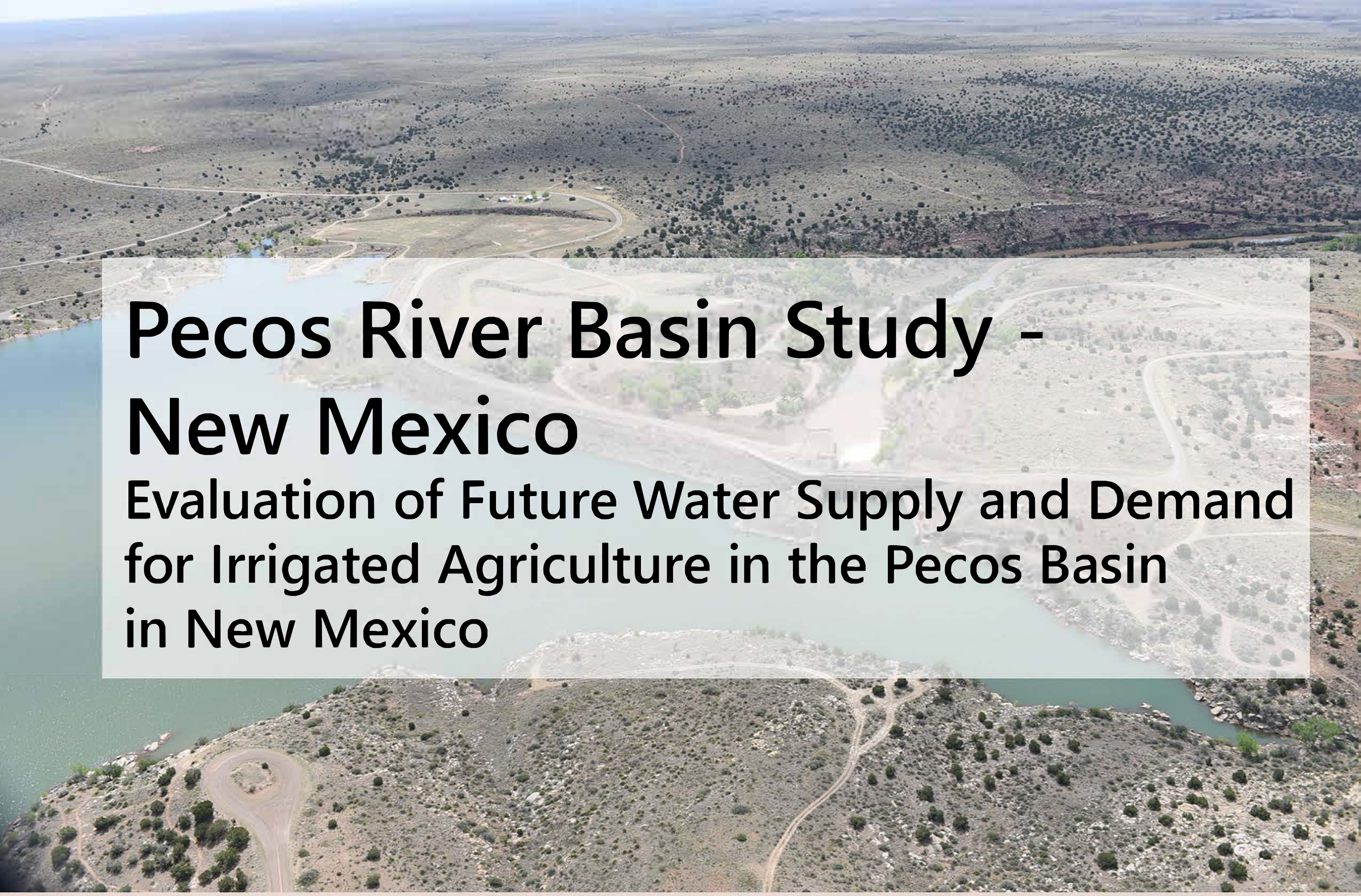

Pecos River Basin Study - New Mexico

Evaluation of Future Water Supply and Demand for Irrigated Agriculture in the Pecos Basin in New Mexico

BUREAU OF RECLAMATION

U.S. Department of the Interior
Bureau of Reclamation
Albuquerque Area Office

Office of the State Engineer
Interstate Stream Commission

New Mexico Office of the State Engineer
Interstate Stream Commission

September 2021

Mission Statements

The **U.S. Department of the Interior** protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated 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.

The **Office of the State Engineer** is charged with administering the state's water resources. The State Engineer has authority over the supervision, measurement, appropriation, and distribution of all surface and groundwater in New Mexico, including streams and rivers that cross state boundaries. The New Mexico Interstate Stream Commission is tasked with ensuring New Mexico's compliance with eight interstate compacts and has broad powers to investigate, develop, conserve, and protect the state's water supplies. The State Engineer is also Secretary of the Interstate Stream Commission.

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Pecos River Basin Study - New Mexico

Evaluation of Future Water Supply and Demand for Irrigated Agriculture in the Pecos Basin in New Mexico

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U.S. Department of the Interior
Bureau of Reclamation

In Partnership with

New Mexico Interstate Stream Commission

Cover photo montage: Aerial view of Sumner Reservoir, Pecos River below Brantley Dam, canal flows through a farm, Pecos River, and low flow conditions at Acme gage (Reclamation).

Disclaimer and Uncertainty Statement

Basin Studies

Basin studies are collaboratively-developed technical assessments of future conditions and adaptation actions. Basin studies do not provide recommendations or represent a statement of policy or position of the Bureau of Reclamation (Reclamation), Department of the Interior (DOI), or the funding partners. Basin studies do not propose or address the feasibility of any specific project, program, or plan and do not represent a commitment to take any further action.

> **Using Basin Study Results**
>
> The complexity of these interactions underscores the importance of using a planning approach that identifies future risks to water resources systems based on a range of plausible future conditions and working with stakeholders to evaluate options that minimize potential impacts to stakeholders.

Global Climate Models

Projections of future climate are developed using the scientific community's best assessment of potential future conditions, as characterized by global climate models (GCMs). GCM projections are based upon selected initial model states, assumptions of future greenhouse gases in the atmosphere, and internal as well as external forcings, such as solar radiation and volcanic activity. Methods for modeling changes in land surface conditions, atmosphere, and ocean dynamics, as well as feedbacks between these and other components of the hydrologic cycle that either magnify or diminish the impacts of changes, are active areas of research and are evolving quickly. This study relies on a specific set of GCM simulations made at a specific point in time.

GCMs simulate the climate on a global scale, and therefore have a resolution that is too coarse for use at a regional or watershed scale. Accordingly, this study relies on techniques that localize or "downscale" GCM output to our basin of interest. These downscaled projections of climate are used as inputs to hydrologic models that project streamflows, as well as by operational models that simulate the effects of reservoirs, water diversions, and other human impacts. All these models, in sequence, are needed to assess impacts of changes in the environment on the water resource system in question. Uncertainties remain within each of the steps necessary to translate GCM output to water resources impacts.

Decision-Making Under Deep Uncertainty

The information presented in this report was developed through collaboration between Reclamation and basin stakeholders and was peer reviewed by subject matter experts and water managers at Reclamation, partner agencies and entities, and outside reviewers, in accordance with DOI's and Reclamation's policies. The analyses described in this report reflect the use of the best datasets, modeling tools, and analysis methodologies available at the time of the study.

These studies rely on the best available science and information to develop plausible scenarios describing potential future conditions within the watershed, and on collaboration with basin stakeholders to develop suites of potential strategies to address water-related changes that occur in those scenarios. In these studies, a range of plausible future scenarios is used to assess risks associated with potential changes in the environment, including supply and demand imbalances, as well as to formulate ways to minimize potential risks and mitigate projected impacts of changes in the environment. The plausible future scenarios are not intended as explicit predictions of future conditions. Rather, the goal is to plan for a range of possible conditions, thereby providing decision support tools for water managers. Trade-off analyses performed between the proposed strategies position communities to take steps now to mitigate future water management challenges, including water shortages, impacts of droughts and floods, variations in water supply, and changing water demands.

Basin Study partners necessarily make assumptions about future conditions, including future water supply and demand, demographics, environmental policies, economic conditions, climate conditions, land use, and numerous other factors. The use of models, including hydrologic models, is valuable in that the models help us to assess complex interactions between many factors and processes. Addressing the cumulative effect of interacting assumptions and uncertainties is an essential component of the planning process.

Acronyms and Abbreviations

1998 Decree	U.S. Supreme Court's 1988 Amended Decree in *Texas v. New Mexico No. 65 Original*
2016 BiOp	Final Biological Opinion for the Carlsbad Project Water Operations and Water Supply Conservation, 2016-2026
°C	degrees Celsius
°F	degree Fahrenheit
AAO	Albuquerque Area Office
ABCWUA	Albuquerque Bernalillo County Water Utility Authority
Acme Gage	USGS Acme Gage 08386000 north of the city of Roswell
ARC	Architectural Research Consultants
Artesia Gage	USGS Artesia Gage 08396500 near the city of Artesia
ASR	aquifer storage and recovery
AWRM	Active Water Resource Management
Basin Study	Pecos River Basin Study - New Mexico:
BCSD	bias-correction spatial disaggregation
BGNDRF	Brackish Groundwater National Desalination Research Facility
BLM	Bureau of Land Management
BTEX	benzene, toluene, ethylbenzene, and xylene
CADSWES	Center for Advanced Decision Support for Water and Environmental Systems
CID	Carlsbad Irrigation District
cfs	cubic feet per second
CMIP5	Coupled Model Intercomparison Project Phase 5
Compact	1948 Pecos River Compact
DDT	dichloro-diphenyl-trichloroethane
DOI	Department of the Interior
E. coli	*Escherichia coli*
EIA	Energy Information Administration
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
ET	evapotranspiration
ETS	segmented evapotranspiration package
FCP	Fish Conservation Pool
FSID	Fort Sumner Irrigation District
FWP	Fish and Wildlife Pool
FY	fiscal year
GCM	Global Climate Model
GIS	Geographic Information Systems
GPS	global positioning software
GWh	gigawatt hours
HDB	Hydrological Database
HE	Hiigher Emissions
HIC	Hagerman Irrigation Company
HMLS	High Monsoon/Low Snowpack storyline
Hope Decree	United States v. Hope Community. Ditch Association, No. 712 Equity, Final Decree 1933
IPCC	Intergovernmental Panel on Climate Change
IUCN	The International Union for Conservation of Nature
LE	Lower Emissions
METRIC	Mapping EvapoTranspiration at high Resolution with Internalized Calibration
mg/l	milligrams per liter
mi2	square miles
MODFLOW	a modular hydrologic model developed by the USGS
mph	miles per hour
msl	mean sea level

MW	megawatt
NASA	National Aeronautics and Space Administration
NAVD	North American Vertical Datum
NMDFA	New Mexico Department of Finance and Administration
NMDGF	New Mexico Department of Game and Fish
NMED	New Mexico Environment Department
NMEMNRD	New Mexico Energy, Minerals and Natural Resources Department
NMISC	New Mexico Interstate Stream Commission
N.M.S.A.	New Mexico Statutes Annotated
NMOSE	New Mexico Office of State Engineer
NMSU	New Mexico State University
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Labs
O&M	operation and maintenance
PCB	polychlorinated biphenyl
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PHWG	Pecos Hydrology Work Group
PRMS	Precipitation Runoff Modeling System
Project	Carlsbad Project
PROM	Pecos River Operations Model
PVACD	Pecos Valley Artesian Conservancy District
QUANT	Quantile Mapping
RAB	Roswell Artesian Basin
RABGWM	Roswell Artesian Basin Groundwater Model
RCP	Representative Concentration Pathway
Reclamation	Bureau of Reclamation
Reserve	Strategic Water Reserve
SCADA	Supervisory Control and Data Acquisition
SECURE	Science and Engineering to Comprehensively Understand and Responsibly Enhance
Water Act	SECURE Water Act Public Law 111-11, Subtitle F of Title IX, §9501 – §9510
Settlement	2003 Pecos Settlement Agreement
shiner	Pecos bluntnose shiner
SNOTEL	Snow telemetry
TDS	total dissolved solids
USACE	U.S. Army Corps of Engineers
U.S.C.	United States Code
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGCRP	U.S. Global Change Research Program
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity
WaterSMART	Water Sustain and Manage America’s Resources for Tomorrow
WCRP	World Climate Research Programme
WQCC	New Mexico Water Quality Control Commission
WRRI	Water Resources Research Institute
WWTP	wastewater treatment plant
W/m^2	watts per square meter

Executive Summary

Problem and Need

From its headwaters in the Sangre de Cristo Mountains of northern New Mexico, the Pecos River flows roughly north to south through eastern New Mexico and western Texas, eventually joining the Rio Grande along the U.S. border with Mexico. Much of the basin is arid or semi-arid, resulting in significant water supply and management challenges. Overall, water supplies are limited, and hydrological variability in the basin is high. Increases in temperature and drought severity seen in recent decades highlight the need to plan for more significant water supply challenges in the future.

The purpose of this basin study is to increase awareness of potential future hydroclimate changes in the study area, and of the kinds of actions that might help sustain viable agriculture in the Pecos River Basin.

This Pecos River Basin Study - New Mexico (Basin Study) encompasses the portion of the Pecos River Basin in New Mexico (Figure ES-1). Within this study area, this study's modeling and analysis focused on the three largest irrigation districts in the basin, which are the primary water users in this study area: Fort Sumner Irrigation District (FSID) and Carlsbad Irrigation District (CID) mostly depend on surface water, while the Pecos Valley Artesian Conservancy District (PVACD) uses groundwater from the Roswell Artesian Basin. The U.S. Fish and Wildlife Service's (USFWS) Final Biological Opinion for the Carlsbad Project Water Operations and Water Supply Conservation, 2016-2026 (2016 BiOp),[1] identifies flow targets for the Pecos bluntnose shiner (shiner). New Mexico must also comply with water delivery requirements to Texas as noted in Section 3.1 *Regulation of Water in the Pecos River Basin.* (The New Mexico Interstate Stream Commission (NMISC), the non-Federal partner for this study, ensures Compact compliance (see Section 3.1. *Regulation of Water in the Pecos River*). All these demands place increasing stress on the limited water supply in the basin.

[1] Note that while the BO covers 2016-2026, the final BO was signed in 2017. The full citation is USFWS, 2017 (2016 BO). Final Biological Opinion for the Carlsbad Project Water Operations and Water. Supply Conservation, 2016-2026. Consultation Number 02ENNM00-2016-F-0506. Field Supervisor, Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, New Mexico December 5, 2017. https://www.fws.gov/southwest/es/newmexico/documents/BO/2016-F-0506_Carlsbad_Project_Water_Operations_BiOp_Final.pdf.

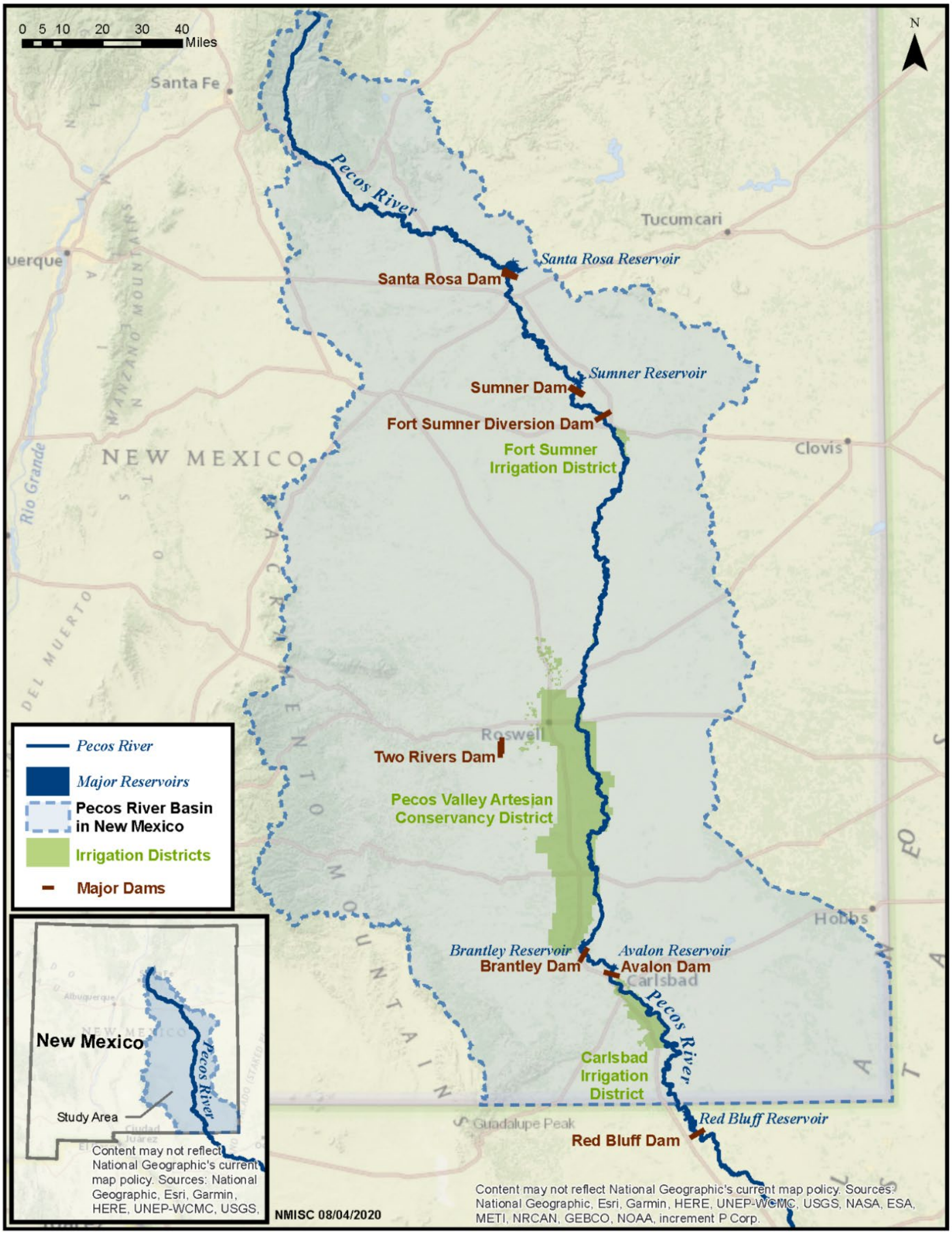

Figure ES-1: Study area location map, showing the Pecos River, irrigation districts, and major dams (NMISC).

Projections of future meteorological and hydrological conditions indicate that the stresses on the limited water supply in the study area are likely to increase over the course of the next century with increasing temperatures, uncertain precipitation trends, decreasing snowpack, and increasing drought intensity (see for example: NMISC and New Mexico Office of State Engineer [NMOSE] 2006, Sheffield and Wood 2008, Reclamation 2011, Reclamation 2013, Zhang et al. 2013, IPCC 2014, Dettinger et al. 2015, Reclamation 2016, USFWS 2017 [2016 BiOp], EPA 2017, Towler et al. 2018, U.S. Global Change Research Program [USGCRP] 2018, WCRP 2018, NOAA 2019 [Climate]). In this basin study, see the Climate Appendix, Section 2.4. *Historical and Recent Climate*¸ and Section 4.1. *Future Meteorological and Hydrological Conditions.* These stresses will pose a major challenge to New Mexico's environmental, agricultural, and socioeconomic systems.

Basin Study Process

The Basin Study is a partnership between the Bureau of Reclamation's (Reclamation) Albuquerque Area Office (AAO) and NMISC, in cooperation with FSID, CID, and PVACD. Although there are other water uses in the Pecos River Basin in New Mexico, this study emphasizes projected impacts to these three irrigation districts, which are the largest water users in the basin, and actions that the irrigation districts might take to better prepare for future conditions. The quantitative analyses performed for this study are limited to the irrigation districts and the infrastructure (including Federal dams and reservoirs) that support their operations. Other uses of water in the basin, by acequias, ranches, independent groundwater-based agriculture, municipalities, and industrial uses (including oil and gas extraction), are described and evaluated qualitatively (see Section 8. *Additional Resource Impacts*)—but were not included in the modeling analyses performed for this Basin Study.

For this Basin Study, we developed projections of future hydrologic and water-management conditions in the basin, and then worked with FSID, CID, and PVACD to develop and model approaches to maintaining a viable agricultural community in the Pecos Basin in New Mexico, including changes to water deliveries, reservoir operations, or infrastructure. In the limited scope of this project, we were not able to model all potentially viable adaptation actions, nor combinations of adaptation actions, but we were able to model enough overarching strategies to provide a roadmap for future planning.

Can Reclamation's and the districts' infrastructure and operations handle future changes?

To assist FSID, PVACD, and CID to determine operations and water deliveries within the context of future changes in the basin, we conducted the basin study and:

- Worked with the irrigation district managers to characterize their operations, identify potential vulnerabilities and challenges, and determine potential needs and actions for addressing those challenges. See Section 3.3. *Irrigation and Conservancy Districts*.

- Made improvements to the irrigation-related surface water models for the Fort Sumner area to provide a better predictive tool for flows in the Pecos River. See Section 4.2. *Model Methodology*.

- Designed and installed two flumes to measure return flows to the river from FSID drains.

- Used satellite-based tools Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) to evaluate evapotranspiration and crop consumptive use within FSID.

- Modeled irrigation district and Endangered Species Act (ESA) operations water footprints using the Pecos River Operations Model (PROM) and the Roswell Artesian Basin Groundwater Model (RABGWM, a MODFLOW groundwater model) to assess their impacts in the basin, see Section 6. *Water Footprint Analyses.*

- Modeled irrigation district water operations and Water Management Strategies by interlinking the PROM and the Roswell Artesian Basin (RAB) Groundwater Model (a MODFLOW groundwater model) to project how these strategies might impact water supplies or mitigate the negative effects of projected changes in supply on agriculture in the basin. See Section 7. *Modeled Water Management Strategies*.

This study can help Federal and State water managers better quantify and assess the possible impacts of ongoing and potential meteorological and hydrological changes to the limited water supplies in the Pecos River Basin on irrigation districts and Federal reservoir operations in New Mexico. As this study focuses on irrigation, the biggest water user in the basin, our modeling sought to answer the following questions:

- What are current and projected hydrological and meteorological trends in the Pecos River Basin in New Mexico?

- How might these trends affect irrigation water supplies and demands for the three irrigation districts?

- What infrastructural or operational changes might the irrigation districts undertake to maintain the viability of irrigated agriculture in this basin?

- How might modeled Water Management Strategies mitigate the projected changes in water supplies?

This study focused on the underlying question:
If the total volume and seasonal availability of water supplies change in the future, what operational changes might irrigation districts need to make to remain viable under future conditions?

Modeling a Range of Storylines

Despite our ability to employ sequences of sophisticated numerical models to project future climate and hydrology, considerable uncertainty remains in these projections. Since long-term trends in fossil fuel and renewable energy usage are difficult to predict, the impacts of these and other human behaviors on climate conditions remain uncertain.

While we cannot predict future climate precisely, we can examine a range of possible future hydrological conditions to provide irrigators in the study area with a more nuanced view of potential climatological and hydrological outcomes.

Climate models are essentially computer programs that describe the most important components, processes, and interactions in earth's climate system, such as energy balance, ocean circulation, atmospheric circulation, and the hydrologic cycle. These models simulate a projected range of potential hydrological and meteorological trends, and the drivers of weather, such as the frequency and magnitude of monsoon storms, or the El Niño Southern Oscillation (ENSO) (an ocean circulation pattern coordinated to seasonal weather patterns). The models also simulate other climate trends, such as how changes in greenhouse gas concentrations affect the energy balance in the atmosphere. To evaluate these potential trends, scientists input greenhouse gas concentrations and changes in land use and land cover into the climate models and run simulations to assess how these factors affect the earth's systems and processes (Figure ES-3).

This study and other modeling and planning studies analyzing future conditions in New Mexico predict rising air and water temperatures. Most model simulations further predict numerous consequences of these rising temperatures, including:

- Water loss through evaporation and transpiration by plants
- Decreasing snowpack
- Smaller/earlier spring runoff
- Changes in water availability and timing
- More frequent high intensity precipitation events

Five possible storylines were used in this study and are based on a set of climate model simulations that simulate future conditions based on a set of standard scenarios representing timelines of heat accumulation in the atmosphere, called Representative Concentration Pathways (RCP). Each of the RCPs represent the associated future radiative forcing on earth, in watts per square meter [W/m^2] (so simulations using RCP 4.5 will include increases in net radiative forcing at earth's surface at a rate of 4.5 W/m^2). Radiative forcing is the difference between the amount of sunlight entering earth's atmosphere and the amount of energy radiated back into space, and therefore represents heat accumulation rates in the lower portion of earth's atmosphere.

The simulations performed using each of the RCPs resulted in a range of potential changes. Rather than try to predict future conditions directly, we selected five projections from which to develop "storylines." Each of these five storylines represents a scenario that is within the likely range of future climatic conditions in the Pecos River Basin (see Section 4, *Projection of Future Conditions*). These five storylines represent three "Higher Emissions" (HE) storylines, derived from RCP 8.5 simulations and represented by high energy demand and emissions, and two "Lower Emissions" (LE) storylines, derived from RCP 4.5 simulations.

The modeling performed for this study, as well as numerous other studies, shows that temperatures in the basin are currently increasing—and will likely continue to increase.

Precipitation in the basin will likely change in total volume, spatial distribution, and timing. Changes in winter precipitation, from snow to rain, are already occurring, and are nearly certain to continue. In addition, any snow that does accumulate in the mountains will likely melt off earlier in the season—and may do so more quickly due to an increased likelihood of rain-on-snow events. Changes in the seasonality of precipitation are also likely. Monsoon storm events may become more intense (i.e., provide more precipitation in one event than historical storms have).

Operational changes may be needed to more effectively use water that rapidly enters the basin either from rapid snowmelt runoff or from more intense monsoon storms.

Higher Emissions Storylines (RCP 8.5)

What will happen if human development and energy use continue according to current trends? These conditions are referred to as Higher Emissions (HE) and are simulated in climate models using RCP 8.5 future conditions, which are associated with high population growth and fossil fuel use, coupled with relatively slow income growth and modest rates of technological improvement throughout the world. The HE future scenario would lead to high energy demands and greenhouse gas emissions.

> "The purpose of using scenarios is not to predict the future, but to explore both the scientific and real-world implications of different plausible futures." Center for International Climate Research, 2015.

The HE Moderate, HE Dry, and HE High Monsoon/Low Snowpack (HMLS) Storylines are projections that represent a range of potential climate storylines that may result from Higher Emissions conditions. By 2099, temperatures rise by 8.8 degrees Fahrenheit (°F) in the HE Moderate Storyline, by 13.3 °F in the HE Dry Storyline, and by 12.3 °F in the HE HMLS Storyline. As temperatures increase, crops require more water. These future projections suggest that there are likely to be increased gaps between water supplies and water demand in the HE Storylines, due to increasing temperatures and decreasing water supplies (in HE Moderate and HE Dry Storylines) or due to changes in timing and availability in water (in the HE HMLS Storyline). In general:

- **HE Moderate:** In this storyline, mild drying occurs across the Pecos River Basin in New Mexico.

- **HE Dry:** This storyline is associated with much drier conditions. River flows, reservoir storage, and water available for irrigation, compliance with delivery requirements decrease substantially.

- **HE HMLS:** This storyline results in similar-to-slightly greater drying than the HE Moderate Storyline in the upstream portion of the basin, due to decreased snowmelt runoff from the headwaters region. However, further downstream, in the vicinities of PVACD and CID, more frequent and higher-intensity monsoon storms lead to wetter conditions.

Lower Emissions Storylines (RCP 4.5)

What would happen if emissions were reduced and greenhouse gas emissions dropped below current levels? These conditions are modeled in our Lower Emissions (LE) storylines, which are associated with RCP 4.5. In RCP 4.5 projections, carbon dioxide emissions worldwide start to fall around 2040, and they fall below current levels by 2070. Atmospheric concentrations stabilize by 2099 to levels at about twice the levels of the pre-industrial period (using the year 1850 as representative of this period). This future could be achieved with stringent climate stabilization policies, lower fossil-fuel-based energy use, reforestation, and other actions to reduce levels of carbon dioxide in the atmosphere. In the RE storylines, temperatures rise—but do not rise as much as in the HE storylines. By 2099, temperatures rise by 2.5°F in the LE Median Storyline and by 4 °F in the LE Increased Monsoon Storyline.

In the LE storylines, water demand still increases due to increasing temperatures, although not as significantly as under the HE storylines. In addition, water supplies decrease slightly under the LE Median Storyline, and increase during the monsoon season under the LE Increased Monsoon Storyline. In general:

- **LE Increased Monsoon:** This storyline is associated with smaller increases in temperature and water demand than in the HE storylines and modest decreases in snowfall. Precipitation increases as a result of much more frequent monsoon storms with slightly greater intensity.

- **LE Median:** In this storyline, the Pecos River Basin in New Mexico experiences minor increases in snowfall and minor decreases in precipitation during other seasons. Like in the LE Increased Monsoon Storyline, basin temperatures and water demand increase less than in the HE storylines, and water availability decreases slightly. Note that this storyline represents the median of the Lower Emissions RCP 4.5 scenarios, not the median of the five storylines examined in this study.

Storyline Baseline Summary

The storyline baselines are the future without any actions taken. Comparing actions against a baseline allows us to determine how much impact an action will have. To help understand the effects that potential Water Management Strategies could have on sustain viable agriculture in the Pecos River Basin, we modeled parameters:

- **Reservoir storage.** The daily average for total reservoir storage (See Section 5.1. in the main report and Figures Appendix Section 2).

- **Surface water irrigation district entitlements, allotments, and shortages.** (See Section 3.1. *Regulation of Water in the Pecos River Basin*, 3.3.1.3 *FSID Current Operations*, and Section 5.2. in the main report and Figures Appendix Sections 3 - 6).

- **River flows are measured by drying days at Acme and FSID bypass flows.** (See Section 5.3. in the main report and Figures Appendix Sections 7 and 8).

- **Availability of water for estimated releases in accordance with the Pecos River Settlement.** The yearly amount of water available for the 2003 Pecos Settlement based on reservoir storage and CID releases (see Section 3.1.4. *2003 Pecos Settlement Agreement* and Section 5.4. in the main report and Figures Appendix Section 9).

- **Groundwater** Projected changes to groundwater levels are based on the Groundwater Base Case (i.e., groundwater stresses/usage conditions in the year 2010 repeated each year for the 100-year analysis period) (See Section 5.5. in the main report and Figures Appendix Section 10).

Table ES-1 summarizes baseline projections for each storyline to provide the modeled historical values for each parameter to compare with the water footprint analyses and the Water Management Strategies as discussed in the next sections.

Table ES-1: Summary of Storyline Changes from 2010-2099

Basin Characteristic (Modeled Historic Value)		Higher Emissions			Lower Emissions	
		Moderate	Dry	HMLS	Increased Monsoon	Median
Changes to Watershed (2010-2099)	Temperature	+8.82°F	+13.32°F	+12.33°F	+4.05°F	+2.52°F
	Precipitation	- 3.6 in	-8.37 in	+1.98 in	+ 3.15 in	-0.63 in
	Runoff	-60,570 af	-140,130 af	+81,270 af	+36,270 af	-26,010 af
Water Supply Measures Under the Storylines (Average in 2070-2099 Period)	Reservoir Storage (102,900 af)	57,736 af	13,525 af	116,987 af	144,234 af	90,397 af
	FSID Shortages (401 af)	2,481 af	6,515 af	2,159 af	446 af	674 af
	CID Allotment (2.47 af/acre)	1.38 af/acre	0.15 af/acre	2.67 af/acre	3.29 af/acre	2.25 af/acre
	CID Shortages (10,995 af)	39,237 af	72,898 af	13,588 af	718 af	12,741 af
	Drying at Acme (11 days)	44 days	117 days	40 days	10 days	21 days
	Available Water for Potential Settlement Releases (14,200 af)	8,005 af	318 af	14,740 af	17,154 af	14,041 af
	Acme-Artesia Gain/Loss (27,266 af/yr)	9194 af/yr	-16,776 af/yr	32,846 af/yr	49,172 af/yr	34,850 af/yr

in = inches, af = acre-feet, f/yr =acre-feet per year

Water Footprint Analyses

The water footprint analyses determined the effects of each irrigation district, as well as ESA operations, on the system overall and on each other. We examined these water footprints based on modeling runs that systematically isolated each system component to evaluate its impact on several parameters: reservoir storage, available supplies to other irrigation districts, flows in the river, and groundwater conditions. These water footprint analyses illustrate the scale of water use in the basin versus the projected changes in water supply, and therefore helped guide the choice of Water Management Strategies modeled for this project. Water footprint analyses are not Water Management Strategies.

The following subsection summarizes impacts of the water footprint analyses on key parameters related to irrigated agriculture in the Basin. See Section 6. *Water Footprint Analyses.*

Reservoir Shortages

Because the rights to store water in the four reservoirs are a part of Reclamation's Carlsbad Project (which serves CID) CID's reservoir storage footprint is larger than that of the other irrigation districts in four of the five storylines. However, the other districts also affect reservoir storage levels (by using water that could otherwise reach the reservoirs), even though they do not draw from CID's stored water. In all but the HE Dry Storyline, CID has the largest footprint, followed by PVACD and FSID. ESA flows have the smallest footprint.

Surface Water Irrigation Districts' Water Supply (i.e., Entitlements, Allotments, and Shortages)

FSID Entitlements and Shortages

Because FSID has a run-of-the river water right and is upstream of the other irrigation districts, FSID entitlements and shortages are not affected by any other water footprint.

CID Allotments and Shortages

CID's allotment depends primarily on the amount of water stored in the Carlsbad Project reservoirs. The footprint of each irrigation district represents its relative impact on this reservoir storage. FSID and PVACD affect these reservoir storage levels indirectly by using water that could otherwise reach the reservoirs. In all storylines, PVACD has the largest footprint, followed by FSID, and ESA flows have the smallest footprint.

CID shortages are the gap between the district's water supply and crop demands. The footprint analysis shows us that in every storyline, the biggest influence on CID shortages is the amount of groundwater pumping in PVACD. FSID's footprints for the HE storylines are about one-fifth to one-quarter of PVACD's. For the RE storylines, FSID has a footprint that is similar or about half that of PVACD. The ESA footprints are smaller than those of the irrigation districts. In most cases, the ESA footprints are 15 to 30 percent that of FSID's footprints.

River Flows

Drying at the Acme Gage

Maintaining a continuous stream and minimizing drying during critically dry years are the primary goals for current river management for ESA purposes. The water footprint analyses are of limited value for drying at Acme because of the model setup. In the model, water that would normally go to FSID is stored as CID project water in Sumner Reservoir instead of flowing down the river. The water footprint analyses are of limited value for assessing FSID's impact on drying at Acme because of the model setup. In the footprint analyses, the model is run with and without the impacts of each irrigation district to determine its footprint. When running the model in the absence of the FSID impacts, water that in reality goes to FSID is instead stored as CID project water in Sumner in this model run. We assume that if not for FSID's existing entitlement to this water, it would be stored in the reservoir, and only released downstream as part of block flows to CID.

However, if FSID's water were released downstream instead of being stored in Sumner Reservoir, then FSID's footprint would go from having the most drying days at Acme to keeping the Pecos River continuously flowing in almost every storyline. The 2016 BiOp notes that FSID affects drying in the upper reaches during drier conditions "… there are times when FSID is the sole surface water diverter and its diversions may cause river intermittency when Reclamation's supplemental water supplies are exhausted …" (page 96).

FSID Bypass Flows

Because FSID is located upstream of the other irrigation districts, their bypass flows are not affected by other irrigation districts. ESA releases also have no effect on bypass flows since they only augment flows below Sumner Dam.

Surface-Water/Groundwater Interactions

Only PVACD has a footprint affecting groundwater conditions in the Roswell Artesian Basin. The PVACD water footprint on groundwater levels in the Roswell Artesian Basin is significant for each storyline as their pumping causes these changes. PVACD pumping does not affect the alluvial aquifers in the vicinity of FSID and CID.

The PVACD water footprint on Pecos River gains from the Roswell Artesian Basin is significant for each storyline, since PVACD's pumping is a primary driver for these changes. As expected, their water footprint is greatest in the drier HE Moderate and Dry Storylines. For the remaining three wetter storylines, the water footprint on gains to the river is somewhat less, since wetter conditions decrease the demand for groundwater pumping for irrigation. In these storylines, the lower irrigation pumping results in a higher water table and steeper hydraulic gradients toward the Pecos, resulting in higher base flows as more groundwater can reach the river.

Water Management Strategies

In this Basin Study, we developed and modeled Water Management Strategies that could help irrigation districts adapt to projected changes in temperature, precipitation, and hydrology in the five storylines. These strategies revolve around ways that irrigation districts and individual farmers can reduce their water use as the gap between water supply and demand grows during the coming century. The Water Management Strategies are scaled to minimize the overall impacts of water shortages in the storylines that project larger changes. Note that these strategies are not specific actions. Model results for these overarching strategies can provide a roadmap for future planning.

> In the future, we can watch for signs that the basin is changing in ways that are consistent with one or more storylines. We can also look for similarities in the changes projected among all the storylines to find Water Management Strategies that help the basin—no matter which trajectory is followed.

Reducing Irrigation Water Consumption within Each Irrigation District

This group of Water Management Strategies looked at the potential impacts of reducing irrigation water consumption in each irrigation district. This modeling focuses on the degree to which the Water Management Strategies compensate for decreasing water availability—not how the reduction in water use is accomplished. The reductions could be accomplished through changing crop types and irrigation methods, increasing operational efficiency in the irrigation district (decreasing system conveyance losses), using improved system monitoring or irrigation technology, or even using greenhouses. To simplify, and because modeling specific reduction actions is not part of this study, we modeled these changes by reducing irrigated acreage within the surface irrigation districts and decreasing the pumping amount for PVACD in the groundwater model. Note that specific actions are discussed in Section 3.3. *Irrigation and Conservancy Districts.* The Water Management Strategies are:

- **20% Reduction by All Districts:** PVACD reduces groundwater pumping by 20% starting in 2045, and FSID and CID reduce irrigated acreage by 20% starting in 2055

- **25% Reduction by All Districts:** PVACD reduces groundwater pumping by 25% starting in 2045, and FSID and CID reduce irrigated acreage by 25% starting in 2055.

These levels were selected to bracket the amount of reduction that would keep the system whole. We chose these years because the HE Moderate Storyline starts to show significant declines in overall water supplies (e.g., decreased reservoir storage levels and increased FSID and CID shortages) by 2055. Due to the average travel time of water from the Roswell Artesian Basin aquifers to the Pecos, it takes up to 10 years for the effect of changes in pumping/stresses on the Roswell Artesian Basin to be reflected in changes in baseflow to the river. Therefore, we chose 2045 for the start date for PVACD groundwater pumping reductions.

As PVACD's groundwater rights are junior to FSID's and CID's surface-water rights, and PVACD irrigates nearly four times as many acres as the two surface-water irrigation districts combined, we also modeled:

- **25% Reduction by PVACD**: PVACD reduces its groundwater pumping by 25% starting in 2045.
- **30% Reduction by PVACD:** PVACD reduces its groundwater pumping by 30% starting in 2045.

Increasing On-Farm Efficiency in Surface-Water Irrigation Districts

Increasing on-farm water-use efficiency (as modeled in the Increased Efficiency Water Management Strategy) involves increases to the proportion of water applied to crops that is used by those crops, and reductions to the proportion that is either lost to evaporation, runoff, or infiltration to groundwater.

In all storylines, increasing on-farm efficiency is a useful strategy, as it allows farmers to either continue to achieve the same crop yields if shortages occur or if crop water demands increase due to temperature increases, or improve yields should supplies remain constant or increase. However, increased efficiency does have potential tradeoffs: since more applied water is consumptively used by the crops, less water is returned to the basin for other users. Managing efficiency increases without unduly favoring upstream users may require cuts to diversions to avoid increasing water consumption in the basin.

Key Model Results

General Trends

Measurements show that temperatures in the Pecos River Basin are currently increasing (see Climate Appendix). All storylines modeled in this Basin Study project that basin air and water temperatures continue to increase through the rest of this century. These temperature increases correlate with decreasing snowpack, earlier snowmelt runoff, lower runoff volumes, decreasing water supply, and increasing crop water requirements.

> "Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands."
> U.S. Global Change Research Program (USGCRP) 2018

There will likely be less snowmelt runoff, and it will likely occur earlier in the year. Precipitation trends vary more among the storylines, since future precipitation is subject to greater uncertainty. Storylines were therefore selected to highlight potential changes in the seasonal distribution of precipitation. All projections for precipitation indicate that changes in timing and location will occur. Some projections show increased precipitation during the monsoon season; others show decreased precipitation year-round.

Effects of Water Management Strategies

Irrigation Districts

As each irrigation district has a different position within the basin and different legal and operational structure, the potential changes described by the Water Management Strategies would affect each district differently.

Fort Sumner Irrigation District

Due to its position as the most upstream of the major irrigation districts, and its "run-of-the-river" (natural-flow-based) water rights, as well as the impact of local groundwater recharge,[2] FSID has some inherent protection from the impacts of decreased water supply, and from the impacts of changes in the operations of the other irrigation districts. Since adaptations will not affect the supply arriving at FSID, the most beneficial Water Management Strategies for FSID are those that improve the district's use of the water it receives to mitigate increasing water demand within the district. In all cases (except for the Dry Storyline) increases in irrigation efficiency are projected to be sufficient to avoid water shortages for FSID. See Section 3.3.1. *Fort Sumner Irrigation District.*

Pecos Valley Artesian Conservancy District

PVACD is a groundwater irrigation district. As such, its operations are not directly affected by the operations of the surface-water irrigation districts (note that PVACD pumping does affect availability of surface water to FSID and CID). PVACD is also not directly affected by short-term droughts, or year-to-year variability. PVACD is, however, impacted by long-term trends in precipitation in the basin. Since PVACD's water demand is limited by the individual water rights of its member irrigators, future changes to groundwater-levels and to groundwater fluxes to and from the river would be associated with changes in groundwater recharge rather than by increases in groundwater pumping. See Section 3.3.2. *Pecos Valley Artesian Conservancy District.*

Carlsbad Irrigation District

CID is the most sensitive of the three irrigation districts to changes in precipitation, especially in the short-term. CID relies heavily on surface water stored in Reclamation's Carlsbad Project reservoirs. Since CID is the downstream-most of the three irrigation districts, it is affected by FSID and PVACD operations. See Section 3.3.3. *Carlsbad Irrigation District.*

Parameters

We modeled what would happen under each storyline (the baseline) and then what would happen under each storyline if the Water Management Strategies were implemented. This analysis shows the effects that potential changes under the range of storylines would have on parameters within the basin that affect irrigation district operations and water supplies.

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[2] Shallow alluvial groundwater in the vicinity of FSID was evaluated qualitatively but was not modeled.

Figure ES-2 summarizes effects of each Water Management Strategy relative to each storyline baseline.

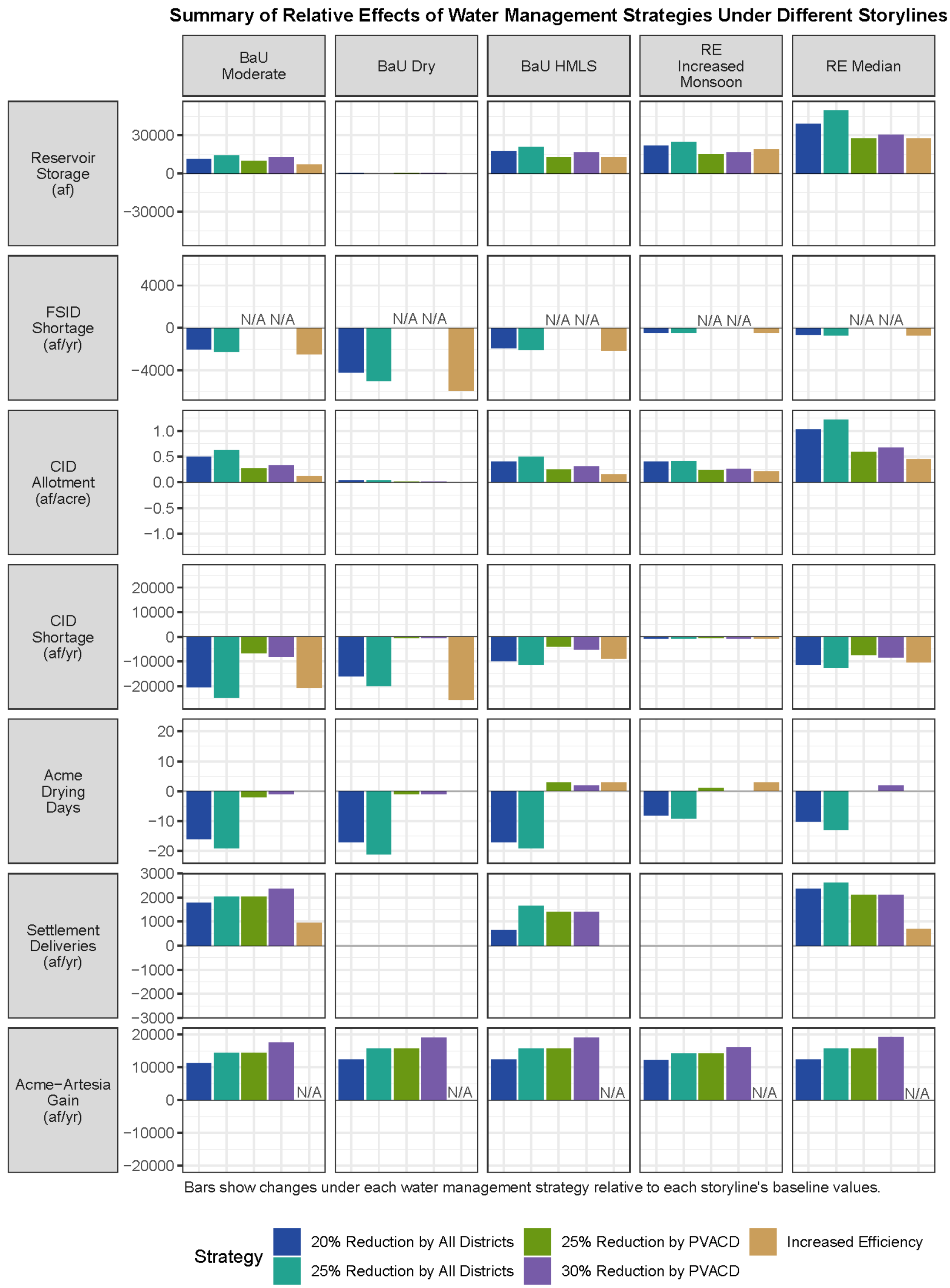


Figure ES-2. Summary of Water Management Strategy impacts for each parameter in each storyline (NMISC).

Reservoir Storage

The 25% Reduction by All Districts Strategy is the most effective strategy for maintaining total reservoir storage in the basin. In the HE Dry Storyline, however, no strategy helps the total storage significantly, since the decrease in precipitation in this storyline is so extreme. In the Dry Storyline, none of the Water Management Strategies are able to bring reservoir storage in 2070-2099 anywhere close to the 1950-2009 historical average.

See Section 5.1. *Reservoir Storage and Operations* for an explanation and a baseline analysis of reservoir storage.

The On-Farm Efficiency Strategy does the least to improve reservoir storage. See Section 7.2.1. *Reservoir Storage and Operations* for a detailed strategy analysis.

Surface Water Irrigation Districts' Water Supply (i.e., Entitlements, Allotments, and Shortages)

FSID Entitlements

FSID entitlements are secure in all future storylines modeled as part of this Basin Study. Since FSID's entitlement is calculated based on natural flows above the district and none of the Water Management Strategies affect natural flows above FSID, none of the strategies have any effect on FSID's entitlement. See Section 7.2.2.1. *FSID Entitlements*.

See Section 5.2.1 FSID Entitlements for an explanation and baseline analysis of FSID entitlements.

FSID and CID Shortages

The On-Farm Efficiency Strategy reduces future FSID and CID shortages under all storylines by decreasing water losses. Water saved from higher efficiencies could be used on farm (e.g., to increase yields or provide sufficient water to bring a crop to harvest within a water right even though demands are increasing) or could be left in the river, benefitting ESA and other purposes. See Section 7.2.2.2. *FSID Shortages* and 7.2.2.2. *CID Shortages* for a detailed strategy analysis.

See Section 5.2.2. *FSID Shortages* and Section 5.2.*4 CID Shortages* for an explanation and a baseline analysis of shortages.

CID Allotments

The 25% Reduction by All Districts Strategy is the most effective, and the 20% Reduction by All Districts Strategy is the second-most effective Water Management Strategy to maintain annual water allotments to irrigators in CID. In these strategies, CID reduces consumption, thus increasing reservoir storage, which, in turn, increases the CID allotment. Reductions to PVACD groundwater pumping also provides benefits, but not as much as reductions to the water consumption by all irrigation districts. The On-Farm Efficiency Strategy also provides some minor benefits to annual CID allotments. See Section 7.2.2.3. *CID Allotments* for a detailed strategy analysis.

See Section 5.2.3. *CID Allotment* for an explanation and a baseline analysis of CID allotments.

River Flows

Drying at Acme

See Section 5.3.1. *Drying at Acme* for an explanation and a baseline analysis of Drying at Acme.

The number of drying days projected at the Acme gage is used to monitor ESA compliance under each storyline and Water Management Strategy. The 25% and 20% Reduction by All Districts Strategies result in the fewest drying days in all storylines. This is mainly due to a reduction in FSID water consumption in these Water Management Strategies. Reductions to only PVACD groundwater pumping (the 25% and 30% Reduction by PVACD Strategies) and On-Farm Efficiency Strategy had little to no impact on the number of drying days at the ESA compliance point. This could have impacts on the number of drying days downstream of the Acme gage; however, this was not evaluated in this analysis.

In the Dry Storyline, from 2040-2060, the Pecos River changes from a gaining river to a losing river in the reach between Sumner and Brantley Reservoirs. In that period, the river flows intermittently; after 2060, it is projected to only flow during large storm events or block releases from reservoirs. See Section 7.2.3. *Drying at Acme* for a detailed strategy analysis.

FSID Bypass Flows

There would be no impacts on FSID Bypass Flows from any water management strategy.

Availability of Water for Estimated Releases in Accordance with the Pecos River Settlement

See Section 5.4. *Availability of Water for Estimated Releases for the Pecos River Settlement* for an explanation and a baseline analysis of Settlement releases.

In the HE Moderate, HE HMLS, and RE Median Storylines, the cooler and wetter the storyline is, the more benefits that the 25% and 20% Reduction by All Districts Strategies provide. The drier and hotter the storyline is, the more efficient it is to reduce PVACD irrigation water consumption. Therefore, in those hotter and drier storylines, the 25% and 30% Reduction by PVACD in 2045 Strategies start to be just as beneficial as reducing all three irrigation districts. With higher demands from higher temperatures, particularly in CID, CID will require more water, which will reduce the estimated amount for the Settlement releases based on Settlement calculations. In all three storylines, the On-farm Efficiency Strategy is the least beneficial for increasing the availability of potential Settlement releases.

None of the strategies help increase potential Settlement releases for the HE Dry Storyline.

RE Increased Monsoon baseline is already at the maximum potential Settlement Releases, so no strategy could increase that further. See Section 7.2.4. *Availability of Water for Estimated Releases* for a detailed strategy analysis.

Groundwater Changes

Roswell Artesian Basin Groundwater Levels

> See Section 5.5 *Groundwater* for an explanation and a baseline analysis of groundwater level changes.

In the HE Moderate Storyline, the 30% Reduction by PVACD Strategy temporarily offsets groundwater impacts in some but not all areas of the Roswell Artesian Basin. In the RE Median and RE Increased Monsoon Storylines, all Water Management Strategies persistently increased water levels in the Roswell Artesian Basin above the Groundwater Base Case (i.e., groundwater conditions in the year 2010 repeated each year for the 100-year analysis period). See Section 7.2.5. *Groundwater* for a detailed strategy analysis.

7.2.5.2. Pecos River Groundwater Gains from Acme to Artesia

Since gains increase in the RE Increased Monsoon Storyline, pumping adjustments in the RE Increased Monsoon Storyline simply increase the amount of gain already predicted for the climatological conditions associated with the RE Increased Monsoon Storyline. In general, each Water Management Strategy provides some degree of offset in the other four storylines. The groundwater levels in each storyline determine the effect of the Water Management Strategy—the lower the levels in the storyline to begin with, the least effect that the strategy will have. Adaptations in the HE Dry Storyline have the least amount of offset, and RE Median Storyline have the most.

The extremely low precipitation projected in the HE Dry Storyline diminishes recharge to groundwater which, along with continuing groundwater pumping, results in the reach between Sumner Reservoir and Brantley Reservoir shifting from a gaining to a losing reach. Reducing groundwater pumping by PVACD would delay the point in time at which this shift occurs, but in the HE Dry Storyline, this would not prevent the shift.

Shallow Alluvial Aquifer Levels in the Vicinity of FSID

Because the water supply for FSID is reliable under most modeled storylines, the FSID irrigation network, along with the river, continues to recharge the shallow alluvial aquifer. Therefore, groundwater levels in the shallow alluvial aquifer in the vicinity of FSID remain relatively stable under baseline conditions in all modeled storylines except for the HE Dry Storyline. In the HE Dry Storyline, groundwater levels in the shallow alluvial aquifer drop slightly over time.

FSID return flows have a substantial effect on local groundwater levels in the alluvial aquifer, raising local aquifer levels by about 4 to 6 feet, depending on the storyline, above what they would be if FSID were not operating. The ESA footprint is also significant, since ESA operations contribute to keeping the river wet, and by extension help raise the local water table. CID’s operations impacts are generally minor. PVACD’s footprint on this shallow aquifer is practically negligible. Water Management Strategies have minimal impact on this aquifer.

Conclusions

Temperature, precipitation, evaporation, and irrigation demands (transpiration) in the Pecos River-Basin are changing now and will continue to change. In this Basin Study, we evaluated how these changes may affect the hydrology of the basin, and how the irrigation districts in the basin might adapt to current and projected changes in water supply and demand.

The range of potential futures for the Pecos River Basin is broad. If future human behavior provides for a future in which greenhouse gas emissions decrease over time (i.e., under the Lower Emissions [RCP 4.5] trajectory, such as the LE Increased Monsoon and LE Median Storylines) then irrigation districts will likely readily adapt to changing hydrological conditions. However, if instead we are on a Higher Emissions (RCP 8.5) path into the future, then the likelihood of a HE Dry Storyline—in which all Water Management Strategies do very little to help meet resource criteria—increases. In this storyline, the likelihood that irrigation districts will be unable to adapt to changing conditions becomes much higher.

Potential Actions

This Basin Study assessed the impacts of the Water Management Strategies on water supply and irrigation district operations, the potential effects of overall strategies to address these, and the degree to which these strategies could mitigate projected changes in water supply and demand. However, the strategies modeled in this study did not evaluate how the irrigation districts would make the needed reductions in water demand. The three irrigation districts (FSID, PVACD, and CID) have identified actions that they are currently taking, or to hope to take, that could increase their water-use efficiency or decrease their overall demand (see Section 3.3. *Irrigation and Conservancy Districts*).

In all of the storylines, there are actions that irrigation districts and government agencies can take that will help prepare for the future and that can prolong viability of irrigated agriculture in the Pecos River-Basin in New Mexico. These actions include reductions in irrigation water consumption in each district (which can be accomplished in a wide variety of ways) and increasing irrigation efficiency in the surface-water districts. Other actions that could help maintain the viability of agriculture in the Pecos Basin in New Mexico include:

- Improving conveyance efficiency of irrigation infrastructure. Rehabilitating or replacing canals, check structures, and diversion structures could improve conveyance efficiency, making more water available for use by irrigators.

- Considering alternative reservoir operations that improve the system's ability to more efficiently capture and use water from monsoon storms and to address changes in runoff volume and timing.

- Improving electronic record keeping within the irrigation districts, including on farms. Evaluating these records could help better understand trends and benefits of actions.
- Improving communication between Reclamation, the State, the irrigation districts, and farmers related to water operations, water distribution, and challenges.
- Controlling invasive species.
- Developing a water banking system specific to Pecos River Basin in New Mexico, to improve flexibility of water usage in the basin.
- Performing channel management in the Pecos River and surface water drainage systems in the study area.
- Working on alternatives for modernizing facilities can help lay a foundation for improved infrastructure maintenance and improvement plans.

Potential Future Analyses

Going forward, the region would benefit from additional studies to:

- Investigate the economic implications of undertaking the Water Management Strategies, such as reducing the total water consumed in each irrigation district or increasing irrigation efficiency.
- Improve understanding of surface-water/groundwater interactions, especially in the Puerta de Luna area, which can help to assess the impacts of groundwater use in those areas on flows in the Pecos River.
- Investigate the potential for water and soil quality issues (such as water/soil salinization) to arise due to changes in irrigation efficiency.
- Determine the potential impacts of actions that increase operational flexibility within the basin.
- Investigate the potential benefits of combining different Water Management Strategies (e.g., improved efficiency with reduction in water use).
- Explore feasibility of options for new water sources such as use/reuse of produced water, and importation of water from other basins/regions.

Contents

Appendices

1. Background

1.1. Problem and Need

The Pecos River and its tributaries are the lifeblood of the arid landscapes of eastern New Mexico. Today, irrigated agriculture, towns, and some of the most biodiverse arid and semiarid ecosystems in the world depend on the Pecos River. However, extraordinarily dry conditions in the basin during the last decade have highlighted the critical need to plan for future droughts and long-term hydrological changes in the basin.

> "Throughout the Pecos River in New Mexico, water is scarce and is allocated completely or in some cases is over allocated as indicated by historic river drying in many locations along the river." Stockton 2011

Flow depletions in the Pecos River have been noted for decades. Thomas (1963) wrote "The Pecos River in New Mexico is an excellent example of a river which has had a progressive diminution of inflow from a large part of its drainage basin. Drought in recent years has been responsible for part of this reduction in inflow, but not for the progressive reduction throughout the past four decades." A half-century later, Harley and Maxwell (2017) noted that flow regulations, increased population, and agricultural irrigation have substantially reduced stream flows in the basin. Moreover, they note that changing temperature and precipitation patterns and increased growth of non-native riparian vegetation
(e.g., salt cedar) have exacerbated low-flow conditions.

In their tree-ring-based streamflow reconstruction for the Pecos River from 1310-2013, Harley and Maxwell (2017) noted that in this reconstructed period, two of the most severe droughts[1] have been within the last two decades. They ranked the 2000-2006 and 2011-2013 dry periods as the 6th and 13th most severe for that 700-year record. They further noted that the intensity of the 2011-2013 event exceeded all higher ranked droughts in this reconstructed period (1310-2013). In 2011, the vast majority of the Pecos River Basin in New Mexico recorded its hottest and driest year since historical records began in 1895. The conditions experienced in these recent severe droughts may occur more frequently as the region continues to undergo hydrological and meteorological changes.

[1]Drought intensity is defined as the deficit in precipitation during a drought on a per-time basis, while drought severity is the total deficit in precipitation accumulated over the course of the drought (essentially severity = intensity x duration).

Water management challenges are likely to intensify along with these projected meteorological and hydrological changes. Advanced planning and implementation of no-regret actions (actions to address water supply and demand issues that are beneficial in any circumstance) will be vital to ensuring reliable water supplies for Pecos River water users and for complying with the 1948 Pecos River Compact (Compact), the Endangered Species Act (ESA), the 2003 Pecos Settlement Agreement (Settlement), and other legal requirements. To better prepare for the future, the Bureau of Reclamation (Reclamation) and the New Mexico Interstate Stream Commission (NMISC) conducted this Pecos River Basin Study - New Mexico (Basin Study) to examine how shortages in the future water supply may occur, and to develop and test strategies to help meet water demands given the reduced future supply.

1.2. Pecos River Basin Study – New Mexico

1.2.1. Purpose, Scope, and Objectives

1.2.1.1. Purpose

Water resource managers balance water supply and demand under complex rules and uncertain conditions. In long-term planning, managers must consider how investments made today may influence their ability to manage both current and future challenges under a wide range of possibilities for how future conditions may unfold. To characterize potential future conditions in the Pecos Basin in New Mexico, and to evaluate potential actions that might help the agricultural community in this basin adapt to coming hydrologic changes, NMISC, Reclamation, irrigation districts, and other partners worked together to conduct the Basin Study. Basin studies are part of the Department of the Interior's (DOI) WaterSMART (Water Sustain and Manage America's Resources for Tomorrow) program and are a key component of Reclamation's implementation of the SECURE Water Act of 2009 (SECURE Water Act).[1]

> "Like many areas of the American West, severe and prolonged drought combined with increased temperatures during the early 21st century amplified attention on water resources and allocation management." Harley and Maxwell 2017

To develop and model approaches to maintaining a vibrant agricultural community in this Basin, including changes to water deliveries, reservoir operations, or infrastructure, we developed projections of future hydrologic and water-management conditions in the Pecos Basin in New Mexico, and then worked with Fort Sumner Irrigation District (FSID), Pecos Valley Artesian Conservancy District (PVACD), and Carlsbad Irrigation District (CID). In the limited scope of this basin study, we were not able to model all potentially viable adaptation actions or combinations of adaptation actions, but we were able to model enough strategies to provide a roadmap for future planning.

[1] Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act (Public Law 111-11, Subtitle F of Title IX, §9501-§9510).

1.2.1.2. Scope

Basin studies are technical assessments and do not provide recommendations or represent a statement of policy or position of Reclamation, DOI, or the funding partners. Basin studies do not propose or address the feasibility of any specific project, program, or plan and do not represent a commitment for provision of Federal funds.

The Pecos River Basin Study – New Mexico Basin Study is a partnership between the Reclamation's Albuquerque Area Office (AAO) and NMISC, in cooperation with FSID, CID, and PVACD. Although there are other water uses in the Pecos River Basin in New Mexico, this study emphasizes projected impacts to these three irrigation districts and actions that the irrigation districts might take to better prepare for future conditions. The quantitative analyses performed for this study are limited to the irrigation districts and the infrastructure (including Federal reservoirs) that support their operations. Other uses of water in the basin, by acequias, ranches, independent groundwater-based agriculture, municipalities, and industrial uses (including oil and gas extraction), are described and evaluated qualitatively, but these were not included in the modeling analyses performed for this Basin Study.

1.2.2. Basin Study History

NMISC submitted a basin study proposal to Reclamation under the WaterSMART program on February 9, 2012. The proposal explained that the recurring extraordinarily dry conditions in the basin made it difficult to deliver enough irrigation water downstream to the Carlsbad Project to meet flow targets in critical habitat reaches of the river to protect the Pecos bluntnose shiner, and to meet New Mexico's water delivery obligations to Texas under the Compact. The proposal warned that as temperatures continue to rise, water supply shortages are likely to worsen.

Reclamation and NMISC entered into a Memorandum of Agreement to implement the proposal dated October 2012. As originally proposed, the Basin Study was to focus only on the Fort Sumner Groundwater Basin and develop a groundwater model to enhance understanding of the complex relationship between surface water and ground water in that reach of the Pecos River. To meet this original purpose, the study team added groundwater simulation capability in the Fort Sumner area to its water operations model, as described in Section 4.2. *Model Methodology*, the Surface Water Modeling Appendix, and the Groundwater Appendix.

In addition, the study team designed and installed two flumes to measure return flows to the river from FSID drains and used satellite-based tools Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) to evaluate evapotranspiration and crop consumptive use within FSID. The study estimated the spatial distribution of actual evapotranspiration (ET) from agricultural lands in the Fort Sumner Underground Water Basin in southeastern New Mexico and included distinct regions of surface water and groundwater-irrigated lands as well as non-irrigated areas. This information provided a more complete and comprehensive overall water budget for the basin.

As the Basin Study developed, Reclamation and NMISC agreed that the study should be expanded to include the entire Pecos River Basin in New Mexico and focus on the three irrigation districts that are the primary water users in this basin.

1.3. Study Objectives

This Basin Study developed an improved irrigation-related groundwater and surface water model for the Pecos River Basin in New Mexico. We performed simulations with these models for a range of potential futures. These improved models and simulations can help Federal and state water managers better quantify and understand the potential impacts of current and future hydrological and meteorological changes on the limited water supplies in the study area.

To assist the three major irrigation districts in the study area (FSID, PVACD, and CID) to determine operations and water deliveries within the context of future changes in the basin, we:

- Worked with the irrigation district managers to characterize their operations, identify potential vulnerabilities and challenges, and determine potential needs and actions for addressing those challenges. See Section 3.3. *Irrigation and Conservancy Districts*.
- Made improvements to the irrigation-related surface water models for the Fort Sumner area, to provide a better predictive tool for flows in the Pecos River. See Section 4.2. *Model Methodology*.
- Designed and installed two flumes to measure return flows to the river from FSID drains
- Used satellite-based tools (METRIC) to evaluate evapotranspiration and crop consumptive use within FSID.
- Modeled irrigation district and ESA operations water footprints using the Pecos River Operations Model (PROM) and the Roswell Artesian Basin (RAB) Groundwater Model (RABGWM, a MODFLOW groundwater model) to assess their impacts in the basin, see Section 6. *Water Footprint Analyses* and to project how these strategies might impact water supplies or mitigate the negative effects of projected changes in supply on agriculture in the basin. See Section 7. *Modeled Water Management Strategies*.

1.3.1. Basin Study Authority

In the SECURE Water Act, Congress declared that "global climate change poses a significant challenge to the protection and use of the water resources of the United States, due to an increased uncertainty with respect to the timing, form, and geographical distribution of precipitation, which may have a substantial effect on the supplies of water for agricultural, hydroelectric power, industrial, domestic supply, and environmental needs." (42 United States Code [U.S.C.] 10361[3].) The SECURE Water Act authorizes

Reclamation, in consultation with appropriate non-Federal participants, to assess specific risks to the water supply of major Western river basins, to analyze the adverse effects of changes in the water supply and demand in major river basins, and to develop strategies to mitigate those effects. (42 U.S.C. 10363[b]).

1.3.2. Partners and Stakeholders

NMISC is the primary cost-share partner for this study. Additional stakeholders who participated in this study include FSID, PVACD, and CID. Other stakeholders who provided input and written support for the study include Chaves County, De Baca County, the Village of Fort Sumner, and the Pecos River Compact Commission. The study team had conversations with stakeholders throughout the course of the project (See Section 10. *Participation and Communication*).

2. Pecos River System Description

2.1. Location

The Pecos River Basin covers much of southeastern New Mexico, encompassing about 25,000 square miles or just over 20% of the state (Figure 1). From its source in the Sangre de Cristo Mountains in north-central New Mexico, the Pecos River flows in a generally south-southeasterly direction for 970 miles to its confluence with the Rio Grande in Amistad Reservoir on the Texas-Mexico border (Figure 1). The locations of the study area and important features of the basin are presented in Figure 2.

2.2. Water Supply

The Pecos River basin's water supply includes surface and groundwater sources. The most recent data for the basin were compiled by the New Mexico Office of State Engineer (NMOSE) for calendar year 2015 (NMOSE 2019), when about 356,000 and 245,000 acre-feet of groundwater and surface water were withdrawn for use, respectively. The total supply was thus roughly 602,000 acre-feet, which was about 20% of the state's total.

> "Water in New Mexico is a complex and important issue. Nowhere is that more true than on the Pecos River in eastern New Mexico."
> New Mexico Bureau of Geology and Mineral Resources et al. 2003

Surface water (the Pecos River and its tributaries) in the study area is derived from three main sources: snowmelt in the Sangre de Cristo and Sacramento Mountains, precipitation from storm events, and groundwater inflows to the river. Annual and seasonal variations in precipitation and snowfall results in highly variable surface water flows.

Groundwater is the largest source of water for irrigators in the basin. For example, the Roswell Artesian Basin contains a prolific bedrock aquifer that is used to reliably irrigate over 100,000 acres of farmland each year. Shallow alluvial aquifers, which are present locally along the course of the Pecos River and its major tributaries, are also used to irrigate farmland.

Figure 1. The Pecos River Basin and the Rio Grande and Pecos River (NMISC).

Figure 2. Location of overall study area, including major dams and modeled irrigation districts (NMISC).

2.2.1. Surface Water

The Pecos River originates in the Sangre de Cristo Mountains about 30 miles northeast of Santa Fe, New Mexico. From its source, the river flows generally south through eastern New Mexico for almost 530 river miles before entering Texas just upstream of Red Bluff Reservoir at the southern edge of the study area. The river then flows a further 440 miles to the southeast to its confluence with the Rio Grande in the backwaters of Amistad Reservoir. Overall, the river is 970 miles long and has a drainage area of roughly 25,000 square miles in New Mexico and 19,000 square miles in Texas.

> "Supplies in one part of the region may not necessarily be available to meet demands in other areas, particularly in the absence of expensive infrastructure projects. Therefore, comparing the supplies to the demands for the entire region without considering local issues provides only a general picture of the balance.
>
> Water supply challenges include the need for adequate funding and resources for infrastructure projects, water quality issues, location and access to water resources, limited productivity of certain aquifers, and protection of source water." NMISC 2016 (Mora)

The Pecos River receives perennial inflows from: numerous streams in the upper headwater area, many springs along the mainstem (particularly in the Santa Rosa area), groundwater inflows from the Roswell Artesian Basin, and several tributary streams in its lower reaches. Additionally, numerous intermittent and ephemeral tributaries throughout the basin provide water during the spring runoff season and after significant storm events.

For discussion purposes, the river has been divided into seven reaches:

- **Headwaters to Santa Rosa Reservoir.** From its headwaters in the Sangre de Cristo Mountains, the Pecos River flows generally southeast, dropping in elevation from 11,700 feet at its source to about 4,800 feet upstream of Santa Rosa Reservoir (U.S. Forest Service [USFS] 2002). The Pecos River above Santa Rosa Reservoir is perennial except for short reaches of intermittent flow between Anton Chico and Colonias. In these reaches, the river loses the entirety of its flow unless flows are very high (e.g., during snowmelt runoff season and after major storms). Much of this water ultimately rejoins the river further downstream. Average annual snowmelt runoff over the past 30 years has been approximately 50,000 to 60,000 acre-feet. Major tributaries to this reach include the Rio Mora, Willow Creek, Glorieta Creek, Cow Creek, Tecolote Creek, and the Rio Gallinas.

- **Santa Rosa Dam to Sumner Reservoir.** From Santa Rosa Dam, the Pecos River flows about 60 miles southwards to Sumner Reservoir, at an elevation of just under 4,300 feet, near the Village of Fort Sumner. The springs near the town of Santa Rosa provide about 36,000 to 60,000 acre-feet of water annually to the river. Major tributaries to this stretch include numerous short, spring-fed creeks in the Santa Rosa area, Agua Negra, and Alamogordo Creek. The springs around Santa Rosa Reservoir provide a fairly consistent flow in this reach of the river.

Figure 3. Terraced floodplain above Acme Gage (Reclamation).

- **Sumner Dam to the Acme Gage.** The Pecos River flows generally southward for approximately 120 miles through the broad plains of eastern New Mexico. In this reach, the river is typically fairly shallow and meanders across a relatively wide channel at low flows, featuring numerous sand bars and frequent sections of braided channels (Figure 3). At moderate flows, the river extends across the channel. In this reach, the Pecos River only overtops its banks and spills onto the surrounding floodplain in extreme floods. These characteristics continue to the downstream end of the reach near the U.S. Geological Survey (USGS) Acme Gage 08386000 north of the city of Roswell (Acme Gage) at U.S. Highway 70 just north of the city of Roswell. Major tributaries to this stretch of the river include Taiban Creek, Yeso Creek, and Salt Creek. This stretch of the river is perennial but prone to occasional drying during drought conditions.

- **Acme Gage to Artesia Gage.** Below the Acme Gage, the Pecos River flows through the Bitter Lake National Wildlife Refuge between U. S. Highway 70 and U.S. Highway 380. Within the refuge, the river retains a moderately active channel. From the refuge downstream to USGS Artesia Gage 08396500 near the city of Artesia (Artesia Gage), the river channel narrows and deepens, becoming more incised and confined to a single channel, but with a broad floodplain. A sometimes-significant source of water in this area is base inflow from the adjacent aquifer that has been as high as 120,000 acre-feet and as low as 15,000 acre-feet per year over the period of record (1905-1998). The Rio Hondo and Rio Felix are the largest tributaries to this reach.

- **Artesia Gage to Avalon Dam.** Downstream of the Artesia Gage, the Pecos River flows about 25 miles through a broad floodplain to Brantley Reservoir. Rio Peñasco is the only significant tributary in this reach, though it and numerous small arroyos in the reach only flow after heavy rains. Several miles upstream of the Brantley Reservoir, the river enters the Kaiser Channel, a man-made canal that traverses the lakebed of the former McMillan Reservoir. Downstream of Brantley Reservoir, the river flows about 10 river miles through a hilly, rocky landscape to the smaller Avalon Reservoir. Rocky Arroyo, an ephemeral stream, is the only significant tributary to this reach, though like other tributaries in the area it flows only after heavy rains. CID uses Avalon Reservoir for staging water and diverts water to its water users at Avalon Dam.

- **Avalon Dam to Red Bluff Dam.** Below Avalon Dam, the river continues for about 65 river miles through plains and low hills to the New Mexico-Texas state line. Except during specific release events, the gates of Avalon Dam are closed and the river downstream of the dam is dry. Several miles below the dam, the Carlsbad Springs discharge water from the Capitan aquifer, river water leaking from the nearby Avalon Reservoir, and return flows from irrigation, making the river perennial again. Notable tributaries to this stretch of the river include Dark Canyon Draw (typically dry outside of storms), the Black River, and the Delaware River. From the state line, the river continues for about 10 miles through Red Bluff Reservoir and then another 430 miles to its junction with the Rio Grande in Amistad Reservoir near Del Rio, Texas, at about 1,100 feet mean sea level (msl). Red Bluff Reservoir is just outside of the study area.

2.2.2. Groundwater

Most of the water supply in the Pecos River Basin in New Mexico is derived from groundwater. There are several major aquifers in the study area; the most important are those in the Roswell Basin, which supply water to the extensive farmland of the PVACD (Figure 4). The groundwater basins and aquifers are listed in this subsection from north to south rather than in order of importance.

2.2.2.1. Fort Sumner Groundwater Basin

The Fort Sumner Groundwater Basin encompasses a shallow alluvial aquifer, composed of Quaternary alluvial sand and gravel deposits. These alluvial deposits are centered around the village of Fort Sumner and span roughly 10 miles east to west and 30 miles north to south. South of this area, the alluvium narrows to a thin (about 1 mile wide) band along the river. These alluvial aquifers serve as the source of fresh water supply for the village of Fort Sumner and a few scattered farms in the area. Farmers in FSID do not use groundwater and rely on surface water from the Pecos River.

2.2.2.2. High Plains/Ogallala Aquifer

The Ogallala Aquifer (also termed the High Plains Aquifer) is one of the largest and most important aquifers in the United States and extends from near Odessa, Texas to the edge of the South Dakota Badlands, underlying an area of about 174,000 square miles (mi^2) in eight states. In New Mexico, the aquifer lies mostly east of the Pecos Basin, along the Texas-New-Mexico border, but a small portion (approximately 800 mi^2) extends into the northeastern-most part of the Pecos Basin, near the town of House about 20 miles northeast of Fort Sumner. Groundwater in this aquifer flows to the east and away from the study area and is not hydrologically connected to the Pecos Basin.

Within this portion of the basin, there are approximately 41,000 acres of farmland (Intera 2014); however, much of this land is used for dryland farming (i.e., unirrigated and dependent upon rainfall). The irrigated areas draw their water from the Ogallala Aquifer. However, given the minimal impact of these agricultural activities on water resource concerns in the rest of the basin, these withdrawals have not been incorporated in this study’s model.

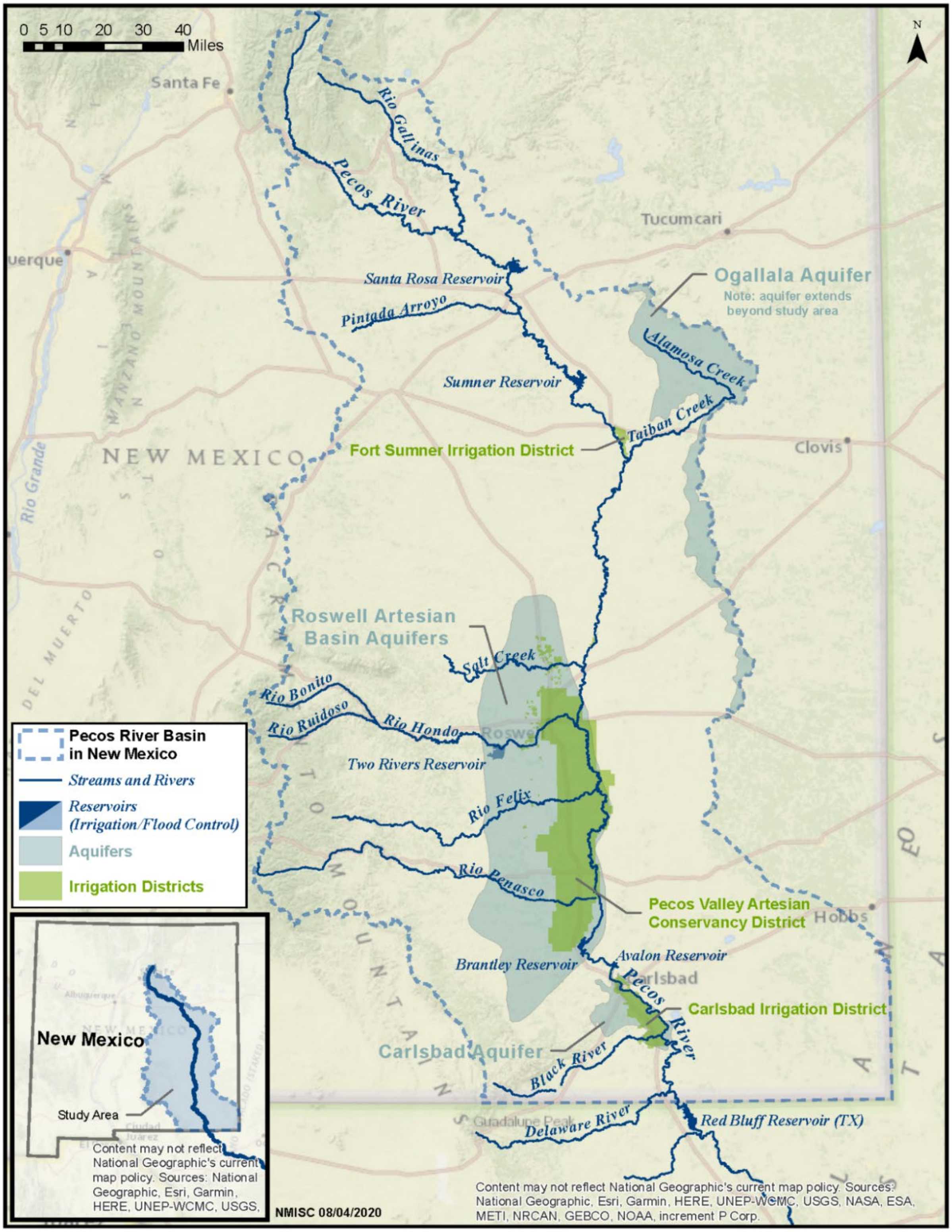


Figure 4. Groundwater and surface water map for the study area only (dashed blue lines). Note that aquifer boundaries extend beyond the study area (NMISC).

2.2.2.3. Roswell Artesian Basin

The Roswell Artesian Basin is a two-aquifer system (Fiedler and Nye 1933), consisting of an eastward-dipping confined limestone aquifer that is overlain nearer the river by a shallow alluvial aquifer (Figure 5). The shallow aquifer underlies the Pecos River from just north of Roswell to the vicinity of Brantley Dam. It extends about 10-15 miles west of the Pecos River and is generally less than 250 feet thick. The two aquifers are hydraulically separated by a layer of low-permeability gypsum and mudstone that forms a semi-confining bed (aquitard). Typically, some of the groundwater in the deeper confined aquifer leaks through the aquitard, recharging the shallow alluvial aquifer and the Pecos River. The shallow aquifer is also recharged by precipitation and irrigation return flow.

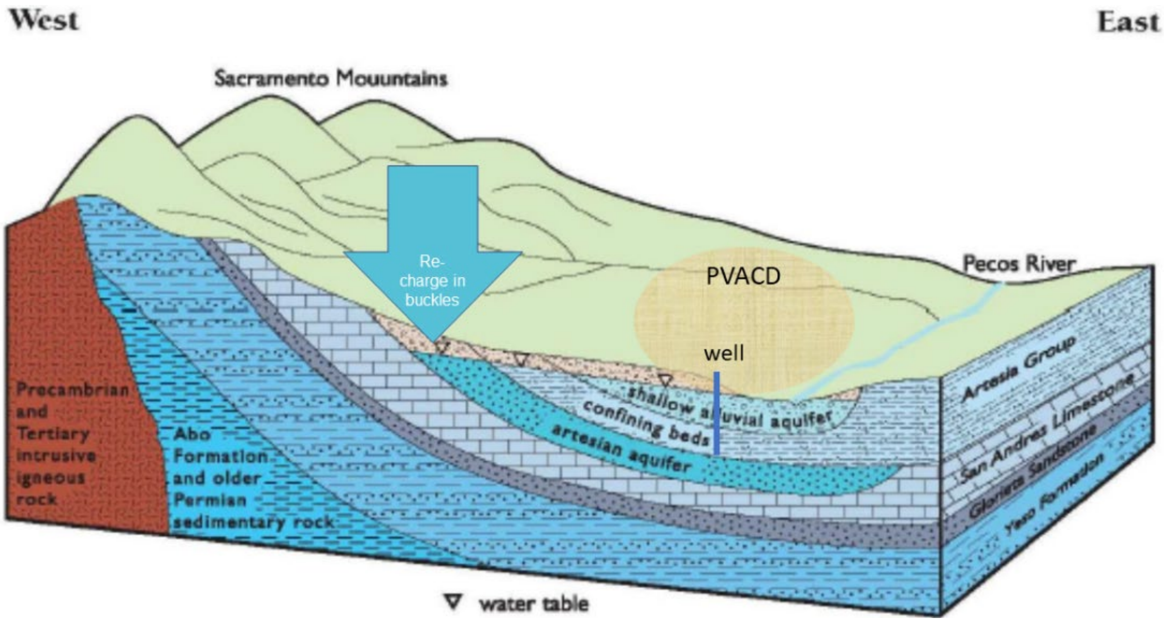


Figure 5. Roswell Artesian Basin aquifers and recharge with PVACD well (Reclamation).

A substantial amount of recharge to the artesian aquifer occurs west of the confining layers, where streams such as the Rio Hondo and Rio Peñasco descend from the Sacramento Mountains and flow across permeable fault zones known as the Pecos Buckles. These fault zones extend from southwest to northeast across the Pecos Slope west of Roswell. In these zones, intensely deformed limestones of the San Andres Formation provide fractures and solution-enlarged conduits through which recharge to the artesian aquifer system occurs. Figure 6 is an aerial view of the Buckle to provide an idea of the extent and visibility of the Buckle as it stretches across counties. Figure 7 shows a cross cut of the Buckle to show the fault zone. (Welder 1983, Land and Newton 2008, and Land and Huff 2010).

Water enters the San Andres Formation and flows downgradient eastward toward the Pecos River (Figure 8). A few miles west of Roswell, the aquifer dips beneath the Seven Rivers Formation confining beds, and the water in the aquifer becomes pressurized (Welder 1983 and Land and Newton 2008).

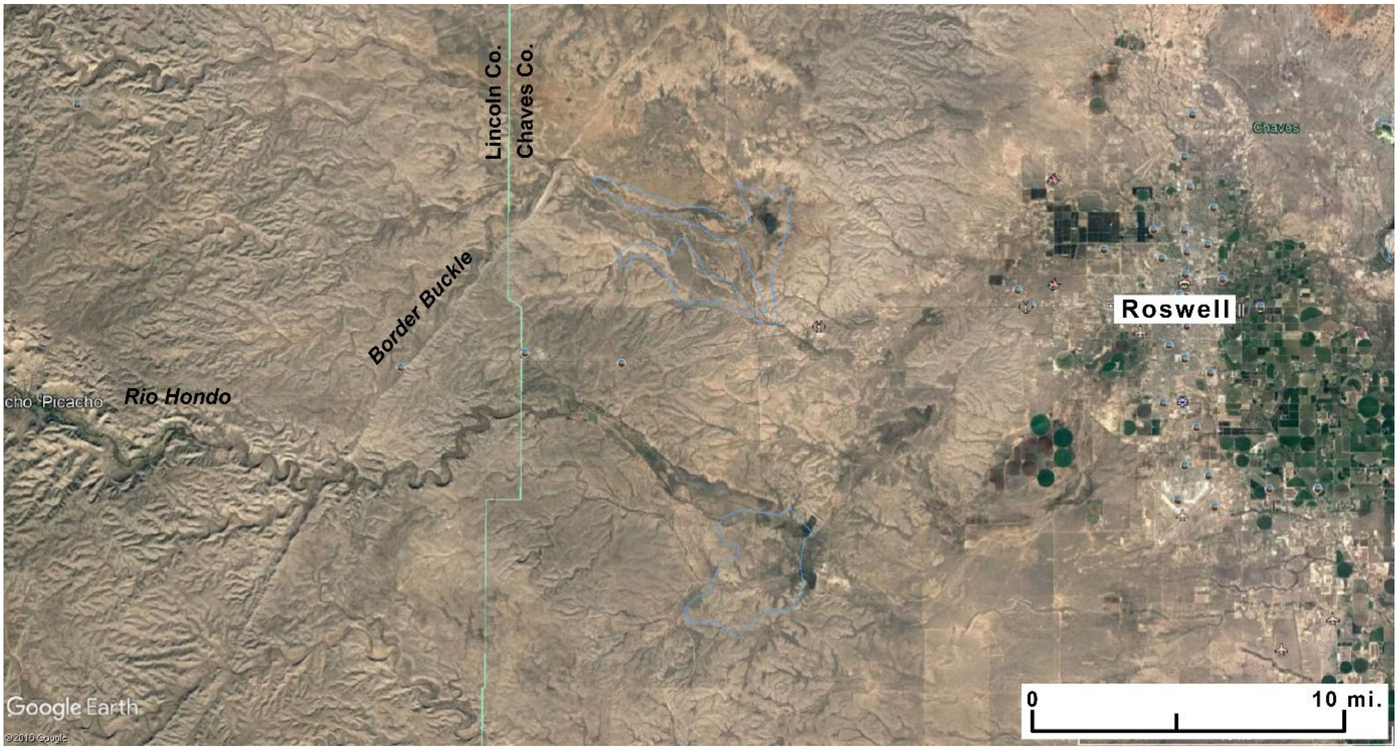


Figure 6. Aerial view of the Border Buckle, seen as a linear feature extending from southwest to northeast across the Pecos Slope west of Roswell (this aerial image is from Land 2018, and is an adapted Google Earth image under a private license used by permission).

Figure 7. Border Buckle fault zone, exposed in a roadcut on the south side of US 70-380, about three miles west of the Lincoln-Chaves county line (Land 2018, used by permission).

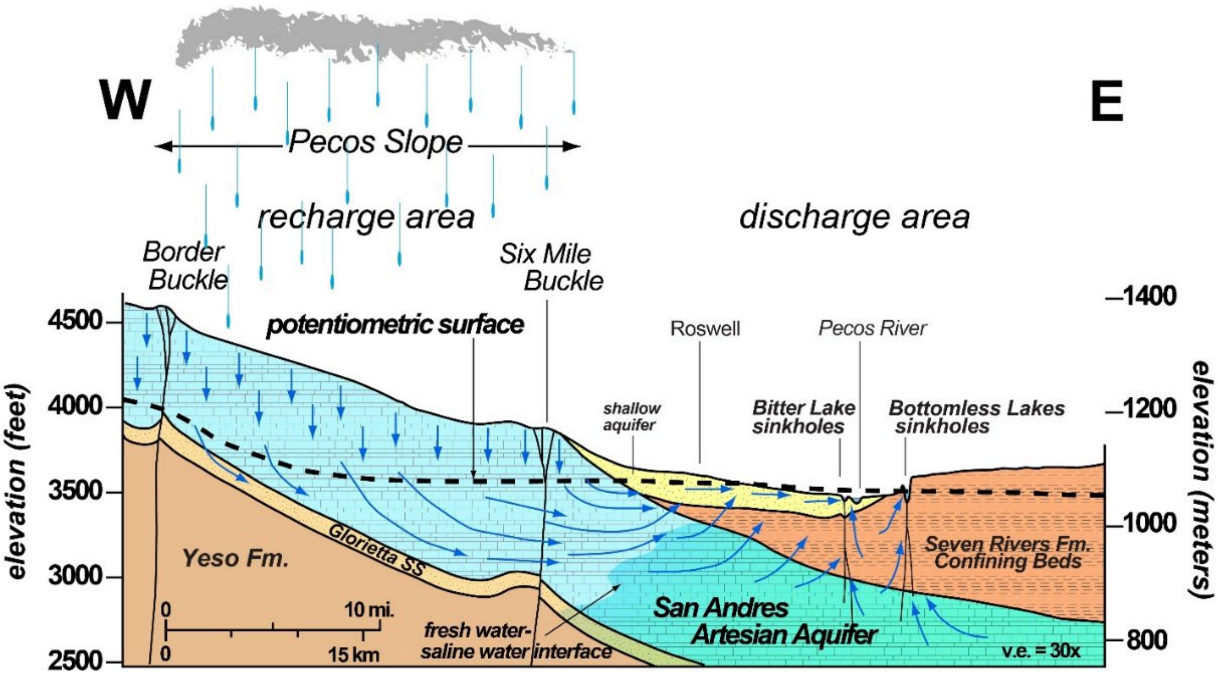


Figure 8. Groundwater movement to the Pecos River from the San Andres Formation to the Pecos River (Land 2018, based on Welder 1983, Land and Newton 2008, and Land and Huff 2010).

Before the Pecos Valley was settled, this artesian groundwater ultimately flowed upward through the overlying leaky semi-confining beds, contributing to high-volume spring discharge in the Roswell area and to baseflow into the Pecos River. Today, most of the groundwater flow in the artesian aquifer is intercepted by irrigation wells, but a significant amount still makes its way to the Pecos River, contributing to baseflow and to the formation of sinkhole lakes on both sides of the river (Land and Newton 2008).

In the early 20th century, the Roswell area was famous for its high-capacity artesian wells (wells that discharged groundwater to the ground surface without any pumping), which were erroneously thought to provide an endless source of water. The extensive use of groundwater in the basin has since lowered water-levels in the artesian aquifer and, with a few exceptions, water no longer flows to the surface freely (Burck and Wahlin 2006).

2.2.2.4. Carlsbad Groundwater Basin

The Carlsbad groundwater basin contains two principal aquifers. The Quaternary Pecos alluvium forms the shallow unconsolidated alluvial aquifer, which is underlain by the Permian Capitan Reef. The reef aquifer is a subterranean structure that underlies the northern part of the alluvial aquifer (Barroll 2004). The Capitan Reef is exposed along the southeast escarpment of the Guadalupe Mountains in southeastern New Mexico and west Texas, and is the host rock for Carlsbad Cavern, the centerpiece of Carlsbad Caverns National Park. However, fresh water is present in the aquifer only in the immediate vicinity of its recharge area in the Guadalupe Mountains. The city of Carlsbad, because of its proximity to recharge areas to the southwest, is thus the only community in the region in a position to exploit fresh-water resources in the reef aquifer (Land 2017).

2.2.3. Surface Water/Groundwater Interactions

Groundwater in the Roswell Artesian Basin generally flows from recharge areas in the west towards the Pecos River along the eastern margin. Groundwater that is not intercepted by wells discharges either to the river or to riparian vegetation within the area of the shallow aquifer along the river corridor. Note that the Pecos River is a highly variable system and can have significant changes in reach behavior from year to year. While this is a highly variable system, in general, the Pecos River currently has general gains and losses in various reaches as shown in Figure 9.

- **Gains from Santa Rosa Reservoir to Sumner Reservoir.** The gains in this reach have a steady flow between 59 cubic feet per second (cfs) and 85 cfs, mostly from the numerous large springs in the Santa Rosa area.

- **Neither loses nor gains from Sumner Reservoir to the Taiban Gage.** There is generally a minor loss in the Pecos River in this reach, when FSID diversions are not taken into account.

- **Loses from Taiban Gage to Acme Gage.** There is generally a moderate to significant loss in the Pecos River in this reach.

- **Gains from the Acme Gage to the Artesia Gage.** Due to groundwater inflows from the artesian aquifer, inflow from the western tributaries, and return flows from agriculture, the Pecos River is generally gaining between the Acme and Artesia Gages (in general, about 30 to 40 cfs averaged daily over the year). During extended periods of drought, however, (e.g., 2011-2013), this reach may become a losing reach.

- **Loses downstream of Artesia Gage to Brantley Reservoir.** The Pecos River loses slightly (in general, about 4 to 5 cfs loss averaged daily over the year) from Artesia to Brantley Reservoir.

- **Loses between Brantley Dam and Avalon Dam.** The Pecos River loses slightly from Brantley Dam to Avalon Dam.

- **Gains between Avalon Dam and Carlsbad**. Downstream from Avalon Dam, the Pecos River becomes a gaining stream near Carlsbad because of the spring discharge from the underlying Capitan Reef aquifer (Cox 1967 and Land 2017) and of water that has leaked from Avalon Reservoir.

Figure 9. Pecos River gains and losses map (NMISC).

2.2.4. Storage, Operations, and Seasonal Variations

The Carlsbad Project is a Reclamation Project that supplies irrigation water encompasses several reservoirs on the Pecos River in eastern New Mexico. The Carlsbad Project stores water in Santa Rosa Reservoir (a U.S. Army Corps of Engineers [USACE] dam), Sumner, Brantley, and Avalon Reservoirs, providing water for about 25,000 acres of farmland within the Carlsbad Irrigation District. Santa Rosa Reservoir and Brantley Reservoir are the largest reservoirs in the basin. Avalon Reservoir is a small, re-regulating reservoir.

Carlsbad Project water is delivered in block releases which convey water from Santa Rosa Reservoir and/or Sumner Reservoir to Brantley Reservoir. Block releases are limited to 15 days each and a maximum of 65 days per calendar year, with a minimum period of 14 days between releases. Block releases from Sumner Reservoir from 1947-2018 averaged roughly 30,000 acre-feet over 15 days. Block releases from 1980-2018 from Santa Rosa Reservoir averaged roughly 22,700 acre-feet over 12 days.

Additional ESA releases are managed from Sumner Reservoir to alleviate intermittency as described in the Final Biological Opinion for the Carlsbad Project Water Operations and Water Supply Conservation, 2016-2026 (2016 BiOp). See Section 3.4.1. *Ecological Resources Water Use*.

Reservoir storage varies annually and seasonally. Droughts can drastically reduce storage volumes, but storage levels can recover rapidly following an extreme storm. Figure 10 shows the relative storage amounts and seasonal and drought year variations. Note the immediate recovery after the drought of 2011-2013, due to a large regional storm.

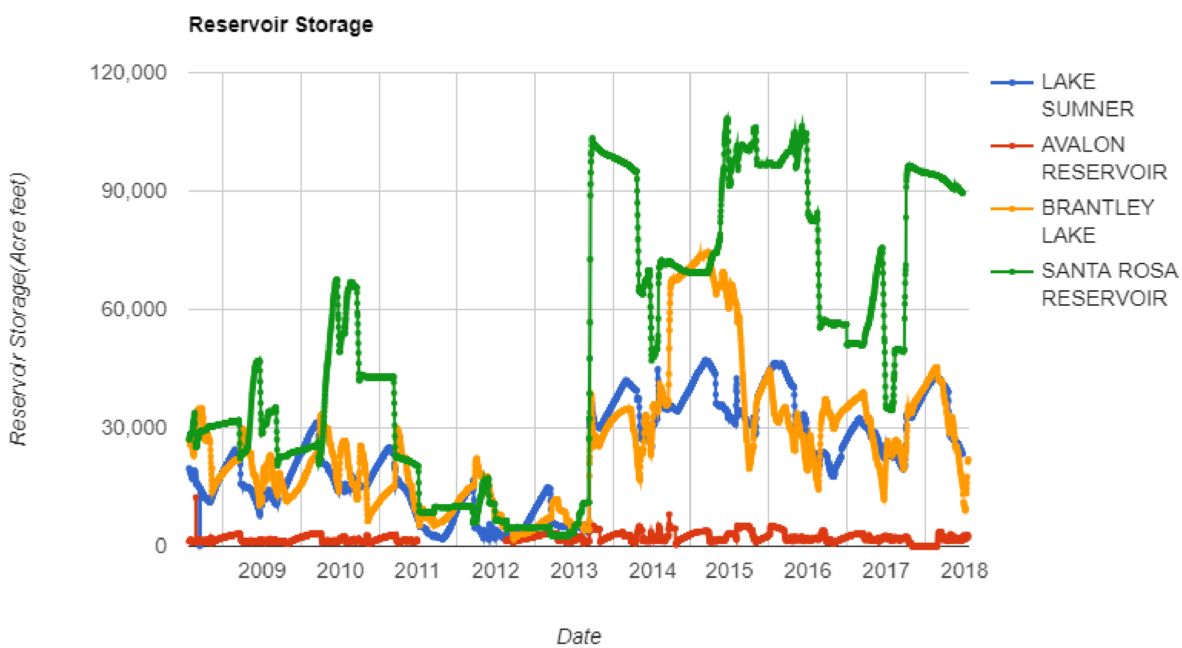


Figure 10. Reservoir storages from 2009-2018 (data derived from Reclamation 2019).

2.3. Irrigation Districts Overview

This study was undertaken to project future changes in hydrological and water-management conditions in the basin that would affect the irrigation districts, and then to work with irrigation districts in the basin to develop and model approaches to maintaining a vibrant agricultural community in the Pecos Basin in New Mexico, including changes to water deliveries, reservoir operations, or infrastructure. The largest irrigation districts in the Pecos River Basin in New Mexico are:

- **Fort Sumner Irrigation District**. FSID, in De Baca County, diverts water directly from the Pecos River about 3 miles northwest of Fort Sumner and about 17 river miles downstream from Sumner Dam. FSID diverts water from the Pecos River's east bank into a large canal to irrigate roughly 6,500 acres of farmland southeast of the village of Fort Sumner (Holdeman 2018).

- **Pecos Valley Artesian Conservancy District.** PVACD lies in Chaves and Eddy Counties, downstream of FSID and upstream of CID. Groundwater from the Roswell Artesian Basin and associated alluvial aquifer is the principal source of water used to irrigate about 110,000 acres of farmland (Balok 2019).

- **Carlsbad Irrigation District**. CID is downstream of both FSID and PVACD in Eddy County and lies mostly to the southeast of the city of Carlsbad and west of the Pecos River. CID irrigates primarily using surface water obtained from the Pecos River, and supplements this with groundwater pumping. CID irrigates about 20,000 acres of farmland extending from just below Avalon Dam to south of the Black River (Ballard 2019).

In very basic, overview terms, FSID has a run-of-the-river right to the "natural flows" in the Pecos River up to 100 cfs. PVACD has groundwater rights, with rights to limited surface diversions from Rio Hondo, and CID has surface water storage rights in four reservoirs on the Pecos River (New Mexico Office of State Engineer [NMOSE] 1972, 1979, and 1990). See Section 3.3. *Irrigation and Conservancy Districts* for a more detailed description of the irrigation districts' history, water rights, operations, water use, current challenges, and potential solutions.

2.4. Historical and Recent Climate

The climate of the Pecos Basin in New Mexico ranges from alpine tundra and humid mountain forest climates in its headwater regions, to semi-arid plains throughout much of the basin, to arid desert climates as the river approaches the New Mexico-Texas border. Rainfall in the basin is typically greater in the summer months, while winter is comparatively dry. The climate is generally cooler and wetter in the higher elevation mountain headwaters, becoming warmer and drier at lower elevations on the plains. The semi-arid to arid climate in most of the basin results in large diel temperature differences (see the Climate Appendix).

Weather and climate are important drivers of water supply and water demands. Changes in precipitation volumes and patterns may impact the volume and timing of groundwater recharge to the aquifers and runoff to the reservoirs. Changes in temperature, humidity, and wind speed may affect evapotranspiration (ET) rates, leading to changes in evaporative losses from reservoirs or in water consumption by irrigated crops. Changes to frequency or timing of extreme events may impact how flood control operations and drought response are managed.

Changes in air and water temperatures throughout the basin have already been observed and already affect water supply and demand. This section discusses changes that have already been experienced. See Section 4. *Projection of Future Conditions* for future projections noted in other scientific reports and in our modeling.

In addition to affecting water supplies and demands, weather and climate extremes also influence water management actions, such as flood control operations and drought response.

2.4.1. Temperature

2.4.1.1. Average Temperature Range

Temperatures in the study area are lower in the mountain headwaters and higher in the plains. Temperatures in the basin vary widely—the high peaks of the Sangre de Cristo Mountains can have annual averages below freezing, while among populated places annual average temperatures range from 49.2 degrees Fahrenheit (°F) at the Pecos Ranger Station, to 57.9 °F in the city of Santa Rosa, to 62.8 °F in the city of Carlsbad.

2.4.1.2. Recent Changes in Temperature

Temperatures increased across almost all of the Southwest region from 1901-2016, with the greatest increases in southern California and western Colorado (Figure 11). Recent historical trends in temperature within the State of New Mexico and the Pecos River Basin in New Mexico are covered in more detail in the Climate Appendix. Some notable observations include:

> "Most of New Mexico has warmed by at least one degree Fahrenheit (°F) in the last century. Throughout the southwestern United States, heat waves are becoming more common, and snow is melting earlier in spring." U.S. Environmental Protection Agency (EPA) 2017

- Temperatures have risen significantly in the Pecos River Basin in New Mexico in all months except December. The rate of increase has been greatest in January and in late spring and summer.

- Temperatures in New Mexico rose more rapidly in more recent decades. Tebaldi et al. (2012) estimated that temperatures increased at an average rate of 0.219 °F (0.10 degrees Celsius [°C]) per decade from 1912 to 2011 but have risen at a faster rate of 0.678 °F (0.34 °C) per decade since 1970.

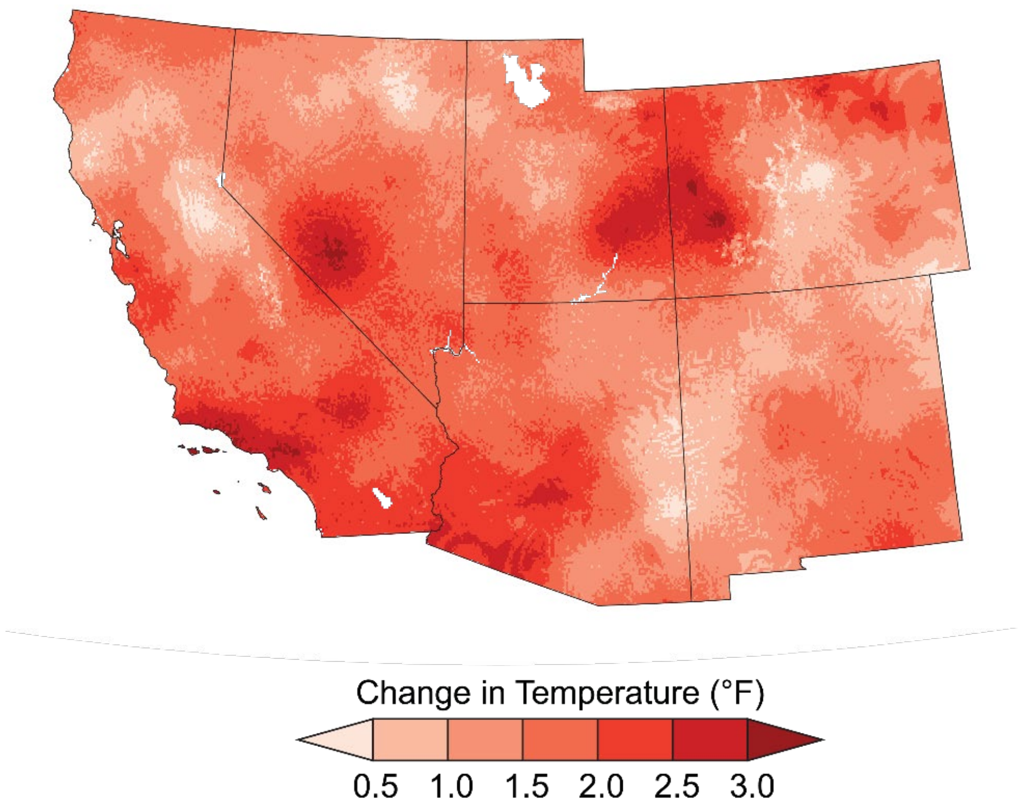


Figure 11. Difference between 1986-2016 average temperature and 1901-1960 average temperature (adapted from Vose et al. 2017, all rights reserved).

- Rising winter temperatures have resulted in an average of 8 fewer days below freezing annually, and a corresponding lengthening of the frost-free period (Bonfils et al. 2008).

- Rates of warming in high elevation areas may be considerably greater than the regional average. Mountain and valley regions analyzed for the Upper Rio Grande Impact Assessment showed that these regions responded differently to warming in the Rio Grande Basin (Reclamation 2013), and the same is likely true for the study area. Further, in a recent analysis of National Weather Service and Snow telemetry (SNOTEL) site data in the San Juan Mountains, Rangwala and Miller (2010) detect a rate of warming of 1.8 °F (1 °C) per decade from 1990-2005.

- Winter minimum temperatures increased faster than winter maximum temperatures at lower elevations, while summer maximum temperatures rose faster than summer minimum temperatures at higher elevations.

2.4.2. Evaporation

Evaporation in the Pecos River Basin in New Mexico is generally lower in the mountain headwaters, increasing at lower elevations downstream. Estimated evaporation ranges from 95.10 inches annually at Santa Rosa Reservoir to 114.37 inches annually at Brantley Reservoir (1999-2018 averages). The estimates are based on a combinations of pan evaporation measurements in the spring through fall and a combination of measurements and estimated daily values during the winter months.

2.4.3. Precipitation

Precipitation in the Pecos River Basin is greatest in the mountain headwaters and significantly lower at lower elevations. The basin receives most of its precipitation in spring and late summer storms. Precipitation amounts vary from an annual average of approximately 40 inches in the highest mountains, to over 20 inches in Ruidoso, 14.5 inches in Santa Rosa, and just 12.5 inches in Carlsbad.

2.4.3.1. Spring

In the spring, the interaction between cold, dry air masses to the north and warm, humid air masses to the south originating over the Gulf of Mexico can produce large frontal systems and convective storms. These storms may produce heavy rain, damaging hail, and tornados.

2.4.3.2. Summer

As temperatures increase into summer, prevailing weather patterns associated with the North American Monsoon draw in moisture from the Gulf of Mexico and East Pacific, fueling strong convective storms independent of frontal systems (Figure 12). These monsoon storms typically begin in July and last through September, often producing heavy, localized rainfall of a relatively short duration.

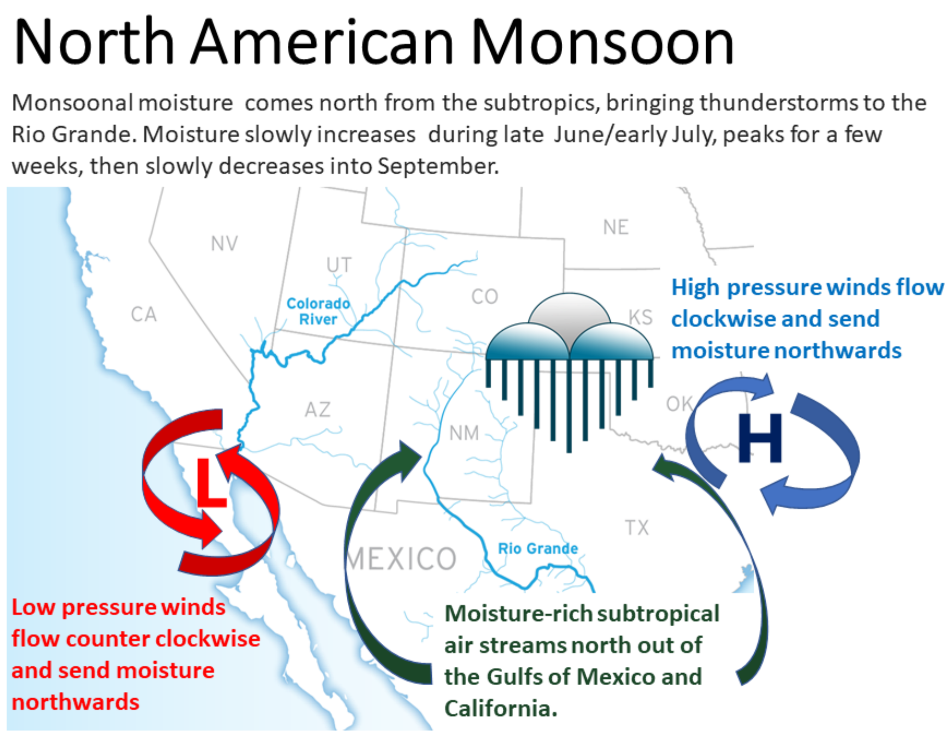


Figure 12. North American monsoon pattern (Reclamation).

Higher elevations average as much as 14 inches of precipitation during this three-month period. However, the amount of precipitation during the monsoon season can vary greatly from year to year.

2.4.3.3. Fall

In the fall, weather patterns associated with the North American Monsoon die out, and frontal systems return to New Mexico. Fall weather can be punctuated by infrequent but intense storms associated with remnant tropical systems, including remnant hurricanes, which can bring high rainfall volumes to the basin.

2.4.3.4. Winter

The Pecos River Basin receives winter precipitation from westerly storms originating over the Pacific Ocean. Most such storms track to the north of the basin, dropping snow mainly in the Sangre de Cristo Mountains. Storms that are exceptionally large or that follow a more southerly track may reach the southern areas of the basin. These storms produce snow in the higher elevations, and steady rain or occasional snow at the lower elevations (see Climate Appendix).

> "El Niño refers to the large-scale ocean-atmosphere climate interaction linked to a periodic warming in sea surface temperatures across the central and east-central Equatorial Pacific. La Niña episodes represent periods of below-average sea surface temperatures across the east-central Equatorial Pacific." National Oceanic and Atmospheric Administration (NOAA) National Ocean Service 2019

Winter precipitation varies considerably from year to year, driven mostly by the El Niño Southern Oscillation (ENSO) cycle, a cyclical variation in sea surface temperatures in the tropical Eastern Pacific Ocean which has global impacts on weather patterns. El Niño and La Niña are opposite phases of the ENSO cycle. During El Niño years, sea surface temperatures in the eastern Pacific Ocean increase significantly, resulting in above-normal winter precipitation throughout the southwestern United States, including the Pecos River Basin. During a La Niña year, winters in the southwestern United States are warmer and drier than normal. From 1971-2012, precipitation experienced statistically significant decreases in every month except for July and October, which experienced no statistically significant changes, and March and December, which both saw statistically significant increases. Overall observed trends in precipitation over the study period amounted to a decrease of approximately 0.785 inches per decade in annual precipitation totals, or well over 3 inches over the length of the study. The largest decreasing trends were in August (-0.263 inches per decade) and September (-0.165 inches per decade) and coincided with decreasing trends in the number of days with >0.1 inches of precipitation. No statistically significant trends were observed in the number of days with >0.5 inches of precipitation or in the number of days with >1.0 inches of precipitation (see Climate Appendix). These data suggest that large storm events are not becoming less frequent, but that light showers during the monsoon season are becoming less frequent.

As the climate warms, precipitation falls less as snow and more as rain, and more of the snow that does build up melts during the winter (rather than during the typical spring snowmelt period). That decreases snowpack (the amount of snow that accumulates over the winter to melt in the spring). Since the 1950s, snowpack has been decreasing in New Mexico. EPA (2017) describes the decreasing snowpack in northern New Mexico, including the Pecos River headwaters.

2.4.3.5. Extreme Events and Drought

Figure 13. CID 2014 flood (CID, all rights reserved).

The basin has always had a highly variable and flashy water supply, characterized by extreme precipitation events (monsoon thunderstorms in the summer and remnants of tropical storms in the late summer and early fall). For example, in 1937, the Pecos River reached 55,200 cfs at Santa Rosa Dam (USGS 1939), a flow rate several hundred times the historical average flow.

> "In addition to possible flooding threats, potentially increasing extreme events could present opportunities for water supply, especially in places where water resources are strained and decreasing snowpack is a vulnerability." Towler et al. 2018

These extreme storm events are a key part of the water supply to the basin, as water produced by major storms can rapidly fill reservoirs and recharge aquifers (Figure 13). See Section 2.2.3. *Surface Water/Groundwater Interactions.*

Droughts are common in New Mexico. However, in recent years, the severity of droughts in the basin, as rated on the Palmer Drought Severity Index (PDSI) as shown in Figure 14 have been increased by warming temperatures.

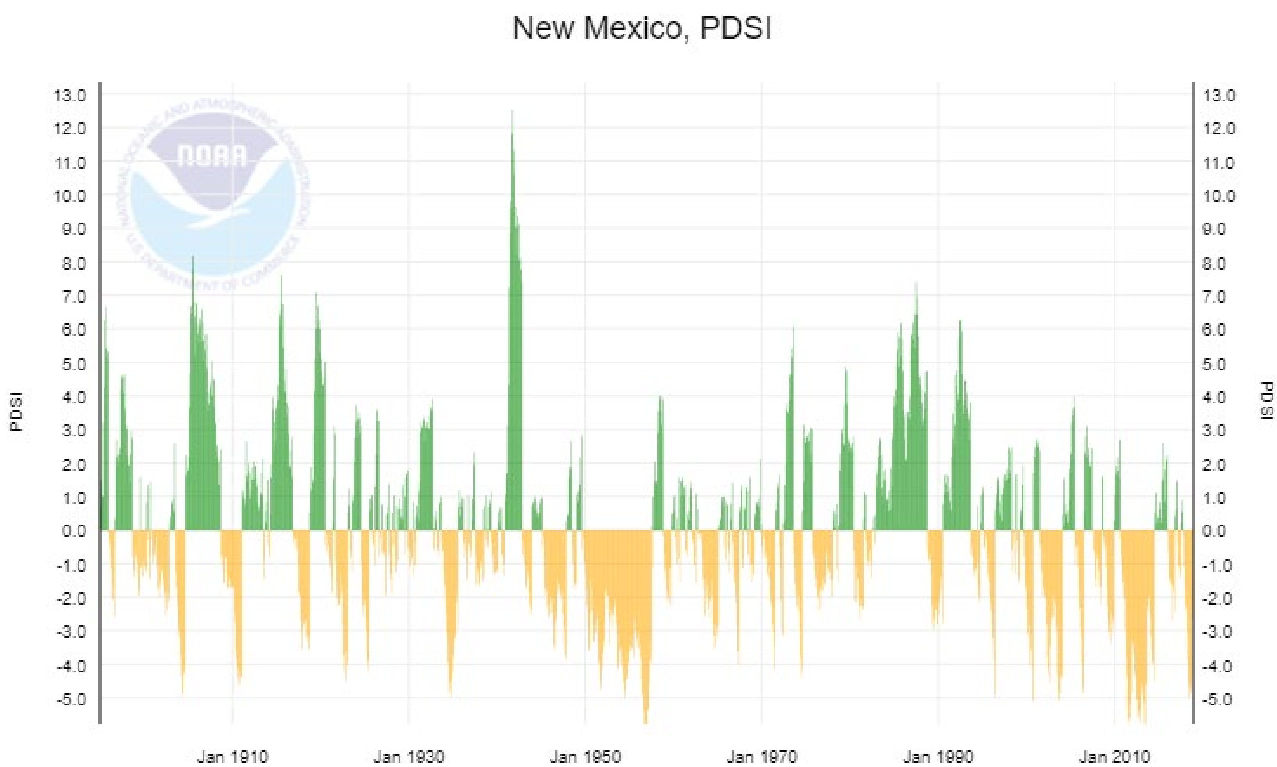
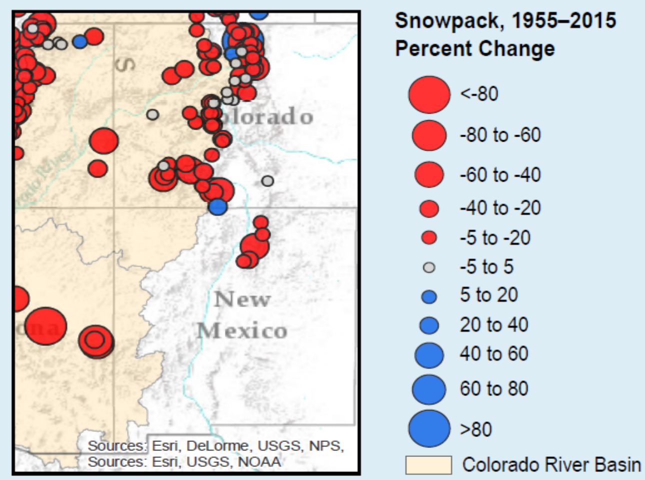


Figure 14. Periods of wet (green) and dry (yellow) years from 1895 to 2018 (NOAA National Centers for Environmental information [NCEI] 2019, used by permission).

2.4.3.6. Recent Changes in Precipitation Timing and Amount

From 1971-2012, precipitation experienced statistically significant decreases in every month except for July and October, which experienced no statistically significant changes, and March and December, which both saw statistically significant increases. Overall observed trends in precipitation over the study period amounted to a decrease of approximately 0.785 inches per decade in annual precipitation totals, or well over 3 inches over the length of the study. The largest decreasing trends were in August (-0.263 inches per decade) and September (-0.165 inches per decade) and coincided with decreasing trends in the number of days with >0.1 inches of precipitation. No statistically significant trends were observed in the number of days with >0.5 inches of precipitation or in the number of days with >1.0 inches of precipitation (see Climate Appendix). This data suggests that large storm events are not becoming less frequent, but that light showers during the monsoon season are becoming less frequent.

As the climate warms, precipitation falls less as snow and more as rain, and more of the snow that does build up melts during the winter (rather than during the typical spring snowmelt period). That decreases snowpack (the amount of snow that accumulates over the winter to melt in the spring). Since the 1950s, snowpack has been decreasing in New Mexico. EPA (2017) describes the decreasing snowpack in northern New Mexico, including the Pecos River headwaters (Figure 15).



Trends in April snowpack in New Mexico and Colorado, 1955–2013. The snowpack has declined at most monitoring sites in both states. Source: EPA.

Figure 15. Trends in snowpack 1955-2013 (EPA 2017, used by permission).

2.5. Wildfires

2.5.1. Potential Impacts from Wildfires

Wildfires can compromise water quality. During active burns, ash can settle on lakes and reservoirs. After fires, burned areas are prone to increased flooding and erosion. Lack of forest cover after a fire can cause more rapid melting of snowpack and earlier runoff, and lack of forest and ground cover can increase runoff rates during storms, causing or exacerbating floods and erosion. Erosion can increase downstream accumulation of sediment and ash in streams, rivers, and reservoirs. Thus, potential impacts from wildfires on the quantity and quality of runoff are considerable and may greatly impact water used for domestic, agricultural, and ecological water supplies. (USGS 2019 [Wildfire]). See Section 2.6.1. *Vegetation* for a description of the upland forests where recent wildfires have occurred.

2.5.2. Recent Changes in Wildfires

The U.S. Global Change Research Program (USGCRP) analyses estimated that the area burned by wildfire across the western United States from 1984-2015 was twice the amount that would have burned under previous climate conditions. Tree death in mid-elevation conifer forests doubled from 1955-2007 due, in part, to climate change (USGCRP 2018). Figure 16 demonstrates the increasing risks of wildfires throughout the Western United States (Arizona, California, Colorado, Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming, as well as New Mexico).

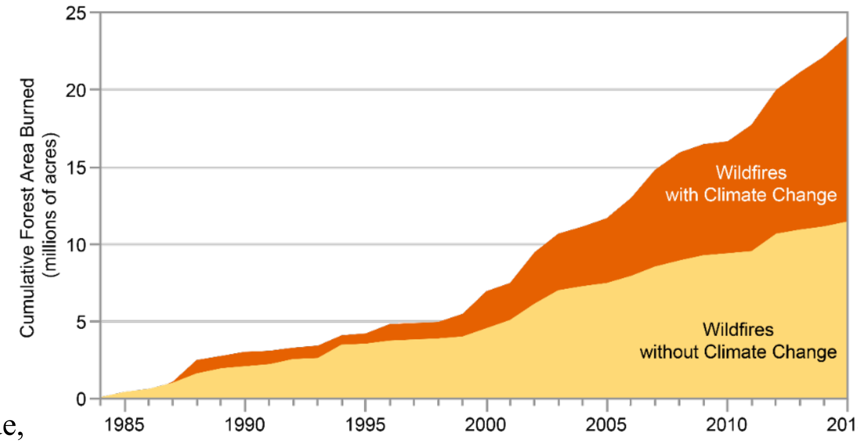


Figure 16. The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western U.S. over that period was twice what would have burned under previous climate conditions. (Gonzalez 2018 adapted from Abatzoglou and Williams 2016, used by permission, all rights reserved.)

2.6. Water Quality

2.6.1. Surface Water Quality Standards

Surface water quality is evaluated using the surface water quality standards in the Federal Clean Water Act and the New Mexico Water Quality Act. The Clean Water Act requires each state to identify and report water bodies that do not meet Federal or State water standards. Most reaches of the Pecos River do not meet these surface water quality standards, while its tributary streams tend to be healthier.

"Water quality management in the Pecos River Basin has long been recognized as a necessary and significant contribution to insuring sustainable human activity within this area of the Southwest. As early as 1942, the National Resources Planning Board stated '. . . For its size, the basin of the Pecos River probably presents a greater aggregation of problems associated with land and water use than any other irrigated basin in the Western U.S.''' New Mexico Environment Department (NMED) 1998.

Water quality in the headwaters is generally very good, but the Pecos River becomes increasingly impaired further downstream (New Mexico Environment Department [NMED] 2018). Throughout the basin, the Pecos River and its tributaries are adversely affected by irrigation return flow, urban runoff, livestock grazing, municipal wastewater treatment plant effluent, and small septic systems. Additionally, trash is washed into the river and its tributaries from populated areas (Stockton 2011).

It is important to note that water quality standards are based on designated uses for the water body, whether it is a stream segment, a lake, or a reservoir. Under the statutes, the New Mexico Water Quality Control Commission (WQCC) first establishes these designated uses for surface water segments in the State. The WQCC then establishes water quality standards according to the designated uses of a stream segment.

Accordingly, the WQCC has established designated uses for stream segments and other water bodies in the Pecos River New Mexico Basin. Such uses include: recreation (primary or secondary contact), wildlife habitat, livestock watering, public water supply, irrigation, and industrial water supply. These designations vary: in the headwaters of the Pecos River, cold water aquatic life is a designated use and so is primary (human) contact; by contrast, in the lower reaches of the Pecos River, warm water aquatic life and secondary (human) contact are designated uses. In addition, thresholds for considering a stream impaired vary; for example, the standard for total dissolved solids (TDS) varies from 250 milligrams per liter (mg/l) in the stretch of the Pecos River above Tecolote Creek, to 20,000 mg/l in the stretch between the Black River and the state line. Stream segments are monitored periodically. Every two years, the WQCC prepares a list of those stream segments that are impaired (i.e., when one or more pollutants prevent a waterbody from meeting its designated use[s]) (NMED 2018). Figure 17 shows the designation for streams within the Pecos River Basin in New Mexico.

2.6.1.1. Above Sumner Reservoir

Most of the Pecos River above Sumner Reservoir, as well as several tributaries to this reach, is classified as impaired due to nutrient loading (nitrogen and phosphorous) and in some cases, *Escherichia coli (E. coli)* bacteria due to municipal wastewater treatment plant discharges, small septic systems, and livestock grazing (NMED 2018). Several stretches of the upper Pecos River and its tributaries are impaired by high water temperatures, largely due to livestock grazing and resulting destruction of riparian vegetation, which increases solar heating of affected streams. Another tributary, Willow Creek, which flows past the inactive Tererro Mine site, is impaired by high salinity and sedimentation. In addition, tissue samples from fish collected in Santa Rosa Reservoir and Sumner Reservoir contain mercury (NMED 2018). However, NMED (2013) observed that "impairments due to some anthropogenic disturbances, such as Tererro Mine, have been corrected, and upgrades at the Village of Pecos wastewater treatment plant (WWTP), Las Vegas WWTP and Santa Rosa WWTP have, or are expected to, improve water quality in the waters receiving their effluent."

2.6.1.2. Below Sumner Reservoir

Downstream of Sumner Reservoir, the relative health of the Pecos River improves for approximately 100 miles before it becomes impaired again for nearly the entirety of its remaining distance to the state line. Most of this distance is impaired by polychlorinated biphenyls (PCB) and dichloro-diphenyl-trichloroethane (DDT). Several tributary streams, (e.g., Rio Ruidoso), are impaired by nutrients, temperature, and turbidity. Fish tissues from fish in and around Brantley Reservoir contain PCBs and DDT (NMED 2018).

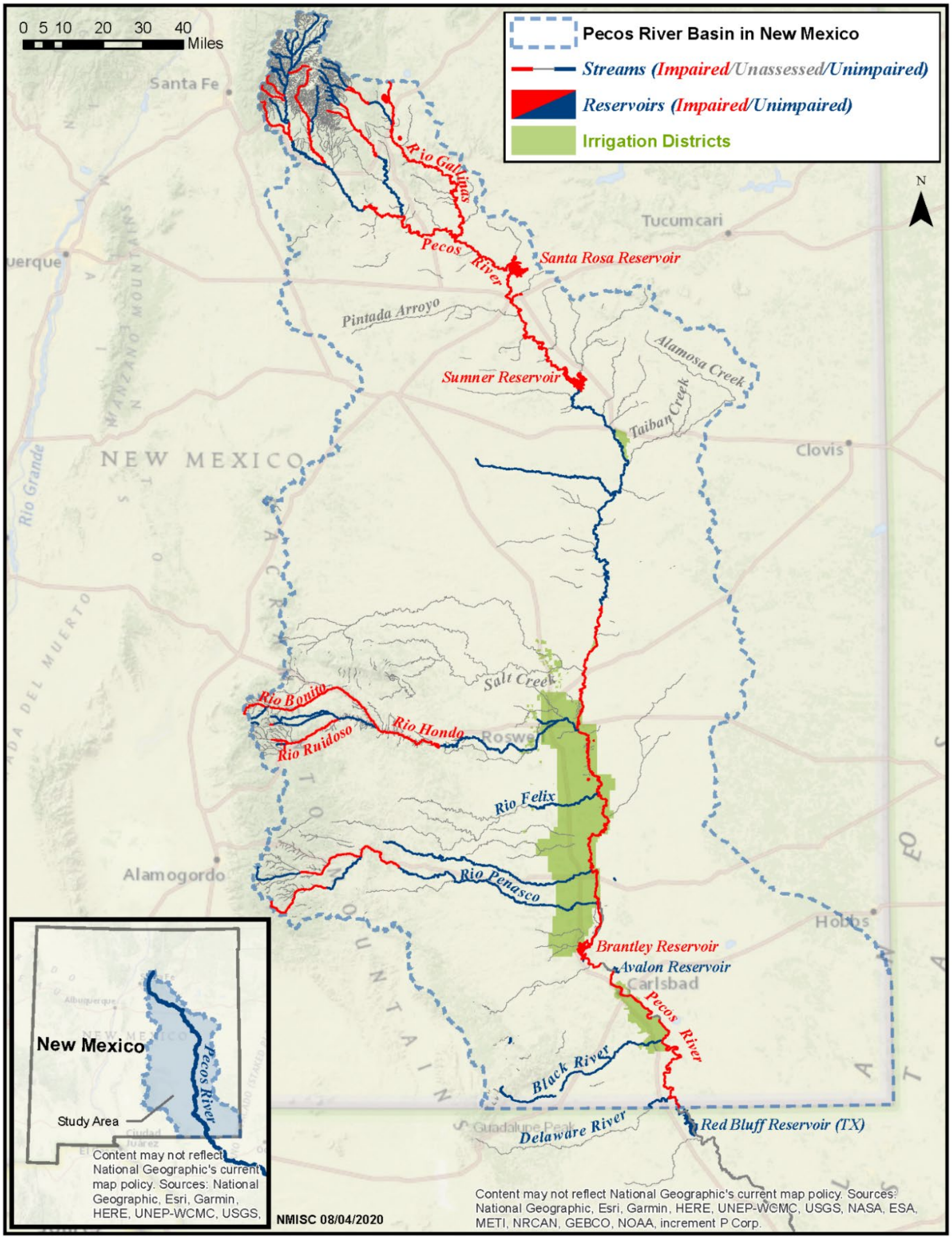


Figure 17. Impaired streams and reservoirs in the Pecos River Basin in New Mexico (NMISC).

2.6.2. Salinity

Water quality is impaired by high salinity in several parts of the basin, and especially in the stretch of the river near Malaga, New Mexico (about 30 miles upstream of the New Mexico-Texas state line). Salinity in the Pecos River is derived from both natural and anthropogenic sources. These sources include saline groundwater as well as agricultural and municipal return flows. At low flows, the river is less capable of diluting saline inflows from these sources, resulting in increased salinization of the Pecos River during drought conditions. However, high salt loading can also occur in high flow conditions; extreme floods can wash large quantities of salt into the river from exposed or near-surface geologic salt deposits (Miyamoto et al. 2007), which are common in parts of the basin. Reservoir evaporation also concentrates dissolved salts and increases the salinity of the river water, another phenomenon that is exacerbated during droughts.

Prior to water resource development on the Pecos River (beginning in the 1880s), higher, fresher stream flows and periodic floods diluted naturally saline groundwater inflows and continuously exported salts from the drainage (Hoagstrom 2009). Hoagstrom further states that hydrological changes that likely contributed to streamflow salinization included: reduced flood frequency and magnitude following the construction of dams to store flood waters; diminished streamflow; increased evapotranspiration; and increased proportions of naturally high-salinity groundwater inflows relative to overall streamflow (as fresher water from upstream tends to be captured by the reservoir network and used for irrigation). Salinization is presently highest where these cumulative impacts were greatest (e.g., Red Bluff Dam to Girvin, Texas).

Finally, if increased streamflow salinity associated with irrigated agriculture occurs, and if higher temperatures cause more water demand, then the threat of salinization due to farming may also increase. In addition, using saltier water to irrigate crops can lead to the salt accumulation in the root zone that degrades soil quality and decreases farm yields.

2.7. Ecological Resources

2.7.1. Vegetation

Vegetation type in the Pecos River Basin is determined primarily by elevation, though there is some variation from north to south as well. Approximately one-fifth of the Pecos Basin in New Mexico is forest or open woodland/savanna, while the remainder is mostly open prairie, scrubland, and desert (Griffith et al. 2006).

The highest peaks of the Sangre de Cristo Mountains, at the northernmost tip of the basin, rise above the treeline (roughly 11,000-12,000-foot msl), supporting alpine tundra communities of hardy grass and forb species. The alpine ecoregion is by far the smallest in the basin, accounting for less than 0.1% of the basin area.

From around 9,000-12,000 feet msl in the Sangre de Cristo, Sierra Blanca, and Capitan Mountains lie areas of thick subalpine forests, dominated by species such as Englemann spruce, blue spruce, aspen, and Douglas fir. Subalpine forests cover a small area of the basin, roughly 1%.

From around 7,000 to 10,000 feet msl in the mountain ranges of the basin lie mid-elevation conifer forests. These forests are typically dominated by ponderosa pine and understory shrubs such as Gambel oak and mountain mahogany. These forests cover roughly 5% of the basin.

From around 5,500 to 8,000 feet msl, in the foothills of the major mountain ranges and on adjacent mesas, lie mixed shrubland/woodlands dominated by pinyon pine, juniper, sagebrush, Gambel oak, and mountain mahogany. These woodlands cover roughly 15% of the basin and thin increasingly from forest to savanna as the elevation decreases and the mountains transition into the Great Plains.

Most of the middle and eastern part of the basin is dominated by short grass and mid-grass prairies, covered mostly by grama grasses and other grass species. Riparian areas provide habitat for cottonwoods, willow, and invasive salt cedar. Areas of degraded or overgrazed land have been taken over by immense fields of cholla cactus. To the east, the grasslands rise onto the high plains, which occupy a narrow strip of land along the eastern edge of the basin atop the Mescalero Escarpment. These grasslands are similar to those further west, but in some areas become moist enough to support dryland farming. These grassland regions make up approximately 52% of the basin.

From Roswell southward, the basin becomes progressively drier as the river descends into the Chihuahuan Desert. These desert areas are dominated by creosote bush, sand sage, mesquite, and other hardy shrubs, with some areas supporting scattered grasslands. Riparian areas again host cottonwood, willow, and salt cedar. As the edge of the desert ascends into the foothills of the Guadalupe Mountains at the southwestern edge of the basin, the desert scrub gives way to a mixture of grassland, sotol and cactus. Chihuahua Desert vegetation makes up approximately 27 % of the basin

Apart from the native vegetation of the region, there are four non-native plants of particular importance:

- **Tamarisk**, also referred to as salt cedar**.** There are currently three species in the genus Tamarix that are invasive in New Mexico: *Tamarix ramosissima* (tamarisk), *Tamarix chinensis* (Chinese tamarisk), and *Tamarix parviflora* (smallflower tamarisk). See Section 2.7.4. *Invasive Species*.

- **Russian Olive** (*Elaeagnus augustifolia*) is another invasive riparian species that is common in riparian areas throughout much of the northern half of the basin. See Section 2.7.4. *Invasive Species*.

- **Alfalfa** (*Medicago sativa*) is the most commonly farmed crop species in the basin. Alfalfa is farmed on over half the land in all three irrigation districts.

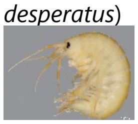
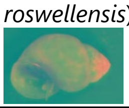
- **Pecans** (*Carya illinoinensis*), though only farmed on a small portion of irrigated cropland, have a high value that makes them one of the most important crops in the basin. The Pecos River Basin in New Mexico alone accounts for nearly 6% of U.S. pecan production (U.S. Department of Agriculture [USDA] 2016).

2.7.2. Threatened and Endangered Species

The Pecos River Basin in New Mexico provides habitat to threatened and endangered species, including species listed under the ESA and the New Mexico Wildlife Conservation Act. Table 1 summarizes species and potential threats (U.S. Fish and Wildlife Service [USFWS] 2006, 2016, 2017 [2016 BiOp], and 2018 and New Mexico Department of Game and Fish [NMDGF] 2016). The threatened and endangered aquatic and riparian species endemic to the Pecos River Basin in New Mexico are vulnerable to increased drying. These species are protected by law and, therefore, Federal agencies must take steps to maintain their habitat. See the Environmental and Recreational Appendix for a description of these species.

Table 1. Listed Species in the Pecos River Basin in New Mexico and Vulnerabilities

Species	Listed Status	Threats
	Birds	
Interior Least Tern 	USFWS listed endangered in 1985	Flooding in rivers harms nests. Lower water tables could reduce population at Bitter Lake National Wildlife Refuge. Altered flow regimes in the river and the changes in elevation at Brantley Reservoir result in habitat loss.
Southwestern Willow Flycatcher *(Empidonax traillii extimus*) 	USFWS listed endangered in 1995	Changing water levels fragment and alter habitat. Eradicating exotic plants, like tamarisk, that provide habitat, without proper restoration of native vegetation, threatens the flycatcher's habitat and its populations.
	Reptiles	
Western river cooter (Rio Grande Cooter) (*Pseudemys gorzugi*) 	NMDGF listed threatened in 2012	Habitat loss and degradation and wildfires, and pollution runoff from oil and gas wells threaten the turtles. They are also killed by recreational hunters and used as bait by fisherman.
	Fish	
Gray redhorse (*Moxostoma congestum*) 	NMDGF listed endangered in 2008	Dams, modification of stream flow patterns, and outbreaks of golden algae have degraded habitat. This has drastically diminished its population in the Pecos River.
Pecos gambusia (*Gambusia nobilis*) 	NMDGF listed endangered in 1975	Depletion of groundwater causes water quality and quantity impacts. Habitat modification by livestock grazing and predation by non-native species are further threats.

Species	Listed Status	Threats
Pecos bluntnose shiner (shiner) (*Notropis simus pecosensis*) 	USFWS listed threatened in 1987 NMDGF listed endangered in 2006	Block releases from reservoirs during summer spawning season carry eggs and larvae into unsuitable habitat. Fish are also impacted by reduced river flow at other times, habitat degradation and fragmentation, and pollution from agricultural runoff.
Pecos pupfish (*Cyprinodon pecosensis*) 	NMDGF listed threatened in 1988	The non-native sheephead minnow displaces this species. Golden algae blooms threaten habitat.
Greenthroat darter (*Etheostoma lepidum*) 	NMDGF listed threatened in 1975	Pumping groundwater and diverting spring surface flows threaten habitat.
Bigscale logperch (*Percina macrolepida*) 	NMDGF listed threatened in 1975	Reduced river flow and diversions reduce flow velocity, and water quality degradation threaten habitat.
		Crustaceans
Noel's amphipod (*Gammarus desperatus*) 	NMDGF listed endangered in 1990	Groundwater pumping and surface water diversions threaten habitat. Other threats include pollution and wildfires.
		Mollusks
Texas hornshell (*Popenaias popeii*) 	USFWS and NMDGF listed endangered in 2018 and 1983 respectively	Habitat is degraded by excessive sedimentation from reduced river flows; impaired water quality due to agricultural and urban runoff and pollution from oil and gas operations and associated vehicular traffic; reduced flows due to diversions and dams. Fish as hosts, so barriers to fish movement also threaten the Texas hornshell.
Koster's springsnail (*Juturnia kosteri*) 	USFWS and NMDGF listed endangered in 2005 and 2000 respectively	Habitat is threatened by groundwater pumping irrigation, municipal water supplies, and oil and gas operations.
Roswell springsnail (*Pyrgulopsis roswellensis*) 	USFWS and NMDGF listed endangered in 2005 and 1983 respectively	Habitat is threatened by groundwater pumping irrigation, municipal water supplies, and oil and gas operations.

Species	Listed Status	Threats
Pecos assiminae (*Assiminea pecos*) 	NMDGF listed endangered in 1983	Habitat is threatened by groundwater pumping for irrigation, municipal water supplies, and oil and gas operations.
Pecos springsnail (*Pyrgulopsis pecosensis*) 	NMDGF listed threatened 1983	Habitat is threatened by groundwater withdrawal for irrigation and oil and gas operations

2.7.3. Environmentally Protected Areas within the Basin

Roughly 46% of the Pecos River Basin in New Mexico is public land, at varying levels of environmental protection. Much of this land is managed by the Bureau of Land Management (BLM) and New Mexico State Land Office for grazing or oil leases, or by the USFS for forestry and recreation. The International Union for Conservation of Nature (IUCN) lists approximately 360,000 acres (2.4%) of the Pecos Basin in New Mexico as protected land in its World Database on Protected Areas, including five major wilderness areas, two national parks, two national wildlife refuges, and several other protected areas (IUCN 2020). Figure 18 shows protected areas within the basin, and the Environmental and Recreational Appendix provides a detailed description of these areas.

2.7.4. Invasive Species

The most prevalent invasive plant species in the study area are tamarisk and Russian olive. The prevalence of these invasive species will likely make water management more difficult in a warmer and drier climate.

Tamarisk. In the study area, tamarisk (*Tamarix ramosissima*), also called salt cedar, is the most common of the invasive species in the genus *Tamarix.* Tamarisk is a small tree or shrub, about 3 to 15 feet high, with deep roots, that grows in riparian ecosystems. Native to Asia, tamarisk was introduced in the United States in the 1930s as an ornamental shrub. It is hardy, drought-tolerant, salt-tolerant, reproduces rapidly, and has successfully invaded riparian ecosystems in the western United States, displacing native cottonwoods and willows. Tamarisk has invaded large areas of the riparian zone of the Pecos River for most of the river outside of its headwater region. It dominates the banks of the river roughly from the Acme Gage to the Texas state line.

Reclamation has implemented clearing and maintenance operations to remove tamarisk infestations in the Pecos River Basin in New Mexico from 1967 to 1982, a project was conducted to replace the tamarisk with saltgrass (*Distichlis Spicata*). Saltgrass is a native perennial about 15 to 35 inches high (Quigley 2013). The goals of this project were to salvage water and to double the base flow to the Pecos River, but these goals were not achieved, as no net increase in base flow or reduction in salinity was observed in the lower Pecos River. In the early 2000s, *Diorhabda* beetles, which feed on salt cedar, were introduced to the Pecos Basin. Studies have indicated that this biological approach can provide effective control of salt cedar (DeLoach et al. 2011).

Russian Olive. Russian olive (*Elaeagnus augustifolia*) is a tall deciduous shrub or tree, up to 45 feet (15 meters) tall, with olive-shaped fruit. It grows in a wide range of habitats, including mountains, plains, and desert, but it is most common in floodplains and along stream banks. It is native to Eastern Europe and Asia and was introduced in the United States in the early 1900s. It is common in the study area (Stockton 2011).

Giant Reed *(Arundo Donax*). This bamboo-like perennial grass infests riparian areas, floodplains, and irrigation ditches. Physical removal must remove rhizomes and stem fragments, or it will regenerate. Herbicides are effective, especially when used in conjunction with cutting. It has been found in southern New Mexico and is on the New Mexico State University's (NMSU) watch list for invasive species (NMSU 2019).

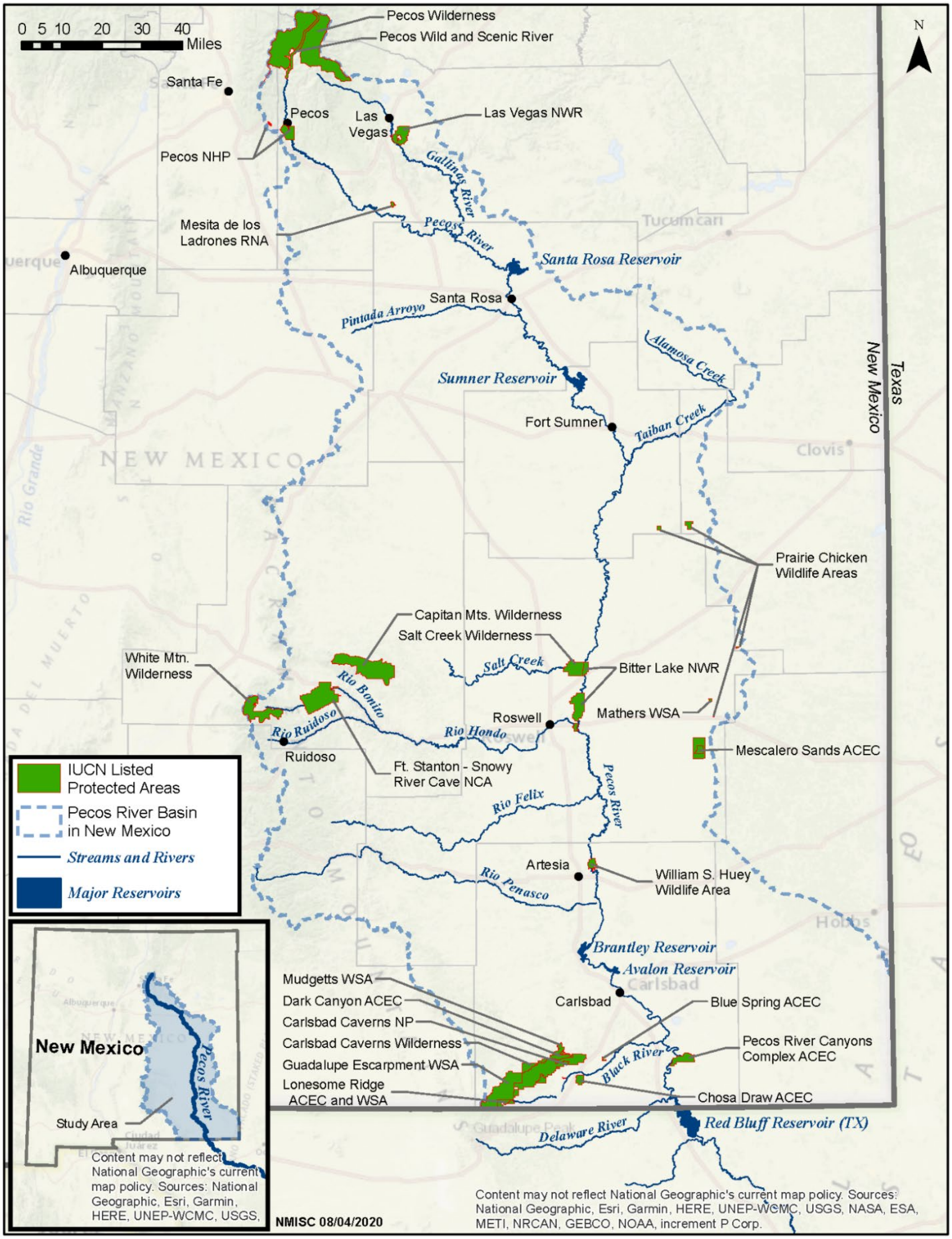


Figure 18. IUCN listed protected areas in the Pecos River Basin in New Mexico (NMISC).

2.8. Recreation

The Pecos River Basin in New Mexico has extensive recreational opportunities, many of them based around the Pecos River itself. Over 40 percent of the basin is public land, including numerous recreational areas. Locations for outdoor recreation within the basin include: seven New Mexico State Parks and three State Historic Sites, two National Park Service units, three National Forests, two National Wildlife Refuges, five US Wilderness Areas, seven BLM recreation areas, one U.S. Wild and Scenic River, and numerous municipal parks within the river corridor (Figure 19).

Additionally, reservoirs in this study provide ample opportunities for swimming, boating, and fishing (see Section 3.2. *Water Development: Dams and Reservoirs*). Throughout the river corridor, opportunities for hunting, fishing, and wildlife viewing abound. See the Environmental and Recreational Appendix for further description of recreation in the Pecos River Basin in New Mexico.

Many of these recreational activities, even those not directly tied to the water, are potentially at risk from any reductions in precipitation or other alterations to the Pecos River Basin's water cycle:

- Reductions in reservoir levels will negatively impact water sports recreation on those reservoirs.

- Drying wetlands will diminish wildlife watching opportunities; drought conditions could lead to reduced game populations for hunters.

- Snowpack reductions will significantly impact downhill and cross-country skiing in the basin.

- Changes in runoff flow and timing could shorten fishing seasons in headwater streams.

Changes to recreational activity availability could result in substantial impacts to the region's tourism sector.

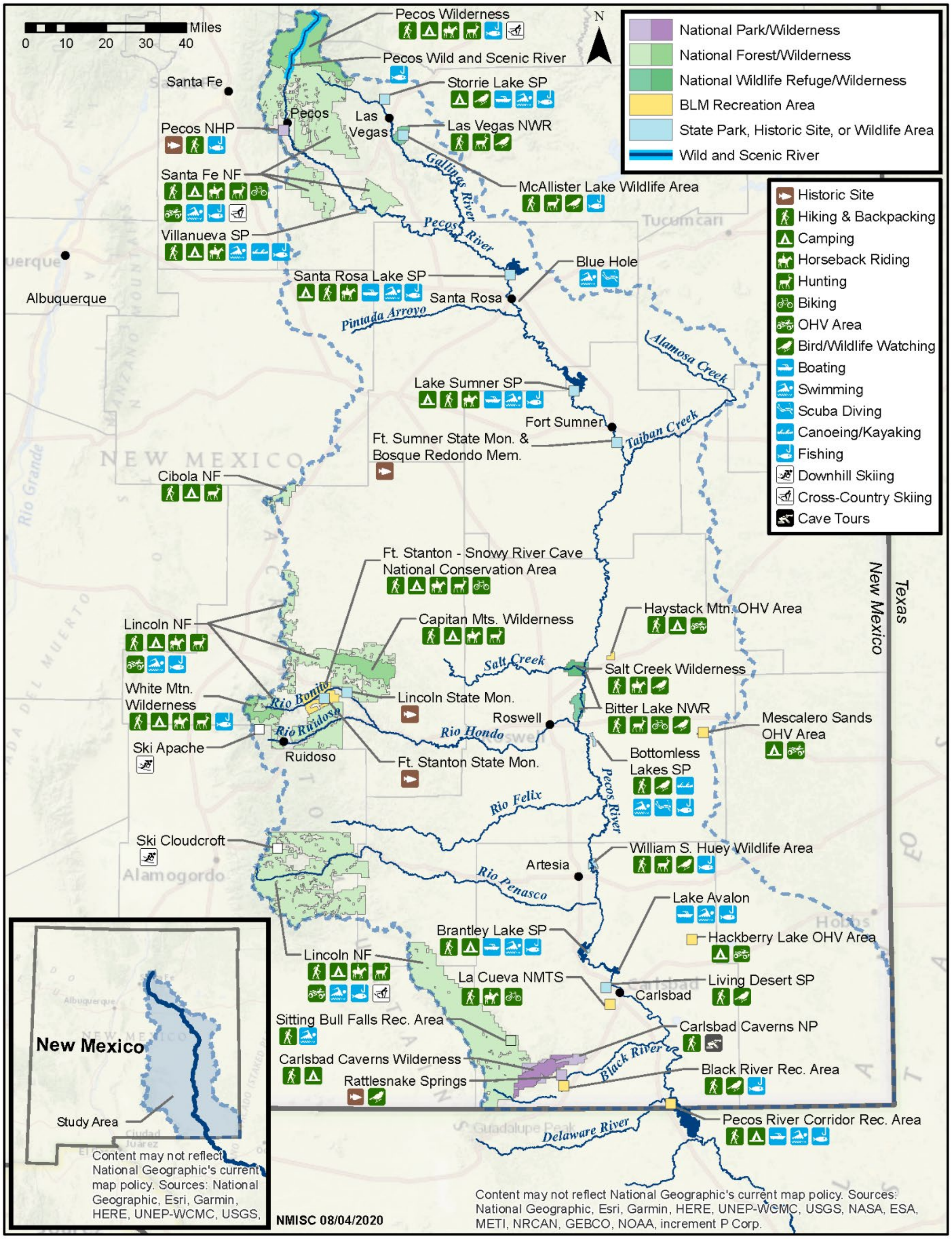


Figure 19. Recreational opportunities in the Pecos River Basin in New Mexico (NMISC).

3. Water Operations, Development, and Use

This section describes water uses and water resources in the study area for the Pecos River Basin, New Mexico Basin Study, including consumptive uses that deplete water from the river system, such as irrigation and municipal use, and the major infrastructure used to provide water to many users, and to regulate and manage streamflow.

As of 2010, water use in the basin is primarily from agriculture and groundwater accounts for over half of that as shown in Table 2. Note that these numbers do not consider the recent oil boom, which has caused a surge in the use of surface and groundwater for hydraulic fracturing in the Pecos Basin, particularly south of Carlsbad.

Table 2. Summary of Withdrawals in the Pecos River Basin in New Mexico, 2015
(in acre-feet) (NMOSE 2019)

Total 601,821 acre-feet				
Groundwater	356,410 (59%)		Surface Water	245,411 (41%)
Irrigated Ag.	278,316 (78%)		Irrigated Ag	190,175 (77%)
All Other	78,095 (22%		Evaporation	42,821(17%)
			All Other	12,415 (5%)

3.1. Regulation of Water in the Pecos River Basin in New Mexico

"River operations on the regulated portion of the Pecos River are largely a function of the conglomeration of political and institutional framework provided by State of New Mexico water law, New Mexico State Engineer regulations, federally mandated laws or constraints (like ESA and flood control), and agricultural practices within the broad spectrum of organized farm communities or irrigation districts." Stockton 2011

Regulation of water in the Pecos River Basin in New Mexico must balance several competing demands. Farmers require water for irrigation; municipalities must supply water to their businesses and residents; industrial facilities, mines, and oil and gas wells require water for their operations; and threatened and endangered aquatic and riparian species, protected under the ESA, depend on continuous river flows to survive. In addition, water users in the State of Texas are entitled to a share of the water of the Pecos River per the terms of the 1948 Pecos River Compact (Compact) and the U.S. Supreme Court's 1988 Amended Decree (1988 Decree). The NMOSE has authority over the supervision, measurement, appropriation, and distribution of all surface and groundwater in the state, including streams and rivers that cross state boundaries.

The flow of the Pecos River can vary greatly, both spatially, seasonally, and due to droughts or flooding. Parts of the river are perennial regardless of drought conditions, while other reaches can go dry in extreme droughts, and some reaches are dry the majority of the time. This variability can make meeting the demands of Pecos River Basin water users more difficult. Consequently, the water of the Pecos River in New Mexico is monitored and closely managed by several Federal and State government agencies.

3.1.1. Water Rights and Priority Administration in New Mexico

New Mexico, like most Western states, manages water rights through a system known as prior appropriation. In this system, water rights are ranked by their priority date, based on when the process of putting the rights to beneficial use was first initiated. In times of water shortage, the earlier or "senior" rights-holders are entitled to receive the full amount of their water rights before the newer or "junior" rights may be exercised. The regulation of water-rights priority is known as priority administration, and is initiated when a senior rights-holder makes a "priority call" to the NMOSE to administer by priority, which entails the State Engineer ordering junior users to stop diverting water until the senior users receive sufficient water.

Determining priorities involves a lengthy and complex legal process of adjudicating water rights. In parts of New Mexico, water rights priorities have yet to be fully adjudicated, complicating priority administration. To address this issue, the State Engineer developed rules known as the Active Water Resource Management (AWRM) regulations, which permit the State Engineer to administer priorities based on other evidence of priority dates until such time as the rights are fully adjudicated. The AWRM regulations also allow water users to develop alternatives to priority administration, termed alternative administration. Water rotations, shortage sharing, and other mutual agreements overseen by the State fall under the umbrella of alternative administration and can help rights-holders avoid having to make a priority call. In general, the State has generally preferred to promote alternative administration, when possible, and has viewed priority administration as a last resort.

Priority administration in the Pecos is particularly complex. In part, this is because the Pecos Basin has not been fully adjudicated. In addition, an equally problematic challenge arises from the nature of the hydrology and settlement patterns of the basin. Among major water users, the Carlsbad and Fort Sumner areas were settled first, and the CID and FSID have relatively senior priorities, while Roswell and its surroundings were settled somewhat later. Therefore, water-rights within the PVACD are generally junior to the other irrigation districts. Because FSID is upstream from PVACD, its seniority over PVACD poses no difficulties. However, CID, a senior surface water district, is ldownstream of PVACD, a junior groundwater district. Should CID initiate a priority call, PVACD ceasing diversions cannot rapidly enable surface flows to reach CID. A delay will occur before increased baseflows to the Pecos become useable by CID. Such a priority call would likely need to be extended for a multi-year period to achieve the desired effect.

3.1.2. 1948 Pecos River Compact

After decades of conflict, in 1945 Texas and New Mexico began negotiations on a compact to allocate the waters of the Pecos River between the two states. Representatives from both states formed a Compact Commission. In January 1948, the Compact Commission's engineering advisory committee submitted a report that, among other things, described in detail the hydrologic conditions of the Pecos River. The engineering advisory committee also drafted a "Manual of Inflow-Outflow Methods of Measuring

Changes in Stream-Flow Depletion" containing charts and tables to be used in determining how much water Texas would be entitled to.

The Pecos River Compact was signed by both states on December 3, 1948, and ratified by both State legislatures and approved by Congress in 1949. The key provision of the Compact, Article III(a), states that "New Mexico shall not deplete by man's activities the flow of the Pecos River at the New Mexico-Texas state line below an amount which will give to Texas a quantity of water equivalent to that available to Texas under the 1947 condition."

"The Pecos River Compact is unique in that it provided that the compacting states would act cooperatively to improve water quality and salvage wasted water to improve the limited, diminishing supply." Kraai 1993, p. 92

3.1.3. U. S. Supreme Court Decree

During the decades following the signing of the Compact, the Pecos River Commission was unable to consistently agree on how to perform the accounting necessary to determine New Mexico's compliance. Consequently, disputes arose between New Mexico and Texas. In 1974, Texas filed a complaint with the U.S. Supreme Court. Texas alleged that New Mexico had breached its obligations under Article III(a) of the Compact "by countenancing and permitting depletions by man's activities within New Mexico to the extent that from 1950 through 1972 there has occurred a cumulative departure of the quantity of water available from the flow of the Pecos River at the Texas-New Mexico State Line in excess of 1,200,000 acre-feet from the equivalent available under the 1947 condition." *Texas v. New Mexico*, 462 U.S. 554, 562 (1983). Texas sought a decree ordering New Mexico to deliver water in accordance with the Compact. The Court appointed a Special Master in the case to determine an appropriate methodology for calculating deliveries, calculate the amount of the alleged under-delivery, and recommend a remedy. In 1986, the Special Master provided a report concluding that New Mexico had chronically delivered insufficient water to Texas in most years since the Pecos River Compact had been signed, amounting to a shortfall of 340,100 acre-feet (as of 1983), recommending an accounting manual (i.e., the Pecos River Master Manual) for the annual calculation of New Mexico's delivery obligations, recommending the appointment of a Federal River Master to administer the annual accounting and that New Mexico repay all underdelivered water within ten years.

In 1987, the Supreme Court, accepted the Special Master's findings regarding New Mexico's historical under-deliveries, as well as his recommendations regarding adoption of a River Master Manual and appointment of a River Master. The Court did, however, agree with New Mexico that remedies other than repayment of the shortfall in water could be considered, and returned the matter to the Special Master for recommendations as to whether a monetary repayment should be allowed, and, if so, how much New Mexico should be required to pay. Ultimately, New Mexico and Texas agreed that New Mexico would be permitted to remedy its shortfall (which had reached 385,800 acre-feet through 1986) through payment of $14 million to Texas. In 1988, the Court issued an amended decree (1988 Decree) which established the Federal River Master, who is tasked with determination of New Mexico's annual delivery obligations to Texas in accordance with a River Master Manual, which includes updated inflow-outflow methods. New Mexico was also prohibited from incurring any net water debt to Texas, though it was permitted to accumulate a net credit. Following any year of net under-delivery, New Mexico is required to repay Texas with water within nine months of receipt of the River Master's final report showing a net debit for the prior year.

3.1.4. 2003 Pecos Settlement Agreement

In the first fifteen years following the 1988 Decree, New Mexico had considerable difficulty meeting its Compact obligations, especially in the late 1990s and early 2000s. Much of the flow of the Pecos River is impounded in reservoirs for CID use, limiting the efficacy of state measures to increase water supplies, as any water savings made upstream of CID. This effectively created additional water for CID, rather than for deliveries to Texas. In addition, disputes over water use and administration of priority rights increased among water users within New Mexico. In the early 2000s, the major water users in the basin began to negotiate a combined resolution of these issues.

> Although additional drought contingency measures are needed, the Settlement's achievements are remarkable and laid the groundwork for continued collaborative, creative, and effective water resources management in the Pecos Basin.

These discussions led to the Pecos Consensus Plan, conceived and refined by a broad spectrum of Pecos Basin stakeholders over about two years. The outcome of this plan was the creation of the 2003 Pecos Settlement Agreement (Settlement), which was ultimately signed on March 25, 2003 by NMISC, NMOSE, PVACD, CID, and Reclamation (NMISC et al. 2003). The objectives of the Settlement include:

- Permanent compliance with the Pecos River Compact and 1988 Amended Decree
- An increased and more stable water supply for CID
- A reduced likelihood of a priority call by CID against junior groundwater pumpers, primarily within PVACD (calls were made in 1976 and 2013)
- Decreased consumptive water use, resulting in an improved hydrologic balance in the Pecos River Basin

The Settlement consists of several measures to achieve these objectives, including:

1. **Water Rights Purchases:** The Settlement required NMISC to acquire the water rights appurtenant to a minimum of 11,000 acres of irrigated land in the Pecos River Basin in New Mexico. These acquisitions would reduce overall depletions and thus increase river flows. State acquisitions to date include about 4,500 acres in CID and 7,500 acres in the Roswell Artesian Basin. State-acquired CID water rights are used for delivery to Texas under certain conditions but can continue to be used by CID otherwise. State-acquired Roswell Basin artesian groundwater rights are used under certain conditions to augment supplies for CID and may be used to augment deliveries to the state-line to help fulfill Compact obligations.

2. **Construction of Augmentation Well Fields:** The Settlement also required NMISC to construct river augmentation well fields with a combined minimum capacity of 15,750 acre-feet per year. NMISC's primary well field, the Seven Rivers Augmentation Wellfield, is adjacent to Brantley Reservoir. A second well field is upstream near Lake Arthur. These NMISC augmentation wells have been added as points of diversion for state-purchased Roswell Basin artesian groundwater rights. The Settlement prescribes specific conditions under which augmentation pumping is required either for augmentation of CID's irrigation supply or for Compact compliance.

3. **CID Settlement Releases:** As part of the settlement, CID is required to release water associated with the state-acquired water rights under certain conditions, to help the state meet its state-line delivery obligations. Required releases by CID depend on CID's project supply (essentially, the effective amount of water in Carlsbad Project storage), and the amount of New Mexico's cumulative Compact credit.

Delivery of State-Owned CID Water Rights to Texas

If New Mexico credit is less than 50,000 acre-feet, then CID can use state-purchased water rights until their project supply exceeds 50,000 acre-feet, then delivery to the state line is required.

If New Mexico credit is equal to or greater than 50,000 acre-feet, then CID can use state-purchased water rights until their project supply exceeds 90,000 *acre-feet*, then delivery to the state line is required.

If New Mexico credit is equal to or greater than 115,000 acre-feet, then CID can use state-purchased water rights up to their maximum allotment of 3.697 acre-feet per acre and no state-line delivery is required.

The Settlement has successfully supported New Mexico's Compact compliance thus far, ensuring local control of Pecos River water administration. New Mexico's cumulative Compact credit increased from 6,900 acre-feet in 2003 to over 150,000 acre-feet by 2018. Of that credit, about 75,000 acre-feet is directly attributable to delivering state-owned CID water-rights to the river. Also, water supplies for CID have been increased, with almost 44,000 acre-feet pumped from NMISC's river augmentation wellfields for CID, and additional indirect gains for CID as a result of NMISC water rights acquisition in the PVACD. Overall, state-acquired water rights have helped reduce water withdrawals from the Pecos River Basin, restoring some hydrologic balance to the system.

Despite the significant progress achieved due to the Settlement, water supply challenges remain. The 2011-2013 drought was one of the most severe on record, and the various measures imposed by the Settlement proved insufficient to prevent CID from issuing a priority call in 2013 due to inadequate supplies. While the Settlement has been mostly successful apart from this anomalously severe drought, the experience of this drought indicates that, should conditions change in the future, and such droughts become more common, balancing the demands of the basin's water users while continuing to comply with the Compact may become a more difficult task.

3.2. Water Development: Dams and Reservoirs

The U.S. Army Corps of Engineers (USACE) and Reclamation manage flood control and conservation storage in four reservoirs as part of the Carlsbad Reclamation Project: Santa Rosa, Sumner, Brantley, and Avalon Reservoirs (Table 3). Together, these four reservoirs are permitted to store up to 176,500 acre-feet of irrigation water as a conservation pool for use by CID.

Table 3. Summary of Reservoirs on the Pecos River in New Mexico

	Santa Rosa Reservoir	**Sumner Reservoir**	**Brantley Reservoir**	**Avalon Reservoir**
Owner	USACE	Reclamation	Reclamation	Reclamation
Purpose	Flood control, irrigation storage	Flood control, irrigation storage	Flood control, irrigation storage	Irrigation storage, reregulation for Brantley
Entitlement Storage for Irrigation (acre-feet)	99,763	32,871	40,000	3,866
Minimum Pool (acre-feet)	0	2,500	2,000	600
Estimated Sediment Accumulation Since Last Survey (acre-feet)	0	546	374	0
Total Conservation Storage (acre-feet)	99,763	35,917	42,374	4,466
Flood Control Storage (acre-feet)	438,364	128,565	414,468	NA
Conservation Elevation (feet)	4,749.55 (NAVD 88)	4,260.88 (NAVD 88)	3,256.27 (NAVD 88)	3,177.40 (Reclamation)

Note that these numbers from 2017 were used in models and do not account for potential further sediment accumulations.
NAVD = North American Vertical Datum

However, this volume is only a small fraction of the reservoirs' total capacity; Santa Rosa Reservoir, Sumner Reservoir, and Brantley Reservoir all provide significantly more storage in their flood control pools (the maximum volume of water that can be stored for flood control purposes) than they do for irrigation. Any storage space above the conservation pool is reserved for flood control.

While Reclamation owns Sumner, Brantley, and Avalon Dams, under normal conditions, CID performs operations and maintenance of these dams and reservoirs. Under flood conditions, however, USACE assumes operation of Sumner and Brantley Dams.

Note that the system does not have enough permitted water storage capacity to consistently ensure adequate volumes for CID users over multiple years (see Section 3.3.3. *Carlsbad Irrigation District*).

3.2.1. Santa Rosa Dam and Reservoir

Santa Rosa Reservoir, the most upstream reservoir on the Pecos River, lies 7 miles north of the city of Santa Rosa in Guadalupe County. USACE owns and operates this dam (Figure 20). The authorized uses for Santa Rosa Dam and Reservoir include flood control and storage of irrigation water for Reclamation's Carlsbad Project. Congress authorized construction of the dam in the Flood Control Act of 1954. USACE completed construction of Santa Rosa Dam (originally Los Esteros Dam) in 1979, and the dam began operations in 1980. It is a rock-fill and earth dam, with a separate spillway cut through rock.

Figure 20. Santa Rosa Dam (Reclamation).

The reservoir is used by the public for recreation, including boating and fishing. It is adjacent to the Santa Rosa Lake State Park.

3.2.2. Sumner Dam and Reservoir

Sumner Reservoir (Figure 21) is 12 miles northwest of the town of Fort Sumner in De Baca County, and about 55 river miles downstream of Santa Rosa Dam. Reclamation began construction of the dam (originally called Alamogordo Dam) in 1935 and completed construction in 1938. It was the primary upstream storage facility on the Pecos River for the Carlsbad Reclamation Project until Santa Rosa Dam was completed in 1980. Sumner Dam is owned by Reclamation and operated by CID. It is a rock-fill and earth dam with a concrete spillway.

Figure 21. Sumner Dam (Reclamation).

The reservoir is adjacent to Sumner Lake State Park and is used for public recreation, including swimming, boating, water skiing, and fishing.

3.2.3. Fort Sumner Diversion Dam

Fort Sumner Diversion Dam (Figure 22) is about 3 miles northwest of the town of Fort Sumner, in De Baca County, about 17 river miles downstream of Sumner Dam. Reclamation began construction of the dam in early 1950, replacing a privately-owned diversion dam, and competed construction in 1951. The dam is owned by Reclamation and operated by FSID. The dam diverts water from the Pecos River directly into the ID irrigation canal. here is no reservoir.

Figure 22. Fort Sumner Diversion Dam (Reclamation).

3.2.4. Brantley Dam and Reservoir

Figure 23. Brantley Dam (Reclamation).

Brantley Reservoir is about 13 miles northwest of the city of Carlsbad, in Eddy County, and about 230 river miles downstream of Sumner Dam. In the Reclamation Project Authorization Act of 1972, Congress authorized construction of the dam to replace the aging McMillan Dam. Reclamation completed construction of the Brantley Dam in August 1988. The dam is owned by Reclamation and operated by CID. It is a rock-fill and earth dam with a concrete center spillway (Figure 23).

The reservoir is partly surrounded by Brantley Lake State Park and is used for public recreation.

3.2.5. Avalon Dam and Reservoir

Figure 24. Avalon Dam (Reclamation).

Avalon Reservoir (Figure 24) is 5 miles north of the city of Carlsbad, in Eddy County, and about 12 river miles (16 kilometers) downstream of the Brantley Dam. The original Avalon Dam was constructed in 1889 by the Pecos Irrigation and Investment Company. That dam was destroyed by a flood in 1893, rebuilt in 1894, destroyed by a flood again in 1903, and partially rebuilt—unsuccessfully—in 1905. Reclamation then took over the project, completing the reconstruction in 1907. (Stockton 2011, p. 47 and Hall 2002, pp. 28-38).

The dam is owned by Reclamation and operated by CID. It is primarily used to regulate deliveries of water into the CID main canal. Avalon Reservoir is open to the public for recreation and is used for boating and fishing.

3.2.6. Reservoir Evaporation

To estimate reservoir evaporation on the Pecos River, there are Class A evaporation pans at Santa Rosa, Sumner, and Brantley Dams. As Avalon Reservoir is close to Brantley Reservoir, and has no evaporation pan of its own, Avalon Reservoir's pan evaporation rate is assumed to be equivalent to that at Brantley Reservoir. The evaporation pans are not maintained year-round. No recordings are taken at Brantley or Sumner Reservoirs' evaporation pans from November through February, while Santa Rosa Reservoir's evaporation pan takes no recordings from November through March. Very little evaporation occurs during the winter months, and pans could freeze. Evaporation data for winter months during a typical year was taken from other measurements, and an average value was used in this study's modeling for reservoir evaporation during November through February.

- Santa Rosa Reservoir averages a lower pan evaporation than the other reservoirs with an average daily April through October pan evaporation of 0.33 inches per day (based on 2000-2017 data from Reclamation's Hydrological Database [HDB]).

- Sumner Reservoir and Brantley Reservoir have similar pan evaporation rates, with both averaging a March through October pan evaporation of approximately 0.38 inches per day (based on 2000-2017 data from HDB, Brantley Reservoir's record is missing data for 2006-2014).

Wind is a key driver of reservoir evaporation. In this basin, there are typically high winds in the spring. However, the impacts of these winds on reservoir evaporation have not yet been quantified.

3.3. Irrigation and Conservancy Districts

In 2010, approximately 135,000 acres of land were irrigated in the study area downstream of Sumner Reservoir. Of this acreage, roughly 25,000 acres were irrigated fully or partially from surface water supplies. Two surface water irrigation districts, FSID and CID, divert surface water from the Pecos River. The remaining 110,000 acres were farmed using groundwater from wells in the PVACD within the Roswell Artesian Basin.

In addition, almost 15,000 acres of farmland are irrigated upstream of Sumner Reservoir (NMOSE 2013). This land is not situated within the extent of this study's modeling scope and is therefore not discussed in this report. These farms include numerous acequias, culturally important community irrigation systems with deep roots in ancient Pueblo and Spanish tradition "water democracies" (University of New Mexico, Utton Center 2014). Additional irrigated land, located in the Rio Hondo and Rio Peñasco valleys and elsewhere, is excluded from consideration for similar reasons. Other water users are discussed in more detail in Section 3.4. Although this report does not specifically address or discuss these water users, the information presented below will hopefully also help these water users to better adapt to changing conditions in the basin.

Because changing temperatures will affect the amount of water available for diversion from the Pecos River, increasing temperatures will more likely than not decrease the amount of water available for irrigated agriculture in the region while also increasing crop demands.

3.3.1. Fort Sumner Irrigation District

3.3.1.1. Location

Fort Sumner Irrigation District (FSID) is the most upstream irrigation district on the Pecos River, located below Sumner Dam. FSID is downstream of the Village of Fort

Sumner on the east bank of the Pecos River, about 75 miles north of Roswell and about 20 river miles downstream of Sumner Reservoir. It extends southeast from the town of Fort Sumner for about 9 miles along the east side of the Pecos River (Figure 25). Fort Sumner is the county seat and the only incorporated municipality in DeBaca County.

3.3.1.2. Historical Operations

The Fort Sumner Project supplies irrigation water to FSID, which currently irrigates roughly 6,500 acres of land on the east side of the Pecos River (NMOSE 2013). As of 2010, alfalfa was by far the most widely grown crop in the irrigation district, grown on over 5,000 acres, followed by pasture, wheat, and corn (NMOSE 2013). Crop patterns have changed over the years; in the 1970s, the main crops in FSID were cotton, forage crops, and pasture for cattle and sheep (Bell 1997).

FSID timeline is:

- Some lands within the FSID service area were first irrigated as early as 1863, and most of the district area has been irrigated continuously since 1907.

- In 1903, a consortium of local farmers, the predecessors to FSID, filed papers establishing their appropriation of 55 cfs of water from the Pecos River.

- In 1906, the farmers formed the Fort Sumner Land and Canal Company and transferred their water rights to this company. The company developed an irrigation system, including a dam and main canal, which was completed in 1906 and began operation in 1907 (Bell 1997).

- In 1918, FSID was organized under New Mexico law to acquire the irrigation works and water rights owned by the Fort Sumner Land and Canal Company (Bell 1997 and Holdeman 2018).

- In 1919, NMOSE granted approval for farmers in the Fort Sumner area for 120 cfs of Pecos River water to irrigate about 10,000 acres of land (Littlefield 1990). In 1933, FSID was adjudicated, through the United States v. Hope Community. Ditch Association, No. 712 Equity, Final Decree 1933 (Hope Decree), the right to divert up to 100 cfs of Pecos River water during the irrigation season (March 1 to October 31) and two additional periods, not to exceed eight days each, between November 1 and February 28. The diverted water could be used to irrigate a maximum of 10,999 acres of land (Bell 1997).

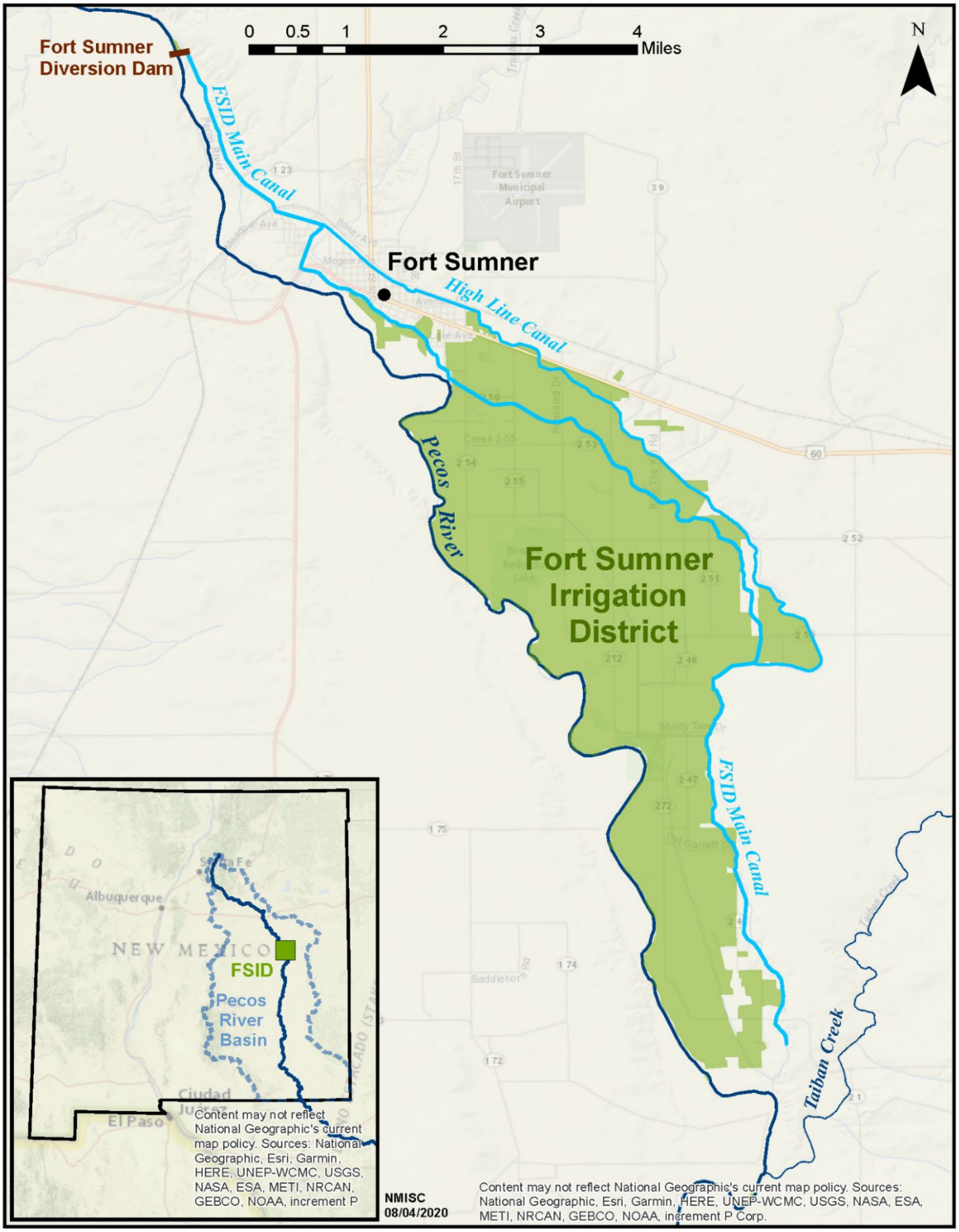


Figure 25. Fort Sumner Irrigation District map (NMISC).

The construction of Alamogordo and Los Esteros Dams (now Sumner and Santa Rosa Dams) upstream of FSID in 1937 and 1979 significantly altered the flow regime of the river at the FSID diversion point (Reynolds 1979). Following the completion of Los Esteros Dam and commencement of CID storage in the reservoir, in 1979 NMOSE outlined the procedure that would be used to determine and administer FSID's water right (Reynolds, 1979). This determination process was revised by the NMOSE in 1990 (NMOSE 1990).

3.3.1.3. Current Operations

FSID has no storage facilities or rights for storage but maintains an entitlement to divert up to 100 cfs of the "natural flow" of the Pecos River (Reynolds 1979) (Figure 26). The construction of Alamogordo Dam (now Sumner Dam) in 1937 and Los Esteros Dam (now Santa Rosa Dam) in 1979 altered the flow regime of the river at the FSID diversion point, affecting how this "natural flow" is determined (Reynolds 1979).

Figure 26. Wade Holdeman, FSID manager, adjusts a sluice gate on an irrigation ditch (Natural Resources Conservation Service [NRCS] Photo by Rey T. Adame, all rights reserved).

Currently, the FSID entitlement is calculated by the NMOSE in two-week increments, using the average measured flow at the stream gage in Puerto de Luna (upstream of Sumner Reservoir), and adding in the net flows at Santa Rosa Reservoir (inflows-releases). This calculation estimates the "natural flow" of the Pecos River (i.e., the amount of water that would arrive at the Fort Sumner Diversion Dam if Sumner Reservoir and Santa Rosa Reservoir did not exist). Even when inflows into Santa Rosa Reservoir are minimal, numerous springs in the Santa Rosa area provide a fairly uniform baseflow to the Pecos River, typically ranging from about 60 to 100 cfs, depending on the time of year and precipitation (Reynolds 1979). FSID's entitlement is limited to the March-October irrigation season, as well as two 8-day periods during the off season. FSID's theoretical maximum entitlement is therefore 51,769 acre-feet, though in practice this is rarely achieved, as the natural flows of the river typically drop below 100 cfs for at least some portion of the irrigation season.

FSID irrigates from the northern to the southern boundaries on a rotating time basis. Each farmer is offered water in turn until all have had opportunity to water (some will pass on the water due to circumstances of crop or field condition or due to weather). Then the rotation starts again at the northern boundary. At the maximum diversion right, farmers receive 12 cfs for 1 hour for each acre of water right. While kept equal for all irrigated acres within the district, watering time is reduced proportionately as the diversion is reduced (for example, cuts can be to 45 minutes or even 30 minutes of water per acre of water right). Famers can determine how to use the water they are entitled to. Thus, farmers use best practices for irrigation, fallowing, and crop priorities.

Actual diversion amounts vary due to maintenance, irrigation requirements, storms, etc. This modeling study used 1950-2009 calculations to determine historical entitlements (Figure 27), and a value of 6,500 acres for the irrigated acreage. Actual FSID entitlements ranged from a low of 38,224 acre-feet in 1956 to the entire entitlement amount from 1992 to 1995 and from 1997 to 1999.

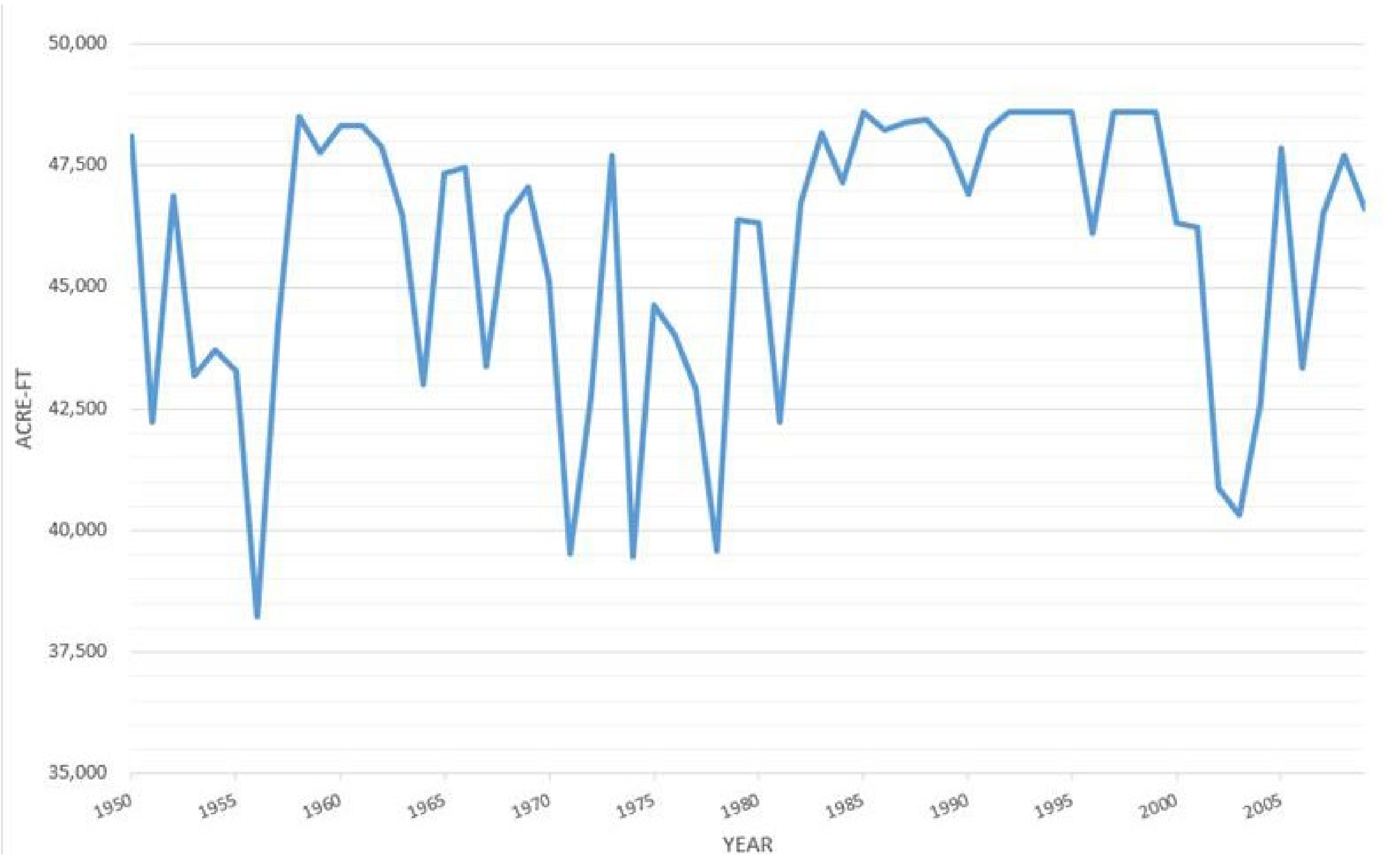


Figure 27. Calculated historical FSID entitlements. Note that entitlements are different from actual use and do not account for additional limited winter diversions. Values range between 35,000 and 50,000 acre-feet (Reclamation).

3.3.1.4. Infrastructure

Historically, the FSID system has grappled with physical and financial operating difficulties, including leaking diversion works, distribution, and flooding, which decreased crop yields. FSID built a new drainage system in 1931 and a new concrete diversion dam in 1934 and rehabilitated the High Line Canal in 1937. Floods washed out a section of the diversion dam in 1941, which was repaired and washed out again in subsequent floods.

By 1943, FSID sought assistance from Reclamation. Reclamation constructed the concrete Fort Sumner Diversion Dam at the site of the original dam. This dam is described in more detail in Section 3.2.3. *Fort Sumner Diversion Dam*.

Reclamation also rebuilt the Main Canal and the High Line Canal, lining 6.2 miles of the Main Canal and 7.9 miles of the High Line Canal with concrete; installed a new hydraulic pumping station; improved the lateral ditches; and restored and extended the drainage system. All of this work was completed by the early 1950s.

Project infrastructure, which FSID operates and maintains, includes the concrete Fort Sumner Diversion Dam (owned by Reclamation) on the Pecos River; a network of irrigation canals, lateral ditches, and drains. Two pumping stations are used to move water within the distribution system. Water from the Pecos River is diverted into the Main Canal, which is about 16 miles long and can carry up to 100 cfs. The Main Canal delivers water through a series of nine lateral ditches to about 5,300 acres of land, and through the second major canal, the High Line Canal, to another 1,200 acres of land. The High Line Canal has a capacity of 20 cfs and is about 8 miles long; a hydraulic pumping plant on the Main Canal pumps up to 20 cfs of water to the High Line Canal. In addition, about 14 miles of drains direct excess water back to the river (Bell 1997).

3.3.1.5. Conservation and Improvement Measures

FSID is committed to conserving water, has implemented water conservation measures in the past, and continues to look for opportunities to do so. Current actions being taken by FSID and its members include:

- Use of laser and global positioning software (GPS) technology for precision leveling and grading of fields by FSID farmers for more efficient water use
- Plans by FSID to install automatic head gates and telemetry in the near future
- Application for funding to develop a strategic plan to address assets, operations efficiency, etc.
- Continued organizing, preserving, and archiving the district's historical records to be ready for adjudication processes

3.3.1.6. Challenges, Vulnerabilities, and Potential Actions

3.3.1.6.1. Planning

FSID's main challenge is to provide effective and comprehensive planning to address variable future supplies. FSID is working with partners, stakeholders, and others to develop comprehensive plans, including:

- Strategic plans
- Water conservation plans
- Drought contingency plans

- Canal flow telemetry and automated headgate project under WaterSMART Small Water Efficiency Projects
- Asset management plans
- Preparations for re-adjudication of water rights

FSID may also apply for planning and implementation projects under other WaterSMART Programs such as the Cooperative Watershed Management Program, Water Marketing Program, and Water Conservation Field Services Program. However, FSID currently lacks the resources needed to fully develop and implement these plans.

In December 2015 and January 2016, as part of the development of a comprehensive plan for DeBaca County, Architectural Research Consultants (ARC) met with members of the Fort Sumner community to discuss their visions, goals, and suggestions for the area's future. These meetings led to the development of a list of potential objectives and actions for the county to pursue (ARC 2016). Potential actions described in the report relating to FSID and water use in the community included:

- Using Geographic Information Systems (GIS) mapping to identify flood risks and potential inundations from dam failures
- Supporting FSID projects when possible, and assisting in developing funding and grant applications for irrigation-specific programs
- Protecting water rights through education and adjusting protected water uses for De Baca County in the current draft Lower Pecos Valley Regional Water Plan
- Coordinating with the De Baca Soil and Water Conservation District to ensure consistent actions and avoid duplicated efforts

For further information, please see the most recent list of projects FSID submitted to the New Mexico Infrastructure Capital Improvement Plan (New Mexico Department of Finance and Administration [NMDFA], 2020, pp. 118-132).

3.3.1.6.2. Infrastructure

FSID infrastructure is about 75 years old and nearing the end of its planned life cycle (typically 50-100 years). Infrastructure concerns include:

- Diversion works in need of rehabilitation, including:
    - The radial arm gates at the FSID diversion works, which leak due to deterioration below the water line.
    - The pumps at the head of the High Line Canal, which are deteriorating due to age and need to be replaced. Replacements need to be studied to determine the best options for improved efficiency and designed accordingly.

  - Head gates, which need replacement with new, automated gates where applicable.

- Deteriorating concrete lining on ditches and canals, which need major repairs (such as sealing cracks) or to be replaced with pipe.

Future actions to improve FSID infrastructure could include:

- Using GIS to inventory infrastructure, assets, water rights, and easements.

- Improving system monitoring capability (e.g., telemetry and remote-control technology such as Supervisory Control and Data Acquisition [SCADA] and computerized record-keeping systems).

- Maintaining the current infrastructure and upgrading it when possible.

- Using standardized components for repair/replacement work throughout the system for consistency, a smaller inventory, and faster and easier repairs.

- Identifying unlined sections of the irrigation network that might benefit from concrete lining and replacing concrete-lined ditches with a pipeline in some locations.

- Investigating flood control and watershed protection projects.

- Identifying and implementing projects to improve subsurface infiltration and surface water drainage.

- Storing water in on-farm storage, which would give farmers the capability to irrigate outside of the standard irrigation cycle, potentially facilitating crop diversification beyond alfalfa. The NRCS is working with an area farmer to install one 5,000-gallon storage tank (ARC 2016).

- Storing water at the district-wide level (e.g. in a small reservoir), which would increase the versatility of the system's water delivery capabilities (ARC 2016).

- Applying under WaterSMART Funding Opportunities Announcements for concrete lining, piping, and telemetry and metering projects.

3.3.1.6.3. Operations

FSID is a run-of-the river operation that currently lacks options for water storage. FSID's entitlement varies from year to year as well as over the course of the irrigation season, depending on conditions in the watershed. Since rainfall and entitlement availability is somewhat unpredictable, farmers may have difficulty planning or prioritizing crops at the beginning of an irrigation season. When farmers receive less water, those employing better practices are more successful, and others are incentivized to implement more efficient watering infrastructure and practices. Farmers can also adapt to lower entitlements by prioritizing water to the most productive fields and fallowing other fields.

A typical rotation cycle in FSID is 21 days, though the cycles can be shorter. This cycle works well for alfalfa, which can handle infrequent but substantial watering. The cycle length can inhibit crop diversification; however, as many other crops are ill-suited for this cycle, requiring more frequent, moderate watering (ARC 2016). As a result, most of the land in FSID is currently used to grow alfalfa.

FSID's future actions to improve operations efficiency could include:

- Developing a computerized asset and maintenance database and record system
- Standardizing processes for infrastructure maintenance, repairs, and improvements
- Implementing SCADA or another automated system to streamline management data collection and operations within the district
- Identifying and evaluating options for water delivery systems other than rotation system, such as an automated system or a demand-response system (ARC 2016)

3.3.2. Pecos Valley Artesian Conservancy District

3.3.2.1. Location

The Pecos Valley Artesian Conservancy District (PVACD) lies in the Pecos River Valley around the cities of Roswell and Artesia (Figure 28). The PVACD spans an area of approximately 10 by 75 miles (though only a fraction of this area is cultivated) overlaying most of the eastern half of the Roswell Artesian Basin (RAB), which is the district's primary water supply. This area is among the most extensive farming regions in New Mexico, and approximately 110,000 acres of farmland are irrigated each year within the PVACD.

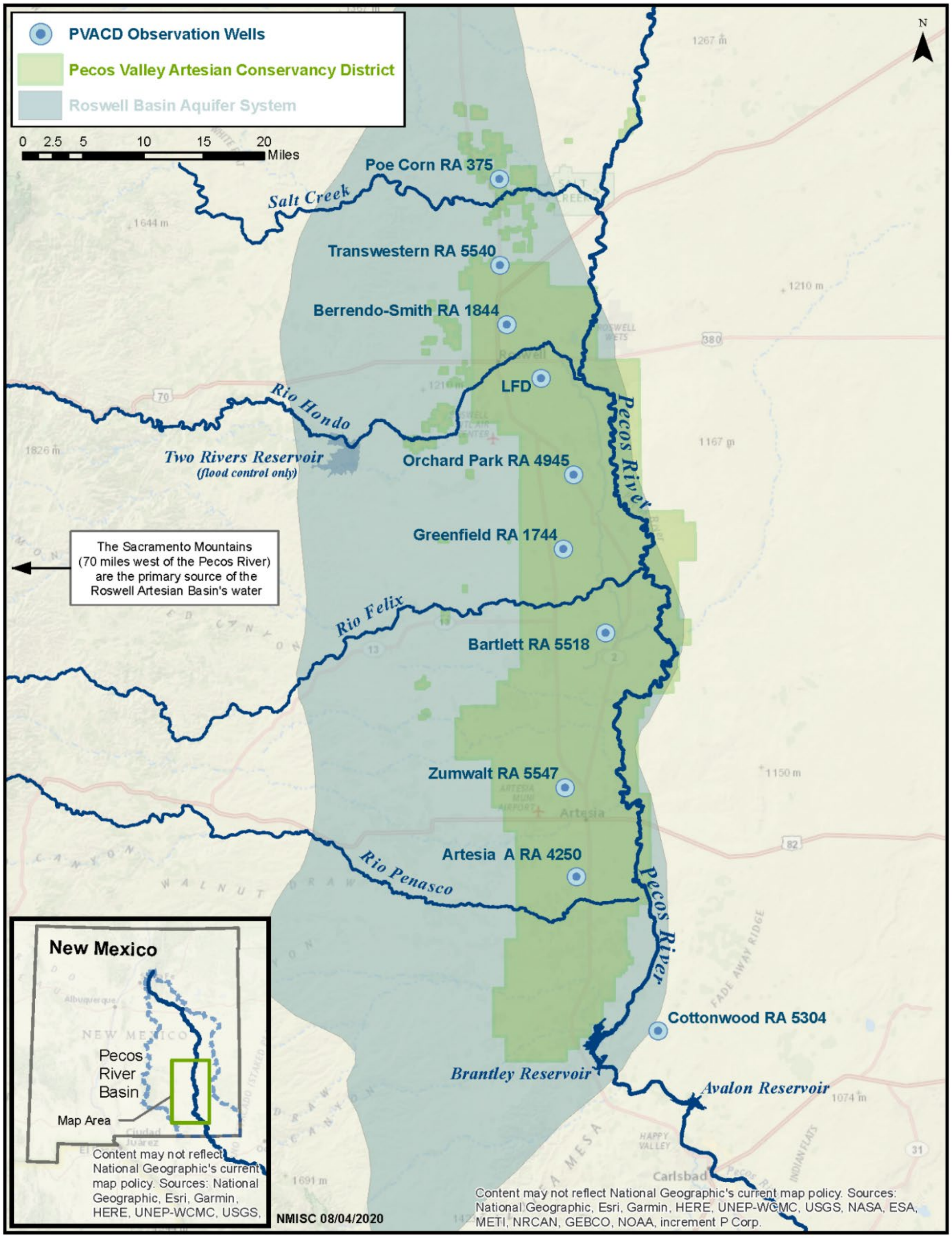


Figure 28. Pecos Valley Artesian Conservancy District map (NMISC).

3.3.2.2. Historical Operations

3.3.2.2.1. Historical Groundwater Use

The first artesian well in the Roswell Artesian Basin was drilled in 1890 and was 250 feet deep. Farmers began drilling irrigation wells into the artesian aquifer in the early 1900s and by 1905, 485 irrigation wells had been drilled. Many of these early wells flowed at rates that ranged from 500 to 1,000 gallons per minute, with no pumping equipment. (Fiedler and Nye 1933). However, artesian pressures soon began to decline due to over-pumping, and before the end of the decade, it became apparent that action would be needed to protect the artesian aquifer in the Roswell Basin. PVACD's timeline is:

- In 1909, the New Mexico Territorial Legislature enacted laws that limited water use in the Roswell area to 3 acre-feet per acre (Clark 1987). The Territorial Engineer reported a gradual diminution in water pressure in the confined aquifer, but with enough recharge during the winter months to maintain good flow for the 500 wells then in the basin. By 1915, however, the number of wells tapping into the RAB had grown to over 1,200.

- The Roswell Chamber of Commerce received $5,000 for a USGS hydrological survey of the wells in the region. The survey found that there were 225 free flowing wells. At that time, drilling new wells was unregulated.

- By 1925, 45,000 acres were irrigated in the basin out of about 1,400 wells. This level of pumping proved to be unsustainable; at roughly that time, farms in the area began to be abandoned because of insufficient water (Clark 1987).

- In March 1927, reacting in part to the depletion of the Roswell artesian aquifer, and to manage surface water and ground water conjunctively, the New Mexico Legislature enacted laws declaring underground waters to be public waters and subject to appropriation, and granting the State Engineer the authority to administer groundwater appropriations. The law confirmed existing appropriations and excluded domestic and stock wells from regulation.5 In 1927, the State Engineer assumed administration of the Roswell Artesian Basin. Within a year, the State Engineer received more than 1,000 declarations of existing water rights and numerous applications for repairing and drilling wells.

[5] New Mexico Laws 1927, ch. 81, §§ 1, 2. The law was largely rewritten in 1931. New Mexico Laws 1931, chapter 131.

- In 1931 a new law was enacted, which furnished a definitive basis for future regulation of ground waters in the area. An investigation concluded that no new land should be placed under irrigation with artesian water, but that the development of shallow ground water should be encouraged (Fiedler and Nye 1933).

- The PVACD was created on January 11, 1932, shortly after enactment of the Artesian Conservancy District Act,[6] to conserve the waters of the Roswell Artesian Basin, including the lands within the Basin in both Chaves and Eddy Counties.

- According to one estimate, the area of land irrigated from both the artesian and the shallow aquifers increased from 120,000 acres in 1940 to 158,000 acres in 1955 (Hall 2002). Increased pumping in the basin caused a marked decline in water levels and a corresponding decrease in artesian and surface water flows, along with increased intrusion of saline water from adjacent aquifers. The increased pumping also prompted extensive litigation, as the large number of applications for groundwater exceeded the volume of water available for withdrawal (Clark 1987).

- In 1956, PVACD and the State Engineer filed a complaint in district court to adjudicate the rights of all water users of the artesian and shallow aquifers in the Roswell Artesian Basin.

- In January 1966, the court entered a decree adjudicating the water rights in the basin. The court determined that 130,000 acres of the total 142,000 acres of irrigated lands had valid rights. The decree also required well metering starting January 1, 1967 and for the State Engineer to appoint a water master to oversee implementation of the decree. The court required that all points of diversion be metered and that PVACD pay for the metering and reading of the meters.

- Since the 1970s, groundwater usage has generally declined, though annual usage has fluctuated significantly. Water meter data (available since 1967) shows a decline in irrigation withdrawals from a high of approximately 420,000 acre-feet in 1976 to 265,000 acre-feet in 2015. During that time, the estimated area of irrigated land within the PVACD also declined from approximately 123,000 acres to approximately 110,000 acres.

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[6]New Mexico Laws 1931, chapter 97, §§ 1 to 13.

3.3.2.2.2. Water Rights Purchases

From 1958 to the present, the PVACD has acquired water rights, initially to reduce aquifer depletions and recently to better manage the aquifer to avoid retiring land. More recently, the district has acquired water rights with the additional intention of entering them into a water bank in the future, allowing these water rights to be made available for lease when the PVACD observation wells indicate that the aquifer is not in decline. Currently, PVACD owns the water rights to 6,756.952 acres (Balok 2019).

The State of New Mexico has also purchased significant water rights in the Roswell Area. Purchases began in the early 1990s in response to the 1988 Decree. Ultimately, NMISC purchased water rights associated with approximately 7,500 acres in the PVACD, largely as part of the Settlement. For more information see Section 3.1. *Regulation of Water in the Pecos River Basin in New Mexico*.

3.3.2.3. Infrastructure

Water supplies in the PVACD are sourced primarily from individual groundwater wells. However, a small portion of PVACD is supplied by the Hagerman Irrigation Company (HIC), which owns the Hagerman Canal (formerly the Northern Canal) and diverts water (when available) from the Rio Hondo. When surface water is not available, water is supplied by several groundwater wells. Due to drying of the Rio Hondo over the years, the HIC has become increasingly dependent on groundwater pumping.

3.3.2.4. Current Operations

3.3.2.4.1. Crops

In recent years, alfalfa has become the dominant crop on PVACD farmland. In 2010, alfalfa was grown on just over half of the cultivated farmland around Roswell. The second most abundant crop was corn, grown on about 15 percent of the land. Pecan orchards, which have replaced many of the fruit orchards that were grown in the past, accounted for about 6 percent of all irrigated farmland. Only about 3 percent of the farmland was used to grow cotton, a dramatic decrease from first half of the 20^{th} century.

3.3.2.4.2. Water Rights and Pumping

Farms within the PVACD mostly irrigate from the artesian aquifer, but some also have wells tapping the shallow aquifer (Barrol and Shomaker 2003). Every point of withdrawal is metered, as required by the 1966 adjudication order. PVACD owns and maintains all the meters and pays the water master from the NMOSE to ensure that farmers adhere to adjudicated volumes.

Water rights are accounted for in five-year periods and are set at 3 acre-feet per acre of land, plus 0.5 acre-feet per acre for conveyance losses. Farmers thus have 17.5 acre-feet per acre to use during every 5-year period, and this amount can be distributed among the five years however the right-holder wishes, up to using the entire five-year amount in a single year and using none in the other four years. This flexibility allows for PVACD farmers to vary their crops; for example, a farmer could grow water-intensive crops one year, drought-tolerant crops another, and leave the land fallow another year. Exceeding the allocated amount in a five-year period can incur fines, and the overage is doubled and deducted from the total allotment for that water rights holder for the next five-year accounting cycle.

3.3.2.4.3. Overall Basin Diversions

Given the flexibility in water use created by the five-year accounting cycle, annual water withdrawals can be highly variable. In this study's modeling work, a single year, 2010, was used as the Base Case year to analyze groundwater trends See Section 4.2.6. *Roswell Artesian Basin Groundwater Model*. 2010 was the fourth year of the ninth five-year accounting cycle, and there were 876 active farming units in PVACD that year (Thomas 2010).

3.3.2.5. Conservation and Improvement Measures

Since its creation, the PVACD has encouraged measures to improve the efficiency of irrigation and conservation of water in the Roswell Artesian Basin. Farmers within the PVACD mostly irrigate with relatively efficient center pivot systems. PVACD plugged more than 1,696 abandoned wells between 1934 and 2019. In addition, PVACD's low-interest loan program for farmers promotes a wide range of conservation efforts. Projects have included lining some 31 miles of earthen irrigation ditches with concrete, replacing ditches with piping, installing over 200 center-pivot irrigation systems, and installing drip irrigation systems to irrigate about 2,500 acres of land (or a little less than 2% of all PVACD farms (PVACD 2017).

3.3.2.6. Challenges, Vulnerabilities, and Potential Actions

3.3.2.6.1. Diversion Tracking for Farmers

PVACD requires accurate metering of all points of diversion in the Roswell Artesian Basin. They ensure that meters at each point of diversion are functioning and pay to have meters read regularly by NMOSE Roswell Basin Water Master staff. The NMOSE primarily records meter readings in paper records and manually calculates diversion amounts. This process is time and resource intensive and often does not provide timely information for farmers to plan crop plantings. Transitioning from paper records to an electronic database and developing a data management system would allow for better and more expedient analysis. Developing a compatible software program that can work with current and future software and operations for both NMOSE, PVACD, and individual farmers would allow for better data collection, communication with farmers, and planning. These actions could also be a starting point for any automation such as a SCADA system to alert all users to potential real-time issues and to plan for variable water supplies.

Ideally, every water right holder would be able to log in at any time, see their current diversion status within the 5-year accounting period, and self-report. Water users could communicate directly with NMOSE or PVACD. If water users' records differ from those of the NMOSE, the NMOSE records take precedence. Having better access to NMOSE records would reduce the risk of inadvertent overuse and potential fines. Real-time communication would allow water users to plan ahead and potentially use water more efficiently.

While PVACD has examined the possibility of automating data management, programs would need to be tailored to PVACD's unique system and coordinated with NMOSE. These advancements should be developed in conjunction with any state technology and regulations, such as compliance with New Mexico's Water Data Act (Legiscan 2020).

3.3.2.6.2. Monitoring Aquifer Levels

In addition to the primary need for data management for each individual diversion, overall aquifer modeling and comprehensive data collection could help address effective aquifer management.

PVACD maintains ten observation wells throughout the Roswell Artesian Basin (see Figure 58 in Section 5.5.2. *Roswell Artesian Basin Groundwater Levels*). These wells are measured three times a month and provide a comprehensive, timely assessment of artesian aquifer levels. Aquifer levels can rise and fall at different rates in different areas of the Roswell Artesian Basin. For example, the northern end of aquifer tends to recover more quickly than the southern end following dry periods.

Additional observation wells on the western side of the district, where a substantial amount of recharge to the artesian aquifer occurs, would be useful to better understand the aquifer recharge, to predict aquifer levels, and to implement management strategies proactively. There are some wells in this area which are measured annually, however, wells would need to be measured at least four times a year to account for variations caused by seasonal changes in precipitation and recharge. The PVACD currently does not have observation wells in the shallow aquifer. Establishing a network of shallow piezometers with recorders might help improve understanding of flow between the two aquifers. While the two aquifers are separate, interconnections between them could be better understood to support future management decisions.

3.3.2.6.3. Water Rights Purchases, Leasing, and Banking

PVACD does not have a central network that distributes water, and the district consists of individual, privately owned wells belonging to water right holders. Farmers are autonomous decisionmakers and can pump irrigation water up to their permitted amount during each 5-year accounting period. The PVACD monitors aquifer levels to protect the artesian aquifer; however, since PVACD has no regulatory authority over water rights holders within the district, water right purchases and water waste reduction activities, such as plugging wells are the primary mechanism at their disposal to ensure the artesian aquifer remains in balance. Water right purchases, by the PVACD and NMISC, have reduced overall depletions and helped to protect the aquifer. However, they have also taken land out of production in a manner that does not allow production to resume in years when there is enough water available to support increased irrigation.

The PVACD would like to implement more flexible methods such as water banking and leasing. In such a plan, PVACD could lease its purchased water rights to farmers during years when water is available. When less water is available, or if excessive aquifer drawdowns are observed, PVACD could stop leasing that water to help the aquifers recover. In 2002 the New Mexico Legislature passed a statute allowing the establishment of a lower Pecos River water bank (NMSA 72-1-2.3, 2002). NMISC would need to propose rules for recognition of a water bank to the State Engineer for adoption. While the rules have not yet been written, PVACD is currently working with NMISC to move that initiative forward. Although models exist of the Roswell Artesian Basin, more detailed hydrologic analysis and data collection will be needed to determine thresholds for when water would be available for lease (through the water bank or otherwise). A water banking system developed for the lower Pecos River Basin in New Mexico could help the PVACD meet the challenges of variable water supplies in the future. To develop this water marketing strategy, PVACD may consider taking advantage of Reclamation's WaterSMART Water Marketing Program.

3.3.2.6.4. Metering Infrastructure

The PVACD maintains, repairs, and replaces the primary groundwater meters. Keeping these meters working is vital to adequately monitoring aquifer storage and determining sustainable pumping rates. PVACD may consider applying under WaterSMART Funding Opportunity Announcements for concrete lining, piping, and telemetry and metering projects.

3.3.2.6.5. Interconnectedness of the Shallow and Artesian Aquifers

While the artesian and shallow aquifers in the RAB are separated by an impermeable confining layer, there are numerous natural fissures in the confining layer that can connect the two aquifers. Wells that penetrate both aquifers and have not been properly completed may be additional pathways for water to flow between the two aquifers. Interconnectedness poses a problem as the elevation of the shallow aquifer and the potentiometric surface of the artesian aquifer are not equal, and increased connections between the aquifers can ultimately result in drawdown in the artesian aquifer if its water moves into the shallow aquifer. Groundwater movement from the shallow aquifer (which is more easily contaminated and often of lower quality than the artesian aquifer) to the artesian aquifer is also a concern (Balok 2019). This water movement could lead to contamination of the artesian aquifer. To limit aquifer fluctuations associated with this interconnectedness, PVACD has encouraged retiring and plugging wells (and will plug these wells free of charge) and requires that new wells be constructed so that communication between the shallow and artesian aquifers is limited.

3.3.2.6.6. Irrigation Efficiency

A typical irrigator is primarily concerned about making the most effective use of water on his farm. However, practices that increase on-farm efficiency will also alter the water budget of the area. Water that is applied to the land—but not consumed by the irrigated crop—may ultimately contribute to underlying aquifers and nearby streams. Although to the water user this unused water is "lost," this water will either recharge the shallow aquifers or flow directly into nearby streams and ultimately to the Pecos River. Therefore, as efficiencies increase (e.g., using center pivots rather than flood irrigation), the amount of water used consumptively increases and there is less recharge to groundwater and return flows to the river. In other words, as less water is "lost" (from the irrigators' point of view), the portion of the total diversion that is consumed increases. In order to maintain the same consumptive amount as before efficiency improvements were implemented, the total permitted diversion amount would need to be reduced.

3.3.2.6.7. Priority Calls

Groundwater rights holders in PVACD are largely junior to CID's surface water rights downstream. PVACD is fortunate to source its water from the Roswell artesian aquifer, which has proven to be very resilient over time. However, their greatest vulnerability in drought conditions may be to a priority call from CID. In the most recent drought of 2011 through 2013, even with augmentation pumping by NMISC in accordance with the 2003 Pecos Settlement Agreement (Settlement), CID did not have sufficient supply and in 2013 called for priority administration by NMOSE (see Section 3.1.4. *2003 Pecos River Settlement Agreement*). Fortunately, in September 2013 significant rain events filled Pecos River reservoirs—negating the need for priority administration.

Water users in the Pecos River Basin in New Mexico must be prepared for future and possibly longer lasting droughts. Enforcing priority on the Pecos River is challenging, and because of the delayed affect to the river of curtailing groundwater pumping, a priority call by CID is likely to be ineffective regardless. PVACD is investigating various solutions, beyond the Settlement, to prevent a priority call in the future.

3.3.3. Carlsbad Irrigation District

3.3.3.1. Location

The Carlsbad Irrigation District (CID) is located in Eddy County in southeastern New Mexico, near the city of Carlsbad (Figure 29).

CID covers about 25,000 acres, extending approximately 25 miles southeast from Avalon Dam past the confluence of the Black and Pecos Rivers. Most of the irrigation district lies downstream of Carlsbad and on the west side of the Pecos River.

3.3.3.2. Historical Operations

CID's timeline is:

- In 1883, the earliest irrigation on land that would become part of CID began (Littlefield 1990).

- In 1888, local businessmen formed the Pecos Irrigation and Investment Company. In 1889, the company constructed the original Avalon Dam to divert water from the river, as well as a 475-foot long wooden flume, which delivered water to the west side of the river, and a system of canals. Beginning in 1892, the company constructed a second dam, McMillan Dam, nine miles upstream of the Avalon Dam site to be used for greater storage volume. It was completed in 1894, with a storage capacity of about 80,000 to 90,000 acre-feet (Hufstetler and Johnson 1993).

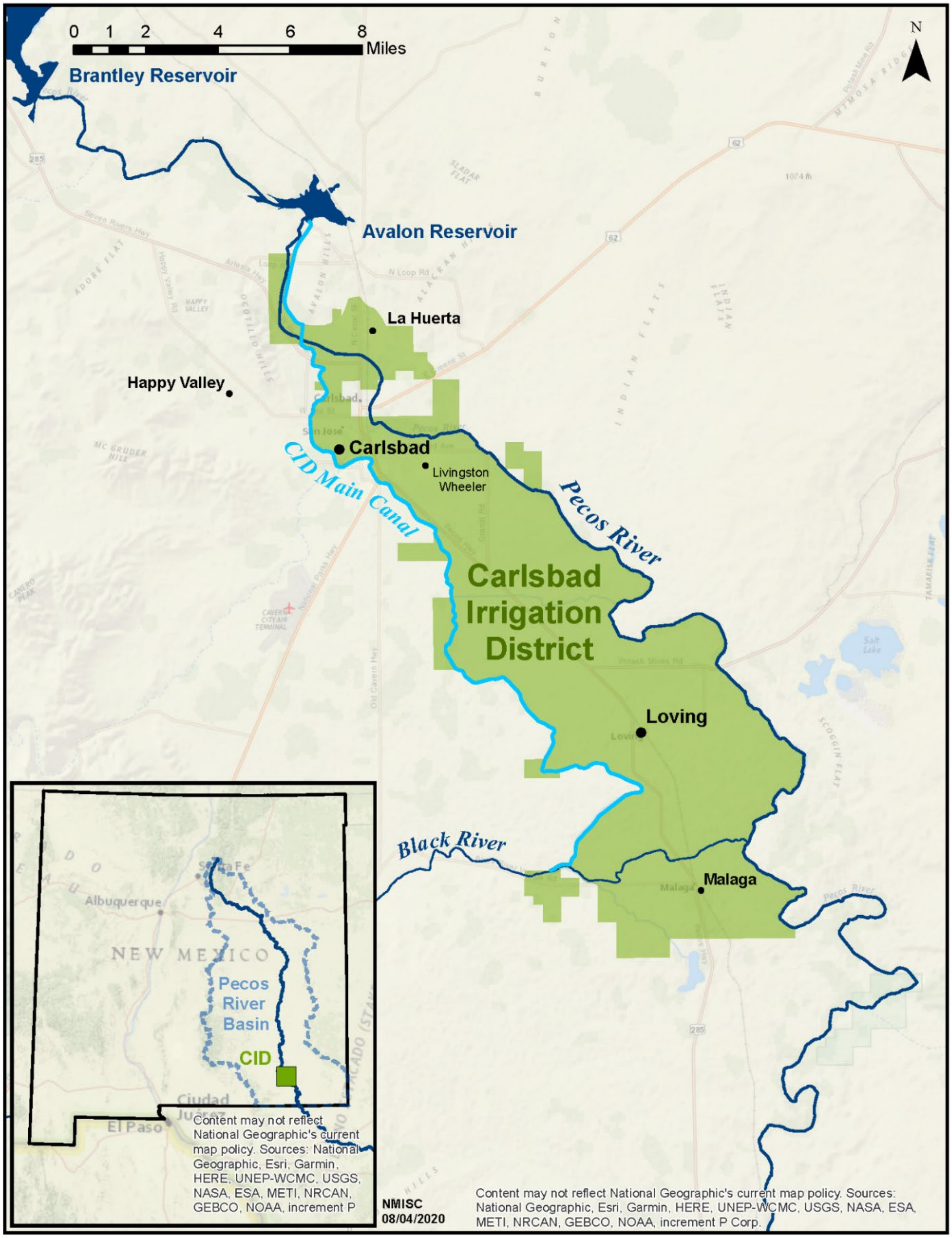


Figure 29. Carlsbad Irrigation District map (NMISC).

- In 1893, the irrigation system began operations. In August 1893, seasonal flooding washed out the Avalon Dam and destroyed the wooden flume across the Pecos River, and damaged the canal system. (Bogener 1993). In 1894, the company rebuilt the Avalon Dam and the wooden flume and repaired the canals. The rebuilt dam had a small storage capacity of 6,000 acre-feet (Hufstetler and Johnson 1993). The system suffered seepage problems from the reservoirs and the unlined earthen canals (Hufstetler and Johnson 1993).

- In 1903, the company reinforced the flume with concrete. At that time, only 13,300 acres of land were under cultivation, although water rights had been authorized for considerably more land. (Littlefield 1990). In October 1904, a flash flood washed out Avalon Dam again and damaged the flume, the canal system, and McMillan Dam. The Pecos Investment and Irrigation Company could not afford to repair the system. Local farmers formed the Pecos Water Users Association and sought assistance from the Federal Reclamation Service (Reclamation's predecessor) to rebuild the irrigation system.

- In 1905, Congress authorized the Carlsbad Project. In December 1905 Reclamation purchased the irrigation system from the Pecos Investment and Irrigation Company, including the reservoirs, canals, rights-of-way, land, and water rights necessary to operate the system. (Littlefield 1990).

- By 1906, water rights had been issued for the irrigation of 62,271 acres of land around Carlsbad. These water rights remain the basis for the Carlsbad Project. (Littlefield 1990).

- In November 1907, Reclamation completed construction of the new Avalon Dam, the flume, and other components of the irrigation system. As the early irrigation project progressed, greater areas of land were opened to irrigation. In December 1907, 20,000 acres were open to irrigation, although fewer than 5,000 acres were actually irrigated. (Littlefield 1990). In 1908, Reclamation renovated McMillan Dam.

- By 1911, about 12,000 acres of the project were irrigated. In 1914, Reclamation lined critical portions of the main irrigation canal with concrete, reducing water loss from seepage (Bogener 1993).

  Nevertheless, drainage problems plagued early attempts to irrigate the land (Clark 1987). Water tended to seep through porous ditch banks, leaving large areas understanding water and inhibiting cultivation. Additionally, excessive water use raised the water table and waterlogged large areas of land.

- In 1913, the drainage problems prompted construction of two new drains to protect 750 acres of land. Drainage problems persisted through the early 1920s.

- In 1915 and 1919, additional land was opened to irrigation, which brought the total area of the project up to slightly more than 25,000 acres (Littlefield 1990).

- On June 30, 1932, the Pecos Water Users Association voted unanimously to form the Carlsbad Irrigation District under New Mexico law[7] (Bogener 1993). The new district was given the legal authority to acquire the physical infrastructure of the irrigation network, issue bonds for further improvements, and assess landowners within the District's boundaries for the costs of the system's operation.

- In 1938, CID assumed control of the project, although Reclamation and USACE own the upstream dams and reservoirs that store CID's water (Hufstetler and Johnson 1993). Water rights for the Carlsbad Project were adjudicated in the 1932 Hope Decree, which provided Reclamation with a right to divert 300 cfs from the Pecos River with a priority date of 1887, and a right to divert an additional 700 cfs with a priority date of July 1888. The decree also provided a right to store 7,000 acre-feet in Avalon Reservoir with a priority date of 1889; a right to store 90,000 acre-feet in McMillan Reservoir with a priority date of 1893; and, additionally, a right to store 300,000 acre-feet at Avalon Reservoir, McMillan Reservoir, and at such other points above Avalon Dam as may be available for such diversions and storage with a priority date of 1906. Of the water rights adjudicated in the Hope Decree, those of the Carlsbad Project are furthest downstream and are among the most senior.

- In 1934 and 1935, Public Works Administration funds were allocated to make improvements to McMillan and Avalon Dams, to line additional canals with concrete, and to begin construction of a new storage dam, Alamogordo Dam (now Sumner Dam) (Littlefield 1990).

- In 1936, work on Alamogordo Dam began and was completed in 1938, forming a reservoir about 15 miles long (Littlefield 1990). Sumner Reservoir became a major storage facility for the Carlsbad Project, with 40,000 acre-feet of conservation storage for irrigation.

- In October 1972, Congress authorized funding for construction of Brantley Dam to replace McMillan Dam,[8] which had been declared unsafe by Reclamation in a

[7] NMSA 1978, § 73-10-1 to 73-10-50.

[8] Public Law No. 92-514, §§ 201-206, 86 Stat. 966-67 (Oct. 20, 1972).

1964 report (Hufstetler and Johnson 1993). This dam was built between McMillan and Avalon Reservoirs and was completed in 1987 (Bogener 1993). The reservoir is authorized for irrigation storage and flood control, with most of its storage reserved for flood control. Conservation storage for irrigation in Brantley Reservoir is limited to 40,000 acre-feet—the amount available in McMillan Reservoir at the time it was replaced.

- In 1979 a fourth dam, Santa Rosa Dam, was completed, providing additional upstream irrigation storage for the Carlsbad Project.

- Further adjudication among the United States, the State of New Mexico, CID, and PVACD resulted in a Partial Final Decree, entered on December 10, 2004. The decree resolved the maximum allowable annual diversion and storage rights of CID and the United States regarding certain waters of the Pecos River stream system, and the right of CID to store up to 176,500 acre-feet of surface water in Carlsbad Project reservoirs and deliver this water to its members. The decree, and the related March 25, 2003 Pecos Settlement Agreement (Settlement), are discussed in Section 3.1.4. *2003 Pecos River Settlement Agreement*.

3.3.3.3. Current Operations

3.3.3.3.1. Crops

Currently, alfalfa is the dominant crop grown at CID. In 2010, of the 17,100 acres of cultivated land in CID, almost 80 percent (13,500 acres) was used to grow alfalfa. Cotton was the next most abundant crop at about 7 percent of acreage. Grazing pasture, corn, and pecan orchards occupied the most acreage after alfalfa and cotton (Ballard 2019).

3.3.3.3.2. Diversions

CID has been fully adjudicated and is authorized to divert 4.997 acre-feet of water per acre of land associated with the water right per year (3.697 acre-feet per acre allotment at the farm, plus 1.3 acre-feet per acre of allowable carriage loss from Avalon Dam to the farm). CID land with adjudicated water rights totals 25,055 acres, allowing a total annual diversion of 125,200 acre-feet of water from the Pecos River. Since the Settlement, which mandated the purchase by NMISC of water rights associated with almost 4,500 acres of CID land, CID has typically irrigated approximately 15,000 to 20,000 acres of land. The model analyses in this study used 20,000 acres as the irrigated acreage. The volume of water that CID has diverted annually from the river, as measured by USGS Gage 08403500 (Carlsbad Main Canal), has fluctuated over the years, in part due to water availability, averaging 72,588 acre-feet (2.897 acre-feet per acre) from 1950-2009.

CID allotments are measured by on-farm deliveries. The historical records of allotments from CID (1950-2009) show an average CID allotment of 2.47 acre-feet per acre on the farm (Figure 30). In 2016, CID was allotted the maximum amount of 3.697 acre-feet per acre. The volume of surface water that CID diverted in 2016 was 71,409 acre-feet as measured at the Main Canal (USGS Gage 08403500). CID irrigated 17,121 acres of land with this water (Ballard 2020).

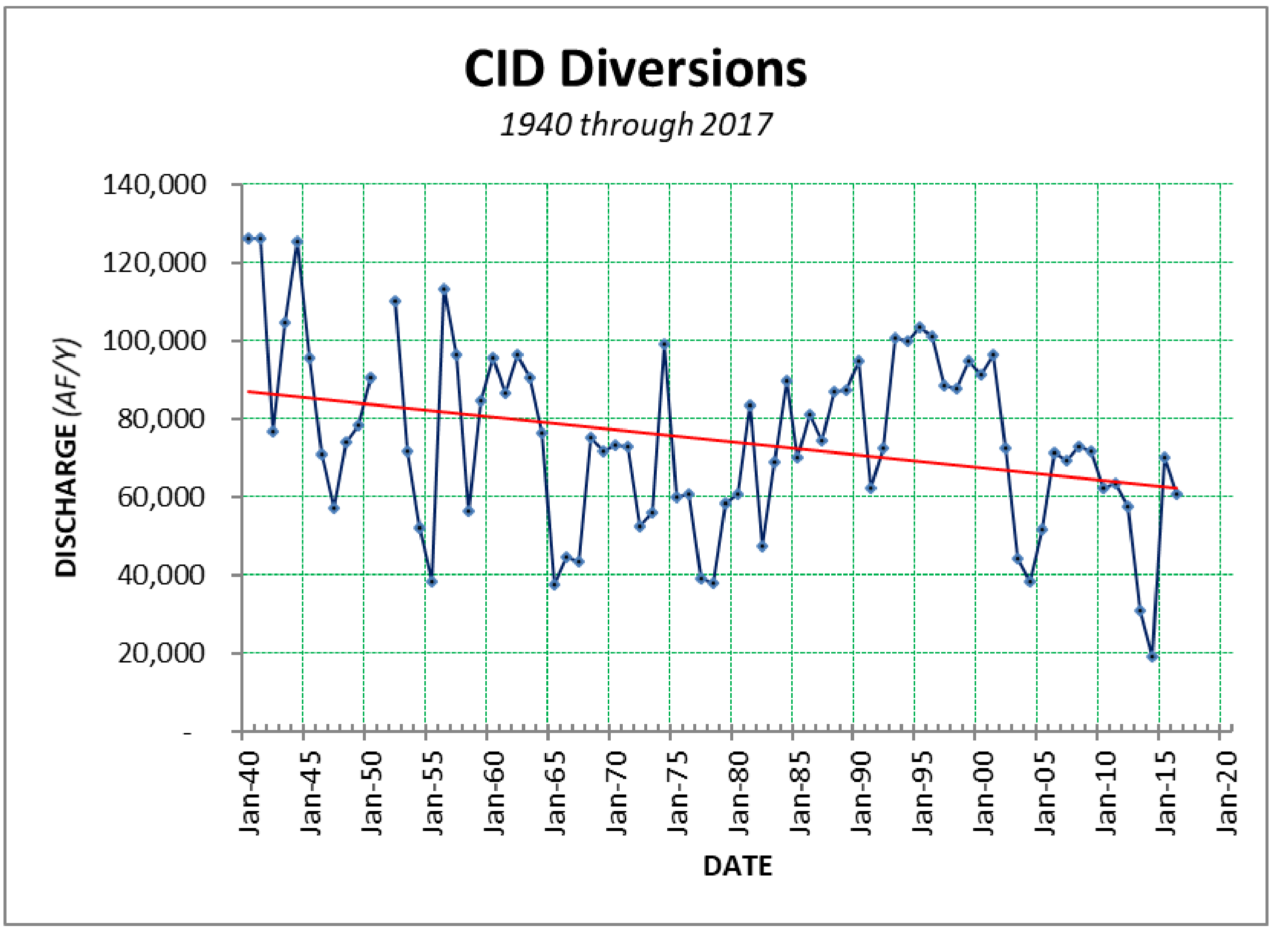


Figure 30. CID Diversions 1940-2017 (Reclamation).

3.3.3.3.3. Return Flows and Supplemental Pumping

Return flows from CID, leakage from the reservoir, and discharge at Carlsbad Springs contribute water to the Pecos River below Avalon Dam. When CID's surface water supplies are low, farmers with supplemental wells can pump groundwater, if they do not exceed their total allotment. NMOSE has not permitted further rights to supplemental groundwater since the 1972 (Hall 2002). This pumping decreases the volume of groundwater inflow to the Pecos River.

3.3.3.4. Infrastructure

CID has the sole storage permit on the Pecos River, with storage in four reservoirs on the main stem of the river. CID operates Sumner, Brantley, Avalon Dams, which are maintained jointly by CID and Reclamation. CID also holds the rights to conservation storage in Santa Rosa Reservoir, which is owned and operated by the USACE (see Section 3.2. *Water Development: Dams and Reservoirs*).

In addition to the four upstream dams, CID infrastructure includes a flume and a series of canals and lateral ditches. The distribution of water to the project is controlled by Avalon Dam, which is at the head of the Main Canal. Water is distributed according to a system of "demand rotation," whereby water is delivered to individual farms on demand with enough notice. If several water users are in line, water is delivered by rotation according to order of application.

3.3.3.5. Conservation and Improvement Measures

In 2013, CID installed advanced water measurement devices and a SCADA system so that real-time, remote monitoring could be used to reduce spills and otherwise ensure that CID's water deliveries match users' needs as accurately as possible.

3.3.3.6. Challenges, Vulnerabilities, and Potential Actions

3.3.3.6.1. Water Availability and Droughts

Droughts are a concern, as shown by the recent 2011-2013 drought. The allotment in 2012 was only 0.8 acre-feet per acre, less than a quarter of the full allotment of 3.697 acre-feet per acre. Increased prevalence of drought conditions could force CID to switch to a rotation schedule (similar to the system used by FSID), rather than the current delivery-on-demand system. This change may not be feasible for CID, as currently their infrastructure does not permit timely rotations. With its current infrastructure, CID could not employ a rotation system with short enough cycles to sustain crops.

Although the four reservoirs can store a maximum of 176,500 acre-feet of irrigation storage, well over double CID's average annual diversions and almost 50% more than their maximum allowed annual use, the system lacks the ability to provide adequate storage during a multi-year drought. Once evaporation from reservoir surfaces and conveyance losses (incurred in moving water from the upper reservoirs to Brantley Reservoir) are accounted for, the effective amount of water stored for CID is substantially lower, and at full capacity the system stores approximately one year's worth of water for the district.

Rainfall patterns in the basin are highly variable. While a single extreme storm event can replenish the entire system and effectively end a drought in a few days, such storms cannot be depended on. Location of storms is also critical—an extreme storm between Sumner Reservoir and Brantley Reservoir could contain enough water to refill the system, but only 40,000 acre-feet could be stored due to Brantley Reservoir's conservation storage limits. Moreover, if the rainstorm is late in the irrigation season, farmers cannot use the water that year. For example, in 2013, CID had a significant rain event in September, and went from 0.8 acre-feet per acre allotment at the beginning of the year, to a much higher allotment of 2.0 acre-feet at the end of the irrigation season. However, due to the storm timing, farmers could not make use of the higher allotment. Those with supplemental wells could pump during the drought, but preparing for the next year was all that those without supplemental wells could do. Lack of resiliency to multi-year droughts is a significant challenge to CID operations—one that will be exacerbated should future conditions become drier and hotter.

3.3.3.6.2. Actions

Potential actions, discussed in the following subsections, include:

- Replacing cylinder gates at Avalon Dam
- Repairing and modernizing the Main Canal to reduce seepage losses
- Expanding and using SCADA system
- Developing best practices for managing required CID state-line deliveries
- Dredging sediment and debris from the Brantley Reservoir tailwaters and Kaiser Channel, to prevent backup of floodwaters into the former McMillan Reservoir lakebed

3.3.3.6.3. Aging Infrastructure

Some CID infrastructure is over 100 years old, predating CID itself, and other work was completed by the Civilian Conservation Corps in the 1930s. Some of these structures are listed in the National Register of Historic Places. Due to their advanced age, many of these structures are deteriorating (Figure 31), but funding mechanisms for improving them remain unclear. Cost allocations for repairs may count as capital improvements or as operation and maintenance costs, and clarifications with Reclamation on whether Reclamation would be able to help fund these costs is needed.

3.3.3.6.3.1. Canals

About 15 to 20 miles of the 50 miles of canal have severe seepage problems. CID is addressing the most severely deteriorating portions of the canal first and has modernized ¾ of a mile of the main canal in the past two years, at a cost of $300,000. These repairs reduced seepage losses to the adjacent drain, which in that stretch alone amounted to an estimated 2-4 cfs.

However, given the short length of the repairs relative to the total length of the canal, the reductions in overall seepage losses from the canal were relatively minor. Lining the full canal would greatly reduce conveyance losses and permit the correction of several sections of the canal that pool water. In some cases, sections of the canal and its laterals may benefit from being converted to pipelines.

Figure 31. Aging infrastructure at CID (CID, all rights reserved).

Rehabilitating one section can influence other sections, and thus modernizing the canal in sections is difficult. Lining, modernizing, and automating the main canal and other CID infrastructure will cost millions of dollars. As only 25,000 acres are assessed, costs to the district to modernize are prohibitive, and outside funding is a necessity for completion of CID's infrastructure needs.

3.3.3.6.3.2. Dams

The four dams in the Carlsbad Project are also aging. The newest facility, Brantley Dam, is over 30 years old, and the oldest, Avalon Dam, is over 100 years old. Although the most pressing operations and maintenance issues have been addressed, major dam repairs are needed, including replacing the cylindrical gates at Avalon Dam and repair of the radial gates at Sumner Dam.

3.3.3.6.3.3. Seepage Issues

As much of the canal network is unlined, loss of water from the distribution system to seepage is a major issue, as it not only represents lost water from the system but can also lead to flooding or waterlogging of adjacent land. Repairing, lining, and modernizing the CID Main Canal would significantly reduce water loss from seepage; however, reducing seepage is not without unintended side effects. Currently, seepage loss from the canal network makes up a substantial component of return flows from CID to the Pecos River.

These return flows form an important part of New Mexico's state-line deliveries to Texas for compliance with the Compact.

Additionally, CID's diversion amounts are predicated on conveyance loss rates of 1.3 acre-feet per acre between Avalon Reservoir and the farms. If conveyance efficiencies were improved, this value could be reduced to compensate, since the farms are still only allotted 3.697 acre-feet per acre at their head gates. The district would still benefit in the form of simpler operations and the reduced likelihood of allotment reductions during water-short years, but full allotments in wet years would not be increased. However, the potential impacts to New Mexico's state-line delivery obligations (which can in turn impact CID through the 2003 Settlement Agreement) indicate that potential reductions in return flows should be considered when undertaking seepage or irrigation efficiency improvements.

Actions that could be taken to reduce seepage from the distribution network would include repairing existing lined sections of the main canal, lining the unlined sections, and lining lateral canals or converting them to pipes.

3.3.3.6.4. Operations

3.3.3.6.4.1. Gate Structures and Reach Operations

The current canal is not conducive to on-demand or automated operations. Currently, CID operates each reach independently and manually. Operation of the system at flows under 70 cfs is challenging. To hold conveyance losses to below 30%, throughout the system CID needs a minimum of 100 cfs in orders to start the system. Further, there is no way to access water pooled within reaches between gate structures after watering down.

Ideally, CID could use a series of step-down locks and gates to improve water delivery between reaches and throughout the system. Overshot gates could allow various levels of water to be diverted. An even pressure throughout the system would allow effective deliveries throughout the system. In a modernized canal that constantly holds water behind the gate, water orders could be carried efficiently through the canal system from the top and bottom. Coordinated systems such as that used in the Salt River Project in Arizona could be investigated.

3.3.3.6.4.2. Automation

CID is in the process of implementing a SCADA system, which facilitates remote monitoring, data collection, and automation, and plans to continue efforts to deploy automated systems within CID. With more efficient operations between structures, a SCADA system or other similar system for controlling monitoring and system automation would facilitate more efficient coordination of water deliveries to CID farmers. However, as with other modernizations, full automation of CID irrigation network is prohibitively expensive for the district to undertake without substantial outside assistance.

3.3.3.6.4.3. Avalon Cylinder Gates

Among the most needed repairs are the cylinder gates that control flows downstream of Avalon Reservoir. At present, these gates are inoperable, leaving only two options for releases from the reservoir: through the CID Main Canal or over the spillway. While for normal operations this does not pose major issues, the inoperability of these gates becomes problematic under the following circumstances:

- Under the 2003 Settlement Agreement, CID is required to release water from Avalon Reservoir to the Pecos River. If CID is required to make state-line deliveries of state-owned water rights, CID must fill up Avalon Reservoir completely to pass water over the spillway and down the river. The spillway is designed for emergency purposes—not for operational deliveries to the river. These deliveries are typically not conducted during the irrigation season (again, to reduce conveyance losses), leaving Avalon Reservoir full until the start of the next irrigation season. Inflows from any subsequent storm that cannot be captured in Brantley Reservoir (either from exceeding its conservation storage limit being exceeded or from inflows between the two reservoirs) will ultimately pass right through Avalon Reservoir and over the spillway, uncaptured and unusable.

- Even when releases from Avalon Reservoir are not required, CID is required to release a minimum of 20 cfs to the reach of the Pecos River between Brantley and Avalon Reservoirs to compensate for the water that flowed into the Pecos prior to the inundation of Major Johnson Springs by Brantley Reservoir. If Avalon Reservoir is full, any additional required releases from Brantley Reservoir will be unusable to CID as they will pass over the spillway at Avalon Reservoir.

With working gates, CID could end a state-line delivery with Avalon Reservoir empty, allowing subsequent storm flows to be captured and used at the start of the next irrigation season. Losses associated with required releases from Brantley Reservoir would also be avoided. However, retrofitting the 110-year-old structure at Avalon Dam is not considered viable, so other options for addressing this issue need to be studied. As the structure is part of New Mexico Historical Society, environmental and historical preservation issues need to be addressed. A proposed glory hole to bypass the gates and spillway would still require Avalon Reservoir to be filled to bypass the dam.

3.3.3.6.4.4. Metering

CID has made minimal use of metering instrumentation. Identifying and addressing the institutional barriers to widespread deployment of metering is estimated to potentially save 4,000 acre-feet annually (Ballard 2020).

3.3.3.6.4.5. Coordination with Required Downstream Flows

Irrigation districts have requested better coordination with Reclamation and the State of New Mexico to improve operations to manage state-line deliveries and losses.

3.3.3.6.5. Physical Barriers to Efficient Water Use

3.3.3.6.5.1. McMillan Lakebed

McMillan Dam was constructed in 1893 about 14 miles northwest of Carlsbad. In 1987 Reclamation completed its replacement, Brantley Dam, about 5 miles downstream, and in 1991 breached McMillan Dam and drained McMillan Reservoir, leaving behind a dry lakebed several square miles in area. Currently, the Kaiser Channel (a roughly 50-foot wide, man-made channel) conveys the Pecos River across the former lakebed; however, this channel is not always adequate to effectively convey flows into Brantley Reservoir (Figure 32).

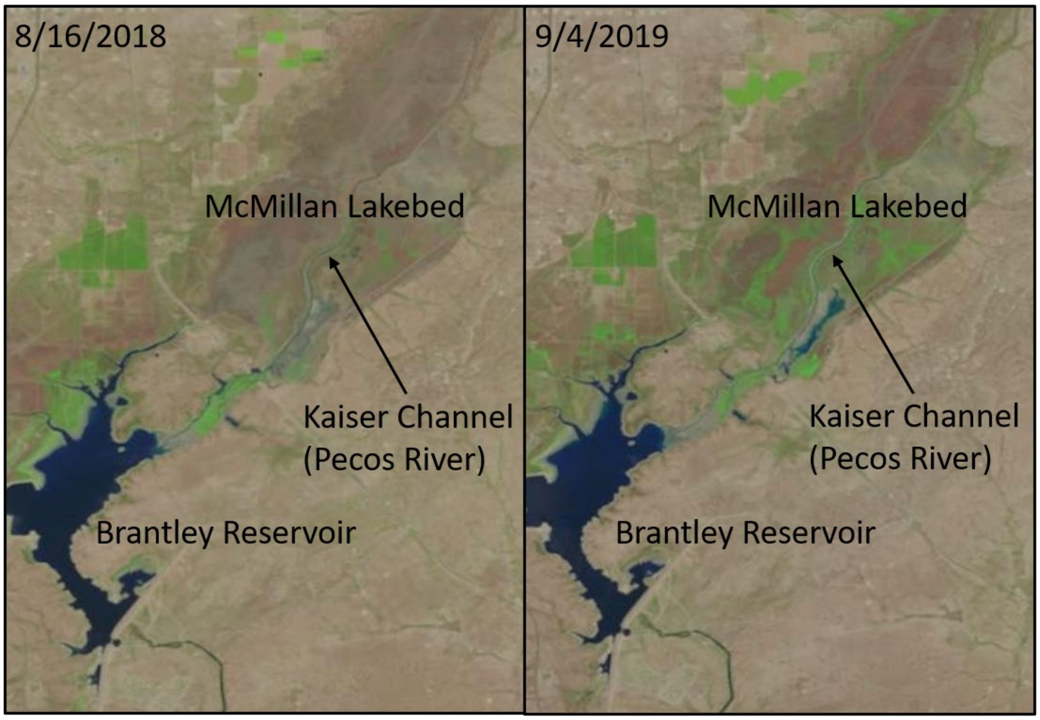


Figure 32. The McMillan lakebed above Brantley Reservoir (NMISC).

During block releases or heavy storm events, the channel can sometimes become clogged with huge masses of tumbleweeds, salt cedar, and other plant debris washed downstream by the high-volume flows. These clogs can reduce the channel capacity of the river, resulting in water backing up and spilling over the banks of the channel and into the dry lakebed. While some of this water infiltrates into the ground and continues to Brantley Reservoir, a significant portion ponds in the old lakebed and either evaporates or is consumed by the large stands of salt cedar and other vegetation that now cover the former lakebed. These effects are further exacerbated by excess sediment deposition where the river flows into Brantley Reservoir near where the old McMillan Dam was breached. At this point the river departs from the man-made channel entirely, forming a quarter-mile wide delta that further backs up water into the old lakebed. The delta itself forms an extensive marsh that consumes additional river water that would otherwise reach Brantley Reservoir.

Dredging or widening the existing channel would likely improve channel capacity and minimize loss of water to the McMillan lakebed and marshes at the entry to Brantley Reservoir. These actions would improve block release efficiencies, allowing CID to make better use of its reservoir storage. The significant challenge associated with these actions is their substantial cost, which exceeds CID's resources.

3.4. Water Use Other than Irrigated Agriculture

Irrigated agriculture is the largest water use in the study area by far. Apart from irrigated agriculture, other categories of water use, as defined by the NMOSE include:

- **Public Water Supply.** Community water systems relying on surface water or ground water diversions, including mutual domestic systems, mutual domestic water user associations, municipalities, prisons, residential and mixed-use subdivisions, and mobile home parks, golf courses, and parks, etc.

- **Self-Supplied Water.** Water from individual wells or diversions, includes:

    - **Domestic Wells.** Residences that depend on a well permit issued by NMOSE under 72-12-1.1 New Mexico Statutes Annotated (N.M.S.A.) 1978.

    - **Livestock.** Water used to raise livestock, maintain self-supplied livestock facilities, and provide for on-farm processing of poultry and dairy products.

    - **Commercial.** Self-supplied water for businesses such as restaurants, hotels, schools, hospitals, golf course, etc.

    - **Industrial.** Self-supplied water for enterprises that process raw materials or manufacture goods, includinging some large-scale construction projects.

    - **Mining.** Self-supplied enterprises that extract minerals from the earth such as coal, petroleum, and natural gas. These uses have spiked in recent years due to the oil/gas production boom in southeastern New Mexico, and therefore the numbers shown in Table 4 are lower than the current values.

- **Reservoir Evaporation.** Net evaporation from man-made reservoirs with a storage capacity of 5,000 acre-feet or more.

Table 4. Withdrawals in acre-feet in the Pecos River Basin in New Mexico 2015 (NMOSE 2019)

Category	Surface Water	Groundwater	Total Withdrawal
Commercial	8,455	6,119	14,574
Domestic	0	2,606	2,606
Industrial	0	2,024	2,024

Category	Surface Water	Groundwater	Total Withdrawal
Irrigated Agriculture	190,175	278,316	468,491
Livestock	659	9,245	9,904
Mining	0	20,783	20,783
Power	0	0	0
Public Water Supply	3,301	37,318	40,619
Reservoir Evaporation	42,821	0	42,821
River Basin Totals	245,411	356,410	601,821

3.4.1. Ecological Resources Water Use

A number of ecologically protected areas are scattered throughout the study area, including the Bitter Lake National Wildlife Refuge and the Wild and Scenic stretch of the river's headwaters (see Section 2.7.3. *Environmentally Protected Areas within the Basin* and the Environmental and Recreational Appendix). Except for riparian vegetation and wetland evapotranspiration, none of these protected reaches have direct consumptive use of water.

The 2016 BiOp established flow requirements at the Acme and Taiban gages (Figure 33). These flows and the methods used to meet these requirements (Vaughan Conservation Pipeline, Seven Rivers Exchange, the Sumner Lake Bypass around FSID, and the Fish Conservation Pool in Sumner Reservoir) are discussed in this subsection.

3.4.1.1. Acme and Taiban Gage Flow Targets

3.4.1.1.1. Gage Flow Targets

3.4.1.1.1.1. Target flows at Acme Gage (5 cfs)

According to the 2016 BiOp, flows above 5 cfs at Acme are an indicator of continuous flow in the river (Figure 34 and Figure 35 show the conditions at Acme at various flow levels). The primary goal of ESA operations for the threatened Pecos bluntnose shiner (*Notropis simus pecosensis*, shiner) is to maintain a constant flow of 5 cfs at Acme.

3.4.1.1.1.2. Target flows at Taiban Gage (35 cfs)

The 2016 BiOp also requires 35 cfs at the Taiban gage. The Taiban gage flow requirements for each year are determined in January based on the US Drought Monitor determination of drought in New Mexico. In critically dry years, this requirement does not have to be met so that flows at Acme can be met. If the drought classification in the Upper Pecos River New Mexico Basin is greater than or equal to 50% of the basin in extreme drought or exceptional drought, then the basin is determined to be critically dry. When in critically dry conditions, the 2016 BiOp requires a continuous river determined by 5 cfs at the Acme gage. Supplemental water supplies will not be used to meet target flows at the Taiban gage, but will be used for augmenting flows for the Acme gage.

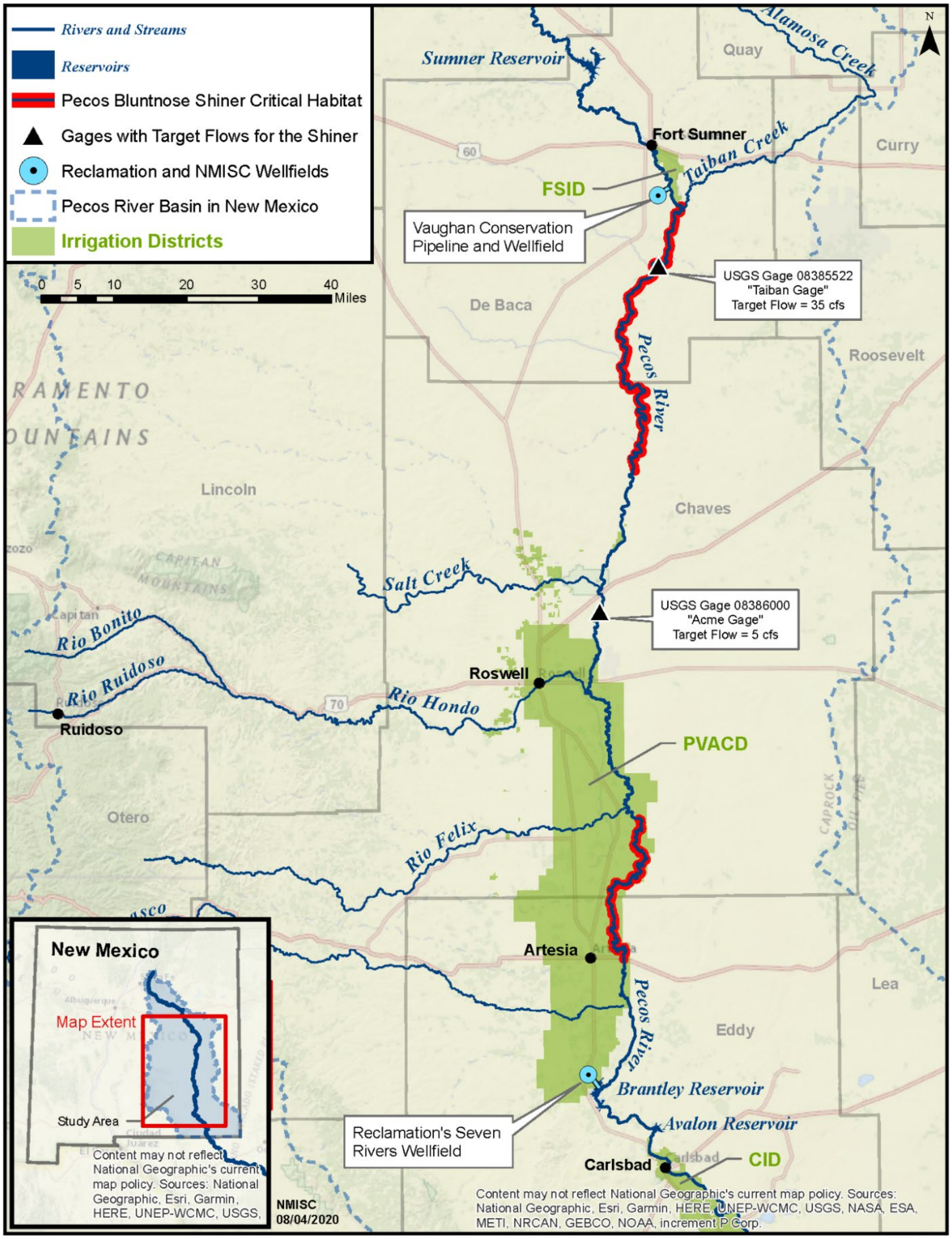


Figure 33. Gages and critical habitat for flow targets (NMISC).

Figure 34. Typical flow conditions at Acme (34.3 cfs) on April 18, 2011 (Reclamation).

Figure 35. Low flow conditions at Acme (1.9 cfs) on August 11, 2011 (Reclamation).

3.4.1.2. Flow Target Actions

Flow targets in the shiner's critical habitat reaches are prescribed by the 2016 BiOp. Reclamation's proposed actions are to divert water to storage, release Carlsbad Project water from storage, acquire additional water, and perform additional conservation measures to facilitate ESA compliance.

Criteria for these flow targets are:

1. Reclamation will divert water to storage, when water is available and flows at Acme are greater than 5 cfs under all hydrologic conditions, and flows at Taiban are greater than 35 cfs, except under critically dry hydrologic conditions. During critically dry hydrologic conditions, Reclamation will focus only on the Acme target flow. This action integrates senior water rights and non-discretionary actions.
2. Reclamation will deliver Carlsbad Project water from storage as contracted for irrigation, consistent with applicable Federal and state laws, and as per the block release constraints from Sumner Dam.
3. Reclamation will continue to use additional water from the bypass or the conservation pool to augment flows and avoid Pecos intermittency.

4. Reclamation will apply conservation measures to facilitate ESA compliance and acquire water to offset depletions to the Project.

Methods that Reclamation and partners use to meet the flow targets include:

- **Pumping supplemental water from the Vaughan Wellfield.** NMISC operates these groundwater wells near Fort Sumner to provide additional water to meet ESA flow requirements. The wellfield can produce approximately 8.5 cfs, depending on the groundwater levels. NMISC supplies the water and Reclamation provides funds for the operation and maintenance (O&M) of the wells, plus payment for water used. The Vaughan Wellfield is often referred to as the Vaughan Conservation Pipeline ("Vaughan Pumps" in the model.)
- **Using water from the Reclamation's Seven Rivers Wellfield in Brantley Reservoir.** The Seven Rivers wells pump water from Reclamation wells directly into Brantley Reservoir. Using a 25% loss rate of water traveling from Sumner Dam to Brantley Reservoir, Reclamation pumps an annual average of 750 acre-feet of water into Brantley Reservoir in exchange for 1,000 acre-feet in Sumner. The 1,000-acre-foot pool in Sumner is called the Fish Conservation Pool. This water is used to supplement CID irrigation demands and instream flow requirements ("Seven Rivers Exchange" in the model.)
- **Storing water in Sumner Reservoir.** An agreement between Reclamation and FSID resulted in Reclamation acquiring 2,500 acre-feet of water annually from FSID and storing this water in Sumner Reservoir for releases needed for the river to maintain ESA-required flows. Sumner Reservoir Bypass water is available before and after irrigation season and during irrigation season when FSID's two-week allotment is 100 cfs. This water is purchased by contractual agreement with downstream water right holders that used to pump water from the river or from surface water users that do not use their surface water. The bypassed water is the water not used by these river pumpers. ("Sumner Lake Bypass" in the model.) 500 acre-feet of water is held in Sumner Reservoir to release water to meet instream flow requirements. ("Sumner Lake Fish Conservation Pool" in the model.)

3.4.2. Municipal and Domestic Water Use

Municipal water use throughout the Pecos River Basin is relatively minor and generally depends on groundwater. The population in the entire basin is about 250,000 people: about 185,000 in New Mexico and 65,000 in Texas (Figure 36).

Figure 36. Counties and population centers in the study area (NMISC).

One area of concern to irrigation districts in the basin and their farmers is the growing number of subdivisions and domestic wells in the region and their impacts on water availability. This concern was voiced at Basin Study community outreach meetings. In years of low river flows, farmers rely on groundwater pumping and are concerned that over-permitting of domestic wells will result in water shortages.

3.4.3. Oil and Gas Water Use

Southeastern New Mexico has seen oil and gas production for over a century, and is currently experiencing a boom in production, due to fracking. Oil production in New Mexico hovered around 65 million barrels annually from 1981 to 2010, when oil production began to rise. Oil production in 2017 was almost 172 million barrels (Energy Information Administration [EIA] 2018). This increased production has in turn resulted in a rapid increase in the amount of water used by the oil and gas industry over just the past few years, an increase that has yet to be fully reflected in the numbers shown in Table 4 earlier in this section.

See Section 9.4. *Oil and Gas Produced Water* for possible strategies to address produced water from oil and gas hydro-fracturing (fracking).

3.4.4. Flood Control

The Pecos River Basin is prone to large precipitation events, so flood control is a critical reservoir function in the Pecos River Basin. USACE takes actions to control floods in the Pecos River Basin when reservoir elevations rise to designated critical levels, or when the Pecos River or its tributaries exceed threshold flow rates at designated control points. USACE operates four reservoirs in the Pecos River New Mexico Basin (Santa Rosa Reservoir, Sumner Reservoir, Brantley Reservoir, and Two Rivers Reservoir) as a coordinated system for flood risk management as described by USACE 1977. USACE also has flood risk management authority over Reclamation's Sumner Dam and Lake and Brantley Dam and Reservoir in accordance with a memorandum of understanding established between the two agencies. USACE conducts flood control operations on three dams and reservoirs on the Pecos River in New Mexico:

- **Santa Rosa Dam.** USACE owns and operates the Santa Rosa Dam and Lake Project (Santa Rosa Project) for flood risk management, water conservation, sediment retention, and incidental recreational benefits. The Santa Rosa Project is operated to limit river discharge in the reach from Santa Rosa Dam to Sumner Reservoir to non-damaging discharge rates insofar as possible. USACE currently considers the channel capacity downstream of Santa Rosa Dam to be 13,000 cfs as measured at the USGS Puerta de Luna river gage.

- **Fort Sumner Dam and Lake.** Reclamation's Sumner Dam and Lake is operated in coordination with the USACE Santa Rosa Project and Two Rivers Project to optimize flood risk management from Sumner Dam downstream to Brantley Reservoir. When there is flood storage in both Santa Rosa Reservoir and Sumner

Reservoir, flood risk management releases from both reservoirs are calculated to target maintaining a proportional balance—so that as far as possible, the Santa Rosa Project would hold 3.6 times more flood water than Sumner Reservoir. The channel capacity from Sumner Dam to Brantley Reservoir is currently 8,500 cfs as measured at Acme.

- **Brantley Dam.** Brantley Dam and Reservoir provide flood risk management for the mainstem of the Pecos River from Brantley Dam to Red Bluff Reservoir in Texas. Due to the large intervening drainage area between the upstream dams and Brantley Reservoir, and the relatively large channel capacity through Carlsbad, Brantley Dam is generally operated independently from the upstream Pecos River reservoirs for flood risk management purposes. Brantley Dam can safely release up to 20,000 cfs during a flood event; however, downstream channel capacities between Brantley and Red Bluff Reservoirs have been greatly reduced by the construction of low-clearance bridges in this reach. The effective channel capacity of the reach has not been assessed for channel capacity in light of this new construction, but the USACE has reduced block release rates significantly as a precaution to prevent potential infrastructure damage. This precaution will not apply if releases are needed for flood management purposes (Ross 2018).

USACE operates the Two Rivers Project on the Rio Hondo watershed upstream of Roswell for the dedicated purposes of flood risk management and sediment retention. The Two Rivers Project is operated primarily to provide flood risk management on the Rio Hondo and Rocky Arroyo[9] for the City of Roswell, as well as additional flood risk management for the mainstem of the Pecos River. Two Rivers is a "dry dam," meaning that it does not normally impound a lake behind the dam except when actively managing flood events. Channel capacities below Two Rivers are 1,000 cfs for the Rio Hondo and 900 cfs for Rocky Arroyo (USACE 2018).

[9]Note that this is a different Rocky Arroyo than the one between Brantley and Avalon that is used in the modeling.

4. Projection of Future Conditions

Understanding a range of possibilities for how future conditions may unfold is vital to preparing for the future. This chapter presents the model methodology, assumptions, inputs and results to explore potential changes and impacts within the Pecos Bain in New Mexico.

4.1. Future Meteorological and Hydrological Conditions

4.1.1. Temperature Changes

The Earth's surface, warmed by the sun, radiates heat into the atmosphere. Most of Earth's atmosphere is composed of simple gases like nitrogen and oxygen, which do not absorb heat, allowing heat to escape into space. However, other gases in the atmosphere, such as carbon dioxide (CO_2), water vapor, and methane have molecular structures that absorb and trap heat in Earth's atmosphere.

> Weather is a description of atmospheric conditions over a short period of time (days to weeks), while climate is how the atmosphere behaves over relatively long periods of time (decades to centuries or longer). Weather cannot be forecasted very far in advance, but long-term trends in the climate can be estimated.

The more of these greenhouse gases are in Earth's atmosphere, the more heat is trapped by the atmosphere. Although CO_2 concentrations have cycled up and down in the past, concentrations are currently higher than at any point in at least the past 800,000 years (see Zhang et al. 2013) (Figure 37). CO_2 concentrations were below 300 parts per million (ppm) throughout all of the last 800,000 years, and only rose above that ppm level in the Industrial Age of the last 200 years.

Humans continue to add carbon dioxide to the atmosphere at a rate far greater than its rate of removal by natural processes, creating a long-lived and growing reservoir of the gas in the atmosphere and oceans that is warming the atmosphere. Greenhouse gas emissions will continue to affect Earth's climate for the next century and far into the future beyond that (U.S. Global Change Research Program [USGCRP] 2018).

Atmospheric and oceanic warming can result in several changes to the earth, some of which warm the air even further. For example, as air and ocean temperatures rise, sea ice and mountain glaciers melt. The underlying land and ocean absorb more sunlight than ice, re-radiating this energy as heat and further warming the atmosphere and oceans.

Increased global temperatures are expected to lead to more precipitation falling as rain rather than snow, earlier snow melt, and increased evaporation and transpiration. Moreover, because warmer air can hold more moisture, a warmer atmosphere can hold more moisture, global ocean and atmospheric circulation patterns are changing.

The Southwest is considered one of the more sensitive regions in the world for increased risk of drought caused by climate change (Sheffield and Wood 2008 and USGCRP 2018) (see Section 4.3.3. *Temperature, Precipitation, and Runoff*). Changes in wind patterns could also lead to changes in the frequency and intensity of extreme storm events.

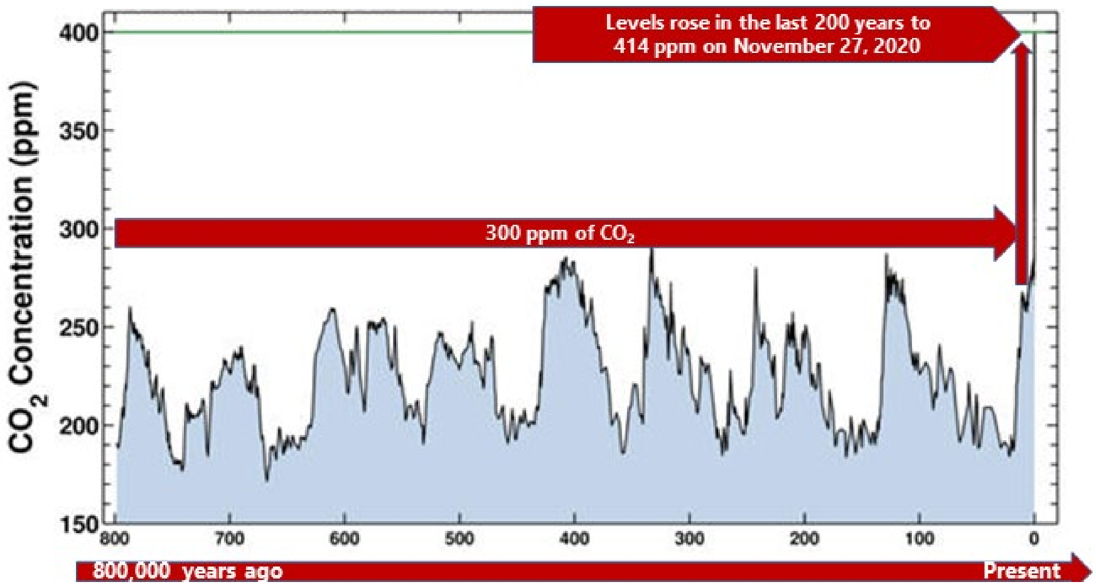


Figure 37. CO_2 in the atmosphere from 800,000 years ago to present (Reclamation, adapted from Scripps Institution of Oceanography at University of California San Diego [2019]). Data before 1958 is from ice cores. Data after 1958 is from the Mauna Loa, Hawaii, observatory. Current CO_2 levels from CO2.earth, 2020.

4.1.2. Literature Overview of Future Climatic and Hydrological Conditions

This Basin Study's analyses correspond with general findings from other studies for future ranges of temperature and hydrology and the issues that these pose for future water supply availability and reliability. The Climate Appendix includes a more detailed study of projected temperature and hydrologic changes over the next century. See Reclamation 2013 for a more complete literature synthesis.

> "Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands." USGRCP 2018, Southwest Water Resources Overview.

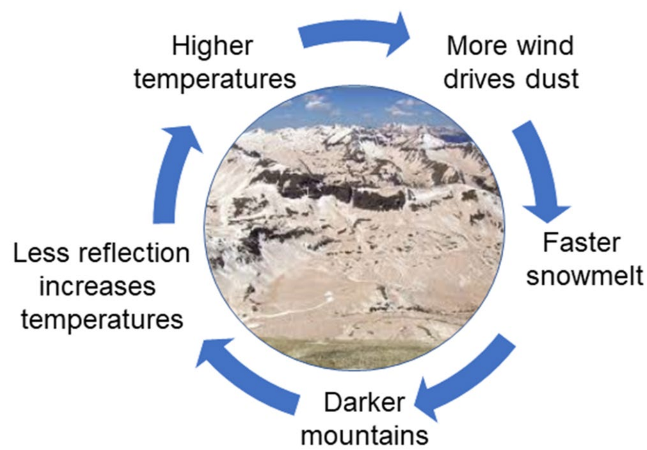
Future temperature increases will lead to drier conditions through increased evapotranspiration, regardless of the prevailing precipitation pattern (Wehner et al. 2011). While climate change will not present new challenges in the West, it will exacerbate current challenges to the point where resources may be stretched beyond the limits (Dettinger et al. 2015). In the Pecos, changes in precipitation, stream flows, and potential evapotranspiration may make balancing irrigation needs, Compact obligations, and environmental flows more difficult.

4.1.3. Feedbacks and Cascading Impacts

Feedback loops occur when a process or system is influenced by its own outputs. In a positive feedback loop, the output tends to amplify the process—leading to a stronger effect and possible exponential increase of the output. Conversely, in a negative feedback loop, the outputs inhibit the process—making the system self-limiting or cyclical.

Feedback loops are important in climatology, with the classic example of a positive feedback being the "ice-albedo effect:" as more snow and ice melt, the albedo (reflectivity) of the surface decreases, leading to greater solar energy absorption, which in turn increases the rate of melt. In contrast, clouds (which can reflect incoming solar radiation, but also absorb and re-emit outgoing thermal radiation) can serve as a positive or a negative feedback to the climate, depending on factors such as their altitude and thickness.

Positive feedback loops amplify changes, and negative feedback loops dampen changes. When systems such as the earth's climate feature multiple feedback loops, some positive and negative, predictive modeling can become much more complex.



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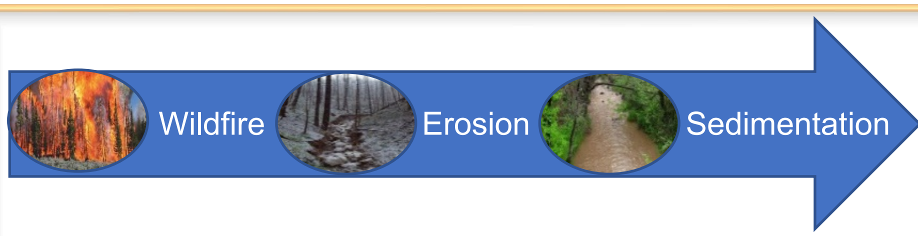
Cascades of changes occur when a single event or change to a system leads to sequential and interrelated effects throughout the system as a result of the initial disturbance. For example, an infestation of pine beetles in a mountain forest increases the number of dead trees, which in turn drier conditions in a forest increases the chance of major forest fires. Major fires increase the erodibility of soils, which in turn leads to significant erosion during subsequent storms and thereby to increased sediment loads in nearby streams (Sankey et al. 2017). Sediment-choked streams could then cause a fish kill, which could then have its own further cascading effects on local wildlife or people that depend on the fish as a food source.



Given the complexity of most natural systems, cascades of change are common. When examining potential impacts of a predicted change, possible indirect outcomes that may result from the cascade effect should be considered. For example, "burned areas increase soil erosion rates within watersheds, which can increase sedimentation in downstream rivers and reservoirs" (Sankey et al. 2017).

4.2. Model Methodology

In this Basin Study, we developed model projections showing a range of potential future hydrologic and water management conditions in the basin. To develop this range, we first reviewed and analyzed the range of possible future hydrologic conditions (e.g., river flows, temperatures, precipitation, and evapotranspiration) and then chose and modeled five representative "storylines" (i.e., a model projection—a set of future hydrologic conditions caused by future hydrological trends discussed in Section 4.1.). These five chosen storylines have model inputs and outputs that are within the range of potential changes for the basin (See Section 4.3.1. *Storyline Projections* for the selection process). These storylines incorporate both global climate projections and greenhouse gas concentration trajectories, the bias correction and downscaling of these climate projections, and hydrologic modeling.

> **A "What if" approach**
> We consider a range of various futures, called storylines to develop flexible, long-term plans and decision making where future conditions are uncertain (e.g., What if drier conditions prevail? What if precipitation timing changes so more rain falls in the monsoon and there is less snow?) Developing and analyzing a range of storylines that capture these "what-ifs" is a way to examine how water management strategies may help address water supplies under a range of potential storylines.

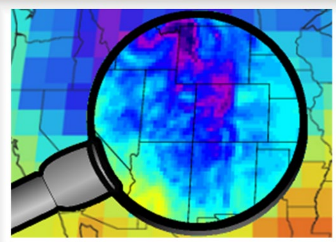
This modeled analysis thus uses these hypothetical future conditions described in the future storylines to determine "baseline conditions" for each storyline (i.e., what is projected to happen in the future under a particular storyline if no actions are taken). These are termed "storyline baselines" in this Basin Study. These initial modeling runs create an initial set of critical observations that are used as a basis for comparison to assess the potential success of the proposed adaptive strategies under each storyline.

We then worked with FSID, CID, and PVACD to develop and model water management strategies, which are approaches to maintaining a vibrant agricultural community in the Pecos Basin in New Mexico to model enough strategies to provide a roadmap for future planning. Note that the quantitative modeling analyses performed for this study are limited to the irrigation districts, and the infrastructure (including Federal reservoirs) that support their operations. Other uses of water in the basin, by acequias, ranches, independent groundwater-based agriculture, municipalities, and industrial uses (including oil and gas extraction), are described qualitatively, but were not included in the modeling analyses performed for this Basin Study.

4.2.1. Global Climate Model Projections

Global Climate Models (GCM) are numerical representations of physical processes in the atmosphere, ocean, cryosphere, and land surface, and are currently the most advanced tool for simulating the earth's response to increasing concentrations of greenhouse gases. For this study, USACE provided hydroclimate projections, which originated from 93 GCM simulations included in the Coupled Model Intercomparison Project Phase 5 (CMIP5) World Climate Research Programme (WCRP) (2018) archive. CMIP is a collaborative effort by the WCRP that enables standardization and comparison of climate models within the international climate-modeling community. CMIP5 models represent the most recent climate modeling activity and were the basis of the IPCC Fifth Assessment Report, released in 2014. They represent the best available understanding of future climate. CMIP5 models are based on standard model scenarios to examine climate "predictability" and exploring the predictive capabilities of forecast systems over decades (Intergovernmental Panel on Climate Change [IPCC] 2013 and Emori et al. 2016). These models help improve our knowledge and understanding of future climate change.

"CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze GCMs in a systematic fashion, a process which serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception in 1995." World Climate Research Programme 2020



Downscaling is the general name for a procedure to take information known at large scales to make predictions at local scales.

4.2.2. Downscaling from Global Climate Models to the Upper Pecos River Basin

The GCMs are global-scale models with large model grid sizes and coarse spatial resolution. To assess potential changes caused by climate on a smaller regional scale, the model domain was revised, and the area of interest was limited to part of New Mexico. Numerous methods have been developed to downscale coarse-resolution GCM simulations to finer spatial resolution over a selected area to support regional and basin-scale analyses, planning, and decision making. USACE applied downscaling and bias correction techniques to the flow projections for 1950-2099 for the 9 river gages along the Pecos River from the Variable Infiltration Capacity (VIC) and Precipitation Runoff Modeling System (PRMS) models (see Section 4.2.5. *Operations Modeling)*.

4.2.3. Representative Concentration Pathways

The GCM simulations are based on past measurements and projections of future trends in atmospheric greenhouse gas emissions. Different assumptions for emissions trends produce different concentration projections, and different accumulations of heat in earth's atmospheres, termed representative concentration pathways (RCP). Figure 38 shows the projected increases in atmospheric CO_2 concentrations based on four different potential trends in greenhouse gas emissions. Figure 39 shows the expected increases in global annual temperature based on these four projections of greenhouse gas concentrations. The lower RCP values represent lower projected levels of greenhouse gas concentrations than the higher values. To analyze a wide range of possible future scenarios, we examined Higher Emissions (HE) (RCP 8.5) projections, which assume that emissions will continue to increase throughout the 21st century as well as Lower Emissions (LE) (RCP 4.5) projections, which assume emissions will peak around 2040 and then decline.

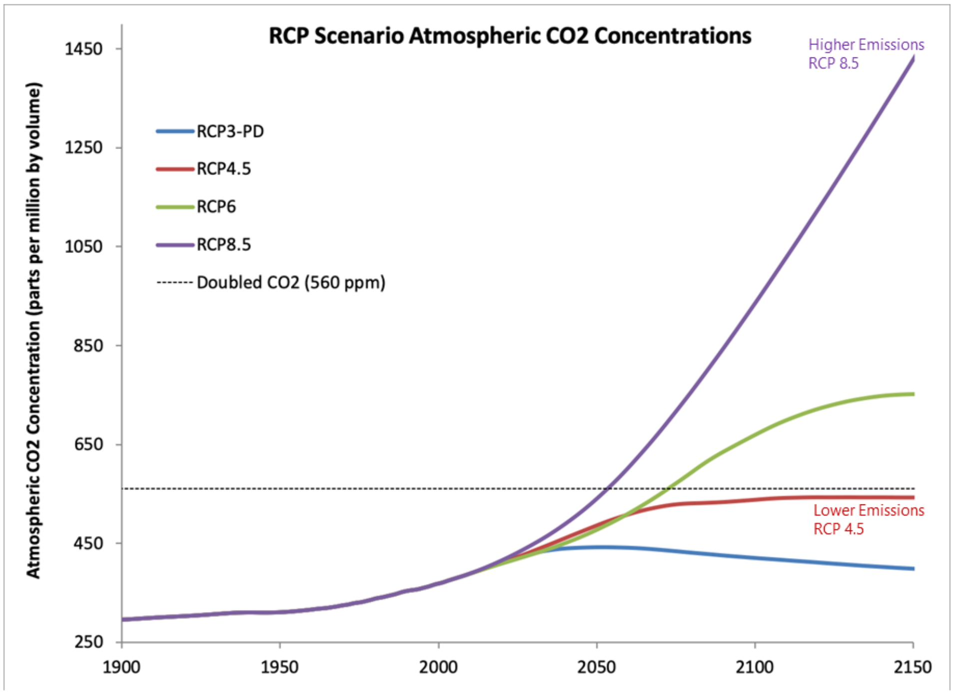


Figure 38. Time series of projected CO_2 concentrations under four RCP scenarios (Dana Nuccitelli, all rights reserved).

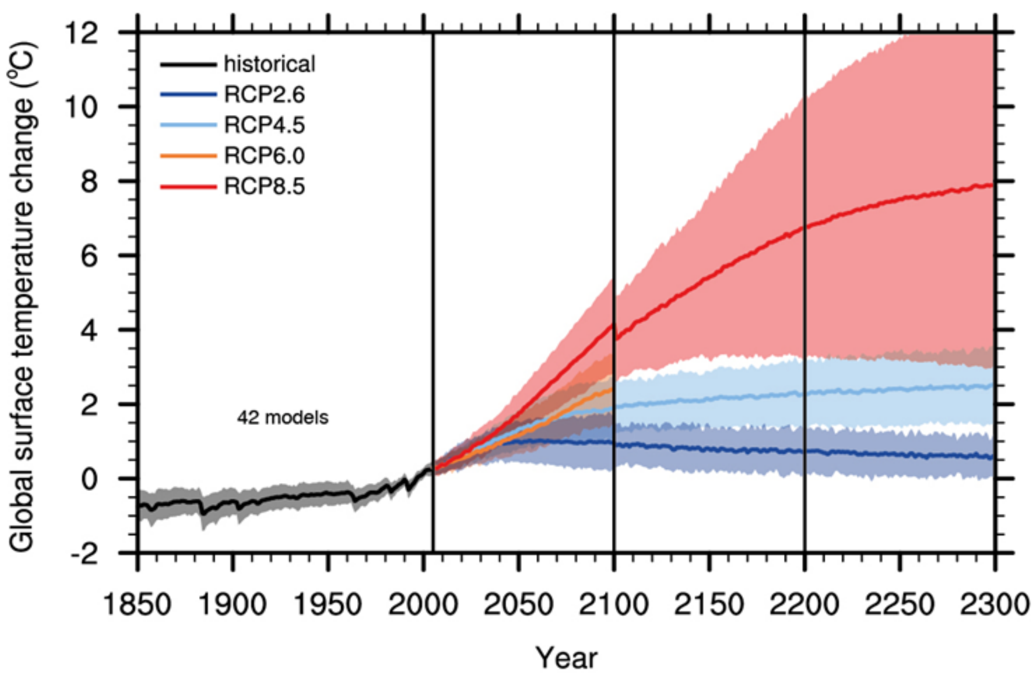


Figure 39. Time series of global annual mean surface air temperature anomalies (relative to 1986 through 2005) from CMIP5 concentration-driven experiments (adapted from Collins et al. 2013, all rights reserved).

4.2.3.1. Higher Emissions (RCP 8.5)

The Higher Emissions (RCP 8.5) projections assume that there would be no major changes to current energy use, consumption, and development practices. This future scenario would lead to high energy demands and greenhouse gas emissions in absence of climate change policies. To develop likely storylines if emissions projections continue to increase on the current trajectory, we evaluated the 28 projections that used the Higher Emissions (RCP 8.5) pathway where greenhouse gas concentrations and radiative forcing continue to rise after year 2100 (Figure 38). We selected the HE Moderate, HE Dry, and HE HMLS Storylines as the projections that represent a range of potential climate storylines under these conditions. See Section 4.3.1 for storyline selection methods.

4.2.3.2. Lower Emissions (RCP 4.5)

The Lower Emissions (RCP 4.5) projections assume a future in which carbon dioxide emissions worldwide start to fall around 2040, and then decrease below current levels by 2070. Atmospheric concentrations stabilize by 2099 to levels at about twice the levels of the pre-industrial period (using the year 1850 as representative of this period). This future could be achieved with stringent climate policies, lower energy use, reforestation, and other actions to reduce levels of carbon dioxide in the atmosphere (Figure 38). We selected the LE Median and LE Increased Monsoon storylines as projections that represent a range of potential climate storylines under these conditions. See Section 4.3.1 on storyline selection methods.

4.2.4. Isolating Climate and Hydrological Projections from Development Projections

Projecting what future development or management actions may be, such as how population may change, how power generation may evolve, or how land use—including the amount and type of irrigated agriculture—may change is beyond the scope of this study. While factors like these would undoubtedly be affected by increasing temperatures and changing precipitation patterns, these factors are also changing due to other societal and economic pressures.

Therefore, this analysis assumes that current patterns of development within the study area will continue. This assumption simplifies our analysis, allows us to isolate the potential impacts of future climate and hydrologic conditions, and enables us to simulate different water demand and supply patterns and to evaluate how well adapted they are to projected conditions.

4.2.5. Operations Modeling

We used the Pecos River Operations Model (PROM) to simulate what would happen to water supply, demands, and operations in the Pecos River Basin in New Mexico under the five storylines. The PROM is an operations model for the Pecos River Basin developed in RiverWare™ by Reclamation, USACE, NMISC and others (Boroughs and Stockton 2010 and Center for Advanced Decision Support for Water and Environmental Systems [CADSWES] 2017). This model was developed per the 1991 Biological Opinion for the Bluntnose Shiner after the shiner was listed as federally threatened under the ESA.

The model is a daily time-step operations computer model of the Pecos River and is used to analyze the effects of different operational scenarios on affected water resources. All PROM runs completed for this study were run at a daily time-step.

The historically modeled period assumes that 2017 operations and infrastructure were in place for the entire historical record. Thus, there are differences between the actual historical record and the historically modeled period. As shown in Figure 40, modeled projections provide data that characterize future evapotranspiration, temperature, and precipitation in the basin.

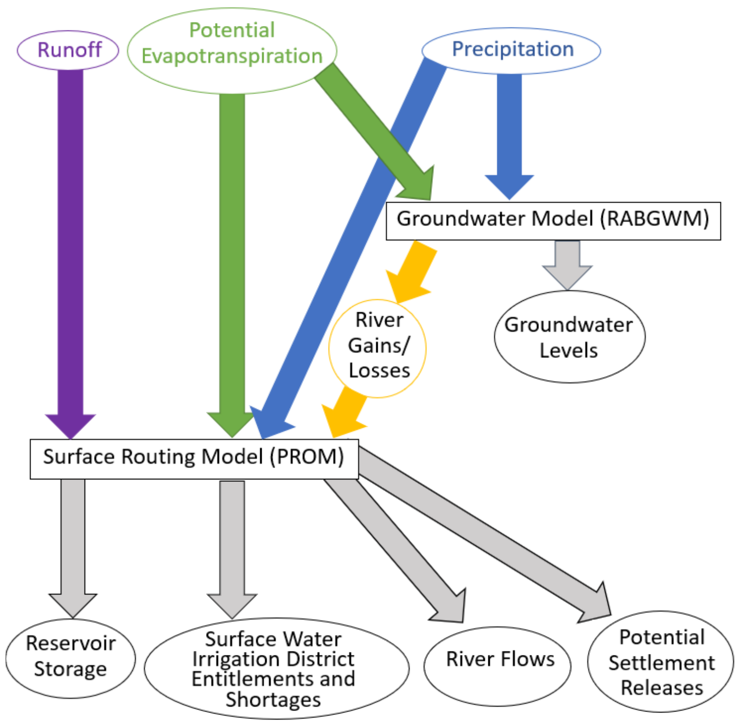


Figure 40. Inputs for modeling surface water (PROM) and groundwater (Roswell Artesian Basin Groundwater Model [RABGWM]) projected changes in the five parameters (reservoir storage, surface water districts, river flows, settlement releases, and groundwater (Reclamation).

As shown in Figure 40, PROM then used surface water supply and demand information (runoff, potential evapotranspiration, precipitation, and river gains and losses) to develop projections for reservoir storage, irrigation shortages, FSID entitlements, CID allotments, and instream flow requirements for environmental and settlement releases. See the PROM and MODFLOW appendices for model development and initial model set-up.

4.2.5.1. Surface Water Inputs

PROM used inflow data from nine gage locations (Figure 41):

- Pecos River above Santa Rosa Lake (USGS Gage 08382650)
- Rio Hondo near Roswell (USGS Gage 08393610)
- Rio Felix at Old Highway Bridge near Hagerman (USGS Gage 08394500)

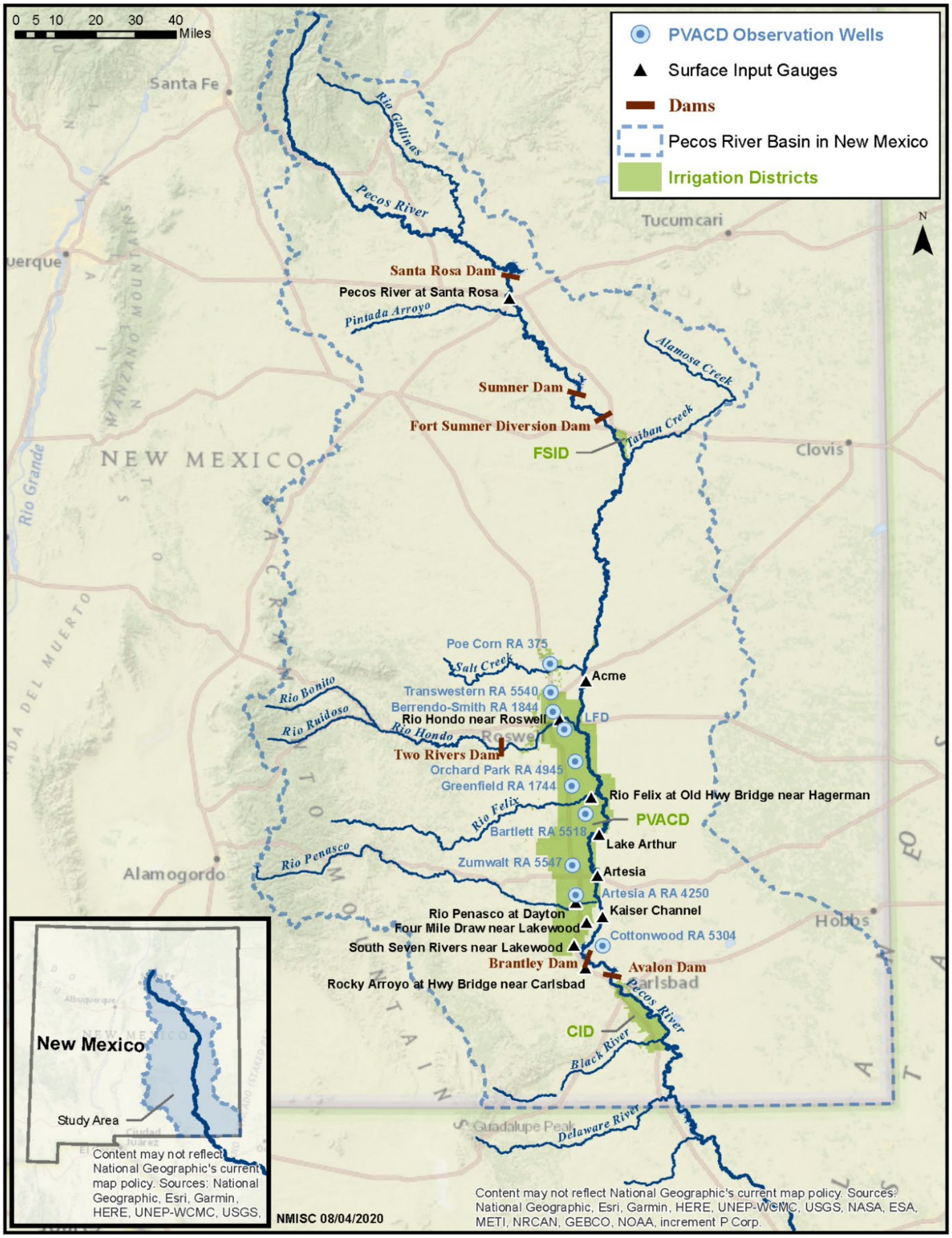


Figure 41. Surface input gages and well locations (NMISC).

- Rio Peñasco at Dayton (USGS Gage 08398500)
- Four Mile Draw near Lakewood (USGS Gage 08400000)
- South Seven Rivers near Lakewood (USGS Gage 08401200)
- Rocky Arroyo at Highway Bridge near Carlsbad (USGS Gage 08401900)
- Dark Canyon at Carlsbad (USGS Gage 08405150)
- Black River at Malaga along the Pecos River (USGS Gage 0406000)

The most downstream two gages (Dark Canyon and Black River) are part of the PROM; however, since they are downstream of all irrigation districts and areas modeled in the study, they have no impact on the outcomes modeled in this study.

4.2.5.2. Assumptions

Pecos River Operations Model (PROM) assumptions include:

- When making decisions about block releases, the model considers both individual reservoir storage limits and the total maximum storage permitted in the system. See Section 3.2. *Water Development: Dams and Reservoirs* for details on reservoir storage limits.

- Infrastructure and operations in place for 2017 exist for the entire 1950-2099 period. While this is not historically accurate, it does provide a consistent basis for comparison. Operational assumptions include:

    - The simplified Settlement Delivery calculation in the model simulates releases by CID to fulfill its obligations under the 2003 Settlement Agreement (see Section 3.1.4). In reality, these deliveries depend on both the amount of water in the Carlsbad Project Supply and the amount of cumulative Compact credit New Mexico has accumulated. However, the latter factor is not incorporated into the model, which assumes that the Compact credit remains below the threshold where it becomes a consideration.

    - FSID will always divert all their entitled water. In reality, they will occasionally defer some to all of their entitled water.

    - When calculating for crop demand and shortages, PROM uses constant values of irrigated acreage for every year (see Surface Water Modeling Appendix).

- PROM's physical assumptions include:

    - All overland and other un-gaged flows (flows that are not accounted for in the model by gages or groundwater interaction) are accounted for through modeled tributary inflows and model calibration.

- That gains from groundwater to surface water in the Puerto de Luna reach change daily, but do not change annually. Thus, the daily values for one year were repeated for each year of the analysis (e.g., the groundwater flow for April 1 was the same for April 1, 1950; April 1, 1951; and so on). See the Groundwater Base Case (i.e., groundwater conditions in the year 2010 repeated each year for the 100-year analysis period) discussion in Section 4.2.6. *Roswell Artesian Basin Groundwater Model*.

- The MODFLOW results for gains and losses in PROM between Acme to Brantley Reservoirs are accurately portraying surface and groundwater interactions.

- Un-gauged flows between Santa Rosa and Hagerman are analogous to flows along the Rio Hondo and Rio Felix, so that a year of high flows along those two tributaries will result in high un-gauged inflow volumes between Santa Rosa and Hagerman (vice versa for dry years). Un-gauged inflows between Hagerman and Brantley Reservoir are similarly analogous to Rio Peñasco flows.

- Precipitation over Santa Rosa Reservoir and Sumner Reservoir is analogous to flows along the Rio Hondo and Rio Felix. In the model, monthly precipitation over the reservoirs is distributed proportionally on days that Rio Hondo and Rio Felix flow. The same process is followed for Brantley and Avalon Reservoirs, where precipitation is proportioned based on flows in Rocky Arroyo.

4.2.6. Roswell Artesian Basin Groundwater Model

In 1995, the New Mexico State Engineer Office had an outside contractor construct a MODFLOW numerical ground-water flow model of the Roswell Underground Water Basin in New Mexico, the Roswell Artesian Basin Groundwater Model (RABGWM) (DBSA 1995). The model is a quasi-three-dimensional groundwater flow model that consists of two layers (aquifers) separated by a semi-confining unit. The upper layer represents the shallow aquifer comprised of valley fill. The semi-confining unit is represented in the model by a leakance term between the two aquifers. The lower layer represents the confined carbonate aquifer (see Section 2.2.3. *Surface Water/Groundwater Interactions*. NMOSE uses this model to administer water in the basin.

Groundwater flow is modeled with RABGWM. Groundwater in the artesian and shallow aquifers flows towards the Pecos River, along the eastern margin of the basin. Most groundwater that is not intercepted by wells discharges either to the Pecos River or is consumed by riparian vegetation along the river corridor. Figure 41 shows the well locations used for input into the RABGWM.

RABGWM simulates irrigation of roughly 110,000 acres in PVACD. In reality, this number varies by year; however, to focus the groundwater analyses on long-term trends rather than any specific annual stresses or variations, the groundwater model was configured to simulate conditions from a typical historical year (the Groundwater Base Case year), 2010, and repeats those conditions through 2099.[10] In Figure 42, 2010 stresses are indicated by the labeled red bar. Box and whisker plots of the quartiles and outliers, respectively, indicate that the 2010 values are within the range and typical variation for the historical period. Pumping for 2010 is between the historical mean and median.

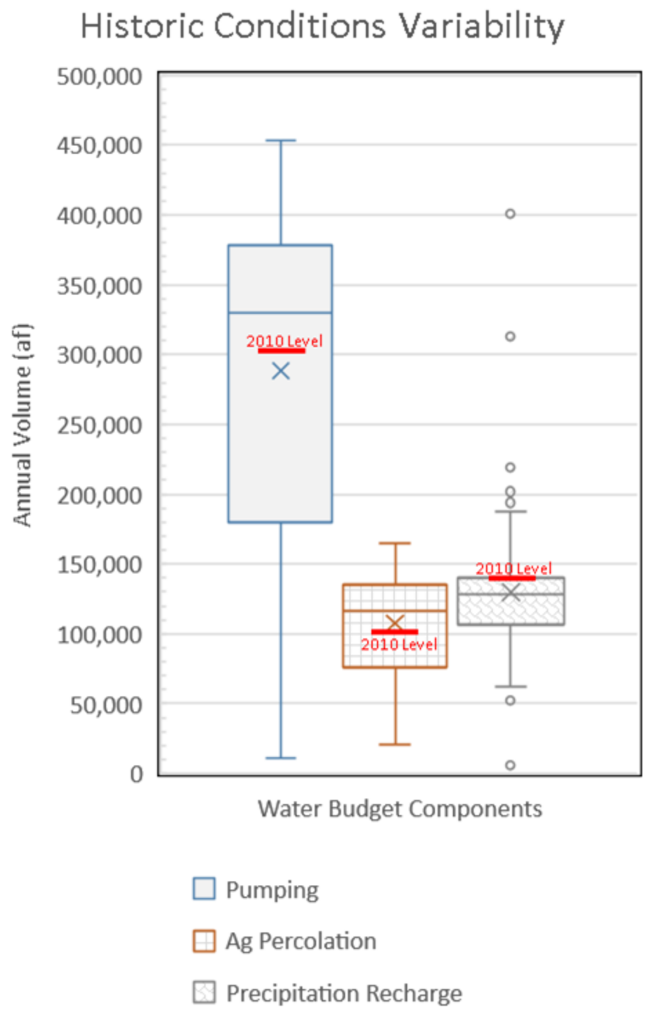


Figure 42. Historical water budget components showing that the Base Case year 2010 falls within the typical range. The whiskers represent the range of historical pumping, agricultural percolation (return flows), and precipitation recharge. The box represents quartiles, the X is the mean value, and the dots represent outliers.

The year 2010 was selected as the Base Case year since it is relatively recent and has values of pumping, agricultural recharge and precipitation that are consistent with those from the last 30 years. Note that agricultural recharge in 2010 was slightly below the mean and median, while the 2010 precipitation was slightly above the mean and median.
roundwater pumping in 2010 was close in volume to the historical median (igure 42) and consistent with use over the prior 30 years. hile 2010 pumping is towards the lower end of pumping during the last five complete years of the 1900-2013 AB M simulation period, the combination of pumping, agricultural recharge and precipitation stresses being consistent within the last 30 years and 2010 being relatively recent, support the choice of 2010 as the base year.

[10] The 2010 Groundwater Base Case may underestimate current pumping, as it depends on assumptions made by the NMOSE Water Master related to the total acreage in irrigation (the irrigation rate in acre-feet/acre is calculated as total pumping divided by that assumed acreage, which is not verified annually). The Groundwater Base Case also does not account for variation in pumping due to the 5-year accounting regulations for the RAB In the RAB, water-rights owners may use their 5 years of water rights over the accounting period however they choose, from distributing pumping evenly across all five years to pumping all water rights in one year of the five. See Section 3.3.2.4.2. *PVACD Water Rights and Pumping*.

Repeating seasonal conditions from the 2010 Groundwater Base Case year provides a simulation period of 90 years with only seasonal cycling of stresses and no trending or variation in the annual stresses. The pattern of repeated 2010 stresses (pumping, recharge, etc.) provides a baseline against which Storyline and Strategy changes in the other simulations can be compared.

Selecting a Base Case year, in this case 2010, has implications regarding the specific values for a variety of model inputs and outputs, but in no way changes the fundamental process of evaluating impacts from Storylines, Water Footprints, and Water Management Strategies. Using pumping as an example, if a different Base Case year is selected, differences between that year and 2010 pumping may affect timing of when the system reaches specific conditions but does not affect trending and the associated evaluation between storyline and strategy impacts. For example, if a pumping rate higher than the 2010 rate is used, then pumping in all subsequent years would also be higher and would reach water rights or physical limits sooner than what would happen under projections using the 2010 Groundwater Base Case. By the same logic, starting with values lower than the 2010 pumping rate would mean that water rights or physical limits would be reached later in the simulation. While this does not affect the comparison between projections, it is worth considering when assessing other factors such as timing and duration of changes.

All model runs use the same initial water levels: modeled water levels from the historical RABGWM simulation at the end of 2009. These initial water levels represent the transient conditions at the end of 2009. From these initial values, water levels in the Base Case simulations then adjust in response to the repeated 2010 stresses. The water level changes in the Base Case simulation reflect adjustment of the basin as it moves towards equilibrium with the repeated 2010 stresses. These minor Groundwater Base Case water-level adjustments can be seen in the Groundwater Appendix. While the modeled Base Case water levels exhibit some minor changes as the basin storage adjusts to the repeated 2010 stresses, these changes are consistent across all model runs—therefore canceling out when assessing Storyline and/or Strategy impacts relative to the baseline.

Agricultural recharge for 2010 is just slightly below the mean and median, while the 2010 precipitation is slightly above the mean and median. These inputs combine to represent 2010 conditions, which are well within the range of a typical historical year:

- **Pumping** was limited in the model to 3.5 acre-feet/acre. Once pumping rates reached this level (the maximum amount that can be pumped per acre of water rights owned in the RAB), the level did not increase—regardless of demands indicated by storyline trending. This limit only needed to be invoked for the HE Dry Storyline.

- **Evapotranspiration** was adjusted to reflect increased demand associated with increasing temperatures.

- **Recharge** was adjusted to reflect trends in precipitation and pumping.

- **Recharge proportions** remained the same for the simulation period as a percentage of both precipitation and agricultural pumping.
- **Irrigated area** was kept fixed at 110,000 acres and is compatible with the 2010 Water Master's report for the Roswell Aquifer Basin, with a total of about 113,000 acres (Thomas 2010). Pumping adjustments were used as surrogates for adjustments of irrigated acreage.
- **Western boundary recharge** was held constant for all storylines, reflecting the long response time associated with impacts of climate changes on inflows at the western boundary of the model. Published discussions (e.g., Duffy and Gelhar 1978, Newton et al. 2012, Eastoe and Rodney 2014, and Rawling et al. 2014) depict a process of artesian aquifer recharge from the Western Boundary on the order of hundreds to thousands of years.

See the Groundwater Appendix for additional details on the groundwater model and results.

4.3. Storyline Projections

To examine the effect of water management strategies under a range of possible future conditions, we selected five storylines based on scientifically modeled projections of potential future meteorological and hydrological conditions.

> We need to plan to help ensure that future water supplies will be able to meet future water demands. Projections for planning require reasonable assumptions about our future, and we used the best available information and consistent methodology to develop these modeled storylines.

4.3.1. Selecting Storylines for the Pecos River Basin

Modeling and analysis of all 93 downscaled-bias corrected GCM simulations (i.e., projections), along with multiple hydrological models and bias-correction techniques, would require excessive computing power and a herculean analytical effort. To make this modeling effort more manageable, the storyline approach selected five statistically reasonable projections from the many possible projections. The multistep process of narrowing down our 93 projections to just five storylines is described below and shown in Figure 43.

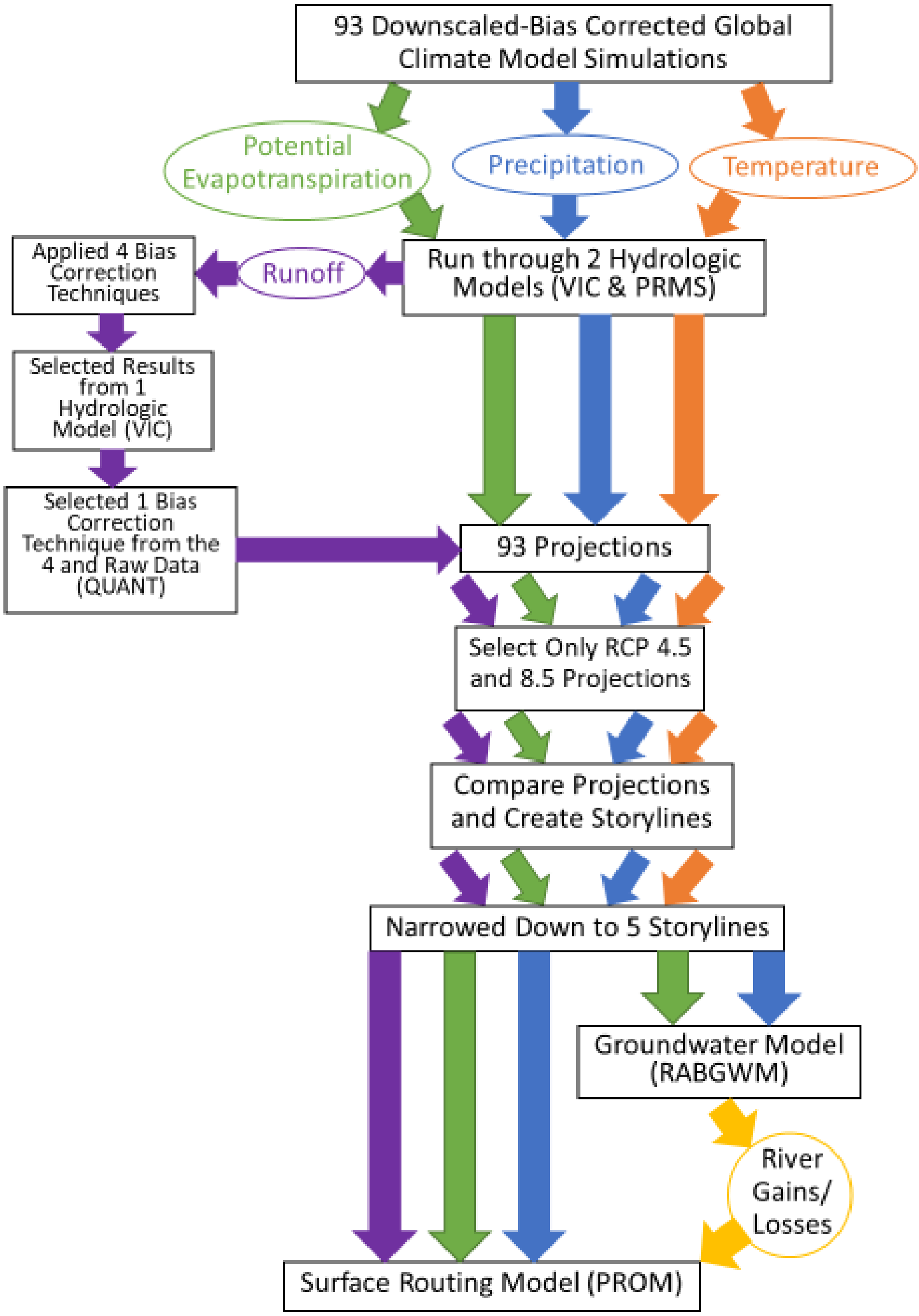


Figure 43. Flow chart for developing and selecting GCM simulations for the five storylines. (VIC = Variable Infiltration Capacity, PRMS = Precipitation Runoff Modeling System, QUANT = Quantile Mapping, RAB = Roswell Artesian Basin, and PROM = Pecos River Operations Model).

The modelers began with the 93 downscaled and bias corrected projections as described in Section 4.2.1, which produced outputs for precipitation, temperature, and potential evapotranspiration for the Pecos River Basin in New Mexico. These outputs were then run through two hydrological models (VIC and PRMS). Runoff outputs were further bias corrected using four bias correction techniques. From these preliminary steps, we selected the VIC model as it had more tributaries that were available for output. Based on a statistical comparison of the historical model data and historical gage data, the most robust runoff projections were processed using the Quant (Quantile Mapping) streamflow bias correction technique, and thus we carried this method forward in this study. Consistent with the Fourth National Climate Assessment (USGCRP, 2018) we have selected our storylines from a range of higher emissions (RCP 8.5) scenarios and lower emissions RCP 4.5 scenarios to ensure a range of possible futures are considered. These projections went through a detailed comparative analysis of temperatures, evapotranspiration, precipitation, and runoff to inform selection of five distinct but statistically viable representations of possible future conditions (i.e., the five storylines). For a more detailed description of the full storyline selection process, please see the Surface Water Modeling Appendix.

> By running the models for the storylines and then for each strategy under each storyline, we can compare what would happen with and without actions.

4.3.2. Summary of Storyline Baseline Projections

The modeling performed for this study, as well as numerous other studies, shows that temperatures in the basin are currently increasing—and will likely continue to increase.

Precipitation in the basin will likely change in total volume, spatial distribution, and timing. Changes in winter precipitation, from snow to rain, are already occurring—and are nearly certain to continue. In addition, any snow that does accumulate in the mountains will likely melt off earlier in the season—and may do so more quickly due to an increased likelihood of rain-on-snow events. Changes in the seasonality of precipitation are also likely. Monsoon storm events may become more intense (i.e., provide more precipitation in one event than historical storms have). Operational changes may be needed to more effectively use water that rapidly enters the basin either from rapid snowmelt runoff or from more intense monsoon storms.

This modeled analysis uses hypothetical future conditions as described in the future storylines to determine "baseline conditions" for each storyline (i.e., what is projected to happen in the future if no actions are taken). These initial modeling runs create an initial set of critical observations that are used as a basis for comparison to assess the potential success of the proposed adaptive strategies under each storyline.

> This study and other modeling and planning studies analyzing future conditions in New Mexico predict rising air and water temperatures. Most model simulations further predict numerous consequences of these rising temperatures, including:
>
> - An associated increase in water loss through evaporation and transpiration by plants
> - Decreasing snowpack
> - Smaller/earlier spring runoff
> - Changes in water availability and timing
> - More frequent high intensity precipitation events

Higher Emissions (HE) Storylines (RCP 8.5)

What would happen if human development and energy use continue according to current trends? These conditions are referred to as Higher Emissions (HE) and are modeled in climate models using RCP 8.5 future conditions, which are associated with high population growth and high fossil-fuel use, coupled with relatively slow income growth, and modest rates of technological improvement throughout the world. The HE future scenario would lead to high energy demands and greenhouse gas emissions.

The three HE storylines (HE High Monsoon/Low Snowpack (HMLS), HE Moderate, and HE Dry Storylines) are selected projections that represent a range of potential climate storylines that may result from Higher Emissions conditions. In the three HE Storylines, temperatures rise. By 2099, temperatures rise by 12.3 °F in the HE HMLS Storyline, 8.3 °F in the HE Moderate Storyline, and by 13.3 °F in the HE Dry Storyline. Physical crop water demands increase along with the temperatures.

The future projections indicate that there are likely to be increased gaps between water supplies and water demand in the HE storylines, due to increasing temperatures and decreasing water supplies (in the HE Dry and HE Moderate Storylines) or due to changes in timing and availability in water (in the HE HMLS Storyline). In general:

- **HE Moderate:** In this storyline, temperatures increase with mild drying across the Pecos River Basin in New Mexico. More precipitation falls as rain during the winter, but less falls in the summer. Mild drying across the whole system starts to show in the 2050s.
- **HE Dry:** This storyline is associated with much drier conditions. River flows, reservoir storage, and water available for irrigation, compliance with the 2016 BiOp, and Compact deliveries all decrease substantially.
- **HE High Monsoon/Low Snowpack (HMLS):** This storyline results in similar to slightly greater drying than the HE Moderate Storyline in the upstream portion of the basin, due to decreased snowmelt runoff from the headwaters region. However, further downstream, in the vicinities of PVACD and CID, more frequent and higher-intensity monsoon storms lead to wetter conditions.

Lower Emissions (LE) Storylines (RCP 4.5)

What would happen if emissions were reduced and greenhouse gas emissions dropped below current levels? These conditions are modeled in our Lower Emissions (LE) atorylines, which are associated with RCP 4.5. In the Lower Emissions storylines, carbon dioxide emissions worldwide start to fall around 2040, and they fall below current levels by 2070. Atmospheric concentrations stabilize by 2099 to levels at about twice the levels of the pre-industrial period (using the year 1850 as representative of this period). This future could be achieved with stringent climate stabilization policies, lower fossil-fuel-based energy use, reforestation, and other actions to reduce levels of carbon dioxide in the atmosphere. In the Lower Emissions storylines, temperatures rise, but do not rise as much as in the Higher Emissions storylines. By 2099, temperatures rise by 2.5 °F in the LE Median Storyline and by 4 °F in the LE Increased Monsoon Storyline.

In the Lower Emissions storylines, water demand still increases due to increasing temperatures, although not as significantly as in the Higher Emissions storylines. In addition, water supplies decrease slightly in the LE Median Storyline, with increasing supplies during the monsoon season in the LE Increased Monsoon Storyline. In general:

- **LE Increased Monsoon:** This storyline is associated with smaller increases in temperature and water demand than in the HE storylines and modest decreases in snowfall. Precipitation increases as a result of much more frequent monsoon storms with slightly greater intensity.

- **LE Median:** In this storyline, the Pecos River Basin in New Mexico experiences minor increases in snowfall and minor decreases in precipitation during other seasons. As in the LE Increased Monsoon Storyline, basin temperatures and water demand increase less than in the HE storylines, and water availability decreases slightly. Note that this storyline represents the median of the Lower Emissions RCP 4.5 scenarios, not the median of the five storylines examined in this study.

4.3.3. Temperature, Precipitation, and Runoff

We analyzed temperature, precipitation, and runoff trends for the full suite of the RCP 8.5 and RCP 4.5 projections in the CMIP5 Archive, including the storylines in the Higher Emissions RCP 8.5 and the Lower Emissions RCP 4.5. Note that some years will have more precipitation and others will have less, so the trends show the average amount of change per year. For example, in the HE Moderate Storyline, the trend in temperature is approximately 0.098 °F per year, or a total increase of almost 9 °F from 2010 to 2099. In summary:

- **Temperature.** All projections show increasing trends in all temperature parameters in the projections, including annual average, annual maximum, and annual minimum temperatures. The Higher Emissions RCP 8.5 projections have the highest temperature increases.

- **Precipitation.** The average annual precipitation projections in each of the Higher Emissions RCP 8.5 and Lower Emissions RCP 4.5 show a slight decreasing trend from 2010 to 2099, with the average of all of the RCP 4.5 projections decreasing less than the average RCP 8.5 projections.

- **Runoff.** Like precipitation, the average annual runoff projections in each of the Higher Emissions RCP 8.5 and Lower Emissions RCP 4.5 projections show a slight decreasing trend from 2010 to 2099, with the average RCP 4.5 projections decreasing less than the average RCP 8.5 projections. In this analysis, the term runoff is used to portray the sum of flows from the Above Santa Rosa Gage and eight tributary gages.

Table 5 compares per-year trends in temperature, precipitation, and runoff for the five storylines.

Table 5. Storyline Trends from 2010 to 2099

Storyline	Temperature (°F)		Precipitation (inches [in])		Runoff (acre-feet [af])	
	Per Year Trend	Change from 2010 to 2099	Per Year Trend	Change from 2010 to 2099	Per Year Trend	Change from 2010 to 2099
Higher Emissions (RCP 8.5)						
HE Moderate	+0.098	+8.82 °F	-0.040	-3.6 in	-673	-60,570 af
HE Dry	+0.148	+13.32 °F	-0.093	-8.37 in	-1,557	-140,130 af
HE HMLS	+0.137	+12.33 °F	+0.022	+1.98 in	+903	+81,270 af
Lower Emissions (RCP 4.5)						
LE Increased Monsoon	+0.045	+4.05 °F	+0.035	+3.15 in	+403	+36,270 af
LE Median	+0.028	+2.52 °F	-0.007	-0.63 in	-289	-26,010 af

Figure 44 compares average temperature trends in the study area for the selected storylines and the other RCP 8.5 and RCP 4.5 projections derived from the CMIP5 archive of projections.

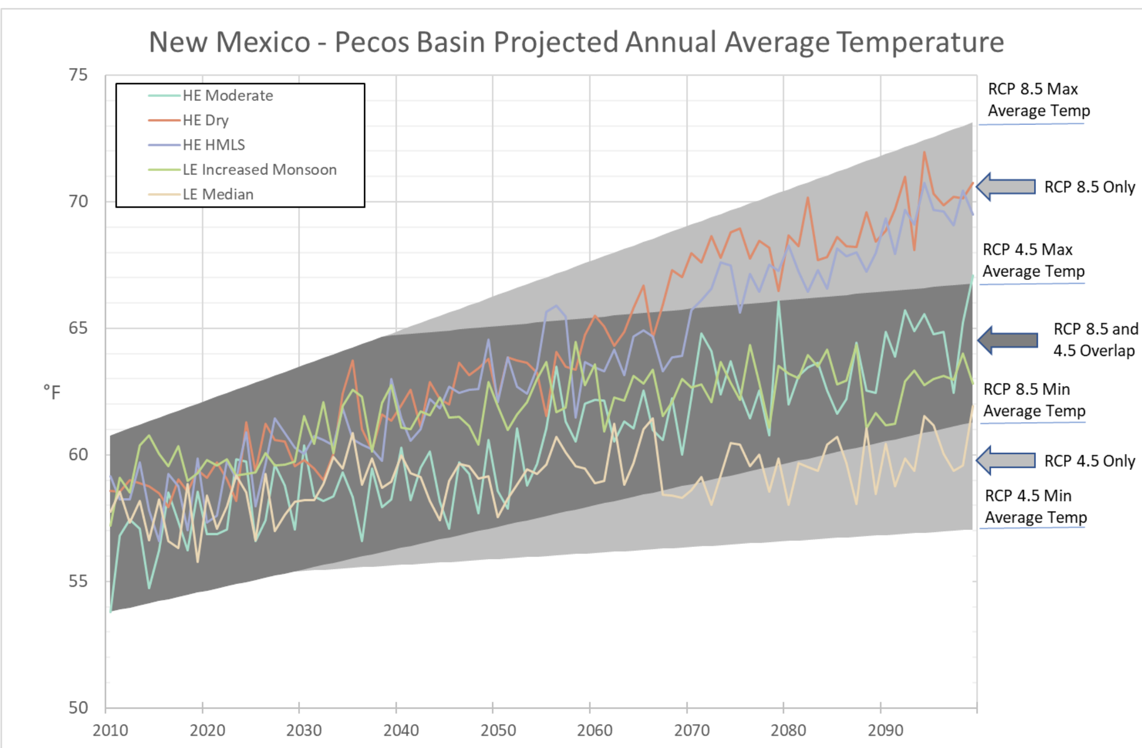


Figure 44. Projected trends for average temperatures in the study area for the selected storylines (colored lines) compared to the range of temperatures in the RCP 8.5 and RCP 4.5 projections in the CMIP5 archive (gray shading).

Figure 45 through Figure 47 show how the selected storylines provide a diverse range of projections of how the system might change. These figures compare temperature, precipitation, and runoff trends for each storyline to the other RCP 8.5 and 4.5 projections for these parameters.

Figure 45 shows how representative the storylines (diamonds) are among the RCP 8.5 projections (Higher Emissions; yellow dots) and RCP 4.5 projections (Lower Emissions; gray dots) in the CMIP5 archive. Out of the Higher Emissions (RCP 8.5) projections, the HE Moderate Storyline (teal diamond) shows lower temperatures and medium precipitation, the HE HMLS Storyline (blue diamond) shows higher precipitation and higher temperature s, and the HE Dry Storyline shows the worst-case storyline (i.e., the lowest precipitation and the highest temperature). Out of the Lower Emissions (RCP 4.5 projections), the LE Median Storyline (brown diamond) is in the middle of the precipitation range and on the lower end of the temperature projections, and the LE Increased Monsoon Storyline (green diamond) has one of the highest projections for precipitation and is in the middle of the range for temperature.

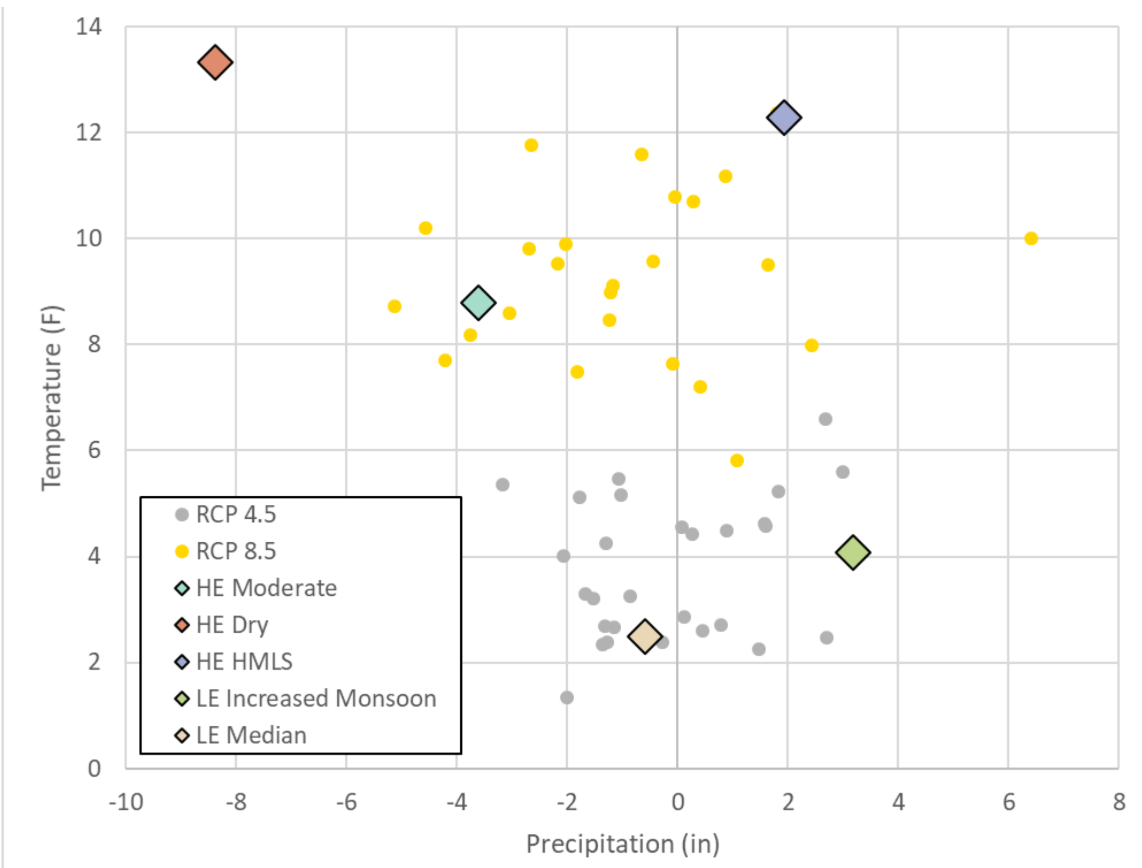


Figure 45. Total change in modeled average temperatures and precipitation in the study area from 2010-2099. Results show comparison between storylines used in this Basin Study and the remaining RCP 4.5 and RCP 8.5 simulations in the CMIP5 archive. 0 represents 2010 conditions.

Figure 46 provides a comparison of the proportion of annual runoff that is derived from spring snowmelt to the proportion of runoff that is derived from monsoons. Figure 46 shows how representative the storylines (diamonds) are among the RCP 8.5 projections (Higher Emissions; yellow dots) and the RCP 4.5 projections (Lower Emissions; gray dots) in the CMIP5 archive. The HE Moderate Storyline (teal diamond) shows lower snowmelt runoff and slightly lower monsoon flows than 2010 conditions. The HE Dry Storyline (red diamond) shows both lower snowmelt and lower monsoon runoff than 2010 conditions. The HE HMLS Storyline (blue diamond) has the lowest of the snowmelt runoff and one of the highest monsoon flows of the RCP 8.5 projections. For the Lower Emissions (RCP 4.5 projections), the LE Increased Monsoon Storyline (green diamond) has slightly lower snowmelt and higher monsoon flows than 2010 conditions. The LE Median Storyline (brown diamond) is the only storyline that projects a higher snowmelt runoff than 2010 conditions.

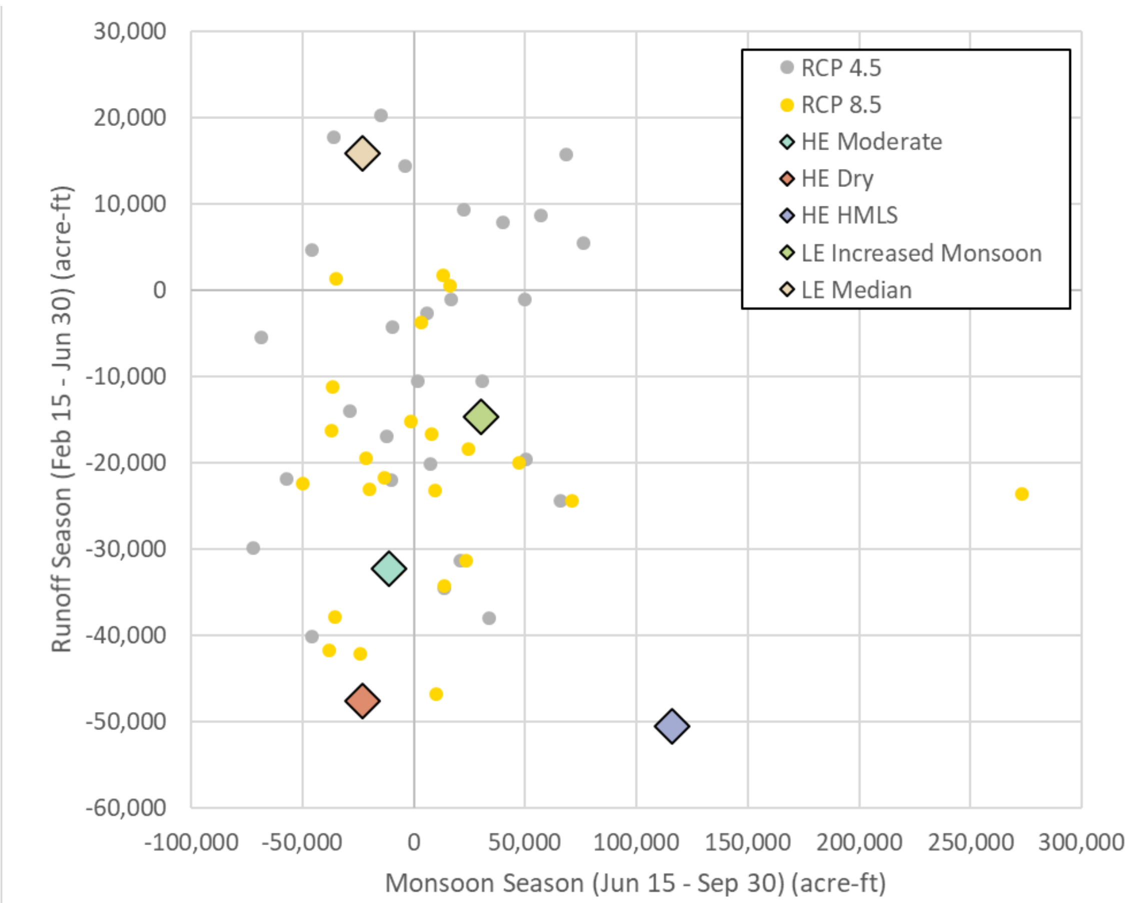


Figure 46. Total change in modeled annual spring snowmelt runoff compared to monsoon flows from 2010-2099 in the Pecos River Basin in New Mexico. The spring snowmelt runoff was based on the Above Santa Rosa Gage, and the monsoon flows were based on the six main monsoon-driven tributaries between Sumner Reservoir and Avalon Reservoir. Results show comparison

between storylines used in this Basin Study and the remaining RCP 8.5 and RCP 4.5 simulations in the CMIP5 archive. 0 represents 2010 conditions.

Figure 47 compares annual precipitation to annual flows for the storylines (diamonds) among the RCP 8.5 projections (Higher Emissions; yellow dots) and RCP 4.5 projections (Lower Emissions; gray dots) in the CMIP5 archive. The HE Moderate Storyline (teal diamond) shows lower annual flows than 2010 conditions. The HE Dry Storyline (red diamond) shows one of the lowest flows and the lowest precipitation of all of the projections evaluated. The HE HMLS Storyline (blue diamond) shows one of the highest annual flows and precipitation among all of the projections. The LE Median Storyline (brown diamond) is in the middle of the annual flow levels for the Lower Emissions (RCP 4.5) projections and is slightly lower than 2010 flows. The LE Increased Monsoon Storyline (green diamond) has the highest annual precipitation of the Lower Emissions projections, although flows are slightly lower than in the HE HMLS Storyline.

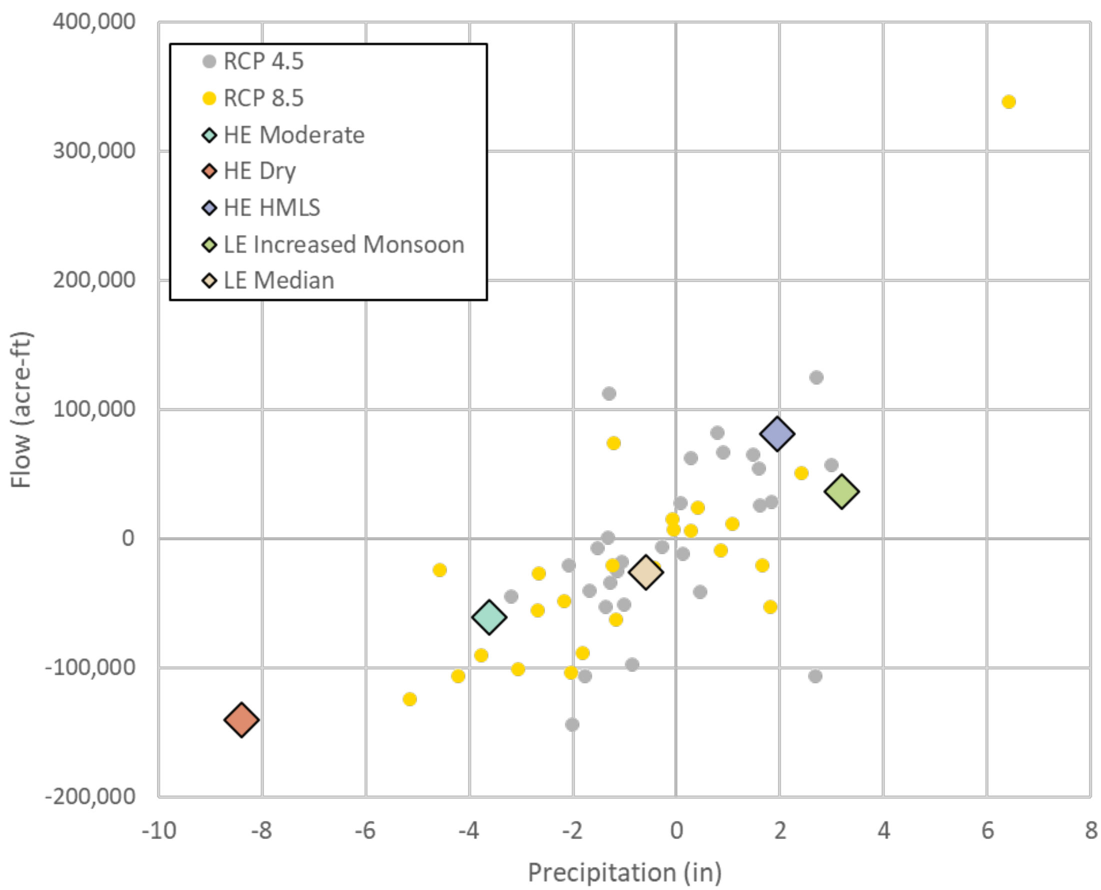


Figure 47. Total change in precipitation and gaged flows. Gaged flows include the Above Santa Rosa Gage and 8 tributary gages from Sumner Reservoir to Red Bluff. Results show comparison between storylines used in this Basin Study and the remaining RCP 8.5 and RCP 4.5 simulations in the CMIP5 archive. 0 represents 2010 conditions.

4.3.3.1. Higher Emissions (RCP 8.5) Projections by Storyline

4.3.3.1.1. HE Moderate Storyline

In the HE Moderate Storyline, conditions would be drier than historical conditions, with less seasonable variability than predicted in other RCP 8.5 projections:

- **Temperature.** Around the mean of the HE (RCP 8.5) projections. Summer temperatures increase more rapidly than winter temperatures.

- **Precipitation.** Slightly less than the median and mean of the HE RCP 8.5 projections. Precipitation increases slightly in winter relative to historical conditions. Snowmelt runoff still indicates decreasing runoff going to Santa Rosa. This possibly indicates greater routing losses, higher sublimation (ice changing to water vapor), and/or more precipitation falling as rain instead of snow. Precipitation decreased in all other seasons, indicating a change in precipitation timing.

- **Runoff.** Slightly less than the median runoff of the HE (RCP 8.5) projections. The HE Moderate Storyline shows less seasonal variability for runoff than the HE Dry or HE HMLS Storylines.

4.3.3.1.2. HE Dry Storyline

In the HE Dry Storyline, conditions would be much drier than historical conditions, with less spring runoff and fewer monsoons—water from sparse, intense storms.

- **Temperature.** The highest increase in temperature of all of the HE (RCP 8.5) projections. Summer and autumn temperatures increase more than winter and spring temperatures.

- **Precipitation.** The lowest precipitation amounts of all of the HE (RCP 8.5) projections. Precipitation is lower in all seasons, but decreases are most extreme in the monsoon season.

- **Runoff.** The second lowest of the HE (RCP 8.5) projections for runoff. Other than a very few large storm events, all inflow into the basin decreases across every season.

4.3.3.1.3. HE HMLS Storyline

The HE HMLS Storyline is one of the more seasonally variable storylines, with sharply increased inflow during the monsoon season and a steep decrease of inflow during the spring runoff.

- **Temperature.** The third highest of all of the HE (RCP 8.5) projection for temperature. Spring and summer temperatures increase more rapidly than fall and winter temperatures.

- **Precipitation.** The third highest of all of the HE (RCP 8.5) projections for precipitation. Increases in the summer and autumn precipitation are greater than the decreases during winter and spring precipitation.
- **Runoff.** The second highest of all of the HE (RCP 8.5) projections for runoff volumes summed from the Above Santa Rosa Gage and six tributary gages. Large increase to monsoon flows make up for the spring runoff decrease.

4.3.3.2. Lower Emissions (RCP 4.5) Projections by Storyline

4.3.3.2.1. LE Increased Monsoon Storyline

This storyline is drier during the spring, with wetter than historical monsoons bringing more water overall than historical conditions.

- **Temperature.** Around the mean of all the LE (RCP 4.5) projections for temperatures. Spring and fall temperatures increase slightly more than winter and summer temperatures.
- **Precipitation.** The highest of all the LE (RCP 4.5) projections for precipitation. Shows very little change to precipitations across all seasons besides the summer months, where it shows an increase to monsoon activity.
- **Runoff.** On the higher end of all the LE (RCP 4.5) projections for runoff. The tributary gages show a modest increase in monsoon events, which is not as large as HE HMLS and slightly lower flows during spring runoff.

4.3.3.2.2. LE Median Storyline

This storyline is about the median to average in the Lower Emissions (RCP 4.5) projectios for precipitation and runoff, with slightly less of an increase in temperatures than other projections.

- **Temperature.** On the lower end of the increasing temperatures for all the LE (RCP 4.5) projections. Summer and fall temperature increase almost twice as much as winter and spring temperatures.
- **Precipitation.** Around the median of all the LE (RCP 4.5) projections for precipitation. This leads to a slight decreasing trend in precipitation across the basin from 2010 to 2099.
- **Runoff.** Around the median of all the LE (RCP 4.5) projections for runoff summed from the Above Santa Rosa Gage and eight tributary gages. This is the only storyline in which the projected flows at the Above Santa Rosa Gage increase during spring runoff.

4.3.4. Irrigation, Evapotranspiration, and Reservoir Evaporation

4.3.4.1. Evapotranspiration Analysis Methods

> Reservoir evaporation and irrigation and riparian evapotranspiration are major sources of water loss along the Pecos River. As temperatures increase, evaporative losses will also increase.

PROM incorporated evapotranspiration (ET) along the Pecos River, but not throughout the entire Pecos River Basin in New Mexico. To determine daily evapotranspiration and pan evaporation rates needed in PROM for this Basin Study, we used monthly bias-correction spatial disaggregation (BCSD) CMIP5 open water and tall vegetation reference potential evapotranspiration data sets for three areas: Santa Rosa Reservoir, Sumner Reservoir, and Brantley/Avalon Reservoirs to calculate a trend (Reclamation 2014). Based on differences in trend directions and magnitude, we determined that Tall Reference Potential Evapotranspiration (PET) was the best analog for crops and the Bosque areas. We evaluated these trends to create annual linear trends for 2010-2099. These trends were then applied to averaged historical ET rates and pan evaporation rates to extrapolate them into the future. For more information, see the Surface Water Modeling Appendix.

Evapotranspiration in the RABGWM MODFLOW simulation is incorporated using the segmented evapotranspiration package (ETS) (Banta 2000). Modeled ET was adjusted based on annual trends in evapotranspiration for the region, in the same manner as the PROM. Trends were applied to the segmented evaporation package to produce a consistent change in evapotranspiration with each year.

4.3.4.2. Summary of Modeled Impacts

Future changes in surface water irrigation demands for FSID and CID depend on changes in evaporation, and changes in demands for all districts depend on transpiration (i.e., crop demand). With increasing evapotranspiration in every storyline, and all else being equal, demand for crop irrigation will increase as a function of evapotranspiration. Figure 48. shows CID ET trends as an example of ET increases in each storyline.

Higher Emissions (RCP 8.5)

- **HE Moderate Storyline** is between the other two HE (RCP 8.5) storylines for evapotranspiration.

- **HE Dry Storyline** shows the highest increase in evapotranspiration rates out of the five storylines.

- **HE HMLS Storyline** shows the lowest increase in ET rates out of the three HE (RCP 8.5) storylines. Although the HE HMLS Storyline has higher annual temperatures and temperature trends than the HE Moderate Storyline, tall and open water potential evapotranspiration are lower. This is assumed to be due to higher atmospheric moisture content in the HE HMLS Storyline, which results in lower potential evapotranspiration even with higher temperatures.

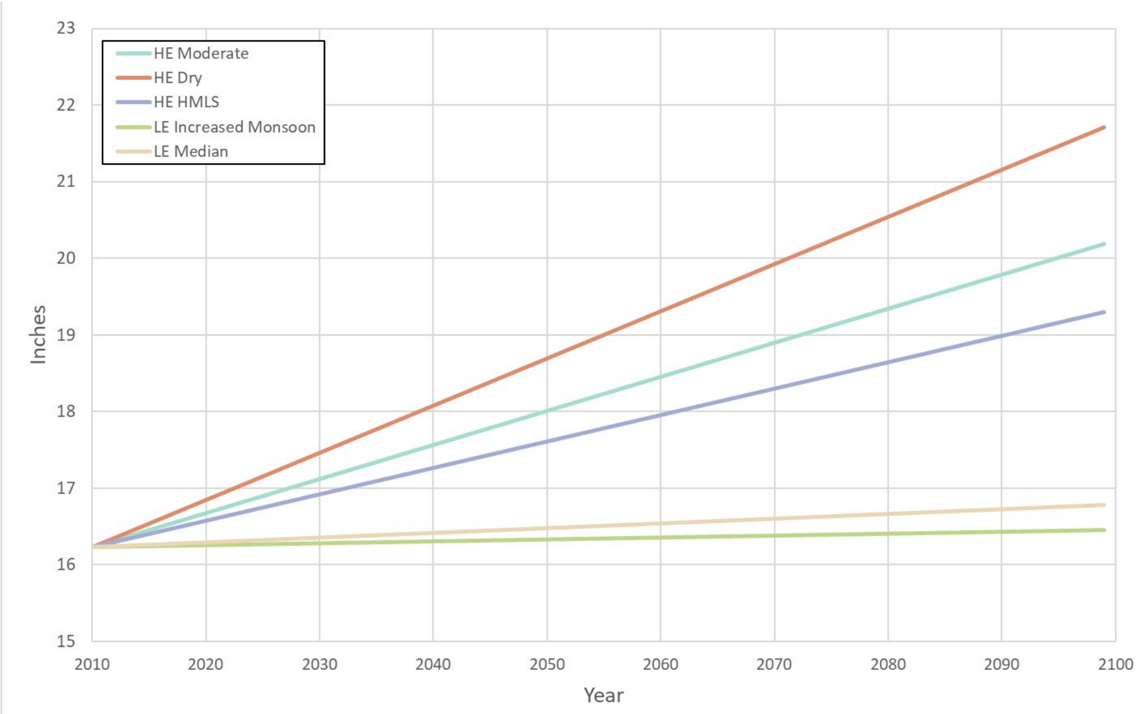


Figure 48. Calculated projected CID evapotranspiration rates used in the CID diversion object within PROM for the five storylines.

Lower Emissions (RCP 4.5)

- **LE Increased Monsoon Storyline** has the lowest increase in evapotranspiration of all five storylines. Like the HE HMLS Storyline, even though temperatures are higher in this storyline than in the LE Median Storyline, lower evapotranspiration rates are likely due to higher moisture.

- **LE Median Storyline** shows slightly higher ET than LE Increased Monsoon Storyline, but this storyline has significantly lower evapotranspiration rates than the HE HMLS Storyline, which is the lowest of the three Higher Emissions (RCP 8.5) storylines.

4.3.5. Frequency and Intensity of Extreme Events

As temperatures increase, so does the energy in the atmosphere. Globally, this energy increase is projected to cause significant increases in the intensity of precipitation events. We analyzed extreme events using flow at gages on the six main monsoon-driven tributaries. Since these tributaries flow only during storm events, flows in these tributaries can be used as an analog for storm frequency and intensity.

Figure 49 shows that the storylines encompass the range of potential futures for extreme events. Figure 49 compares the change in the frequency of extreme events (i.e., storms that bring over 1,000 acre-feet of water per day) from 2010 conditions with the total change in streamflow (acre-feet) contributed by the most extreme storms (99^{th} percentile of any flow) for the storylines (diamonds) among the RCP 8.5 projections (Higher Emissions; yellow dots) and the RCP 4.5 projections (Lower Emissions; gray dots) in the CMIP5 archive. The HE Moderate Storyline (teal diamond) has decreased flows above 1,000 acre feet and slightly less flow from the most extreme storms than other Higher Emission projections. The HE Dry Storyline (red diamond) shows the lowest frequency for flows greater than 1,000 acre-feet in all projections. The HE HMLS Storyline (blue diamond) has one of the highest frequency for extreme events and the highest flows from the most extreme events among all of the projections. The LE Median Storyline (brown diamond) is in the middle of the Lower Emissions (RCP 4.5) projections for the change in flow for the most extreme events and is among the lowest for the frequency of extreme events but has more frequent events than in the HE Dry Storyline. The LE Increased Monsoon Storyline (green diamond) has the most frequent storms over 1,000 acre-feet by far in the Lower Emissions projections,with more flows than in 2010.

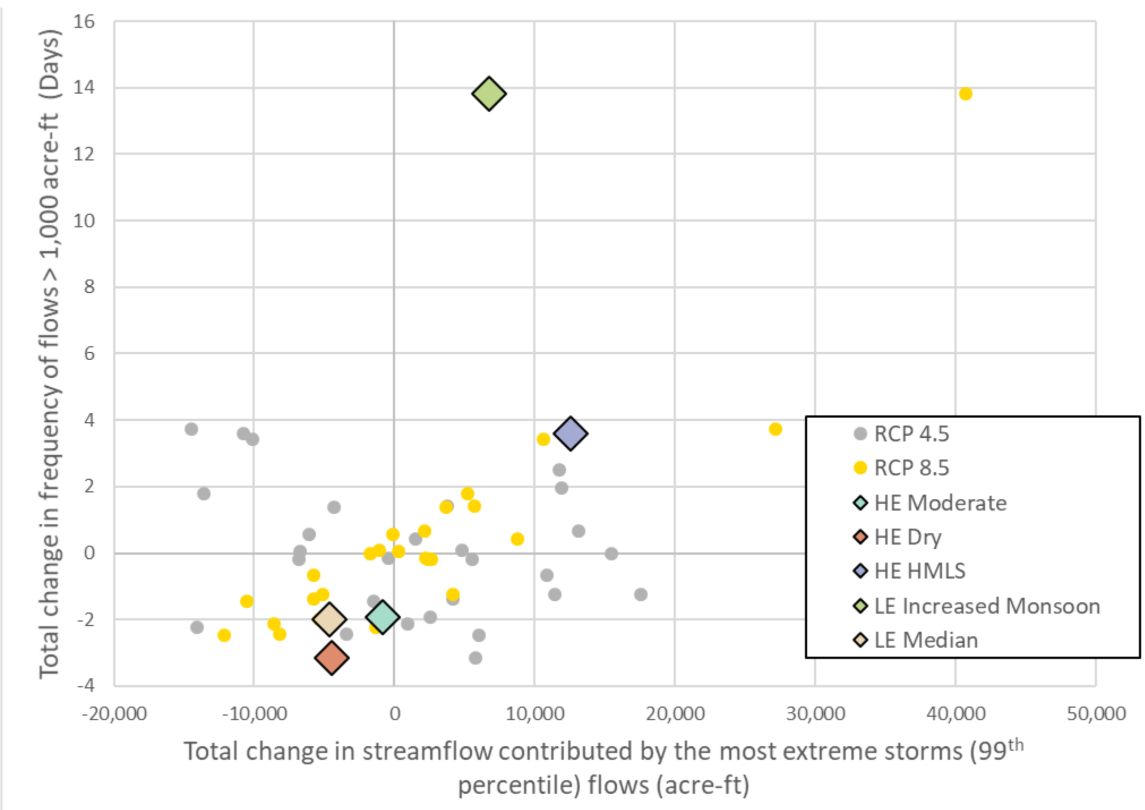


Figure 49. Total change in streamflow (acre-feet) contributed by the most extreme storms (99^{th} percentile) from 2010 to 2099 compared to the frequency of flows greater than 1,000 acre-feet per day. Results show comparison between storylines used in this Basin Study and the remaining RCP 4.5 and RCP 8.5 simulations in the CMIP5 archive.) 0 represents 2010 conditions.

- **HE Moderate.** The 90, 95, and 99th percentile of flows from storm events slightly decrease in intensity, with the 99th percentile of monsoon storm flows decreasing by 852 acre-feet per year on average by 2099, and there are about 2 fewer days per year where monsoon storm flow events reach 1,000 acre-feet per day by 2099.

- **HE Dry.** The 90, 95, and 99th percentile monsoon storm flows all decrease in intensity, with the 99th percentile showing the largest decrease. Flows from the 99th percentile of monsoon storms would bring in about 4,400 acre-feet less water per year and there are about 3 fewer days per year where monsoon storm flow events would reach 1,000 acre-feet per day by 2099.

- **HE HMLS.** The HE HMLS Storyline has an increase in storms and in precipitation within those storms. The storms have more precipitation than those in the LE Increased Monsoon. The 90, 95, and 99th percentile monsoon storm flows increase in intensity, with the 99th percentile showing the largest increase in intensity. By 2099, flows from the 99th percentile of monsoon storms bring in 12,600 acre-feet more water per year and there are about 4 more days per year where storm flow events would reach over 1,000 acre-feet per day by 2099.

- **LE Increased Monsoon.** This storyline has an increase in the number of storms and in precipitation within those storms. The storms are more frequent than those projected for the HE HMLS Storyline (as can be seen on Figure 49, this storyline has more projected storms than the other Lower Emissions projections). Like the HE HMLS Storyline, the 90, 95, and 99th percentile storms increase in intensity, with the 99th percentile showing the largest increase in intensity. Flow from monsoon storms bring in 6,800 acre-feet more water per year and there are about 14 more days per year where storm flow events reach over 1,000 acre-feet per day by 2099.

- **LE Median.** Like the HE Moderate Storyline, the 90th, 95th, and 99th percentile of flows from storm events slightly decrease in intensity, with the 99th percentile of monsoon storm flows decreasing by about 2,000 acre-feet on average per year by 2099. On average, by 2099, there are about 2 fewer days per year where monsoon storm flow events reach 1,000 acre-feet per day.

Table 6 shows the trends in extreme precipitation events for the storylines.

Table 6. Trends in Daily Streamflow Volume from Extreme Storms and in Extreme Storm Frequency

	Total increase/decrease in average daily streamflow volume from monsoon storms of a given magnitude, 2010 to 2099 (acre-feet)						
Storm Percentile	**RCP 8.5 Average**	**Moderate**	**Dry**	**HMLS**	**RCP 4.5 Average**	**LE Increased Monsoon**	**LE Median**
90th Percentile	-18	-86	-156	+265	0	+118	-74
95th Percentile	+411	-1,077	-460	+2364	+187	+737	-521
99th Percentile	+2,048	-852	-4,449	+12,592	+1,231	+6,760	-4,621

	Total (# of days) more/less storm flows occur in 2099 than in 2010						
Days at Flow of	**RCP 8.5 Average**	**Moderate**	**Dry**	**HMLS**	**RCP 4.5 Average**	**LE Increased Monsoon**	**LE Median**
100-999 acre-feet	-1	-5	-13	+4	0	+9	-3
> 1,000 acre-feet	0	-2	-3	+4	0	+14	-2

5. Baseline Projections in Each Storyline

Each storyline has its own baseline (i.e., the projected future conditions without any Water Management Strategy). These baselines provide reference points for each storyline to compare the effects of Water Management Strategies. As each of the three irrigation districts has a different position within the basin and different legal and operational structure, the potential hydrological and meteorological changes will affect each district differently.

5.1. Reservoir Storage and Operations

> Historically, there is a wide range of annual reservoir storage. The average total reservoir storage from 1990-2009 is about 101,000 acre-feet. The maximum conservation storage is approximately 180,000 acre-feet, with any storage above that reserved for flood control. See Section 2.2.4. *Storage, Operations, and Seasonal Variations*.

To examine how potential changes in hydrology would impact the system over time, we used daily average for total reservoir storage. The four reservoirs were added together and then the daily series data was plotted as a box and whisker plot to show the quartiles (i.e., 25, 50, 75, and 100%), outliers (i.e., a value that is 1.5 times the inner quartile is considered to be an outlier, and is shown as a dot in the graphs) and average for the baseline, adaptations, and modeled historical values. Figure 50 shows baseline conditions for all storylines in three time periods to show the projected progression of changes through the 21st century. The box and whiskers diagram show the range of storages throughout each time period, reflecting flood and drought conditions.

In the three wetter storylines, the baseline storage values are greater or only slightly lower than the modeled historical average of approximately 103,000 acre-feet (about 117,000 acre-feet in the HE HMLS Storyline, 144,000 acre-feet in the LE Increased Monsoon, and 90,000 acre-feet LE Median Storyline. In the two drier storylines, baseline 2070 -2099 storages drop significantly (to about 58,000 acre-feet in the HE Moderate Storyline and 14,000 acre-feet in the HE Dry Storyline).

In general:

Higher Emissions (RCP 8.5)

- **HE Moderate Storyline.** In the HE Moderate Storyline, average reservoir storage decreases by approximately 45,000 acre-feet in 2070-2099 from the historical storage of 103,000 acre-feet to about 58,000 acre-feet in the HE Moderate Storyline.

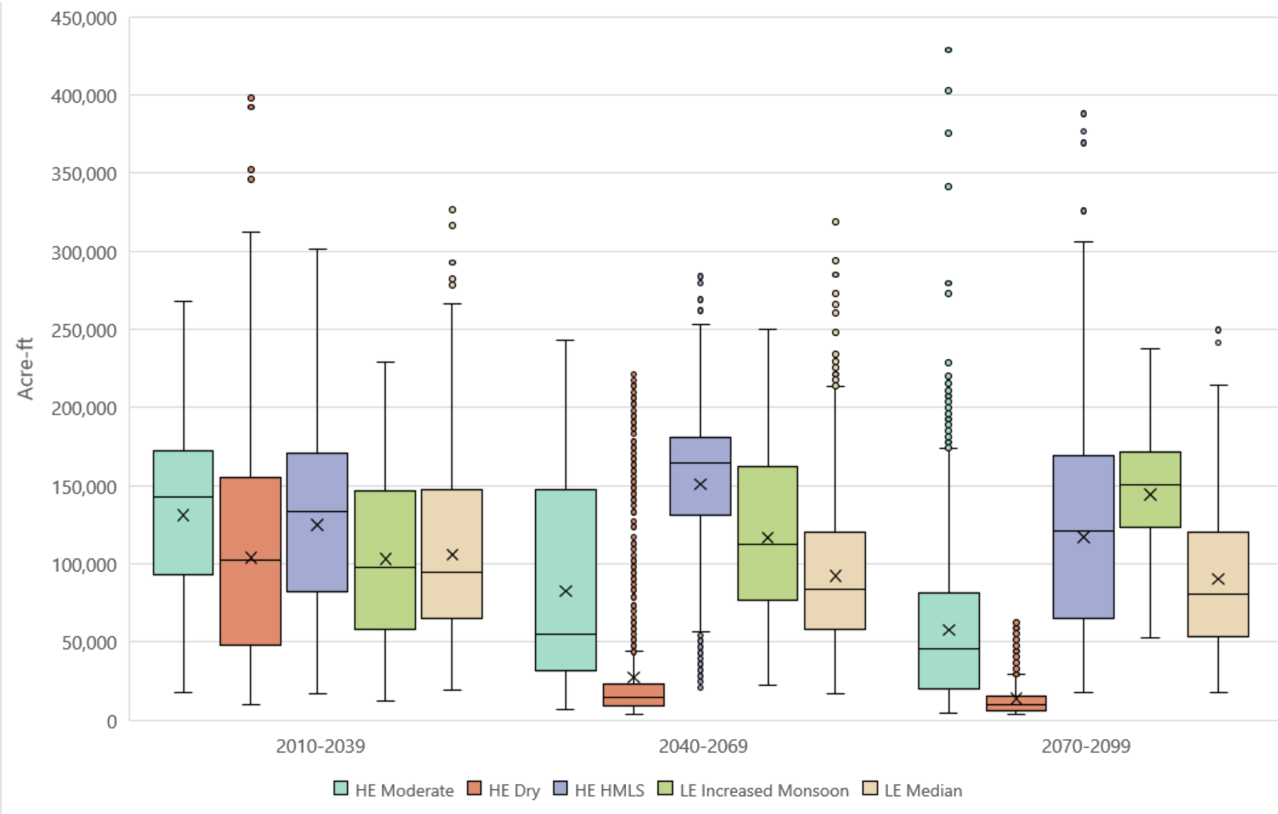


Figure 50. Reservoir storage: storyline baselines.

- **HE Dry Storyline.** In the HE Dry Storyline, projected average storage is about 89,000 acre-feet less in 2070-2099 than historical storage. In the HE Dry Storyline, in the 2040-2060 period, the Pecos River goes from a gaining reach to a losing reach between Sumner Reservoir to Brantley Reservoir. In general, the Pecos River has flow until 2060. After 2060, the Pecos River would only flow from block releases or from large storm events that reach Brantley Reservoir.

- **HE HMLS Storyline.** In the HE HMLS Storyline, average reservoir storage has about 14,000 acre-feet more in 2070-2099 than historical storage. This is due to more inflow from monsoon storms making up for the reduced snowpack.

Lower Emissions (RCP 4.5)

- **LE Increased Monsoon Storyline.** In the LE Increased Monsoon Storyline, average reservoir storage increases by approximately 41,000 acre-feet in 2070-2099 relative to historical storage. As temperatures do not rise as much in this storyline, ET and irrigation demands also do not rise as much, contributing to increases in reservoir storage.

- **LE Median Storyline.** In the LE Median Storyline, average reservoir storage decreases by approximately 12,500 acre-feet in 2070-2099 relative to historical storage.

5.2. Surface Water Irrigation Districts' Water Supply (i.e., Entitlements, Allotments, and Shortages)

5.2.1. FSID Entitlements

As explained in Section 3.3.1.3 *FSID Current Operations,* FSID is entitled to divert up to 100 cfs of the natural flow of the river during irrigation. While FSID's entitlement is calculated on a two-week average, we modeled this entitlement daily. The model assumes that FSID will always take their entire entitlement. The model also assumes that while groundwater gains between Santa Rosa Reservoir and Sumner Reservoir may vary daily, they are constant year-to-year. Similar to reality, the model calculates FSID's entitlement by taking the sum of the Above Santa Rosa Gage and the Puerto De Luna Gage minus Santa Rosa Reservoir outflow.

> FSID's average annual entitlement from 1950-2009 is about 46,040 acre-feet.
>
> FSID's entitlement is based on two-week gaged flow at the Puerto De Luna and Above Santa Rosa gages. Puerto De Luna baseflow varies between 59 cfs during the summer to 85 cfs in the winter. This yearly fluctuation is constant through all time periods and scenarios.
>
> The volume of water that FSID diverts from the Pecos River varies somewhat each year, but it is invariably less than the volume authorized in the FSID entitlement.

Both gages are above the effects of the irrigation districts. None of the Water Footprints described in Section 6 or the Water Management Strategies described in Section 7 caused any changes to FSID's baseline entitlements. Because this was one of the two parameters that PROM was bias corrected to for the 1950-2009 period, both the modeled and observed 1950-2009 average FSID entitlement are equal.

The average annual FSID entitlement is very stable in most of the storylines. Four of the five storylines project little change in the average annual FSID entitlements, while the fifth decreases by less than 20% (Figure 51).

In general:

- **HE Moderate, HE HMLS, LE Median, and LE Increased Monsoon Storylines.** By 2070-2099, the average FSID entitlement changes by 3% or less compared with the historical average of approximately 45,700 acre-per year.

- **HE Dry Storyline.** By 2070-2099, the average FSID entitlement decreases by 16% compared with the historical average.

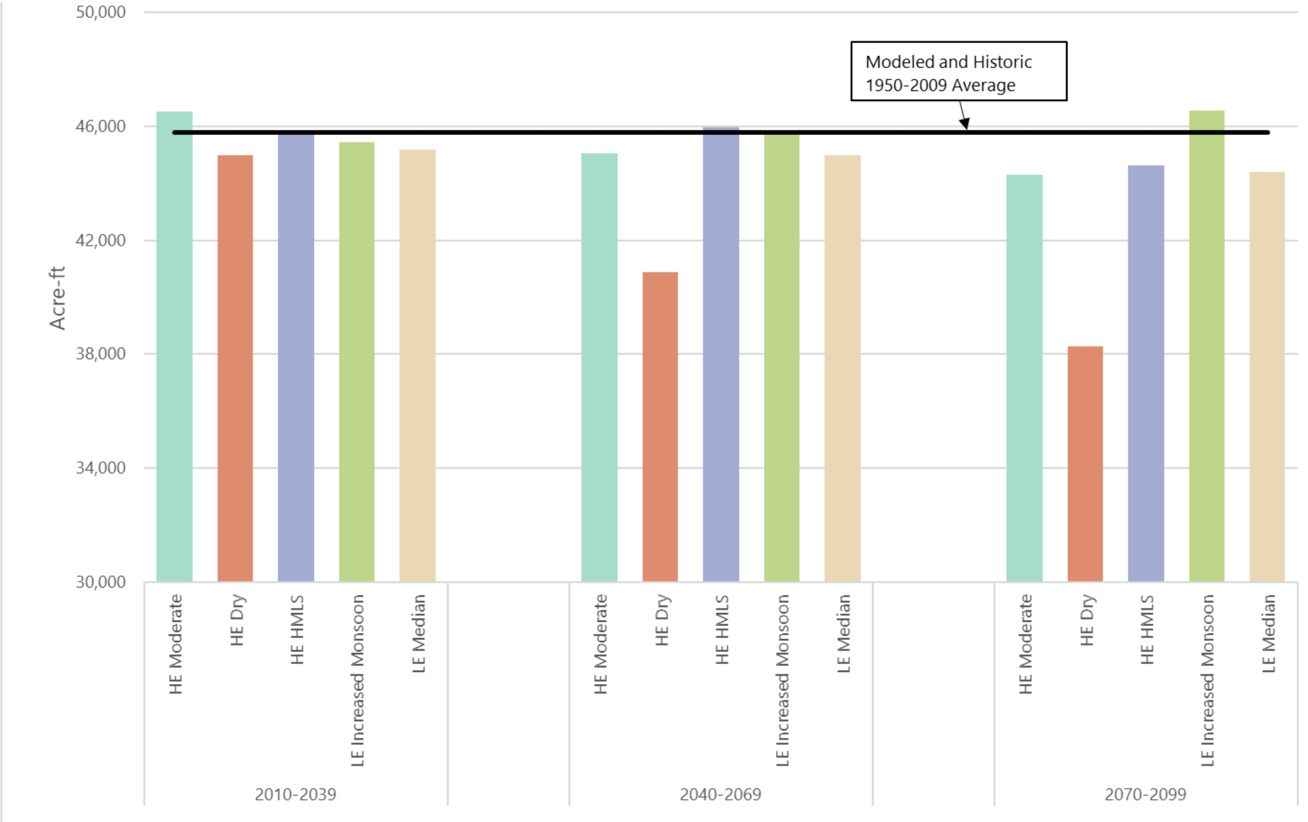


Figure 51. Annual FSID entitlements: storyline baselines. The black line is the average actual entitlement from 1950 to 2009. Note that the figure starts at 30,000, and the range is between 38,000 and 46,000 acre-feet.

5.2.2. FSID Shortages

To analyze the effects of storylines on FSID shortages, the model calculated shortages to see whether FSID would have enough water to irrigate all their acres through the entire irrigation season by:

1. Calculating the depletions, which is based on the irrigation area and the evapotranspiration rate.
2. Calculating how much water is available (amount diverted), what the crop needs (depletion), and what is lost to evaporation or groundwater recharge (efficiency). Shortages occur when the amount of water available is less than what is needed for depletion and efficiency.

Figure 52 shows the projected FSID shortages under the baseline conditions for all storylines.

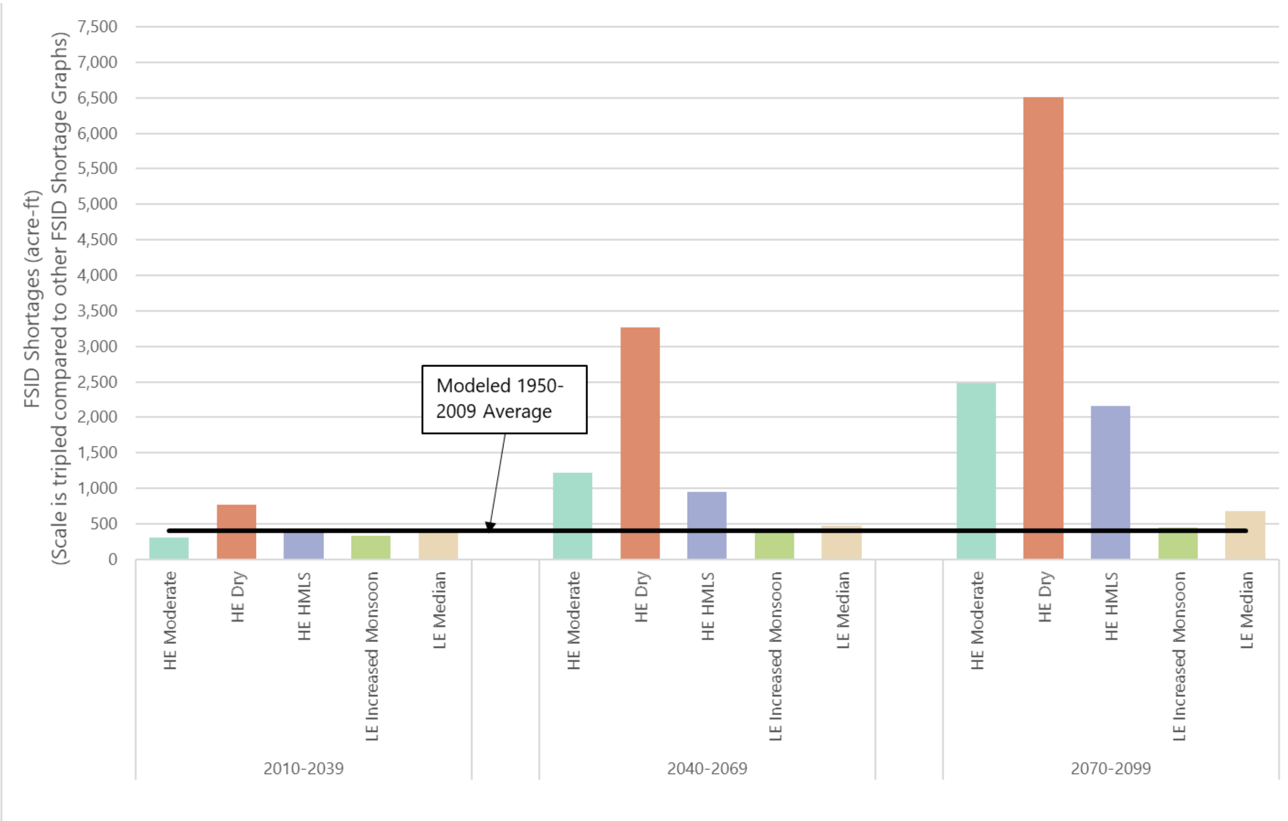


Figure 52. FSID shortages: storyline baselines.

FSID average annual historical shortages (1950-2009) are about 400 acre-feet.

In the storylines, there are few additional shortages early on in all but the HE Dry Storyline. However, by 2070-2099:

- **HE Dry Storyline**. FSID shortages increase by more than 15 times the historical average to about 6,500 acre-feet, as there is less spring runoff from the Sangre De Cristo mountains.

- **HE HMLS and HE Moderate Storylines.** FSID shortages increase by much less than the HE Dry Storyline—by 4 and 5 times the historical average—to about 2,200 to 2,500 acre-feet.

- **LE Increased Monsoon and LE Median.** FSID shortages in the two Lower Emissions storylines either stay about the same or increase very slightly compared to the HE storylines.

5.2.3. CID Allotment

CID's average annual allotment from 1950- 2009 was about 2.5 acre-feet per acre.

CID's allotment is limited to 3.697 acre-feet per acre delivered to the farm. The annual allotment may vary each irrigation season and is based on the volume of water stored in the project reservoirs and diverted by CID during the year. As CID is downstream of FSID and PVACD, when FSID and PVACD use less water, CID's allotment will likely increase. PROM was bias-corrected for the CID allotment for the historical period (1950-2009), therefore, both the modeled and observed 1950-2009 average allotment are 2.5 acre-feet per acre. Figure 53 shows the projected CID allotment under the baseline conditions for all storylines.

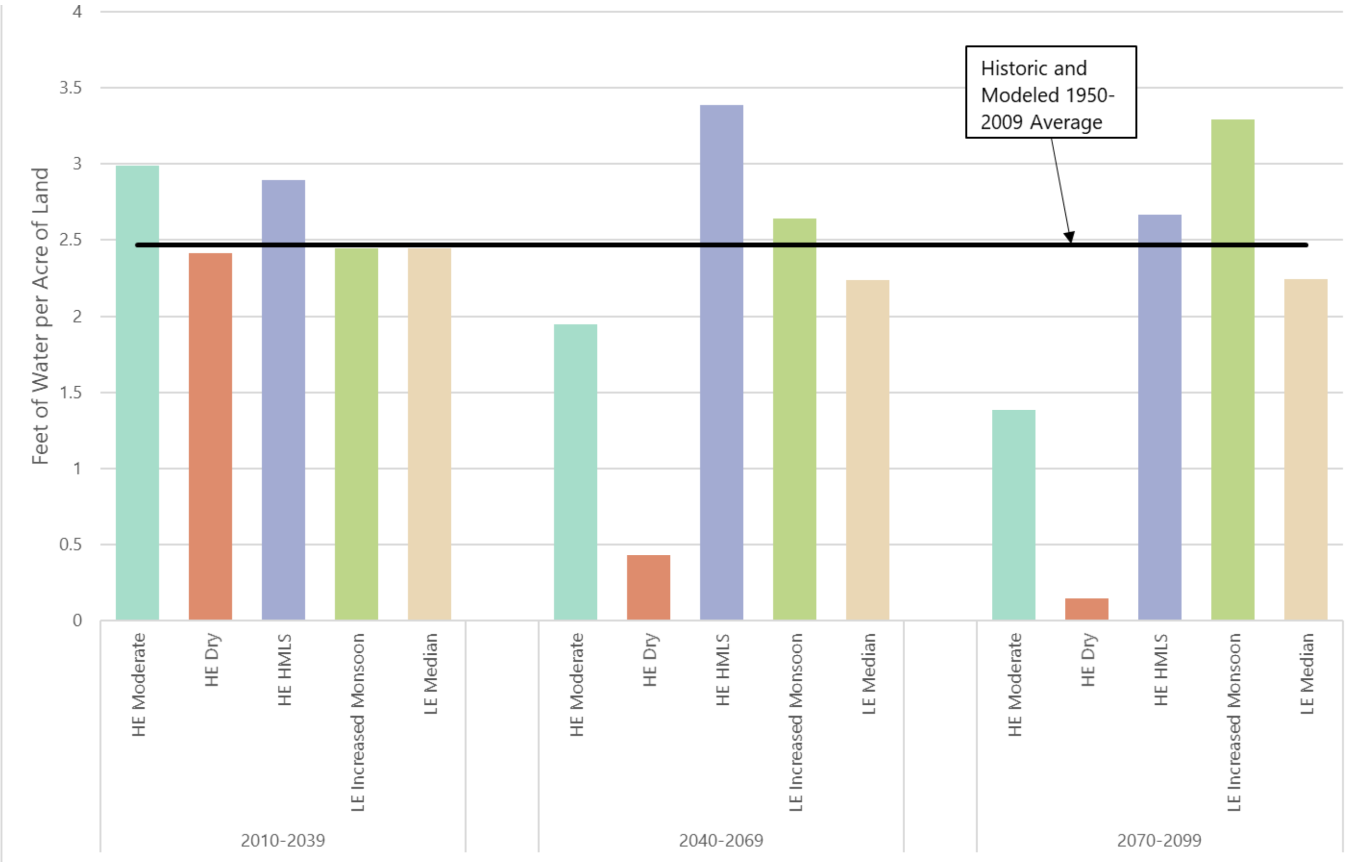


Figure 53. CID allotment: storyline baselines.

The baseline CID allotments remain relatively high in three of the storylines with allotments of 3.29 acre feet per acre in the LE Increased Monsoon, 2.67 in the HE HMLS, and 2.25 in the LE Median Storylines in the 2017-2099 period, which is above or slightly less than the historical average of 2.47. The HE Moderate and HE Dry Storylines, in contrast, are much drier:

- **HE HMLS and LE Increased Monsoon Storylines.** CID average allotment increases up to 25% (or 0.8 acre-feet per acre compared to historical) in both 2040-2069 and 2070-2099**.**

- **LE Median Storyline.** For this storyline, the CID average allotment is more stable and decreases by less than 10% about 2.2 acre-feet per acre by 2040-2069.

- **HE Moderate and HE Dry Storylines.** The CID average allotment for these two storylines is very low compared to historical allotments, with an 80% decrease in 2070-2099 for the HE Moderate Storyline to 1.4 acre-feet/acre. The HE Dry Storyline has very little water with only 0.15 acre-feet/acre by 2070-2099.

5.2.4. CID Shortages

As it does for FSID, the model assumes that CID will meet estimated crop demand on any given day if the water is available. There is a shortage if water is not available. The amount of shortages provides a relative measure of water supply/use trends and thresholds in each storyline. To model shortages before 2011, we assumed that CID requires about 60,000 acre-feet annually delivered the CID Main Canal for a full growing season without shortages (more information about this assumption and the shortage calculation is in Surface Water Modeling Appendix). The modeled historical shortage was 10,995 acre-feet of water. Figure 54 shows the projected CID shortages under the baseline conditions for all storylines.

CID shortages increase for the two drier storylines (HE Dry and HE Moderate), stay about the same in two other storylines (HE HMLS and LE Median, and decrease in the last storyline (LE Increased Monsoon) compared with the historical average shortage.

- **HE Dry and HE Moderate Storylines.** CID average shortage increases significantly to approximately 73,000 acre-feet in the HE Dry and 40,000 acre-feet in the HE Moderate Storylines by 2070-2099.

- **HE HMLS and LE Median Storylines.** CID average shortages increase by approximately 12,000 acre-feet in the LE Median Storyline to 13,000 acre-feet in the HE HMLS Storyline by 2070-2099.

- **LE Increased Monsoon Storyline.** CID average shortages decreases to less than 1,000 acre-feet by 2070-2099.

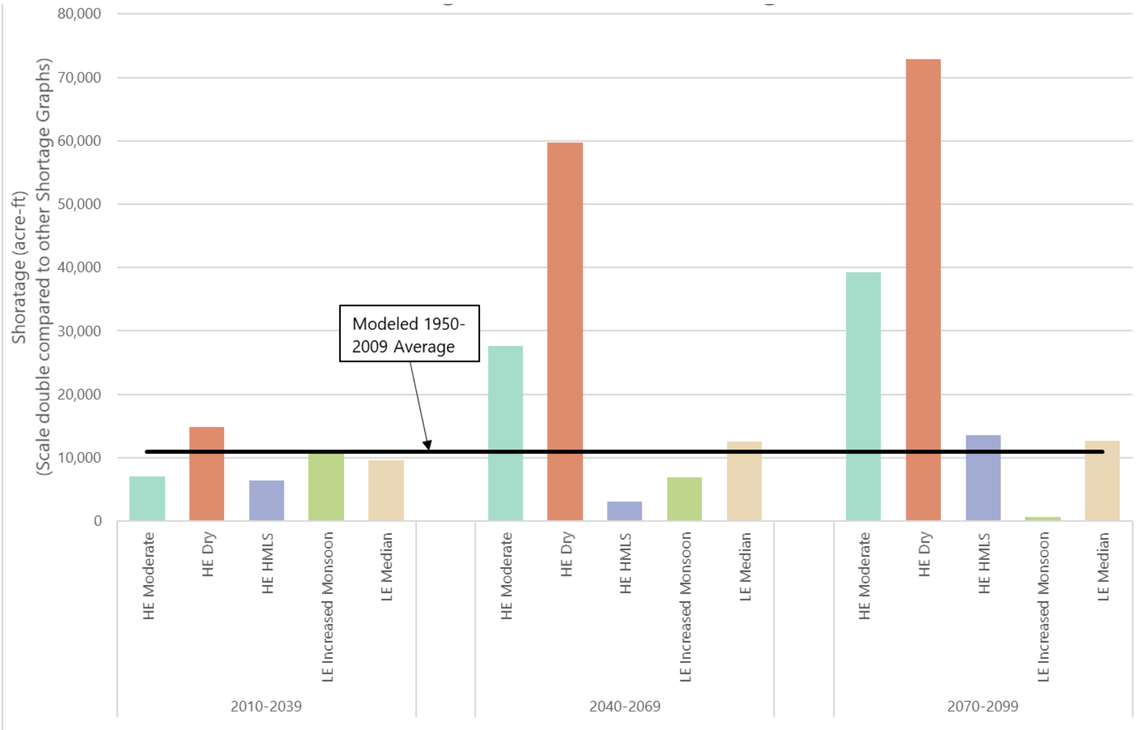


Figure 54. CID shortages: storyline baselines.

5.3. River Flows

Continuous river flows are an important goal of environmental management activities on the Pecos River. The Pecos bluntnose shiner (*Notropis simus pecosensis*), the primary species of concern in mainstem of the Pecos River, benefits from multiple years of perennial stream flow, and populations can be severely impacted by extended periods of stream intermittency ("drying"). Accordingly, assessing how drying frequency may be affected by future conditions is a key part of the study and benefits future management activities for ESA purposes. See Section 3.4.1. *Ecological Resources Water Use* and the Environmental and Recreational Appendix for more information on ESA flow requirements.

5.3.1. Drying at Acme

Between 2000 and 2016, there were an average of 33 drying days at Acme per year.

The Acme Gage discharge has been used to inform flow management decisions to meet the objective to keep the river continuously flowing since 2003. Since 2000, 5 years had significant drying along the Pecos River (i.e., 3 years with over 100 days in which flows at Acme dropped below 5 cfs and 2 years with 50 to 100 days). Pecos River intermittency between the USGS Taiban and Acme Gages (shown in the map in Figure 9 in Section 2.2.3. *Surface Water/Groundwater Interactions*) generally begins to occur once the Acme Gage drops below 5 cfs. Therefore, in the model drying at Acme is defined as an average daily discharge of under 5 cfs at the Acme Gage. Drying at Acme only occurs between May through November. The 2016 BiOp notes that FSID affects drying in the upper reaches during drier conditions ". . . there are times when FSID is the sole surface water diverter and its diversions may cause river intermittency when Reclamation's supplemental water supplies are exhausted. . . ." (page 96).

The model uses criteria from the 2016 BiOp to try to simulate keeping the river continuous for the entire run period. However, active management of the river to minimize drying has only occurred since 2003. Since the model is assuming active management over the entire run, model results during 1950-2009 indicate fewer drying days than occurred in that time. Figure 55 shows the projected number of drying days at Acme under the baseline conditions for all storylines.

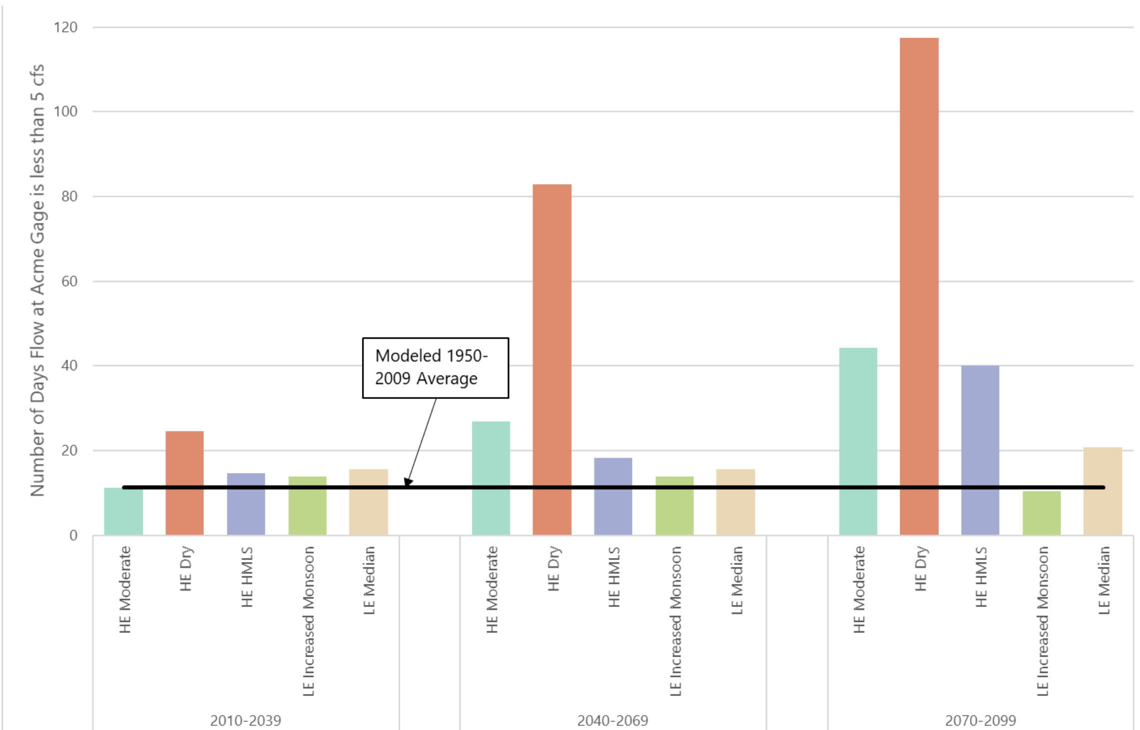


Figure 55. Drying days at Acme: storyline baselines.

The number of drying days at Acme in the Lower Emissions (RCP 4.5) storylines are lower than the Higher Emissions (RCP 8.5) storylines—even though the LE Median Storyline is drier overall than the HE HMLS Storyline. This is because FSID's demands are greater in the Higher Emissions (RCP 8.5) storylines, which results in less water for return flows at Acme. Toward the end of the 21st century, in the HE Moderate and HE Dry Storylines, the reach below Acme switches from a gaining reach to a losing reach, which causes Artesia to start drying before Acme after this point.

Figures in the Figures Appendix (Section 7. *Drying Days at Acme*) show the modeled number of drying days by year in each storyline as a general idea of how the timing and duration of river drying could vary. For more information, see the Surface Water Modeling Appendix.

In general:

- **HE Moderate Storyline.** By 2050, the number of drying days starts to increase, but these increases are not as significant as in the HE Dry Storyline. Drying varies from year to year with a maximum of two and a half months when there are less than 5 cfs at Acme. Drying days at Acme (Acme < 5 cfs) increase moderately in this storyline to 44 days per year on average by 2070-2099, an increase of 33 days from the modeled historical average of 11 days. In the late 2080s, Artesia starts drying more often than Acme.

- **HE Dry Storyline.** By 2035, the number of drying days starts to increase significantly. Drying days at Acme increase considerably to 117 days per year by 2070-2099. By 2099, all days from June through September have less than 5 cfs at Acme. Starting in mid-2040s, Artesia starts drying more often than Acme. By late 2060s, Artesia is dry almost all year round.

- **HE HMLS Storyline.** The HE HMLS Storyline is similar to the HE Moderate Storyline, but the number of drying days starts increasing earlier (by the 2030s) with another slight increase in drying occurring in the 2070s. Drying days at Acme increase to 40 days per year by 2070-2099. Artesia does not dry before Acme.

- **LE Increased Monsoon Storyline.** The number of drying days are similar to the historically modeled period throughout 2010-2099. Drying days at Acme decrease very slightly from the historical average of 11 days per year to just 10 days per year by 2070-2099. Artesia does not dry before Acme.

- **LE Median Storyline.** The number of drying days slightly increases throughout 2010-2099. Drying days at Acme increase slightly to 20 days per year by 2070-2099. Artesia does not dry before Acme.

5.3.2. FSID Bypass Flows

When FSID receives its maximum 100 cfs entitlement, any additional inflows into Sumner Reservoir (above 100 cfs) are released from Sumner Reservoir and continue flowing down the river. These are referred to as FSID bypass flows. Figure 56 shows modeled results for the projected percentage of years in the 21st century under each storyline that bypass flows occur over 20% of the irrigation season, and therefore are not designated as critically dry years under the 2016 BiOp. For more information, see the Surface Water Modeling Appendix.

> One of the 2016 BiOp criteria for determining if a year is critically dry is the percent of the time during the irrigation season that these bypass flows occur. If these bypass flows occur less than 20% of the irrigation season, then that year is considered "critically dry".

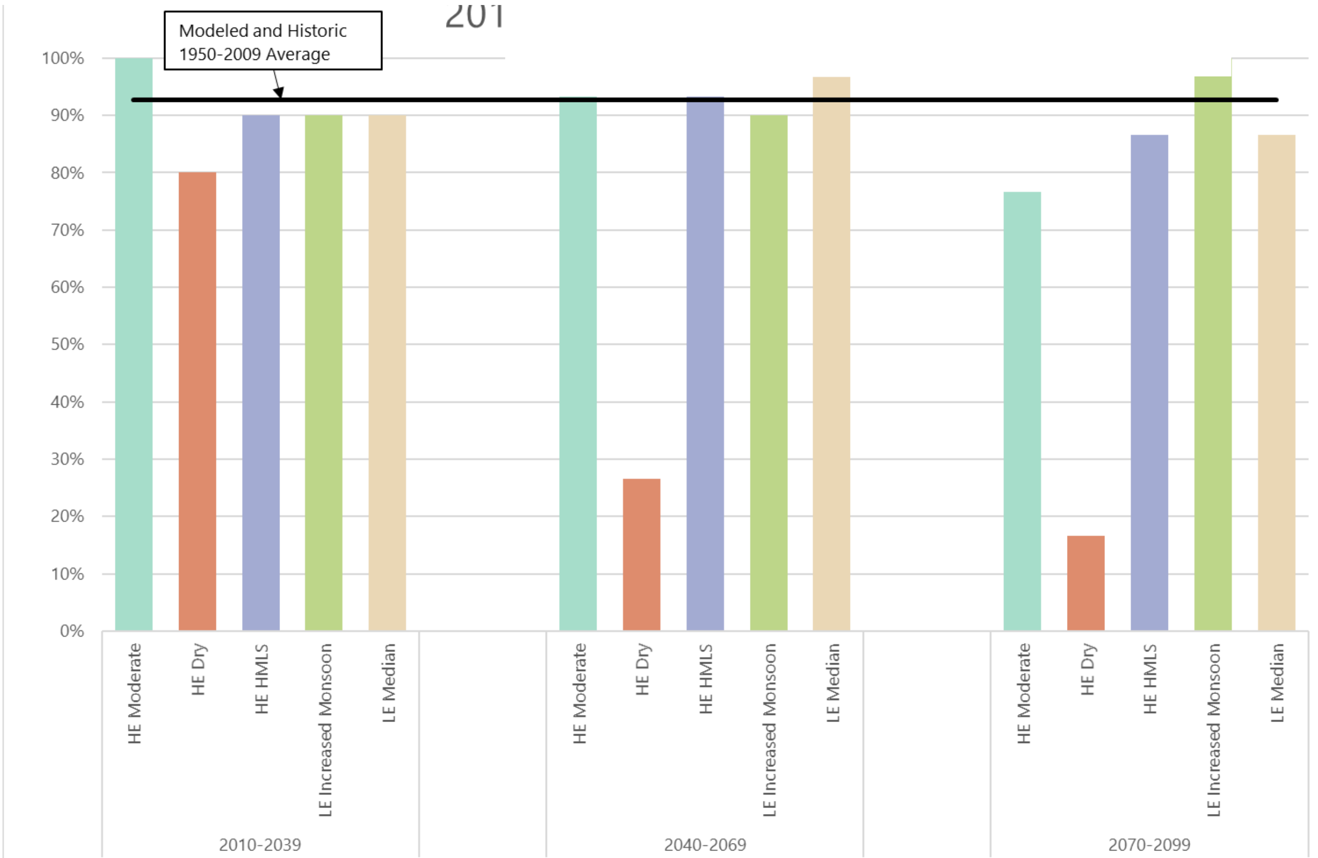


Figure 56. Percent of years that FSID bypass flows occur at least 20% of the irrigation season: storyline baselines.

In general:

- **HE Moderate Storyline.** From 2010-2039, the HE Moderate Storyline has no critically dry years. However, the trend decreases, and, this storyline from 2040-2069 is about the same as the historical conditions. The trend continues to decrease, and from 2070-2099, 77% of years would be above critically dry.

- **HE Dry Storyline.** The HE Dry Storyline starts to greatly depart from the historically modeled period and trends toward almost every year being critically dry by the end of the century, as by the 2070-2099 period only 17% of the years would be above critically dry.

- **HE HMLS Storyline.** The HE HMLS Storyline stays about the same with slightly below the average number of critically dry years in the historically modeled period throughout 2010-2099.

- **LE Increased Monsoon Storyline.** From the 2010 to 2069 periods, the LE Increased Monsoon Storyline shows slightly more critically dry years than the historically modeled period, but between 2070-2099, there are no critically dry years.

- **LE Median Storyline.** The LE Median Storyline's pattern is almost the same as the HE HMLS Storyline, staying around or slightly below the historically modeled period throughout 2010-2099.

5.4. Availability of Water for Estimated Releases for the Pecos River Settlement

The model calculates a yearly amount of water available for the 2003 Pecos Settlement based on reservoir storage and CID releases (see Section 3.1.4 *2003 Pecos Settlement Agreement*). We used the same method to calculate 1990-2016 historical data to compare to observations (Modeled Historical). A full description of these calculations is in the Surface Water Modeling Appendix.

> The model estimates water available for Pecos River Settlement Releases using equations from the 2003 Pecos Settlement Agreement. While this water is available, it might not be required, as many factors are involved in determining the actual annual releases for Compact compliance. The unavailability of water shown in the model may not reflect actual water decisions and operations.

Historical reservoir storages and flows at CID Main Canal Gage were used to calculate a 1990-2016 analysis of Settlement release estimates based on the calculation method used in the model. The result from modeled calculations is an average Settlement release of 15,390 acre-feet for 1990-2016 (Figure 57).

The amount of potential Settlement releases increases in the LE Increased Monsoon Storyline, but decreases in the rest of the storylines, and decreases the most in the HE Dry Storyline. In general, the amount of potential Settlement release water:

- **HE Moderate Storyline.** Decreases considerably by an average of 6,000 acre-feet between 1950-2009 to 2070-2099.

- **HE Dry Storyline.** Decreases substantially by an average of 14,000 acre-feet between 1950-2009 to 2070-2099, resulting in less than 500 acre-feet available for Settlement releases on average.

- **HE HMLS Storyline.** Increases slightly by an average of 500 acre-feet between 1950-2009 to 2070-2099.

- **LE Increased Monsoon Storyline.** Increases on average, resulting in every year being able to make the maximum potential settlement release.

- **LE Median Storyline.** Decreases slightly by 200 acre-feet on average between 1950-2009 and 2070-2099.

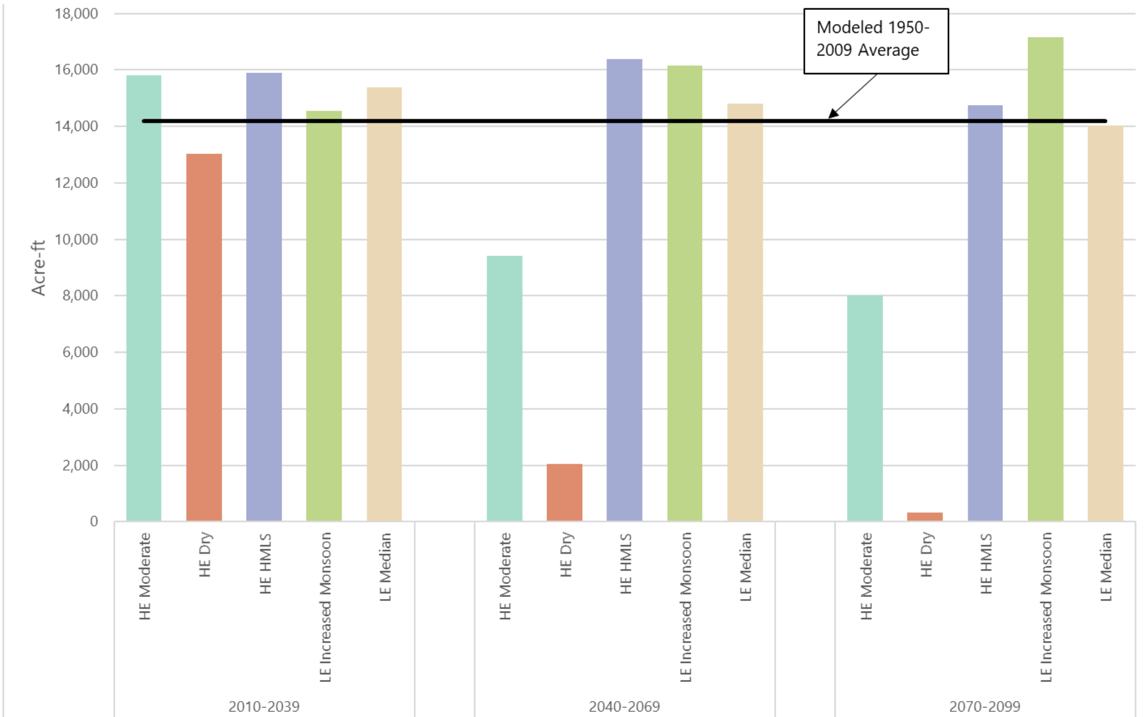


Figure 57. Average annual potential settlement releases: storyline baselines.

5.5. Groundwater

Projected changes to groundwater levels are based on RABGWM simulations for the five storylines built from the Groundwater Base Case (i.e., groundwater stresses/usage conditions in the year 2010 repeated each year for the 100-year analysis period) (see Section 4.2.6. *Roswell Artesian Basin Groundwater Model*).

For each storyline, model inputs (e.g., pumping and recharge) are adjusted based on climate conditions associated with the respective storyline, and the results are compared to those from 2010 Base Case. In the LE Increased Monsoon Storyline, pumping decreases—reflecting smaller demands for irrigation water in that storyline. In the other four storylines, pumping increases due to the increasing water demands in those storylines. Details of the stresses associated with each storyline are provided in the Groundwater Appendix.

5.5.1. Roswell Artesian Basin Groundwater Levels

Differences in water levels in the artesian aquifer in the five storylines reflect the differing hydrologic conditions in each storyline. For brevity, this analysis focuses solely on water level changes in the deeper confined aquifer in the RAB. Note that although water levels in the shallow aquifer were also impacted in these storylines, these are not addressed/described in the current analysis. Groundwater levels are affected by both seasonal and longer-term trends, as well as location within the RAB, and proximity to areas of pumping and the Pecos River. Two PVACD observation wells were chosen to illustrate how groundwater levels fluctuate over time in each storyline: well LFD and well Artesia A (Figure 58).

The 5 storylines each had similar impacts on both wells (Figure 60 and Figure 59), with the greatest water level drop taking place in the HE Dry Storyline, followed by HE Moderate and HMLS, LE Median, and LE Increased Monsoon where water levels rise slightly. Well Artesia A had smaller impacts in each storyline.

Modeled water levels in the HE HMLS, LE Median, and LE Increased Monsoon Storylines are quite similar to the 2010 Base Case. LE Increased Monsoon levels increase slightly from the 2010 Base Case and HE HMLS and LE Median Storylines decrease slightly. Water levels drop significantly in the HE Moderate and HE Dry Storylines.

- **HE HMLS, LE Increased Monsoon, and LE Median Storylines** have the smallest water level impacts. The LE Increased Monsoon is the only storyline with increasing water levels, generally less than about 15 feet by 2099. The HE HMLS and LE Median Storylines decrease less than 20 feet from historical levels by 2099.

- **HE Moderate Storyline.** Water levels drop by 50 to 100 feet below historical levels by 2099.

- **HE Dry Storyline.** The HE Dry Storyline results in significantly greater groundwater level declines compared to the 2010 Base Case, with projected water levels dropping by more than 100 feet from 2010 to 2099. Decreases are smaller in the beginning of the century and grow larger—with decreases ranging between 100 and 200 feet below historical levels by 2099, depending on well location. For example, water levels at water levels at well LFD drop by almost 150 feet while well Artesia A are projected to fall by about 80 feet.

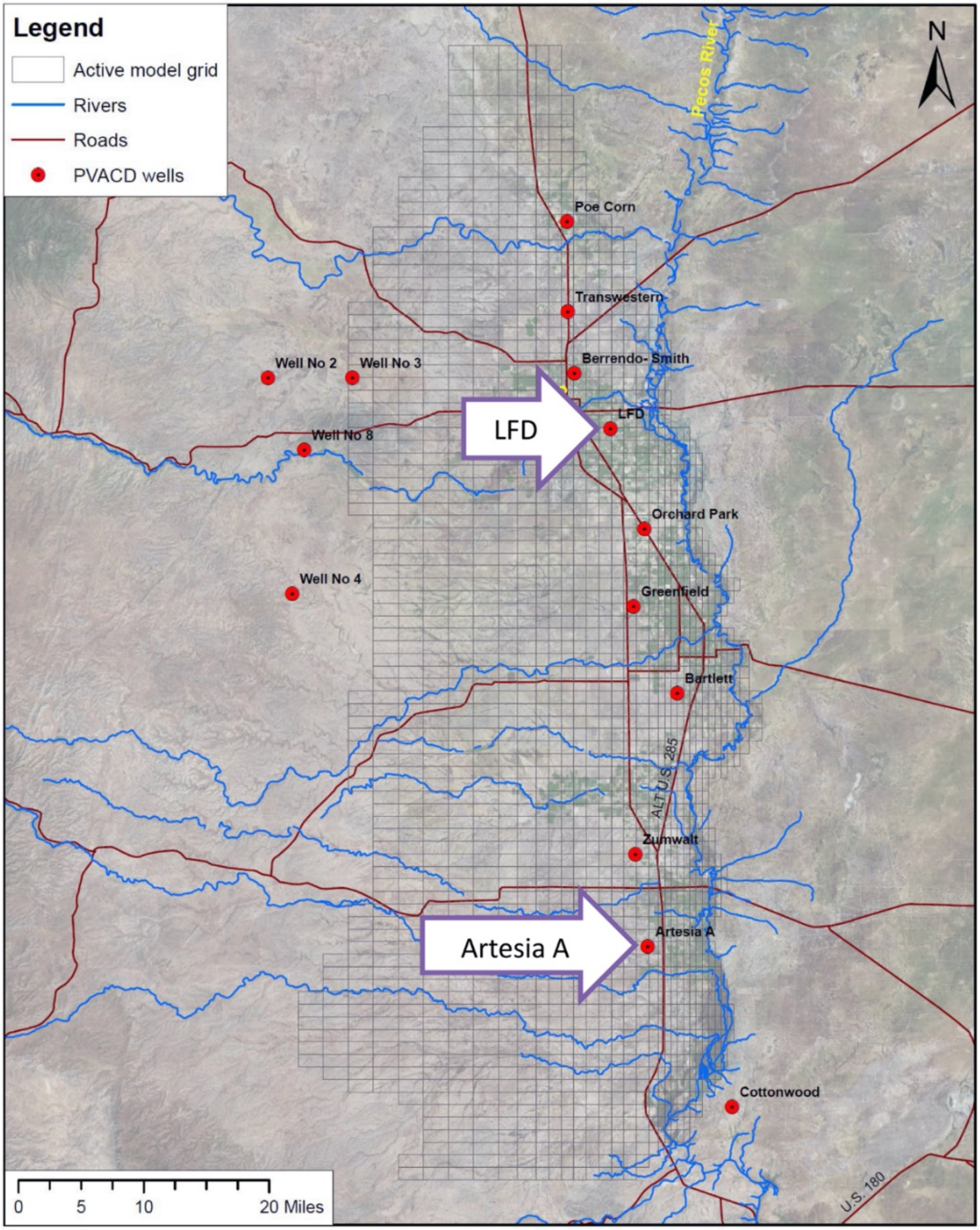


Figure 58. PVACD observation wells within the RABGW model grid. LFD and Artesia A wells are used as examples in this main report. Other wells are discussed in the Groundwater Appendix (SS Papadopulos & Associates Inc.).

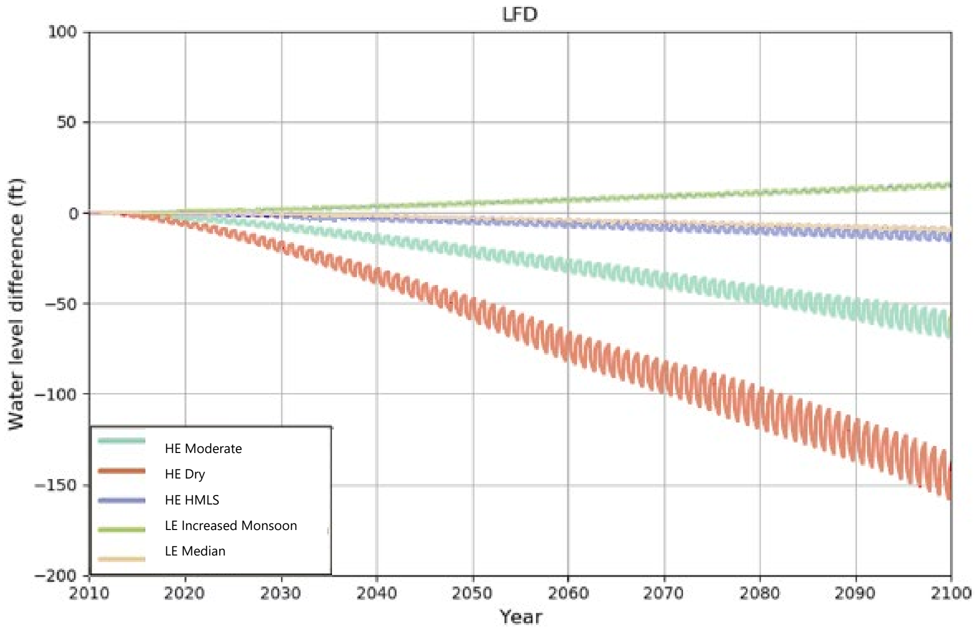


Figure 59. Groundwater-level changes in well LFD: storyline baselines.

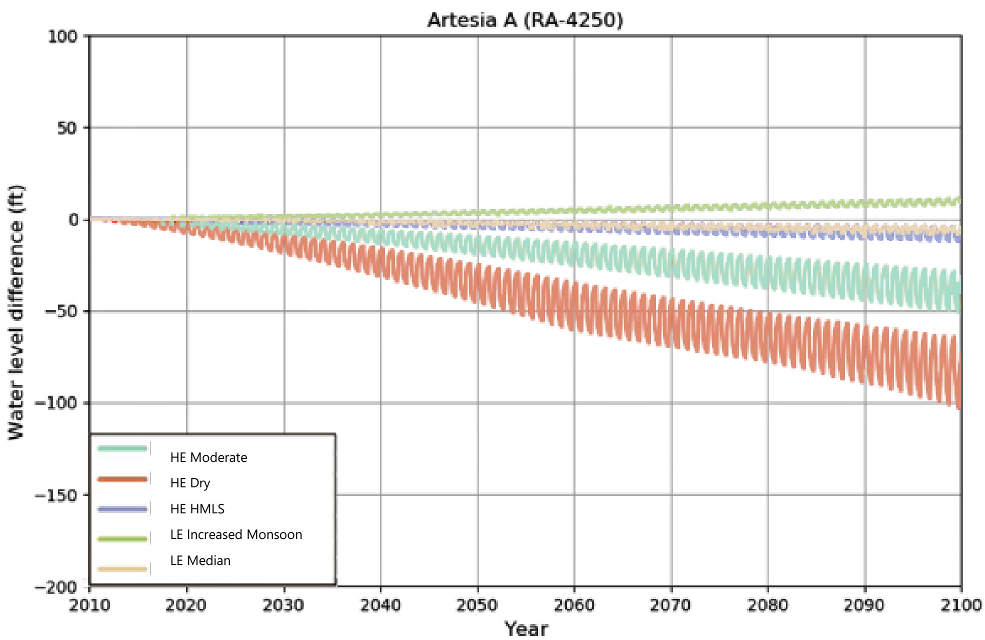


Figure 60. Groundwater-level changes in well Artesia A: storyline baselines.

5.5.2. Pecos River Groundwater Gains from Acme Gage to Artesia

River gains caused by groundwater inflows from the Roswell Artesian Basin are an important source of water to the river near Roswell. The amount of water that the Pecos River gains as it traverses the Roswell Artesian Basin varies depending on many factors, including precipitation, evaporation as well as surface and groundwater use. As a general rule, inflows to the river diminish during droughts. During extended droughts, river reaches that are typically gaining may become losing reaches, with new losses from the river to the water table.

The RABGWM is used to simulate groundwater inflow to the river at the Acme to Artesia reach. Figure 61 shows predicted differences in Pecos River gains for each storyline from the Groundwater Base Case (year 2010 conditions repeated throughout the period). The HE Moderate and HE Dry Storylines have much lower groundwater inflows to the river than to the historical average of 75,000 acre-feet per year. The remaining three storylines all produce higher inflows to the river compared to the historical average.

In general:

- **HE Moderate Storyline.** River gains steadily decreased, dropping by almost 40,000 acre-feet per year (55 cfs) by 2099.

- **HE Dry Storyline.** River gains decreased substantially lowering by almost 60,000 acre-feet per year (about 83 cfs) by 2099. The decrease in river gains slows starting around 2060—probably because the river reach switches from gaining to losing.

- **HE HMLS Storyline.** River gains decrease slightly with almost 10,000 acre-feet per year (about 14 cfs) less by 2099.

- **LE Increased Monsoon Storyline.** As in the case of changes in groundwater levels, this Storyline is the only one in which gains increase. Gains increase slightly by about 15,000 acre-feet per year (about 21 cfs) by 2099.

- **LE Median Storyline.** Like the HE HMLS Storyline, river gains decrease slightly, reaching close to 10,000 acre-feet per year (about 14 cfs) by 2099.

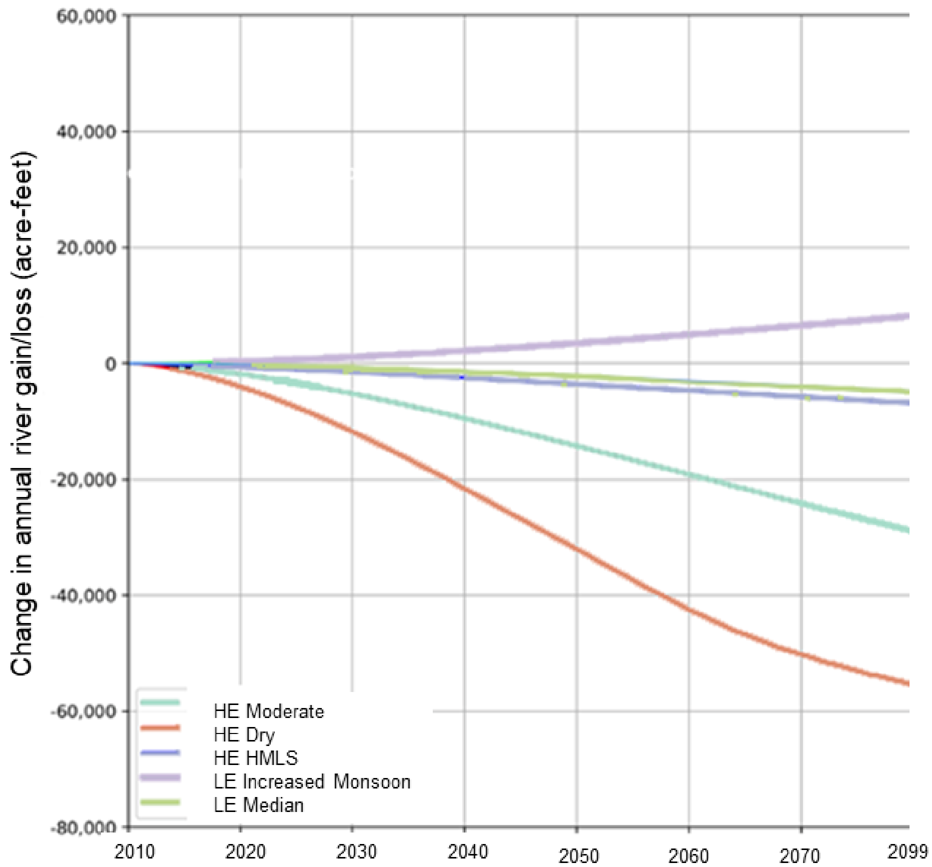


Figure 61. Differences in river gains between Acme to Artesia: storyline baselines.

5.5.3. Shallow Alluvial Aquifer Levels in the Vicinity of FSID

Groundwater surface interactions between the Pecos River, irrigation systems, and the shallow alluvial aquifer in the vicinity of FSID were modeled by creating groundwater objects in RiverWare^{TM} as part of this Basin Study. Because the water supply for FSID is reliable under most modeled storylines, and therefore the FSID irrigation network continues, along with the river, to recharge the shallow alluvial aquifer, groundwater levels in the shallow alluvial aquifer in the vicinity of FSID remain relatively stable under baseline conditions in all modeled storylines except for the HE Dry Storyline. In the HE Dry Storyline, groundwater levels in the shallow alluvial aquifer drop slightly over time.

6. Water Footprint Analyses

To better understand the ways that individual system components affect each other, we performed Water Footprint Analyses that assess the effects of each irrigation district, as well as ESA operations, on the system overall and on each other. The “water footprint” is that entity’s or activity’s water use in the basin. The Water Footprint Analyses are assessments of the relative footprint or impact of a given district or activity on the overall system and should not be confused with actions, such as the Water Management Strategies that are described in Section 7.

6.1. System Knowledge Gained from Water Footprint Analyses

The Water Footprint Analyses start from the Base Case Year (2010) in all storylines (see Section 4.2.6. *Roswell Artesian Basin Groundwater Model* (RABGWM). We ran model runs under each storyline that individually isolate the effects of each irrigation district on the basin. The water footprint of each irrigation district was evaluated by examining six parameters: reservoir storage, surface irrigation district water availability (i.e., entitlements, allotments, and shortages), river flows, and groundwater levels in PVACD and inflows (gains) to the Pecos River.

We also ran model runs under each storyline that provide information on what would happen to the system overall if there were no ESA constraints as described in Section 3.4.1. *Ecological Resources Water Use*. These include the required flows targets at the Acme and Taiban gages and the methods used to meet these flows (Vaughan Pumps, Seven Rivers Exchange, removing the Sumner Reservoir Bypass around FSID, and removing the Fish Conservation Pool in Sumner Reservoir). The ESA bypass volumes, which are the depletions. For more information, see the Surface Water Modeling Appendix.

6.2. Water Footprint Analyses

This section evaluates various water footprints using key parameters: reservoir storage, surface irrigation district water availability, river flows, and groundwater storage and inflows (gains) to the river.

6.2.1. Reservoir Storage and Operations

The footprint of each irrigation district represents the relative impact that that irrigation district has on total storage in the four Pecos River reservoirs. Baseline reservoir storages represent the projected reservoir storage in the five storylines when *all* footprints are considered (see the baseline discussion in Section 5.1. *Reservoir Storage and Operations*). Because CID owns the rights to store water in the four reservoirs and is the primary user of this water, CID’s reservoir storage footprint is larger than that of the other irrigation districts in four of the five storylines. However, the other districts also affect reservoir storage levels by using water that could otherwise reach the reservoirs—even though they do not draw from CID's stored water. In all but the HE Dry Storyline, CID has the largest footprint, followed by PVACD and FSID, and ESA flows have the smallest footprint.

See Figures Appendix, Section 2. *Reservoir Storage* for the water footprint projections for each storyline throughout the 21st century. Table 7 shows the water footprints on reservoir storage. Table 7, and other water footprint tables in this section, show the size of water footprints in the different storylines for the three irrigation districts and ESA operations. Shading indicates the size—the stronger the shade, the larger the footprint. The baseline values incorporate the impacts of all four footprints (i.e**.**, a negative footprint does not reduce the baseline value further; rather, it represents a reduction from a hypothetical value without the footprint towards the baseline). As an example, in the HE Moderate Storyline, the baseline reservoir storage is 57,736 acre-feet, and CID's footprint is -63,342 acre-feet. Therefore, in this case, CID's footprint reduces average reservoir storage by 63,342 acre-feet. To estimate what the storages would be without CID's footprint, subtract its footprint from the baseline, (57,736 – [-63,341] = 121,078).

Table 7. Reservoir Storage: Water Footprints Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
2070-2099 Water Footprint					
CID	-63,342	-3,932	-48,857	-31,348	-78,085
FSID	-17,972	-9,303	-11,889	-14,715	-23,415
PVACD	-61,532	-18,986	-37,168	-27,619	-71,998
ESA	-2,704	-3,964	-623	-2,519	-2,938
	Drying Footprint (-) reduces storage		**0**		**Wetting Footprint (+) increases storage**
1950-2009 Modeled Historical Reservoir Storage: 102,900 acre-feet (Baseline includes cumulative effects from all four footprints and interactions)					
2070-2099 Baseline	57,736	13,525	116,987	144,234	90,397
	Lower Storage		**102,900**		**Higher Storage**

CID and PVACD reservoir storage footprints are largest in the HE Moderate and LE Median storylines, where they depend more on reservoir storage (in the case of CID) and more intensive pumping (in the case of PVACD) to support their irrigation demands. CID and PVACD footprints are smaller in the HE HMLS and LE Increased Monsoon storylines, since in these cases monsoon rains tend to keep more water in the reservoirs for CID and reduce the amount of pumping needed in PVACD. FSID footprints on reservoir storage are generally lower than the other districts because of its small size relative to the other districts. Also, FSID has rights to natural flows of the Pecos River and thus does not make use of the water stored in reservoirs.

In all but the HE Dry Storyline, ESA releases have the smallest footprint, due to the relatively small size of required releases.

In the HE Dry Storyline, however, PVACD, FSID, and ESA releases all have larger footprints on reservoir storage than CID. In this storyline, there is very little runoff water filling the reservoirs (so there is little water for CID to use, and thus its footprint remains small). In contrast, PVACD continues to intercept baseflow from the Roswell Artesian Basin that might otherwise reach the Pecos River and Brantley Reservoir, and FSID continues to use its entitlement (kept more consistent due to the stable baseflow from the Santa Rosa area), so their footprints do not shrink as much. The ESA footprint is greatest in the HE Dry Storyline, as ESA releases will be less likely to reach Brantley Reservoir, while these releases are more likely to reach the reservoir in wetter storylines.

6.2.2. Surface Water Districts' Water Supply (i.e., Entitlements, Allotments, and Shortages)

6.2.2.1. FSID Entitlements and Shortages

Because FSID has a run-of-the river water right and is upstream of the other irrigation districts, FSID entitlements and shortages are not affected by any other water footprint.

6.2.2.2. CID Allotment

The footprint of each irrigation district represents its relative impact on CID's annual allotment. (See the baseline discussion in Section 5.2.3. *CID Allotment*.) Table 8 shows the water footprints for CID allotments. See Figures Appendix, Section 5. *CID Allotment* for the water footprint projections for each storyline throughout the 21st century. The baseline values represent the projected allotments in the five storylines when all footprints are considered. CID's allotment depends primarily on the amount of water stored in its reservoirs. As discussed above for reservoir storage, FSID and PVACD affect reservoir storage levels indirectly by using water that could otherwise reach the reservoirs. In all storylines, PVACD has the largest footprint, followed by FSID, and ESA flows have the smallest footprint. The CID baseline allotment increases for the two wetter storylines (HE HMLS and LE Increased Monsoon Storylines), is only slightly drier for the LE Median Storyline, and decreases significantly for the HE Moderate and HE Dry storylines.

The smallest irrigation district water footprints occur in the driest storyline, HE Dry Storyline (when there is little water to begin with, so the affect that each irrigation district can have is small), and the two wettest storylines (HE HMLS and LE Increased Monsoon) (when there is ample water, so CID is more likely to have full or near-full allotments regardless of the impacts of the other irrigation districts). The largest irrigation district footprints occur in the HE Moderate and LE Median Storylines.

As ESA releases are small, they have the smallest footprint on CID Allotments, (0.02 acre-feet per acre in the LE Increased Monsoon Storyline and 0.14 acre-feet per acre in the HE Dry Storyline). As an example, in the HE Moderate Storyline, the baseline CID allotment is 1.38 acre-feet per acre and FSID's footprint is -0.39 acre-feet per acre. Therefore, in this case, FSID's footprint reduces average CID allotment by 0.39 acre feet per acre. To estimate what the CID allotment would be without FSID's footprint, subtract its footprint from the baseline, (1.38 – [-0.39] = 1.77 acre feet per acre).

Table 8. CID Allotment: Water Footprints Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet per acre)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
2070-2099 Water Footprint					
FSID	-0.39	-0.14	-0.21	-0.22	-0.46
PVACD	-1.46	-0.56	-0.72	-0.41	-1.37
ESA	-0.11	-0.14	-0.03	-0.02	-0.08
Drying Footprint (-) reduces allotment			0		**Wetting Footprint (+) increases allotment**
1950-2009 Modeled Historical CID Allotment: 2.47 acre-feet per acre					
2070-2099 Baseline	1.38	0.15	2.67	3.29	2.25
	Lower Allocation		2.47		**Higher Allocation**

6.2.2.3. CID Shortages

CID shortages are the gap between the district's water supply and crop demand. (See the baseline discussion in Section 5.2.4. *CID Shortages*.) Table 9 shows the water footprints on CID shortages. See Figures Appendix, Section 6. *CID Shortages* for the water footprint projections for each storyline throughout the 21st century.

The footprint analysis shows us that in every storyline, the biggest influence on CID shortages is the amount of groundwater pumping in PVACD. This footprint is largest at approximately 31,000 acre-feet of water in the HE Moderate Storyline; which is a significant percentage of the storyline's baseline shortage of about 39,000 acre-feet. The next three highest footprints are also for PVACD and range from about 12,000 in the HE HMLS to 15,000 acre-feet for LE Median Storylines. In the HE Dry storyline, the baseline shortage of almost 73,000 acre-feet is much larger than any of the water footprints; therefore, a shortage of almost 58,000 acre-feet remains when PVACD's footprint of about 15,000 acre-feet is considered. The smallest PVACD footprint of less than 1,000 acre-feet coincides with the wettest storyline (LE Increased Monsoon) and that storyline's baseline's smaller shortages. PVACD's footprints for the HE storylines are about 4 to 5 times larger than FSID's. For the LE storylines, FSID has a footprint that ranges from approximately half of to approximately equal to that of PVACD. In most cases, the ESA footprints are 15 to 30 percent that of FSID's footprints.

As an example, in the HE Moderate Storyline, the baseline CID shortage is 39,237 acre feet per year and FSID's footprint is +8,167 acre feet per year. Therefore, in this case, FSID's footprint increases average CID shortage by 8,167 acre feet per year. To estimate what the CID shortage would be without FSID's footprint, subtract its footprint from the baseline, (39,237 - 8,167 = 31,070 acre feet per year).

Table 9. CID Shortages: Water Footprints Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
2070-2099 Water Footprint					
FSID	+8,167	+3,929	+2,581	+522	+5,155
PVACD	+30,553	+15,350	+12,318	+505	12,733
ESA	+2,610	+2,952	+421	+119	814
Drying Footprint (+) increases shortage		**0**			**Wetting Footprint (-) decreases shortage**
1950-2009 Modeled Historical CID Shortages: 10,995 acre-feet					
2070-2099 Baseline	39,237	72,898	13,588	718	12,741
	Higher Shortages		**10,995**		**Lower Shortages**

6.2.3. River Flows

As discussed above, maintaining continuous flow on the Pecos River is a primary goal of current river management for ESA purposes.

6.2.3.1. Drying at Acme

The water footprint analyses are of limited value for this parameter due to the idiosyncrasies in the model setup as discussed in the baseline projections in Section 5.3.1. *Drying at Acme*. For example, the FSID footprint ranges from 112 to 147 fewer days drying at Acme (Table 10). When the river receives FSID's return flows, there are 112 to 147 fewer drying days than there would be if the return flows were not in the river. However, this is an artifact of the model's operational assumptions that were not changed for the storyline runs. In the footprint analyses, the model is run with and without the impacts of each irrigation district to determine its footprint. When running the model in the absence of the FSID impacts , water that in reality goes to FSID is in this model run instead stored as CID project water in Sumner. We assume that if not for FSID's existing entitlement to this water, it would be stored in the reservoir, and only released downstream as part of block flows to CID.

However, if the model had assumed that FSID's water was released downstream instead of being stored in Sumner Reservoir, then FSID's footprint would have increased the number of drying days, as without FSID's return flows, the system would still be receiving the diverted water. The 2016 BiOp notes that FSID affects drying in the upper reaches during drier conditions ". . . there are times when FSID is the sole surface water diverter and its diversions may cause river intermittency when Reclamation's supplemental water supplies are exhausted. . . . (p. 96).

As expected, the ESA footprint was largest for all storylines, with 15 to 28 fewer days of drying at the gage as a result of ESA operations. CID and PVACD had the smallest water footprints, ranging from 4 more to 11 fewer days of drying. As PVACD is mostly downstream of the Acme Gage, PVACD operations have little effect on the quantity of water in the river at this gage. CID is also below the Acme Gage on the river, but their operations can affect flow at Acme (e.g., block releases from Sumner reservoir can help wet the river). See Figures Appendix, Section 7. *Drying at Acme* for the water footprint projections for each storyline throughout the 21st century. Table 10 shows the water footprints on drying days at Acme.

As an example, in the HE Moderate Storyline baseline, there are 44 drying days at Acme per year. CID's footprint results in five fewer drying days at Acme. To estimate what the drying days at Acme would be without CID's footprint, subtract its footprint from the baseline, (44 – [-5] = 49 drying days).

Table 10. Drying at Acme: Water Footprints Compared to Baselines and Modeled Historical Values in all Storylines (Drying Days)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
2070-2099 Water Footprint					
CID	-5	0	-10	-4	-11
FSID	-120	-112	-116	-147	-138
PVACD	-3	+4	-7	-4	-10
ESA	-28	-104	-27	-18	-15
Drying Footprint (+) more drying days		0			**Wetting Footprint (-) fewer drying days**
1950-2009 Modeled Historical Drying Days: 11 Days					
2070-2099 Baseline	44	117	40	10	21
More Days		11			**Fewer Days**

6.2.3.2. FSID Bypass Flows

Because FSID is upstream of the other irrigation districts, their bypass flows are not affected by other irrigation districts. ESA releases also have no effect on bypass flows since they only augment flows below the dam.

6.2.4. Groundwater

Only PVACD has a footprint affecting groundwater levels in the artesian aquifer and on groundwater inflows to the Pecos River, since the other districts do not overlay any part of the Roswell Artesian Basin.

6.2.4.1. Roswell Artesian Basin Groundwater Levels

PVACD's footprint on groundwater levels in the Roswell Artesian Basin was estimated by comparing two sets of simulation runs of the RABGWM, one run that models the baseline in each storyline (see Section 5.5.1. *Roswell Artesian Basin Groundwater Levels*), and a second set of runs modeling these baselines without PVACD pumping stresses (see the Groundwater Appendix, Section 8. *PVACD Water Footprint Analysis*). The water footprint analysis results were not explicitly simulated, but were instead generated from differencing these two simulations, and as a result do not distinguish between differences in the two simulations caused by PVACD and differences caused by other factors (for example, effects caused by disconnection of the RAB and the Pecos River). In other words, the simulation shows differences between the storyline baselines and the storyline baseline without PVACD footprints, but doesn't distinguish between which of these simulation differences are caused directly by PVACD and which may be artifacts of other elements of the model.

For this footprint analysis, we assumed that the differences in PVACD pumping dominate other differences between those simulations. An explicitly modeled simulation of the footprint, however, could produce different estimates of the PVACD footprints.

As expected, the PVACD water footprint on groundwater levels in the Roswell Artesian Basin is significant for each storyline. PVACD's footprint is larger than any storyline impact. In general, the size of the PVACD footprint mostly depends on the differences in the baseline conditions in the five storylines, since the footprint analysis compares simulated water levels with and without the impacts of PVACD. Without PVACD impacts, water levels in the RAB would quickly rise, but only by a certain amount before aquifer levels reach the surface, allowing artesian springs to begin flowing again and limiting further water level increases. As a result, the differences between the Groundwater Base Case and the simulated groundwater levels without the impact of PVACD tend to be relatively consistent between storylines (see the Groundwater Appendix, Section 8), while the differences between the Groundwater Base Case and the baselines for each storyline (for which aquifer levels do not reach the surfaces and therefore stabilize) tend to diverge.

The estimated water footprints for the observation wells Artesia A and LFD are provided as examples (Figure 63 and Figure 62). Figures for water footprints for the remaining wells are in Groundwater Appendix, Section 8. As an example, at the LFD observation well, simulated groundwater levels when the storylines are modeled without considering PVACD pumping stresses (Figure 62) are roughly 50 feet higher than the Groundwater Base Case (i.e., year 2010 conditions repeated throughout the projected years) in all storylines by the 2099, while under the storyline baseline conditions (see Section 5.5.1, Figure 59), the storylines range from a groundwater level increase over the same period, relative to the Groundwater Base Case, of about 20 feet in the LE Increased Monsoon Storyline to a decrease of nearly 150 feet in the HE Dry Storyline. As a result, our estimates of the PVACD footprint at the LFD observation well by 2099 range from approximately 30 feet of drawdown (reducing from a 50-foot increase to a 20 foot increase) in the LE Increased Monsoon Storyline to a drawdown of almost 200 feet (from a 50-foot increase to a 150-foot decrease) in the HE Dry Storyline.

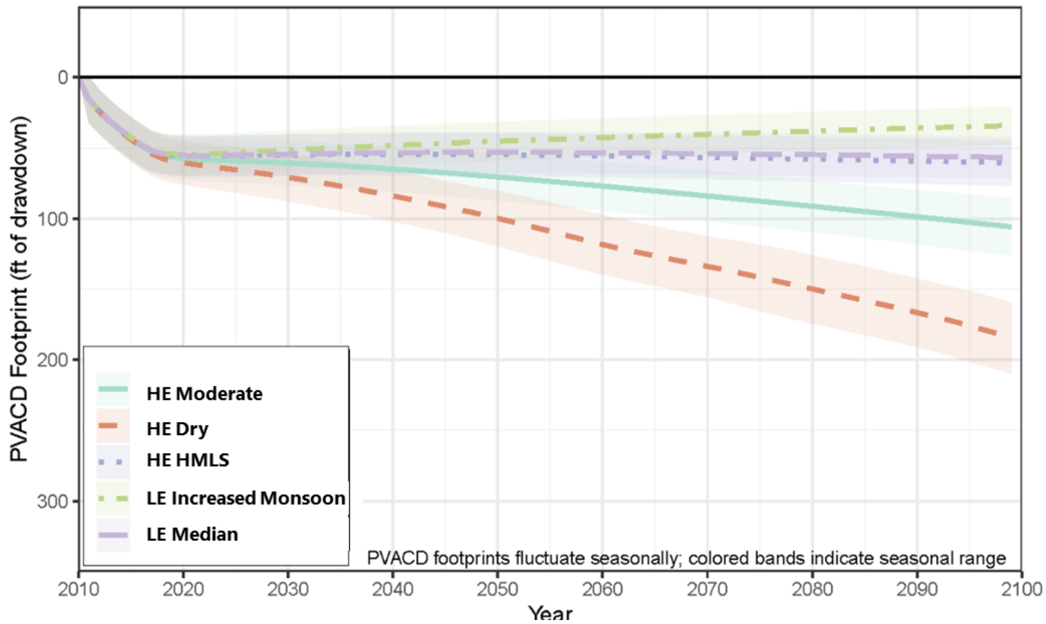


Figure 62. RAB groundwater levels: Estimated water footprint at the northern LFD observation well in the five storylines, in feet of additional drawdown.

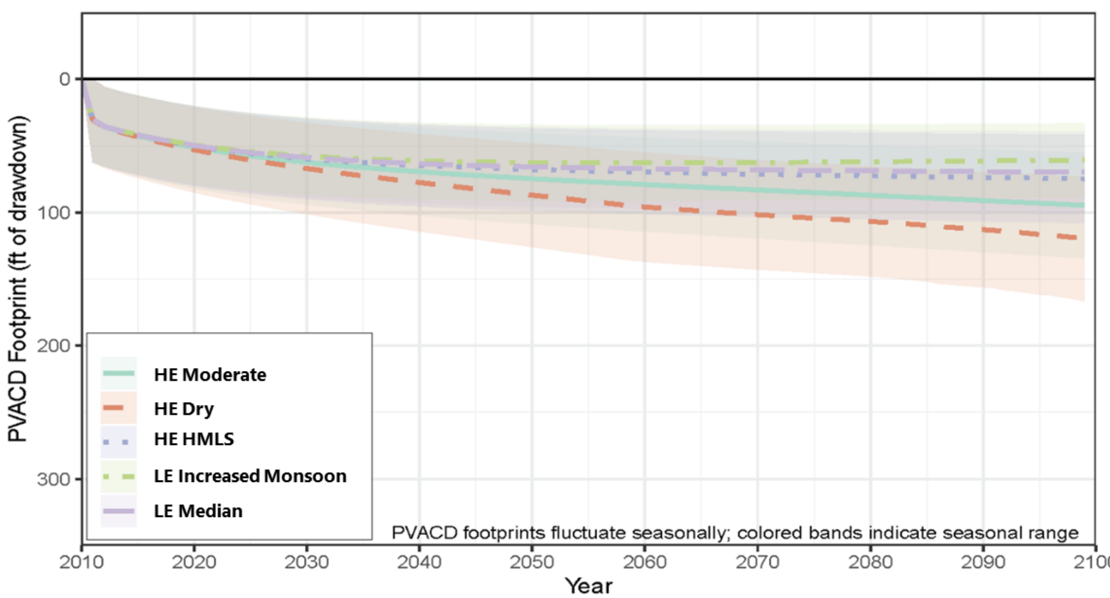


Figure 63. RAB groundwater levels: Estimated water footprint at the southern Artesia A well in the five storylines, in feet of additional drawdown.

6.2.4.2. Pecos River Groundwater Gains from Acme to Artesia

PVACD pumping does not affect the alluvial aquifers in the vicinity of FSID and CID.

The PVACD water footprint on Pecos River gains from the Roswell Artesian Basin is significant for each storyline, since PVACD's pumping is a primary driver for these changes. See Figures Appendix, Section 10. *Groundwater* for projected average annual gains to the Pecos River between the Acme and Artesia Gages for the PVACD footprint ad the Water Management Strategies in each storyline. As expected, PVACD's water footprint is greatest in the drier storylines, HE Moderate Storyline (about 55,000 acre-feet/year) and HE Dry Storyline (about 60,000 acre-feet/year) (Table 11). For the remaining three wetter storylines, the water footprint on gains to the river is somewhat less, since wetter conditions decrease the demand for groundwater pumping for irrigation. Consequently in these storylines, the lower irrigation pumping results in a higher water table and steeper hydraulic gradients toward the Pecos, resulting in higher base flows as more groundwater reaches can reach the river.

Storyline baselines for groundwater gains ranged from a maximum of approximately 22,000 additional acre-feet/year on average by 2099 (increasing from the modeled historical gains of approximately 27,000 acre-feet/year to over 49,000 acre-feet/year) in the LE Increased Monsoon Storyline to a decrease of nearly 44,000 acre-feet/year (decreasing from the historical gains of 27,000 acre-feet/year to a loss of almost 17,000 acre-feet/year) in the HE Dry Storyline. PVACD's water footprint on gains from groundwater to the Pecos River in the HE Moderate and HE Dry Storylines is significantly larger than any projected climate change impacts.

As an example, in the HE Moderate Storyline baseline, annual gains from the Roswell Artesian Basin in the Acme to Artesia reach of the Pecos River are 9,194 acre-feet. PVACD's footprint reduces the annual gains by 54,760 acre feet. To estimate what the annual gains from Acme to Artesia would be without PVACD's footprint, subtract its footprint from the baseline, (9,194 – [-54,760] = 63,954 acre feet).

Table 11. Pecos River Groundwater Gains from Acme to Artesia: Water Footprints Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet per year)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
Water Footprint	2070-2099 Water Footprint				
PVACD	-54,760	-59,899	-43,874	-35,996	-43,581
	Drying Footprint		0		Wetting Footprint
1950-2009 Modeled Historical Gains: 27,266 acre-feet per year					
2070-2099 Baseline	9,194	16,776	32,846	49,172	34,850
Less Gains			27,266		More Gains

6.2.4.3. Shallow Alluvial Aquifer Levels in the Vicinity of FSID

Since FSID is hydraulically connected to the alluvial aquifer that underlies it, FSID return flows have a substantial effect on local groundwater levels in the alluvial aquifer, raising local aquifer levels by about 4 to 6 feet, depending on the storyline, above what they would be if FSID were not operating. The ESA footprint is also significant, since ESA operations contribute to keeping the river wet, and by extension help raise the local water table. Since CID's operations impact the flows of the Pecos River alongside FSID, CID also can impact the groundwater levels in the shallow alluvial aquifer beneath FSID, although this impact is generally minor. PVACD's footprint on this shallow aquifer is practically negligible, since its impact is even more indirect than CID's (i.e., PVACD's operations may affect CID's operations, which in turn could impact the shallow alluvial aquifer). Table 12 shows the water footprints for these shallow alluvial aquifer levels.

As an example, in the HE Moderate Storyline baseline, modeled historical elevations in the FSID shallow aquifer. CID's footprint increases elevations by 0.09 foot msl. To estimate what the elevations would be without CID's footprint, subtract its footprint from the baseline, (4,006.38 – 0.09 = 4,006.29 feet msl).

Table 12. Difference in Average FSID Shallow Groundwater Elevations from 2070-2099 to 1950-2009 for Storylines and Water Footprints (in feet msl).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
2070-2099 Water Footprint (Relative to Baseline)					
CID	+0.09	0.00	+0.15	+0.05	+0.10
FSID	+5.31	+4.38	+5.33	+5.51	+5.32
PVACD	+0.05	+0.06	+0.09	+0.05	+0.08
ESA	+1.86	+4.50	+1.51	+1.52	+1.42
Drying Footprint (-) decreases elevations		**0**			**Wetting Footprint (+) increases elevation**
1950-2009 Modeled Historical Elevations: 4,006.18 feet msl					
2070-2099 Baseline	4,006.38	4,004.91	4,006.45	4,006.85	4,006.66
Lower Elevation			**4,006.18**		**Higher Elevation**

7. Modeled Water Management Strategies

Based on the knowledge gained from the water footprint analyses, we devised and modeled a set of potential Water Management Strategies to assist in maintaining agricultural viability in the range of projected storylines.

7.1. Water Management Strategies Description

The projections of future conditions described in Section 4 suggest that there are likely to be increased gaps between available water supplies and crop water demands in the Higher Emissions (RCP 8.5) storylines due to increasing temperatures and decreasing water supplies (the HE Dry and HE Moderate Storylines) or due to changes in timing and availability in water (the HE HMLS Storyline). In the Lower Emissions (RCP 4.5) storylines, crop water demands still increase due to increasing temperatures—although not as significantly as in the Higher Emissions RCP (8.5) storylines, since temperature increases are less severe. Overall water supplies decrease slightly in the LE Median Storyline. Water supplies increase during the monsoon season in the LE Increased Monsoon Storyline.

Basin Study participants developed prospective strategies for mitigating these impacts, based on stakeholder meetings and input about the types of changes that could improve water use efficiency and operations management in the Pecos River Basin. These Water Management Strategies would help water users adapt to shortages projected in some of the storylines, and better meet their needs in these conditions.

> "Water management strategies that account for changing climate conditions can help reduce present and future risks to water security." USGCRP 2018.

We modeled future conditions associated with various water supply and demand strategies in the five storylines to contextualize potential futures and to build a foundation for practical actions to prepare for these futures.

7.1.1. Reducing Irrigation Water Diversions within Each Irrigation District

This group of Water Management Strategies looked at the potential impacts of reducing irrigation water diversions in each irrigation district. We modeled this reduction by decreasing pumping volumes starting in 2045 for the groundwater model and reducing irrigated acreage within the surface irrigation districts starting in 2055. We chose these years because the HE Moderate Storyline starts to show significant declines in overall water supplies (e.g., decreased reservoir storage levels and increased FSID and CID shortages) by 2055. The effect of changes in pumping stresses on the Roswell Artesian Basin takes about 10 years to be reflected in changes in baseflow to the river. Therefore, we chose 2045 for the PVACD reduction start date. This modeling focuses on the impacts from the reduction—not how the reduction is accomplished.

For each strategy, the reduction in irrigation water consumption was implemented through a combination of modeling adjustments. These levels were selected to bracket the amount of reduction that would keep the system whole.

- **Surface Water Modeling for Reductions.** For surface water irrigation districts (FSID and CID), PROM calculated reductions as in the irrigated acreage rather than as the water conservation. See Section 5.2. *Surface Water Irrigation District Entitlements.*

- **Groundwater Modeling for Reductions.** In the RABGWM model, reducing acreage would require considerable effort and assumptions regarding the location of acreage to fallow. Instead, reductions in PVACD are represented in the RABGWM model as reduction in the total amount of PVACD pumping in years starting with 2045. This approach captures the essential decrease, pumping will decrease as acreage is fallowed, but avoids the need to delineate specific acreage fallowed. Reducing PVACD pumping is a surrogate for acreage adjustments. Reducing PVACD pumping is a surrogate for acreage adjustments. The amount of the reduction depends on the storyline, but in each case represents the associated decrease in the 2045 acreage. See Section 5.5. *Groundwater.*

Two reductions to all districts were modeled:

- **20% Reduction by All Districts Strategy.** PVACD reduces acreage by 20% by 2045 and FSID and CID reduce acreage by 20% by 2055

- **25% Reduction by All Districts Strategy.** PVACD reduces acreage by 20% by 2045 and FSID and CID reduce acreage by 25% by 2055

As PVACD generally hold junior water rights, and PVACD irrigates 110,000 acres, while FSID and CID only irrigate a combined total of 26,500 acres, we also modeled cuts to PVACD only by 2045. As discussed in Section 4, pumping in the HE Dry Storyline is curtailed around mid-century, when projected pumping begins to exceed total available water rights. This limit on pumping does not, however, affect the Water Management Strategy model projections since they are implemented before the projected pumping exceeds water rights.

Two reductions to PVACD only were modeled:

- **25% Reduction by PVACD Strategy**
- **30% Reduction by PVACD Strategy**

For more information, see the Surface Water Modeling and the Groundwater Appendices.

7.1.2. Increased Surface Water Districts' On-Farm Efficiency

The On-Farm Efficiency Strategy involves improvements to on-farm efficiency (i.e., increasing the proportion of water applied to crops that is used by those crops, and reducing the proportion that is either lost to evaporation or runs off or infiltrates to surface or groundwater). On-farm efficiency is a variable in our water operations model that is higher when crops use a larger proportion of irrigation water (for example, crops that are flood irrigated use proportionally less water than crops irrigated by center-pivots, so farms that use center-pivot irrigation generally have higher on-farm efficiencies than those using flood irrigation). Using practices that provide more water to plants and decrease the amount of water that evaporates, seeps to the water table, or flows to the river increases on-farm efficiency.

In all storylines, increasing on-farm efficiency is a useful strategy, as it allows farmers to either continue to achieve the same crop yields if shortages occur or if crop demands increase due to temperature increases, or improve yields should supplies remain constant or increase. However, increased efficiency does have potential tradeoffs: since more applied water is consumptively used by the crops, less water is returned to the basin for other users. Managing efficiency increases without unduly favoring upstream users may require cuts to diversions to avoid increasing water consumption in the basin as a whole.

7.1.2.1. Model Definition of On-Farm Efficiency

For each irrigation district, PROM calculates a crop depletion value that depends on acres of farmland and ET. This depletion is then divided by the on-farm efficiency variable—so that model variable for on-farm efficiency is equal to one.

Because FSID and CID are modeled slightly differently, both are affected by on-farm efficiency slightly differently as well:

- **FSID.** FSID is assumed to always divert all their entitlement, whether they need the water or not. In reality, irrigators in the district typically take only what they need for their crops, so the full entitlement is not always used even if it is diverted. In the model, whatever water is delivered to the farm but is not consumed by cropland evapotranspiration is split between the return flows to the groundwater (60%) and return flows to the river (40%) via the FSID drain system. This proportion is held constant regardless of changes to the overall efficiency in the model.

- **CID.** In contrast to FSID, CID diverts only the amount of water needed for irrigation and retains the remainder in the reservoirs. In this case, increasing efficiency will reduce the amount they have to divert to fulfill crop needs, which will either reduce the amount of shortages CID has, or if they would have had no shortages, will decrease the amount of water that is being taken from Avalon Reservoir.

7.1.2.2. Model Efficiency Values

To quantify the effects of hypothetical water conservation actions that improve irrigation efficiencies, we modeled an exponential increase in on-farm efficiency from 50% in 2010 to 75% in 2050 (Figure 64). This increase assumption is based on the United Nation’s Food and Agriculture Organization’s (1997) estimates of irrigation efficiency. We used an exponential increase over time since we are assuming that there will be early adopters of efficiency improvement methods, followed by an increasing number of farmers who adopt these methods over time. To provide a consistent basis for analysis, in addition to the calculations for on-farm efficiency, we assume that the efficiency for water conveyed to the farm remains 85% from 1950 to 2099.

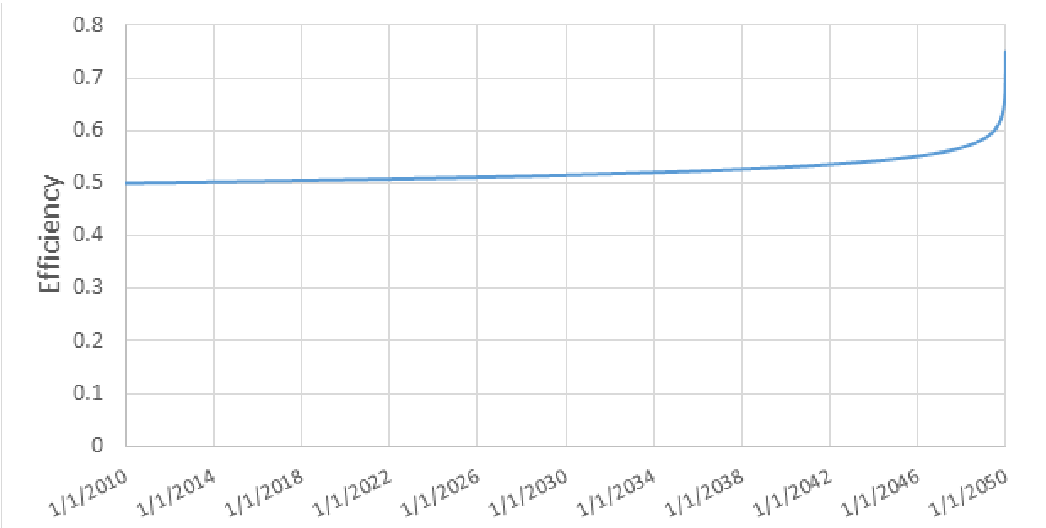


Figure 64. Rate of efficiency increase in FSID and CID from 2010-2050 used in the model.

A 50% on-farm efficiency rating means that the irrigation district needs to divert twice the amount of water needed by its crops. As a simplified example, assume that a farm requires 7.5 acre-feet of water to achieve a satisfactory crop yield in a given year. In a water-short year, this example farm might receive 10 acre-feet of water delivered to the edge of the fields. Since on-farm irrigation efficiency is only 50%, only 5 acre-feet are successfully used by the crop, resulting in a shortage of 2.5 acre-feet to the crop, and by extension reducing yields below what they would be under full irrigation. If more efficient on-farm delivery practices are used, raising the on-farm efficiency to 75%, then 7.5 acre-feet of the 10 acre-feet of water delivered would get to the crop (the amount of water needed), and there would be no shortage—even though the amount of water delivered to the farm was exactly the same.

7.2. Comparison of Modeled Water Management Strategies

This study modeled water supplies and operations under Water Management Strategies for each of the five modeled storylines. For more information about how these strategies were modeled, see the Surface Water Modeling and Groundwater Appendices.

7.2.1. Reservoir Storage and Operations

Baseline values for the average reservoir storage range from very dry to drier in the drier storylines and wetter to very wet in the wetter storylines (see the baseline discussion in Section 5.1. *Reservoir Storage*).

In the HE Dry Storyline, no Water Management Strategy helps by more than 500 acre-feet. This is due to the lack of recharge to groundwater, along with consistent pumping, which result in the reach between Sumner Reservoir and Brantley Reservoir shifting from a gaining to a losing reach. Reducing PVACD pumping would delay the point at which this shift occurs.

For all storylines other than the HE Dry Storyline, the 25% Reduction by All Districts Strategy increases reservoir levels the most. The 20% Reduction by All Districts Strategy is the next best strategy, except in the HE Moderate Storyline. In the HE Moderate Storyline, the 30% Reduction by PVACD Strategy increases total reservoir storages more than the 20% Reduction by All Districts Strategy does. This is because the HE Moderate Storyline reaches the point that the HE Dry Storyline reached, where the river gains/losses between Sumner Reservoir and Brantley Reservoir are headed more toward losses toward the end of the century, and the reduction to PVACD delays that response. The On-Farm Efficiency Strategy increases reservoir storage levels the least, although it still helps.

See Figures Appendix, Section 2. *Reservoir Storage* for the Water Management Strategies projection figures for each storyline throughout the 21st century. Table 13 shows the potential impacts for reservoir storage in each alternative and in each storyline from 2070-2099. Table 13, and others in this section, show the level of impact in the different storylines for Water Management Strategies. Shading indicates the size—the stronger the shade, the larger the impact. Positive numbers indicate a wetter strategy. As an example, the HE Moderate Storyline baseline reservoir storage is 57,736 acre-feet, and the 20% Reduction by All Districts Water Strategy would add 11,354 acre-feet, for a projected total of 69,090 acre-feet of reservoir storage.

Table 13. Reservoir Storage: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical Reservoir Storage: 102,900 acre-feet					
2070-2099 Baseline	57,736	13,525	116,987	144,234	90,397
	Lower Storage		**102,900**		**Higher Storage**
2070-2099 Change from Baseline in each Water Management Strategy					
20% Reduction by All Districts	+11,354	+223	+17,384	+21,938	+38,848
25% Reduction by All Districts	+14,192	-76	+20,819	+24,795	+49,504
25% Reduction by PVACD	+9,945	+355	+12,512	+15,220	+27,373
30% Reduction by PVACD	+12,664	+421	+16,334	+16,397	+30,476
On Farm Efficiency	+7,047	+16	+12,576	+18,862	+27,534
Drying Strategy (-) reduces storage			**0**		**Wetting Strategy (+) adds storage**

7.2.2. Surface Water Irrigation Districts' Water Supply (i.e., Entitlements, Allotments, and Shortages)

For this analysis, shortages are calculated as the difference between the amount that is diverted and the modeled required crop demand. Increasing efficiency will reduce shortages. If on any given day, the modeled shortages reach zero, the excess water will be either sent downstream (FSID) or stay in Avalon Reservoir (CID). If even with increased efficiency, there are still shortages during a given day, the irrigators would have used the same amount of water whether or not they had increased efficiency. See the equations in the Surface Water Appendix.

In all storylines, the On-Farm Efficiency Strategy reduces FSID and CID shortages the most. However, the On-Farm Efficiency Strategy has little to no effect on FSID entitlements or CID allotments (i.e., the amount of water legally available) in the model. In the PROM, this water is shown as return flows to the river. In reality, water saved from higher efficiencies could be used on farm or left in the river.

These improvements increase the proportion of the available water that goes to crops, rather than to system losses. Therefore, these improvements can help farmers maintain crop yields and continue to bring crops to harvest without taking more water than is allowed under their existing water rights. These improvements also increase water available in reservoir storage (which primarily benefits CID) and decrease FSID and CID shortages.

It is important to note that increasing on-farm efficiency does not necessarily decrease the consumptive use of farms within an irrigation network but may actually increase the consumptive use—if a greater proportion of applied water is used by the crops, then less water may be returned to the river or water table via runoff/infiltration. See the baseline discussion in Section 5.2. *Surface Water Irrigation District Entitlements, Allotments, and Shortages*.

7.2.2.1. FSID Entitlements

As PVACD and CID are downstream of FSID, only strategies that involve FSID affect FSID. Average annual FSID entitlements will stay the same under all water management strategies.

7.2.2.2. FSID Shortages

Because FSID has run-of-the-river rights and is the furthest upstream irrigator of the three largest irrigation districts in the system, only water management strategies that involve FSID will reduce the FSID shortages. In every storyline, the On-Farm Efficiency Strategy resulted in the lowest shortages, eliminating shortages in every storyline except for the HE Dry Storyline. Even in the HE Dry Storyline, this strategy cuts shortages from a storyline baseline increase of 1,383% to slightly more than historical conditions.

See Figures Appendix, Section 4. *FSID Shortages* for the Water Management Strategies projection figures for each storyline throughout the 21st century. Table 14 shows the potential impacts for FSID shortages in each alternative and storyline from 2070-2099. In Table 14, negative numbers indicate a wetter strategy. For example, in the 20% Reduction by All Districts in the HE Moderate Storyline, shortages would reduce by 2,026 acre-feet from the storyline baseline of 2,481 acre-feet (i.e., a shortage of 455 acre-feet). As the PVACD reductions do not affect FSID, these are not listed in the table.

Table 14. FSID Shortages: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical FSID Shortages: 401 acre-feet					
2070-2099 Baseline	2,481	6,515	2,159	446	674
	Higher Shortage		**401**		**Lower Shortage**
2070-2099 Percent Change from Baseline in each Water Management Strategy					
20% Reduction by All Districts	-2,026 (-82%)	-4,224 (-65%)	-1891 (-88%)	-443 (-99%)	-648 (-96%)
25% Reduction by All Districts	-2,255 (-91%)	-4,986 (-77%)	-2,060 (-95%)	-446 (-100%)	-673 (-100%)
On-Farm Efficiency	-2,459 (-99%)	-5,929 (-91%)	-2,154 (-100%)	-446 (-100%)	-674 (-100%)
Drying Strategy (+) increases shortages			**0**		**Wetting Strategy (-) decreases shortages**

7.2.2.3. CID Allotment

The baseline CID allotments remain above or slightly less than the historical average of 2.47 acre-feet per acre in three storylines: LE Increased Monsoon, HE HMLS, and LE Median Storylines in the 2017-2099 period. The HE Moderate and HE Dry Storylines are much drier. See the baseline discussion in Section 5.2.3. *CID Allotment.*

In the HE Dry Storyline, no strategy will make much of a difference. For all other storylines, out of all of the Water Management Strategies, the 25% Reduction by All Districts Strategy is the most effective, and the 20% Reduction by All Districts Strategy is second-most effective. In these strategies, CID reduces consumption, thus increasing reservoir storage, which increases the CID allotment. The 25% Reduction by PVACD and by 30% Strategies will also increase the CID allotment over the storyline baselines, but not as much as reductions to all irrigation districts. The On-Farm Efficiency Strategy also increases the CID allotment over the storyline baselines slightly.

See Figures Appendix, Section 5. *CID Allotments* for the Water Management Strategies projection figures for each storyline throughout the 21st century. Table 15 shows the potential impacts for CID allotments in each alternative and in each storyline from 2070-2099. Positive numbers indicate a wetter strategy. As an example, in the HE Moderate Storyline, the baseline allotment is 1.38 acre-feet per acre, and the 20% Reduction by All Districts Water Strategy would add 0.49 acre-feet per acre, for a projected total of 1.87 acre-feet per acre of allotment.

Table 15. CID Allotment: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet per /acre)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical CID Allotment: 2.47 acre-feet per acre					
2070-2099 Baseline	1.38	0.15	2.67	3.29	2.25
	Lower Allotment		**2.47**		**Higher Allotment**
2070-2099 Change from Baseline in each Water Management Strategy					
20% Reduction by All Districts	+0.49	+0.03	+0.40	+0.40	+1.02
25% Reduction by All Districts	+0.62	+0.04	+0.49	+0.41	+1.22
25% Reduction by PVACD	+0.27	+0.01	+0.25	+0.24	+0.59
30% Reduction by PVACD	+0.33	+0.01	+0.31	+0.26	+0.67
On-Farm Efficiency	+0.12	0.00	+0.15	+0.21	+0.45
	Drying Strategy (-) decreases allotment		**0**		**Wetting Strategy (+) increases allotment**

7.2.2.4. CID Shortages

CID shortages are the gap between the district's water supply and crop demands. CID shortages increase from the historical average shortages for the two drier storylines (HE Dry and HE Moderate), stay about the same in two wetter storylines (HE HMLS and LE Median, and decrease in the LE Increased Monsoon Storyline. See the baseline discussion in Section 5.2.4. *CID Shortages.*

In general, all strategies that conserve irrigation water decrease the number of shortages from the baseline in all storylines. The On-Farm Efficiency Strategy and the 25% and 20% Reduction by All Districts Strategies were the most beneficial strategies for all five storylines. The 30% and 25% Reduction by PVACD Strategies showed some improvement, but less than the other strategies.

See Figures Appendix, Section 6. *CID Shortages* for the Water Management Strategies projections for each storyline throughout the 21st century. Table 16 shows the potential impacts for CID shortages in each alternative and in each storyline from 2070-2099. Negative numbers indicate a wetter strategy. For example, in the 20% Reduction by All Districts in the HE Moderate Storyline, average annual shortages would decrease by 20,326 acre-feet from the storyline baseline of 39,237 acre-feet to a shortage of 18,911 acre-feet.

Table 16. CID Shortages: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet per year). Note that higher numbers correspond to higher shortages (i.e., less water available). Negative numbers in the change indicate a lesser shortage (i.e., the higher the negative number, then the more water would be available).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical CID Shortages: 10,995 acre-feet					
2070-2099 Baseline	39,237	72,898	13,588	718	12,741
	Higher Shortage		**10,995**		**Lower Shortages**
2070-2099 Change from Baseline under each Water Management Strategy					
20% Reduction by All Districts	-20,326 (-52%)	-16,043 (-22%)	-9,922 (-73%)	-718 (-100%)	-11,205 (-88%)
25% Reduction by All Districts	-24,705 (-63%)	-19,833 (-27%)	-11,256 (-83%)	-714 (-99%)	-12,515 (-98%)
25% Reduction by PVACD	-6,554 (-17%)	-342 (0%)	-3,907 (-29%)	-566 (-79%)	-7,411 (-58%)
30% Reduction by PVACD	-8,081 (-21%)	-371 (-1%)	-5,134 (-38%)	-605 (-84%)	-8,292 (-65%)
On-Farm Efficiency	-20,675 (-53%)	-25,487 (-35%)	-8,787 (-65%)	-718 (-100%)	-10,325 (-81%)
	Drying Strategy (+) increases shortages		**0**		**Wetting Strategy (-) decreases shortages**

7.2.3. River Flows

7.2.3.1. Drying at Acme

The number of drying days at Acme in the Lower Emissions (RCP 4.5) storylines are lower than the Higher Emissions (RCP 8.5) storylines. See the baseline discussion in Section 5.3.1. *Drying at Acme.*

The 25% and 20% Reduction by All Districts Strategies result in the fewest drying days at Acme in all storylines—mainly due to reducing FSID water consumption, which results in higher return flows. The 25% and 30% Reduction by PVACD and On-Farm Efficiency Strategies had little to no impact to the number of drying days at Acme. The groundwater model only shows changes due to PVACD pumping up to Acme. The effects that are seen are from delayed block releases as more groundwater flows into Brantley Reservoir from the block releases.

See Figures Appendix, Section 7. *Drying at Acme* for the Water Management Strategies projections for each storyline throughout the 21st century. Table 17 shows the potential impacts for drying days at Acme in each alternative and in each storyline from 2070-2099. In Table 17, the negative sign indicates fewer drying days, and therefore a wetter strategy. For example, in the 20% Reduction by All Districts Strategy in the HE Moderate Storyline, there would be a projected 16 fewer drying days at Acme than the 44 drying days in the HE Moderate Storyline baseline, for a total of 28 drying days.

Table 17. Drying at Acme: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines in Days (Note that positive numbers mean more days will be dry).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical Drying Days: 11 days					
2070-2099 Baseline	44	117	40	10	21
	More Drying Days		**11**		**Fewer Drying Days**
2070-2099 Change from Baseline in each Water Management Strategy					
20% Reduction by All Districts	-16	-17	-17	-8	-10
25% Reduction by All Districts	-19	-21	-19	-9	-13
25% Reduction by PVACD	-2	-1	+3	+1	0
30% Reduction by PVACD	-1	-1	+2	0	+2
On-Farm Efficiency	0	0	+3	+3	0
	Drying Strategy (+) increases drying days		**0**		**Wetting Strategy (-) decreases drying days**

In the HE Moderate and HE Dry Storylines toward the end of the 21st century, the reach below Acme switches from a gaining reach to a losing reach, which causes Artesia to start drying before Acme after this point as shown in Figure 65. See Figures Appendix, Section 8. *Drying at Acme and Artesia Gages.*

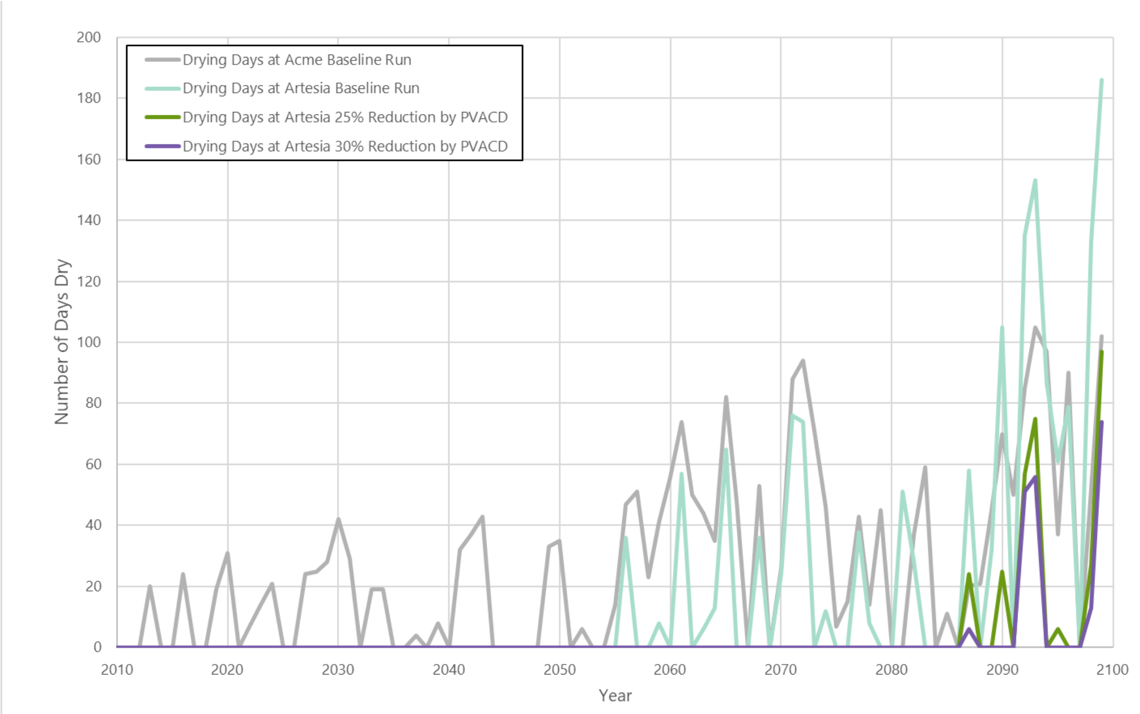


Figure 65. Comparison between Acme (gray) and Artesia baselines (teal): storyline baselines and the 25% and 30% Reduction by PVACD Water Management Strategies in HE Moderate Storyline.

For the HE Moderate Storyline, reducing PVACD water usage by 25% or 30% was enough to keep the number of drying days at Artesia lower than the number of drying days at Acme, although Artesia is still drying more than in the earlier 21st century. In the HE Dry Storyline, reducing PVACD water usage by 25% or 30% decreases the drying at Artesia compared to the storyline baseline, but not enough to go below the amount of days dry at Acme. Those two strategies do delay Artesia from going dry almost all year long until the 2080s as shown in Figure 66.

7.2.3.2. FSID Bypass Flows

There would be no impacts on FSID bypass flows from any water management strategy.

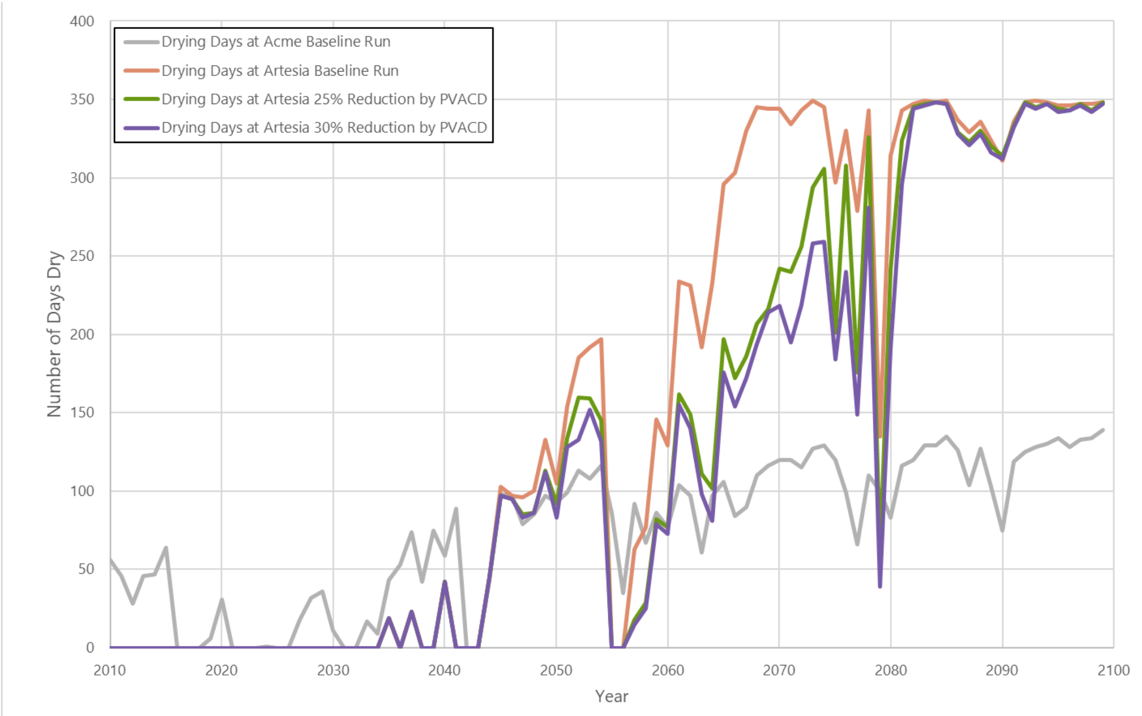


Figure 66. Comparison between Acme (gray) and Artesia (red): storyline baselines and the 25% and 30% Reduction by PVACD Water Management Strategies in the HE Dry Storyline.

7.2.4. Availability of Water for Estimated Releases for the Pecos River Settlement

The amount of potential Settlement releases increases in the LE Increased Monsoon Storyline, but decreases in the rest of the storylines, and decreases the most in the HE Dry Storyline. See the baseline discussion in Section 5.4. *Availability of Water for Estimated Releases for the Pecos River Settlement.*

None of the strategies help increase potential Settlement releases for the HE Dry Storyline.

LE Increased Monsoon Storyline baseline is already at the maximum potential Settlement Releases, so no strategy could increase that further.

For the other three (HE Moderate, HE HMLS, and LE Median Storylines), the cooler and wetter the storyline is, the more benefits that the 25% and 20% Reduction by All Districts Strategies provide. The drier and hotter the storyline, the more efficient it is to reduce PVACD irrigation water consumption, and the 25% and 30% Reduction by PVACD in 2045 strategies start to be just as beneficial as reducing all three irrigation districts. With higher demands from higher temperatures, particularly in CID, CID will require more water, which will reduce the estimated amount for the Settlement releases based on Settlement calculations.

Storage in Brantley Reservoir would be reduced in the HE Dry Storyline and at the end of the HE Moderate Storyline when groundwater gains start becoming losses in the Pecos River between Acme Gage and Brantley Reservoir. As Settlement calculations incorporate Brantley Reservoir levels, Settlement amounts would be reduced. Reducing PVACD demands delays this point.

In all three storylines, the On-farm Efficiency Strategy is the least beneficial for increasing the availability of potential Settlement releases.

See Figures Appendix, Section 9. *Potential Settlement Releases* for the Water Management Strategies projections for each storyline throughout the 21st century. Table 18 shows the potential impacts for potential settlement releases in each alternative and in each storyline from 2070-2099. Positive numbers indicate a wetter strategy. As an example, in the HE Moderate Storyline, the baseline amount available for potential Settlement releases is 8,005 acre-feet, and the 20% Reduction by All Districts Water Strategy would add 1,779 acre-feet for a projected total of 9,784 acre-feet.

Table 18. Potential Settlement Releases: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Inc. Monsoon	LE Median
1950-2009 Modeled Historical Potential Settlement Releases: 14,200 acre-feet					
2070-2099 Baseline	8,005	318	14,740	17,154	14,041
	Less Settlement Releases		**14,200**		**More Settlement Releases**
2070-2099 Change from Baseline in each Water Management Strategy					
20% Reduction by All Districts	+1,779	0	+635	0*	+2,351
25% Reduction by All Districts	+2,033	0	+1,652	0*	+2,605
25% Reduction by PVACD	+2,033	0	+1,398	0*	+2,097
30% Reduction by PVACD	+2,351	0	+1,398	0*	+2,097
On-Farm Efficiency	+953			0	+699
Drying Strategy (-) decreases amount of water available for Settlement releases			**0**		**Wetting Strategy (+) increases amount of water available for Settlement releases**

7.2.5. Groundwater

7.2.5.1. Roswell Artesian Basin Aquifer Levels

Modeled groundwater water levels reflect the magnitude of changes associated with each of the strategies that affect groundwater levels in the Roswell Artesian Basin (i.e. the 20% and 25% Reduction by All Districts and the 30% Reduction by PVACD Strategies). As PVACD pumping decreases, groundwater levels increase at a proportional rate. In some storylines and Water Management Strategies, water levels may be more than the Groundwater Base Case (year 2010 conditions) for brief or extended periods of time from 2045, the start of the PVACD reductions, through 2099. The positive differences indicate that the Water Management Strategies offset the storylines' impacts on groundwater levels. For both PVACD wells LFD and Artesia A, the 20% and the 25% Reduction by All Districts Strategies are not enough to offset HE Moderate or HE Dry Storyline impacts. The 30% Reduction by PVACD Strategy was also not enough to offset the HE Dry Storyline impacts through 2099, but it was enough to have some temporary success offsetting HE Moderate Storyline impacts.

Figure 67 through Figure 69 provide the PVACD Well LFD and Artesia A water level results for the Water Management Strategies. In the HE Dry Storyline, none of the strategies result in water levels recovering to the Groundwater Base Case (year 2010) levels: water-level differences remain below at both wells, for all strategies by 2099. In the HE Moderate Storyline, the 30% Reduction by PVACD Strategy can temporarily offset impacts at Artesia A—but not for the LFD observation well in the HE Moderate or HE Dry Storyline impacts. In the LE Median and LE Increased Monsoon Storylines, all Water Management Strategies persistently increased water levels above the 2010 Base Case (values are greater than zero) for both wells.

LFD is a well in the northern part of PVACD, and Figure 68 shows that in the wetter storylines (the LE increased Monsoon, LE Median, and HE HMLS Storylines) groundwater levels in this well are steady at the 2010 Groundwater Base Case conditions (0 in the figure) through 2045 and then increase above these conditions after the 20% Reduction by All Districts Strategy is implemented. In the HE Moderate and Dry Storylines, groundwater levels start to decrease below the 2010 Groundwater Base Case conditions through 2045; however, the decreasing trend is less steep after the 20% Reduction by All Districts Strategy is implemented.

In Artesia A, a well in the southern part of PVACD, similar trends as in LFD well are seen: groundwater levels in the wetter storylines noticeably increase after 2045 when the 20% Reduction by All Districts Strategy is implemented and the declines in the drier storylines are less severe after the strategy is implemented.

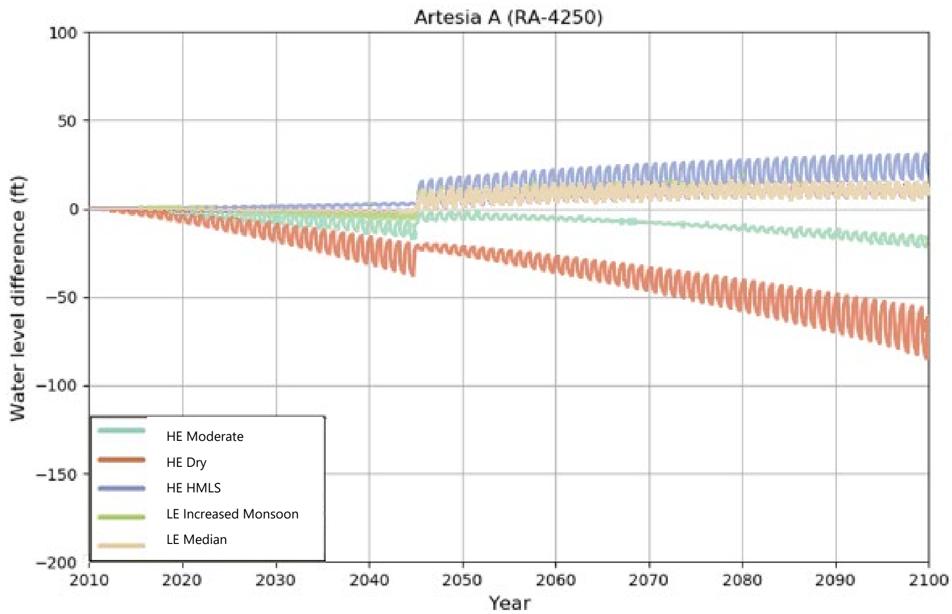
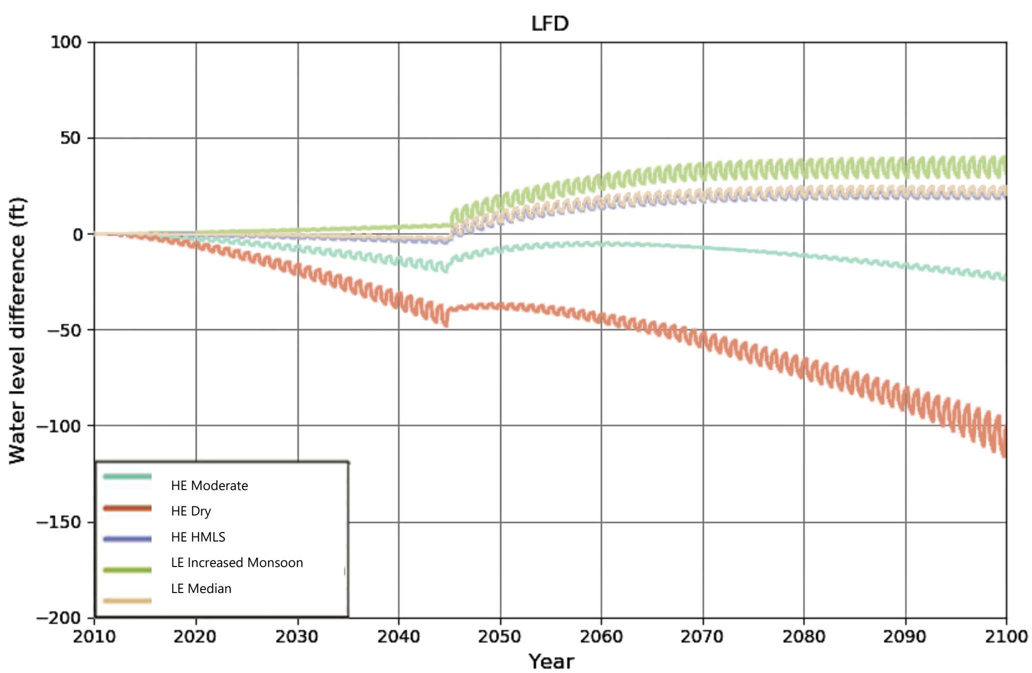


Figure 67. Change in modeled water levels at PVACD well LFD (upstream) and Artesia A (downstream) in the 20% Reduction by All Districts Strategy in all storylines relative to the Groundwater Base Case (as PVACD reduces in 2045, changes from the strategy appear in 2045).

The 25% Reduction by All Districts Strategy shows similar patterns as in the 20% Reduction by All Districts Strategy as shown in Figure 68 only with slightly higher increases in the wetter storylines (LE: Increased Monsoon, HE HMLS, and LE Median Storylines) and slightly less decreases in the drier storylines (HE Dry and HE Moderate).



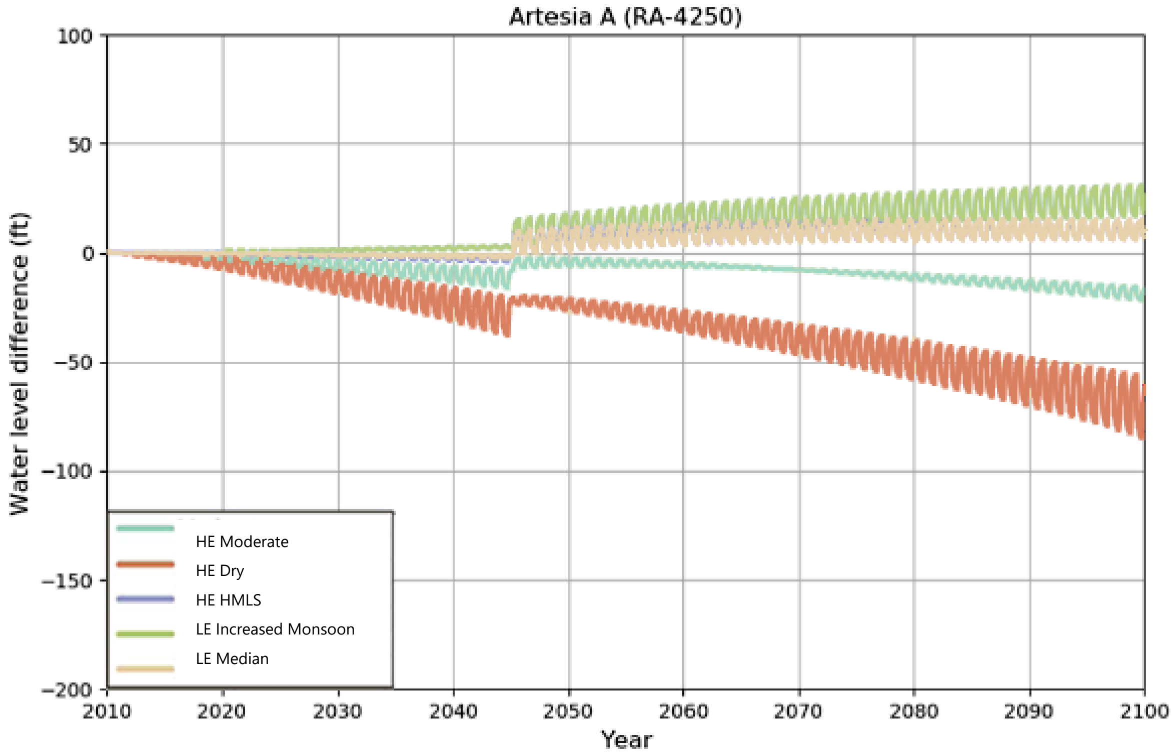
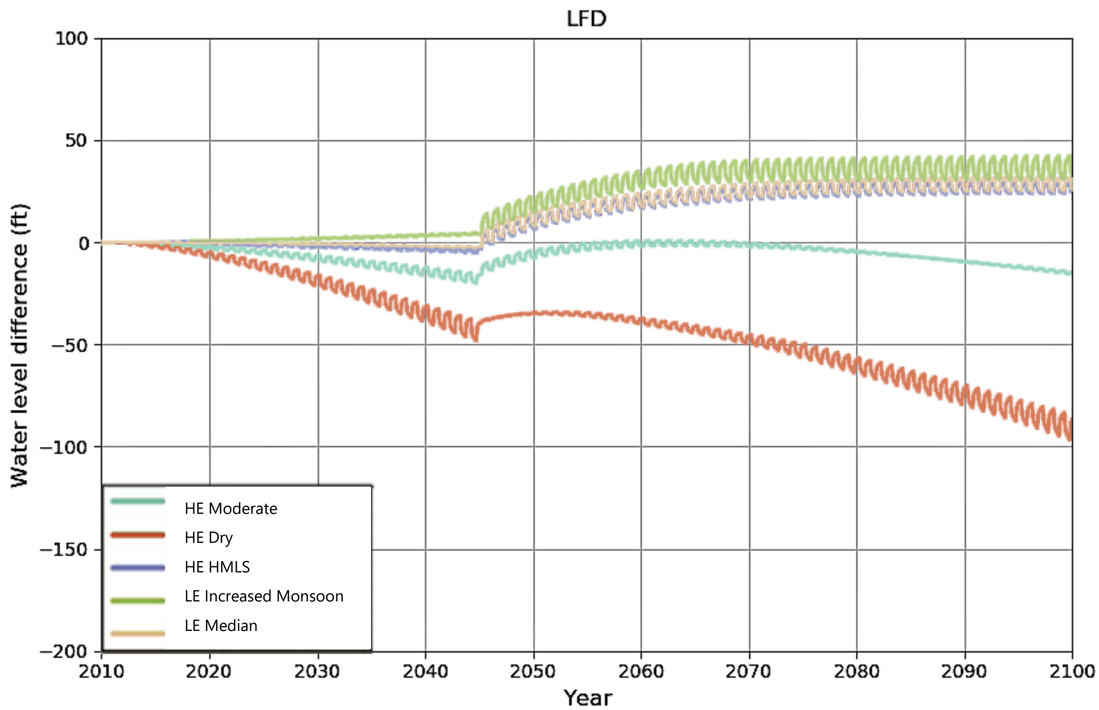


Figure 68. Change in modeled water levels at PVACD wells LFD and Artesia A in the 25% Reduction by All Districts Strategy in all storylines relative to the Groundwater Base Case (as PVACD reduces in 2045, changes from the strategy appear in 2045).

The 30% Reduction by All Districts Strategy shows similar patterns as in the other two Reduction by All Districts Strategies in Figure 69, only with slightly higher increases in groundwater levels in the wetter storylines (LE: Increased Monsoon, HE HMLS, and LE Median Storylines) and slightly lower decreases in groundwater levels in the drier storylines (HE Dry and HE Moderate).



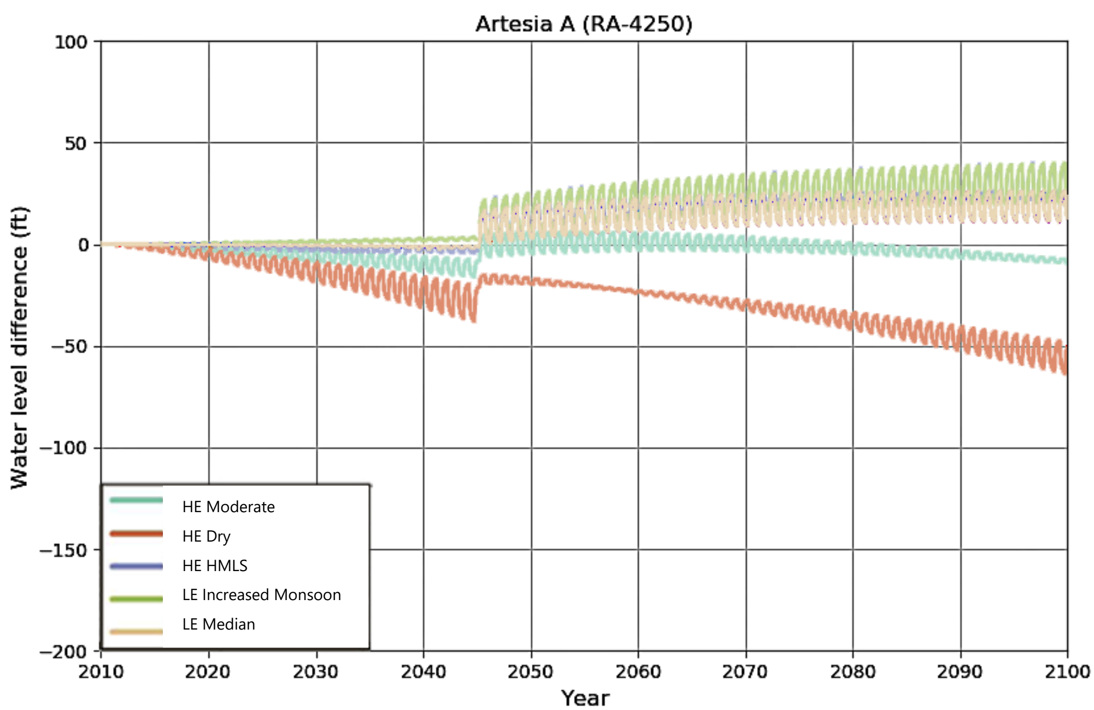


Figure 69. Change in modeled water levels at PVACD wells LFD and Artesia A in the 30% Reduction by PVACD in all storylines relative to the Groundwater Base Case (as PVACD reduces in 2045, changes from the strategy appear in 2045).

7.2.5.2. Pecos River Groundwater Gains from Acme to Artesia

In general, each Water Management Strategy provides some degree of offset in the other four storylines. The groundwater levels in each storyline determine the effect of the Water Management Strategy—the lower the levels in the storyline to begin with, the least effect that the strategy will have. Adaptations in the HE Dry Storyline have the least amount of offset, and LE Median Storyline have the most. As HE Dry Storyline conditions represent higher temperatures and less runoff, a decrease in pumping has less potential for creating a significant offset. Reducing groundwater pumping by PVACD would delay when the river shifts from gaining to losing in the extremely low precipitation projected HE Dry Storyline but would not prevent the shift. On the other hand, the LE Median Storyline, with relatively minimal drying and flow reduction, experiences far more offset from the adjustments to pumping.

Pumping adjustments in the LE Increased Monsoon Storyline simply increase the amount of gain already predicted for the climatological conditions associated with the LE Increased Monsoon Storyline. It is interesting to note that, since the storyline itself produces increased gains, Water Management Strategy offsets are smaller. Impacts of the storyline itself dominate any offsets associated with the strategy.

Specifics of strategy impacts on Pecos River gains between Acme and Artesia for each combination of storyline and adaptation strategy are summarized in Table 19. Positive numbers indicate a wetter strategy. As an example, in the HE Moderate Storyline, the river gains are 9,194 acre-feet, and the 20% Reduction by All Districts Water Strategy would add 11,290 acre-feet for a projected total of 20,484 acre-feet. Figures in the Figures Appendix, Section 10. *Groundwater* show the projected average annual gains to the Pecos River between the Acme and Artesia Gages in each storyline.

Table 19. Pecos River Gains from Acme to Artesia: Water Management Strategies Compared to Baselines and Modeled Historical Values in all Storylines (acre-feet)

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical River Gains: 27,266 acre-feet					
2070-2099 Baseline	9,194	16,776	32,846	49,172	34,850
	Less Gains		**27,266**		**More Gains**
2070-2099 Change from Baseline under each Water Management Strategy					
20% Reduction by All Districts	+11,290	+3,952	+12,340	+12,135	+12,403
25% Reduction by All Districts	+14,367	+5,921	+15,625	+14,280	+15,721
30% Reduction by PVACD	+17,589	+7,954	+19,030	+16,017	+19,152
Drying Strategy (-) decreases gains			**0**		**Wetting Strategy (+) increases gains**

7.2.5.3. Shallow Alluvial Aquifer Levels in the Vicinity of FSID

Because the shallow alluvial aquifer is recharged by FSID operations, groundwater levels in this area remain stable in most storylines, and the modeled Water Management Strategies have minimal impact on the groundwater levels. Changes due to PVACD-only reductions are not considered, as PVACD is downstream and has negligible effects on groundwater conditions in the vicinity of FSID. Table 20 shows the difference in elevations for the Water Management Strategies. For example, in Table 20 in the HE Moderate Storyline, the 20% Reduction by All Districts would increase the elevations by 0.15 feet for a total elevation of 4006.53 feet msl. Positive numbers indicate a wetter strategy.

Table 20. Difference in Average FSID Shallow Groundwater Elevations from 2070-2099 to 1950-2009 for Storylines and Water Management Strategies (in feet msl).

Storyline	HE Moderate	HE Dry	HE HMLS	LE Increased Monsoon	LE Median
1950-2009 Modeled Historical FSID Shallow Groundwater Elevations: 4,006.18 feet msl					
2070-2099 Baseline	4,006.38	4,004.91	4,006.45	4,006.85	4,006.66
	Lower Elevation		**4006.18**		**Higher Elevation**
2070-2099 Change from Baseline under each Water Management Strategy					
20% Reduction by All Districts	+0.15	+0.20	+0.14	+0.09	+0.11
25% Reduction by All Districts	+0.18	+0.24	+0.15	+0.11	+0.12
Increase Efficiency	0.00	0.00	-0.02	-0.03	-0.01
Drying Strategy (-) decreases elevations			**0**		**Wetting Strategy (+) increases elevations**

8. Additional Resource Impacts

This study focused on changes in agricultural water supply and demand. Other resources will also be impacted by changes in water supply and demand but have not been modeled. These uses are described briefly in this section, but they have not been quantified.

8.1. Water Deliveries

Both the timing and quantity of runoff are expected to continue to be impacted by the changing climate. Together with changes in the magnitude and timing of the demands for water and energy, this will impact the ability of existing water infrastructure to satisfy public interests in diverting, storing, and delivering water when and where it is needed. Shifts in water availability will impact water uses and increase reliance on deliveries of water from reservoir storage or groundwater.

8.2. Agricultural

Agricultural water deliveries for the three main irrigation districts (FSID, PVACD, and CID) are the focus of the modeling work in this basin study. However, other agricultural users in the basin could be impacted by the projected changes that may occur in the basin in the future.

8.2.1. Acequias

Acequias, or community ditches, are culturally and historically important water distribution networks found throughout the state of New Mexico. Acequias are a form of irrigation system found in Spain and former Spanish colonies and are recognized by New Mexico law as political subdivisions of the state. A typical acequia consists of a community operated watercourse, which may have anywhere from just a few to several hundred users. Acequia associations have historically been a principal local government unit involved in managing surface water distribution. Many of New Mexico's acequia associations date to the Spanish colonial period in the 17th and 18th centuries. (NMISC 2020).

In the Pecos River Basin, acequias can be found in numerous small communities along the upper Pecos River upstream of Santa Rosa Reservoir, as well as along major headwater tributaries such as the Rio Gallinas. They are also common along the Rio Peñasco and Rio Ruidoso, where they supply tens of thousands of acres of irrigated land. Acequias are typically found in or adjacent to mountainous regions, where streams are more likely to be perennial or at least flow longer into the summer. There are also several acequias near Santa Rosa, whose springs provide dependable water supplies.

Since acequias typically have no ability to store water and depend on consistent stream flows to irrigate their users crops, these communities can be vulnerable to changes in temperature or precipitation which may impact volume and availability of irrigation water. While they have not been incorporated into the modeling efforts of this Basin Study, acequias may face many of the same challenges as the irrigation districts.

8.2.2. Other Irrigated Agriculture

Aside from the major irrigation districts and the acequia communities, several other areas of irrigated agriculture in the basin, mostly in the form of large center-pivot irrigated farms depend on local groundwater. Such farming includes irrigation around the town of House (see Section 2.2.2.2. *High Plains/Ogallala Aquifer*), a few thousand acres of groundwater-irrigated land north of Fort Sumner, and other farms scattered throughout the basin outside of the main irrigation districts. These irrigators are vulnerable to groundwater drawdown that may occur from changing precipitation patterns, or due to increased pumping that might be needed if temperatures (and therefore crop water demands) increase.

8.2.3. Ranching

In much of the remainder of the basin, the wide-open rangeland is used predominantly for ranching. Ranching activity is generally dependent on groundwater, with thousands of livestock wells supplying stock tanks throughout the basin. As with irrigation wells, these wells—and the stock that depend on them—may be threatened by decreases in the water table caused by precipitation declines.

8.3. Municipal and Domestic Water Supplies

Municipal and Domestic use comprise a small portion of water use in the Basin (see Section 3.4.2. *Municipal and Domestic Use*). Municipal and domestic water supplies are primarily drawn from groundwater. If groundwater levels decline over time, then municipal and domestic supplies might be affected. Likewise, if domestic well withdrawals substantially increase, the overall water table could be impacted.

Many municipalities across the West are using much less water per capita than previously, and some communities have reduced per-capita use enough to significantly reduce overall consumption, despite increases in population. According to University of New Mexico Water Resources Program Director, John Fleck, author of *Water is for Fighting Over (and Other Myths about Water in the West)* (2016), research shows that generally, cities facing water shortages and decreased supply, usually respond with a decrease in overall use. Fleck gives the example of Albuquerque, New Mexico: "In the midst of the drought, Albuquerque cut its per capita water use nearly in half, and the great aquifer beneath the city actually began rising as a result of a shift in supply and reduced demands." He goes on to state that "When people have less water . . . they use less water" (Fleck 2016 p. 5). Figure 70 shows this downward use trend.

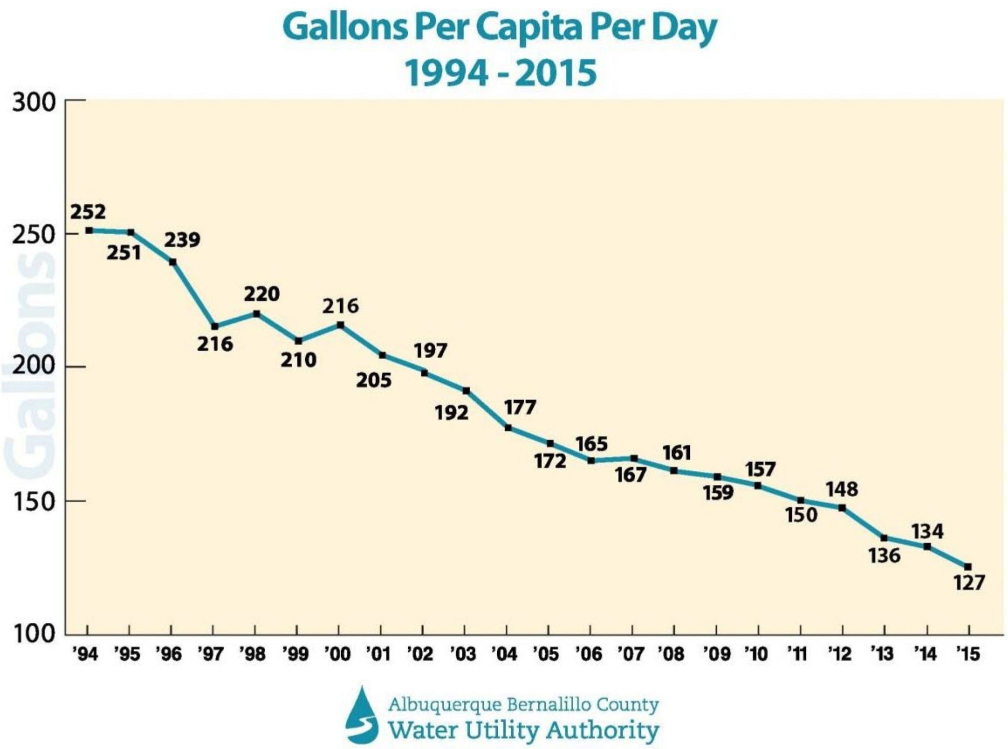


Figure 70. Use trends from Albuquerque Bernalillo County Water Utility Authority (courtesy of ABCWUA, all rights reserved).

Municipal water use is also decreasing in the Pecos River Basin; however, much of the municipal water use is groundwater rather than surface water. Roswell, the largest city in the Pecos River Basin, depends on groundwater from the Roswell Artesian Basin and does not use water from the Pecos River.

> "From 2013 to 2016, the amount of water used by the City of Roswell decreased from 4,304,613,000 gallons to 3,908,711,000 gallons, a nearly 10% drop." Buckley 2019

8.4. Energy

8.4.1. Oil and Gas

New Mexico is currently experiencing an oil and gas development boom, with significant oil and gas development in Eddy and Lea counties. These operations generate produced saline water and consume fresh water for use in hydrofracking. As available fresh water supplies decrease in the basin, oil corporations are under pressure to increase the use of produced water for hydrofracking to reduce their fresh water demands. See Section 9.4. *Oil and Gas Produced Water*.

8.4.2. Hydropower

The Pecos River Basin in New Mexico does not currently contain hydropower facilities, and hydropower resources on the river are minimal. The small amount of hydropower resources that do exist on the river would be unaffected by any changes resulting from the adaptation strategies discussed in this study.

Apart from short, high flow periods during block releases, the Pecos River usually flows at less than 100 cfs over the most of its length. Small or micro-hydroelectric projects could be generated during block releases either from flows from Sumner Reservoir or from within the irrigation infrastructure; however, as there are minimal releases the rest of the time, hydropower is probably not worthwhile. Sequoia Energy Corporation (1980) estimated the capacity for generating hydropower at Santa Rosa Dam (then called Los Esteros) to be 2.75-3.0 megawatts (MW), and the average annual energy output to be 5.8-6.3 gigawatt hours (GWh). Sequoia Energy Corporation was issued a permit to study the feasibility of developing this hydropower capacity in 1981 (USACE 1981). These applications were not pursued further. Given the small size of any possible hydropower installation, (equivalent in output to just one or two modern wind turbines), hydroelectric retrofitting of Santa Rosa Dam and other dams on the Pecos may not be viable.

8.4.3. Floatovoltaics

Floating photovoltaic solar, or "floatovoltaic" systems can produce renewable energy while also reducing reservoir evaporation by absorbing incoming solar radiation. In the Pecos River Basin in New Mexico, the latter benefit could be as important as the power generation. Air and water temperatures are projected to rise over the coming decades, leading to significant increases in evaporation in a region that already experiences high evaporation rates. Unlike hydropower resources, there are plenty of opportunities for floatovoltaics in the basin, as the major lakes in the basin total several thousand acres in surface area. In 2018, Reclamation's Albuquerque Area Office (AAO) was awarded funding from Reclamation's Power Resources Office to partner with the National Renewable Energy Labs (NREL) to evaluate obstacles to implementing "floatovoltaic" systems at Reclamation facilities (Figure 71).

Figure 71. A photovoltaics installation by the State of Colorado in Walden, Colorado (Courtesy of the State of Colorado, all rights reserved).

8.5. Recreation

See Section 2.8. *Recreation* for a description of recreation in the study area.

8.5.1. Headwater Forest Recreation

Increased temperatures, drier winters, and prolonged drought threaten the survival of headwater forests. Increased susceptibility to uncharacteristic wildfire and mass tree mortality due to insect infestations reduce the forest canopy and threaten the infrastructure of the existing trail system. See Section 9.5. *Upland Forest Management Practices*. Decreased snowpack may result in reduced flows in the upland forests of the Pecos Headwaters in the Pecos Wilderness Area. USFS typically closes forest areas in times of severe forest drought to minimize risk of human-caused wildfires. The amount of time that forests are closed may increase in the future as snowpack declines.

8.5.2. Flatwater Recreation

Decreased snowpack could also result in decreased flows in the Pecos River and lower water levels in the reservoirs it feeds. As discussed in Section 2.2.4. *Storage, Operations, and Seasonal Variations*, annual storage has historically varied substantially. Lower water levels in reservoirs could impact fishing, swimming, and boating.

According to personnel at Sumner Reservoir, in 2012, all boating access ramps and docks at the lake were closed due to low water conditions (Stinson 2018). Such closures could become more frequent in the future as droughts intensify.

Reduction of reservoir elevations greatly affects visitation. Lowering water levels decreases fishing availability and water recreation ability, and previously submerged islands and rocks pose dangers for boaters. Further, lower water levels often affect marinas and concession availability to boaters (e.g., water levels can drop below dock levels). Without general stores and gas stations near the lake, visitors are less likely to recreate at the lake. This has economic ramifications for the state of New Mexico.

8.6. Flood Management

Although the USACE's Albuquerque District has very little discretion in how the Santa Rosa Project's conservation storage is operated and managed, the USACE Albuquerque District does recognize the potential threats that an increase in extreme weather events could present to flood risk management operations on the Pecos River. To continue to provide flood control protection, USACE is aware that as conditions change, changes to its operating principles may be required to ensure downstream safety (Ross 2018).

It is likely that any operational changes required in response to changing hydrological conditions will be identified during the routine thorough assessments of each project. USACE evaluates the hydrologic adequacy of projects in conjunction with Periodic Assessments every ten years, as required by the established USACE Dam Safety Program. During these assessments, if it is determined that existing studies and hydrologic loading assumptions are no longer valid, USACE evaluates and updates the design storms and other hydrologic loading factors. The completed Periodic Assessment report may contain recommendations for modifications to project structures, changes to operations and maintenance procedures, modifications to the monitoring program or emergency management procedures, or other required changes (Ross 2018).

This study did not model flood management in detail. There may be times when actions that decrease storage might increase available flood control pools and affect the flexibility to handle extreme events. After a long drought, the temptation is to store more water. However, extreme events may be more intense, and actions that address long-term droughts still need to consider the potential for these extreme events and provide effective flood control planning. Implementing any action may need coordination with the USACE to determine any needed changes in flood control. See Section 9.2. *Alternative Reservoir Operations*.

A trend toward earlier annual peak flows associated with warming temperatures and an increased frequency of rain-on-snow events and other causes of rapid melting could also trigger changes in flood control operations.

Other issues, such as designated floodplains, may need to be addressed as the intensity of extreme events increases.

8.7. Flow and Water Dependent Ecological Resiliency

Ecosystems are complex and dynamic natural systems encompassing living organisms and their interactions with their physical environment. Ecosystems may respond in myriad ways to potential temperature and precipitation changes, as well as to changes in water use, population growth, and other factors. Rather than focusing on a single resource, effective planning approaches consider ecosystem responses, recognizing these complex interactions.

The resiliency of an ecosystem refers to its capability to continue functioning with its same basic structure and function even during times of change or disturbance. For example, resilient ecosystems can weather floods or droughts—and while some adverse impacts may be observed, the habitat and populations within the ecosystem rebound following the impact. However, even resilient ecosystems have some threshold disturbance size (such as the size of a flood or the intensity of a drought) beyond which the system cannot recover. At that point, the system will undergo a transformation to a new type of system, with a different basic structure and function, and in some cases, radically different characteristics. These new ecosystems may not be desirable to humans and might not be able to support some species that were present in the previous system. Many ecosystems in the Western United States have been significantly altered and may now be dominated by non-native species and new processes. These ecosystems may no longer be hospitable to native plants and animals but may be highly stable in the current climate (i.e., highly resilient).

Resiliency can be defined at any scale, but is typically defined at a systems level, rather than at a single species level. For example, a non-native species may be highly adaptable and stable when introduced to a given ecosystem, but that ecosystem could suffer because these non-native species crowd out native species. Resiliency is also not inherently good or bad, although humans tend to value resiliency in ecosystems that they would like to preserve, and do not value the resiliency of systems that they do not wish to see preserved.

Risks to ecosystem resiliency in the Pecos River Basin in New Mexico include:

- Extreme events could change river topography and flows, affecting habitat (particularly during vulnerable times such as bird nesting seasons or fish spawning seasons).
- Longer droughts could affect populations and balances within food chains and other interrelationships between species.
- Warmer water holds less dissolved oxygen, decreasing the water body's ability to support fisheries and other aquatic life.
- Lower flows or longer periods of intermittency on the Pecos River could pose long-term threats to ecosystems that depend on flows in the Pecos River.

Resiliency also considers the timing, frequency, and duration of risks. If the risks noted above were to occur in an isolated manner and slowly over time, then the ecosystem might be able to adapt. However, current trajectories indicate that many of these disturbances could occur simultaneously and rapidly, which poses a significant challenge to the Pecos River Basin's ecosystems.

8.8. Fish, Wildlife, and Ecological Resources

8.8.1. Fish and Wildlife

ESA actions described Section 3.4.1. *Ecological Resources Water Use* and in the 2016 BiOp were designed to protect fish, wildlife, and ecological resources (especially the threatened Pecos bluntnose shiner).

The potential threats to fish and wildlife habitats, federally listed species, and ecological systems in the West are complex and diverse. Current stresses on species and their habitats in the basin may be impacted by increasing temperatures, changes in precipitation availability and timing, extreme events, decreasing water availability, habitat loss due to loss of flows, wildfire, ground water depletion, sedimentation, and water quality changes. Changes in temperature and hydrology will shift the location and distribution of species and their preferred habitats. This may improve conditions for certain species and degrade conditions for other species.

8.8.2. Invasive Species

Tamarisk (also known as salt cedar) has proliferated throughout the Pecos River Basin, and there have been many unsuccessful attempts to decrease the spread. However, its natural predator (tamarisk beetle *Diorhabda elongate*) has now been imported and released throughout Western U.S. river basins, with significant impacts on the health of tamarisk. The future of tamarisk in Western U.S. river basins is an open question (see Section 2.7.4. *Invasive Species*).

8.8.3. Upland Forests

> "Theoretical understanding and modeling have suggested continued tree mortality in the coming years from insects, hotter droughts, and wildfires." Hicke et al. 2016

This Basin Study's modeling work focused on the regions downstream of the upland forests; however, changes in upland forests can influence water supply and demand in the study area. While much of the Pecos River Basin in New Mexico is non-forested, its critical headwaters lie in the Santa Fe National Forest in the Sangre de Cristo Mountains. Additionally, the vital Roswell Artesian Basin aquifer system is fed primarily by rain and snow falling in the forested Sacramento Mountains. Increased temperatures, drier winters, and prolonged droughts could threaten the survival of headwater forests. See Section 9.5. *Upland Forest Management Practices*.

8.8.3.1. Insect Damage

With increase aridity and temperatures throughout the Western U.S., forests are becoming more susceptible to insects and disease. Freezing winter temperatures kill off insects, but in warm winters, insect populations can boom, causing infestations and killing trees. The USFS manages the Pecos Wilderness Area within the Santa Fe National Forest and has documented a marked increase in Spruce Beetle, Douglas-fir Beetle, and the Western Tent Caterpillar as mortality and damaging agents in the forest and the headwaters of the Pecos River Basin in New Mexico (USFS 2017). In the Pecos Wilderness specifically, spruce mortality was mapped in the northern region, Douglas-fir disturbance was mapped along the western edge, and aspen defoliation was found throughout.

8.8.3.2. Potential for Fire

> "As wildfires become more frequent and destructive in a warming world, they are increasingly leaving in their wake debris and toxic runoff that are polluting rivers and fouling water supplies. Some municipalities are having to upgrade their water treatment methods to counter the new danger." Struzek 2018

Fire was historically an important component of the Pecos River Basin in New Mexico and surrounding Pecos Wilderness (Margolis et al. 2007, Margolis and Balmat 2009, and Margolis 2019). Fire was largely excluded from the area over the 20th century through a combination of overgrazing and active fire suppression. Historically, the drier forests (e.g., ponderosa pine and dry mixed conifer) burned with regular, low- to moderate-intensity through the fine fuels below the canopy, while many of the larger trees survived.

Due to fire exclusion, much of the dry conifer forest of the Pecos River Basin, like many Western U.S. forests, has seen stand density increase substantially over the past 100 years. This increased stand density and accumulation of fuel, combined with drought and hotter temperatures, is driving uncharacteristically severe fires across the Southwest (Allen et al. 2002). Since 2000, there have been ten wildfires that have affected the Pecos River and its tributaries within its headwater's region in the Santa Fe National Forest.

In the Western U.S., increases in spring and summer temperatures lead to changes in snowmelt runoff volumes and timing, reduced soil moisture, and reduced fuel moisture conditions. More intense droughts and higher temperatures have led to a greater moisture deficit in the region's forests and have made them more susceptible to catastrophic wildfires. This, in turn, affects wildland fire activity. Declines in soil moisture are likely to contribute to altered fire regimes and changes in vegetation communities—changes that are likely to alter existing rainfall-runoff relationships.

Along with the warmer and drier climate in the Western U.S. over the past two decades (1990-2009), forest fires have grown larger and more frequent throughout the Western U.S. (Abatzoglou and Williams 2016). With the expectation of more intense droughts and higher temperatures, upland forests in the Pecos River Basin in New Mexico will be stressed and more susceptible to forest insect infestations, disease, and more intense wildfire. Table 21 shows the fires in the Pecos River headwater region from 2002-2015.

Table 21. Wildfires in Pecos River Headwaters within the Santa Fe National Forest from 2002-2015 by Size. (New Mexico Forest and Watershed Restoration Institute 2018)

Year	Name	Acres Burned
2013	Jaroso Fire	11,148.63
2013	Tres Lagunas Fire	10,224.54
2010	Tecolote Fire	7,974.45
2002	Trampas Fire	4,750.62
2015	Commissary Fire	2,534.29
2002	Roybal Fire	894.50
2002	Dalton Fire	804.84
2003	Apache Fire	228.98
2009	Soldier Fire	146.87
2010	Hartman Fire	71.83
Total Acres Burned		**38,779.55**

More intense wildfires in upland forests and subsequent post-fire flooding have adverse effects on downstream water supply and quality. High severity fires cause extreme damage to soil and can often prevent the possibility of regrowth. Further, the threats that debris flows place on downstream communities after a wildfire are substantial.

Thunderstorms tend to build over fire scars because heat builds up over the blackened ground, and intense thunderstorms on fire-scarred land can wash ash into nearby rivers and can cause debris flows (Figure 72). Debris flows can lead to sediment accumulation in reservoirs, which in turn can lead to less flood protection for downstream human infrastructure. Debris flows can also directly damage or destroy infrastructure. In the longer-term aftermath of a fire, the forests' ability to retain snowpack can be decreased, leading to more rapid spring runoff, and water quality can be severely affected for many years.

Response to these threats have been growing in recent years and there has been an increase in forest treatments such as thinning and prescribed fire. See Section 9.5. *Upland Forest Management Practices.*

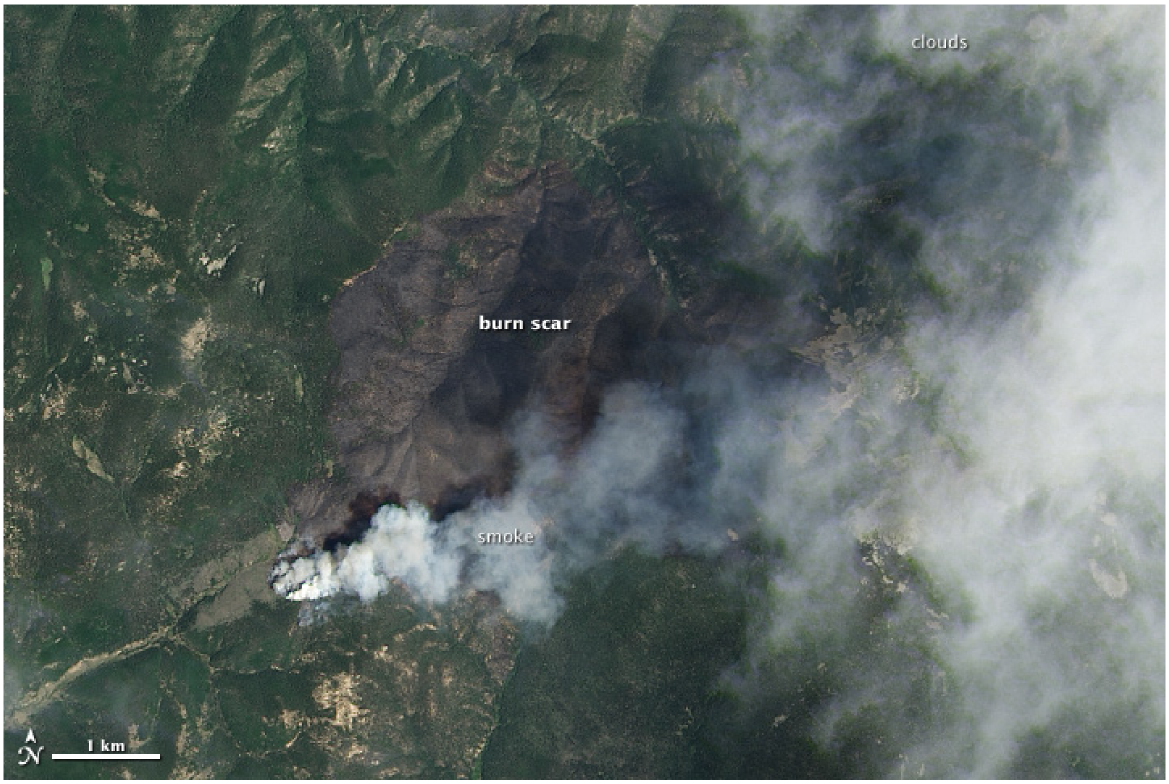


Figure 72. Burn scar from Jaroso Fire June 22, 2013 (National Aeronautics and Space Administration [NASA] 2013).

8.8.4. Water Quality

The quality of water in western river basins is vital to human and environmental health. Whether water quality improves or deteriorates under a changing climate depends on multiple variables, including water temperature; the rate, volume, and timing of runoff; and the physical characteristics of the watershed. In general, the potential for reduced flows and the warmer ambient air anticipated by the projected future conditions would be expected to exacerbate both water temperature and dilution-related water quality issues. Changes in temperature and precipitation could alter numerous variables that impact water quality, such as water temperature, runoff rates, and runoff timing. These changes can also alter surface water ecosystems, very likely affecting their capacity to remove pollutants and improve water quality. However, the timing, magnitude, and consequences of these impacts are not well understood (Reclamation 2011).

As water demands for agriculture increase, salinity may increase. High salinity in the Lower Pecos River has been attributed to increased evapotranspiration associated with irrigated agriculture, as well as natural sources such as substantial brine inflows near Malaga, New Mexico (downstream of Carlsbad and just south of the Pecos River Basin) (Hoagstrom 2009). Evaporation from reservoirs may increase salinity downstream depending on climatic conditions, water residence time, magnitude and frequency of diluting inflows, and precipitation of salts (Hoagstrom 2009).

Typically, water quality problems in the Pecos River Basin become more pronounced during droughts, when dissolved chemical concentrations and water temperatures are highest, although suspended sediments are higher during high-flow events such as spring runoff. Irrigation can contribute to water quality degradation. Where runoff decreases without a corresponding reduction in pollutants, maintaining acceptable water quality becomes more difficult, especially during low flows. Problems typically occur when irrigation diversions result in low river flows and when return flows from fields contain higher concentrations of salts, nutrients, suspended solids, and pesticides (Reclamation 2016).

Although low flows are typically associated with heightened water quality issues, extremely high flows can result in impairments to water quality as well. High-intensity precipitation events can rapidly transport large quantities of pollutants off the land and into waterways, and when storm intensity and severity increases, there is a corresponding increase in land surface erosion, sediment transport, and occurrences of elevated surface water turbidity. Increases in frequency and intensity of storms may therefore result in net increases to erosional loading to the basin’s waterways. Moreover, an increase in the frequency, extent, and intensity of forest fires associated with temperature or drought-stressed forests will increase sediment production and surface water turbidity.

As water warms, less oxygen can dissolve in the water column, affecting the ability of reservoirs and rivers to support fisheries and other aquatic life. In addition, higher water temperatures can increase the incidence of toxic algal blooms.

9. Additional Water Supply and Demand Challenges and Opportunities

While the primary focus of this study was to examine the potential challenges that might be faced by the three irrigation districts under different potential future conditions and the potential actions that might be influenced by future changes in the basin, additional actions that might be taken by other entities in the basin to mitigate the effects of changing conditions were considered as well. These additional potential actions, challenges, and opportunities were evaluated qualitatively for potential impacts on water delivery—but were not modeled as the amount of water savings could not readily be determined.

9.1. Municipal and Domestic Use Conservation

While agricultural irrigation is the primary water use in the Pecos River Basin, municipal and domestic water use is another sector where there are opportunities to reduce water consumption to help adapt to changing conditions. Domestic water users can take many actions to conserve water, including reducing household water waste, xeriscaping, limiting outdoor watering, and installing low water use appliances. Municipalities can take steps to incentivize such actions, through rebate programs or other similar methods. Municipalities can also take direct actions to reduce municipal water use, including reuse of treated wastewater on city parks and golf courses, upgrades to municipal buildings to improve efficiencies.

As discussed in Section 3.4. *Water Use Other than Irrigated Agriculture*, total municipal and domestic water use makes up a small percentage of overall water use in the Pecos River Basin. However, every drop counts and conservation efforts at home, scaled up across cities, can have significant impacts.

9.2. Alternative Reservoir Operations

Currently, physical and legal restraints on reservoir operations within the Pecos River Basin preclude maximum water management flexibility. All reservoir storage on the Pecos is for Carlsbad Project storage, and permitted storage amounts at each reservoir limit CID's ability to respond to changing conditions. Potential actions that would help address this inflexibility include:

- **Increasing overall storage**. Increasing the overall permitted storage amounts, while ensuring that New Mexico is meeting all of its Compact obligations as required by the 1988 United States Supreme Court's Amended Decree (1988 Decree) and the associated Pecos River Master Manual, would provide additional capacity, potentially helping CID, or others, better weather extended droughts. Any increase would necessarily be achieved in a manner that would not jeopardize the fulfillment of New Mexico's Compact obligations as calculated in accordance with the 1988 Decree.

- **Increasing storage flexibility within the current overall storage limit**. Even if overall storage is not enlarged, increasing the flexibility of where that water can be stored would improve operational efficiency of the system. Currently, the CID's 176,500-acre-foot entitlement storage is simply the sum of the permitted storage volumes at each of the four reservoirs. However, both Santa Rosa and Brantley Reservoirs have several hundred thousand acre-feet of excess space, currently being used only during flood control operations. If CID's entitlements at individual reservoirs could be more flexible within that overall total, it would allow for efficient capture of extreme storm events. As an example, if Brantley and Avalon Reservoirs were at their entitlement storage limits (representing only a quarter of the overall limit), a major storm event in the Roswell area would be legally uncapturable, even if Sumner Reservoir and Santa Rosa Reservoir were both empty. This could become more common in the HE HMLS Storyline as models suggest most water will fall in storms below Sumner Reservoir, causing Brantley Reservoir to release any water above the current conservation limit—even though there is additional storage capacity there. With more flexible storage rules, this water could be captured, provided that the CID's overall total entitlement storage in the system remains below 176,500 acre-feet. As another example, if water were not needed in Brantley Reservoir (for example, outside of the irrigation season), it could be left mostly empty and the unneeded water left in Santa Rosa Reservoir, where evaporative losses are lower. Again, any adjustments in permitted storage volume could not impact New Mexico's ability to comply with its Compact obligations as calculated in accordance with the Pecos River Master Manual.

- **Establishing a conservation pool for ESA flows.** Reclamation is working to establish an additional 30,000-acre-foot conservation pool at Santa Rosa Reservoir for environmental flows to allow storage of water needed to ensure ESA compliance during prolonged droughts.

9.2.1. Settlement Next Steps

Despite the Settlement's success in ensuring New Mexico's compliance with the Compact and the 1988 Decree, additional agreements amongst the basin's largest water users will be needed to weather future prolonged droughts. The Settlement is currently New Mexico's strongest tool to ensure deliveries under the Compact. Besides contributing to an overall reduction in depletions in the Pecos Basin in New Mexico, Settlement releases of state-owned CID water rights alone contributed approximately 75,000 acre-feet more water to the state-line between 2009 and 2019.

However, the Settlement has been less successful in ensuring a sufficient supply for CID. During the drought of 2011-2013, CID's annual allotment fell to 0.8 acre-feet per acre in 2012 (maximum allotment is 3.697 acre-feet per acre), and in 2013 CID called for priority administration. Fortunately, the crisis was abated by unusually high precipitation from monsoon storms in September of that year. To avoid a future priority call while continuing to ensure New Mexico's Compact compliance, additional creative solutions in the study area will likely be necessary. This will be particularly true if droughts become longer or more intense.

9.2.2. Strategic Water Reserve Activities

In 2005, the New Mexico Legislature created the Strategic Water Reserve (Reserve). It was supported by a broad coalition of stakeholders including representatives from business, agricultural, environmental, wildlife and municipal organizations. The Reserve gave NMISC a new management tool to acquire water rights and water for one of two purposes:

1. To comply with interstate river compacts and court decrees; and

2. To assist the state and other water users in efforts to benefit threatened and endangered species.

As of 2019, the Reserve contained approximately 2,750 acre-feet per year of water rights either purchased or leased by NMISC. Water in the reserve is largely currently used to support management efforts related to ESA compliance. The Reserve continues to present a valuable and underused tool for the State's water management efforts.

9.3. Aquifer Storage and Recovery

Aquifer storage and recovery (ASR) systems replenish groundwater by injecting or infiltrating surface water into the ground when it is available and recovering it during drought or high-demand conditions. Aquifer storage has the potential advantage of minimal losses compared with the high evaporative losses associated with reservoir storage in a hot, dry climate.

ASR wells inject and recover water for:

- Drinking water supplies
- Irrigation
- Ecosystem restoration projects

ASR could be accomplished incrementally. Any investigation of aquifer storage and recovery would need to consider the legal implications of the Compact.

As an example, the Albuquerque Bernalillo County Water Utility Authority (ABCWUA) conducted a pilot ASR program, tracking a small amount of water released into Bear Canyon Arroyo to determine if it reached the underlying aquifer (Figure 73). Results were positive, and the Water Authority is moving forward with plans to recharge the aquifer on a larger scale.

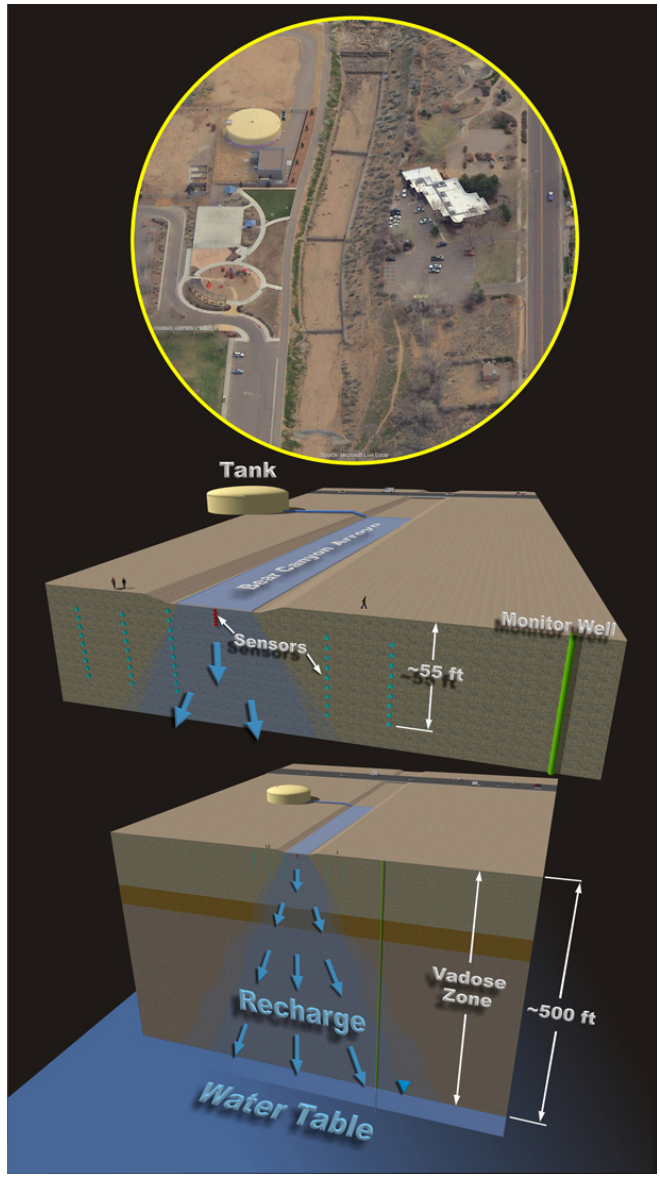


Figure 73. Schematic for Albuquerque Bernalillo County Water Utility Authority's (ABCWUA) Bear Canyon Project (courtesy of ABCWUA, all rights reserved).

9.4. Oil and Gas Produced Water

Excess water generated from oil and gas drilling ("produced water") is another potential alternative source of water, particularly in the area south of Carlsbad. Southeastern New Mexico has been home to oil and gas operations for over a century, primarily in Eddy and Lea Counties. The region is currently experiencing a boom in production due to the use of hydraulic fracturing ("fracking") technology. Oil production in New Mexico hovered around 65 million barrels annually from 1981 to 2010, when the boom began, nearly quadrupling production to nearly 250 million barrels in 2018. (Energy Information Administration [EIA] 2019).

Understanding the patterns of usage and disposal of water in the oil and gas industry is necessary to assess industry effects on water resources. Fracking fluid (a mixture of water, sand, and fracturing chemicals) is injected into the formation during well development. Following well development and the start of pumping, the fracking fluids are brought back to the surface along with the oil or gas, though there is typically variation in the temporal distribution of this "flowback." Water that naturally exists in subsurface formations is also brought to the surface alongside the hydrocarbon resources and is termed "produced water." Produced water is by far the largest by-product of oil and gas generation and is generally managed as a waste product.

> "However, as technologic advances are made in water treatment and the demand for water grows, the use of produced water as an alternative water source in Southeast New Mexico continues to garner attention."
> New Mexico Water Resources Research Institute 2016

Typically, produced water is returned to the ground through reinjection wells. The volumes of fracturing water used and produced water generated can be enormous, with 1.05 billion barrels of produced water generated from oil and gas operations in New Mexico in 2018 alone. While the majority of New Mexico's produced water is likely generated in the Pecos River Basin, the exact amount is difficult to determine, as Lea County produces 60% of New Mexico's produced water, but only half of Lea county is in the basin. Eddy County, which is almost entirely in the basin, produces a further 36% of the state's produced water (New Mexico Energy, Minerals and Natural Resources Department [NMEMNRD] 2019). In any case, the total amount of produced water in the basin is likely in the range of 600-800 million barrels (roughly 77,000-103,000 acre-feet) and is continuing to increase (Figure 74).

Produced water quantity and quality varies significantly based on geographical location, type of hydrocarbon produced, and the geochemistry of the producing formation. In general, the total dissolved solids concentration can range from 100 mg/l to over 400,000 mg/l. Silt and particulates, sodium, bicarbonate, and chloride are the most commonly occurring inorganic constituents in produced water. Benzene, toluene, ethylbenzene, and xylene (BTEX) compounds are the most commonly occurring organic contaminants in produced water. The types of contaminants found in produced water and their concentrations have a large impact on the most appropriate type of beneficial use and the degree and cost of treatment required (Dahm 2014).

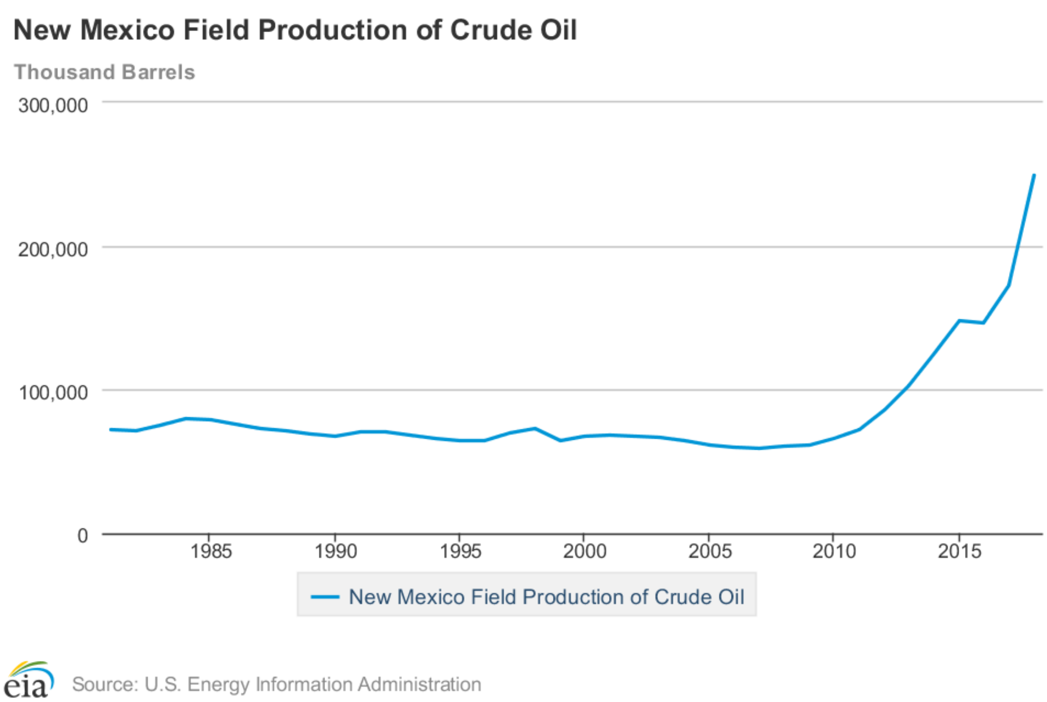


Figure 74. New Mexico field production of crude oil from 1980 to 2018 (EIA 2019).

A number of studies have focused on treating and using produced water for beneficial purposes, such as irrigation, livestock watering, streamflow augmentation, rangeland restoration, and industrial uses (Guerra et al. 2011). Using produced water as an alternative water supply might benefit communities in oil and gas producing regions. Sullivan-Graham and Sarpong (2016) note that "Treated product streams, however, may be useful in many applications, and may not retain the characteristics that render produced water a waste (e.g., toxic organic compounds, metals, or high levels of salt)."

However, recycling produced water within the industry to meet water needs for fracking and other operations may be a more viable, safer, and more palatable form of reuse when compared with reuse of produced water for irrigation. Sullivan-Graham and Sarpong (2016) note that "Recently, the oil and gas industry began to reuse produced water for drilling, stimulating, and completing oil and gas wells in unconventional (tight shale) formations." By using treated produced water in place of fresh water consumption during hydraulic fracturing, oil and gas operations could reduce both the amount of outside fresh water brought in for fracking (which entails significant costs for water acquisition and transport) and the amount of water that must be disposed of in injection wells.

Produced water management strategies will also depend on the geographical relationships between the produced water source and potential beneficial uses. Ideally, beneficial use of produced water will require minimal water conveyance.

Further, a future study could partner with Reclamation's Brackish Groundwater National Desalination Research Facility (BGNDRF) is in Alamogordo, New Mexico. BGNDRF researches technologies for enhancing water supplies by desalinating and treating brackish groundwater resources, including produced water. See https://www.usbr.gov/research/bgndrf/about.html.

9.5. Upland Forest Management Practices

Wildfires in the upland areas of the Pecos River Basin in New Mexico could threaten water quality and the environment in the upland watersheds. In the face of increased drought and temperatures, managing forests to avoid catastrophic fires is vital to securing the Pecos River Basin's water supply. There are many options for upland forest management for fire mitigation. These descriptions are intended to give an overview of these practices and should not be used as a decision-making mechanism for treatment type. Fuel reduction can reduce the overall intensity of fires in treated area sand can help ensure forests rebound after fires. Methods include:

> "Allowing naturally ignited fires to burn in wilderness areas and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change." USGCRP 2018

- **Thinning.** Thinning reduces stand density and remove fuels from the forest. Generally, forest thinning involves strategically removing smaller diameter trees from forests to clear the understory of forests and allow for regrowth of grasses.

Larger trees can be removed as well.

- **Mastication.** This technique essentially mulches the forest. Vegetation is reduced into small chunks either mechanically or manually. Small trees, brush, and slash is ground, chipped, and broken apart to reduce ladder fuels to prevent crown fires spread in the event of a fire.

- **Prescribed fires.** Across the American West, natural historical fire regimes have been disturbed in the past century due to active fire suppression. Many western forest ecosystems, including those of the Pecos River Basin headwaters region, are "fire-dependent," meaning they rely on fire to maintain forest health. Trees can be stressed by overcrowding. Historically, fire has been a natural force limiting the spread of pest insects and disease, removing non-native species, and recycling nutrients back to the soil. Prescribed fires are planned and administered by fire-management specialists in order to reintroduce fire onto the landscape. Burn plans are written with extreme caution and awareness of climate, weather, and forest type. Often, prescribed fires will be executed on lands that have already undergone thinning or mastication treatment as fuel reduction has already taken place.

- **Managed fire.** Managed fires are similar to prescribed fires and are used to clear the forest's overgrown understory while allowing older growth trees to remain. This tactic starts when a fire occurs naturally. Rather than suppressing the fire, the response agency (usually USFS or BLM) allows the fire to burn with active and attentive management. These types of fires are done with extreme sensitivity to the current climate, weather, and forest conditions. They are also well staffed with firefighter response teams to properly manage the fire. However, because managed fires are by nature more unpredictable than a prescribed fire, a range of fire severity can be seen in a managed fire footprint.

10. Participation and Communication

10.1. Stakeholder Meetings

10.1.1. November 5, 2014

On November 5, 2014, a meeting was convened at the BLM Office in Roswell, New Mexico. Representatives from Reclamation, USACE, NMISC, NMOSE, BLM, FSID, PVACD attended. The focus of the meeting was to review initial modeling efforts and gather information on possible strategies and actions for evaluation. Representatives from Reclamation presented initial modeling results for climate projections that showed likely future strains on water supplies in the basin. In addition, NMISC presented an overview of data from the recent drought experienced in 2011-2013.

The participants discussed strategies such as rotational water delivery, crop changes, changes in irrigation methods, improvements in conveyance efficiency, increased metering of diversions and return flows, fallowing and water banking, and other infrastructure improvements. Agricultural representatives stressed that any adjustments to current practices will be driven by economics. For example, changing crop patterns to include increased cotton cultivation was not economically viable as most cotton farmers in the basin must travel long distances to the nearest gin. Aging infrastructure, especially in FSID, was noted to be a considerable problem which, if addressed, could significantly improve efficiency. PVACD representatives expressed interest in aquifer storage and recovery, but more information is needed to guide efforts at implementation. All in attendance were concerned about another drought like that of 2011-2013 and emphasized the need to plan ahead.

10.1.2. November 2, 2016

The November 2, 2016 meeting at the NMOSE office in Roswell, New Mexico was attended by representatives from Reclamation, NMISC, NMOSE, BLM, FSID, CID, PVACD, the Village of Ruidoso, and the City of Roswell. At this meeting, Reclamation provided a status update on the study and gathered additional information on strategy strategies to guide final modeling efforts. Reclamation reviewed the general purpose and requirements of the basin study program and the SECURE Water Act, the history of the study including its expansion from the Fort Sumner area to the entire Pecos River Basin in New Mexico, and the climate projections to be used in the study.

The primary water management challenges that participants noted included: variability in supply, aging infrastructure, and the limitations of New Mexico water laws and the State's capacity to enforce existing laws. The participants discussed several possible solutions, including better data collection and supply forecasting, increased metering and stronger penalties to prevent over-diversion, minimizing conveyance losses, municipal conservation, and protection of aquifer recharge areas and wetlands.

10.1.3. September 25, 2018

The September 25, 2018, meeting was convened at the NMOSE District 2 office in Roswell, New Mexico. In attendance were representatives from Reclamation, NMISC, NMOSE, FSID, CID, PVACD, the Village of Ruidoso, the City of Roswell, Hope Community Ditch, De Baca Soil and Water Conservation District, Carlsbad Soil and Water Conservation District, Upper Hondo Soil and Water Conservation District, and New Mexico Department of Agriculture. The purpose of the meeting was to provide partners with an update on the current status of the Basin Study and present its preliminary findings from modeling efforts.

The participants of this meeting provided comments and questions on the topics of the groundwater modeling used in the Study, the limitations placed on these groundwater users in the modeling, the salinity in the Roswell Artesian Basin, the Pecos Settlement Agreement, inefficient channels in the Pecos River Basin system, climate, discipline in water use, and domestic wells.

A major follow up item that came out of this meeting was the need for more accurate modeling to better capture the administrative limitations on water use in the basin.

10.1.4. July 24, 2019

The July 24, 2019 webinar was held to present the new model findings to the partnering irrigation district managers. This new modeling was conducted in part in response to requests by various stakeholders at the September 2018 meeting. Attendees included representatives from Reclamation, NMISC, FSID, PVACD, and CID. The new modeling:

- Analyzed two storylines that represented a range of potential trends under the Reduced Emissions (RCP 4.5): LE Increased Monsoon and LE Median. The major commentary that arose from this meeting was a general need for a better description of how the modeling projections were chosen and the science behind them. This resulted in a fuller description in Section 4.2.3.2. *Lower Emissions Scenarios (RCP 4.5).*

- Accounted for scenarios that more accurately modeled administrative limitations on water use in the basin. These results helped show a more accurate representation of future irrigation districts' operations. This resulted in a fuller description of groundwater impacts.

- Addressed stakeholder questions about how meteorological and hydrological trends have changed in the past decades and the physical mechanisms behind these changes. This is explained in Section 4.1. *Future Meteorological and Hydrological Conditions*, which explains basic climate dynamics and how they are expected to trend into the future.

The results were generally well received. Various irrigation districts' contributions were discussed with each district. Reclamation and NMISC teams worked with the irrigation districts to accurately represent their infrastructure conditions, challenges, and vulnerabilities (discussed in Section 3.3. *Irrigation and Conservancy Districts*). This meeting was followed up with numerous conversations with the irrigation district managers. A series of meetings were held after the July 2019 meeting with the internal Basin Study team (Reclamation and NMISC) and the Pecos Basin's three individual primary irrigation district managers. These meetings went over the individual irrigation districts contributions to this study in great detail to ensure their accuracy.

10.2. Pecos Hydrology Work Group Field Trips

The Pecos Hydrology Work Group (PHWG) is a group of government agencies and Pecos Basin stakeholders that regularly meets to discuss Pecos Basin issues. The working group is jointly led by representatives of Reclamation and NMISC; work group participants include representatives from CID, PVACD, FSID, NMOSE, USGS, USACE, USFWS, and on occasion other stakeholders. The work group typically meets on a roughly quarterly basis, and these meetings allow the agencies and stakeholders to keep abreast of each other's activities in the basin, share updates on hydrological conditions in the basin, and guide model development and investigations being undertaken by the group. The PWHG typically conducts an annual field trip within the basin for agency representatives and stakeholders.

On September 29 and 30, 2016 the inter-agency PHWG organized tours of CID and FSID to develop greater understanding of existing infrastructure and operating practices. Participants included representatives from Reclamation, USGS, NMISC, NMOSE, FSID, PVACD, and CID.

On October 11 and 12, 2017, the PHWG organized a tour of the Roswell Artesian Basin and Hagerman Irrigation Company (HIC). The purpose of the tour was to learn from experts on the artesian aquifer and gain a better understanding of PVACD's and HIC's history, infrastructure, and current operating practices. Participants included representatives from Reclamation, NMISC, NMOSE, FSID, PVACD, and the National Cave and Karst Institute.

On September 26 and 27, 2018, the PHWG organized a tour of the Upper Pecos River, including several acequias. Reclamation and NMISC presented the preliminary results of this Basin Study and solicited feedback.

11. Other Studies and Inter-related Actions

11.1. State Water Planning

In 1996, the New Mexico Legislature passed the State Water Plan statute (72-14-3.1 N.M.S.A.) which required NMISC, in collaboration with NMOSE and the Water Trust Board, to prepare and implement a comprehensive state water plan to:

- Promote stewardship of the state's water resources
- Protect and maintain water rights and their priority status
- Protect the diverse customs, culture, environment and economic stability of the state
- Protect both the water supply and water quality
- Promote cooperative strategies, based on concern for meeting the basic needs of all New Mexicans
- Meet the state's interstate compact obligations
- Provide a basis for prioritizing infrastructure investment
- Provide statewide continuity of policy and management relative to New Mexico's water resources

The first State Water Plan was released in 2003. By statute, the plan must be reviewed, updated, and amended in response to changing conditions at least every five years. NMISC and NMOSE, along with other state agencies, prepared State Water Plan reviews in 2008 and 2013.

In 2017, NMISC began work on a 2018 update to the State Water Plan. For the first time, and due to the application of a consistent technical approach statewide, technical work from regional planning efforts was able to be integrated within a State Water Plan. That draft was released for public comment in the summer of 2018 and finalized in December 2018.

11.2. Regional and State Water Planning Process

The state of New Mexico is actively planning for its water future. NMISC is tasked with overseeing the state's water planning efforts, including both regional and statewide planning. New Mexico has 16 water planning regions, each with its own water plan (Figure 75). This effort began in 1987 when the legislature recognized the state's need for water planning and created the regional water planning program (72-14-43 and 72-14-44 N.M.S.A.). NMISC officially accepted regional water plans from all sixteen water planning regions between 1999 and 2008.

New Mexico experienced one of the most extreme droughts on record between 2011 and 2013. This signaled an urgent need for regional water plan updates from all sixteen planning regions. The State Water Plan statute encourages the integration of the regional plans into the State Water Plan "where appropriate" (72-14-3.1 N.M.S.A.). However, because the first round of plans accepted by NMISC did not use consistent methodologies, integration proved difficult. To apply a consistent technical approach in updates to all regional water plans, in 2013 NMISC created an Updated Regional Water Planning Handbook. In 2015, NMISC approved updated Acceptance Criteria for all regional water plan updates.

In 2016 and 2017, updates to all regional water plans, using a consistent technical approach, were completed and accepted by NMISC. All the original regional water plans and updates are on the NMOSE website.

11.3. Pecos River Basin Salinity Assessment

In 2014, the Pecos River Basin Salinity Assessment was begun as a joint effort of USACE, the Texas Water Development Board, the Texas Commission on Environmental Quality, NMISC, and USGS. The study area is the Pecos River watershed from Santa Rosa Reservoir to the confluence of the Pecos and Rio Grande Rivers.

As part of this effort, USGS is conducting literature reviews, compiling extant salinity data, collecting additional salinity data, and identifying areas of elevated salinity within the basin (USGS 2019 [Salinity]).

The USGS has found that salinity is affecting water quality in the Pecos River Basin, reducing availability of usable surface water and impacting aquatic life in the river.

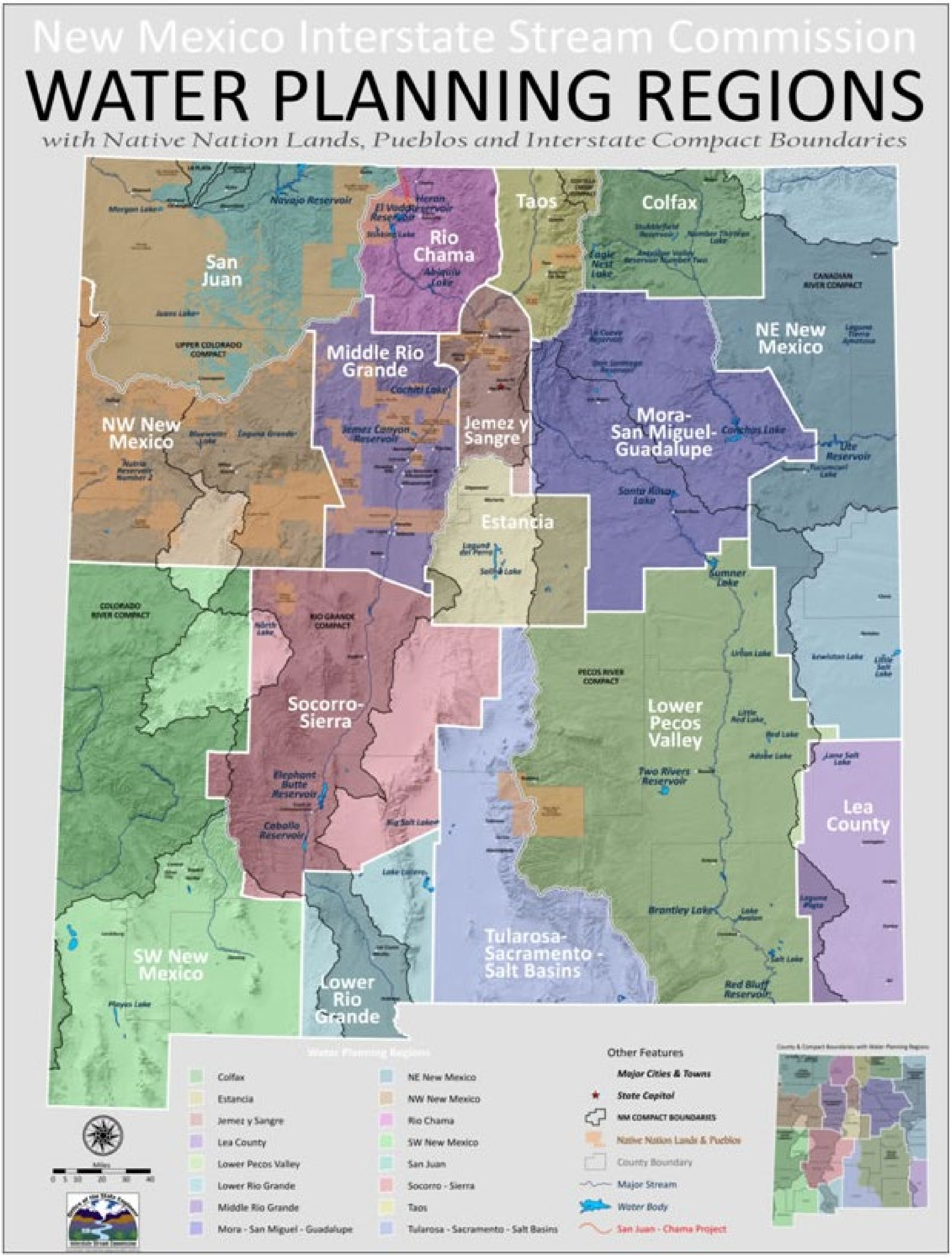


Figure 75. New Mexico water planning regions.

11.4. Endangered Species Act Consultation Process

Reclamation and USFWS are in formal ESA consultation related to modified water operations and water supply conservation for the Carlsbad Project on the Pecos River, including analysis of the effects of these actions on federally listed species (the Pecos Bluntnose Shiner (*Notropis simus pecocensis*), and the Interior Least Tern (*Sternula antillarum athalassos*). Reclamation follows the 2016 BiOp for water operations, as discussed in Section 3.4.1. *Ecological Resources Water Use*.

11.5. WRRI-State Water Budget

With the support of New Mexico's Governor and the New Mexico Legislature, the New Mexico Water Resources Research Institute (WRRI) has been developing a New Mexico legislative initiative that includes a Statewide Water Assessment from fiscal year (FY) 2015-FY2018. The Statewide Water Assessment is an effort that will complement existing state agency water resource assessments. It will provide new, dynamic (updated frequently), spatially representative assessments of water budgets for the entire state of New Mexico. Projects included in the Statewide Water Assessment bring new technologies that expand existing studies and are applicable statewide. Of particular interest are water budget components for which state agencies require improved information, such as evapotranspiration (ET), crop consumptive use, groundwater recharge, and streamflow.

With funds that were provided by the New Mexico Legislature from FY2015-FY2018, WRRI is coordinating different components of the Statewide Water Assessment effort with work being done by researchers from New Mexico State University, New Mexico Tech, University of New Mexico, USGS, New Mexico Bureau of Geology and Mineral Resources, Petroleum Recovery Research Center, NMOSE, Sandia National Laboratories, and Tetra Tech Inc.

11.6. Santa Rosa Reservoir Fish and Wildlife Pool

Reclamation is currently working with USACE and NMISC to establish a 30,000-acre-foot Fish and Wildlife Pool (FWP) in Santa Rosa Reservoir. Although the pool can be modeled in PROM, this was not done in this study, as final approvals are not yet in place. See Section 3.4.1. *Ecological Resources Water Use* for a discussion and map of diversions.

Reclamation has developed conservation measures, including supplemental water and a variety of additional conservation activities for the Interior Least Tern and the Pecos Bluntnose shiner. Santa Rosa Reservoir’s Fish and Wildlife Pool would allow for significant additional ability to comply with the Biological Opinion for the shiner.

Reclamation intends to complete the environmental documents required by USACE to authorize the Santa Rosa FWP. Because Reclamation will not have water to initially fill the pool, any supplemental water in Sumner Reservoir at the end of a calendar year will be transferred to the FWP, zeroing it out from Project storage. This water can then be used in future years to augment flows instead of the current policy whereby it reverts to the Carlsbad Project. Most likely, water stored in the FWP will only be used to augment flows in critically dry years, similar to 2011-2013. The projected permitted storage in the Upper Reservoirs after FWP approval is shown in Figure 76. (See the 2016 BiOp).

"Reclamation will work to complete the agreement with the USACE to increase storage capacity as proposed at Santa Rosa Reservoir within 5 years. If completed in this timeframe and additional water is stored, then we anticipate that the BiOp could be extended for a total of 15 years before reconsultation is necessary." 2016 BO

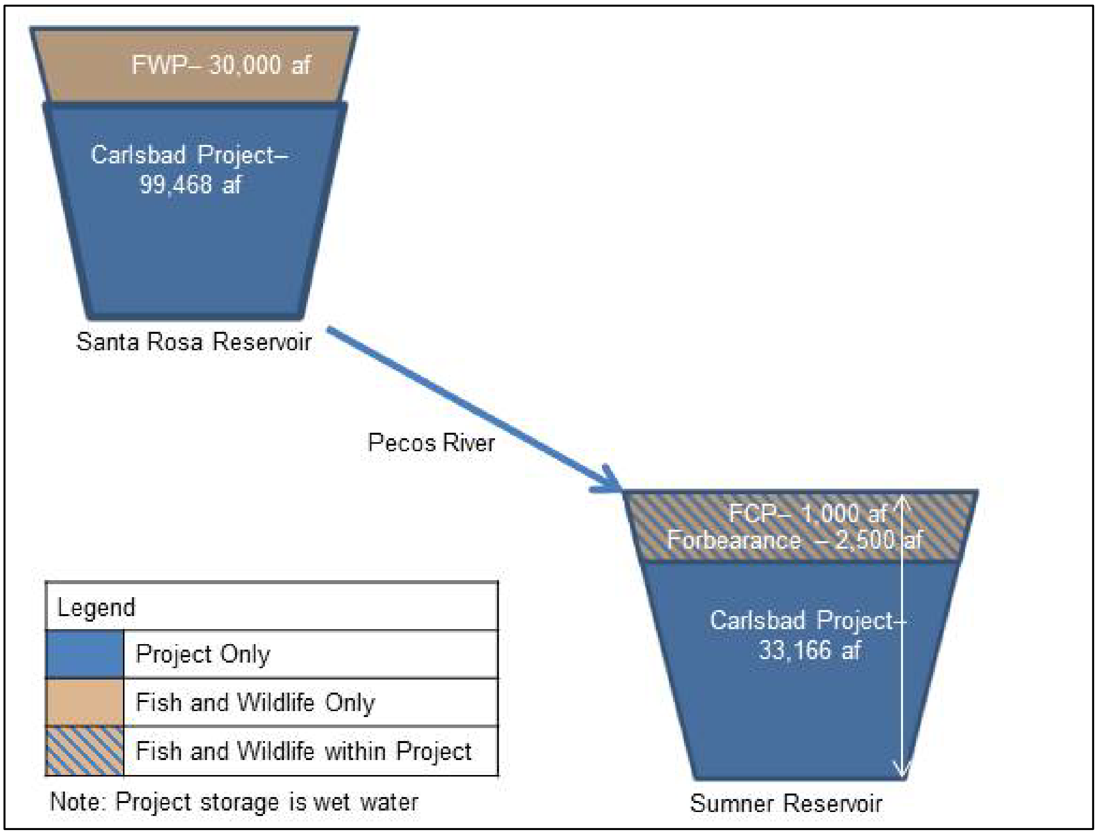


Figure 76. Diagram of storage in upper reservoirs, Pecos River (2016 BiOp). FCP =Fish Conservation Pool, FWP = Fish and Wildlife Pool.

12. Summary and Conclusions

12.1. Summary of Impacts

12.1.1. General Storyline Trends

Measurements show that temperatures in the Pecos River Basin are currently increasing (see Climate Appendix). All storylines modeled in this Basin Study project that basin air and water temperatures continue to increase through the rest of this century. These temperature increases correlate with decreasing snowpack, earlier snowmelt runoff, lower runoff volumes, decreasing water supply, and increasing crop water requirements.

> Temperature, precipitation, evaporation, and irrigation demands (transpiration) in the Pecos River Basin are changing now and will continue to change. These changes may affect the hydrology of the basin.
>
> In all of the storylines, there are actions that irrigation districts and government agencies can take that will help prepare the Basin for the future and that can prolong viability of irrigated agriculture in the Pecos River Basin in New Mexico.

Precipitation trends vary more among the storylines, since future precipitation is subject to greater uncertainty. Precipitation seasonality and spatial distribution changes in all storylines. Storylines were therefore selected to highlight the variation in potential changes in winter precipitation and snowmelt runoff, and in summer monsoon volumes and distribution. There will likely be less snowmelt runoff, and snowmelt runoff will likely occur earlier in the year. All projections for precipitation indicate changes in timing will occur. Some projections show increased precipitation during the monsoon season; others show decreased precipitation year-round. In general, the storyline trends show:

- **HE Moderate.** In this storyline, mild drying occurs across the whole system, starting in the 2050s.
- **HE Dry.** This storyline is associated with much drier conditions. Around the year 2040, river flows, reservoir storage, and water available for irrigation, compliance with delivery requirements decrease substantially.
- **HE HMLS.** This storyline results in similar to slightly greater drying than the HE Moderate Storyline in the upstream portion of the basin, due to decreased snowmelt runoff from the headwaters region. However, further downstream, in the vicinities of PVACD and CID, more frequent and higher-intensity monsoon storms lead to wetter conditions. Wet conditions increase compared to the 1950-2009 period below Acme due to increased flow along the tributaries from storm events that are fewer but bring more precipitation in each storm. Flows decrease from less snowpack above Santa Rosa Reservoir.

- **LE Increased Monsoon.** This storyline is associated with minor increases in temperature and water demand. Precipitation increases as a result of much more frequent monsoon storms with slightly greater intensity. This storyline would also be modestly hotter with less snow.

- **LE Median.** This storyline would have modest increases in temperature. In this storyline, the Pecos River Basin in New Mexico experiences minor increases in snowmelt runoff, and minor decreases in precipitation during other seasons. Basin temperatures and water demand increase slightly, and water availability decreases slightly.

12.1.2. Irrigation Districts

As each irrigation district has a different position within the basin and different legal and operational structure, the potential changes described in the range of storylines and the Water Management Strategies would affect each district differently. The baseline for each storyline shows the impact of each storyline on each irrigation district without any Water Management Strategies.

12.1.2.1. Fort Sumner Irrigation District

Due to its position as the most upstream of the major irrigation districts, and its "run-of-the-river" (natural-flow-based) water rights, as well as the impact of local groundwater recharge, FSID has some inherent protection from the impacts of decreased water supply, and from the impacts of changes in the operations of the other irrigation districts. Since adaptations will not affect the supply arriving at FSID, the most beneficial Water Management Strategies for FSID are those that improve the district's use of the water it receives, to mitigate increasing water demand within the district. In all cases except for the Dry Storyline, increases in irrigation efficiency are projected to be sufficient to avoid water shortages for FSID.

12.1.2.2. Pecos Valley Artesian Conservancy District

PVACD is a groundwater irrigation district. As such, its operations are not directly affected by the operations of the surface-water irrigation districts (note that PVACD pumping does affect availability of surface water to FSID and CID). PVACD is also not directly affected by short-term droughts, or year-to-year variability. PVACD is, however, impacted by long-term trends in precipitation in the basin. Since PVACD's water demand is limited by the individual water rights of its member irrigators, future changes to groundwater-levels, and to groundwater fluxes to and from the river, would be associated with changes in groundwater recharge rather than by increases in groundwater pumping.

12.1.2.3. Carlsbad Irrigation District

CID is the most sensitive of the three irrigation districts to changes in precipitation, especially in the short-term. CID relies heavily on surface water stored in Reclamation's Carlsbad Project reservoirs. Since CID is the downstream-most of the three irrigation districts, it is affected by the operations of FSID and PVACD.

12.1.3. Water Management Strategies

Basin Study participants developed prospective strategies for mitigating the potential impacts as projected in the storylines. These Water Management Strategies would help water users better prepare for shortages projected in some of the storylines. As shown in Figure 77, these Water Management Strategies would help water users adapt to shortages projected in some of the storylines—and better meet their needs in these conditions. This modeling focuses on the degree to which the Water Management Strategies compensate for decreasing water availability—not how the reduction in water use is accomplished. The reductions could be accomplished through changing crop types and irrigation methods, increasing operational efficiency in the irrigation district (decreasing system conveyance losses), using improved system monitoring or irrigation technology, or even using greenhouses. To simplify, and because modeling the specific reduction actions is not part of this study, we modeled these changes by reducing irrigated acreage within the surface irrigation districts and decreasing the pumping amount for PVACD in the groundwater model.

To help understand the effects that potential Water Management Strategies could have to help sustain viable agriculture in the Pecos River Basin, we modeled future projected impacts on parameters:

- **Reservoir storage.** In all but the HE Dry Storyline, the 25% Reduction by All Districts Strategy is the most effective strategy for maintaining total reservoir storage in the basin.

- **Surface water.** The On-Farm Efficiency Strategy reduces future FSID and CID shortages under all storylines by decreasing water losses. In the 25% and 20% Reduction by All District Strategies, CID reduces consumption, thus increasing reservoir storage, which, in turn, increases the CID allotment.

- **River flows.** The 25% and 20% Reduction by All Districts Strategies result in the fewest drying days in all storylines, mainly due to reduced FSID water consumption.

- **Availability of water for estimated Settlement releases.** In the HE Moderate, HE HMLS, and LE Median Storylines), the cooler and wetter the storyline is, the more benefits that the 25% and 20% Reduction by All Districts Strategies provide. The drier and hotter the storyline, it is more efficient to reduce PVACD irrigation water consumption, and the 25% and 30% Reduction by PVACD in 2045 strategies start to be just as beneficial as reducing all three irrigation districts

- **Groundwater.** The groundwater levels in each storyline determine the effect of each Water Management Strategy—the lower the levels in the storyline to begin with, the least effect that the strategy will have. Adaptations in the HE Dry Storyline have the least amount of offset, and LE Median Storyline have the most.

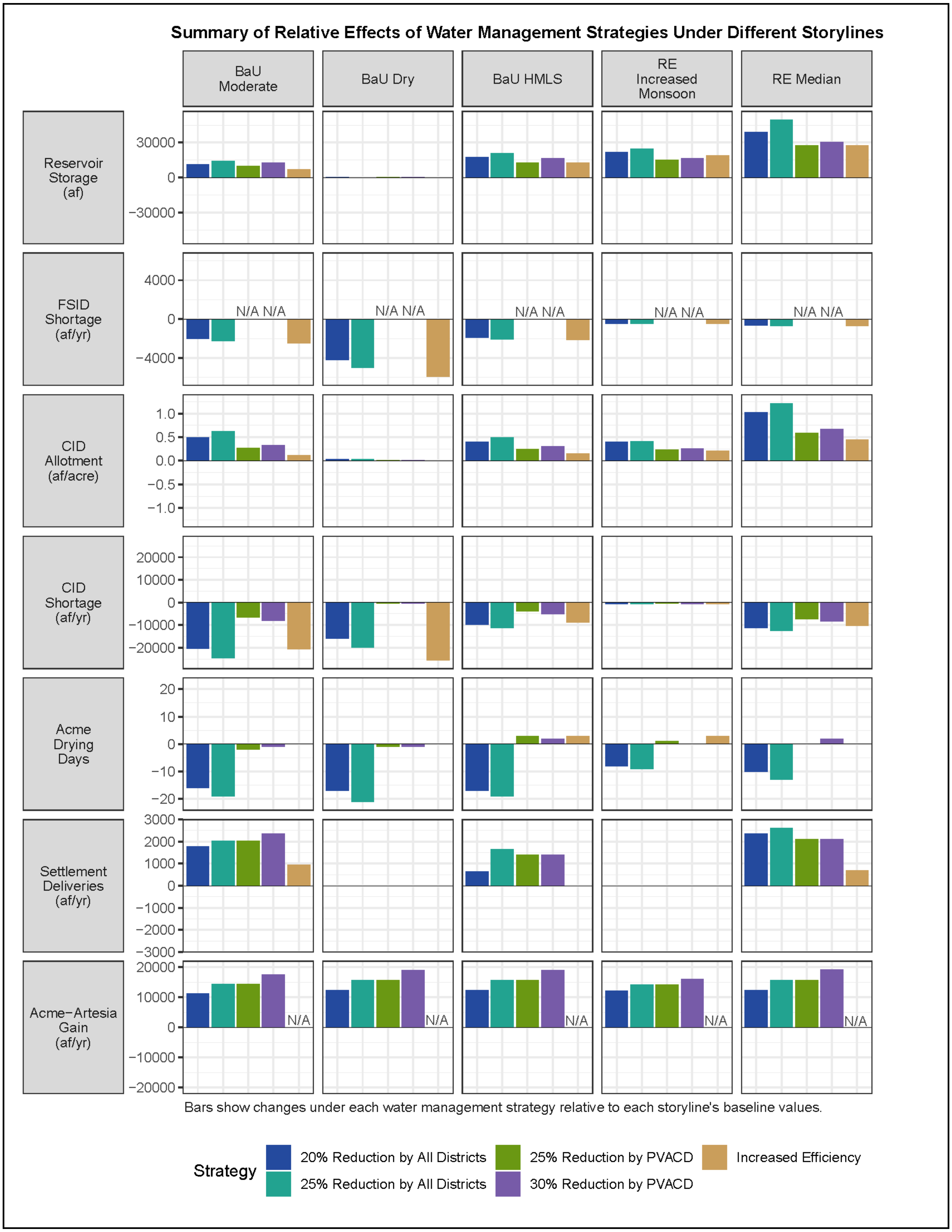


Figure 77. Summary of Water Management Strategy impacts for each parameter in each storyline.

12.2. Potential Future Actions and Analyses

This study provides a comprehensive analysis to help structure specific and basin-wide actions. These have been carefully modeled to help basin stakeholders to make the case for partnerships and further funding of resilience projects in the Basin. Although this project does not specifically authorize any future Federal funding, the modeling will help lay the foundation for future studies and help agencies and stakeholders prepare proposals for future Federal, state, non-governmental organization, or other funding partnerships.

12.2.1. Potential No-Regret Actions

This section provides an overview of general techniques that can be used to achieve this report's modeled overarching Water Management Strategies described in Section 7.2. These strategies are not mutually exclusive, and the potential benefits of combining different Water Management Strategies (e.g., improved efficiency with reduction in water use) could be further analyzed.

> "Adapting to climate change will not be a smooth process and will require multiple management tactics rather than a one-time solution. Given the latest scientific research and modeling on the impacts of climate change, New Mexico could gain substantial benefits from anticipatory stoking of its water management toolbox with proactive policies and clearly beneficial 'no regrets' strategies that also alleviate the additional pressures to the State's water resources."
> NMISC and NMOSE 2006

However, no-regret actions could be taken now without further analysis. No-regret actions increase irrigation districts' ability to adapt to changing hydrologic conditions and to improve the ability of the overall system to handle potential changes in water demands and supplies in a timely, efficient, and equitable manner. These actions could be taken on their own or included in a comprehensive plan. Note that this Basin Study modeled general results from actions such as these as a technical assessment. Listing these potential actions does not address the feasibility of any specific project, program, or plan and does not represent a commitment for provision of Federal funds. See Section 3.3. *Irrigation and Conservancy Districts* for irrigation-specific challenges and potential actions. These subsections summarize general actions.

12.2.1.1. Operational and Institutional

- **Alternative reservoir operations.** Operational changes (such as changes to the overall volume of irrigation storage or changes in allocation of irrigation storage between reservoirs) could improve the system's ability to more efficiently capture and use water from monsoon storms and to address changes in runoff volume and timing.
- **Improving automation.** Automating operations and infrastructure of the irrigation system could improve water delivery efficiency. With the passage of the Water Data Act, now codified as New Mexico Statute NMSA 1978, Section 72-4B-3, agencies are required to identify state water data, manage it and make it accessible. Improving water metering data has already been identified as an important state goal. Integrating automated instrumentation, metering, and infrastructure (e.g., remotely controlled check gates) into water operations could conserve water.

- **Improving electronic record keeping.** Improved electronic record keeping could help farmers improve planning and could be used in future analyses to establish trends (e.g., provide indicators of oncoming droughts).

- **Improving communication.** Maintaining and improving communication channels between Reclamation, districts, the State, and farmers would potentially lead to improved efficiency and other positive outcomes

- **Invasive species study and control.** Invasive species such as salt cedar (*Tamarix sp.*), Russian olive (*Elaeagnus angustifolia*), and giant reed (*Arundo donax*) are current and future threats and should be evaluated and managed to prevent negative impacts such as excess water consumption and obstruction of canals and other infrastructure.

- **Water banking.** Developing a water banking system that meets the study area needs would help improve flexibility of water usage in the basin. This would entail determining ways that water rights transactions (e.g., the voluntary lease, sale or exchange of water, or water rights), or voluntary agreements governing water rights, water use, or water management (e.g., non-diversion agreements, dry-year options, and agreements governing groundwater recharge and storage) could be undertaken in accordance with state and Federal laws.

12.2.1.2. Infrastructure

- **Improving conveyance efficiency.** Rehabilitating or replacing canals, check structures, and diversion structures could improve conveyance efficiency, making more water available for use by irrigators.

- **Channel management.** The Pecos River and surface water drainage systems in the study area could be examined for opportunities for better physical channel management. For example, the channel of the Pecos as it crosses the bed of the former McMillan Reservoir cannot handle high flows from block releases or large storms, resulting in water overflowing into the lakebed and evaporating. Widening the channel or dredging it more frequently could help more water get to Brantley Reservoir.

- **Facility modernization.** Working with all interested parties on alternatives for modernizing facilities can help lay a foundation for improved infrastructure maintenance and improvement plans.

12.2.2. Potential Future Studies

In the multi-year process of conducting this Basin Study, partners have given suggestions for potential future studies that could help further define needs for water security projects in the region. Areas where studies could benefit future water planning in the Pecos River-New Mexico River Basin include:

12.2.2.1. Water Supply and Demand Options

Actions detailed in Section 9. *Additional Water Supply and Demand Challenges and Opportunities* could be pursued. The viability of options for new water sources such as use/reuse of produced water, aquifer storage and recovery, and importing water from other basins/regions could be explored.

12.2.2.2. Modeling Studies

- **Model actions.** Model other actions such as water marketing using the same consistent model as a basis for comparison.

- **Groundwater:** Tracking both groundwater quality and quantity and its relationship to Pecos River gains and losses is critical for comprehensive water planning in the study area. Future improvements to groundwater modeling include:

    - Developing groundwater simulation tools upstream of Fort Sumner.

    - Examining relationships between pumping at Lake Arthur, Brantley Reservoir, and PVACD well levels.

    - Improving our understanding of groundwater conditions and the role of groundwater in conveyance efficiency and return flows.

    - Tracking groundwater for domestic and sub development use (especially in the New Mexico’s lower Pecos Basin). Currently there are no groundwater basins in the Pecos under special administrative restrictions with regard with withdrawals. In addition, it is easy to acquire permits for withdrawal of up to 3 acre-feet per year for commercial sales from any domestic or stock well. The cumulative impacts of increased depletions from these wells have not been assessed.

- **Water quality.** Analyzing the potential for salinity increases within the Roswell Artesian Basin and assessing the sensitivity levels of salinity to the changes in efficiency, would facilitate a better understanding of salinity processes in the groundwater and irrigation returns. A transport or particle tracking model might be used to track the salinity.

- **Paleo data.** The long-term paleo history, along with recorded history of the Pecos River could inform modeling and identify potential risk management and decision strategies for managing water during a drought.

- **Fire.** Partnering with the Los Alamos National Laboratory to use its fire model to simulate effects of wildfire on the water balances of burned sites would result in improved understanding of how snowmelt patterns and headwater runoff could be impacted by a catastrophic fire. A wildfire behavior model, FIRETEC, employs a multiphase approach to analyze fuel bed and study the interaction between vegetation, topography, and atmospheric conditions (Linn 2019).

12.2.2.3. Economic and Ecological Studies

- **Economic and Financial.** Studying economic and financial implications of actions water conservation and irrigation efficiency actions could help inform cost-benefit analyses for specific actions. For example, analyzing costs of importing food to New Mexico rather than growing it in New Mexico could provide insights into economic efficiency.

- **Ecological.** Future studies could examine ecosystem resiliency:
  - Studying ecological responses to ESA actions, including quantifying impacts of Biological Opinion, specifically fish populations response to 5 cfs at Acme gage, could help with decision making related to the ESA.
  - Identify the current state of the system and changes to the system (either in recorded history or using paleo-historical data) could inform our understanding of the system's current and projected trends, structures, interactions, and possible cascade or feedback processes.
  - Assess risks to ecological resources (decreasing water availability, habitat loss due to loss of flows, wildfire, ground water depletion, sedimentation, water quality changes, etc.).
  - Determine ways to make the ecological system more flexible to increase resiliency.
  - Examine potential impacts of flows and current Pecos River operations to determine actions in the lower reaches that could improve habitats for fish (e.g., Pecos bluntnose shiner eggs and juveniles).

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14. Glossary

Albedo. A measure of the reflectivity of a surface. Darker surfaces reflect less light and thus have lower albedos, while lighter surfaces, such as snow and ice, have higher albedos and reflect more light.

Aquitard. A geological formation of extremely low permeability, allowing only limited flow of groundwater through the formation. Aquitards often form the confining layers that cap artesian aquifers.

Baseline condition. The future without any actions taken. Comparing actions against a baseline allows us to determine how much impact an action will have.

Base Case. See Groundwater Base Case.

Bias. In science and engineering, a bias is a systematic error.

Bias Correction. A procedure involving techniques to adjust the value of a parameter to remove estimated biases from the value.

Block release. A large-volume release of a "block" of water from one reservoir to another, in response to irrigation or flood control needs. Releasing water in blocks helps minimize channel and evaporative losses.

Cascade of changes. A series of changes occurring when a single event or change to a system leads to sequential and interrelated effects throughout the system as a result of the initial disturbance.

CMIP5 projections. A group of projections that has been analyzed by the scientific community worldwide to produce the results that underlay the IPCC Fifth Assessment Report (AR5; IPCC, 2013) and continues to be available for further analyses.

Downscaling. The general name for a procedure to take information known at large scales to make predictions at local scales.

Drought intensity. The deficit in precipitation during a drought on a per-time basis.

Drought severity. The total deficit in precipitation accumulated over the course of the drought (severity = intensity x duration).

El Niño (See ENSO).

ENSO. El Niño-Southern Oscillation (ENSO) cycle. The ENSO cycle is a scientific term that describes the fluctuations in temperature between the ocean and atmosphere in the east-central Equatorial Pacific (approximately between the International Date Line and 120 degrees West). The term El Niño refers to the large-scale ocean-atmosphere climate interaction linked to a periodic warming in sea surface temperatures across the central and east-central Equatorial Pacific. Typical El Niño effects are likely to develop over North America during the winter season. Those include warmer-than-average temperatures over western and central Canada, and over the western and northern United

States. The large-scale ocean-atmosphere climate interaction linked to periodic warming in sea surface temperatures across the central and east-central Equatorial Pacific. La Niña episodes represent periods of below-average sea surface temperatures across the east-central Equatorial Pacific." (National Ocean Service, 2019.) La Niña episodes represent periods of below-average sea surface temperatures across the east-central Equatorial Pacific. Global climate La Niña impacts tend to be opposite those of El Niño impacts. In the tropics, ocean temperature variations in La Niña also tend to be opposite those of El Niño.

Evaporation pans. An evaporation pan is used to hold water during observations for the determination of the quantity of evaporation at a given location. Class A evaporation pans are cylinder with a diameter of 47.5 inches and 10 inches deep. The pan rests on a carefully leveled, wooden base and is often enclosed by a chain link fence to prevent animals drinking from it. Evaporation is measured daily as the depth of water (in inches) evaporates from the pan.

Evapotranspiration (ET). Water lost to the atmosphere from evaporation and plant transpiration.

Feedback loops. Processes which are influenced by their own outputs, which either limit the process (negative feedback) or amplify it (positive feedback)

Global Climate Models (GCM). Numerical representations of physical processes in the atmosphere, ocean, cryosphere, and land surface, and are currently the most advanced tool for simulating the earth's response to increasing concentrations of greenhouse gases. Global climate models represent the planet as millions of grid boxes and then solve mathematical equations to calculate how energy is transferred between those boxes using the laws of thermodynamics.

GCM simulation. A model run that creates the GCM projection (output from the simulation).

Greenhouse effect. The retention of heat in the atmosphere due to greenhouse gases, which permit the passage of incoming short-wave solar radiation but trap outgoing thermal (infrared) radiation, leading to higher temperatures and meteorological and hydrological changes.

Greenhouse gas. A gas that contributes to the greenhouse effect by absorbing infrared radiation, e.g., carbon dioxide, methane, and chlorofluorocarbons.

Groundwater Base Case. The groundwater model simulates conditions from a typical historical year, 2010 (the Base Case year), and repeats those annual conditions through 2099. The same pattern of repeated stresses (pumping, recharge, etc.) provides a baseline against which changes in other model simulations (e.g., storyline, sensitivity analyses, and strategy runs) can be compared. Repeating seasonal conditions from the 2010 Base Case year provides a simulation period of 90 years with only seasonal cycling of stresses and no trending or variation in the annual stresses.

Impaired waters. Water bodies that the New Mexico Water Quality Control Commission (WQCC) has listed that do not meet one or more water quality standards.

Karst. Landscape underlain by limestone which has been eroded by dissolution, producing ridges, towers, fissures, sinkholes, caves, and other characteristic landforms.

La Niña See ENSO.

No-regret actions. Actions that can be taken to improve a situation no matter what the future holds. For example, no-regret actions include increasing the resilience of desirable systems, which would make those systems more able to withstand a diversity of potential hazards.

Outlier. A data point that differs significantly from other observations. An outlier may be due to variability in the measurement or it may indicate experimental error.

Radiative forcing. The difference between the amount of sunlight entering earth's atmosphere and the amount of energy radiated back into space. Radiative forcing therefore represents heat accumulation rates in the lower portion of earth's atmosphere.

Recharge. A hydrologic process, where water moves downward from surface water to groundwater. Recharge is the primary method through which water enters an aquifer.

Representative Concentration Pathway (RCP). A set of future greenhouse gas, aerosol and land use scenarios used in CMIP5.

Resilience. A system's capability to continue functioning with its same basic structure and function even during times of change or disturbance

Settlement Releases. Releases of water by CID to the Pecos River made under certain conditions. These releases help the State of New Mexico meet its obligations under the 1948 Pecos River Compact and 1988 US Supreme Court Amended Decree.

Snowpack. The amount of snow that accumulates over the winter to melt in the spring.

Storylines. Final product of modeling steps. These storylines use projections with additional analyses, including downscaling, bias correction, other hydrologic and operation modeling (VIC and PRMS). Five storylines were selected to represent a range of potential futures.

Transpiration. Water movement through a plant and its evaporation from aerial parts, such as leaves, stems, and flowers.

Water banking. A water bank is an institutional mechanism used to facilitate the legal transfer and market exchange water.

Water footprint analyses. Analyses isolating the effects of each irrigation district (as well as ESA release) on the Pecos River and irrigation network.

Water Management Strategies. Potential actions that could be taken to mitigate reduced water supplies or other impacts of the storylines, and modeled in this study as reductions to irrigation district use or increases in on-farm efficiency.

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