentiles with the ensemble (25, 50, and 75). The change values are scaled from -20 percent (red shows decreases) to +20 percent (blue shows increases). For each future time period the 25th and 75th percentile projections span decreasing and increasing temperature. The median values (in the center row) show a slight increase in precipitation in the 2020s, followed by progressively larger decreases in the 2050s and 2070s. Trends are, for the most part, spatially consistent; however, slightly lower precipitation is projected in the headwaters than historical conditions.

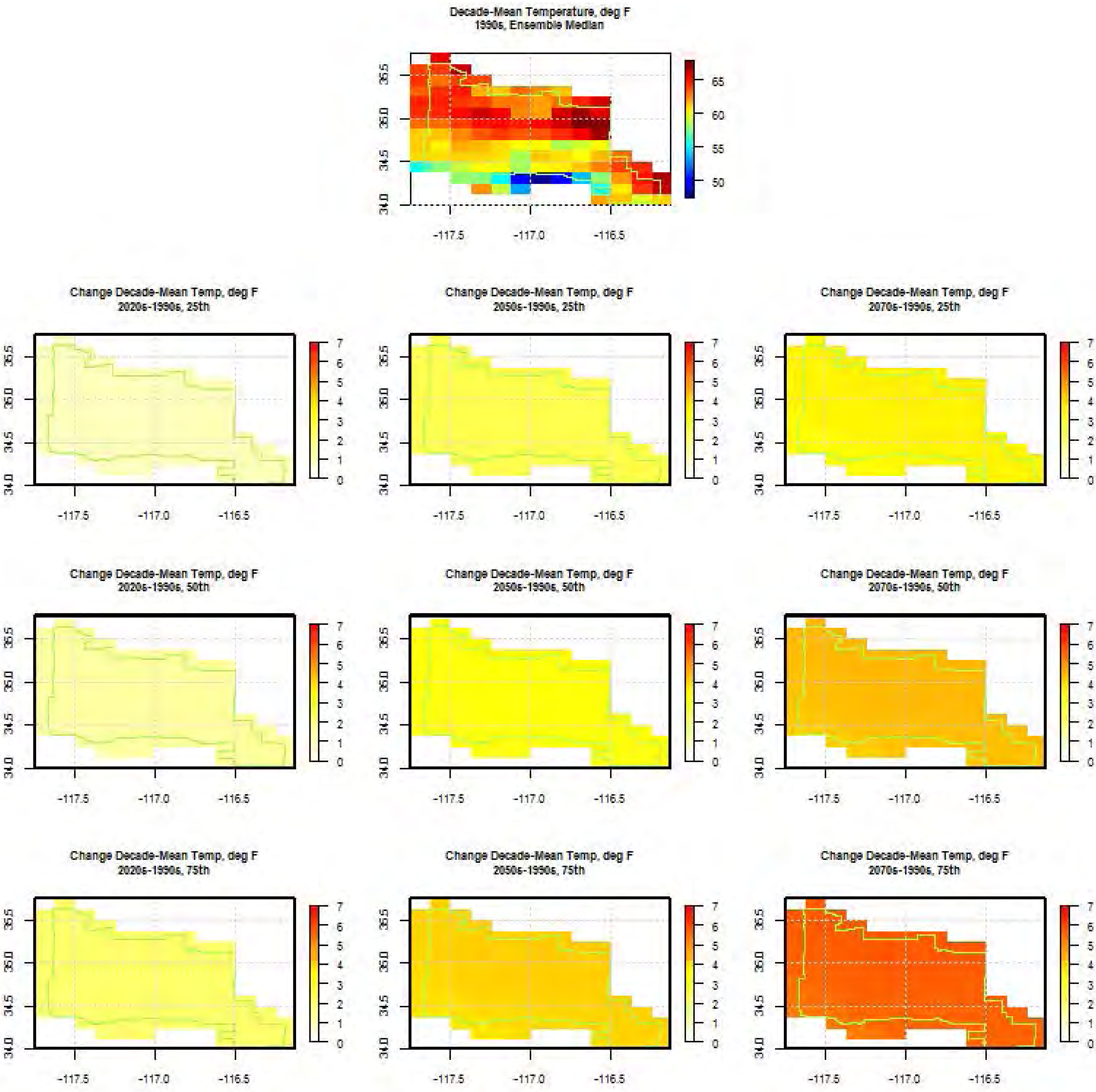

Figure 5. Spatial distribution of simulated decadal temperature.

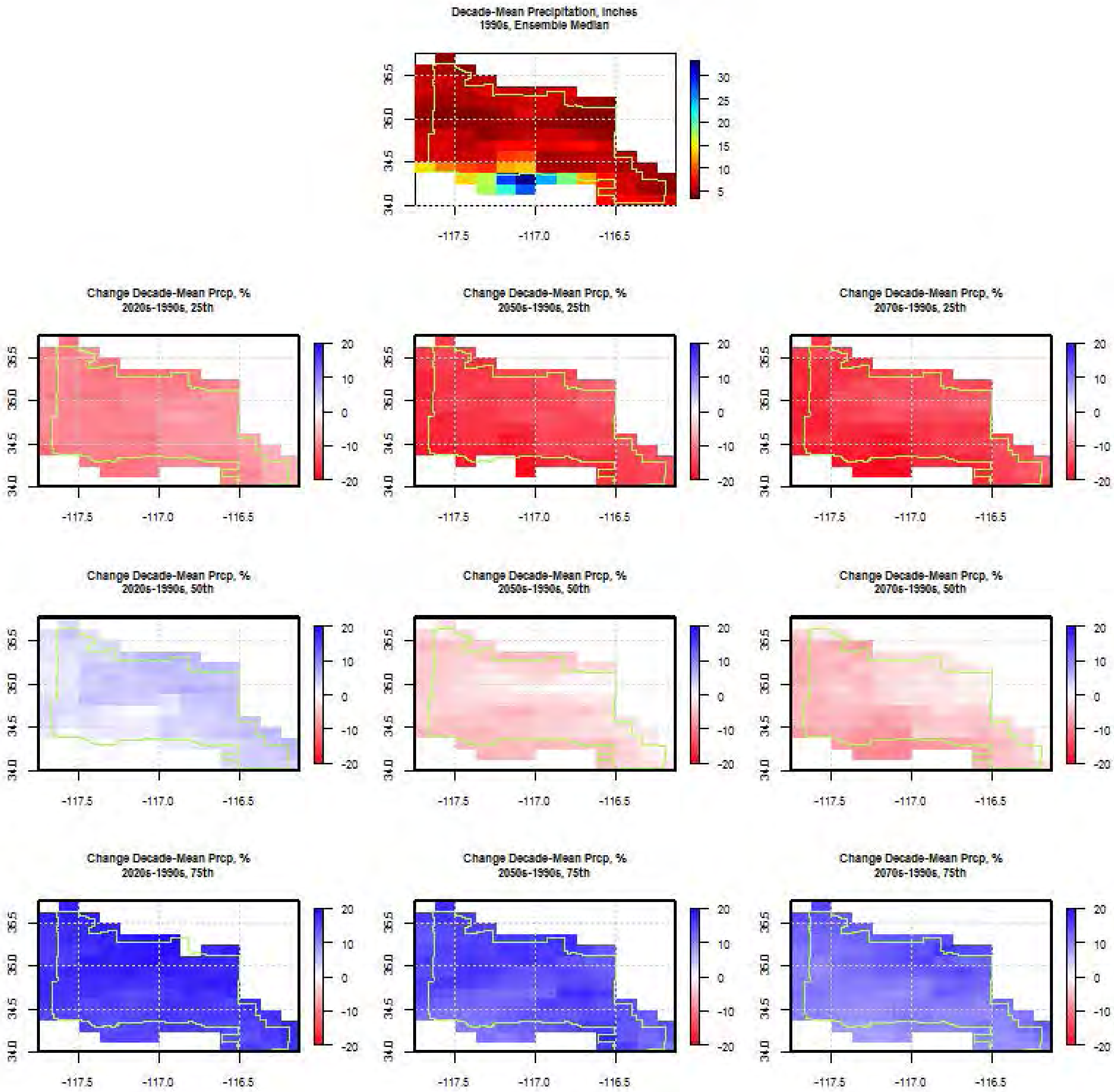

Figure 6: Spatial distribution of simulated decadal precipitation.

Figure 7 shows three ensembles of hydroclimate projections for the MWA service area: annual total precipitation (top), annual mean temperature (center) and April 1st SWE (bottom). Appendix A has similar plots for each of the sub-basins. The heavy black line is the annual time series of 50th percentile values (i.e., the ensemble-median). The shaded area is the time series of the 5th to 95th percentiles (i.e., the uncertainty envelope). Total annual precipitation over the basin is seen to have a very nominal decline over the period from 2000 through 2099. The uncertainty envelope appears to be largely constant over time, implying that there is no increase or decrease in the uncertainty envelope from the present for total annual precipitation magnitudes through time. The mean annual temperature shows a clear increasing trend and an expanding uncertainty envelope through time. The median SWE remains constant at roughly zero from 1950 through 2099; however, there is a decreasing trend in the upper bounds of the uncertainty envelope, indicating that the probability for snowpack will decrease in the future.

Streamflow

Figure 8 to Figure 10 show projection ensembles for six hydroclimate indicators for the three streamflow prediction locations:

- Annual total precipitation (top left)
- Annual mean temperature (top right)
- April 1st SWE (middle left)
- Annual runoff (middle right)
- December to March runoff (bottom left)
- April to July runoff (bottom right)

The heavy black line portrays the annual time series of 50th percentile values (i.e., ensemble-median). The shaded area is the time series of the 5th to 95th percentiles (uncertainty envelope).

Results for the three gage locations are very similar to the west-wide climate assessment results for precipitation, temperature, and SWE (Reclamation 2011): with a slight decrease in precipitation, a clear increase in temperature with expanding uncertainty and a decrease in the upper uncertainty bounds of April 1st SWE. Runoff trends are also consistent between gages. All locations show a nominal decline in annual and December to March, while the uncertainty envelope remains largely constant. April to July runoff shows the clearest declining trend and has a corresponding decrease in the upper bounds of the uncertainty envelope.

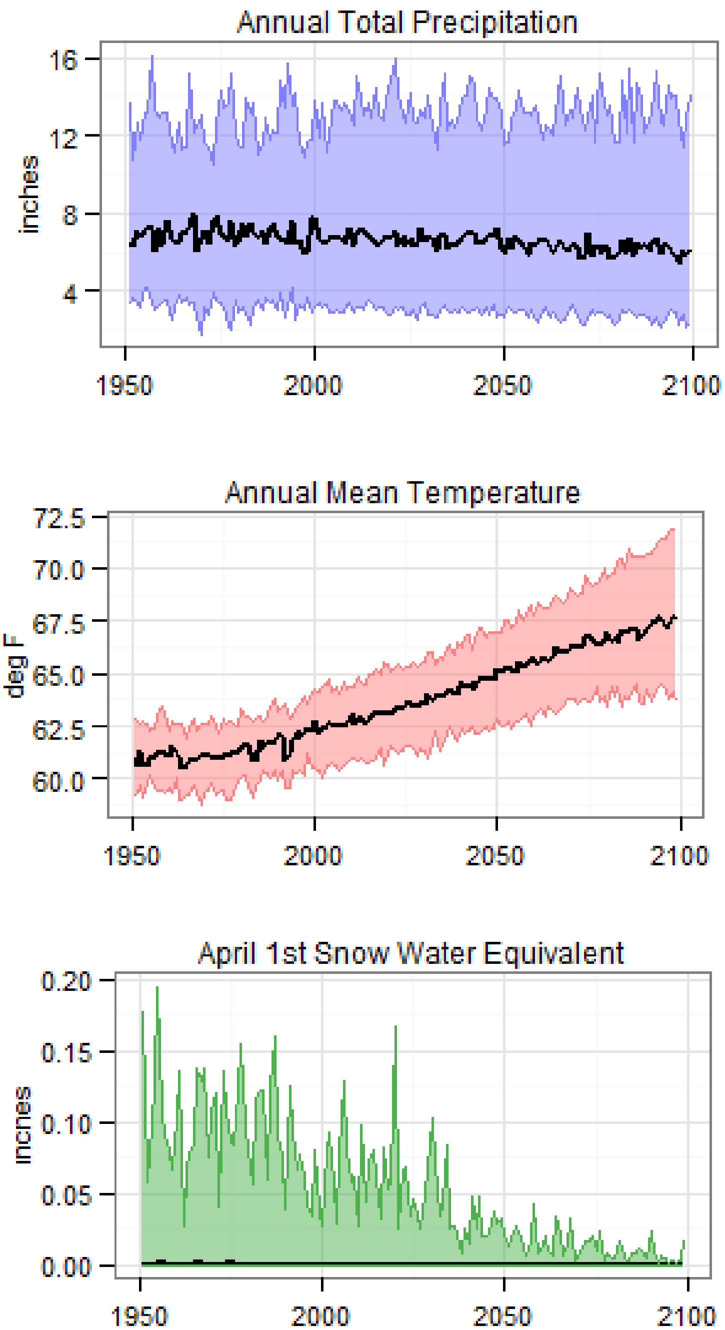

Figure 7: MWA service area projections ensemble for precipitation, temperature and snow water equivalent (SWE) (black line is 50th percentile [ensemble median]).

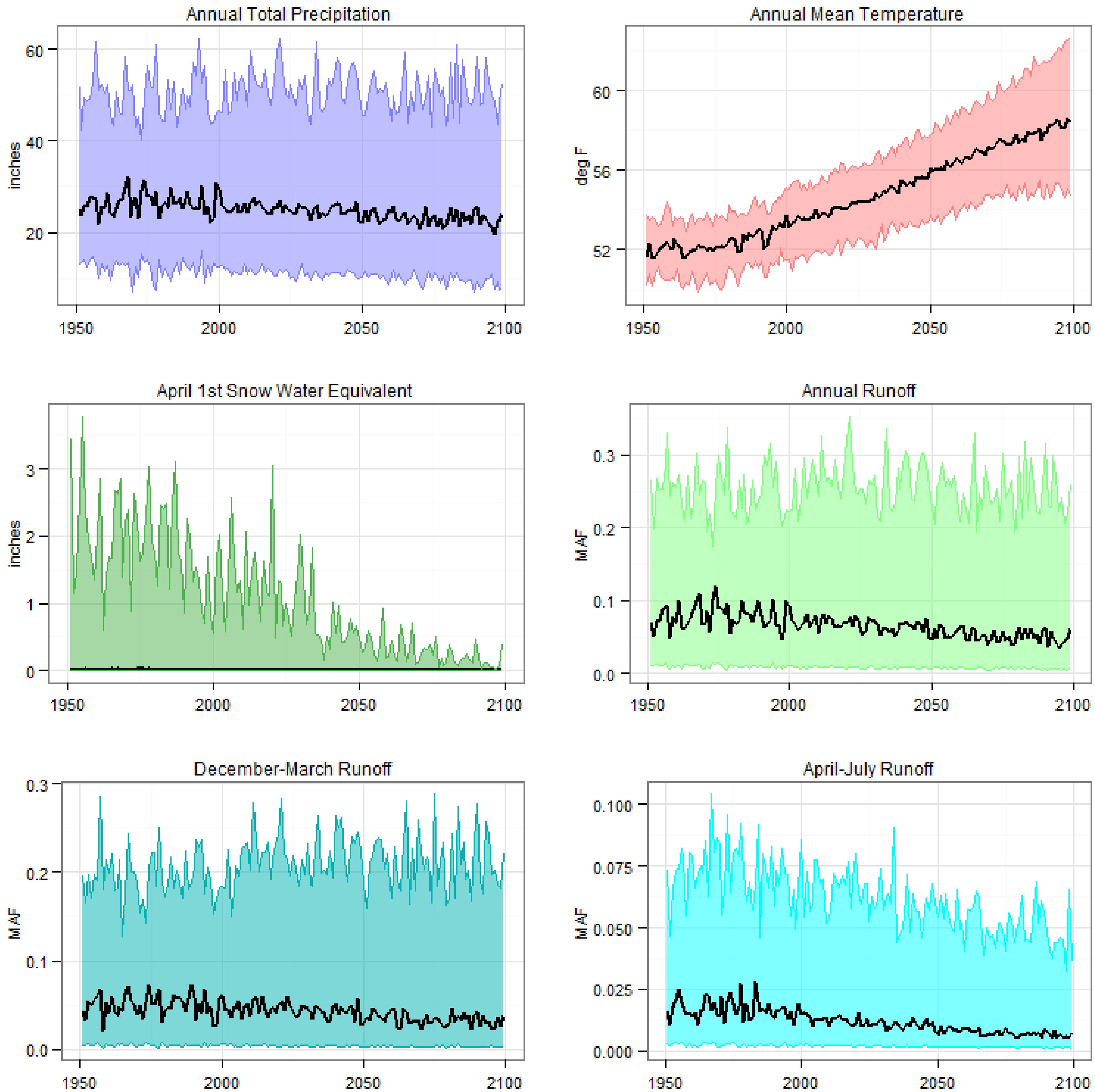

**Figure 8: Deep Creek near Hesperia—
projection ensemble for six hydroclimate indicators
(black line is 50th percentile [ensemble median]).**

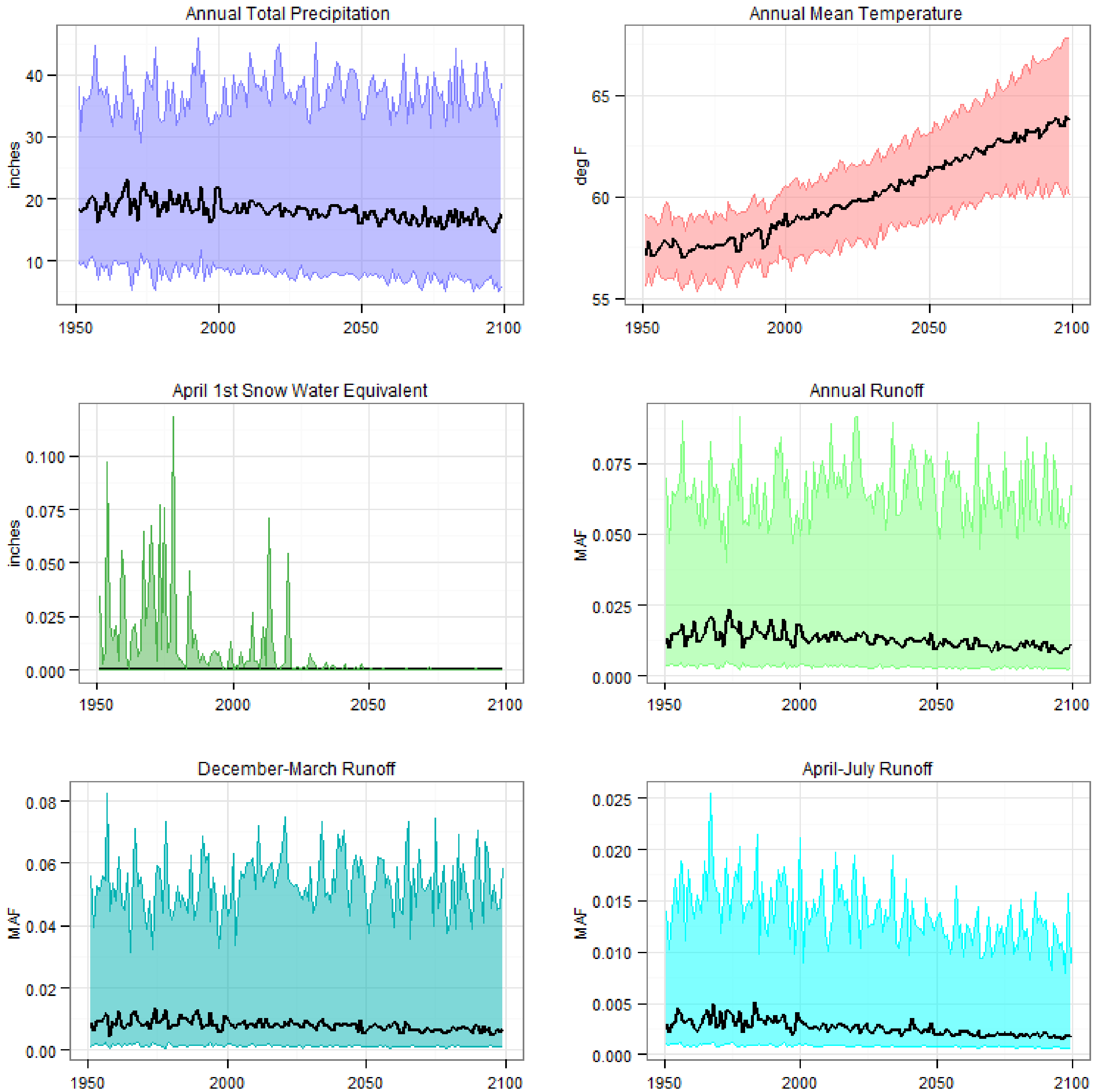

Figure 9: West Fork near Hesperia — projection ensemble for six hydroclimate indicators (black line is 50th percentile [ensemble median]).

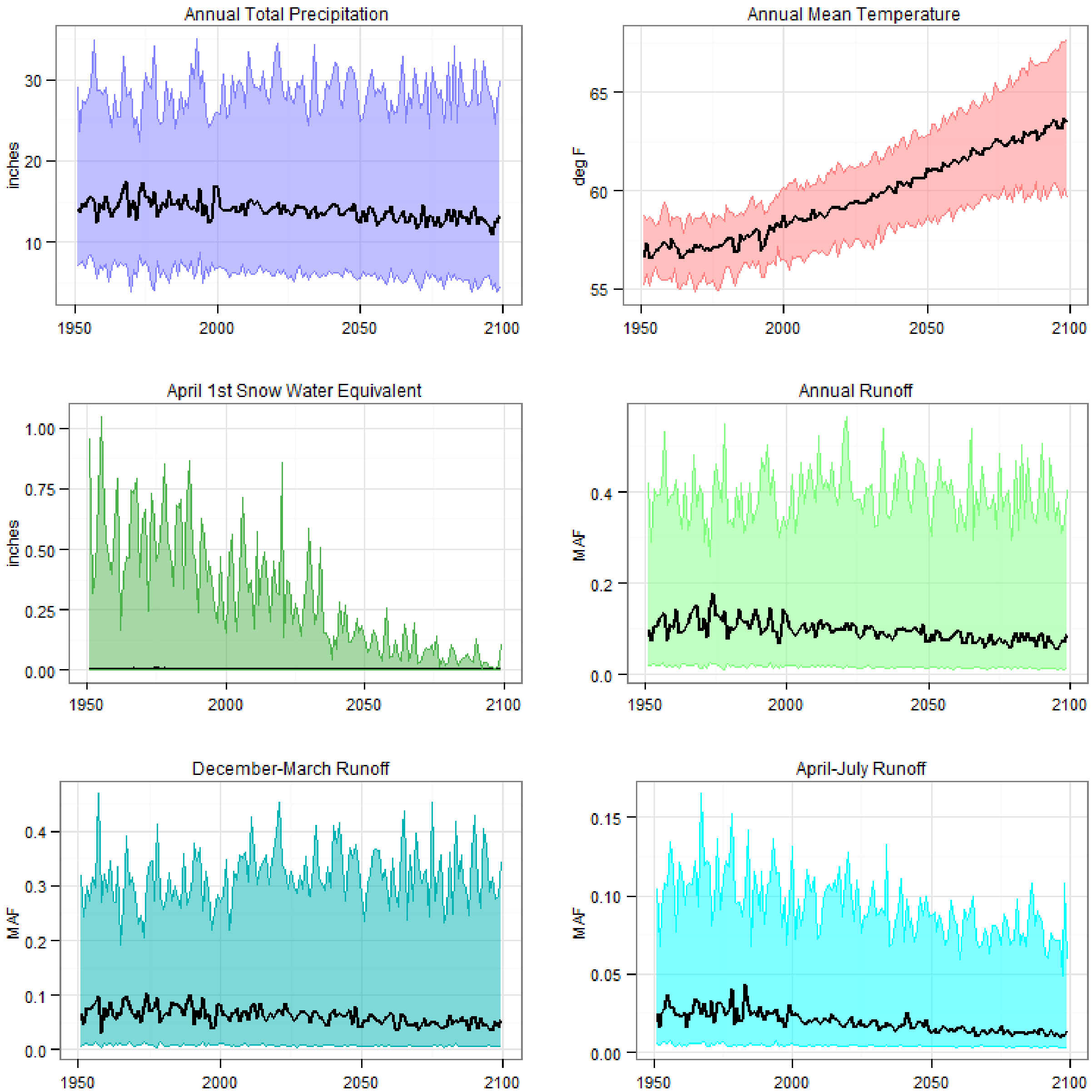

**Figure 10: Lower Narrows near Victorville—
projection ensemble for six hydroclimate indicators
(black line is 50th percentile [(ensemble median]).**

Runoff

Figure 11 summarizes the median ensemble projected decadal percentage changes in mean runoff for each of the three prediction locations relative to 1990s flow. Results are presented for three future decades: 2020s (orange), 2050s (yellow), and 2070s (blue). Trends are relatively consistent between gages, although the West Fork gage shows a slightly smaller range in predicted values. All gage locations show a slight increase in December through March flow in the 2020s, along with a corresponding decrease in April through July flow. Overall, there is a slight increase in annual runoff. For the 2020s and 2050s flows are projected to decrease both seasonally and annually with the largest decreases occurring in April through July flow.

Figure 12 and Figure 13 present changes in “low flows” (i.e., the ensemble median of the 25^{th} percentile) and “high flows” (i.e., 75^{th} percentile flows) respectively rather than the mean (as was presented in Figure 11), and are similar to Figure 11. All gage locations show consistent decreases in low flows that get progressively larger for later time periods. Changes in April through July runoff are consistently larger than the changes in December to March flows. Changes in high flows show more variability. All gages show increased high flows for the 2020s from December through March, but decreased high flows from April through July. Significant decreases in April through July flows are observed at all gage locations for the 2050s and 2070s future periods. Appendix B contains tables summarizing the results from Figure 11 to Figure 13. Also the tables present the 25^{th} and 75^{th} ensemble quantiles in addition to the median.

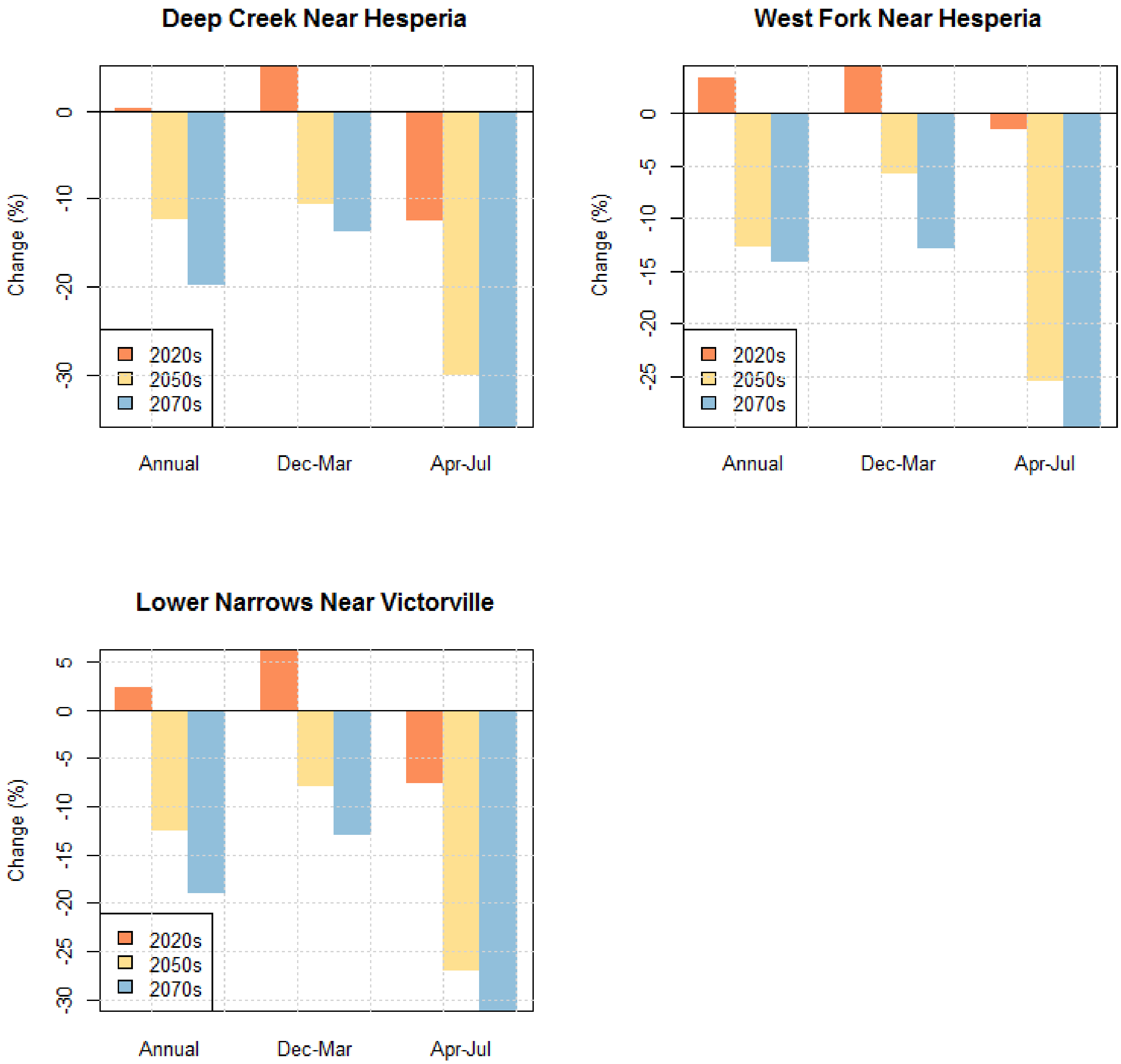

Figure 11: Flow summary of the median projected changes in mean flow as compared to the 1990s base period for the three streamflow prediction locations.

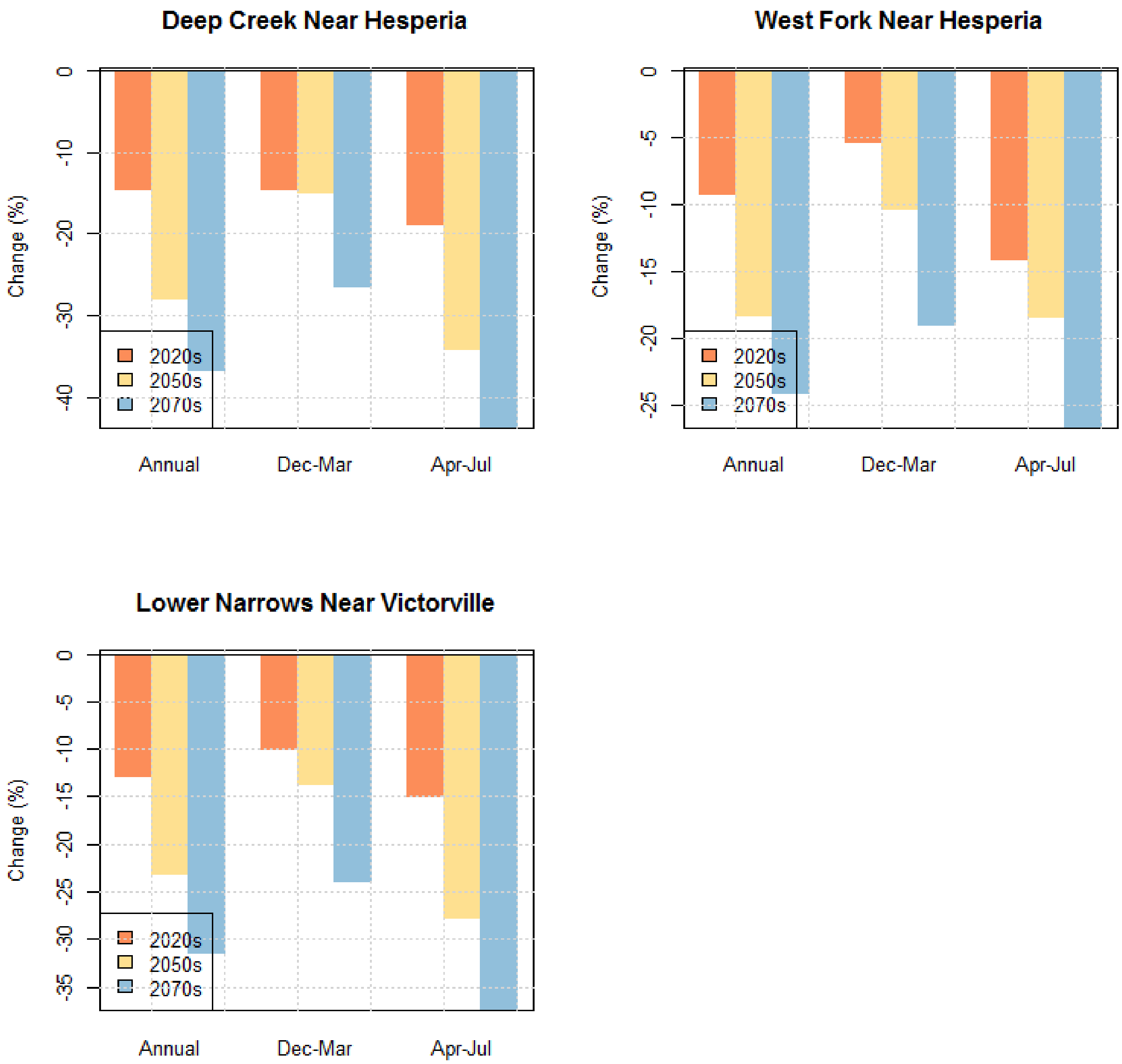

Figure 12: Flow summary of the median projected changes in the lower 25th percentile flow as compared to the 1990s base period for the three streamflow prediction locations.

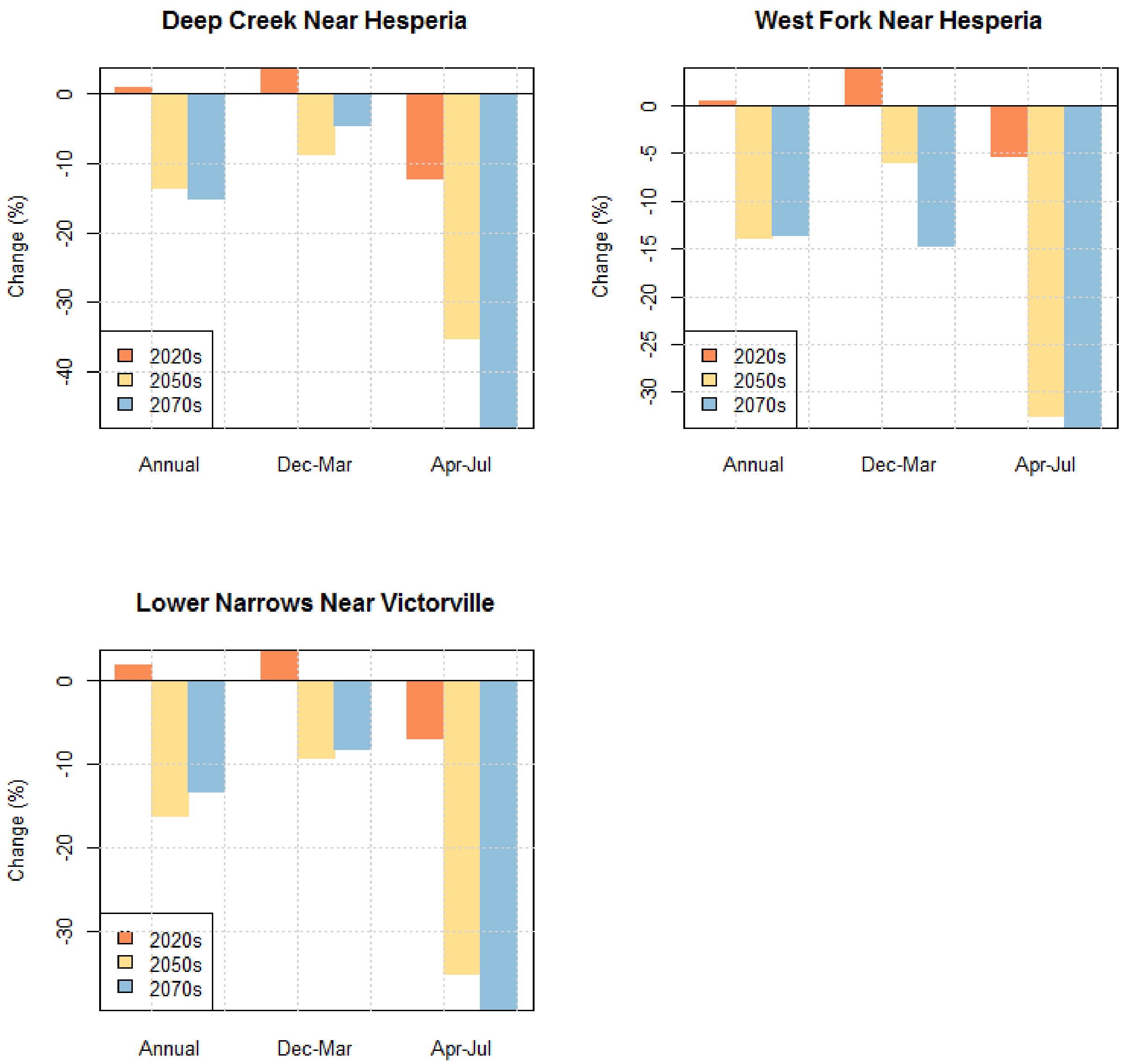

Figure 13: Flow summary of the median projected changes in the upper 75th percentile flow as compared to the 1990s base period for the three streamflow prediction locations.

2.2.2 State Water Project Imports

SWP Water Supply Projections

The 2011 SWP reliability report projects a temperature increase of 1.3° to 4.0 °F by mid-century and 2.7° to 8.1° F by the end of the 21st century. The State of California predicts that increased temperatures will lead to less snowfall at lower elevations and decreased snowpack. By mid-century, the Sierra Nevada snowpack will be reduced by 25 percent to 40 percent of the historical average. Decreased snowpack is projected to be greater in the northern Sierra Nevada (closer to the origin of SWP water) than in the southern Sierra Nevada. Furthermore, an increase in "rain on snow" events may lead to earlier runoff. Given these changes, it is expected that water shortages worse than the 1977 drought could occur in one out of every six to eight years by the middle of the 21st century and in one out of every two to four years by the end of the 21st century. Also, warmer temperatures might lead to increased demand. This demand, combined with declining flows, will likely lead to decreased carryover storage from year to year.

Finally, sea levels have already risen 7 inches along the California coast over the last century, and sea levels are estimated to rise an additional 4 to 16 inches by mid-century and 7 to 55 inches by the year 2100. Increased sea levels will increase pressure on the Delta's levee system and could lead to breaches. Higher sea levels may also increase saltwater intrusion, making some groundwater resources unusable and increasing surface water demand (State of California 2012a).

SWP Water Demand Projections

Table 4 summarizes the projected deliveries for the entire SWP, assuming that there is no climate change. As shown here, the average annual delivery is projected to be 61 percent of the total contracted water, but deliveries can vary greatly in wet and dry years.

Table 4. Estimated Deliveries of SWP Table A Contract Water in TAFY1 (SWP Scenario for Existing Conditions).

Mean	Single Dry Year (1977)	4–Year Drought (1931-1934)	Single Wet Year (1983)	4–Year Wet (1980-1983)
2,524 (61%)	380 (9%)	1,454 (38%)	2,886 (70%)	2,872 (69%)

[1] The percent of maximum SWP Table A Contract Amounts (i.e., 4,133 TAFY) from State of California 2012a, Tables 6.3 and 6.4.

Figure 14 plots exceedance probability curves (i.e., the chance of exceeding a given amount of delivery) from the MWA delivery data provided in the SWP 2011 Reliability Report Technical Addendum (State of California 2012b).

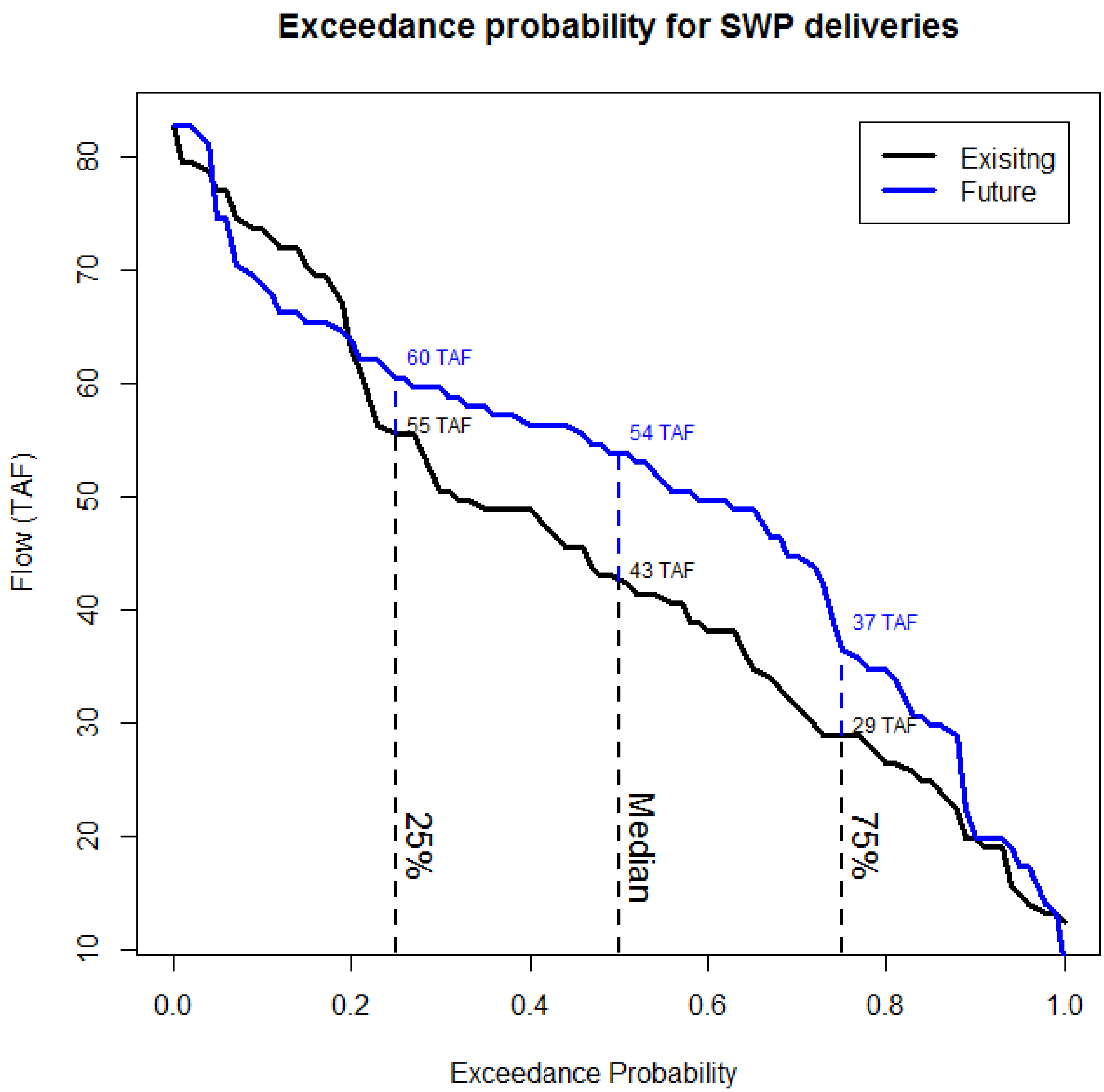

Figure 14: Projected SWP deliveries based on projections using existing and climate change conditions.

The two curves represent the two SWP scenarios modeled:

- **Existing Conditions:** This assumes that there is no climate change and uses historical hydrology for 1922 through 2003 for future water supplies, assuming 2011 land use and demand patterns for future demands.

- **Future Conditions:** This assumes climate change and uses the historical climate record perturbed (i.e., with modified precipitation and temperature) using a single climate change projection and interpolated for a 2031 level of climate change.

Dashed lines on the plot show the median, 25^{th} percentile, and 75^{th} percentile of the expected delivery amounts for both scenarios. Note that, except in the case of very high and very low flows, the expected delivery volume for a given exceedance probability is generally greater for the future scenario than the historical scenario. The median projected delivery ranges from 43 TAF to 54 TAF for the existing and future scenarios respectively. Flows for the existing scenario range from 29 TAF in the 25^{th} percentile to 55 TAF in the 75^{th} percentile flows and from 29 to 55 TAF in the 25^{th} percentile and 37 to 60 TAF in the 75^{th} percentile for the future scenario (State of California 2012b).

2.3 Summary and Conclusions

Overall, results for the 2020 time period indicate that there would be a slight increase in annual natural flows (less than 5 percent) and that SWP deliveries would be slightly lower than the estimates used in previous MWA planning studies (54 TAF used in the 2010 Urban Water Management Plan [MWA 2011b]). For the Deep Creek gage, the mean annual flow for the 1990s was roughly 72 TAF and the 2020 projected flows range from 58 TAF to 92 TAF (for the 25^{th} to 75^{th} percentile range). The 1990s mean annual flow for the West Fork gage was about 31 TAF and the range for 2020 annual projections from the 25^{th} to the 75^{th} percentile is 24 TAF to 41 TAF. Similarly, for the Lower Narrows gage, the mean annual flow for the 1990s was 50 TAF and the 2020 projected flows range from 40 TAF to 67 TAF. Refer to Appendix B for additional projected flow numbers. As shown in Figure 11, all stations have a projected increase in annual flow of less than 5 percent for 2020. However, by 2050 and 2070, flows are projected to decline between 10 and 20 percent, respectively.

It should be noted that even though the ensemble median projected flows for all gages were positive in 2020, the median trend in April through July runoff is expected to be negative. Furthermore, 25^{th} to 75^{th} percentile range of the ensemble predictions includes both increases and decreases in annual flow. Natural flows were also projected for the 2050s and 2070s. Results show greater decreases in flows moving further into the future especially in the spring/summer runoff season (April through July). Analysis of climate forcings in the basin show slight declines in precipitation with large variability and clear increases in temperature with diverging uncertainty bounds.

It is likely that changes in supply will be felt more severely in some sub-basins than in others. For example, the Morongo Basin relies almost entirely on SWP imports, so this basin may not be impacted as greatly by declines in natural flows. Furthermore, increases in temperature will likely impact demand differently, depending on the primary water uses (e.g., agricultural uses vs. urban). It should be noted that results from this analysis do not cover potential changes in wastewater discharge, which could be an important factor in locations like Este. Finally, the focus of this analysis is total surface water supply. However, groundwater supplies the majority of demand in the basin and contributes significantly to baseflow, especially in downstream reaches of the Mojave River. In many locations, water availability may be impacted by changes in groundwater development or operations that influence water table depths.

Care should also be taken to understand the limitations of the VIC model used to project changes in natural flows. Although the VIC model contains several sub-grid scale mechanisms, the coarse-grid scale should be noted when considering results and analysis of local-scale phenomenon. Also, as with any model, results from the VIC model are only as good as the inputs. Several limitations to long-term gridded meteorology related to data, spatial-temporal interpolation, and bias correction that should be considered. The inputs to the model do not include any transient trends in the vegetation or water management that may affect streamflows; they should only be analyzed from a naturalized flow standpoint. Finally, the VIC model includes three soil zones to capture the vertical movement of soil moisture, but does not include groundwater. In areas where groundwater connectivity with surface process or streamflow is important, the VIC model may not have sufficient subsurface characterization to capture hydrologic response.

3. Climate Change Impacts on Flood Flow Frequency in the Mojave River Watershed

The second task of this project was to use climate projections to analyze future flood frequency for two locations on the Mojave River: inflows to the Mojave River Dam and the Lower Narrows near Victorville.

3.1 Historical Flooding

The Mojave River has the propensity for large flood events, although many reaches of the Mojave River remain dry for the greater part of the year. Historically, the most severe floods occurred along the Mojave River near Victorville, just downstream of where the Mojave River emerges from the San Bernardino Mountains. Figure 15 provides a more detailed map of the basin headwaters with relevant stream gages and other points of interest. For additional background on the Mojave River Basin, see Section 1.2.2., Surface Water Resources and Section 2.1.1, Native Flows.

Most of flooding takes place during the rainy season from December through March, when multi-day, widespread storms saturate the headwaters (U.S. Army Corps of Engineers [USACE] 1969). However, localized flooding also occurs throughout the basin as a result of summertime thunderstorms. Historically, flood durations have been short—generally about a half day. The largest flood of record occurred on March 2, 1938, when a peak discharge of 70,600 cubic feet per second (cfs) in the Mojave River at Victorville damaged railroad and highway bridges and agricultural lands adjacent to the river (USACE 1969). The second largest flood, which reached 37,500 cfs at Victorville, occurred on January 25, 1969. During this flood, residents in lowlands adjacent to the Mojave River were forced to evacuate, and parts of crossings were washed out. Other smaller but notable floods at Victorville occurred in February 1932, November 1965 and in April 1958 (USACE 1969). Often floods are thought of as destructive; however, in the desert environment, floods can be the source of important groundwater recharge. For example, the wet year 1969 generated an 18,000 cfs flood at Afton and contributed 245,000 AF to groundwater recharge. The wet year in 1978 generated a 24,800 cfs flood at Deep Creek and contributed 282,000 AF for groundwater recharge (Buono and Lang 1980).

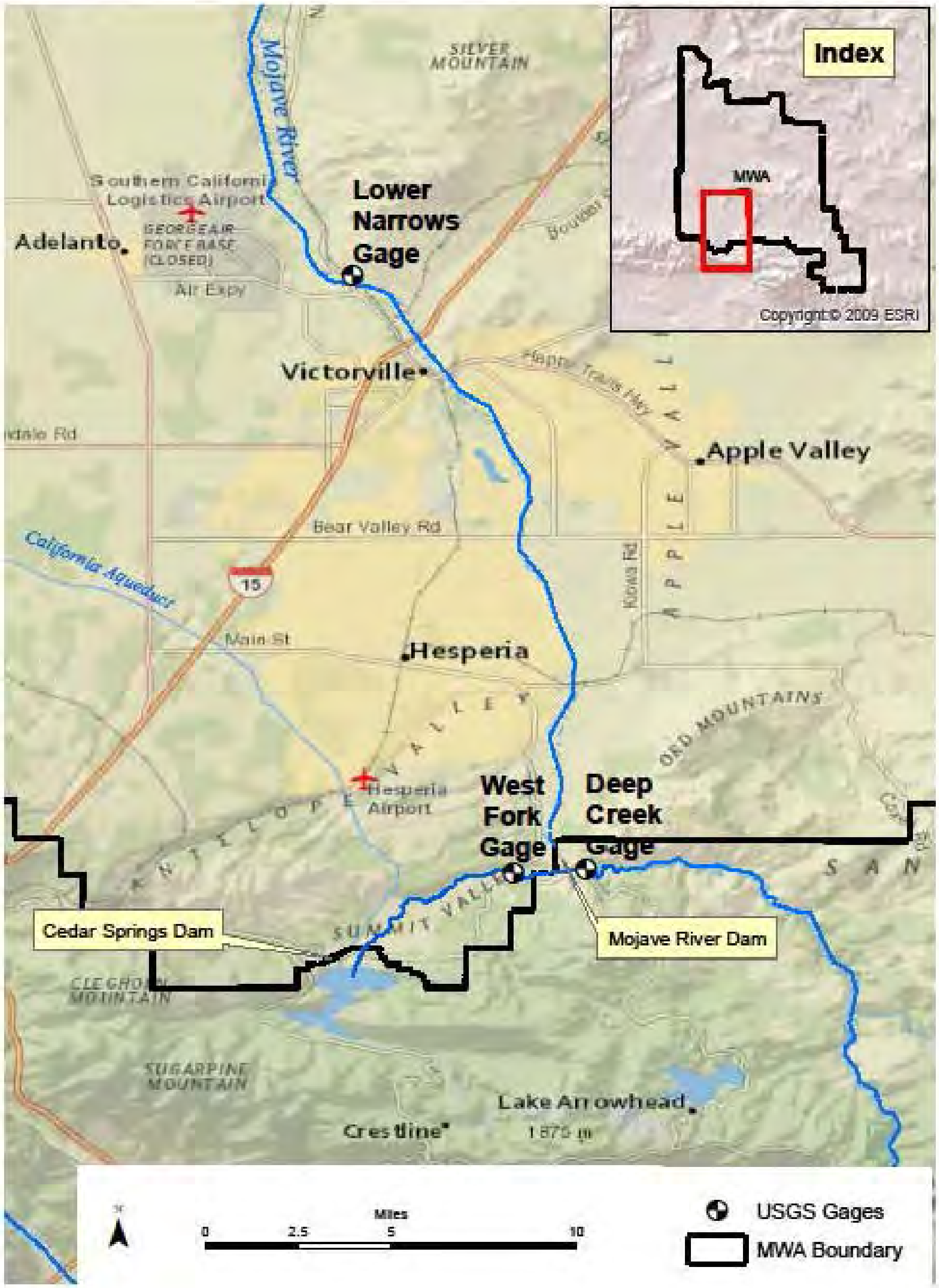

Figure 15: Map of the Mojave River headwaters.

Two dams are in the headwaters of the Mojave River:

- Cedar Spring Dam, on the West Fork of the Mojave River at Silverwood Lake, was constructed primarily as a storage facility for SWP imports and does not provide flood control.

- The Mojave River Dam, at the Forks where Deep Creek and the West Fork of the Mojave River converge, serves entirely to attenuate peak flood flows greater than 7,250 cfs (Buono and Lang 1980). As the Mojave River Dam is not a storage facility, it does not have control gates. Thus, all streamflow below an inflow of 23,500 cfs does not get stored in the dam. Flows greater than this are temporarily impounded, but these flows are released as quickly as water can leave the reservoir (i.e., at an outflow rate of 23,500 cfs) (Todd Engineers 2013). The total capacity of the dam is 78,700 AF, after accounting for 11,000 AF of potential accumulated sediment (Todd Engineers 2013).

Since the 1970s, the peak flow rates at Victorville have decreased significantly, due to the construction of the Mojave River Dam. Since its construction, at most one third of the Mojave River Dam's storage has been occupied, and this only occurs during infrequent storms roughly every six years with an average flow of about 41,000 cfs (Winkel 2013). Thus, large floods like those seen in 1938, 1967, and 1969 are not expected at Victorville in the future. Still, floods larger than 23,500 cfs at Victorville are possible —while the Mojave River Dam will generally slow the speed of flood rises, rapid flooding can still occur from thunderstorms downstream of the dam, reaching Victorville.

Prior to the Mojave River Dam construction, USACE determined intermediate regional flood and standard project flood values for the Lower Narrows gage that can be used to bracket probable maximum floods. All calculations were performed assuming the same specifications as the fully functioning dam. The intermediate regional flood (i.e., the flood with an expected recurrence interval of 100 years) was calculated to be 89,000 cfs without a dam, but 23,200 cfs with the dam (USACE 1969). This intermediate regional flood was estimated to generate water depths of about 2 feet on the floodplain (USACE 1969). The standard project flood is defined as the flood "that may be expected from the most severe combination of meteorological and hydrological conditions considered reasonably characteristic" (USACE 1969). In most locations, the standard project flood is considerably larger than any historically observed flood. For Victorville, the standard project flood was projected to be 94,000 cfs without the dam, but 23,500 cfs with the dam. The standard project flood would generate flood depths of about 2.5 feet on the flood plain (USACE 1969).

The scope of this analysis is on potential future flooding on the main stem near Victorville and above the Mojave River Dam; however, flooding does occur throughout the basin. Several USGS studies have determined flood frequency curves for ungaged ephemeral streams in the Apple Valley and Lucerne Valley Dry Lakes (Busby 1975 and 1977). In addition to flooding within the basin, the MWA can also be impacted by flooding that affects SWP infrastructure. Although not common, short- term outages have occurred on the California Aqueduct. For example, the Arroyo Pasajero flood in 1994 (near Coalinga in Fresno County) caused a short outage, but managers were able to respond effectively and deliveries were not interrupted. The most recent SWP reliability report provides additional details on the potential impacts of Delta levee failures and seismic flood events on SWP deliveries (State of California 2012a).

3.2 Methodology

We used non-stationary generalized extreme value (GEV) functions to analyze how changing climate conditions may influence flood frequency at two locations along the Mojave River (the Mojave River Dam and the Lower Narrows). Models were fit to historical streamflow and climate data so that the function parameters vary with precipitation and temperature. Future estimates of precipitation and temperature generated from 112 GCM projections were then used to fit GEV curves for future periods and to estimate potential changes in flood frequency at both Lower Narrows gage locations and the Mojave River Dam.

3.2.1 Non-Stationary GEV Method

Standard statistical approaches, like normal distributions, are focused on the average behavior of a system and have less skill in predicting tails (i.e., the lowest and highest values of a distribution). Extreme value analysis (EVA) deals with the examination of the extremes of a distribution. EVA is a robust approach for flood frequency analysis because it is designed to model low frequency, high impact events. An extreme value time series must be generated from observations to conduct an EVA.This time series can be generated using one of two methods:

- Points over threshold time series are generated by selecting all of the values above a user defined threshold.

- Block maxima are generating using the maximum vales for a given block of time (i.e., monthly max streamflow).

For this analysis, we use the block maxima approach, calculating monthly maximum daily flows for the flood season (December through March). Given a time series of block maxima, GEV distributions are a general class of probability models that can be used to model extreme values. These models have three parameters—location (μ), scale (σ) and shape (ξ). Equation 1 shows the GEV Cumulative Distribution Function (CDF) of maximum streamflow (z) as a function of the model parameters.

$$G(z;\mu,\sigma,\xi) = exp\left\{1 + \left(\frac{z-\mu}{\sigma}\right)^{1\frac{1}{\xi}}\right\} \quad (1)$$

GEV analysis is well suited for climate change projections because non-stationary models can be fit to allow model parameters (e.g., location and scale) to vary, based on covariates like temperature and precipitation. Equations 2 and 3 show general forms for non-stationary parameters where, t represents time, $x_1 \ldots x_n$ are the covariates and $\beta_0 \ldots \beta_n$ are the regression coefficients. Using this approach, future changes in flood frequency can be estimated based on variables from climate projections without explicitly modeling future flows.

$$\mu(t) = \beta_{0\mu} + \beta_{1\mu}\chi_1(t) \ + \cdots \beta_{n\mu\chi_n(t)} \quad (2)$$

$$\sigma(t) = \beta_{0\sigma} + \beta_{1\sigma}\chi_1(t) \ + \cdots \beta_{n\sigma\chi_n(t)} \quad (3)$$

For this analysis, we followed the methodology shown by Katz and Naveau (2002) and Towler et al. (2010). First, we fit a non-stationary model to the time series of observed block maxima flow using different model forms and combinations of covariates. Models with non-stationary (i.e., allowed to vary with covariates like precipitation and temperature) location and scale as well as location and scale were considered. The shape parameter is usually stationary (and was stationary for this analysis) because it is noisy and adding covariates does not generally improve model performance. Precipitation or temperature or both were tested as potential covariates in each of the model formats noted. Coefficients for parameters were estimated using the maximum likelihood approach (e.g., Katz and Naveau 2002). The best model was selected by pairwise comparing models using likelihood ratio test (Katz and Naveau 2002). This test weighs the goodness of fit for each model with the level of complexity. In this test, the negative log likelihood (NLLH) score was reported as a measure of model fit, with lower values representing better fits. P-values were reported for each model comparison with a significance threshold set to 0.05 as shown in Table 5.

Once we selected the best non-stationary model, we estimated the model parameters for each of the 112 GCM climate projections, for every month, given the projected precipitation and temperature values. In each projection, every future month within every climate projection has its own GEV CDF where the location and scale are determined based on that month’s climate variables. Using these curves, future estimates of the return period (i.e., the recurrence interval over a long time period) of a given flood level or the projected number of exceedances can be estimated.

3.2.2 Data Inputs

As noted above, historical streamflow and covariate values are needed to fit a non-stationary GEV model. We estimated floods at the Mojave River Dam as well as the Lower Narrows gage location. For both locations, USGS gages provide records of daily flow. We used the Deep Creek, West Fork, and Lower Narrows gages (described in Section 1.1.2, Physical Setting, and shown on Figure 15). Flows at the Mojave River Dam were calculated by summing Deep Creek and West Fork gage flows. Time series of block monthly maxima were generated for each location from 1950 through 1999 for the flood season December through March (i.e., four values for every year). Similar to other studies (e.g., Towler et al. 2010), we used temperature and precipitation as covariates in the non-stationary models. Historical climate observations were gathered from a 1/8° gridded dataset from Maurer et al. (2002). December through March monthly mean temperature and total precipitation were aggregated for each study location using data from their respective upstream areas.

One advantage of the GEV methodology is that there is no need to explicitly model future streamflows. Rather, flood estimates can be generated based on projections of covariates (i.e., precipitation and temperature). To provide a range of flow estimates, we analyzed results from 112 different GCM projections, similar to the analysis done in Task 1 (see Chapter 2). The projections cover 16 different CMIP3 models simulating three different emissions paths (i.e., B1[low], A1b[middle] and A2[high]) and starting from different ends of the 20th century climate conditions. Each projection provides monthly values of temperature and precipitation, from 1950 through 2099. The data used for this study was downscaled to 1/8° (about 12 kilometers) spatial resolution from GCM outputs using the BCSD approach demonstrated in Wood et al. (2002). Although there are some drawbacks, compared to dynamical downscaling methods, the BCSD approach has been shown to perform comparably with respect to hydrologic impacts (Wood et al. 2004). Monthly temperature and precipitation values were extracted for the flood season (December through March) from 2000 through 2099 for each scenario.

3.3 Results

3.3.1 Model Fitting

Following the methodology described above, GEV models were fit to historical monthly maximum flow (for the Mojave River Dam and the Lower Narrows gage location) using a variety of non-stationary parameters and covariates. Due to the flashy nature of flows in the basin and the large number of months with zero flow, models were fit to the natural log of flows. Table 5 summarizes the non-stationary relationships for each of the models that were tested. For the tables in this section, P represents monthly precipitation and T monthly temperature.

Table 5: Summary of GEV Models Tested.

Model #	Description	Location (μ)	Scale(σ)	Shape (ξ)
1	Stationary	μ	σ	ξ
2	Non-stationary scale precipitation and temperature covariates	μ	$\sigma(t)= \beta_{0\sigma} + \beta_{1\sigma}P(t) + \beta_{2\sigma}T(t)$	ξ
3	Non-stationary scale precipitation covariate	μ	$\sigma(t)= \beta_{0\sigma} + \beta_{1\sigma}P(t)$	ξ
4	Non-stationary scale temperature covariate	μ	$\sigma(t)= \beta_{0\sigma} + \beta_{2\sigma}T(t)$	ξ
5	Non-stationary location precipitation and temperature covariates	$\mu(t)= \beta_{0\mu} + \beta_{1\mu} P(t) + \beta_{2\mu}T(t)$	σ	ξ
6	Non-stationary location precipitation covariate	$\mu(t)= \beta_{0\mu} + \beta_{1\mu} P(t)$	σ	ξ
7	Non-stationary location temperature covariate	$\mu(t)= \beta_{0\mu} + \beta_{2\mu}T(t)$	σ	ξ
8	Non-stationary location and scale precipitation and temperature covariates	$\mu(t)= \beta_{0\mu} + \beta_{1\mu} P(t) + \beta_{2\mu}T(t)$	$\sigma(t)= \beta_{0\sigma} + \beta_{1\sigma}P(t) + \beta_{2\sigma}T(t)$	ξ
9	Non-stationary location and scale precipitation covariate	$\mu(t)= \beta_{0\mu} + \beta_{1\mu} P(t)$	$\sigma(t)= \beta_{0\sigma} + \beta_{1\sigma}P(t)$	ξ
10	Non-stationary location and scale temperature covariate	$\mu(t)= \beta_{0\mu} + \beta_{2\mu}T(t)$	$\sigma(t)= \beta_{0\sigma} + \beta_{2\sigma}T(t)$	ξ

As highlighted in Table 5, the non-stationary location and scale model with both precipitation and temperature used as covariates (model 8 in Table 5) has the lowest NLLH score for both the Mojave River Dam site and the Lower Narrows gage location. The second best model is the non-stationary location model with both precipitation and temperature as covariates (model 5). The ratio test comparing model 8 to model 5 shows that model 8 is a statistically significant improvement over model 5, even given the additional degree of freedom introduced by having two non-stationary parameters rather than one. Similar results are shown for the Lower Narrows (Table 7) where model 8 also has the lowest score and is a statistically significant improvement over model 5.

Table 6 and Table 7 show the parameters for each of the fitted models for the Mojave River Dam location and the Lower Narrows respectively. In addition to the parameters, the negative log likelihood (NLLH) scores as well as the p-values for the log likelihood ratio test are also reported.

Table 6: Model Summary for Mojave River Dam.

Model Name	Stationary Model	Non-Stationary Scale			Non-Stationary Location			Non Stationary Location and Scale		
Model #	1	2	3	4	5	6	7	8	9	10
Covariates		P & T	p	T	P & T	p	T	P & T	p	T
$\beta_{0\sigma}$		-0.9196	1.2539	2.4015				-0.1454	1.1657	1.3107
$\beta_{1\sigma}$		0.2584	0.2573					0.0401	0.0418	
$\beta_{2\sigma}$		0.0520		-0.0079				0.0309		0.0172
$\beta_{0\mu}$					-0.8884	3.1899	7.2119	0.7359	3.0016	3.6687
$\beta_{1\mu}$					0.3936	0.3697		0.4153	0.4119	
$\beta_{2\mu}$					0.0944		-0.0649	0.0533		0.0179
Location (μ)	4.4503	3.8297	3.7514	4.4473						
Scale (σ)	2.0618				1.3820	1.3865	2.0469			
Shape (ξ)	-0.2060	-0.5119	-0.4483	-0.2084	-0.3301	-0.2910	-0.2036	-0.2939	-0.2639	-0.1768
NLLH	439.2	402.0	405.7	439.2	342.0	347.2	438.0	**339.1**	343.9	440.2
p-value		< 0.05	< 0.05	0.81	< 0.05	< 0.05	0.13	< 0.05	< 0.05	NA
Compared to Model #		1	1	1	1	1	1	5	6	7

Table 7: Model Summary for the Lower Narrows.

Model Name	Stationary Model	Non-Stationary Scale			Non-Stationary Location			Non-Stationary Location and Scale		
Model #	1	2	3	4	5	6	7	8	9	10
Covariates		P & T	p	T	P & T	p	T	P & T	p	T
$\beta_{0\sigma}$		0.3410	0.3139	1.1521				0.1947	0.2832	2.1526
$\beta_{1\sigma}$		0.2492	0.2497					0.1782	0.1780	
$\beta_{2\sigma}$		-0.0006		-0.0088				0.0018		-0.0311
$\beta_{0\mu}$					1.3468	3.2649	3.7904	2.6478	3.3196	5.1776
$\beta_{1\mu}$					0.3811	0.3484		0.3457	0.3309	
$\beta_{2\mu}$					0.0415		0.0008	0.0145		-0.0302
Location (μ)	3.8271	3.5827	3.5830	3.8148						
Scale (σ)	0.7700				0.7559	0.7632	0.7695			
Shape (ξ)	0.3839	-0.0504	-0.0515	0.3970	0.0415	0.0607	0.3852	0.0156	0.0072	0.4010
NLLH	309.4	269.1	269.1	308.6	264.5	268.7	309.4	225.2	226.6	307.0
p-value		< 0.05	< 0.05	0.22	< 0.05	< 0.05	0.93	< 0.05	< 0.05	< 0.05
Compared to Model #		1	1	1	1	1	1	5	6	7

Figure 16 and Figure 17 plot histograms of the observed log flows overlaid with probability density functions estimated from the different GEV models for the Mojave River Dam and the Lower Narrows respectively. The non-stationary scale models are not plotted here because NLLH scores showed that they perform significantly worse than the other two model forms. As can be seen in both figures, the models with temperature as the only covariate (dashed green line) are generally a much closer match to the stationary model (solid black line) and may qualitatively appear to be a better fit than the non-stationary models that include precipitation (blue and red dashed lines). However, the temperature-only models (models 4, 7, and 10) are shown in Table 6 and Table 7 to have much larger (i.e., worse) NLLH scores. As such, the precipitation and temperature models were selected for analysis based on their superior NLLH scores. Furthermore, it makes physical sense for precipitation to be a covariate for flood frequency, particularly for a system that is not snowmelt driven.

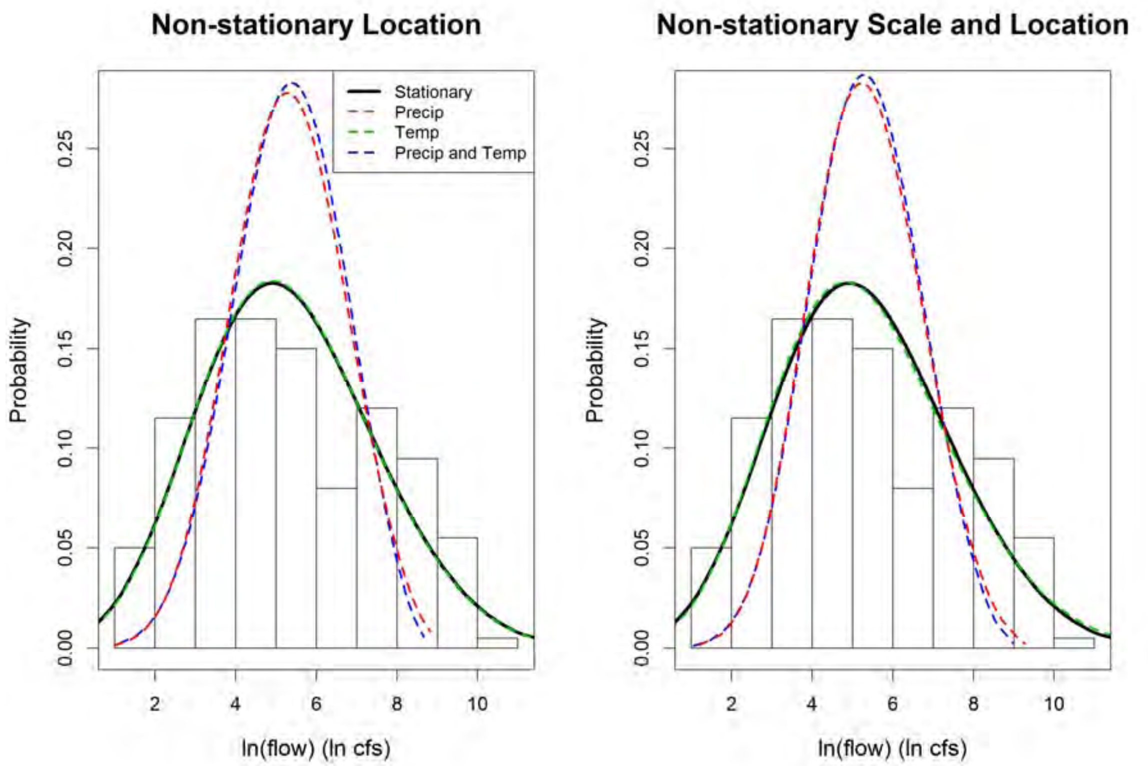

Figure 16. Histogram of Mojave River Dam flows with lines for GEV models.

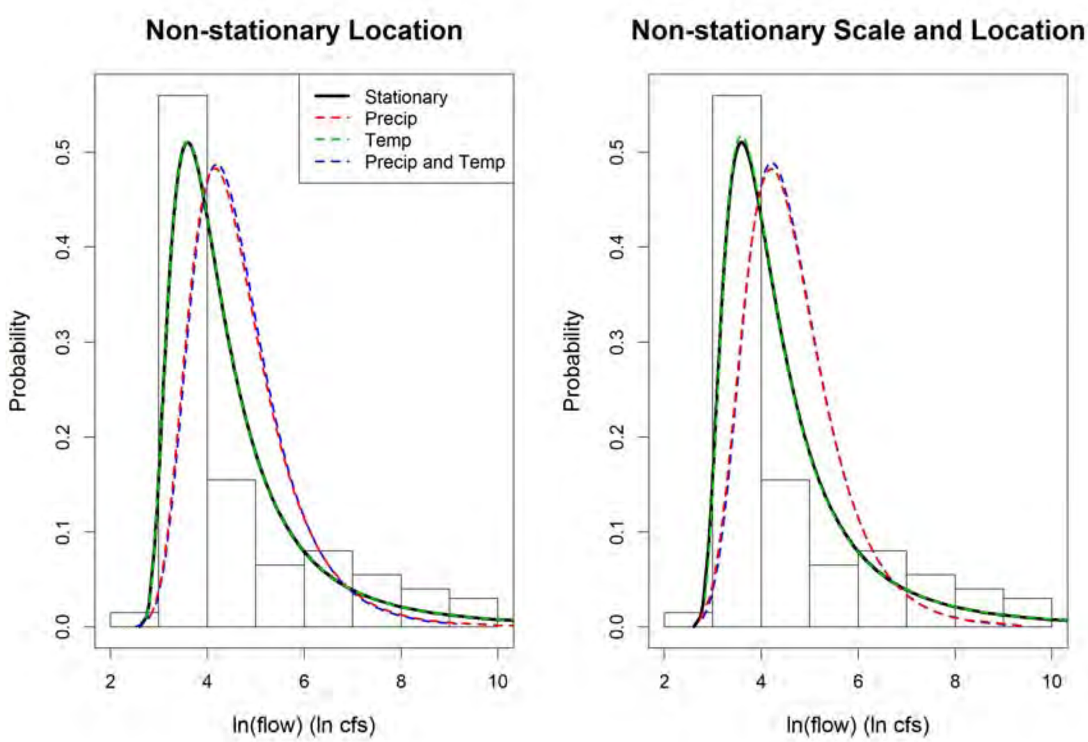

Figure 17. Histogram of Lower Narrows flows with lines for GEV models.

Model fit can also be demonstrated by comparing time series of historical observations and historical model predictions. Figure 18 shows the Mojave River Dam results and Figure 19 shows the Lower Narrows results. Figure 18 and Figure 19 plot the historical USGS observed flow (red) with the 10th to 90th percentile range (grey) as well as the median (blue) of the modeled historical flows determined using the observed historical temperature and precipitation. For both locations, there is good agreement between observed and simulated flows. There are only a few instances where the observed (red) line falls outside the 10th to 90th percentile range. Furthermore, the cases where the red lines falls below the 10th percentile have little implication, if any, on extreme flood events. In most cases, the peak flows are very close to the median modeled value.

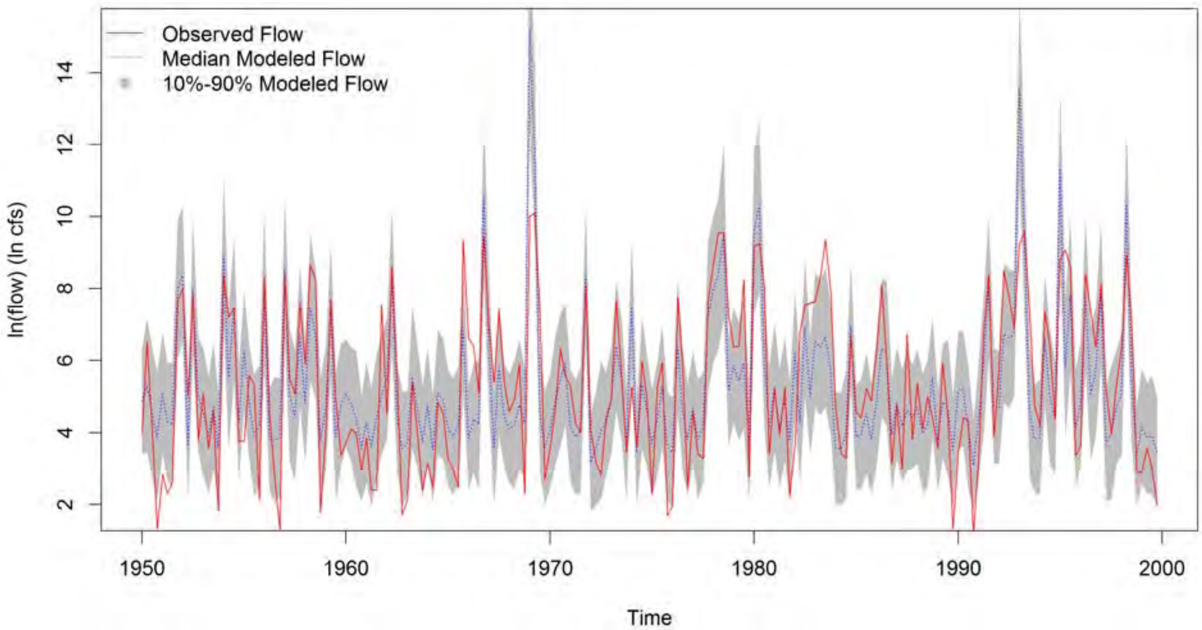

Figure 18: Time series of natural log of observed flow at the Mojave River Dam and the range of historical modeled results.

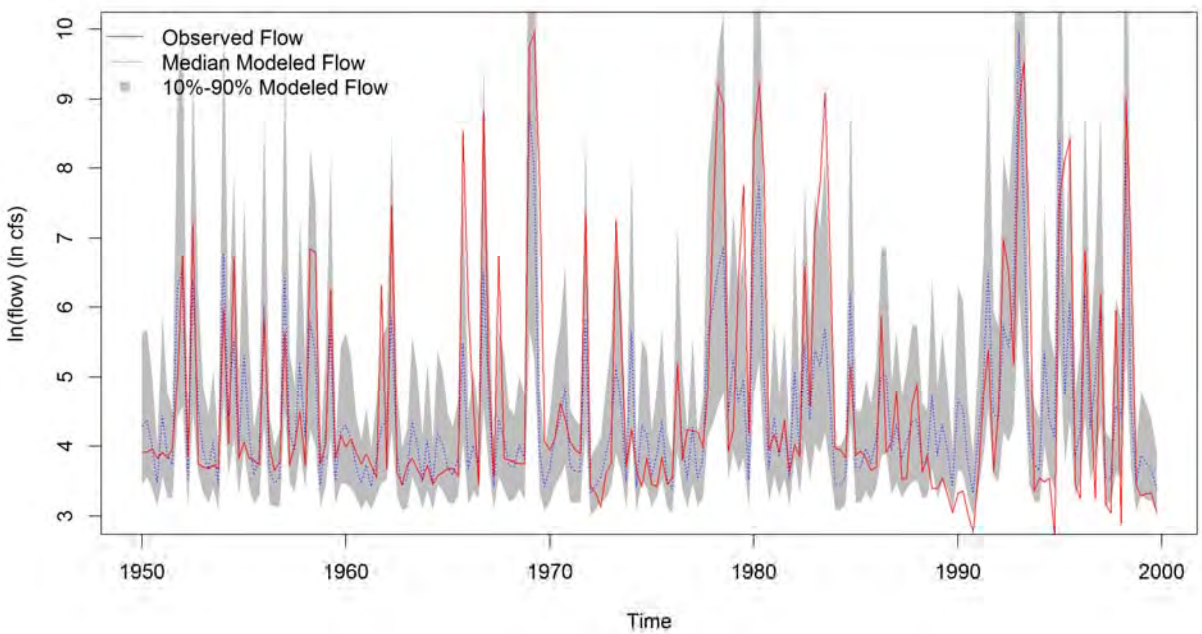

Figure 19: Time series of the natural log of observed flow at the Lower Narrows and the range of historical modeled results.

3.3.2 Mojave River Dam Future Flood Frequency Analysis

Using monthly temperature and precipitation values from 2000 through 2099 for each of the 112 GCM climate projections, probability curves were generated for every month (from December through March) for every scenario. For the purposes of this discussion we will refer to max flow as the maximum flow, we used the 99th percentile flow (i.e., the flow value that has a 1 percent chance of being exceeded). Given the monthly curves generated with the non-stationary model, we generated a time series of monthly maximum flows for each projection by selecting the 99th percentile flow for each month. Figure 20 plots the probability density function for each of the 112 GCM climate projections overlaid with the historical values estimated using the non-stationary model with historical precipitation and temperature. The historical line shows data from 1950 through 1999, and the climate projection lines are grouped into twenty year future time periods in each subplot. Projections show both increased and decreased likelihood of high flow values; and the spread of the climate projections generally increases moving further into the future.

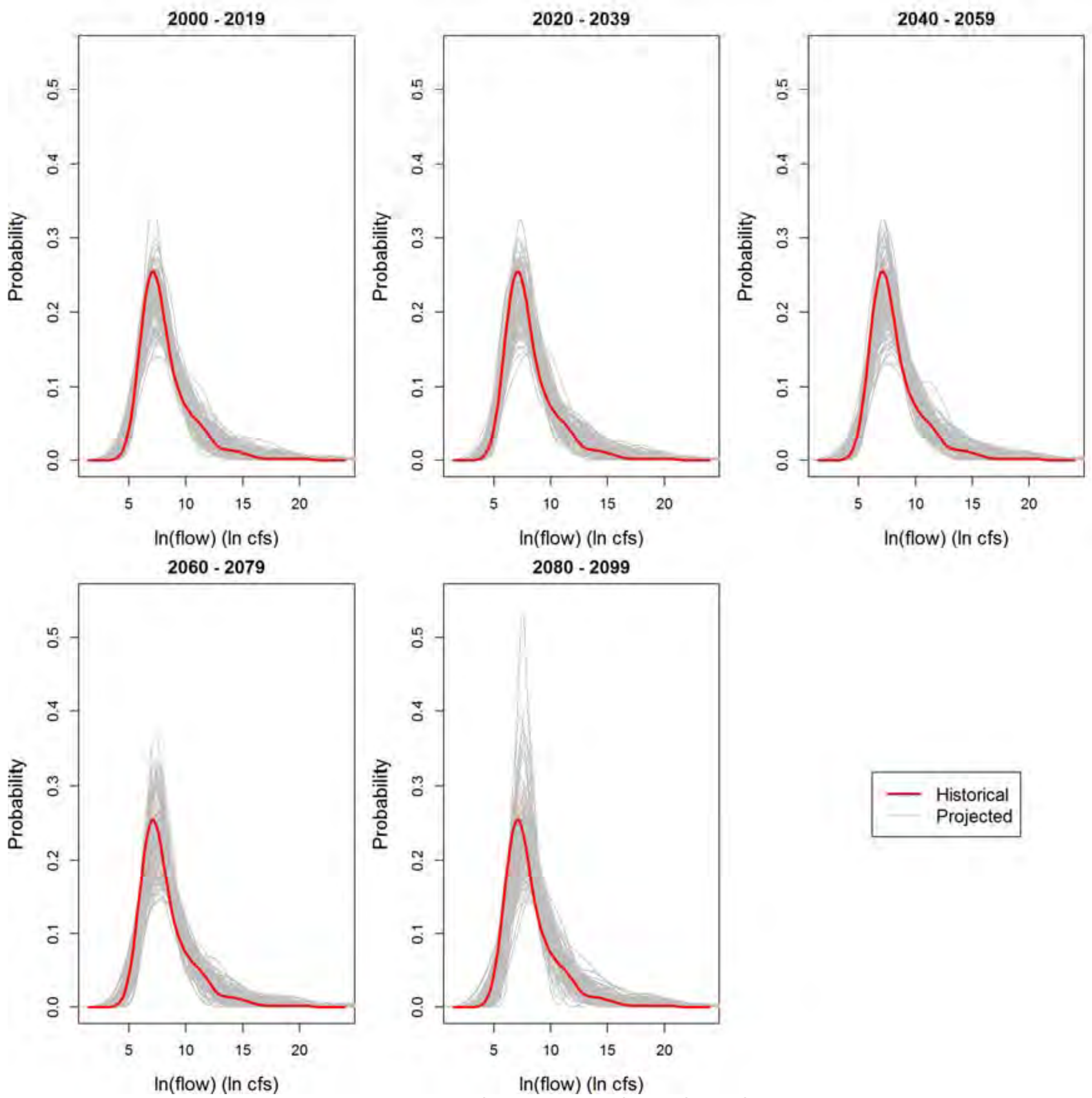

Figure 20: Probability density functions of log flow for the historical time period, 1950 through 1999 (red) and each of the 112 climate projections (grey) at the Mojave River Dam.

Threshold flow values of 7,250 cfs (when the Mojave River Dam starts to attenuate flows) and 23,500 cfs, (the maximum flow rate through the dam) were selected for analysis. To better quantify differences shown in Figure 20, we calculated the number of times that a given maximum flow (i.e., 7,250 or 23,500 cfs) is exceeded for each of the 112 GCM climate projections for each twenty-year future time period.

Figure 21 provides boxplots of the number of times each flow value is exceeded. Boxes span the estimates from each of the 112 GCM climate projections for the five twenty-year future time periods. The red dashed line shows the number of times each flow was exceeded using the historical model. Appendix C contains the numerical values for the 25th percentile, 75th percentile, and median values show in the boxplots. As can be seen in Figure 21, the climate projections show a slight increase in the number of times each flood volume is expected. However, these changes are relatively small, given the variability of the projections. The historical exceedance count for a 7,250 cfs flood is 21.6 times per 20 years while the median 2090 value is 25. Similarly, for 23,500 cfs the 2090 median value is 16 while the historical is 12. Changes between the median value and the historical value are generally less than the variability between climate projections. In all cases, the historical value falls within the 25th to 75th percentile range of the climate projections. Furthermore, in all cases the range of the data extends above and below the historical line, indicating that there are projections that predict decreased as well as increased flood likelihood.

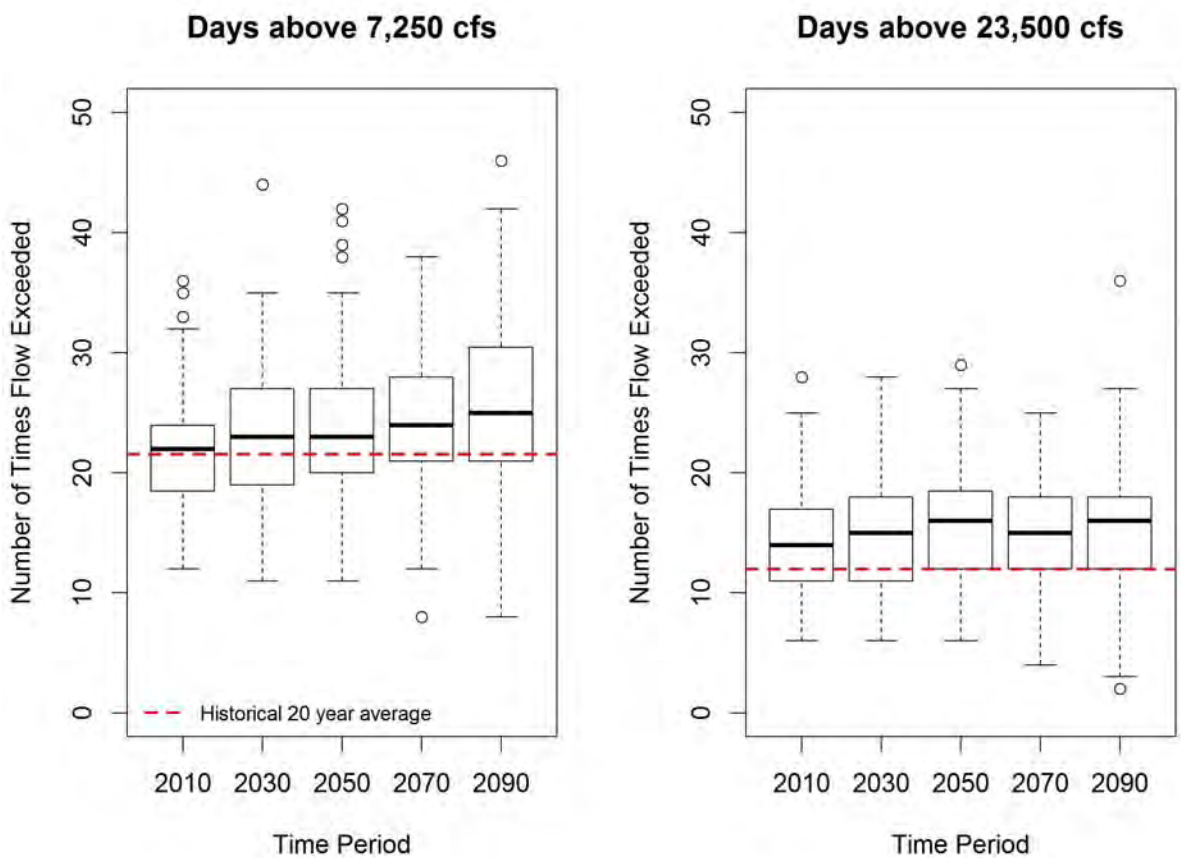

Figure 21: Boxplots of the number of days that a given flow is exceeded at the Mojave River Dam for 20-year future time periods centered around 2010, 2030, 2050, 2070, and 2090 (red dashed line is the historical value).

Similar to Figure 21, Figure 22 plots the mean return periods estimated for each of the 112 GCM climate projections averaged separately over each of five twenty-year future time periods. There are 112 values for each twenty-year future time period, and the red dashed line plots the mean historical return period estimated from 1950 through 1999 (using the non-stationary model applied to historical climate variables). Given the slight increase in flood frequency shown in

Figure 21, it makes sense that Figure 22 shows a small decline in return periods. However, once again, it is important to point out that declines are small (3.4 years historically versus 3.0 years for median 2090 for 7,250 cfs and 6 years historically versus 5.1 years for median 2090 for 23,500 cfs) relative to the spread of the data. The historical line falls within the 25^{th} to 75^{th} percentile range for all future time periods. Although the median future return periods are slightly less than the historical value, the distribution is skewed and there are multiple outliers that show return periods much larger than were observed historically. Finally, there is no clear trend between time periods—either in median values or in the spread of the projections.

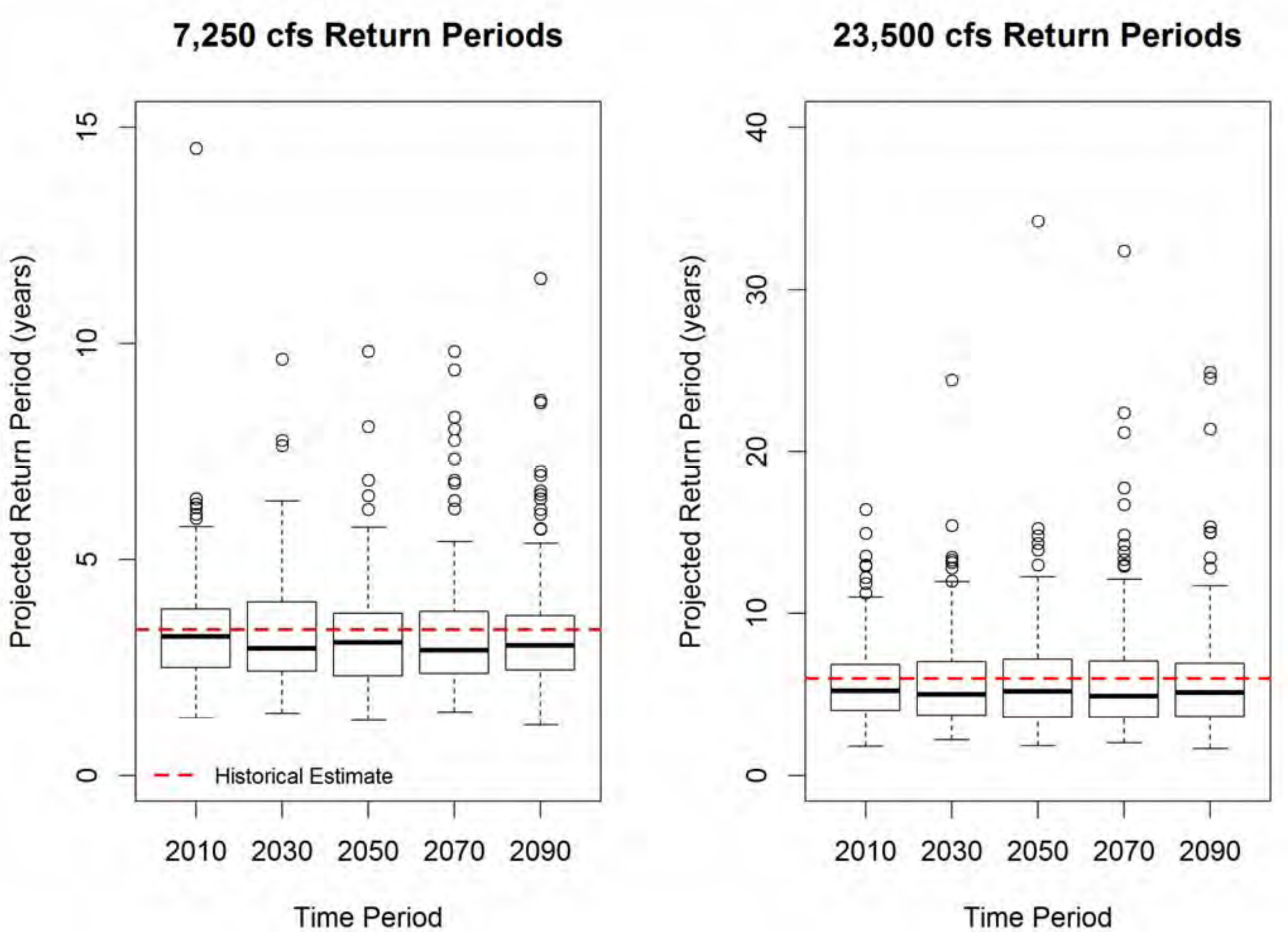

Figure 22: Boxplots of the return period for given flow for twenty-year periods centered around 2010, 2030, 2050, 2070, and 2090 (red dashed line is the historical value) at the Mojave River Dam.

3.3.3 Lower Narrows Future Flood Frequency Analysis

Analysis for the Lower Narrows followed the same method as the analysis presented for Mojave River Dam. Once again, two flood thresholds are considered: 7,250 cfs and 23,500 cfs. The flows at Lower Narrows were taken directly from the USGS gage values and were not adjusted to account for Mojave

River Dam operations. As the two flood magnitudes considered are below or at the range where the dam retains flows and mitigates the flood peak, this approach is acceptable. Furthermore, no adjustments are made to the projected flows to account for dam operations. As such, the projections should be viewed as 'natural flows' absent any flood retention.

As with the Mojave River Dam analysis, monthly temperature and precipitation values from 2000 through 2099 for each of the 112 GCM climate projections were used to generate probability curves for every month (from December through March) for every scenario. Given the monthly curves generated with the non-stationary model, we generated a time series of monthly maximum flows (i.e., the 99th percentile flow) for each projection by selecting the 99th percentile flow for each month.

Figure 23 plots the probability density function for each of the 112 GCM climate projections overlaid with the historical values estimated using the non-stationary model with historical precipitation and temperature. The historical line shows data from 1950 through 1999, and the climate projection lines are grouped into twenty-year future time periods in each subplot. Results appear very similar to the Mojave River Dam, with the spread of the climate projections generally increasing moving further into the future. Again, the range of climate projections encompasses predictions above and below the historical values.

Figure 24 shows the number of times that a given maximum flow is exceeded for each of the 112 GCM climate projections for each future time period. Boxes span the estimates from each of the climate projections for the five twenty-year future time periods. The red dashed line shows the number of times that each flow was exceeded using the historical model. Appendix D contains the numerical values for the 25th percentile, 75th percentile, and median values show in the boxplots. In contrast to the Mojave River Dam, at the Lower Narrows, the climate projections show a slight decrease in the number of times each flood volume is expected. However, once again, these changes small relative to the variability between projections and therefore the trend is not significant. The historical exceedance count for a 7,250 cfs flood is 20.8 times per 20 years, while the median 2090 value is 18. Similarly, the 2090 median value for a 23,500 cfs flood is 14 while the historical is 16.4. Changes between the median value and the historical value are generally less than the variability between climate projections. In all cases, the historical value falls within the 25th to 75th percentile range of the climate projections. Whiskers (i.e., the vertical lines extending from the boxes that designate the range of the 5th to the 95th percentile values) extend above and below the historical line, indicating that projections show decreased and increased flood likelihood.

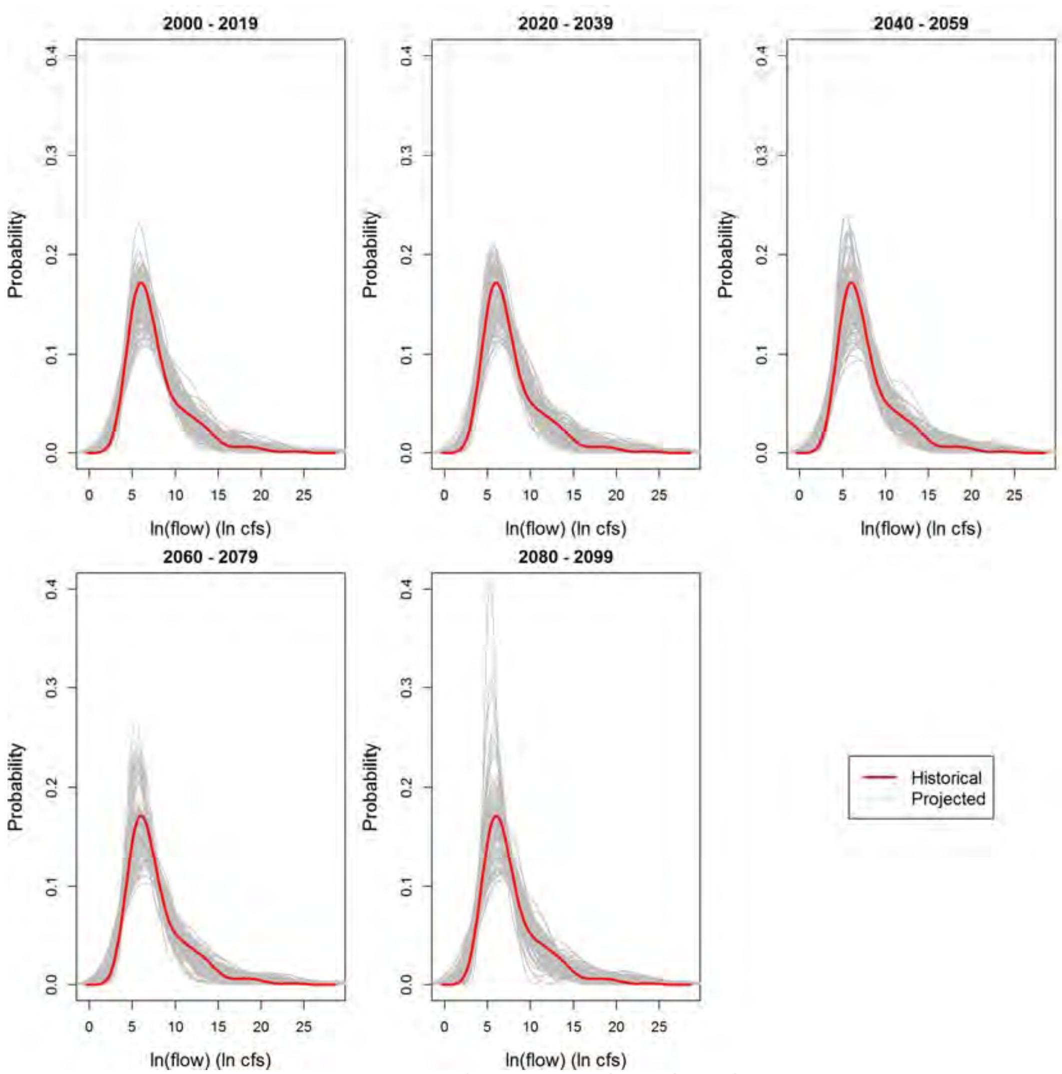

Figure 23: Probability density functions of log flow for the historical time period, 1950 through 1999 (red) and each of the 112 climate projections (grey) at the Lower Narrows.

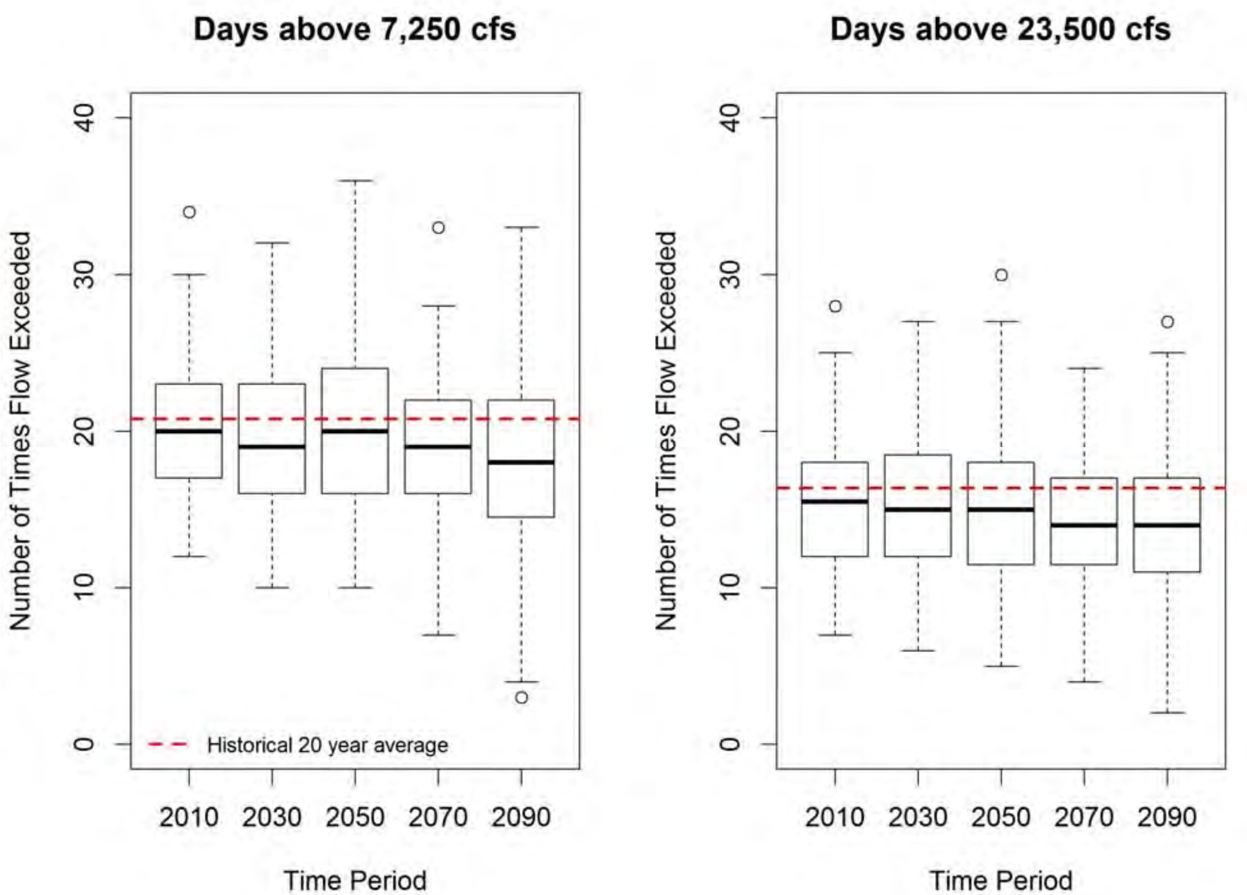

Figure 24: Boxplots of the number of days a given flow is exceeded at the Lower Narrows for twenty-year future time periods centered around 2010, 2030, 2050, 2070, and 2090 (red dashed line is the historical value).

Similar to Figure 24, Figure 25 plots the mean return periods estimated for every climate projection, averaged over each of five twenty-year future time periods. There are 112 values for each time period, and the red dashed line plots the mean historical return period estimated from 1950 through 1999 using the non-stationary model applied to historical climate variables. Figure 25 shows that the median return periods for all future times are very close to the historical mean values of 7.8 years for a 7,250 cfs flood and 13.6 years for a 23,500 cfs flood. Once again, the distribution is skewed, and there are multiple outliers that show return periods much larger than were observed historically. There is no clear trend between time periods—either in median values or in the 25^{th} to 75^{th} percentile range; however, there is a slight increase in the outlying values for the 23,500 cfs flood moving further into the future.

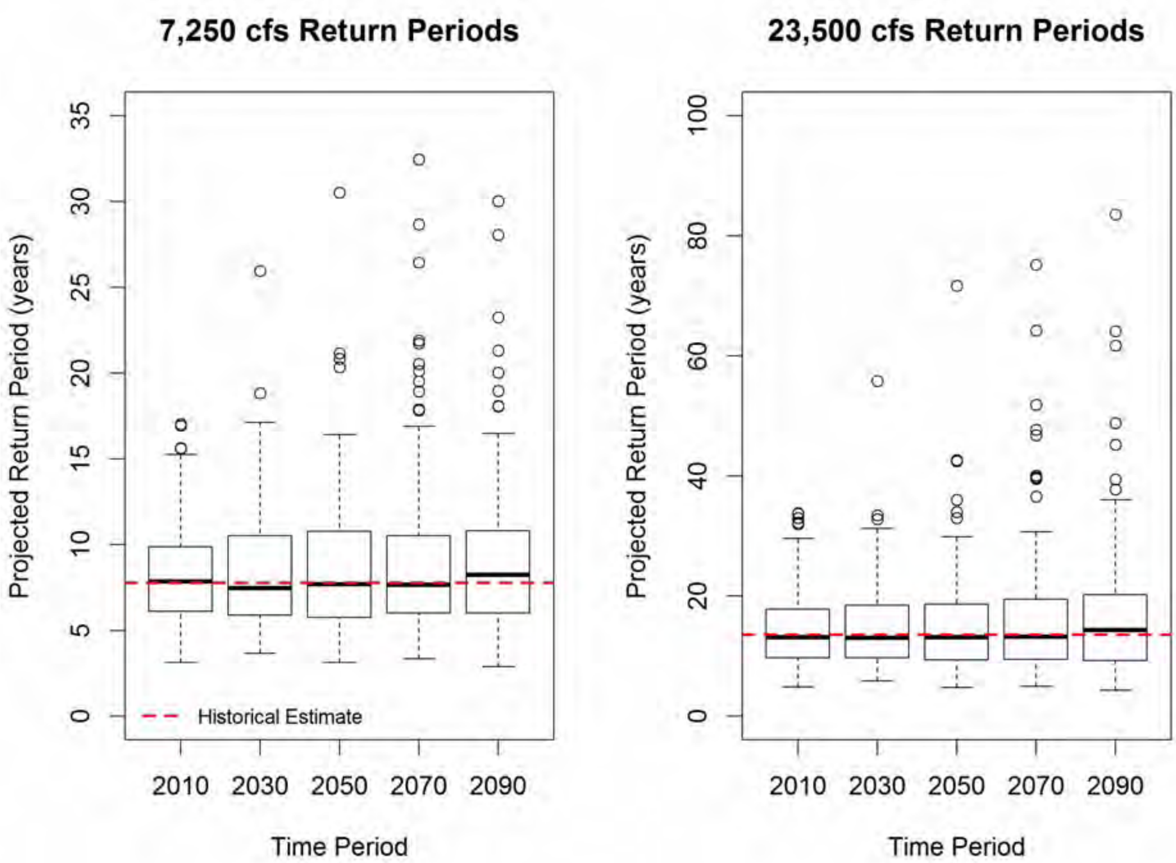

Figure 25: Boxplots of the return period for given flow for 20 year periods centered around 2010, 2030, 2050 2070 and 2090 (red dashed line is the historical value).

3.4 Summary and Conclusions

Future flood frequencies were analyzed for two locations on the Mojave River, inflows to the Mojave River Dam and the Lower Narrows near Victorville. Analysis focused on two flood rates: 7,250 cfs (when the Mojave River Dam starts to attenuate flows) and 23,500 cfs (the maximum flow rate through the dam).

Non-stationary GEV models were fit to observed maximum monthly streamflow and historical precipitation and temperature values for the flood season (December through March) from 1950 through 1999. For both locations, the best GEV model consisted of non-stationary location and scale parameters using both temperature and precipitation as covariates (i.e., model 8 as shown in table 5). Future GEV curves were then generated for every month of the potential flood season (December through March) from 2000 through 2099 for 112 GCM climate change projections.

Results for both stations show variability between the 112 GCM projections that spans both increased and decreased flood frequency. For the Mojave River Dam, there is a slight trend of increased flood frequency and decreased return periods for future time periods. The opposite trend is seen at the Lower Narrows, although it should be stressed that, for both locations, the differences are quite small. In all cases, the mean historical values fall within the 25^{th} to 75^{th} percentile range for boxplots of flood exceedance counts as well as return periods. Both locations also show skewed results, with a number of outliers, indicating significantly longer return periods than are currently observed.

Overall, results do not indicate a clear increase in flood risk for either location. This finding makes sense in the context of the results reported in Task 1 (Chapter 2). Plots of temperature and precipitation for all 112 GCM climate projections presented in Task 1 show a clear increasing temperature trend and a very slight negative trend in precipitation. However, there is significant variability between the 112 GCM projections. Similarly, while the central tendency of the projections is for little or no change in flood frequency, there are still multiple projections (i.e., equally likely) that indicate both significant increases and significant decreases in the future.

While the flood frequency analysis takes advantage of state-of-the-art statistical methods, it is also important to understand the limitations of this approach. All results are driven by projections for future temperature and precipitation. As previously noted, there is significant variability between projections, and all values must be considered equally likely. Furthermore, the projected climate variables are downscaled from global circulation models that are run on a very coarse resolution. The 1/8° downscaled values have grid cells encompassing roughly 140 square kilometers (km^2). The drainage area for the Mojave River dam is roughly 500 km^2, which equates to less than four grid cells. This methodology has limited ability to capture localized convective storms that can result in flooding.

Also, no adjustments to flow rates were made either in the observed flood values or in the climate change projected values for the operations of the Mojave River Dam. This is justified as the flood thresholds that were used for analysis fall below the rate at which the dam stores water. The exceedance probabilities for the 23,500 cfs are still relevant; however, additional local-scale models would be required to determine the projected flood volumes above 23,500 cfs—taking into account the dam operations and local storm behavior in the area between the dam and the Lower Narrows. In other words, this approach can predict the probability of a flood greater than 23,500 cfs occurring; however, to estimate these flood magnitudes, additional tools are required to model dam operations and convective storms between the Mojave River Dam and Victorville.

4. Greenhouse Gas Emissions Inventory of the Mojave River Watershed's Water Sector

To conduct a greenhouse gas emissions (GHG) inventory for the water sector, a GHG Emissions Calculator was used to determine GHG emissions from 1990 through 2050 for the MWA service area.

4.1 Background

Water resource managers are currently being faced with the challenge of developing sustainable methods for adaptation and mitigation to climate change. Across the U.S., our demand for electricity is colliding with our need for healthy and abundant fresh water. Large amounts of electricity are required to develop, treat, and transport the water required for a growing population and increasing water demands. However, a large amount of water is required for processing that electricity, regardless of the source (Bauer 2009, Sovacool 2009, Department of Energy [DOE] 2006). The interdependence of water and energy has long been referred to as the “water-energy nexus.”

Moreover, climate change threatens California’s natural environment, economic prosperity, public health, and quality of life. Energy production results in GHG emissions, thus, conserving water lowers GHG emissions. Recognizing the need for action California has put in place ambitious GHG emission reduction and water conservation goals:

- **GHG Emissions.** California Assembly Bill 32 (AB 32) requires that every major economic sector in California, including water, reduce its GHG emissions to the 1990 levels by 2020 and to 80 percent below the 1990 levels by 2050.

- **Water Conservation.** In February 2008, California directed State agencies to develop a plan to reduce statewide per capita urban water use by 20 percent by the year 2020 (California Department of Water Resources 2010).

4.2 The Impact of Water Conservation on GHG Emission Reduction

Reclamation developed the GHG Emissions Calculator—an important tool for decision makers to developing water supply plans and evaluate impacts to GHG emissions. The GHG Emissions Calculator can also be used to evaluate additional measures to reduce GHG emissions, including changes to water supply portfolio, gray water reuse, and rainwater harvesting (Reclamation 2013).

While other energy reducing methods are possible (e.g., using renewable energy, graywater reuse, and adjusting the water supply portfolio), this study analyzed whether water conservation alone would be enough to meet California's Assembly Bill 32: The Global Warming Solutions Act (AB 32) GHG emission reduction targets in the MWA service area. Results from the GHG Emissions Calculator show that a 20 percent reduction in water use will not be sufficient to meet these goals. Rather water use would have to be reduced further to meet the AB 32 targets for GHG emissions by:

- **AB 32 Target for Year 2020 (i.e., 1990 GHG emission levels)**. Lowering GHG emissions using water conservation only would require reducing water use by 50 percent from the No Action baseline scenario[3].

- **AB 32 Target for Year 2050 (i.e., 80 percent below 1990 GHG emission levels).** Meeting these requirements would necessitate an 80 percent reduction in water use from the No Action baseline scenario.

4.3 Literature Review

4.3.1 Water Management

Demands for treatment and transportation of water are increasing globally due to developments in industrial, agricultural and domestic water use, and in water quality regulation (King et al. 2008). Large increases in energy use in the water sector are being driven by rising international demands for food and bio-fuels, increasing areas irrigated cropland and cropping intensity (Curlee and Sale 2003 and DOE 2006). Worldwide food production is expected to increase by 50 percent by 2030, at the cost of considerable increase of irrigated area and water use (Bruinsma 2003). This estimate excludes the effects of climate change, which in many cases will put further pressure on water resources (IPCC Secretariat 2008). The demand for irrigation water is likely to increase further with higher temperatures and greater variability of precipitation (Döll 2002, Bruinsma 2003, Fischer et al. 2007, Rosenberg et al. 2003, and Xiong et al. 2010). With increased irrigation, further development of ground water is highly likely. Declining

[3] The GHG Emissions Calculator was used to develop this baseline water use based on future population, water demands, and other factors.

groundwater levels will compound energy use, as deeper wells require more carbon-intensive electric-driven pumps.

Growing populations are creating a higher water demand, and accelerated research will be required in areas where water is already scarce to develop sustainable mitigation and adaptation scenarios to climate change while still meeting the demand. Research on planning and mainstream adaptation in water management is growing (Subak 2000, Charlton and Arnell 2011, and Farley et al. 2011).

4.3.2 Greenhouse Gas Emission Management

Few studies consider, in detail, the energy and emission implications of climate adaptation measures, and there is a need to achieve better linkage between adaptation and mitigation. Comparisons between the few studies that have been conducted become a challenge due to the lack of a common carbon assessment methodology for the water sector (Frijns 2011).

Energy use and GHG emissions are poorly understood and have only been partially considered in water management and planning. The River Network (2009) provides a qualitative analysis of GHG emissions from energy use in the water sector, developing a baseline estimate of water related energy use in the U.S., as well as a comparative overview of the energy embedded in different water supplies and end uses.

Very little research has been done on what would happen if energy were to become the limiting factor, let alone research on the effects of adaptation and mitigation strategies (Racoviceanu 2007). There has been some research on GHG emissions from the various water supply methods. Stokes and Horvath (2006) showed that there are higher GHG emissions from desalination than either recycled water use or importation—1.5 percent to 2.4 percent higher for most U.S. utilities analyzed.

Previous studies have highlighted the importance of end use when relating GHG emissions to the water sector (Cohen et al. 2004 and Klein et al. 2005). However, many studies tend to overlook end water uses, likely due to confusion of where to draw boundaries when conducting an energy or GHG analysis of the water sector (Frijns 2011). Decisionmakers considering alternative water supply sources, treatment technologies, or water allocation may have a tendency to overlook the carbon cost. This is particularly the case in the absence of regulatory pressure.

4.4 Legislation to Reduce GHG Emission

National and international actions are necessary to fully address the issue of climate change. However, action taken by California to reduce GHG emissions has and will continue to have far-reaching effects by encouraging other states, the

Federal government, and other countries to act. The following section summarizes legislation and policy that California has passed to reduce GHG emissions.

4.4.1 Executive Order S-3-05

California began to lead the charge to reduce GHG emissions back in 2005 when Governor Schwarzenegger passed Executive Order (EO) S-3-05, which laid the groundwork for establishing the California Environmental Protection Agency's Climate Action Team (CAT) and developed GHG reduction targets for California including:

- Reducing GHG emissions to 2000 levels by 2010
- Reducing GHG emissions to 1990 levels by 2020
- Reducing GHG emissions to 80 percent below 1990 levels by 2050

CAT established a sub-group known as the Water-Energy group (WET-CAT) to monitor the progress of GHG emission reduction efforts and coordinate GHG mitigation strategies.

4.4.2 Assembly Bill 32: The California Global Warming Solutions Act of 2006

Climate change threatens California's natural environment, economic prosperity, public health, and quality of life. The passing of AB 32 codified the GHG emission reduction targets set forth in EO S-3-05. By requiring, in law, a reduction in GHG emissions, California set the stage to transition to a sustainable, clean energy future and put climate change on the national agenda spurring action by many other states. For example, in 2008 Massachusetts Governor Deval Patrick signed into law a State Global Warming Solutions Act that mirrors AB 32. Also in 2008, the United Kingdom (UK) government launched a new strategy for the water sector that includes the same GHG emissions targets as AB 32. AB 32:

- Directly links anthropogenic GHG emissions and climate change
- Provides a timeline for statewide GHG emissions reduction
- Requires quantitative accounting of GHG emissions
- Enforces disclosure of GHG emissions from every major financial sector in California

AB 32 requires that every major financial sector in California reduce its GHG emissions to the 1990 levels by 2020, and to 80 percent below the 1990 levels by 2050, shown in Figure 26. These targets were developed from the levels of reduction climate scientists agree is required to stabilize our climate (IPCC 2007). The 2020 Statewide baseline, shown in Figure 26, represents the projected GHG emissions out to 2050 if no action is taken. GHG emissions are measured in million metric tons of carbon dioxide equivalent (CO_2e).

The only way for the water sector to achieve these ambitious GHG emissions reduction goals is to drastically reduce its energy use (Friedrich et al. 2007). This brings up one of the major issues when accounting for GHG emissions in the water sector—most GHG emissions come from electricity used for pumping, treating, and transporting water. GHG emissions from electricity used in the water sector are thus also accounted for in the electricity sector, resulting in double accounting.

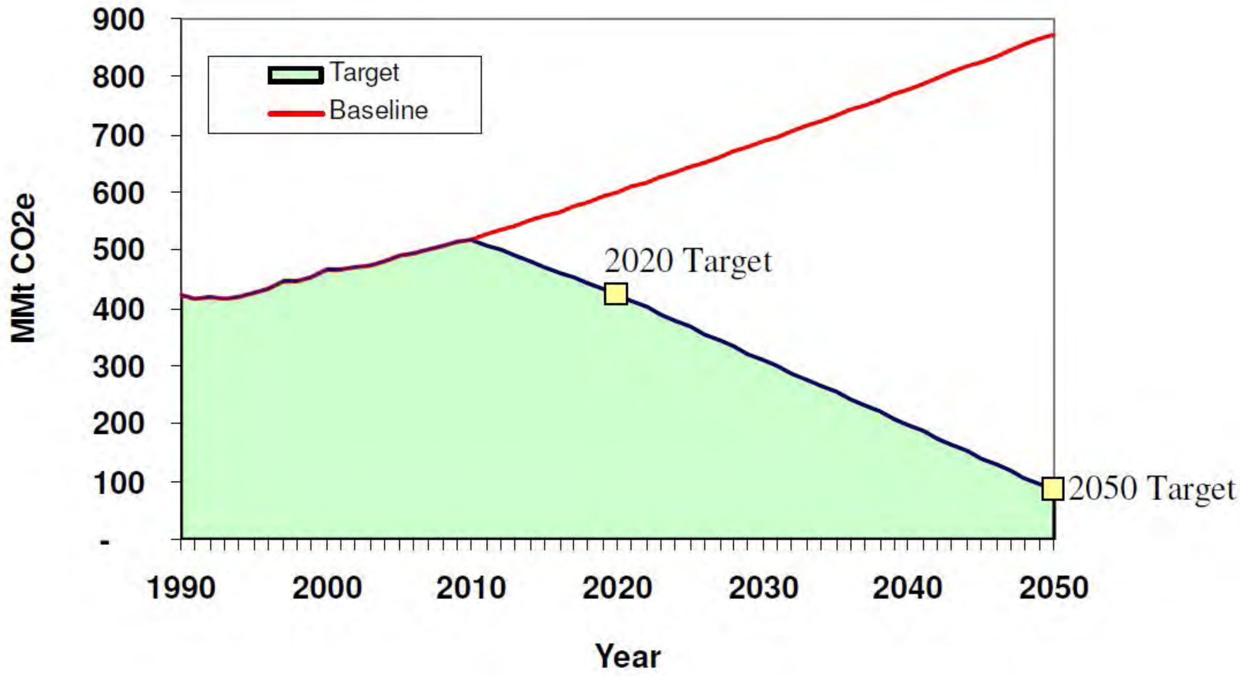

Figure 26: AB 32 targets.

4.4.3 Climate Change Scoping Plan

The Climate Change Scoping Plan (California Air Resources Board 2008) developed pursuant to AB 32, recommends specific strategies for each sector to achieve the GHG emission reduction goals set out by AB 32. The scoping plan identifies water use as a sector requiring significant amounts of energy and sets a goal to use cleaner energy to treat and move water as well as working towards higher efficiency. The scoping plan, adopted in 2008, addresses double accounting by the water sector and lays out six areas of focus to encourage the water sector to do its part:

- Water use efficiency
- Water recycling

- Water system energy efficiency
- Reuse urban runoff
- Increased renewable energy production
- Public goods charge for water

4.4.4 Water Code Section 10541

California Water Code Section 10541 requires that all Integrated Regional Water Management (IRWM) Plans address climate change by evaluating the water management systems ability to adapt to climate change and by considering GHG emissions of all identified water management programs and projects. The MWA is developing an IRWM to address these issues.

4.5 Methods

Figure 27 illustrates the different energy consuming processes involved in supplying, treating, and distributing water. Note that the end-use of water (e.g., the energy used for heating water in the home) is not considered in this analysis. The energy intensity of each of these processes—and the volume of water passing through each—will need to be known to accurately inventory emissions associated with water consumption. The degree to which each of the processes used to deliver water is identified—and to which the energy intensity of each of those processes is known—will determine the accuracy of the methods for determining the GHG emissions from water consumption.

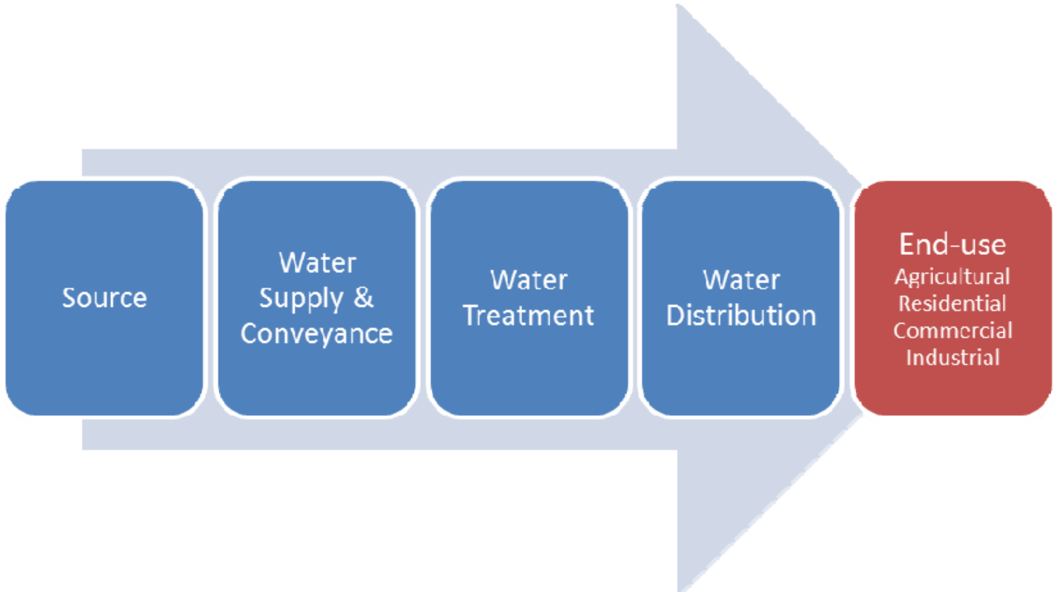

Figure 27: Energy consuming process in the delivery and treatment of water (end use in red is not included in analysis).

In California, water conveyance can have the most impact of any element in this process. Communities in the south, such as the MWA using imported water, draw significant amounts of water from vast distances over elevated terrain.

For this analysis, we used site-specific data applying to the MWA (MWA 2011a). In order to obtain the most accurate GHG emissions results possible. If site-specific information was not available, southern California defaults were used. Default utility specific emission factors were obtained from the California Climate Action Registry Power/Utility Protocol reports. Annual average electricity emission factors came from the California Air Resources Board` Greenhouse Gas Inventory (2007), and eGRID (2009).

Equation 4 depicts how total annual CO_2e emissions are calculated:

Annual CO_2e emissions = Extraction + Conveyance + Treatment + Distribution……. (4)

Where:

Extraction =

Σ (Source Percentage * Population * per capita Use * Process Energy Intensity $_{\text{Groundwater extraction}}$)* Energy Emissions Factor * Unit Conversions

Conveyance =

Σ (Source Percentage * Population * per capita Use * Process Energy Intensity $_{\text{Conveyance}}$)* Energy Emissions Factor * Unit Conversions

Treatment =

Σ (Source Percentage * Population * per capita Use * Process Energy Intensity $_{\text{Treatment}}$)* Energy Emissions Factor * Unit Conversions

Distribution =

Σ (Source Percentage * Population * per capita Use * Process Energy Intensity $_{\text{Distribution}}$)* Energy Emissions Factor * Unit Conversions

4.6 GHG Emissions Calculator Application

Reclamation's GHG Emissions Calculator allows users to implement previously described method to easily and quickly evaluate how their water management decisions affect their water demand, energy use, and GHG emissions. The GHG Emissions Calculator will be provided to the MWA as part of the deliverables for this report.

Many factors affect future water demands such as population growth, hydrologic conditions, public education, and economic conditions, among others. In 1990, 273 thousand people lived in the MWA service area. In the 1990s, the population grew by 16.8 percent, and continued to grow to the present population of approximately 473 thousand, as shown in Figure 28. By 2050, the population is projected to reach 868 thousand (MWA 2011a).

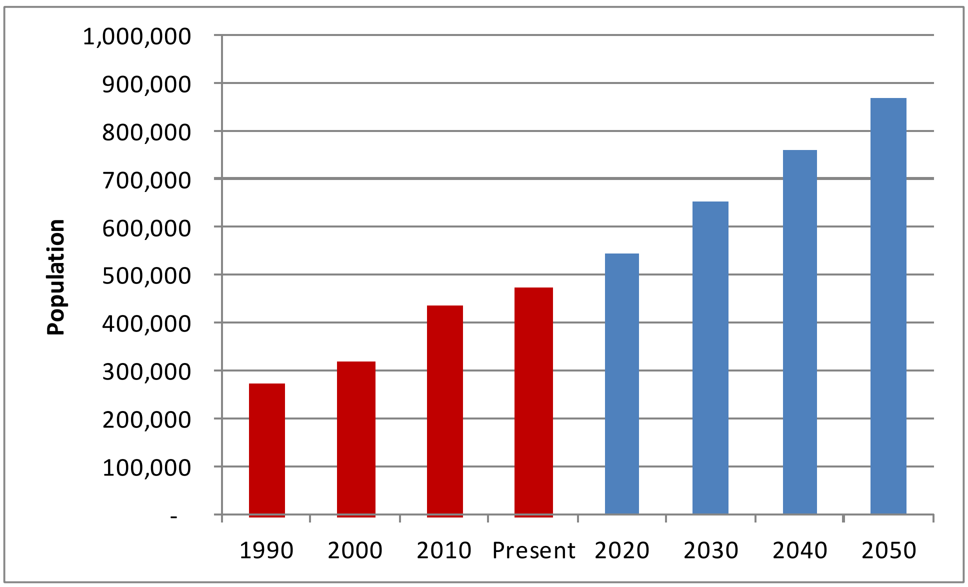

Figure 28: Population for the MWA service area. Note that red is observed, and blue is projected using GHG Emissions Calculator. (Data from MWA 2011a).

Using the GHG Emissions Calculator, we calculated the baseline GHG emissions for the MWA service area as a whole for every decade from 1990 through 2050, shown in Figure 29. To calculate the baseline GHG emissions, the population projections from Figure 28, historic per capita water use, and historic and projected imported water and groundwater volumes were used. Note that the baseline does not incorporate water conservation measures. The four scenarios developed and discussed below incorporate water conservation.

4.6.1 Meeting the AB 32 2020 GHG Emissions Target

In February 2008, California Governor Schwarzenegger directed State agencies to develop a plan to reduce statewide per capita urban water use by 20 percent by the year 2020. Although the GHG emissions targets do not apply directly to MWA the following scenarios were developed to illustrate one of many ways the targets might be reached when looking at the water sector in MWA.

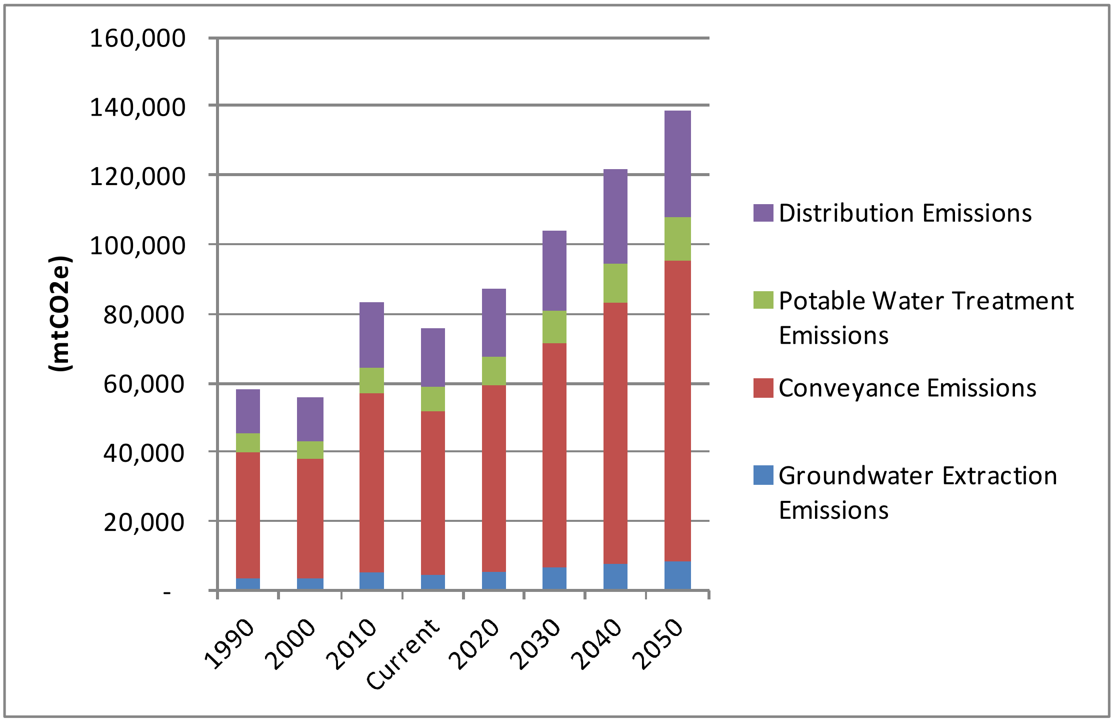

Figure 29: Baseline GHG emissions for the MWA service area.

The GHG Emissions Calculator was used to evaluate whether this conservation measure alone would be enough to meet AB 32 targets in the MWA service area (i.e., to return to the 1990 level of GHG emissions, which is approximately 58,000 metric tons CO_2e). The results show that reducing water use by 20 percent by the year 2020 does not allow the MWA service area to meet the 2020 target (of reducing GHG back to 1990 levels), as shown in Figure 30. To determine this, we developed two scenarios to analyze the 2020 target:

- **A 20x2020 scenario** where there would be a 20 percent reduction in water use by 2020, with no future change in per capita use beyond 2020 (Figure 30). This is based on the State of California's 20x2020 water conservation goals.

- **A 44x2020 scenario** where there would be a 44 percent reduction in water use by 2020, with no future change in per capita use beyond 2020 (Figure 31). This is based on what would be needed to meet the AB 32 2020 GHG emissions target.

The results show that 20 percent reduction by the year 2020 does not allow the MWA service area to meet the 2020 target (back to 1990 levels), as shown in Figure 30. A 44 percent reduction in per capita water use is required to meet the 2020 AB 32 target. However, this level of conservation still does not meet the 2050 AB 32 target of 80 percent below 1990 levels, as shown in Figure 31.

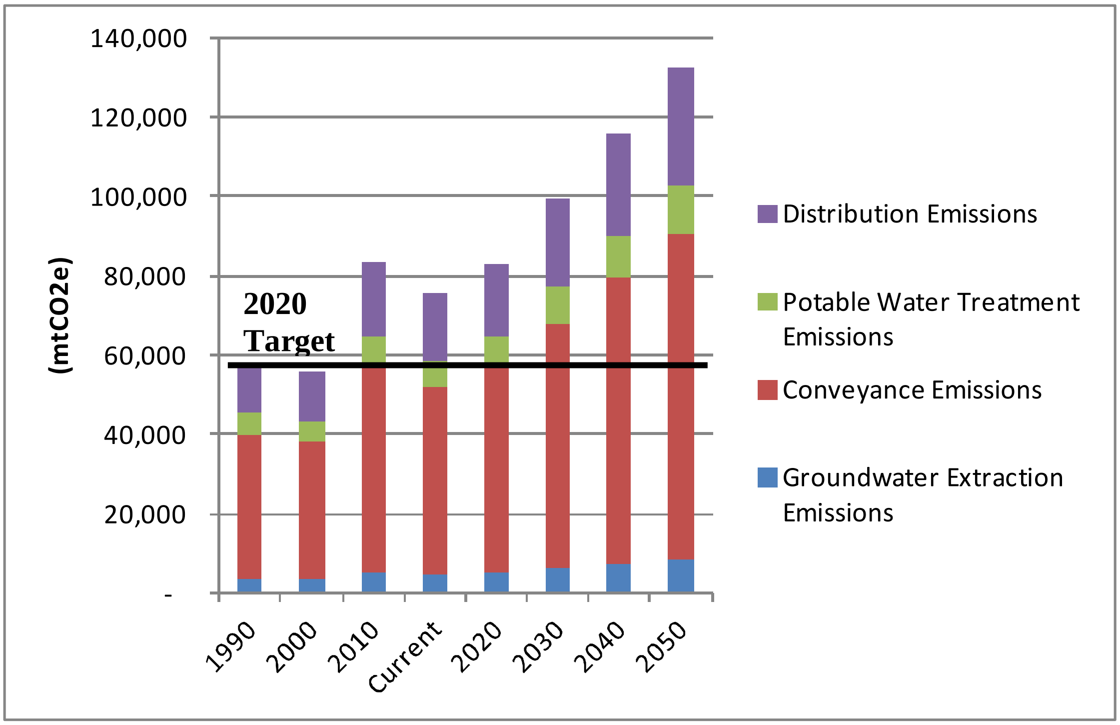

Figure 30: GHG emissions resulting from the 20x2020 scenario.

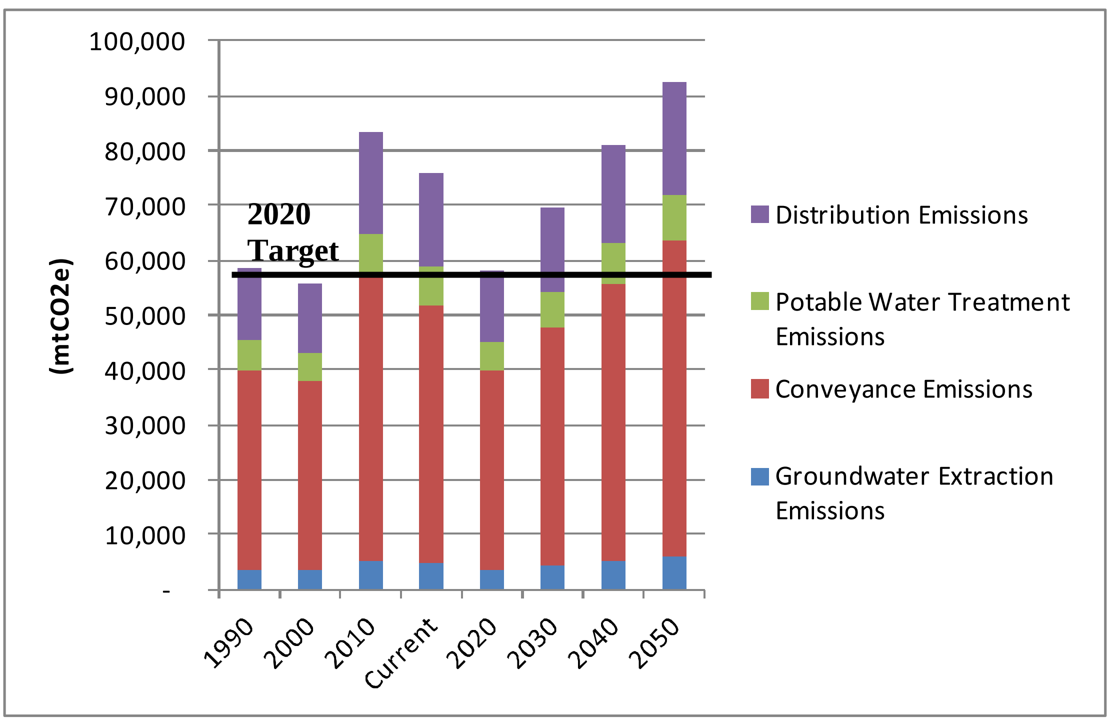

Figure 31: GHG emissions in the MWA service area resulting from the 44x2020 scenario.

4.6.2 Meeting the AB 32 2050 GHG Emissions Target

The AB 32 2020 Emissions target is to reduce GHG by 80 percent below the 1990 level of GHG emissions, which is approximately 11,600 metric tons CO_2e. Although the GHG emissions targets do not apply directly to MWA the following scenarios were developed to illustrate one of many ways the targets might be reached when looking at the water sector in MWA.

As shown in Figure 31, a 44 percent reduction in per capita water use by 2020, then remaining at that level of per capita water use is not enough to meet the 2050 GHG emission targets. Therefore, we analyzed two further scenarios to analyze the 2050 target:

- **44x2020 & 20 percent each decade (2030-2050).** This scenario incorporates the 44 percent reduction in water use in 2020 and mandates a further reduction of 20 percent in per capita water use every decade from 2030 to 2050. This is an intermediate scenario (Figure 32).

- **44x2020 & 30 percent each decade (2030-2050).** This scenario incorporates the 44 percent reduction in water use in 2020 and further per capita water use reduction of 50 percent each decade from 2030 through 2050. This is based on what would actually be needed to meet the AB 32 2050 GHG emissions target of 80 percent below the 1990 levels (Figure 33).

These additional conservation measures in the 44x2020 and 20 percent scenario only reach 30 percent below the 1990 GHG emission levels, as shown in Figure 32. To reach the AB 32 2050 target of 80 percent below the 1990 levels of GHG emissions through conservation alone, 44x2020 and 50 percent scenario is required as shown in Figure 33. These scenarios are hypothetical, based on water conservation as the only GHG emissions reducing actions.

In Figure 34, the four conservation scenarios described above are compared to the no action scenario; a task easily accomplished using the GHG Emissions Calculator. The GHG Emissions Calculator can also be used to evaluate additional measures to reduce GHG emissions, including changes to water supply portfolio, gray water reuse, and rainwater harvesting among many others.

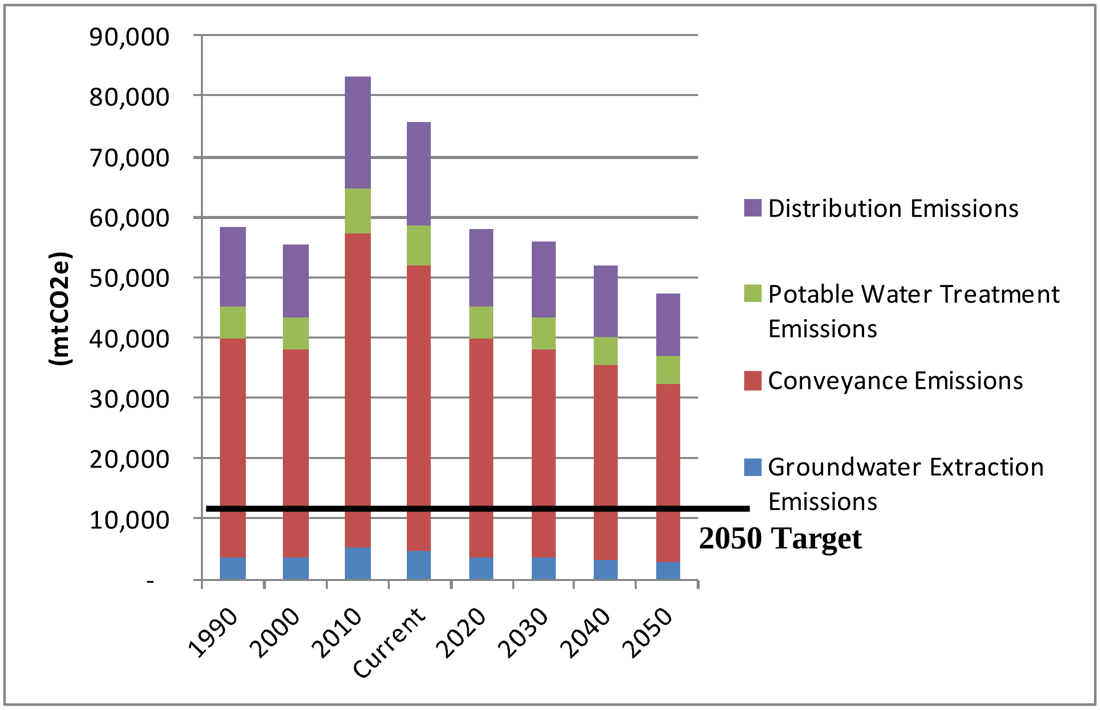

Figure 32: GHG emissions in the MWA service area resulting from the 44x2020 & 20 percent each decade scenario.

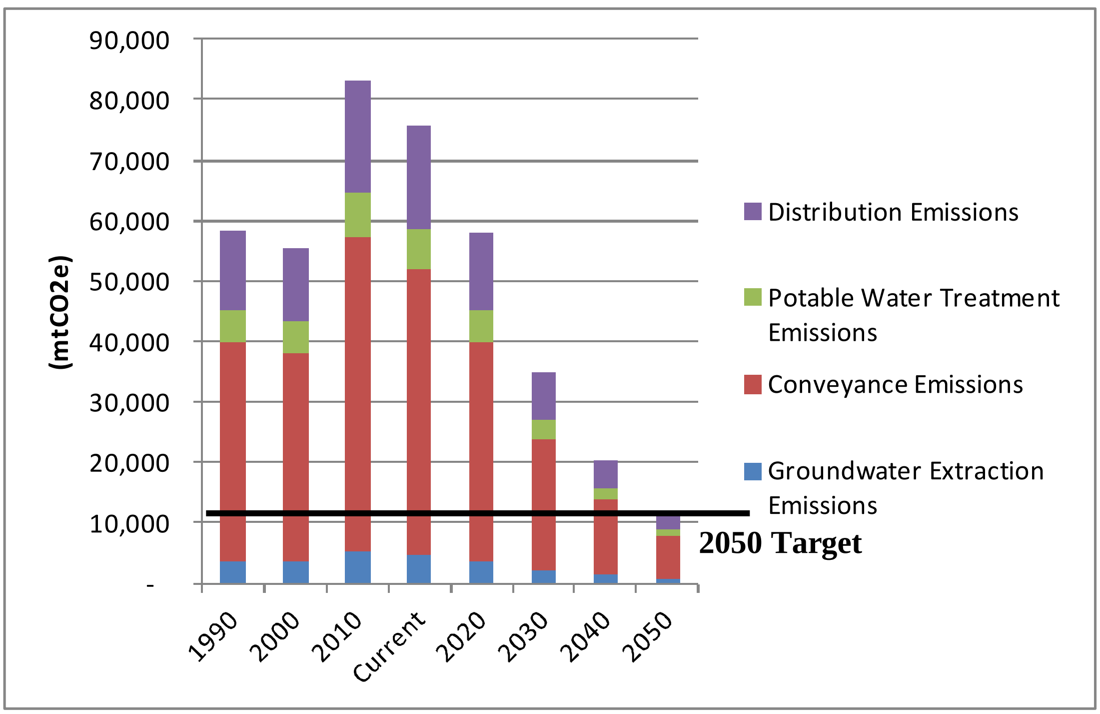

Figure 33: GHG emissions in the MWA service area resulting from the 44x2020 & 30 percent each decade scenario.

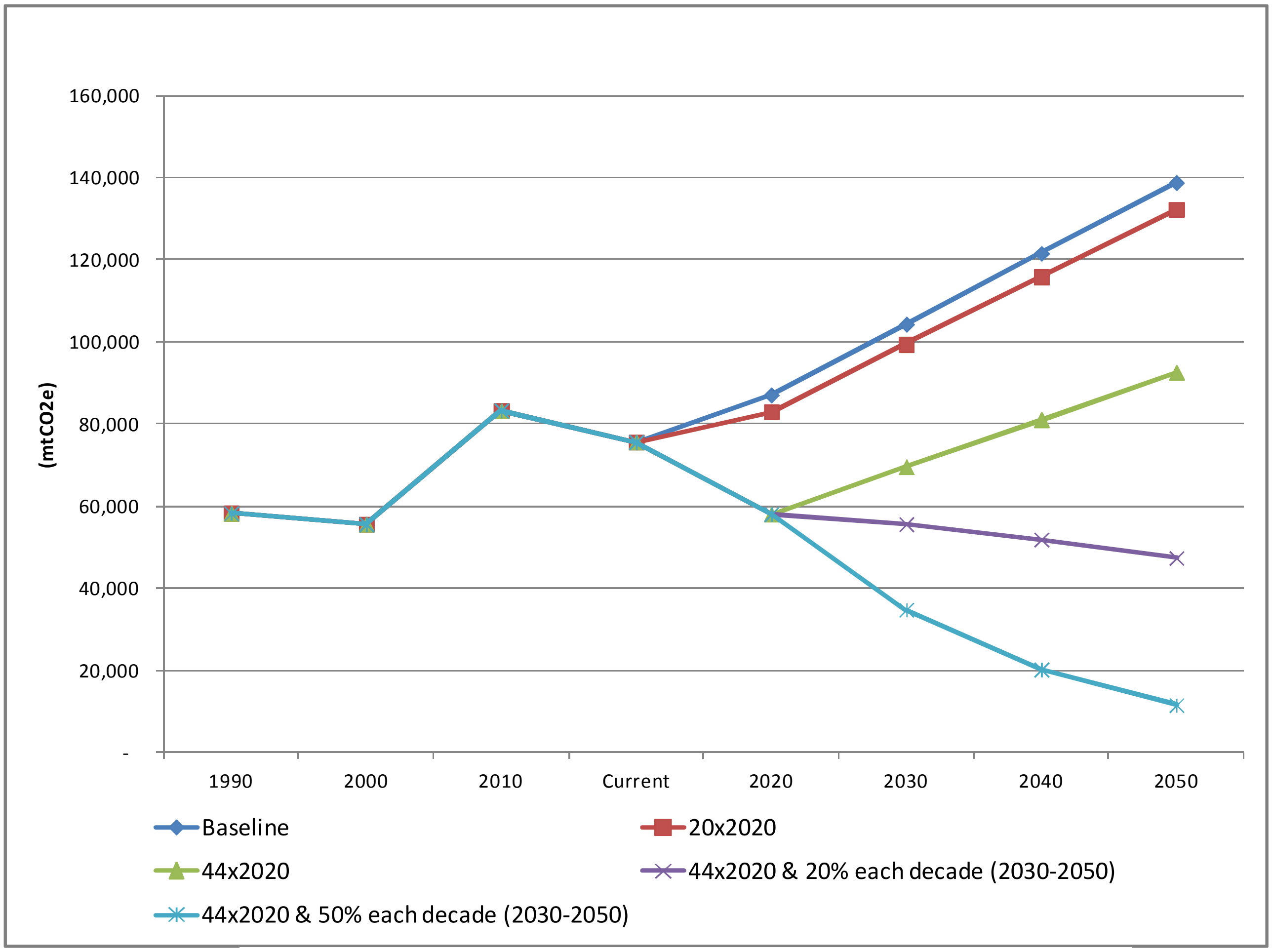

Figure 34: Comparison of GHG emissions resulting from the baseline and the four water conservation scenarios for the MWA service area.

4.7 Summary and Conclusions

To address the climate change mitigation, California has put in place ambitious GHG emission reduction goals. Although the GHG emissions targets do not apply directly to MWA, water conservation scenarios were developed to illustrate one of many ways the targets might be reached when looking at the water sector in MWA. As the four water conservation scenarios show, the amount of water that would need to be conserved to meet these goals may not be realistic. Thus, it is likely that a combination of measures will be required to meet the GHG emission reduction targets laid out in AB 32. Measures could include:

- Changes to water supply portfolio to increase local water supply. SWP and other imported sources require energy to transport water longer distances and over large changes in elevation.

- Gray water reuse and rainwater harvesting can help increase self-supplied water (i.e., local sources of water), which does not require as much energy.

- Implementing renewable energy sources for developing, treating, and transporting would greatly reduce GHG emissions without constraining energy use.

- The GHG Emissions Calculator can also be used to evaluate these additional measures to reduce GHG emissions (Reclamation 2013).

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Appendix A—Supplemental Graphs

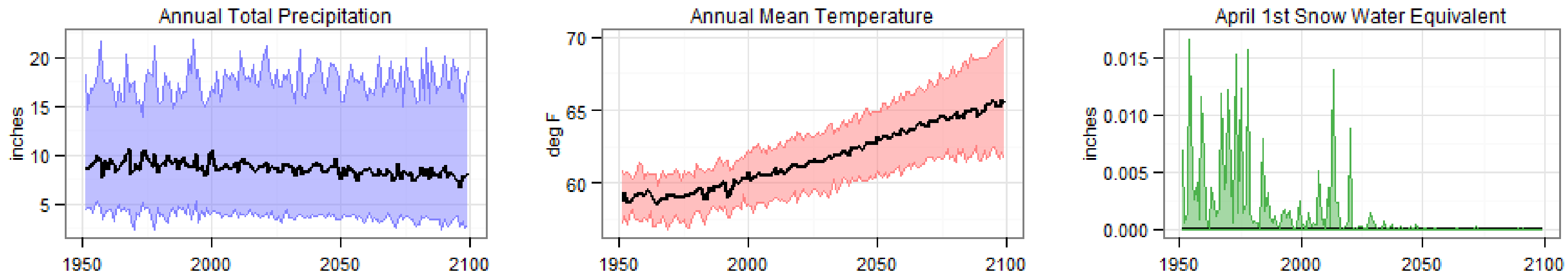

Figure A-1: Alto sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

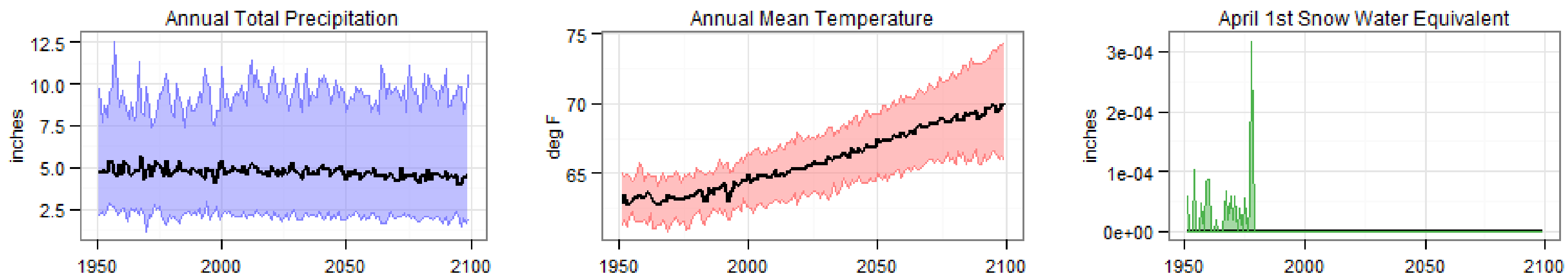

Figure A-2: baja sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

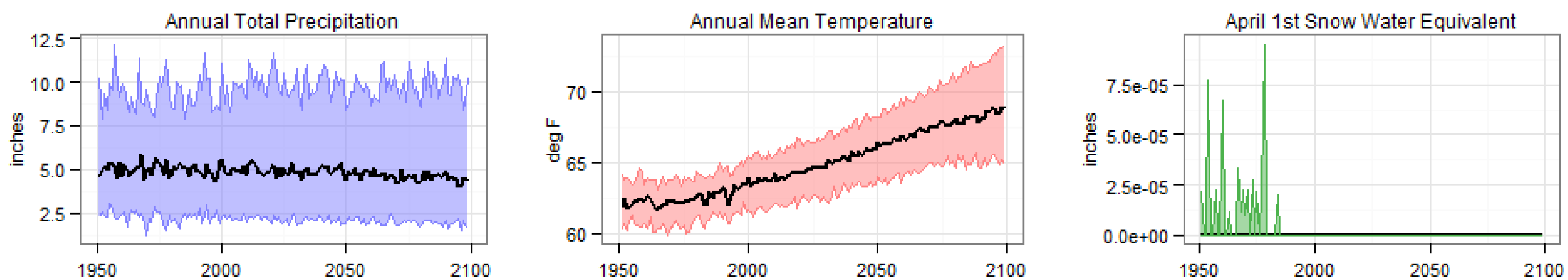

Figure A-3: Centro sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

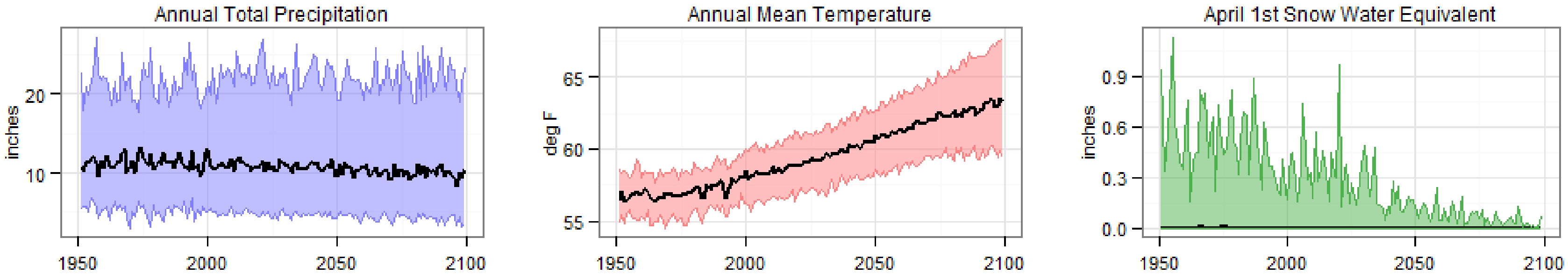

Figure A-4: Este sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

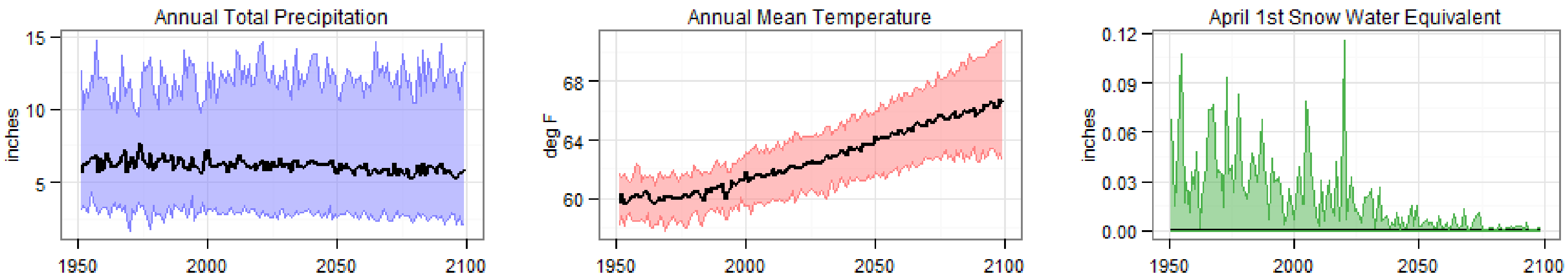

Figure A-5: Morongo sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

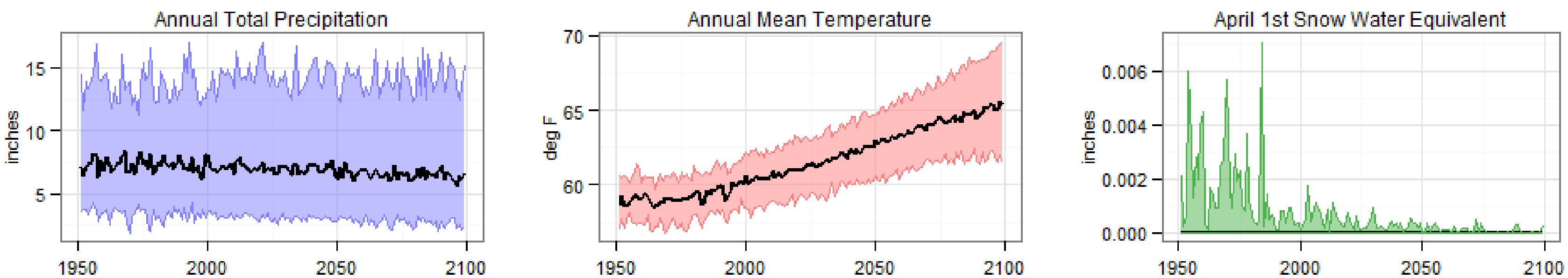

Figure A-6: Oeste sub-basin—projection ensembles for precipitation, temperature and snow water equivalent (SWE)

Appendix B—Summary Tables of Streamflow Projections

Table B-1: Summary of Percentage Change in Mean Streamflow as Compared to 1990s Base Period for Three Change Percentiles with the 112 GCM Climate Projections (25, 50, and 75)

Season	STN Name	2020s			2050s			2070s		
		25%	50%	75%	25%	50%	75%	25%	50%	75%
Annual	Deep Creek Near Hesperia	-20%	0%	27%	-39%	-12%	25%	-36%	-20%	17%
	West Fork Near Hesperia	-21%	3%	33%	-39%	-13%	28%	-33%	-14%	25%
	Lower Narrows Near Victorville	-20%	2%	33%	-37%	-12%	30%	-34%	-19%	18%
Dec. - Mar.	Deep Creek Near Hesperia	-23%	5%	36%	-37%	-10%	38%	-32%	-14%	24%
	West Fork Near Hesperia	-22%	4%	43%	-40%	-6%	40%	-34%	-13%	29%
	Lower Narrows Near Victorville	-23%	6%	38%	-37%	-8%	38%	-32%	-13%	26%
Apr. - Jul.	Deep Creek Near Hesperia	-39%	-12%	20%	-51%	-30%	4%	-60%	-36%	-16%
	West Fork Near Hesperia	-30%	-2%	28%	-46%	-25%	8%	-52%	-30%	-2%
	Lower Narrows Near Victorville	-35%	-7%	19%	-47%	-27%	6%	-56%	-31%	-12%

Table B-2: Summary of Percentage Change in 25th Percentile Streamflow as Compared to 1990s Base Period for Three Change Percentiles with the 112 GCM Climate Projections (25, 50, and 75)

Season	STN Name	2020s			2050s			2070s		
		25%	50%	75%	25%	50%	75%	25%	50%	75%
Annual	Deep Creek Near Hesperia	-47%	-15%	44%	-56%	-28%	20%	-61%	-37%	-4%
	West Fork Near Hesperia	-31%	-9%	22%	-42%	-18%	16%	-44%	-24%	-2%
	Lower Narrows Near Victorville	-40%	-13%	35%	-50%	-23%	17%	-55%	-31%	-3%
Dec. - Mar.	Deep Creek Near Hesperia	-47%	-15%	76%	-46%	-15%	51%	-59%	-26%	17%
	West Fork Near Hesperia	-35%	-5%	34%	-40%	-10%	34%	-46%	-19%	11%
	Lower Narrows Near Victorville	-41%	-10%	58%	-44%	-14%	45%	-55%	-24%	14%
Apr. - Jul.	Deep Creek Near Hesperia	-46%	-19%	12%	-59%	-34%	8%	-64%	-44%	-15%
	West Fork Near Hesperia	-32%	-14%	14%	-40%	-18%	10%	-45%	-27%	-3%
	Lower Narrows Near Victorville	-35%	-15%	8%	-51%	-28%	13%	-58%	-38%	-13%

Table B-3: Summary of Percentage Change in 75th Percentile Streamflow as Compared to 1990s Base Period for Three Change Percentiles with the 112 GCM Climate Projections (25, 50, and 75)

Season	STN Name	2020s			2050s			2070s		
		25%	50%	75%	25%	50%	75%	25%	50%	75%
Annual	Deep Creek Near Hesperia	-19%	1%	34%	-35%	-13%	19%	-42%	-15%	24%
	West Fork Near Hesperia	-20%	0%	46%	-40%	-14%	32%	-43%	-14%	38%
	Lower Narrows Near Victorville	-18%	2%	38%	-34%	-16%	22%	-42%	-13%	30%
Dec. - Mar.	Deep Creek Near Hesperia	-20%	4%	36%	-39%	-9%	38%	-42%	-5%	30%
	West Fork Near Hesperia	-25%	4%	49%	-42%	-6%	43%	-42%	-15%	48%
	Lower Narrows Near Victorville	-22%	4%	35%	-40%	-9%	36%	-43%	-8%	34%
Apr. - Jul.	Deep Creek Near Hesperia	-40%	-12%	29%	-62%	-35%	-3%	-64%	-48%	-20%
	West Fork Near Hesperia	-34%	-5%	38%	-55%	-33%	28%	-56%	-34%	-4%
	Lower Narrows Near Victorville	-36%	-7%	26%	-59%	-35%	8%	-61%	-40%	-14%

Appendix C—Values from Flood Frequency Boxplots for Mojave River Dam

Table C-1: Count of Days above 7,250 cfs at Mojave River Dam (Historical =21.6 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	18.5	19	20	21	21
Median	22	23	23	24	25
75thPercentile	24	27	27	28	30.5

Table C-2: Count of Days above 23,500 cfs at Mojave River Dam (Historical = 12 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	11	11	12	12	12
Median	14	15	16	15	16
75th Percentile	17	18	18.5	18	18

Table C-3: Return Period for 7,250 cfs Flood at Mojave River Dam (Historical = 3.4 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	2.5	2.4	2.3	2.4	2.4
Median	3.2	2.9	3.1	2.9	3.0
75th Percentile	3.8	4.0	3.8	3.8	3.7

Table C-4: Return Period for 23,500 cfs Flood at Mojave River Dam (Historical = 6 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	4.0	3.7	3.6	3.6	3.6
Median	5.2	5.0	5.2	4.9	5.1
75th Percentile	6.8	7.0	7.2	7.1	6.9

Appendix D—Values from Flood Frequency Boxplots for Lower Narrows

Table D-1: Count of Days above 7,250 cfs at Mojave River Dam (Historical = 20.8 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	17	16	16	16	14.5
Median	20	19	20	19	18
75thPercentile	23	23	24	22	22

Table D-2: Count of Days above 23,500 cfs at Mojave River Dam (Historical = 16.4 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	12	12	11.5	11.5	11
Median	15.5	15	15	14	14
75th Percentile	18	18.5	18	17	17

Table D-3: Return Period for 7,250 cfs Flood at Mojave River Dam (Historical = 7.8 years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	6.1	5.9	5.8	6.0	6.0
Median	7.9	7.5	7.7	7.7	8.2
75th Percentile	9.9	10.5	10.8	10.5	10.8

Table D-4: Return Period for 23,500 cfs Flood at Mojave River Dam (Historical = 13.6 Years)

	2000-2019	2020-2039	2040-2059	2060-2079	2080-2099
25th Percentile	9.7	9.7	9.4	9.5	9.2
Median	13.2	13.0	13.1	13.2	14.3
75th Percentile	17.8	18.5	18.6	19.5	20.2