Santa Fe Basin Study

Adaptations to Projected Changes in Water Supply and Demand

Santa Fe Basin, New Mexico

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

City of Santa Fe
Water Division
Water Resources and
Conservation Section

Santa Fe County
Utilities Division

August 2015

Mission Statements

Department of Interior

Protecting America’s Great Outdoors and Powering our Future.
The U.S. Department of the Interior protects America’s natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

Bureau of Reclamation

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

City of Santa Fe, Water Division

Our mission is to provide a reliable, safe and sustainable water supply to meet the needs of our customers and our community.

Santa Fe County Utilities

The mission of Santa Fe County Utilities is to provide fully sustainable, reliable water services, in compliance with applicable regulatory requirements and industry standards, for a full spectrum of use by all residents of Santa Fe County.

Santa Fe Basin Study:

Adaptations to Projected Changes in Water Supply and Demand

Report partners

Bureau of Reclamation

City of Santa Fe

Santa Fe County

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Acronyms and Abbreviations

AAO	Albuquerque Area Office
AF	acre-feet
AFY	acre-feet per year
amsl	above mean sea level
ASR	aquifer storage and recovery
BCSD	Bias Correction and Spatial Disaggregation
CIP	Capital Improvement Plan
City	City of Santa Fe
County	Santa Fe County
CMIP3	Coupled Model Inter-comparison Project Phase 3
DOI	United States Department of Interior
ET	evapotranspiration
GCM	General Circulation Models
GDD	growing degree days
GHG	greenhouse gas
gpcd	gallons per capita per day
HD(e)	Hybrid-Delta Ensemble Unit
IPCC	Intergovernmental Panel on Climate Change
MOA	Memorandum of Agreement
MRGCD	Middle Rio Grande Conservancy District
NMED	New Mexico Environment Department
O&M	operation and maintenance
OSE	New Mexico Office of the State Engineer
Reclamation	Bureau of Reclamation
RWRP	City of Santa Fe Reclaimed Wastewater Resource Plan
STELLA	Systems Thinking Experimental Learning Laboratory with Animation
SURFS	Stream Unit Response Function Solver
TSC	Technical Services Center
URGWOM	Upper Rio Grande Water Operations Model
URGSiM	Upper Rio Grande Simulation Model
VIC	Variable Infiltration Capacity
WCRP	World Climate Research Programme
WaterMAPS	Water Management and Planning Simulation
WaterSMART	Sustain and Manage America's Resources for Tomorrow

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Study Purpose

Climate change, in concert with human development and other changes, promises to alter many aspects of life in the Santa Fe basin, including the availability of water to the City of Santa Fe (City) and Santa Fe County (County), and the resources that depend on the Santa Fe watershed (Figure E-1). The health of forests, fish and wildlife, and other ecosystems as well as human development, food security, and quality of life are likely to be affected. This Basin Study has been undertaken by the City and County along with the United States Department of Interior (DOI) Bureau of Reclamation (Reclamation), to evaluate these projected changes and to develop potential strategies for adaptation that can be used for planning.

Figure E-1. Map of Santa Fe County.

WaterSMART: Authorization and Program

This Basin Study was performed under the U.S. Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Basin Study Program. The Federal SECURE Water Act of 2009 and Secretarial Order 3297 established the WaterSMART Program, which authorizes Federal water and science agencies to work with State and local water managers to pursue and protect sustainable water supplies and plan for future climate change by providing leadership and technical assistance on the efficient use of water. WaterSMART allows all bureaus of the Department to collaboratively work with States, Tribes, local governments, and non-governmental organizations to pursue a sustainable water supply for the Nation, and integrate water and energy policies to support the sustainable use of all natural resources.

Basin studies, one of WaterSMART's tools, are basin-wide efforts to evaluate and address the impacts of increased competition for limited water supplies, climate change, and other stressors, and to define options for meeting future water demands in river basins in the Western United States where imbalances in water supply and demand exist or are projected. This Basin Study is consistent with Reclamation's Basin Study Framework and Section 9503 of the SECURE Water Act (Subtitle F of Title IX of P.L. 111-11, the Omnibus Public Land Management Act of 2009).

Cost Share and Funding

The cost-share partners for this study are the City, County, and Reclamation, which performed the study in partnership under a Memorandum of Agreement (Reclamation et al., 2011 [MOA]). The Santa Fe Basin Study analyses, modeling, evaluations, and reporting have been developed through the combined efforts of the City and County working in consultation with Reclamation's Albuquerque Area Office (AAO), with technical support from Reclamation's Technical Service Center (TSC), Sandia National Laboratories, and CDM Smith, an engineering firm.

Scope and Objectives

The opportunities for adaptation to future water supply shortages identified through this Basin Study are based on a better understanding of the future effects of, and associated risks from, climate change and population growth on the City and County's combined water supply portfolio. Through the Santa Fe Basin Study, the study partners seek to improve the resilience of the Santa Fe watershed and the communities the watershed supports, as well as the municipal water systems for the City and County, in the face of projected changes in population, human development, and climate. This Basin Study consisted of the following actions:

- Identify the vulnerabilities of systems in the Santa Fe watershed to climate change. A preliminary assessment qualitatively evaluated climate-change impacts on water supply sources, ecosystems, quality of life, agriculture and local food production, landscapes, land use, and water demand. This assessment was based on input obtained during a March 6, 2012 workshop and from research conducted by the authors and is summarized in this report and presented in full in Appendix A.
- Assess Santa Fe's changing water supply and demand, including native surface-water supplies from the Santa Fe Watershed, the Upper Rio Grande, and the San Juan Basin (imported water of the San Juan-Chama Project), as well as groundwater supplies to the city and county's well fields. This portion of the study includes an assessment of the likely water supply and demand conditions in 2050 for the City and County's combined water supply. There is a small amount of agricultural land (as of 2005, OSE estimated 590 acres irrigated with surface water and 130 acres

irrigated with groundwater) in the Santa Fe Watershed. However, the quantitative analyses in this study focused on municipal supply, demand, and adaptation measures, since municipal use represents the largest portion of water use within the basin, and is the primary area of interest of Reclamation's study partners. This assessment included:

  - Developing climate and hydrology projections for use in this Basin Study. This work by Reclamation and Sandia National Laboratories is described in Appendices B, C1, and C2.
  - Developing an independent transient analysis of the projected changes over the course of the 21st century of the reliability of Reclamation's San Juan-Chama Project. This work by Reclamation and Sandia National Laboratories is presented in full in Appendix D.
  - Updating the City's Water Management and Planning Simulation (WaterMAPS) model to include the County as a partnering entity and to enhance the model to include functionality to assess projected climate impacts. This work by CDM-Smith is discussed in detail in Appendix E.
  - Using the updated WaterMAPS model, running simulations to determine the impacts to the City and County's combined water supply under future demand and projected climate conditions. These simulations by CDM-Smith are described in detail in Appendix F.

- Identify and analyze potential adaptation strategies for the combined City and County water supply. This portion of the study included:
  - Assessing the vulnerability and possible shortcomings of the current long-range water supply strategies.
  - Identifying management or infrastructure changes that might strengthen the entire basin, its component systems, and its inhabitants to provide more flexibility in the face of an uncertain future.
  - Combining these adaptation strategies into portfolios that would provide adequate water supply in the 2050s, considering projected population growth and climatic changes. Since it is likely that no single adaptation strategy will suffice to fill the gap between supply and demand, these combined portfolios helped the City and County select adaptive strategies that best meet the regional water supply needs. Appendix G describes the adaptation strategies and alternative climate mitigation portfolios evaluated.

Location and Description of the Study Area

This Basin study focuses on the Santa Fe River watershed, a sub-basin to the Rio Grande watershed. The Santa Fe watershed is in the high-elevation desert of northern New Mexico (Figure E-1). It spans the Sangre de Cristo Mountains on the east and the Rio Grande on the west. The City of Santa Fe is the main municipality in the watershed and within the northern portion of Santa Fe County

(Figure E-2). The Santa Fe Basin includes the City and the portion of the County that has the highest population density and the highest growth rate, as well as the part that has historically depended on the City of Santa Fe for its water supply.

For water-supply assessment purposes, the study area also encompasses:

- The upper Rio Grande watershed (upstream of Otowi stream gage)
- Tributaries within the San Juan River watershed, a portion of which are delivered to Santa Fe through Reclamation's San Juan-Chama Project
- Groundwater from the aquifers of the Santa Fe Group

Each of these sub-basins is a source of surface-water for the combined municipal water supply for the City and County. The first two sub-basins are within the Rio Grande basin; the third lies within the Upper Colorado River Basin (Figure E-2).

Santa Fe averages over 300 days of sunshine a year, with a temperate climate and four distinct seasons. The summer months in Santa Fe, from May to September, feature typically hot, sunny weather, with fairly low humidity and cooler evenings. Daily summer temperatures in Santa Fe peak at around 93°F during July and August. Thunderstorms typically occur in the early evening during this season. Rainfall in the Santa Fe area is spread throughout the year, although the highest frequency and intensity of rain occurs as part of the summer monsoons, which occur primarily during the months of July and August. The average annual precipitation in Santa Fe is about 14 inches.

Problems, Needs, and Opportunities

The City and County water supply systems are interconnected, with the County system surrounding the City system to the north, south, and east of the City boundary and service area. The two water utilities also co-own one of the region's sources of supply (Figure E-2). The City and County water utilities have a diverse water supply portfolio, providing water to their customers with surface water from the three sub-basins and groundwater from two well fields. Because of this shared resource and infrastructure, cooperation between the City and County is essential for planning. The City and County are concerned about potential decreases in the availability and reliability of their joint surface water supply, as well as the quality of the water. The water utilities recognized the need for long-range planning efforts to identify future water supply deficiencies, identify strategies for meeting those shortfalls, and implement those strategies.

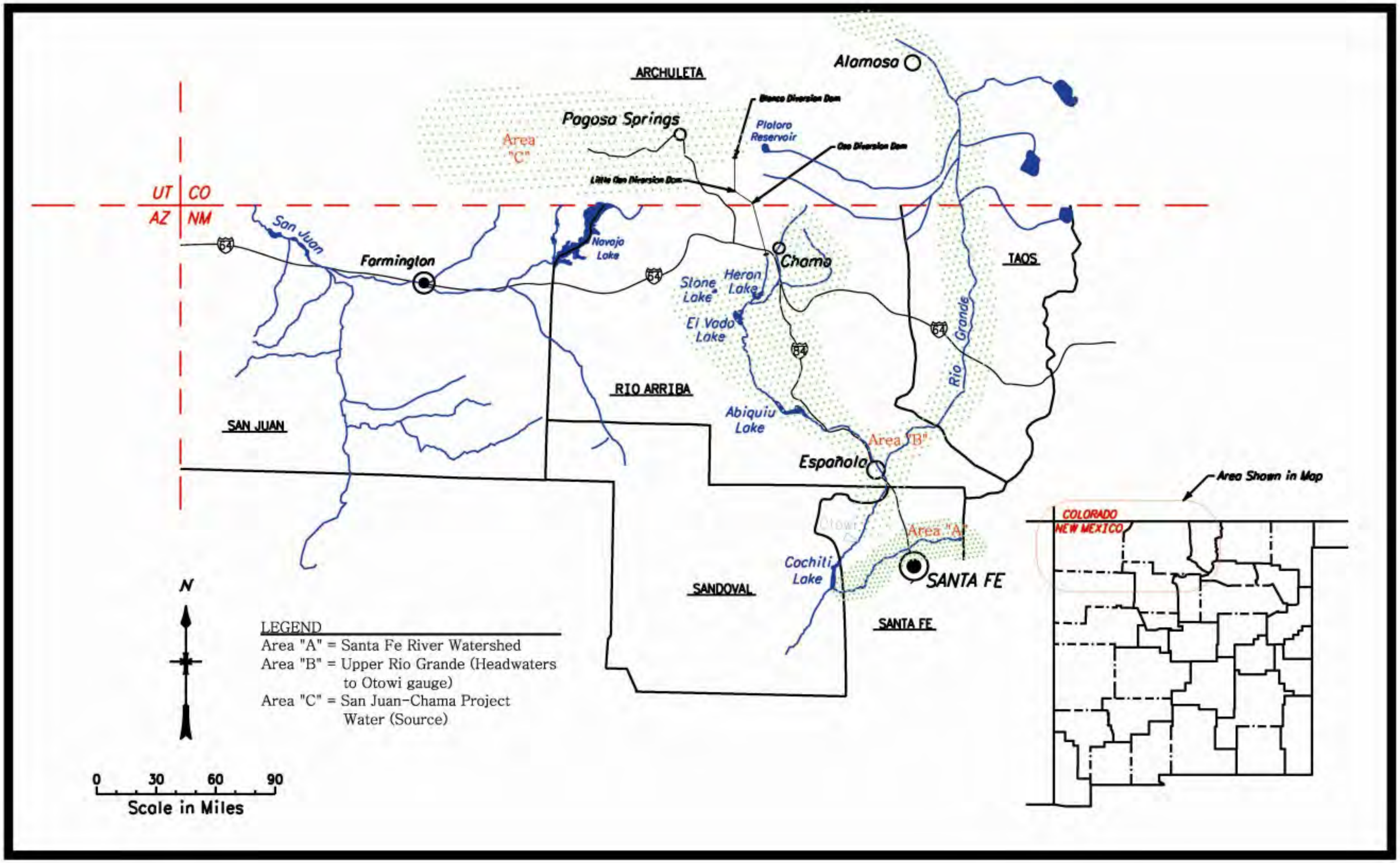

Figure ES-2. The Santa Fe watershed (shaded green) receives water supply from the Santa Fe sub-basin, the upper Rio Grande sub-basin (green stipple) and the San Juan-Chama River sub-basin (all green stipple).

The population continues to grow and the needs of the community continue to expand. Like many surface waters in the arid Southwest, however, supplies from the Santa Fe River, the Upper Rio Grande and the tributaries to the San Juan River are all limited, highly variable, and. dependent on seasonal snowpack and runoff conditions, They are also all vulnerable to climate-change-induced impacts. The groundwater is pumped from aquifers that are slow to recharge. In response to these conditions, the City and the County have been working for a more resilient, sustainable, diverse, and innovative water supply system for many years. To increase the sustainability of their water supply, the City and County water utilities have developed new surface-water sources. However, they also recognize that additional increases in supply and/or decreases in demand will be required to meet the challenges ahead. This Basin Study is the latest in a series of efforts to understand and strengthen water supply management in the Santa Fe area.

Characterization of Future Conditions

Future water supply conditions, water availability, and water demands were projected based on climate scenarios and population increases. The climate-projections used for this study were developed from The World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project Phase 3 (CMIP3) (Meehl et al. 2007), and Reclamation's Bias-Corrected and Spatially Downscaled Surface Water Projections (Reclamation 2011[BCSD]).

Imported San Juan-Chama Project Reliability Analysis

To assess the reliability of Reclamation's San Juan-Chama Project. Reclamation and Sandia National Laboratories provided an independent, separate transient analysis of the projected changes over the course of the 21st century. The methods used for this analysis are described in Llewellyn, et. al. (2013) and results are more fully described in Appendix D. Projected changes to the water supply and project operations are:.

- Flows would decrease by one-quarter overall
- Flows would decrease in summer and increase in spring.
- Storage in Heron Reservoir would be reduced.
- Sufficient water for a full allocation to contractors will be available less frequently.

Even if sufficient water is available in tributaries to the San Juan River for diversions to the San Juan-Chama Project, shortages within the Colorado River Basin could lead to priority calls or shortage sharing agreements that would result in decreased supply to New Mexico under the Colorado River Compact. Such shortages could result in decreases in Reclamation's authorization to divert water to the San Juan-Chama Project, even if sufficient water is available locally.

Santa Fe Municipal Supply Analysis (WaterMAPS)

As the 2050s are the period consistent with the study's 40-year planning cycle, the model generated five climate scenarios representing the range of variability expected in basin hydrology in the 2050s (Reclamation 2010).

Three of these five climate scenarios were deemed to represent the range of temperature and precipitation changes that are expected due to climate change: Warm-Wet, Hot-Dry, and Central Tendency groups. Therefore, these three scenarios were simulated by Sandia National Laboratories in the monthly-timestep operations model, Upper Rio Grande Simulation Model (URGSiM). Analysis is in Llewellyn et. al. 2013 and results are discussed in Appendix E. The output from these URGSiM simulations were used as input to Santa Fe's municipal supply operations model, Water Management and Planning Simulation (WaterMAPS), to generate the projections and alternatives evaluated in this Basin Study. A baseline scenario, referred to as "simulated historic" was used for comparison to climate-change impacted hydrologies. The simulated historic scenario combines current infrastructure and operations with synthetic, spatially distributed historic climate and inflows (Maurer et. al. 2002). The components of total demand, as modeled in WaterMAPS, are:

- **Population.** Population projections for the 2055 populations used for developing water demand are 125,019 and 44,673 persons for the City and County water service areas, respectively. The City's Long-Range Water Supply Plan completed in 2008 did not directly include the adjacent County population. The combined population leads to much greater demand without a commensurate increase in supply, so the gap between supply and demand reported in this study is not similar to previous City or County documents.

- **Per-capita water demand.** The current average annual per-capita water demand of 114 gallons per capita per day (gpcd) was derived from monthly water production data provided by the City and the City population data from 2002 to 2010. For the demand projections, the unit demand representing the annual average is assumed to be fixed at 114 gpcd (e.g., no conservation efforts assumed for future conditions). This average annual unit demand represents the baseline demand that is compared to the projected 2055 demands to identify the potential water supply gap. Demand values for reclaimed water used in this analysis were obtained from the City of Santa Fe Reclaimed Wastewater Resource Plan (Borchert, 2013), which outlines specific allocations for reclaimed water use. Demand for reclaimed water was based on the allocations and was not modified to account for climate change.

- **Seasonal variations.** In the water supply assessment portion of this study, projected changes to temperature and precipitation were input into a local dynamic systems water operations model (WaterMAPS) to assess potential changes to water supply. The simulated supply conditions were then compared with demand projections to evaluate deficits and needs in the future water supply for the Santa Fe area. Seasonal variability of demand and impacts on that variability due to climate change are also predicted as part of this study and included in the analysis. Other water demands include court ordered provision of water for irrigation systems (i.e., Acequia Madre, Acequia Cerro Gordo).

Water Supply and Demand

The analysis of water supply in the Santa Fe Basin uses the City's WaterMAPS model. WaterMAPS is a multi-criteria dynamic systems simulation model that was built on the Systems Thinking Experimental Learning Laboratory with Animation (STELLA) programming environment. STELLA, developed by Isee Systems, Inc. is a systems modeling industry standard. The results produced from WaterMAPS are used to evaluate how well the City and County will be able to meet future water supply objectives under the four climate scenarios.

The total present supply for the City and County is about 19,000 acre-feet per year (AFY), based on water rights, current water usage, administrative requirements, and current management targets. Although more water is currently available from groundwater sources, management targets for groundwater pumping are used in this analysis because these targets are considered to be sustainable and they add resilience to the overall water supply. The primary water supplies available are:

Surface Water Sources:

- **Rio Grande -** San Juan-Chama Project water and Rio Grande Native Water diverted through the Buckman Direct Diversion roughly 10 miles west of the City limits. The City's contract for San Juan-Chama Project Water is for 5,230 AFY. The County owns 1,325 AFY and plans to acquire an additional 590 AFY acre-feet/year (AFY) of native Rio Grande surface-water rights.

- **Santa Fe River Watershed -** The Santa Fe River originates in the Sangre de Cristo Mountains above downtown Santa Fe. The water from this watershed is stored in two reservoirs: McClure and Nichols, both owned and operated by the City, and treated at the Canyon Road Water Treatment Plant. The City has 5,040 AFY of water rights from the Santa Fe Watershed.

Groundwater Sources:

- **City Well Field (along the Santa Fe River)**: This supply includes the Osage, Northwest, St. Michael's wells, and "Other City wells" all located within the City limits (Agua Fria, Torreon, Alto, Ferguson, Santa Fe, and Hickox). The City has the right to produce roughly 4,865 AFY from this well field.

- **Buckman Well Field (near the Rio Grande)**: This source consists of 13 wells outside of the City limits and near the Rio Grande. Capacity 10,000 AFY, but management restrictions for sustainable yield limit pumping to 3,000 AFY.

Note: Under New Mexico water administration rules, use of groundwater results in depletion of rivers and the depletions must be offset (paid back to the river) by replenishing river flow. Offsets are part of the administrative requirements and are included in the water accounting in WaterMAPS.

The average annual per capita demand for the City of Santa Fe (114 gpcd) was used with future population for the City and the County to derive estimates of average future per-capita water demand. The effect of climate change on demand was estimated using the relationship between water use, temperature and precipitation from City data. The same relationship between water use, temperature and precipitation was applied to temperature and precipitation data for the climate change and simulated historic scenarios.

The gaps between water supply and demand under the climate change scenarios if no adaptation strategies are implemented are summarized in Table E-1. As can be seen on this table, a 2055 water supply gap of just over 5,000 AFY is projected to occur under simulated historic climate conditions (assuming climate similar to historic), due to population increases. However, the magnitude of the water supply gap is larger when we consider projected population growth under any of the three climate change scenarios.

Table E-1. Santa Fe Basin Projected Average 2055 Water Supply Gap

	Climate Change Scenario			
	Simulated Historic (no climate change)	Central Tendency	Warm Wet	Hot Dry
Total Demand - Average Annual (AFY)	21,643	22,925	22,646	23,299
Total Supply - Average Annual (AFY)	16,488	15,550	16,304	13,976
Water Supply Gap – Difference between Demand and Supply Average Annual (AFY)	**(5,155)**	**(7,375)**	**(6,342)**	**(9,323)**

The Hot-Dry scenario has the highest maximum annual deficit, about 14,000 AF while the Warm-Wet scenario has the lowest maximum annual deficit falling just below 9,000 AF.

System Reliability and Risk Assessment

This Basin Study is intended to assess adaptation strategies that may help reduce a projected gap between supply and demand for the City and County. This study has identified where vulnerabilities exist in the supply and has pinpointed adaption strategies and portfolios to address these system weaknesses to ensure a more resilient water supply to meet 40-year water demand projections.

On an annual basis, the predicted deficit ranges from 3,500 acre-feet (AF), the minimum projected deficit for the baseline scenario (i.e., considering population growth without climate change) to almost 14,000 AF, the maximum projected deficit for the Hot-Dry scenario. On a monthly basis, there is a 68 to 95 percent chance that there will be a water supply shortage in any given month in one of the scenarios by the year 2055, based on current supplies and management targets. Predicted deficits are more frequent and severe in the summer months (when demands and ecological needs are higher) than in the winter.

These deficits are expected to impact the Santa Fe area in the following ways:

- **Ability to Deliver Water:** All modeled scenarios, including the baseline as well as the three climate-change impacted scenarios, show an annual deficit ranging between 3,500 AF and 14,000 AF. Without adaptation actions, such shortages would severely impact the ability of the City and County to deliver enough water to meet demands.

- **Recreation:** Decreased flow in the Rio Grande during the summer months will likely impact water-based recreation.

- **Flow and Water Dependent Ecological Resiliency:** Decreased flow in the Rio Grande during the summer months will likely impact the habitat of aquatic and riparian species, including threatened and endangered species, and decrease the resilience of riverine and riparian ecosystems.

The potential impact to other key water resources categories identified in the SECURE Water Act, including hydroelectric power generation facilities, water quality issues (including salinity levels), and flood control management, were not directly evaluated in this study, although the impacts to these water-related components are discussed in Appendix A.

Consequences of Taking No Action

If no adaptation actions are taken to offset the growing gap between supply and demand in the Santa Fe Basin, deficits discussed above would severely impact the ability to deliver enough water to meet demands, leading to grave regional economic impacts. Additionally, water-based recreation and flow and water dependent ecological resiliency are likely to be impacted by decreased flow in the Rio Grande and the Santa Fe River, especially in summer months.

Adaptation Strategies

Developing Adapation Strategies

Representatives of the City and County identified adaptation strategies appropriate for the arid climate and landscape of the Santa Fe region that could meet future water demands (summarized in Table E-2).

Table E-2. Adaptation Strategies for the Santa Fe Basin study area

Adaptation Strategy	Description	Infrastructure Components
Direct/Indirect Reclaimed Water Reuse	Use reclaimed water from the City wastewater treatment plant to meet contract obligations; remaining reclaimed water for potable reuse or return flow credits for pumping	New conveyance for reclaimed water from wastewater treatment plant to existing Buckman Regional Water Treatment Facility and distribution system or new conveyance to the Rio Grande for return flow credits
Water Conservation	Reduce water use on a per person per day basis	None
Direct Injection for Aquifer Storage and Recovery	Inject treated water into the aquifer in wet and normal years for use in dry years	Construction and operation of injection well(s); withdrawal using existing wells and distribution system
Infiltration for Aquifer Storage and Recovery in the Santa Fe River	Maintain flow in the Santa Fe River to induce infiltration into the aquifer for use in dry years	Withdrawal using existing wells and distribution system.
Additional Surface Water Rights	Additional surface water would be diverted at the Buckman Direct Diversion and treated at the Buckman Regional Water Treatment Facility.	Existing diversion, conveyance, treatment, and distribution systems

Formulating Adaptation Portfolios

These adaptation strategies were combined in different proportions to create adaptation portfolios (see Appendix G). These portfolios were modeled to evaluate which combination of adaptation strategies is most likely to meet the water supply needs of Santa Fe under projected conditions in the 2050s. Some of the evaluations performed using the local water operations model were to:

- Identify trends in water use, such as more pronounced spikes in use rates during drier and hotter summers, which could be preemptively addressed by increased conservation education.

- Identify likely water supply gaps (i.e., the difference between projected supply and projected demand) during the planning period (through 2055), under projected management, population, development, and climatic conditions.

- Evaluate a range of adaptation portfolios for addressing the projected supply gap in terms of cost, technical feasibility, public acceptance, permitting considerations, and the likely availability of funding assistance for individual alternatives.

- Evaluate the limits of individual adaptation strategies such as conservation or water rights acquisition to better understand potential limitations of existing practices in the future.

Evaluating and Comparing Adaptation Portfolios

The adaptation portfolios were evaluated to select the adaptation portfolio that best meets the needs of the Santa Fe Basin under projected population growth and climatic changes. (See Appendix G).

The initial step in evaluating the adaptation strategies and portfolios was to screen them against reliability criteria:

1. Average Buckman Well Field pumping does not exceed the management target by more than 500 AFY on average.
2. Total deficit does not exceed 2,000 AFY in any year in the simulations.
3. No more than 10 percent probability of deficits over 100 AFY (meaning that in 90% of the years, the deficit is less than 100 AFY)

Table E-3 summarizes the adaptation portfolios and the supply based on WaterMAPS simulations. Table E-4 provides the results of the reliability screening. Only those portfolios that provide a reliable water supply in 2055 were then evaluated against performance criteria. Portfolios 1 through 3 presented single adaptation strategies, and the results presented confirm that no single adaptation strategy will suffice to fill the gap between supply and demand. The solution for the Santa Fe Basin area must be a portfolio of adaptation strategies.

Findings

The five combination portfolios (Portfolios 4 through 8) that met the threshold of the reliability criteria were then evaluated using performance criteria. The performance criteria address multiple aspects of the water supply system and are both quantitative and qualitative. For each criterion, there is a corresponding performance measure that describes the metric that will be used to evaluate that criterion. All criteria are not of equal importance. Each criterion was assigned a weight to indicate its relative importance. The weights were developed on a consensus basis by the City, County, and Reclamation. The criteria, performance measures, and weights are shown in Table E-5.

The ranking process for the Santa Fe Basin Study was based on scoring each adaptation portfolio with respect to each of the performance criteria shown in Table E-5. The higher the score, the better the portfolio meets the criteria.

The ranking of the portfolios, based on the consensus scoring and the criteria weighting, is in Figure E-3. The ranking of the portfolios clearly shows that Portfolio 5, with an overall score of 3.8 out of 4.0, meets the performance criteria better than the other portfolios (Figure E-3). One common element of the three highest ranked portfolios is increased use of reclaimed water. This suggests that the City and County focus efforts to use reclaimed water from both the City wastewater treatment plant and the County’s Quill wastewater treatment plant. The three highest ranked portfolios also use the maximum number of adaptive strategies, demonstrating the value of a multi-faceted approach to meet future water demands in the Santa Fe region.

Table E-3. Santa Fe Basin Study Portfolios and Simulated Supply

	Simulated Supply from Adaptation Strategy (AFY)					
	Direct Reclaimed Water Reuse	Conservation	Direct Injection Aquifer Storage and Recovery	Infiltration Santa Fe River Aquifer Storage and Recovery	Additional Water Rights	**Portfolio Simulated Supply**
Portfolio 1: Conservation Only		4,005				**4,005**
Portfolio 2: Direct Reuse Only	4,024					**4,024**
Portfolio 3: Additional Water Rights Only					1,400	**1,400**
Portfolio 4: More Conservation & Water Rights (Reuse to Potable)	2,224	4,005	559	149	1,400	**8,337**
Portfolio 5: More Conservation & Water Rights (Reuse to Offsets)	2,224	4,005	559	149	1,400	**8,337**
Portfolio 6: More Infiltration ASR		3,003	0	2,841	1,400	**7,244**
Portfolio 7: More Direct Reuse (to Potable)	3,243	2,002		148	920	**6,313**
Portfolio 8: More Direct Reuse (to Return flow credits)	3,243	2,002		148	920	**6,313**

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Table E-4. Performance of Adaptation Portfolios Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	**Maximum Annual Deficit <2000 AFY**	**Annual Deficit at 10% probability > 100 AFY**
Portfolio 1: Conservation Only	NO (Exceeds by 2,674 AFY)	YES (1,372 AFY)	NO (391 AFY)
Portfolio 2: Direct Reuse Only	NO (Exceeds by 2,225 AFY)	YES (1,159 AFY)	NO (378 AFY)
Portfolio 3: Additional Water Rights Only	NO (Exceeds by 4,451 AFY)	NO (3,978 AFY)	NO (2,363 AFY)
Portfolios 4 and 5:* More Conservation and Water Rights	YES (Does not exceed)	YES (57 AFY)	YES (0 AFY)
Portfolio 6: More ASR	YES (Exceeds by 291 AFY)	YES (553 AFY)	ALMOST (Keep) (161 AFY)
Portfolios 7 and 8: More Direct Reuse**	YES (Exceeds by 323 AFY)	YES (211 AFY)	YES (32 AFY)

*Portfolios 4 and 5 have the same water-supply reliability rating, so are grouped together in this table. The differences between them show up in terms of Performance Measures.

**Portfolio 8 is the same as Portfolio 7 except the treated water is returned to the Rio Grande for return flow credits.

Table E-5. Performance Criteria, Performance Measures, and Criteria Weight

Performance Criteria	Performance Measure	Criteria Weight
Cost Considerations		**15%**
Capital Cost	Qualitative: estimate	40%
O&M Cost	Qualitative: estimate	40%
Potential for Cost Share	Qualitative	20%
Reliability and Sustainability		**25%**
Drought Supply	Quantitative: assessment of annual deficit probability curves	50%
Groundwater Use	Quantitative: average and maximum pumping compared to management target	50%
Acceptance		**10%**
Regulatory Compliance Complexity	Qualitative	50%
Public Acceptance	Qualitative	50%
Environmental /Cultural		**30%**
SF River Flows	Quantitative: flow in Santa Fe River	50%
Wetland Preservation	Qualitative	50%
Technical Implementability		**20%**
Technology Viability	Qualitative	100%

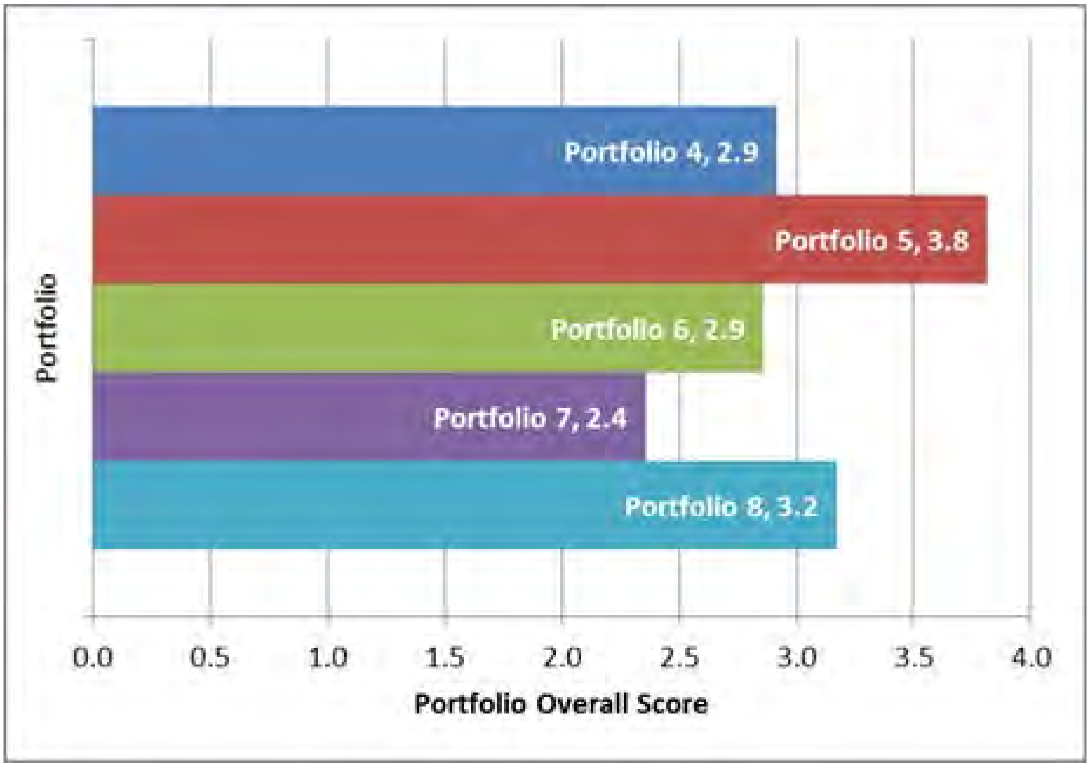


Figure E-3. Ranking of Santa Fe Portfolios.

Next Steps and Future Considerations

The highest ranked portfolio, Portfolio 5, includes over 2,200 AFY of direct water reuse, approximately 4,000 AFY of additional conservation, nearly 600 AFY of direct aquifer storage and recovery, nearly 150 AFY of indirect aquifer storage through infiltration below the Santa Fe River, and the acquisition of approximately 1,400 AFY of additional native Rio Grande water rights.

One of the primary adaption alternatives identified in this study is to “augment potable water supplies with reclaimed wastewater” as described in the report, Climate Change and the Santa Fe Basin: A Preliminary Assessment of Vulnerabilities and Adaptation Alternatives Bureau of Reclamation WaterSMART Program Initiative (February, 2013; Appendix A) and the City of Santa Fe Reclaimed Wastewater Resource Plan (RWRP) for the City (City of Santa Fe 2013) which identified potential alternatives to using reclaimed water as a supply source. City Council Resolution 2013-55 was enacted and approved and directs City Staff to pursue opportunities to evaluate and implement engineering and cost analysis of using reclaimed water alternatives to supplement water supplies. In June, 2014, the City and County were also awarded a grant through Reclamation’s Title XVI Program to conduct a water reuse feasibility study. The water reuse feasibility study will evaluate alternatives for both potable and non-potable applications of reclaimed water to augment water supplies. The feasibility study will evaluate ways to cost-effectively use reclaimed wastewater in a more efficient manner and will consider both potable and non-potable alternatives to meet water demand requirements while better balancing environmental conditions in the watershed.

Disclaimers

The Santa Fe Basin Study was funded jointly by Reclamation, the City of Santa Fe and Santa Fe County, and is a collaborative product of the study participants as identified in Section 1.4. Coordination and Participants of this report. The purpose of the study is to assess current and future water supply and demand in the Santa Fe Basin and other basins providing water to the City and County, and to identify a range of potential strategies to address any projected imbalances. The study is a technical assessment and does not provide recommendations or represent a statement of policy or position of Reclamation, DOI, or the funding partners. The study does not propose or address the feasibility of any specific project, program or plan. Nothing in the study is intended, nor shall the study be construed, to interpret, diminish, or modify the rights of any participant under applicable law. Nothing in the study represents a commitment for provision of Federal funds. All cost estimates included in this study are preliminary and intended only for comparative purposes.

While the best available information and consistent methodology was used in developing this Basin Study, projections into the future require many assumptions and result in inherent uncertainty. While this is necessary and appropriate for planning-level analyses, more detailed feasibility- and design-level studies would be needed when implementing some of the adaptation strategies identified. The purpose of this study is to provide a reasonable path forward based on the best information available. Some specific items to note are discussed below:

- Climate change impacts on groundwater supply were not explored for this Basin Study. The analysis accounted for likely reductions in groundwater supply through the use of management targets, which are significantly less than actual water rights.

- Water rights, management targets, and capacity constraints are changing annually and must be verified before using in future studies or planning projects.

- The predicted water supply gap is sensitive to population projections, which were not closely studied as part of this Basin Study. The future water service area for the County is not well known. Previous studies and input from the project team members were relied upon for this information.

Chapter 1. Introduction

1.1. Study Purpose, Authorization, and Funding

Climate change, in concert with human development and other changes, promises to alter many aspects of life in the Santa Fe basin, including the availability of water to the City of Santa Fe and Santa Fe County, and the resources that depend on the Santa Fe Watershed. The health of forests, fish and wildlife, and other ecosystems as well as human development, food security, and quality of life are likely to be affected. This Basin Study has been undertaken by the City and County along with Reclamation to evaluate these projected changes and to develop potential strategies for adaptation that can be used for planning. Figure 1-1 shows the general location of the City and County.

Figure 1-1. Location of Santa Fe City and Sante Fe County, New Mexico.

1.1.1. Authorization and Funding

This Basin Study was performed under the DOI’s WaterSMART Basin Study Program. The Federal SECURE Water Act of 2009 and Secretarial Order 3297 established the WaterSMART Program, which authorizes Federal water and science agencies to work with State and local water managers to pursue and protect sustainable water supplies and plan for future climate change by providing leadership and technical assistance on the efficient use of water. WaterSMART allows DOI bureaus to collaboratively work with States, Tribes, local governments, and non-governmental organizations to pursue a sustainable water supply for the Nation, and integrate water and energy policies to support the sustainable use of all natural resources. Basin Studies, one of the tools of this program, are basin-wide efforts to evaluate and address the impacts of increased competition for limited water supplies, climate change, and other stressors, and to define options for meeting future water demands in river basins in the Western United States where imbalances in water supply and demand exist or are projected. The study is consistent with Reclamation’s Basin Study Framework and Section 9503 of the SECURE Water Act (Subtitle F of Title IX of P.L. 111-11, the Omnibus Public Land Management Act of 2009).

1.1.2. Cost-Share Partners

The cost-share partners for this study are the City, County, and Reclamation, which performed the study in partnership under a Memorandum of Agreement (MOA).

1.2. Scope and Objectives

Through the Santa Fe Basin Study, the study partners seek to improve the resilience of the Santa Fe watershed and the communities that it supports, as well as of the municipal water systems for the City and County, in the face of projected changes in population, human development, and climate. This Basin Study consisted of the following actions:

- Identify the vulnerabilities of systems in the Santa Fe watershed to climate change. A preliminary assessment qualitatively evaluated climate-change impacts on water supply sources, ecosystems, quality of life, agriculture and local food production, landscapes, and land use and water demand. This assessment was based on input obtained during a March 6, 2012 workshop and from research conducted by the authors and is summarized in this report and presented in full in Appendix A.

- Assess Santa Fe's changing water supply and demand, including native surface-water supplies from the Santa Fe Watershed, the Upper Rio Grande, and the San Juan Basin (imported water of the San Juan-Chama Project), as well as groundwater supplies to the city and county's well fields. This portion of the study includes an assessment of the likely water supply and demand conditions in 2050 for the City and County's combined water supply. There is a small amount of agricultural land (as of 2005, OSE estimated 590 acres irrigated with surface water and 130 acres irrigated with groundwater) in the Santa Fe Watershed. However, the quantitative analyses in this study focused on municipal supply, demand, and adaptation measures, since municipal use represents the largest portion of water use within the basin, and is the primary area of interest of Reclamation's study partners. This assessment included:

    - Developing climate and hydrology projections for use in this Basin Study. This work by Reclamation and Sandia National Laboratories is described in Appendices B, C1, and C2.

    - Developing an independent transient analysis of the projected changes over the course of the 21st century of the reliability of Reclamation's San Juan-Chama Project. This work by Reclamation and Sandia National Laboratories is presented in full in Appendix D.

    - Updating the City's Water Management and Planning Simulation (WaterMAPS) model to include the County as a partnering entity and to enhance the model to include functionality to assess projected climate impacts. This work by CDM-Smith is discussed in detail in Appendix E.

    - Using the updated WaterMAPS model, running simulations to determine the impacts to the City and County's combined water supply under future demand and projected climate conditions. These simulations by CDM-Smith are described in detail in Appendix F.

- Identify and analyze potential adaptation strategies for the combined City and County water supply. This portion of the study included:

    - Assessing the vulnerability and possible shortcomings of the current long-range water supply strategies.

    - Identifying management or infrastructure changes that might strengthen the entire basin, its component systems, and its inhabitants to provide more flexibility in the face of an uncertain future.

    - Combining these adaptation strategies into portfolios that would provide adequate water supply in the 2050s, considering projected population growth and climatic changes. Since it is likely that no single adaptation strategy will suffice to fill the gap between supply and demand, these combined portfolios helped the City and County select adaptive strategies that best meet the regional water supply needs. Appendix G describes the adaptation strategies and alternative climate mitigation portfolios evaluated.

1.3. Location and Description of the Study Area

The focus area for this Basin Study is the Santa Fe River watershed, which is a sub-basin to the Rio Grande watershed. The study also includes, for water-supply assessment purposes, the upper Rio Grande watershed (upstream of Otowi stream gage), tributaries within the San Juan River watershed, a portion of which are delivered to Santa Fe through Reclamation's San Juan-Chama Project, and groundwater from the aquifers of the Santa Fe Group. Each of these sub-basins is a source of surface-water for the combined municipal water supply for the City and County. The first two sub-basins are within the Rio Grande basin; the third lies within the Upper Colorado River Basin. The Santa Fe watershed is located in the high-elevation desert of northern New Mexico (Figure 1-2). It spans the Sangre de Cristo Mountains on the east and the Rio Grande on the west. The City of Santa Fe is the main municipality in the watershed and within the northern portion of Santa Fe County (Figure 1-2). The Santa Fe Basin includes the City and the portion of the County that has the highest population density and the highest growth rate, as well as the part that has historically depended on the City of Santa Fe for water supply.

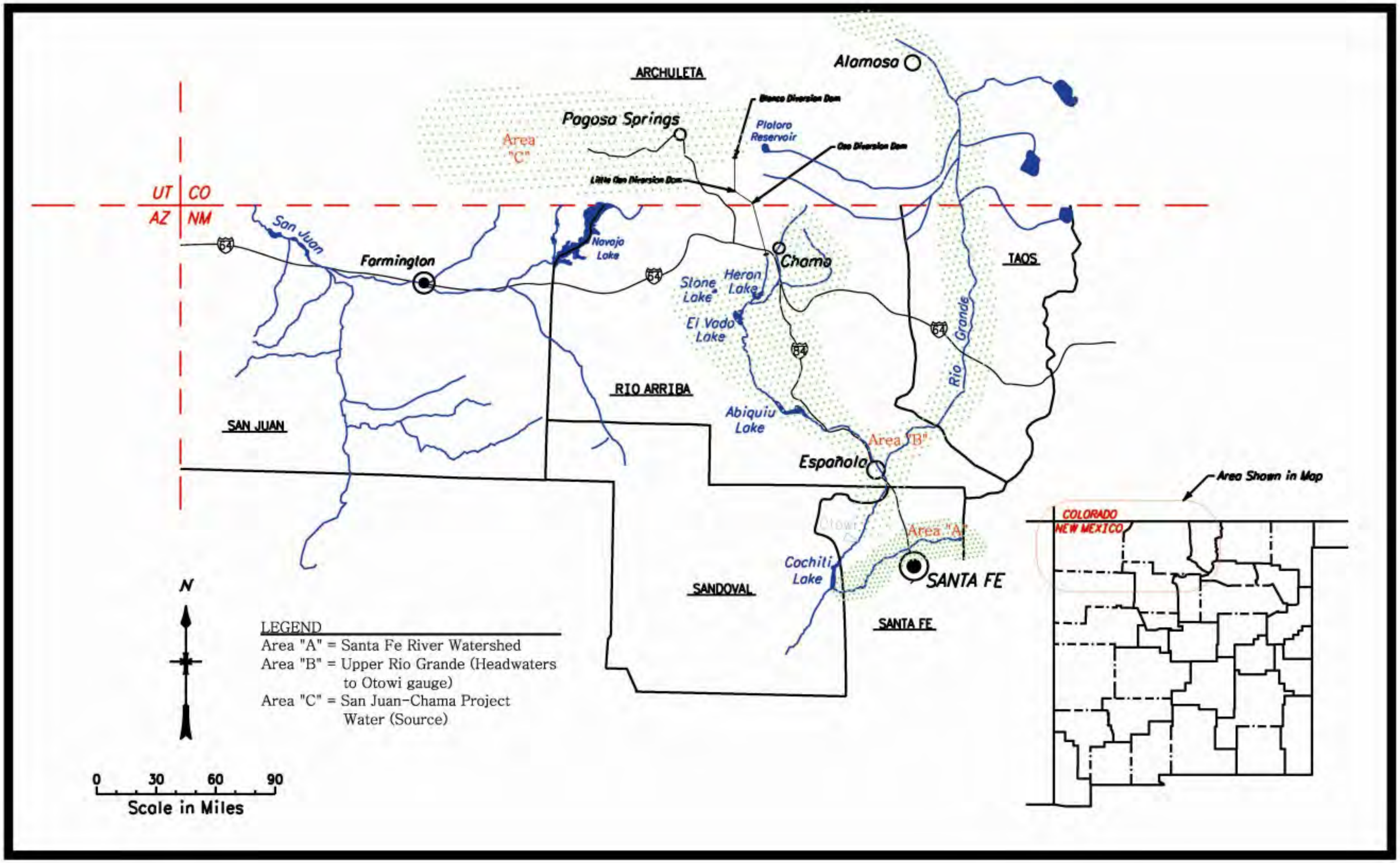


Figure 1-2. The Santa Fe watershed (shaded green) receives water supply from the Santa Fe sub-basin, the upper Rio Grande sub-basin (green stipple) and the San Juan-Chama River sub-basin (all green stipple).

Santa Fe has a temperate climate with four distinct seasons. Santa Fe averages over 300 days of sunshine a year. The summer months in Santa Fe, from May to September, feature typically hot, sunny weather with fairly low humidity and cooler evenings. Daily summer temperatures in Santa Fe peak at around 93°F during July and August. Thunderstorms typically occur in the early evening during this season. Rainfall in the Santa Fe area is spread throughout the year, although the highest frequency and intensity of rain occurs as part of the summer monsoons, which occur primarily during the months of July and August. The average annual precipitation in Santa Fe is about 14 inches.

1.4. Coordination and Participants

The City and County water supply systems are interconnected with the County system surrounding the City system to the north, south, and east of the City boundary and service area. The two water utilities also co-own one of the region's sources of supply. Recognizing the shared resource and infrastructure, cooperation between the City and County is essential for planning. Reclamation provided technical analyses of climate scenarios and resultant hydrology as well as guidance throughout the Basin Study process.

Other participants in for this Basin Study are:

1. **Stakeholders:** The stakeholders are the residents of the Santa Fe Basin and other regional interests. These stakeholders participated in the Santa Fe Basin Study through the Preliminary Assessment Workshop described in Appendix A.

2. **State:** Representatives of State agencies participated in the Preliminary Assessment workshop.

3. **Local:** Representatives of local agencies and nonprofit organizations participated in the Preliminary Assessment workshop.

4. **Tribes:** Representatives of Tribal agencies participated in the Preliminary Assessment workshop.

5. **Irrigation Districts:** Members of acequias and representatives of the Acequia Commission participated in the Preliminary Assessment workshop.

The Santa Fe Basin Study analyses, modeling, evaluations, and reporting have been developed through the combined efforts of the City and County working in consultation with Reclamation's Albuquerque Area Office (AAO), with technical support from. Reclamation's Technical Service Center (TSC), Sandia National Laboratories, and CDM Smith, an engineering firm.

1.5. Collaboration and Outreach

The project partners sponsored an interactive workshop on March 6, 2012 in Santa Fe to introduce climate change and its potential impacts in the Santa Fe Basin area to a broad group of local stakeholders and community members. Over 100 workshop participants eagerly shared their thoughts and ideas on actions that local governments and citizens could take to create a more resilient water supply within the Santa Fe Basin in response to likely climate change impacts.

Climate change experts provided the foundation for the workshop by giving a summary of climate change projections for the Santa Fe Basin area, the southwestern forest response to drought, and the historical and sociological impacts of climate change.

Through facilitated breakout groups, participants from Federal, State, local, private, and non-profit groups as well as the public provided input on a range of climate change impacts on various physical, biological, and socioeconomic systems within the Santa Fe Basin area. The breakout groups were asked to identify how climate change may threaten a system of concern, prioritize how those risks should be responded to, and to brainstorm adaptation strategies that can be taken at the City and County level to build resilience into those systems in the face of those impacts.

The Preliminary Assessment Report (Appendix A) provides the list of potential solutions to the projected impacts of climate change and summarizes what is being done or has been done and what remains to be implemented. Table 1-1 shows the adaptation strategies that were identified by the Preliminary Assessment and which were used to build the adaptation portfolios evaluated in the subsequent project phase. Some strategies were not included because they were beyond the scope of the Basin Study.

Table 1-1. Adaptation Strategies from the Preliminary Assessment Incorporated in Adaptation Portfolios

Adaptation Strategies from Preliminary Assessment (Appendix A)	Included in Adaptation Portfolio?	Notes
Demand Adaptation Strategies		
Incorporate urban agriculture in water and land use planning	No	Unable to quantify water demands
Cultivate climate appropriate crops	No	Unable to quantify water conserved
Provide incentives and programs to reduce water use, especially during drought	Yes	Water conservation included in all adaptation portfolios
Increase solar panel installation to reflect heat and produce energy	No	Unable to quantify impact on water supply
Expand water harvesting techniques	Yes	Water conservation included in all adaptation portfolios
Availability Adaptation Strategies		
Encourage limited term urban lease of agricultural water rights during drought	Yes	Water rights acquisition included in all adaptation portfolios
Adjudicate Santa Fe Basin water rights	No	Unable to quantify water availability; not a City or County function
Augment potable supplies with reclaimed wastewater	Yes	Reclaimed water reuse included in all adaptation portfolios
Increase above and below groundwater storage capacity	Yes	Aquifer storage and recovery included in all adaptation strategies
Require pervious pavement where appropriate	No	Unable to quantify water availability
Improve soils and watershed resiliency	No	Unable to quantify water availability
Design of modify bridges and culverts to handle higher intensity runoff events	No	Unable to quantify storm flow intensity
Combined Adaptation Strategies		
Manage and plan restoration holistically	No	Unable to quantify water availability or conservation
Improve ecosystem biodiversity	No	Unable to quantify water availability or conservation
Decentralize energy infrastructure	No	Unable to quantify water availability or conservation
Establish a climate change targeted monitoring system	No	May be included in future adaptation programs

1.6. Summary of Previous and Current Studies

A summary of previous and current studies are presented below. Studies that are included as one of the appendices of this report are not summarized.

1.6.1. Sustainable Santa Fe Plan

The Sustainable Santa Fe Plan (City of Santa Fe 2008 [Sustainable]) was drafted to assess options for reducing Santa Fe's greenhouse gas (GHG) emissions in a manner that is consistent with evolving social values, traditional New Mexican practices, and existing economic realities. The plan draws from a diverse range of documents which address spanning a range from public transportation to watershed health to economic development. Detailed consideration of issues in the report is given to: GHG Emissions Inventory, City Operations, Green Building Code, Development and Zoning Code, Clean Renewable Energy, Transportation, Ecological Adaptation, Water Conservation, Solid Waste Reduction, Food Systems, Education and Outreach, and Implementation strategies. Of these topics, the most directly relevant to this study is the section on Water Conservation, summarized here.

The Sustainable Santa Fe Plan addresses water conservation as an important issue both because of the need to conserve water for its own sake and also because water conveyance is a substantial user of power and power generation is a significant consumer of water. For these reasons, water consumption is a significant contributor to GHG emissions. The goal of the Water Conservation Committee is "to define and develop and integrated strategy to accomplish long-range water policies." Specific steps to accomplish this goal include:

- Develop a Water Conservation Strategic Plan which recognizes the need for commercial, residential, and industrial users to share in conservation efforts. This can better integrate related functions in city government including: water conservation, long range water supply planning, land use planning, and billing. The plan can also address complex issues of water conservation with a focus on interconnections.

- Adopt new technologies to better track water use and to help customers conserve water include improvements to measurement and infrastructure in order to quantify the effects of conservation measures.

- Proactively plan and run tests to identify leaks, including expedient repair of leaks and expansion of leak identification processes beyond residential and into other water customer sections.

- Expand public outreach and education.

- Initiate a program to maximize water harvesting.
- Initiate a program to process and use water for multiple purposes.
- Continue and increase the use of treated effluent.
- Consider the energy requirements of any potential new water sources and seek opportunities to use clean, renewable energy sources for the energy requirements of both existing and new water sources.

1.6.2. Santa Fe County Sustainable Growth Management Plan

New and challenging issues today require Santa Fe County to be proactive about how growth is addressed within our communities. The Sustainable Growth Management Plan (Santa Fe County 2010) is a guiding document that incorporates local community values, goals, and strategies on how to best manage and sustainably use the County's limited natural, economic, and cultural resources. The plan is also a tool that addresses the existing and future needs of communities in Santa Fe County and serves as a guide for planning, land use, housing, resource and environmental protection, public and facility service, renewable and green development, fiscal responsibility, and administrative regulation. The plan serves as the framework for the County’s Sustainable Land Development Code and replaces the 1999 Santa Fe County Growth Management Plan.

1.6.3. Santa Fe County Sustainable Land Development Code

The Santa Fe County’s Sustainable Land Development Code (Santa Fe County 2013) provides a legal framework for implementing land development and growth management policies of the Sustainable Growth Management Plan. The code will be implemented once the County zoning map has been approved.

1.6.4. City of Santa Fe Long Range Water Supply Plan

The City of Santa Fe’s Long Range Water Supply Plan (City of Santa Fe 2008 [Water]) is the result of a process that began in 2004 and did not conclude until 2008. The Long Range Water Supply Plan was conceived as a road map for optimizing existing water supplies and for providing new supplies to address a supply gap projected to begin in 2021 and to reach 2,700 AF by 2045 despite the construction of the Buckman Direct Diversion and the availability of that water for municipal supply. This project is where the WaterMAPS water systems operation model was initially developed. WaterMAPS is described in Appendix E and discussed later in this report (Section 2.3.2).

The Long Range Water Supply Plan considered over 30 different water supply and demand management options and ultimately compared 11 different supply portfolios to address the projected supply gap. These portfolios were compared on the basis of six objectives designed to assess the feasibility, sustainability, cost, and practicality of each approach. Following the assessment of these portfolios, eight major policies were developed by which the City would seek to meet future water supply needs. The scenarios evaluated in this Basin Study report are consistent with these policies. The policies are:

- The City will continue and improve its aggressive water conservation program.
- The City will acquire the necessary water and environmental permits to meet the City's future demands.
- The City will use groundwater sustainably.
- The City will optimize its use of treated effluent.
- The City will optimize its use of existing water rights and infrastructure to stretch existing water supplies.
- The City will seek to minimize or eliminate the use of emergency drought restrictions.
- The City will provide water to maintain a living Santa Fe River, except under drought or emergency conditions.
- The City will monitor system performance and revisit its water needs, and adjust its actions as necessary to fully meet its demand sustainable, and cooperate in securing a reliable water supply for the region.

1.6.5. State Water Plan, Jemez Y Sangre Regional Water Plan

The Jemez y Sangre region is one of 16 regions in the state, each of which has its own plan. The Jemez y Sangre region, in particular, includes Espanola, Los Alamos, Santa Fe, and the surrounding areas as shown in Figure 1-3. The Jemez y Sangre Regional Water Plan (Jemez y Sangre Water Planning Council 2003) is part of the State of New Mexico's State Water Planning process. The document is wide ranging and addresses many aspects of the regional water picture including evaluation of conflicting values and priorities between municipalities and between urban and rural portions of the

Figure 1-3 Map of the Jemez y Sangre Region.

region. As is stated in the Jemez y Sangre Regional Water Plan, “Some stakeholders will argue that economic development can occur without growth and others will claim that a significant portion of the agricultural water rights are not being used anyway, and that the regional character is already changing due to the low profitability of farming.”

The Jemez y Sangre Regional Water Plan has six components of a successful plan:

- Rural and Wildlands Character
- Water Sustainability
- Economic Sustainability
- Water Quality
- Acknowledgement of Rights and Responsibilities associated with responsible use of the resource
- Collaborative Decision making emphasizing open, inclusive dialogue and decision making

The Jemez y Sangre Regional Water Plan anticipates an increased regional demand of 31,500 AFY by 2060, with the bulk of that growth in demand centered in the Santa Fe, North Galisteo, Tesuque, Santa Cruz, and Nambe-Pojaque sub-basins. Vulnerabilities to water supply identified in the plan include:

- Groundwater mining
- Variability in surface water supply based on drought
- Watershed health
- Catastrophic wildfire
- Water quality risks
- Limitations on the understanding of groundwater resources within the region, including the need for an improved understanding of regional hydrogeology and a regional numerical groundwater and surface water model acceptable to all parties
- Lack of a comprehensive adjudication as well as the secondary absence of metering to determine that users are exercising their rights within their adjudicated constraints
- Scale of domestic well use (which is assumed in the Jemez y Sangre Regional Water Plan to divert an estimated 7,700 AFY, representing 35 percent of the total demand in the area).

One anticipated outcome of this convergence of factors is a projected supply gap.

1.7. Identification of Interrelated Activities

1.7.1. International

The water in the Rio Grande and Santa Fe River is subject to the Rio Grande Compact. This Basin Study involves articles of the Rio Grande Compact, and to that extent, there is an international nexus with Mexico in that international water delivery obligations exist on the rivers.

1.7.2. Federal

The City and County were awarded a grant in June 2014, from Reclamation through the Title XVI Program to conduct a water reuse feasibility study. The water reuse feasibility study will evaluate alternatives for both potable and non-potable applications of reclaimed water to augment water supplies.

1.7.3. Interstate

The Santa Fe watershed is subsidiary to the Rio Grande watershed. All waters in the Rio Grande watershed are subject to the 1938 Interstate Rio Grande Compact, which is managed by the New Mexico Interstate Stream Commission within New Mexico. The water diverted by the City through the Buckman Direct Diversion facility originates in the San Juan Basin and is diverted from the San Juan Basin via a series of tunnels. This diversion is subject to the Colorado River Basin Compacts. The continued allocation of this water and its use are subject to scrutiny by the partners both in New Mexico and in the other Colorado River Basin states.

1.7.4. State

1.7.4.1. Water Rights Management

Water quantity and water rights in New Mexico are managed by a state agency, the New Mexico Office of the State Engineer (OSE). Water quality, which is an essential aspect of reclaimed water use and aquifer storage and recovery adaptive strategies, will also involve the New Mexico Environment Department (NMED). Continuing compliance with regulatory standards remains a priority for the Santa Fe area water utilities.

1.7.4.2. Relationship to State Law including State Water Plan

Compliance with State laws, as described above, is a priority for the Santa Fe area water utilities. The New Mexico State Water Plan is built up of plans from 16 water planning regions. The Santa Fe Basin is in the Jemez y Sangre Regional Planning area. The information from this Basin Study will be incorporated as part of the Jemez y Sangre Regional Water Plan (summarized in Section 1.6.5) as future updates are made.

1.7.5. Local

Within the Santa Fe Basin, the City of Santa Fe, Santa Fe County, Agua Fria Community Water Association, La Cienega Mutual Domestic Association, and La Bajada Mutual Domestic Water Association provide water utility services to local residents. However, the City of Santa Fe and the surrounding area also have a number of local non-profit entities that are active in water matters and have interrelated activities. Examples include:

- The Santa Fe Watershed Association that focuses on restoration of the upper watershed and educational outreach
- The Nature Conservancy working to protect the Rio Grande watershed
- WildEarth Guardians, who have re-vegetated significant portions of the Santa Fe River

Chapter 2. Problems and Needs

The City and County are concerned about potential decreases in the availability and reliability of their joint surface water supply, as well as water quality. The water utilities recognized the need for long-range planning efforts to identify future water supply deficiencies, develop strategies for meeting those shortfalls, and implement those strategies.

The City and County water utilities have a diverse water supply portfolio, providing water to their customers with surface water from the three sub-basins and groundwater from two well fields. Additionally, thousands of single- and multiple-household domestic wells provide water to users within the Santa Fe study area and outside the utility service area.

To increase the sustainability of their water supply, the City and County water utilities have developed new surface-water sources. Like many surface waters in the arid Southwest, however, supplies from the Santa Fe River, the Upper Rio Grande, and the tributaries to the San Juan River are all limited, highly variable, and dependent on seasonal snowpack and runoff conditions. They are also all vulnerable to climate-change-induced impacts. The groundwater is pumped from aquifers that are slow to recharge. Overreliance on, and inadequate regulation of, groundwater has led to significant declines in aquifer water levels resulting in depletions of water from nearby streams, rivers, and springs connected and supported by the aquifers. The population continues to grow and the needs of the community continue to expand. In response to these conditions, the City and the County have been working for a more resilient, sustainable, diverse, and innovative water supply system for many years.

The City and County recognize looming threats to the water supply and have addressed them in multiple ways. Together, the water utilities have embarked on long-range planning efforts to identify future water supply deficiencies, identify strategies for meeting those shortfalls, and implement those strategies. Aggressive water conservation programs have reduced per capita utility customer demand by 42 percent since 1995, which has brought the current average demand down to about 114 gcpd. The City and County have reduced their reliance on groundwater extraction by constructing the Buckman Direct Diversion to divert surface water, through which the utilities' customers receive water from the imported San Juan-Chama Project and native Rio Grande surface water. This surface water supply is renewable.

This Basin Study is the latest in a series of efforts to understand and strengthen water supply management in the Santa Fe area. The opportunities for adapting to future water supply shortages identified through this Basin Study are based on a better understanding of the future effects of, and associated risks from, climate change and population growth on the City and County's combined water supply portfolio. The adaptive strategies for the identified risks are grouped into portfolios so that the City and County can select the portfolio of adaptive strategies that best meets the regional water supply needs. Through this Basin Study, the City, County, Reclamation, and their consultants have developed a better understanding of the future effects of and associated risks from climate change on its water supply portfolio.

2.1. Future Challenges and Considerations

Water managers in the Southwest face a myriad of threats, including long-range climate change impacts and short-term drought conditions, both of which cause reductions in surface water supplies. Of greatest concern for the City and County are potential decreased San Juan-Chama Project water apportionments and the risk of Buckman Direct Diversion and Canyon Road Water Treatment Plants' shutdowns due to low flows and/or poor water quality. Diversions at the Buckman Direct Diversion are curtailed by low flows in the Rio Grande in compliance with the Record of Decision (U.S. Forest Service and Bureau of Land Management 2007) and Final Environmental Impact Statement (U.S. Forest Service and Bureau of Land Management 2006) for the Buckman Water Diversion Project.

Surface water resources in the Southwest depend on seasonal snowpack and runoff conditions, which are prone to fluctuation and which will, in the long term, be impacted by global climate change. Regional groundwater resources are also threatened—well yields have decreased and groundwater levels near the City's two well fields have declined substantially. The cone of depression that developed in the vicinity of the Buckman Well Field was a result of prolonged well use in the area. From 1995 to 2001, an average of 5,200 AFY of water was pumped from the Buckman Well Field. In 2001, the depth-to-groundwater at the center of the cone of depression for the Buckman Well Field was approximately 260 feet, as measured in a City observation well located near the center of the well field. Furthermore, decreases of surface water could trigger onerous administrative conditions (i.e., increased offsets) to groundwater pumping.

Significant reduction in groundwater use in recent years has resulted in some recovery of the aquifer. Since the Buckman Direct Diversion project has come online, the average pumping has been 2,000 AFY (2010-2012), with only 1,050 acre-feet (AF) pumped in 2012. With increasing demand and decreasing surface supplies, these achievements in increasing groundwater levels could be reversed.

These threats to water supply are compounded by other factors, such as:

- Reductions in groundwater recharge when flows in the river are diminished
- The advanced age of large portions of both the City and Buckman well fields
- The City's Living River Ordinance, which allocates up to 1,000 AFY to sustaining flow in the Santa Fe River

The overall impact of these factors is uncertainty in the resiliency of the water supply system.

In addition to variations in supply, population growth is expected to increase the demand for water in the region. 2050 projections suggest an 80 percent population increase, resulting in an additional water demand of about 23,000 AFY (see Appendix E, Section 4.2.3). The current combined water rights portfolio for the City and County is about 26,000 AFY. However, when considering current management targets for groundwater use and the City's Living River Ordinance, the available supply decreases significantly to about 18,900 AFY, as discussed in Section 2.3 Present Water Supply Portfolio.

2.2. Characterization of Future Conditions

Future water supply and demand will be affected by climatic conditions and population. This study is built on previous water planning efforts to incorporate predicted climate change impacts into 40-year water availability estimates and water demand projections. The City and County use these projections to identify adaptation strategies that will maintain a continuing supply to customers under the projected conditions and to protect the resource to ensure available supply beyond that time. This study provides water managers and decision makers with a tool to evaluate multiple criteria in evaluating the ability of various adaptation strategies individually and in combination (adaptation portfolios) to best meet and manage the Partner's future demand.

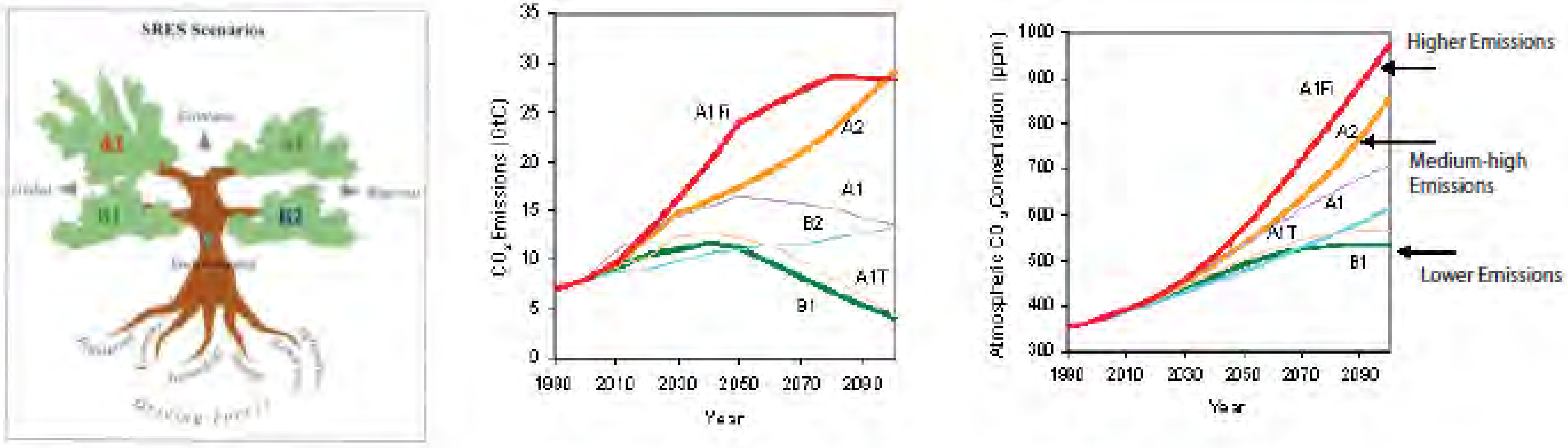
2.2.1. Climate Change Modeling and Analysis

Climate is defined by the statistical characteristics of meteorological conditions including temperature, precipitation, solar radiation, wind, atmospheric pressure and humidity in a given region over a period of decades. In contrast, weather is characterized by the condition of these factors over periods of time extending from days to weeks. Although significant advancements in weather forecasting have occurred, the nonlinear nature of atmospheric processes makes skillful forecasting of even seasonal and annual weather extremely difficult. However, over most of human history, the non-linear dynamics that characterize weather systems have tended to average out with some consistency over a period of a few decades. Therefore, although we could not predict weather conditions at any given time, we had an understanding of long-term average conditions, and could characterize the extremes likely to be encountered.

Because of the past climate stability over many decades, climate has been characterized using the concept of stationarity. Stationarity assumes that the future climate will be the same as the past. Under that assumption, longer-term average weather conditions were used as a basis for water supply and infrastructure planning and engineering design. Paleo-climate based surrogate data from studies of tree rings, pollen, ice cores, ocean and lake sediments, stable and radioisotopes, and other long-term climatic records have been used to capture the natural variability of climate. This information has also been used with stochastic methods to characterize the uncertainties in climatic conditions.

Climate change, however, imposes future trends on both the magnitude and variability of climate parameters such as temperature and precipitation. Therefore, although much insight can be gained from the analysis of retrospective climate data, stationarity no longer characterizes average conditions, and water planning and engineering designs in the future will need to also rely on new methods and information sources.

Projections of future climate changes are currently being made through the use of global climate models referred to as General Circulation Models (GCM), which have been steadily increasing in sophistication and complexity over the past several decades. The World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project Phase 3 (CMIP3) (Meehl et al. 2007) produced multiple 20th - 21st century climate projections for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007). These climate projections are based on an assemblage of GCM simulations of coupled atmospheric and ocean conditions, with a variety of initial conditions of global ocean – atmosphere system and four distinct “storylines” about how future demographics, technology and socioeconomic conditions might affect the emissions of greenhouse gases. The four families of emissions scenarios (A1, A2, B1, and B2) are described in the IPCC Special Report on Emissions Scenarios, which states that “the scenarios are images of the future, or alternative futures. They are neither predictions nor forecasts” (IPCC 2000). Corresponding carbon dioxide (CO_2) emissions and atmospheric concentrations for some of the emissions scenarios are shown in Figure 2-1.



(a) Conceptual representation

(b) Time-evolution of $C0_2$ emissions

(c) Time-evolution of $C0_2$ concentrations

Figure 2-1. Carbon dioxide emissions and atmospheric concentrations for some emission scenarios.

The spatial resolution of the GCM climate projections is typically on the order of one degree of latitude/longitude (about 110 kilometers x 110 kilometers), which is too coarse for use in regional and project-scale planning. Additionally, local climates are likely to differ from the average climatic conditions across an entire degree of latitude or longitude, due to elevation differences and other local conditions within that grid cell. Therefore, projections of local conditions require a method of downscaling GCM projections to regional and local scales. Statistical methods have been widely applied to produce spatially-continuous fields of temperature and precipitation at fine scales (< 10 miles or <16 kilometers) covering the entire United States. These statistical methods are typically coupled with bias corrections of coarse global data to more representative regional and local conditions.

Reclamation and several partner organizations, including: Lawrence Livermore National Laboratory, Santa Clara University, Climate Central, and the Institute for Climate Change and its Societal Impacts have applied the Bias Correction and Spatial Disaggregation (BCSD) technique of Wood et al (2004) to create an archive of 112 downscaled CMIP3 monthly temperature and precipitation projections covering the entire United States on a $^1/_8$ degree (^{o}) grid (12 kilometers) for the period from 1950 to 2099. These projections were produced from results of 16 different CMIP3 GCMs simulating 3 different emissions scenarios (A2 [higher], A1B [middle], and B1 [lower]) along with various assumptions about initial ocean – atmosphere conditions. A more detailed description of BCSD method is contained in Reclamation's Bias-Corrected and Spatially Downscaled Surface Water Projections report (Reclamation 2011 [BCSD]).

The climate-change conditions used for the Santa Fe Basin Study were developed from the CMIP3 project set (Meehl et al. 2007), and Reclamation's Bias-Corrected and Spatially Downscaled Surface Water Projections (Reclamation 2011 [BCSD] and [Act Report]). From these projections, five sets of scenarios were generated, representing the range of variability expected in Basin hydrology in the 1950s, through the Hybrid Delta ensemble method (Reclamation 2010).

Three of these five scenarios were deemed to represent the extremes of predicted temperature and precipitation changes that are expected due to climate change: Warm-Wet, Hot-Dry, and Central Tendency groups. Therefore, these three scenarios were used as input to Santa Fe's municipal supply operations model, WaterMAPS, to generate the projections and alternatives evaluated in this Basin Study. A baseline scenario, referred to as "simulated historic" was used for comparison to climate-change impacted hydrologies. The simulated historic scenario combines current infrastructure and operations with synthetic, spatially distributed historic climate and inflows (Maurer et. al. 2002). See Appendix B for further information on developing the climate change hydrographs for WaterMAPS.

The development of these five projection sets is shown in Figure 2-2 and described as follows:

- **Hot-Wet:** above the 50th percentile for both precipitation and temperature changes
- **Warm-Wet:** above the 50th percentile for precipitation change and below the 50th percentile for temperature change
- **Hot-Dry:** below the 50th percentile for precipitation change and above the 50th percentile for temperature change
- **Warm-Dry:** below the 50th percentile for both precipitation and temperature changes
- **Central Tendency:** An overlapping group was defined as being between the 25th and 75th percentile for both the change in precipitation and change in temperature

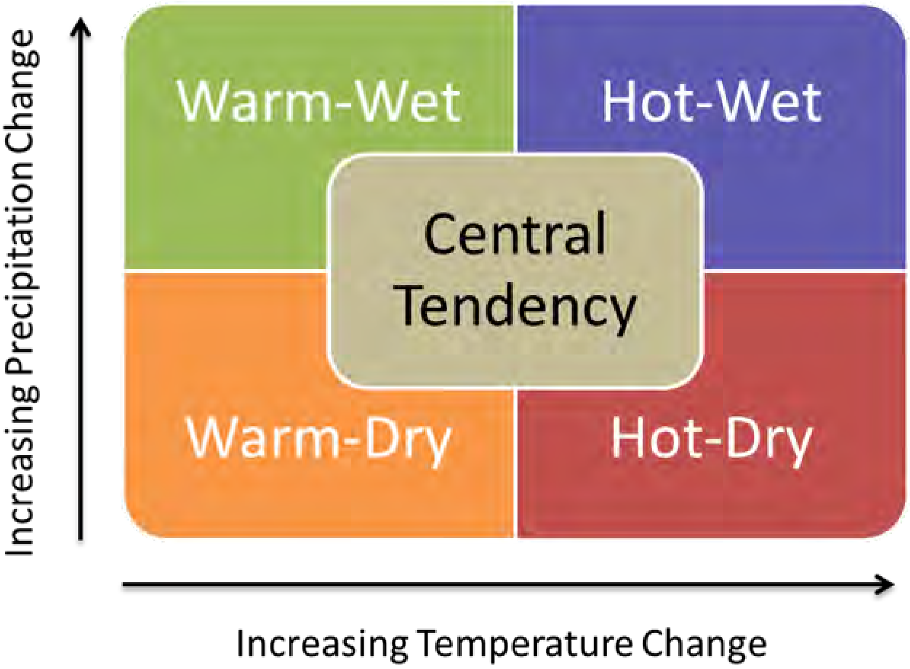


Figure 2-2. Climate change scenarios.

2.2.2. Population Projections

Population projections analyses are described in Appendix E. The City water service, County water service, total water service (i.e., City plus County), and total County population projections for 2020, 2030, 2040, and 2050 are shown in Figure 2-3. The difference between the total County population and the total water service population represents the population that is not served water by either the County or City water systems. The ultimate 2055 populations used for the climate change analysis and for development of the water supply plan are:

- City water service area: 125,019
- County water service area: 44,673

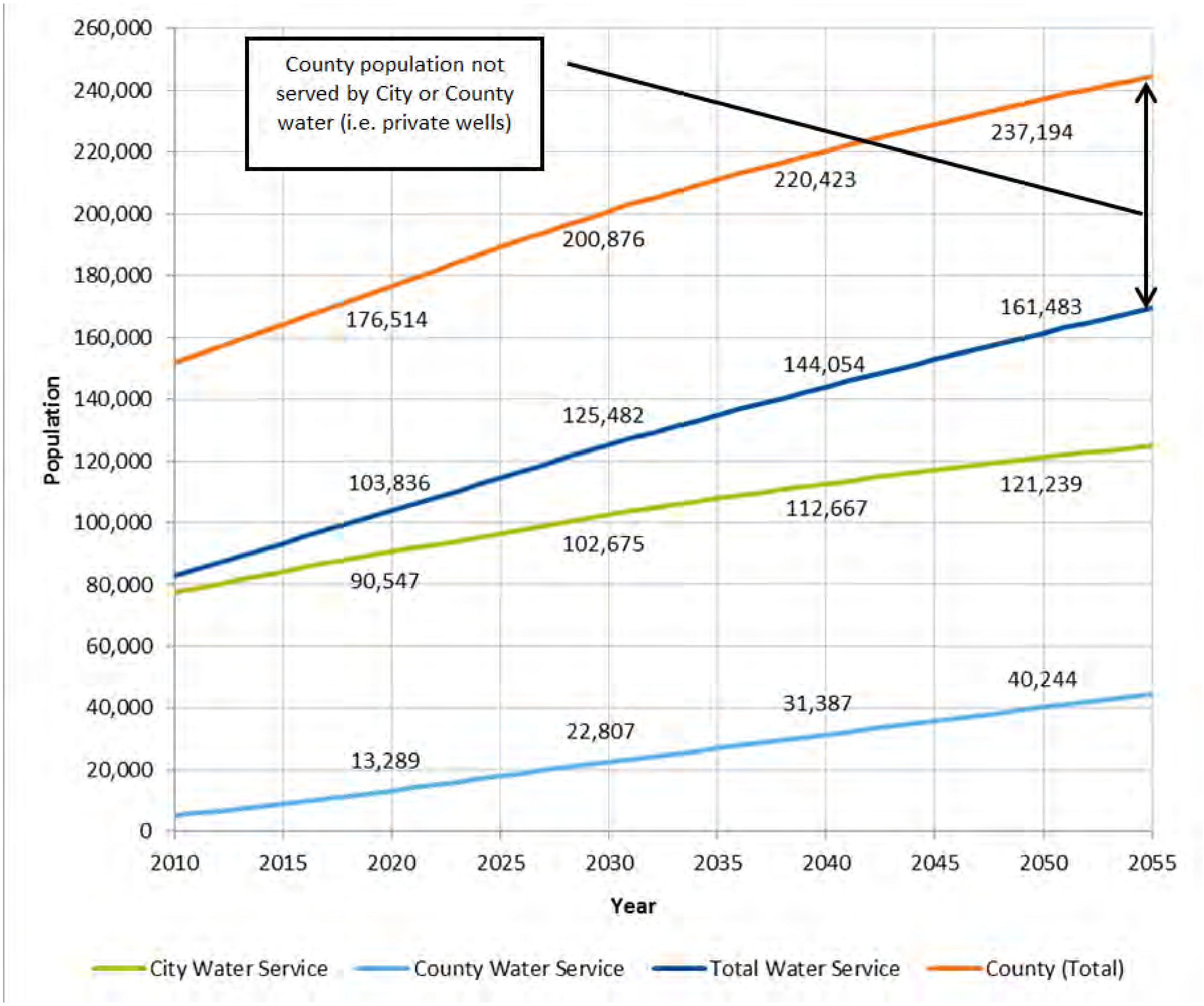


Figure 2-3. Population projections (labeled values are for 2020, 2030, 2040, and 2050).

2.3. Present Water Supply

The water supply currently available to the City and to the County in the study area consists of surface water sources and groundwater sources that are used conjunctively, as shown in Figure 2-4. In an average year and given current management of water supplies, surface water provides about 70 percent of the City and County water supply and groundwater provides the remaining 30 percent. Each of the water supply sources are subject to regulatory limitations (water rights), sustainable management targets (management targets), and water utility constraints (capacity constraints). Water rights and system infrastructure capacity are physical constraints, but the management targets are subjective administrative objectives for water use that are always less than the water rights. For this study, supplies were restricted by the management targets (Table 2-1).

Table 2-1. Management Targets for Santa Fe Area Water Supply

Source	Management Target (AFY)	
	County	City
Buckman Wells	-	3,000
City Wells (including Northwest and Osage Wells)	-	3,500
Canyon Road Water Treatment Plant (including St. Michael's Well)[1]	-	4,040
St. Michael's Well	-	241
County Wells[2]	153	-
Native Rio Grande Rights[3]	1,915	590
San Juan Chama Project Water	375	5,230
TOTAL	**2,290**	**16,601**

[1] Assumed based on subtracting the desired Living River Ordinance target flow of 1,000 AFY from 5,040 AFY (water right). Actual availability based on modeling conducted as part of this project.

[2] Santa Fe basin, in-basin groundwater rights is 153 AFY. Wells do not currently exist for this right, but it is assumed that they will be used in the future and possibly through the City Well Field.

[3] Rights include 590 AFY each for County and City that are expected to be obtained in the near future.

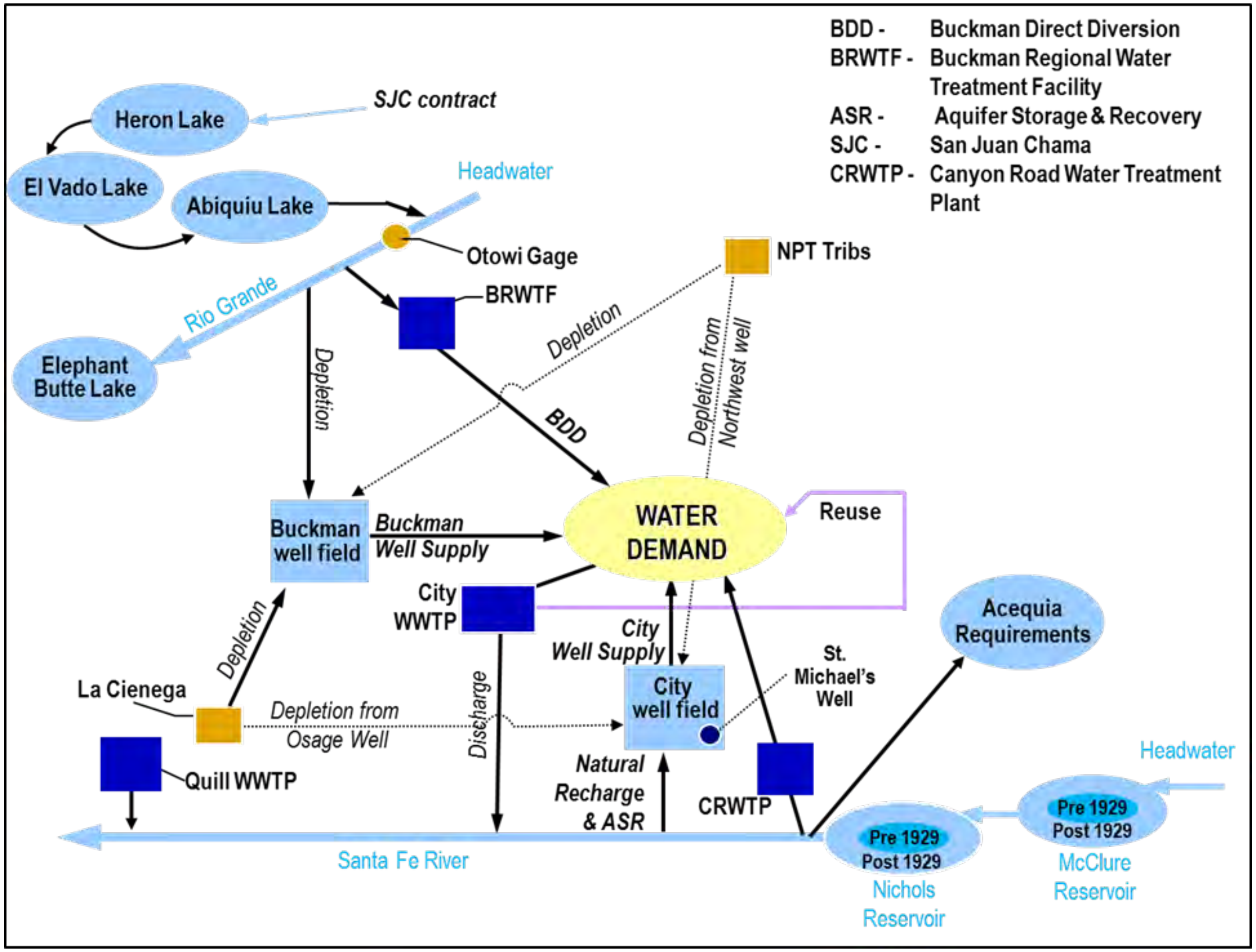


Figure 2-4. Santa Fe water supply system.

2.3.1. Native Groundwater

In New Mexico, the right to use surface water and groundwater are linked. The basis of that linkage is the understanding that pumping groundwater will eventually deplete the surface water where there is a surface-groundwater connection. Therefore ,some groundwater pumping must offset the impact to surface water either by returning water to the river (return flow) or acquiring groundwater rights that will not be pumped (offsets) to “pay back” the river.

The groundwater supply comes from the aquifers within the Santa Fe Group, which underlies the study area.

2.3.1.1. Buckman Well Field (near the Rio Grande)

This supply includes 13 wells outside of the City limits and near the Rio Grande and along the Buckman Well Field water transmission lines. These Buckman wells are permitted to produce up to 10,000 AFY, but they have strict offset requirements from state regulators, high transmission costs, and some arsenic and uranium exceedence issues, which limits their use. Historically, pumping of the Buckman Well Field has been as high as 5,900 AFY. Since the Buckman Direct Diversion has come online, pumping has reduced significantly.

Use of the Buckman Well Field results in depletions from the Rio Grande and tributaries to the Rio Grande: Rio Pojoaque, Rio Tesuque and La Cienega (labeled as “NPT Tribs” in Figure 2-4). On the Rio Grande, these river depletions are repaid with Rio Grande surface water rights acquired by the City and dedicated to Buckman Well depletion offsets, native Rio Grande water rights permitted for both diversion and offset (e.g. “dual use”), or San Juan-Chama Project water, if necessary. Depletions to the Rio Tesuque and Rio Pojoaque are replenished with retired tributary surface water rights. Depletions in the La Cienega area are predominantly repaid by flows from the City’s wastewater treatment plant. Offsets for depletions are also required for the Northwest and Osage wells, but the depletions are minimal in comparison.

2.3.1.2. City Well Field (along the Santa Fe River):

This is a series of 11 wells, 8 of which are currently producing water, located within City limits and generally along the Santa Fe River to which the City has the right to produce roughly 4,865 AFY. These wells include the Osage, Northwest, St. Michael’s wells, and “Other City wells”—all located within the City limits. The Osage, Northwest, and St. Michael’s wells are modeled individually, whereas the “Other City wells” (Agua Fria, Torreon, Alto, Ferguson, Santa Fe, and Hickox) are combined as a single supply source (due to permitting requirements).

2.3.1.3. County Wells

The County owns a series of small wells in the area surrounding Santa Fe city limits that are currently equipped for utility production.

2.3.2. Native Surface Water

2.3.2.1. Santa Fe River Watershed

The Santa Fe River originates in the Sangre de Cristo Mountains above downtown Santa Fe (Figure 2-5). The upper watershed is located on U.S. Forest Service land and is protected from public access and development. The water from this watershed is stored in two reservoirs - McClure and Nichols, both owned and operated by the City, in the mountains above downtown Santa Fe, and treated at the Canyon Road Water Treatment Plant.

The City of Santa Fe owns 5,040 acre-feet of Santa Fe River water rights. The water from this watershed is stored in McClure and Nichols. Both reservoirs are owned and operated by the City and together hold roughly 4,000 acre-feet of water. The water from the reservoirs treated at the Canyon Road Water Treatment plant and is distributed to customers through the City distribution system. The Santa Fe River watershed has provided up to 40 percent of the City and County water supply in recent years up to 2011. Water from this source is also used to meet Acequia requirements.

2.3.2.2. Native Rio Grande

The County owns 1,325 AFY and plans to acquire an additional 590 AFY of native Rio Grande surface-water rights. These water rights have been purchased and transferred from the middle Rio Grande Basin (below Cochiti Reservoir) to the Buckman area.

2.3.2.3. Future Rio Grande (Pojoaque Basin Regional Water System)

By 2024, some portions of the County near the northern edge of Santa Fe's City Limits may be served by the Pojoaque Basin regional water system, which will divert water from the Rio Grande, in a manner similar to the Buckman Direct Diversion. This water system will be built to comply with the Aamodt Settlement Agreement to provide water for four Pueblos and northern Sante Fe County residents.

Figure 2-5. Map of the San Juan-Chama Project.

2.3.3. Imported Water: Reclamation's San Juan-Chama Project

2.3.3.1. Project Description

Reclamation's San Juan-Chama Project consists of facilities that divert water from the San Juan Basin (Colorado River Basin) in southern Colorado and feeds that water by gravity through 26 miles of tunnels beneath the Continental Divide to the Rio Chama in the Rio Grande Basin in New Mexico (Figure 2-5). The San Juan-Chama Project was authorized by Congress in 1962 and has a firm yield of 96,200 AFY, based on a hydrologic analysis originally performed by Reclamation and updated in 1989. The City and County have a contract with Reclamation for 5,605 AFY of San Juan-Chama Project water.

The Buckman Direct Diversion facility is used to divert San Juan-Chama Project water and native Rio Grande water from the Rio Grande River roughly 10 miles west of the City limits. The City and County partnered to design and construct this project in 2011. It diverts water and pumps it about 11 miles to the Buckman Regional Water Treatment Facility. Treated water is delivered to City and County customers.

Reclamation's San Juan-Chama Project brings a portion of New Mexico's allocation under the Colorado River Compact into the Rio Grande system. The system, shown in Figure 2-6, diverts water from tributaries to the San Juan River, through the Azotea Tunnel and stores that water in Heron Reservoir, from where it is distributed. The San Juan-Chama Project supply depends on flows in three tributaries to the San Juan River: the Rio Blanco, the Little Navajo River, and the Navajo River. The project allocates its current firm yield of 96,200 AFY. The City of Santa Fe contracts for 5,200 AFY of this water.

2.3.3.2. San Juan-Chama Project Supply Projections

As an independent analysis from the Water MAPS (described in Section 2.4, Approach to Overall Water Supply Analysis), Reclamation, with support from Sandia National Laboratories, performed a monthly-timestep analysis of the projected future reliability of Reclamation's San Juan-Chama Project over the course of the 21st century. The methods used for this analysis are described in Llewellyn et. al. (2013). The following summarizes the projected changes to the water supply and operation of the Project.

- **Flows would decrease by one-quarter overall.** The ensemble average trans-basin diversion decreases steadily from around 90,000 acre-feet per year during the historic simulation period (1950 through 1999) to between 70,000 and 80,000 acre-feet per year during the 2050 through 2099 period.

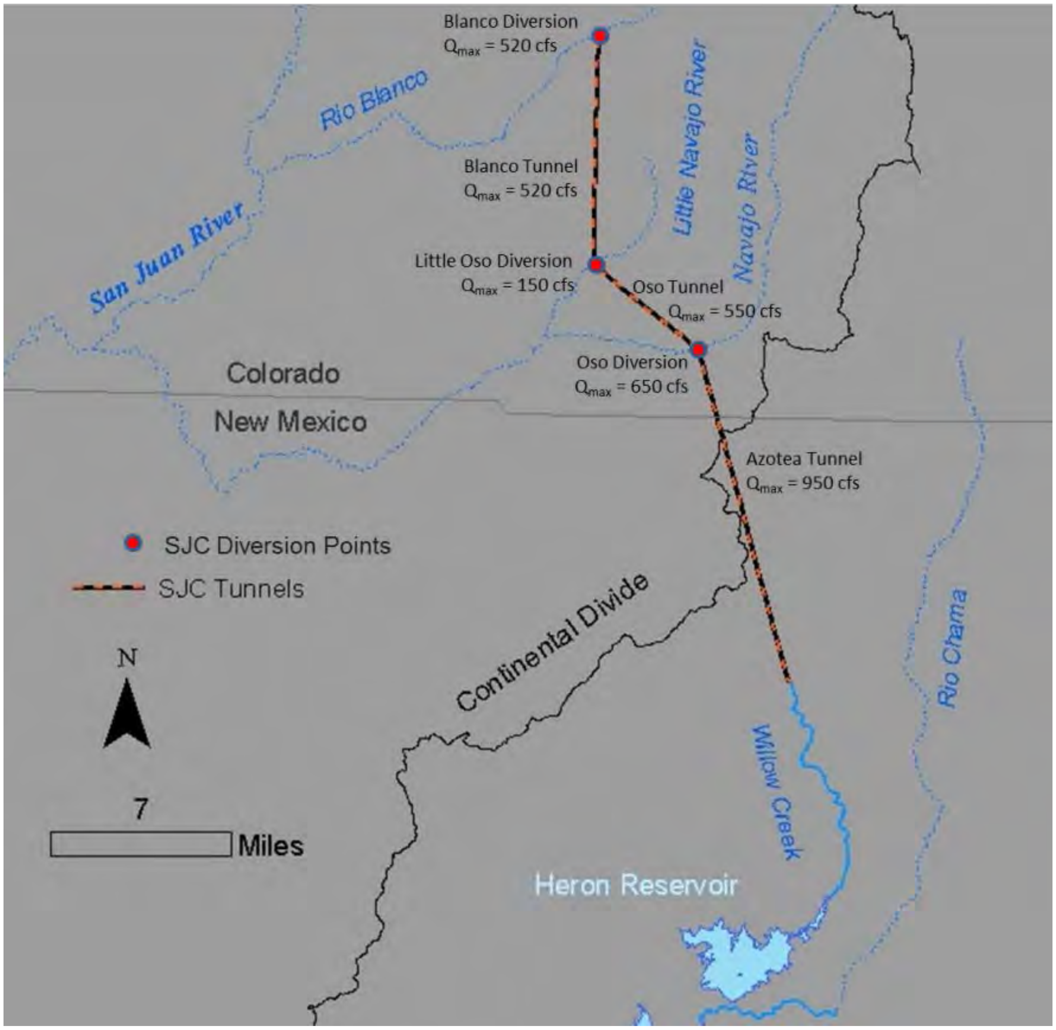


Figure 2-6. Location and capacities in cfs of San Juan-Chama Project diversions and tunnels.

- **Flows would decrease in summer and increase in spring.** Overall, Project flows are projected to decrease, with a larger portion of the flows occurring earlier in the year. The overall reduction in tunnel flows would come from large decreases in divertible flows from May through October, even while divertible flows increase in March and April.

- **Storage in Heron Reservoir would be reduced.** A projected reduction in storage in Heron Reservoir in Northwestern New Mexico, the storage reservoir for the San Juan-Chama Project could be caused by a combination of the decreases in supply noted above and increases in use of San Juan-Chama allocations by contractors as temperature-driven demands in the Rio Grande basin (especially agricultural demands) rise as the simulations progress.

- **Sufficient water for a full allocation to contractors will be available less frequently.** San Juan-Chama contractors are projected to receive a full allocation in 99 percent of simulated years from 1950 through 1999, 94 percent during the 2020s, 72 percent during the 2050s, and only 61 percent in the 2090s.

The analyses on the availability of flows to the San Juan-Chama Project diversion tunnels were performed on a monthly basis. Therefore, these analyses do not capture potential changes to the volume or duration of snowmelt runoff at less than a monthly scale. Since snowmelt runoff is projected to occur earlier, and at potentially higher flow rates for a shorter period of time, the impacts on the San Juan-Chama Project's ability to divert could be larger than shown in this analysis. However, infrastructure changes might be made to allow for a greater capture of short, high-discharge runoffs, so that these changes in runoff flows and timing do not significantly affect the San Juan-Chama Project's ability to divert sufficient water.

Also, it is important to note that, even if sufficient water is available in tributaries to the San Juan River for diversions to the San Juan-Chama Project, shortages within the Colorado River Basin could lead to priority calls or shortage-sharing agreements that would result in decreased supply to New Mexico under the Colorado River Compact. Such shortages could result in decreases in Reclamation's authorization to divert water to the San Juan-Chama Project, even if sufficient water is available locally. Results from this analysis are presented in more detail in Appendix D.

2.3.4. Water Use Constraints

The use of these surface-water and groundwater sources is subject to a number of constraints.

- The Rio Grande Compact between New Mexico and Texas limits the amount of water that can be stored in New Mexico reservoirs. Article VI determines if New Mexico is in debit or credit status with regards to water storage, and restricts water storage amounts when in debit status. Article VII restricts storage if storage in Elephant Butte reservoir (the reservoir from which water is released to Texas) is below 400,000 AF.

- In New Mexico, surface water and groundwater are used conjunctively, under a legal structure that recognizes that the pumping of groundwater will eventually deplete the surface water. Therefore post-1956 groundwater pumping impacts to surface water must be offset, either through returning water to the river (return flow) or through dedicating a portion of groundwater rights that will not be pumped to "pay back" the river. This mostly applies to the Buckman Well Field, as the connection of that well field to surface water is more pronounced.

- Diversions at the Buckman Direct Diversion are constrained by the Record of Decision for the Buckman Direct Diversion Environmental Impact Statement (U.S. Forest Service and Bureau of Land Management 2007.). Under this Record of Decision, diversions can be curtailed by low flows or poor water quality in the Rio Grande. Large portions of both the City and Buckman Wells Fields are of advanced age, which can limit their ability to provide water.

The City has made a commitment to a "Living River," which sustains flows in the Santa Fe River as it passes through the city. Although these flows provide some groundwater recharge, they also constrain other uses.

2.4. Approach to Overall Water Supply Analysis

Analysis of water supply in the Santa Fe Basin uses the City's WaterMAPS model. The Water MAPS models all of the water sources listed in Section 2.3. Present Water Supply.

WaterMAPS was originally developed for the City as part of the long-range planning process in 2008, and was updated for this Basin Study to include the County and to simulate changes in water availability due climate variability. WaterMAPS is a multi-criteria dynamic systems simulation model that was built on the STELLA programming environment. STELLA (Systems Thinking Experimental Learning Laboratory with Animation), developed by Isee Systems, Inc. is a systems modeling industry standard. The results produced from WaterMAPS are used to evaluate how well the City and County will be able to meet future water supply objectives under the four climate change scenarios.

Other models were used to develop data used as input to the WaterMAPS model. Those models are discussed in this section. The data that was produced are discussed in Section 2.5). Water Availability, where the impacts of climate change are discussed. Other data used directly in WaterMAPS related to this Basin Study are also discussed in this section, while details of all updates made to the model are presented in Appendix E. Additional information regarding WaterMAPS can be found in the City of Santa Fe Long-Range Water Supply Plan (2008).

Note that all Santa Fe Basin water sources, both groundwater and surface water, are conjunctively managed and, for this reason, are evaluated together in the WaterMAPS model. Data and separate models used for groundwater and surface water are presented separately in the next sub-sections.

2.4.1. Data and Models Used—Groundwater

The WaterMAPS simulation used pumping and groundwater level data for the Buckman Well Field (Section 2.3.1.1) and the City Well Field (Section 2.3.1.2).

The impacts of groundwater pumping on aquifer drawdown, reservoir storage, offsets, and stream depletions over time are projected using forty-year hydrology sequences that were selected from the historical hydrology data.

An important element of the Santa Fe system is the groundwater-surface water interaction and the surface water depletions caused by pumping of some wells. To estimate the effects of pumping in groundwater and surface water, an additional model, the Stream Unit Response Function Solver (SURFS) was used. SURFS works in tandem with WaterMAPS but can also be used as a stand-alone tool to solve simple groundwater pumping scenarios for depletions and drawdown.

2.4.2. Data and Models Used—Surface Water

The climate change modeling described in Section 2.2.1 Climate Change Modeling and Analysis provides temperature and precipitation estimates. To translate temperature and precipitation into stream flow, a land surface model known as the Variable Infiltration Capacity (VIC) model was used. The VIC model generates runoff hydrographs that can then be routed through a known river network. As discussed in Appendix B, it was necessary to correct biases in the VIC model for use in the Upper Rio Grande Basin modeling.

Hydrologic inflows at 21 locations were generated by the bias-corrected VIC model output for use in the Upper Rio Grande Simulation Model (URGSiM) (Llewellyn, et. al. 2013). URGSiM is a monthly timestep mass balance model that uses hydrologic and climatic inputs to simulate the movement of surface water and groundwater through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico, including the Rio Chama and Jemez River tributary systems, and the Española, Albuquerque, and Socorro regional groundwater basins (see Appendix B). URGSIM also simulates reservoir operations, interbasin transfers, and agricultural diversions and depletions.

The climate-change-projected stream flow hydrographs from the URGSiM model are used in WaterMAPS. These hydrographs and other UGSiM output related to projected climate change are discussed in Section 2.4.3.

Other data used to update WaterMAPS for this Basin Study that is not directly related to future climate change impacts include the following:

- Water rights, management targets, and capacity constraints
- Water use priorities
- Santa Fe’s Living River Ordinance (or Santa Fe River Target Flow)

Water rights, management targets, and capacity constraints were updated according to the information presented previously in Table 2-2. This was updated to include County supplies as well as any changes to the City’s quantities. It is important to note that these values may change annually; the City and County are continually acquiring water rights or adjusting management targets to meet the needs of the water service area. These values must be verified at any time when performing any future analysis of water supply for this basin.

The order in which water supplies were used in the WaterMAPS model changed since it was first developed. When the Buckman Direct Diversion was completed in 2011, San Juan-Chama project water became the first priority of water used.

Water released from the McClure and Nichols reservoirs flows down the Santa Fe River. Flow that is not diverted and treated at the Canyon Road Water Treatment Plant continues down the Santa Fe River, through the City. An ordinance and associated administrative procedure (City of Santa Fe, New Mexico, Ordinance No. 2012-10 and City of Santa Fe, Administrative Procedures for Santa Fe River Target Flows and City of Santa Fe) was adopted in February of 2012 to provide 1,000 acre-feet per year (AFY) to the Santa Fe River. The purpose of the Santa Fe River Target Flow is to increase water flow in the river below the City's reservoirs in order to maintain a "living river," except under emergency conditions. The administrative procedure outlines specific hydrographs for daily releases throughout the year based on the expected annual yield (Figure 2-7). For normal and wet years, the annual target is 1,000 AFY. This target decreases in dry and critical years according to the percent of normal annual yield expected.

The hydrographs representing releases required to meet the desired target flow are shown in Figure 2-8. Each hydrograph is based on the percent of normal expected annual yield (e.g., "Dry – 70%" means the expected annual yield is 70 percent less than normal). If the expected annual yield is 30 percent or less of normal, the "Critical-Dry" hydrograph is used. This means that even under drought conditions, the City plans to release at least 300 AFY to support in-stream flows in the Santa Fe River.

2.5. Water Availability

2.5.1. Present Availability

The present availability of water was not directly modeled for this Basin Study. Previous reports, current water usage, and current management targets were used to understand the state of present supplies. Surface water and groundwater supplies were discussed in Section 2.3 Present Water Supply. The total present supply for the City and County is about 18,900 AFY. Although more water is currently available from groundwater sources, previous analysis and historical data have shown that use of these supplies above the management targets threatens to deplete the supply.

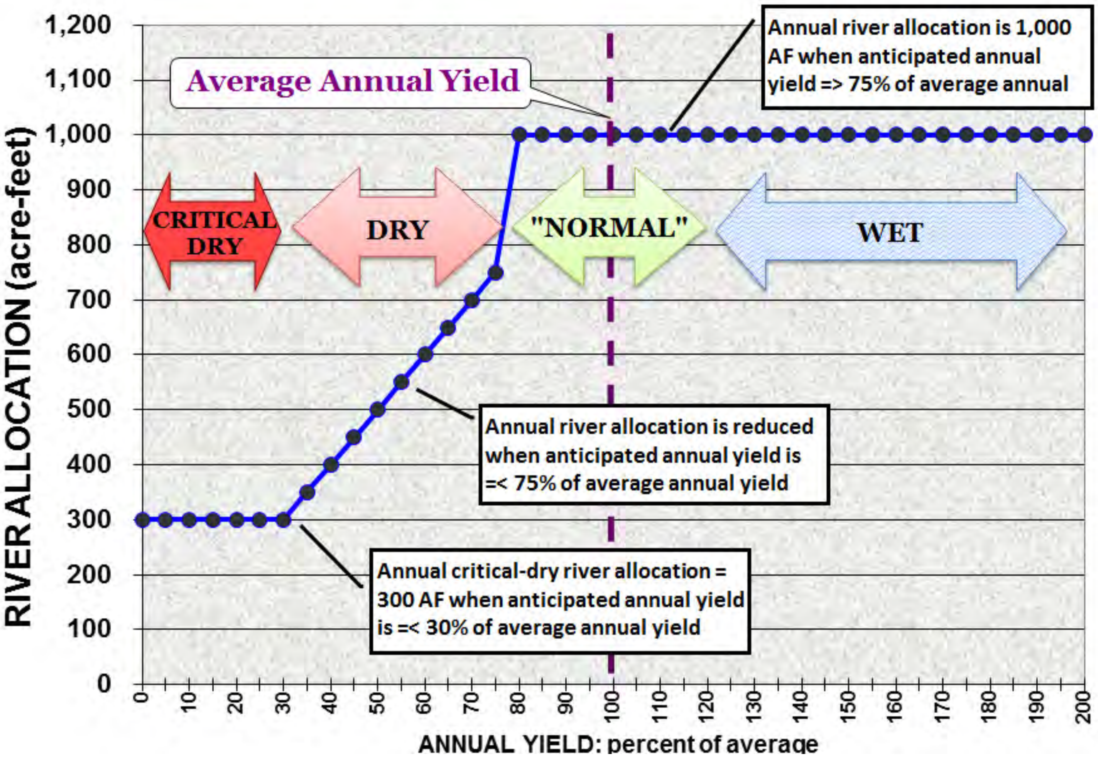


Figure 2-7. Santa Fe River target flow allocation as a function of annual yield (Adapted from City of Santa Fe 2012).

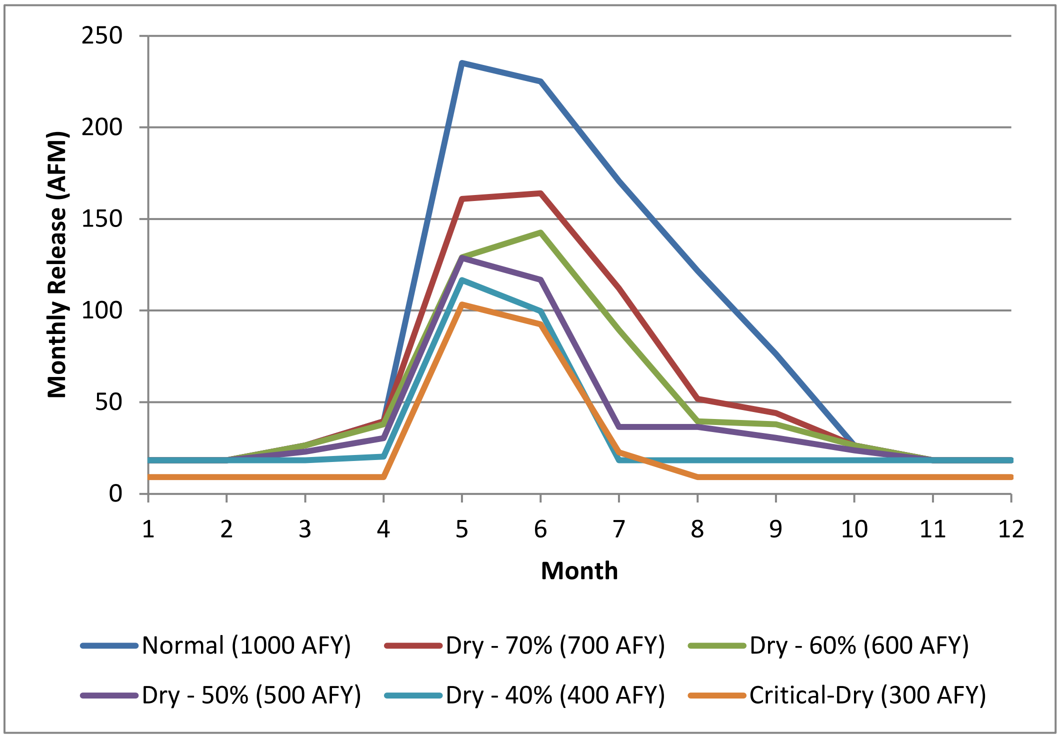


Figure 2-8. Hydrographs used to model Santa Fe River target flows.

2.5.2. Future Availability—Projected Changes in Water Supply for the City and County

The updated WaterMAPS model was used to simulate the availability of City and County water supplies given climate change impacts. The four climate change scenarios were discussed in Section 2.2.1 Climate Change Modeling and Analysis:

- Simulated Historic (baseline without climate change; based on historic flow conditions projected through the planning period)
- Warm-Wet
- Central Tendency
- Hot-Dry

The future availability of water predicted by WaterMAPS under the modeled climate scenarios is shown in Figure 2-9. The climate-impacted inputs to WaterMAPS that relate to the projected supply are discussed in the following sections.

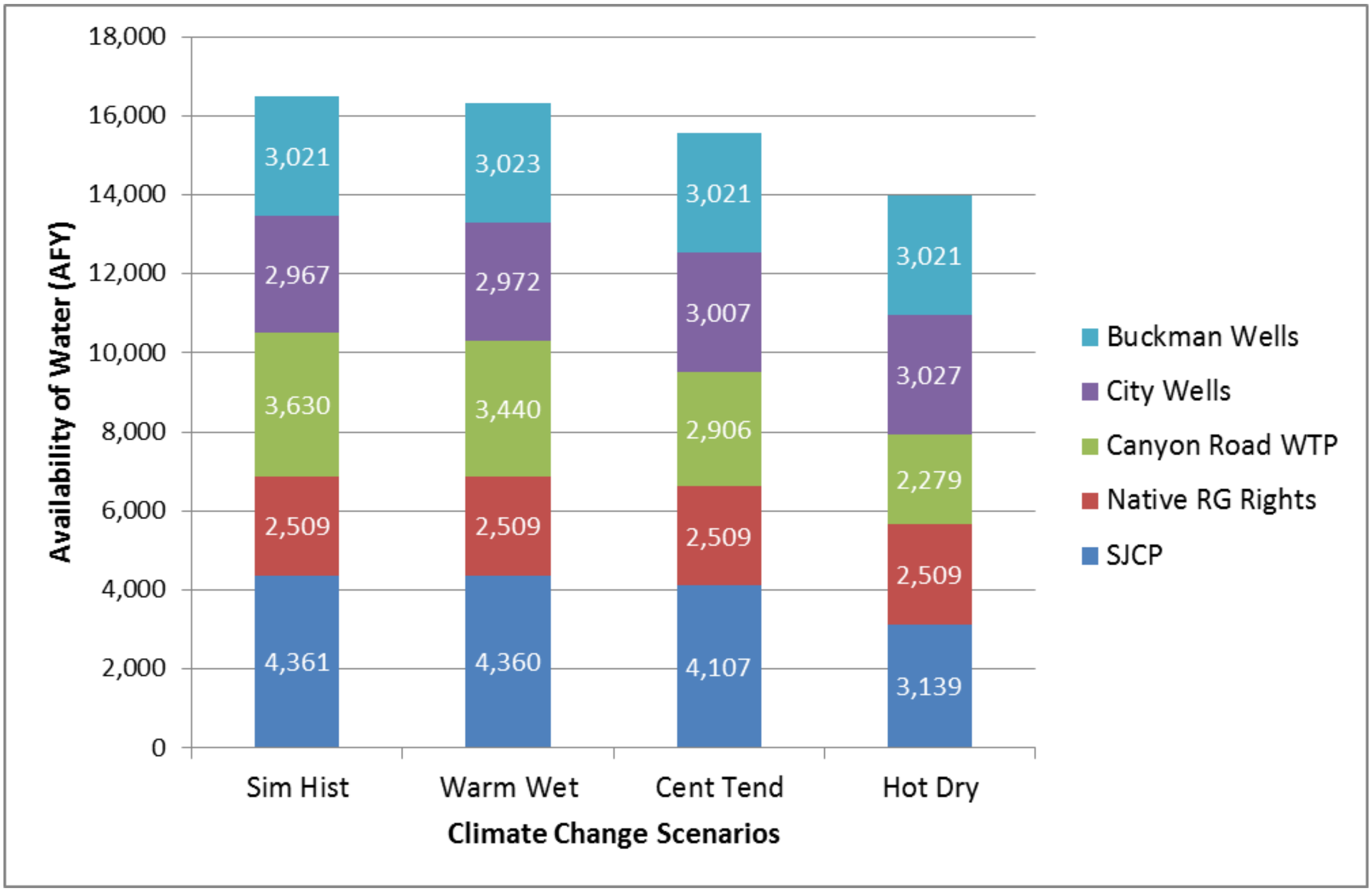


Figure 2-9. Future availability of water predicted by WaterMAPS.

2.5.2.1.1. Changes in Snowpack

The impact of changes in snowpack due to predicted changes in the magnitude and timing of temperature was translated into the hydrographs of stream flow that were developed for this Basin Study, which focused on water supply availability. This was accomplished using the VIC model.

2.5.2.1.2. Changes in Timing and Quantity of Runoff

The URGSiM model was used to develop stream flow hydrographs for input to WaterMAPS. These hydrographs reflect the predicted changes in timing and quantity of runoff based on projected climate-change impacts. Hydrographs included flow into the Santa Fe Basin above McClure Reservoir (Santa Fe River flow) and flow in the Rio Grande at Otowi Bridge. The resulting hydrographs developed for each climate change scenario are in Appendix B.

An interesting way to view the hydrographs for the Santa Fe River flow is as a percentage of the historic normal flow. The average annual yield of stream flow in the Santa Fe River according to gage data from 1914 to 2007 is 4,909 AFY. This value represents “normal” conditions. The average annual yield for each year simulated and each climate change scenario was developed from the projected stream flow hydrographs and are presented as a percentage of this normal condition (4,909 AFY) in Figure 2-10. The frequency of flow above or below normal over the entire time series for each climate change scenario is shown in Figure 2-11, which illustrates the significant increase in the predicted frequency of below normal flows for the hot-dry climate change scenario.

2.5.2.1.3. Changes in Evaporation and Precipitation

Evaporation rates for Santa Fe Reservoirs were developed for the climate change scenarios for simulation in WaterMAPS. Appendix C discusses the development of the temperature and precipitation data used to calculate reference evapotranspiration. Additional detail on the evapotranspiration calculations is presented in a report on the Upper Rio Grande Simulation Model (URGSiM) is also in Appendix C.

Evaporative losses from Abiquiu Reservoir are applied to any San Juan-Chama Project water stored there. Evaporative losses as simulated by URGSiM are based on the entire reservoir volume to which a percent loss was applied specifically to the San Juan-Chama Project water for the City and County. Because WaterMAPS uses a percent loss to simulate evaporative losses out of Abiquiu Reservoir, percent losses were developed for each of the climate change scenarios as part of the Basin Study. The annual average percent loss due to evaporation out of Abiquiu Reservoir for each of the climate change scenarios is shown in Figure 2-12. As expected, the Hot-Dry scenario results in the greatest percent loss to evaporation.

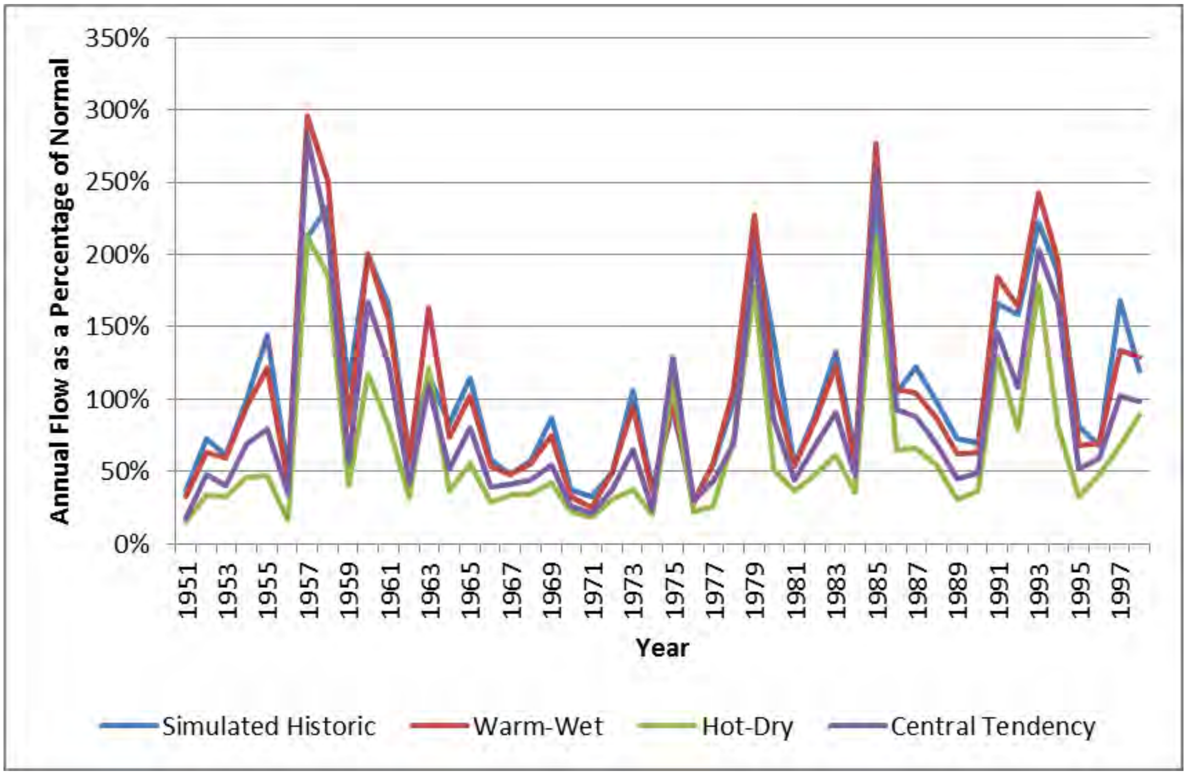


Figure 2-10. Santa Fe River projected average annual yield as a percent of normal (4,909 AFY) by climate change scenario.

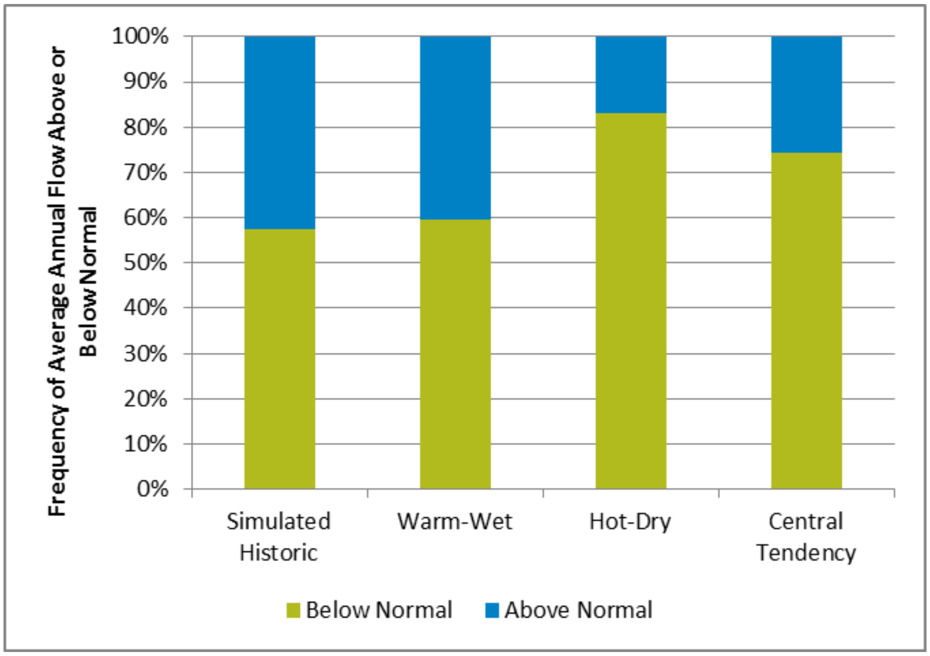


Figure 2-11. Frequency of years below and above normal (4,909 AFY) Santa Fe River flow conditions, for each climate change scenario.

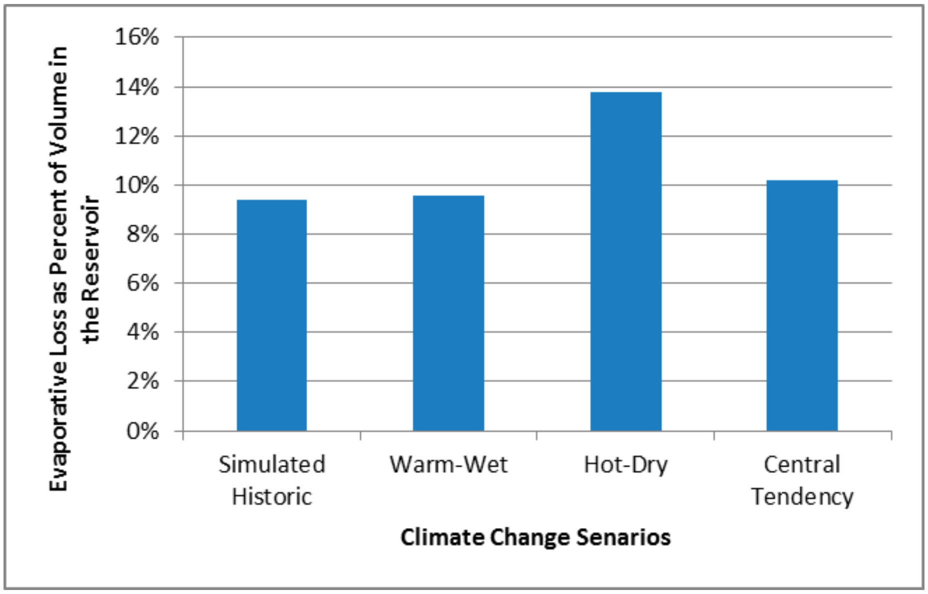


Figure 2-12. San Juan-Chama Project water loss by evaporation in the Abiquiu Reservoir under different climate change scenarios.

2.5.2.1.4. Changes in groundwater recharge and discharge

In the WaterMAPS modeling performed for this study, surface water supplies were modified to account for climate change while groundwater supplies were not. Groundwater supplies are constrained by management targets (rather than water rights, which are greater than management targets) determined by the City and County (Table 2-1). While climate change conditions do affect groundwater recharge and discharge in reality, these changes have not been as well characterized and are smaller than the surface-water impacts. For these reasons, groundwater storage changes due to climate change were not modeled in the study. The management targets are used to represent possible depletions in the availability of groundwater in the future.

2.5.2.1.5. Other Impacts

Other projected climate-change impacts that affect the availability of supply include:

- San Juan-Chama Project water percent allocation
- Rio Grande Compact Article VI status
- Rio Grande Compact Article VII status

Until 2014, Reclamation had consistently been able to provide a full supply of San Juan-Chama Project water to its contractors in New Mexico. In 2014, less than a full supply was allocated, and projections (in Appendix D) indicate that the frequency of full supply for this project will decrease over the course of the century. Using URGSiM percent allocation of San Juan-Chama Project water was simulated for each climate change scenario. Appendix B shows the reduced percent allocation predicted under the Hot-Dry and Central Tendency climate change scenarios.

URGSiM also predicted Article VI and VII status of the Rio Grande Compact, which determines whether storage in McClure and Nichols Reservoirs is authorized at any given time. These inputs were needed to simulate the water pool accounting logic in WaterMAPS, which determines where and when water can be stored. Appendix B shows when Article VII is in effect (i.e., Elephant Butte Reservoir storage is below 400,000 AF), and under Article VI (New Mexico’s Rio Grande Compact Balance). When the Compact balance is greater than 0, New Mexico is in “credit” status, and when the balance is less than 0, New Mexico is in “debit” status.

2.6. Water Demands

Groundwater and surface water are an integrated supply and the demand is also integrated demand. Surface water is used first in the Santa Fe water system because it is considered a more sustainable resource. Note that the WaterMAPS modeling analysis includes only the municipal supply for the City and County. While there are non-utility demands for groundwater and surface water for agriculture in the Santa Fe Basin study area, especially along the lower Santa Fe River, these water demands are not included in the WaterMAPS modeling. However, their demands are described qualitatively in this section.

Water demands for this Basin Study are based on the population projections described in Appendix E and current per-capita demand values. This Basin Study is the first to combine the population projections both the City and the County. The combined population leads to much greater demand without a commensurate increase in supply, so the gap between supply and demand reported in this study is not similar to previous City or County documents.

More recent information could be considered in future analyses. In October 2014 the County completed a population projection study under a contract with the University of New Mexico’s Bureau of Business and Economic Research and Geospatial and Population Studies: Population Estimates and Forecasts for Growth Management Areas, Sustainable Development Area, and the Water/Wastewater Service Area of Santa Fe County. Future efforts could use these projections and compare them with the data used in this Basin Study to update the region’s projected water demand.

2.6.1. Description of Groundwater and Surface Water Demand

The City strives to manage its water supply in a sustainable manner and, for that reason, prioritizes the use of surface water. Because the supplies are integrated there are not separate demands for groundwater and surface water. Modeled demand on both supply types are described in the following sections.

2.6.2. Approach to Water Demand Analysis

The components of demand that are used in the WaterMAPS model include population projections, annual unit demands, and seasonal variability factors. As noted above, the WaterMAPS model was revised to add County demands.

2.6.2.1. Population

Population projections were discussed under the characterization of future conditions (Section 2.2.2 Population Projections). The ultimate 2055 populations used for developing water demand are 125,019 and 44,673 persons for the City and County water service areas, respectively.

2.6.2.2. Use

For the demand projections, the unit demand representing the annual average is assumed to be fixed at 114 gpcd. As population increases, total water demand increases, but the unit demand remains the same. This average annual unit demand represents the baseline demand that is used to identify the potential water supply gap. Seasonal variability of demand and impacts on that variability due to climate change are also predicted as part of this study and included in the analysis as discussed in Section 2.5.2. Future Availability—Projected Changes in Water Supply for the City and County.

Other water demands include irrigation for local agriculture along the Acequia Madre, Acequia Cerro Gordo, and Las Campanas (an independent water system). The Acequia Madre and Acequia Cerro Gordo water demand is assumed to remain constant at the court-ordered right of 70 and 25.4 AFY, respectively. Las Campanas is a wholesale customer of the County, and so the demand is assumed to be included as part of the calculated County water demand.

2.6.2.3. Reclaimed Water

Demand on reclaimed water is incorporated in this Basin Study analysis in accordance with the values delineated in the City of Santa Fe Reclaimed Wastewater Resource Plan, which outlines specific allocations for reclaimed water use (City of Santa Fe 2013). The total annual reclaimed water demand modeled in WaterMAPS is 3,489 AFY. Although the demand for reclaimed water varies monthly, for this Basin Study, it was not necessary to vary the demand for reclaimed water based on the climate change scenarios. The currently allocated amounts were assumed to be used in all scenarios.

The RWRP discusses the anticipated supply of reclaimed water that will be available. WaterMAPS calculates this dynamically, and the supply will adjust according to the demand scenario simulated. The supply available is based on indoor water use, which does not change significantly in any given month, nor is it expected to change significantly with climate change. Therefore, the supply is based on the demand multiplied by a return factor. The return factor is the expected return of water to the wastewater treatment plant given the amount of water produced. The return factor reported in the RWRP and used in WaterMAPS is 62 percent (i.e., 62 percent of water produced returns to the wastewater treatment plant; 38 percent is consumed). See Section 3.1.4.1 Direct Reclaimed Water Reuse for how water discharged from the wastewater treatment plant that is not used by one of the contracts is considered as an additional supply.

2.6.2.4. Data and Models Used

The demands based on population projections were used in WaterMAPS to estimate the adequacy of the water sources in meeting water utility demands.

2.6.2.5. Present Uses and Demands

Both groundwater and surface water in the Santa Fe Basin study area are used primarily for municipal distribution, and the demands are based on population projections. The amount of water used to meet demands is tied to the management targets, regulatory limitations, and capacity constraints.

2.6.3. Effects of Climate Variability and Change on Demand

The effect of climate variability on demands is included in the WaterMAPS model. It provides a means of varying future water demand estimates for the City and County of Santa Fe given future weather conditions projected under the climate change scenarios.

2.6.3.1. Calculating Variations in Water Use (gcpd)

Monthly water production, monthly average maximum daily temperature, and monthly total precipitation were obtained for January 2002 through December 2010 for the City of Santa Fe. The variation in monthly gpcd is strongly correlated with the average of maximum daily temperatures in the month (max. temp.) as shown in Figure 2-13. The relationship between monthly gpcd and monthly precipitation is not as clearly defined as shown in Figure 2-13. Also notable in Figure 2-13 and Figure 2-14 is that the gpcd data for the year 2004 are abnormal. This may be due to reporting or data formatting errors. Therefore, observations for the year 2004 were not used in this analysis.

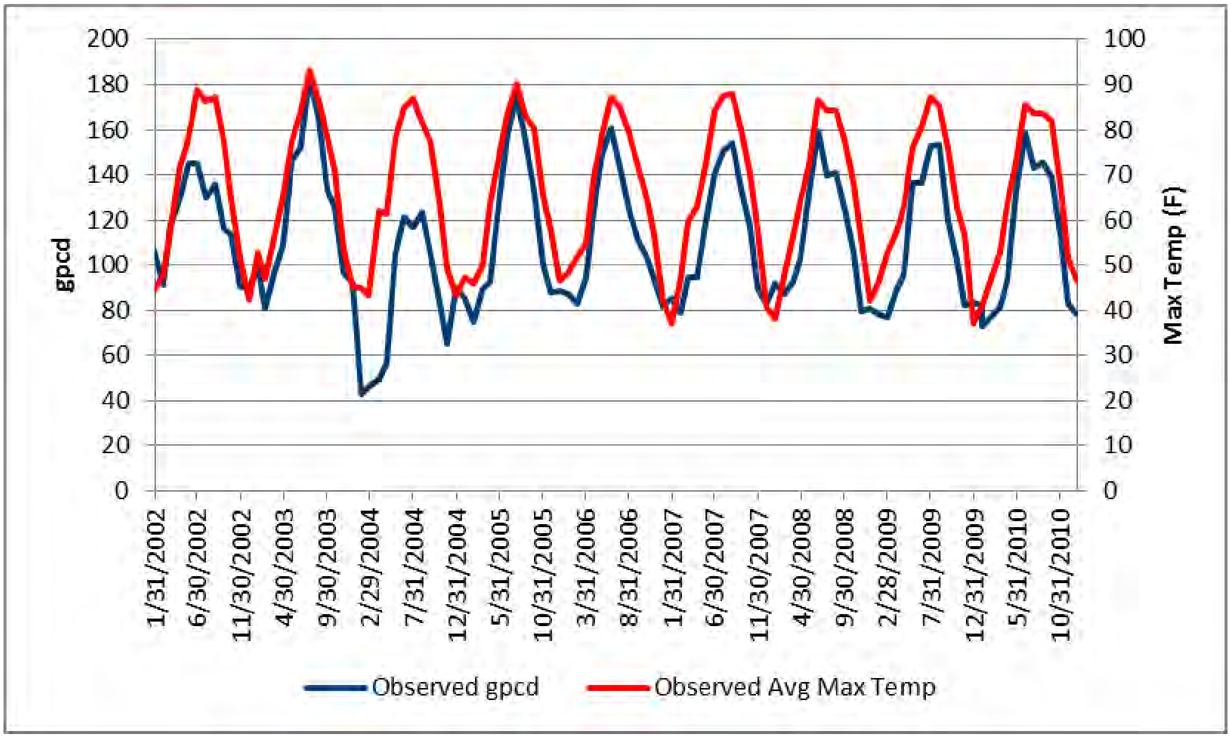


Figure 2-13. Monthly observed gpcd and average maximum daily temperatures for the City of Santa Fe.

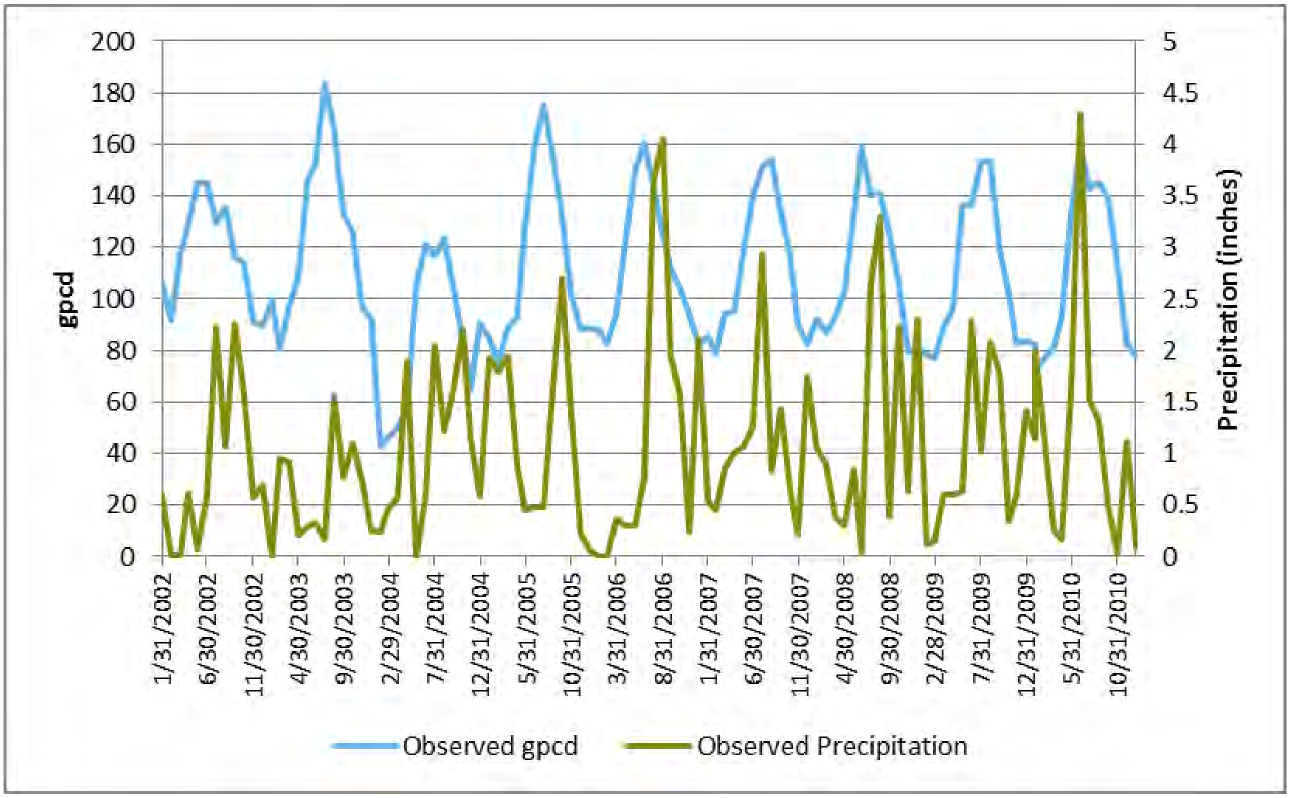


Figure 2-14. Monthly observed gpcd and precipitation for the City of Santa Fe.

To develop the relationship of temperature and precipitation to water use, a number of regression models were tested. Figure 2-15 shows the results of using the selected regression formula developed to estimate historical monthly gpcd from the historical monthly weather values relative to the observed historical gpcd (see Appendix E).

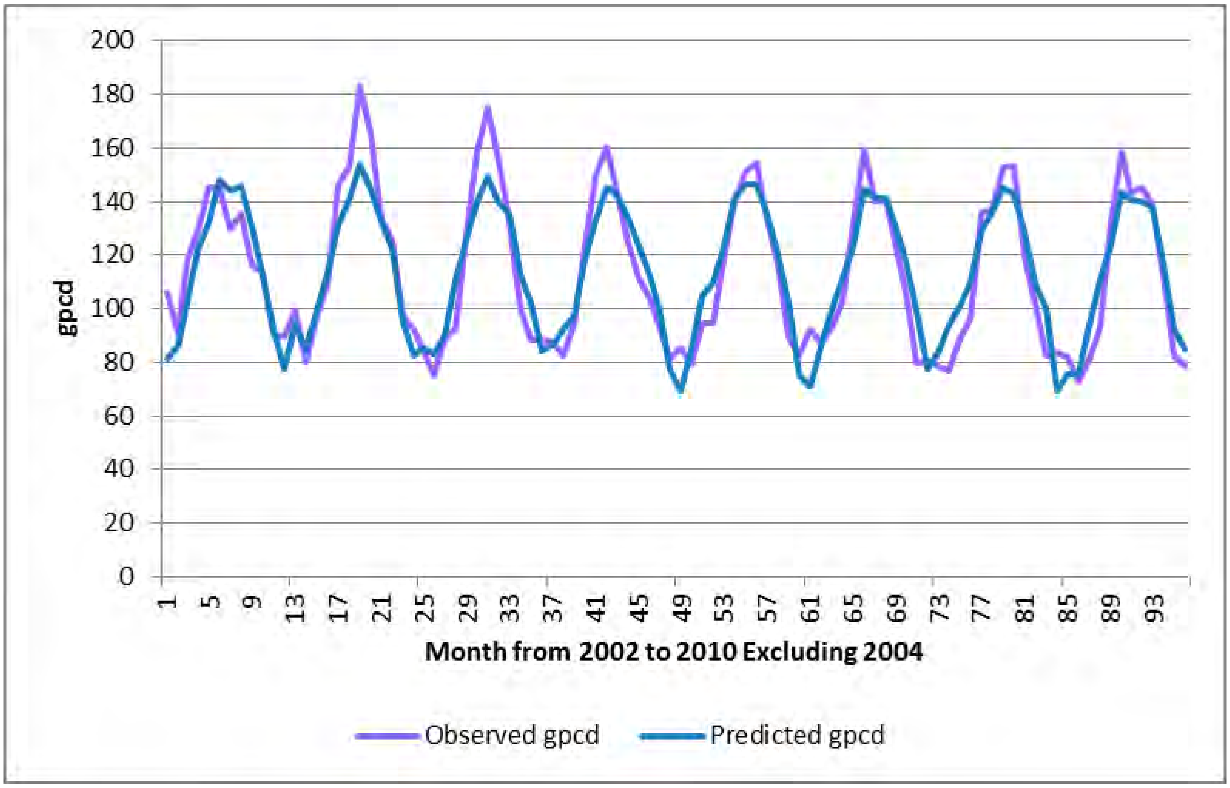


Figure 2-15. Comparison of predicted water use to observed water use for the City of Santa Fe.

The average annual per capita demand for the City of Santa Fe from 2002 to 2010 (excluding 2004) is about 113.8 gpcd. This value can be used in conjunction with projections of future population for the City and the County to derive estimates of average future water demand. The average value for monthly average maximum daily temperature for this time period is 65.66 °F and the average value for monthly precipitation is 1.04 inches. These values may be considered as representative of “normal” conditions. Deviation from these “normal” values can be calculated and used to adjust the average gpcd for the month.

2.6.3.2. Projecting Future Water Use

The formula discussed in Section 2.6.3.1 Calculating Variations in Water Use can be used to assess the impacts of alternative climate change scenarios on future water demand for the City and County. Reclamation has provided temperature and precipitation data for the climate change and simulated historic scenarios.

The above formula is used with temperature and precipitation time series in the climate change scenarios to predict water demand in WaterMAPS simulations. The average and maximum monthly gpcd simulated for each climate change scenario is shown in Figure 2-16. The labels in Figure 2-16 indicate the unit demand value for Synthetic Historic and the percent increase from the Synthetic Historic unit demand for each of the climate change scenarios. Figure 2-16 shows there is a predicted increase in demand as a result of increasing temperatures and decreased precipitation.

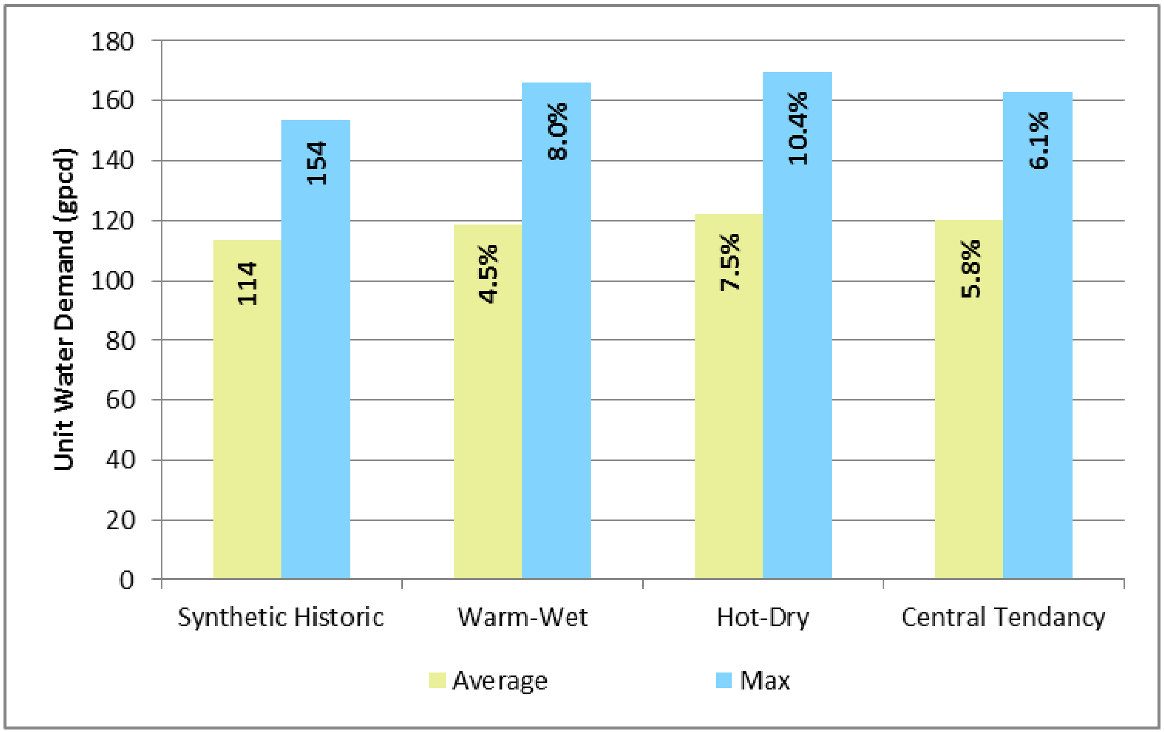


Figure 2-16. Average and maximum monthly gpcd simulated. Labels indicate the unit demand value for Synthetic Historic and the percent increase from the Synthetic Historic unit demand for each of the climate change scenarios.

2.7. System Reliability and Impact Assessment

This Basin Study is intended to assess viable options to fill the projected future gap between water supply and water demand for the City and County given climate change impacts by:

- Identifying where vulnerabilities exist in the supply
- Pinpointing adaption strategies and portfolios to address these system weaknesses to ensure a more resilient water supply to meet 40 year water demand projections

Additional information on impacts to water supply as analyzed using WaterMAPS can be found in Appendix F. The overall impacts assessment that looked at climate change impacts beyond water supply can be found in Appendix A.

2.7.1. Water System Reliability

The impact of climate change and future 2055 water demands was simulated using WaterMAPS. WaterMAPS provides the probability of deficits (or water shortages) on an annual basis and on a monthly basis. The output graphs show the percent likelihood of a deficit of a particular amount in any given year based on the simulation results.

Figure 2-17 shows the annual deficit probability for each climate change scenario as a separate line. An example of how to interpret the graph is shown in Figure 2-17 is shown in a box explaining that there is a 10 percent probability that there will be an annual deficit of 12,200 AF or more under the Hot-Dry climate condition. For the baseline condition (Simulated Historic), the WaterMAPS model predicts a 100 percent probability of an annual deficit of about 3,500 AFY or more, assuming that all management targets and administrative obligations are met. Thus the Santa Fe water supply is not adequate to meet demands even without the influence of climate change unless management targets are adjusted.

All modeled scenarios, including the baseline as well as the three climate-change impacted scenarios, show an annual deficit ranging between 3,500 acre-feet (AF) and 14,000 AF (Figure 2-17). To compare the climate change scenarios, the Hot-Dry scenario has the highest maximum annual deficit, about 14,000 AF while the Warm-Wet scenario has the lowest maximum annual deficit falling just below 9,000 AF. The annual deficit probability curve for the Central Tendency climate change scenario falls in between the Hot-Dry and Warm-Wet probability curves.

It is important to understand that these results do not solely reflect climate change impacts, but also the combination of City and County supply and demand, which has not been studied previously. The combined result is much greater demand without a commensurate increase in supply. Also, groundwater pumping is being restricted by the management targets. The most restrictive is the Buckman Well Field limitation of 3,000 AFY, which is based on a goal of sustainable management despite the significantly higher permitted pumping level of 10,000 AFY.

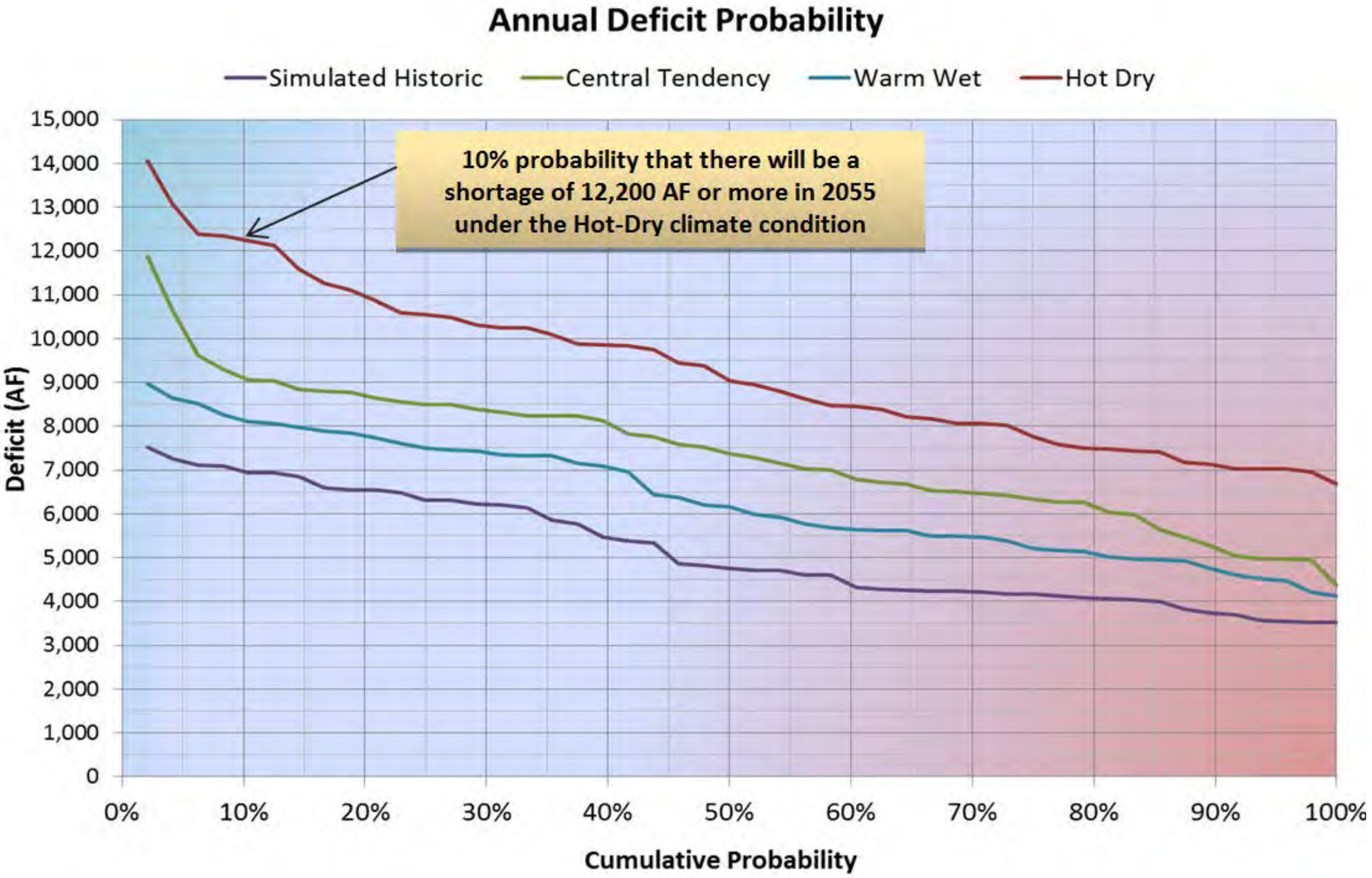


Figure 2-17. Cumulative probability curves for the annual deficit for each climate change scenario.

Reliability results from WaterMAPS are also produced in terms of monthly deficits. Figure 2-18 shows the monthly deficit probability for each climate change scenario. Similar to Figure 2-17, each line represents a climate change scenario and the range of deficits predicted. An example of how to interpret the graph is shown in a box explaining that there is a 10 percent probability that there will be a monthly deficit of 1,300 AF in any given month of 2055 under the Hot-Dry climate condition.

A monthly deficit ranging from zero to 1,900 AF is likely for all climate change scenarios including the baseline (Figure 2-18). The Hot-Dry climate change scenario has the highest maximum monthly deficit of approximately 1,900 AF while the Warm-Wet scenario has the lowest maximum monthly deficit of about 1,500 AF. These graphs represent the probability of deficits of a particular magnitude and not the probability of no deficits. For example, under the Simulated Historic climate conditions, the information on the graph indicates that that there is a 68 percent chance of deficits between 0 and 1,350 AF (not that there is a 68 percent chance of no deficits). To state the probability of any deficit, the cumulative probability should be inverted (i.e., the probability of no deficits for Simulated Historic in 2055 is 32 percent).

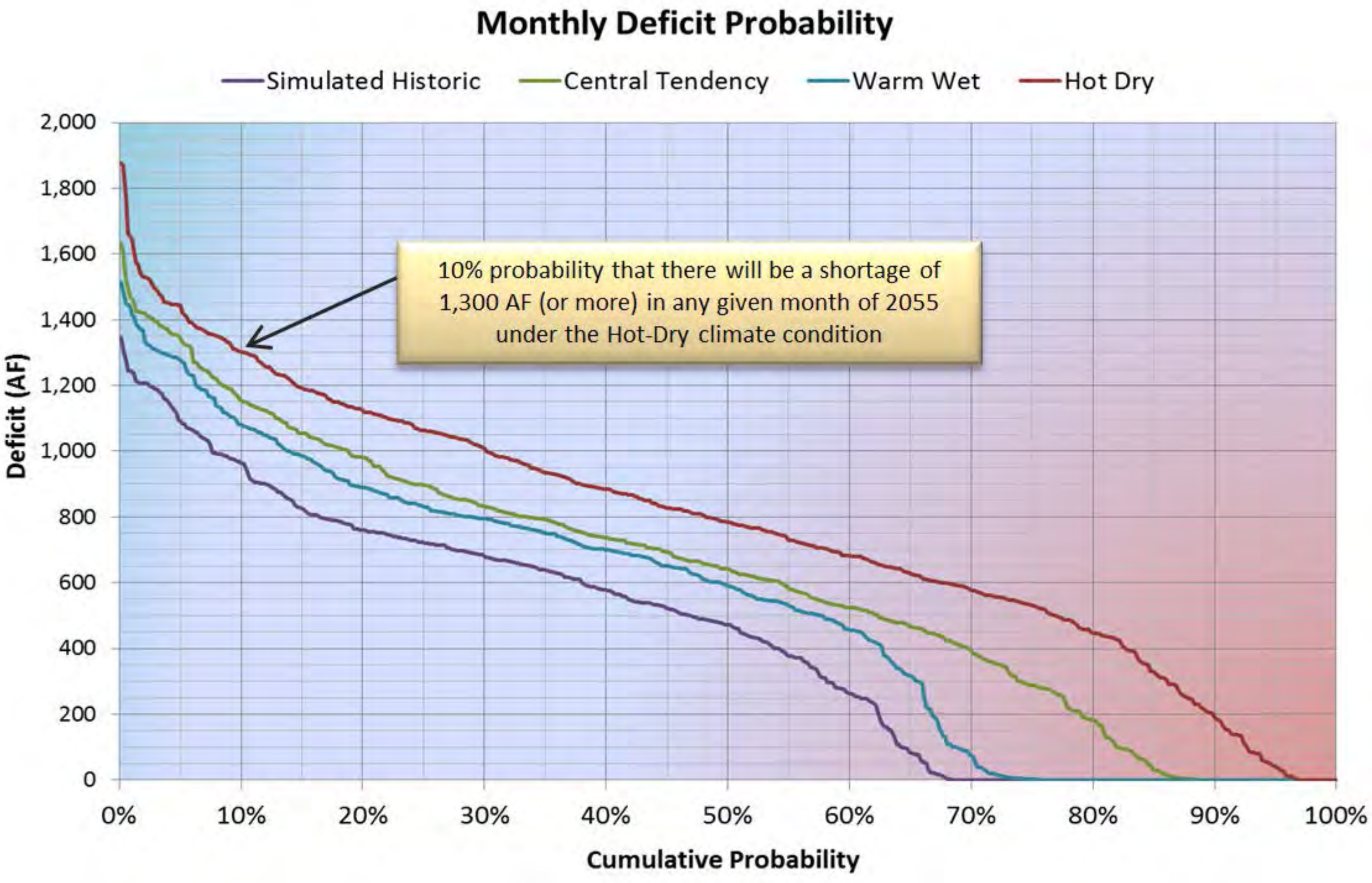


Figure 2-18. Probability curves for the monthly deficit for each climate change scenario.

As with the annual deficit, the monthly deficit probability curve for the Central Tendency scenario falls in between the Hot-Dry and Warm-Wet probability curves. Based on these results for monthly deficit, there is a 68 to 95 percent chance that there will be a water supply shortage in any given month by year 2055.

To better understand the seasonality of deficits, the summer and winter monthly probability curves for each climate change scenario were developed

(Figure 2-19 and Figure 2-20). The summer months were designated as June, July, and August while the winter months are December, January, and February.

Predicted deficits are more frequent and severe in the summer months than in the winter. Within the summer months, the largest deficit occurs in the Hot-Dry scenario as compared to the Central Tendency and Warm-Wet scenarios. The summer monthly deficit ranges from zero to 1,900 AF over all climate change scenarios. Comparing the climate change scenarios to the baseline in Figure 2-19 indicates the change in water availability: the difference between baseline and the climate change scenarios at 10 percent probability ranges from 200 to 350 AF.

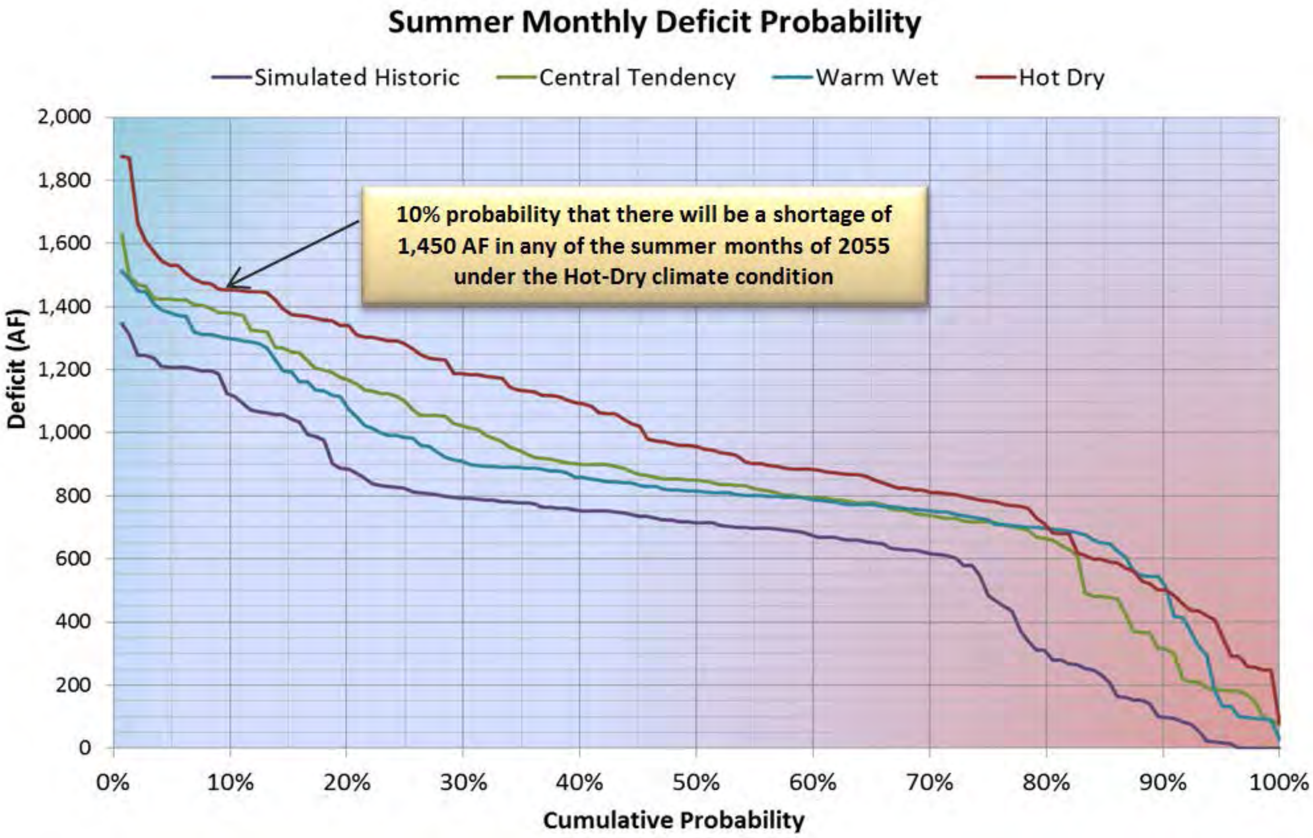


Figure 2-19. Probability curves for the summer monthly deficit for each climate change scenario.

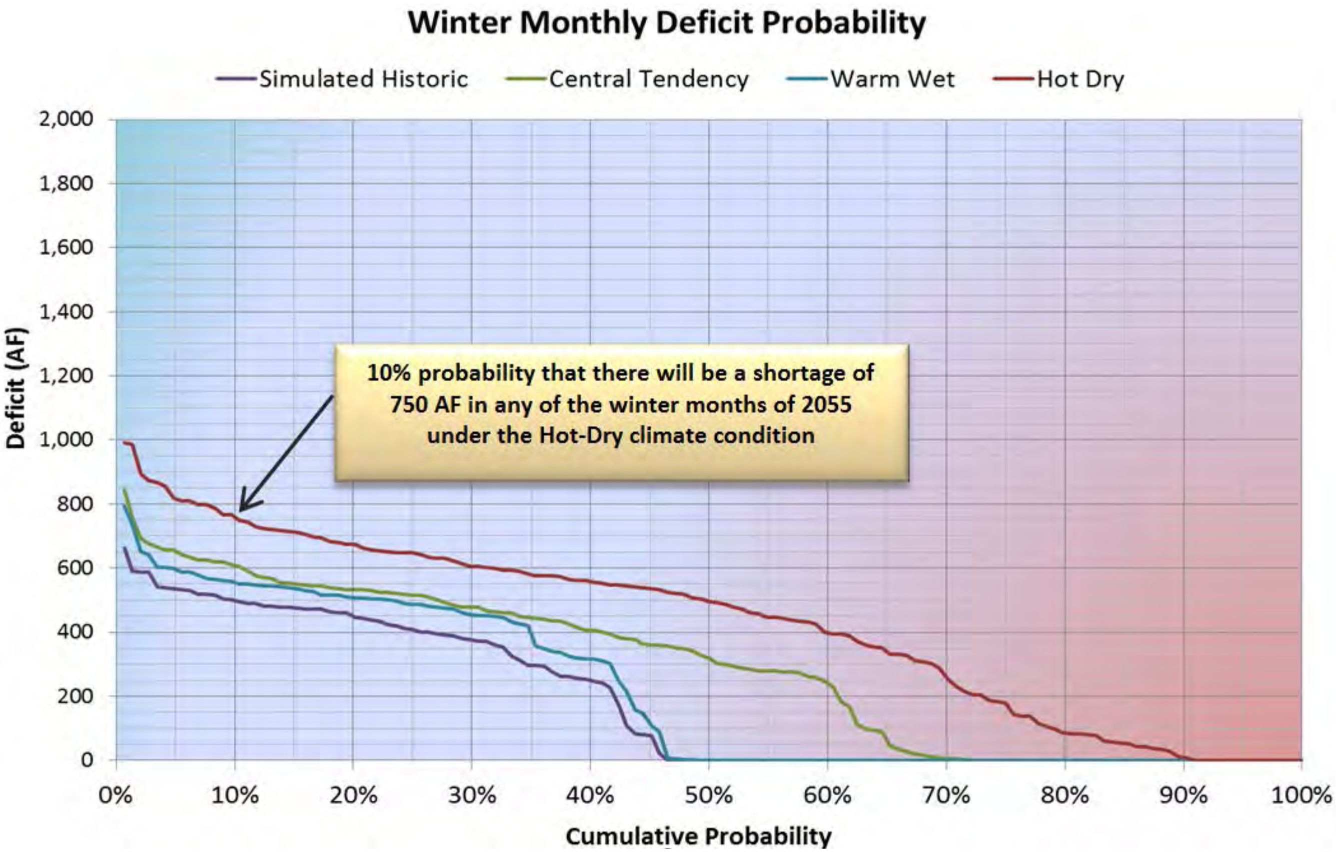


Figure 2-20. Probability curves for the winter monthly deficit for each climate change scenario.

During the winter months, the largest deficit occurs in the Hot-Dry scenario and is approximately 1,000 AF, considerably less than the summer maximum monthly deficit (Figure 2-20). The Central Tendency and Warm-Wet scenarios have a maximum deficit in the winter months of about 850 AF and 800 AF, respectively. The difference between the maximum deficits for each climate change scenario in the winter months is minimal. The significant difference in probability occurs when deficits of less than 400 AF occur. The monthly deficits predicted to occur during the winter are low in comparison to the summer months and annual deficits.

2.7.2. Analysis of Impacts by Key Water Resources Categories

The deficits in water supply are shown in the cumulative probability graphs presented in Section 2.7.2. These deficits are expected to impact the Santa Fe area in the following ways:

- **Water Delivery:** The predicted annual deficits under climate change scenarios (Figure 2-16) indicate a likely deficit of 4,000 AFY or more in any given year. The ability to deliver enough water under these scenarios would be severely limited. Additionally, there are other communities not included in this Basin Study that will be affected by the decrease in downstream flows. Impacts to water supply that were identified are discussed further in Appendix A, Section 4.1. Water supply reduction impacts on agriculture and food security are discussed in Appendix A, Section 4.3.

- **Hydropower:** There are no hydroelectric power generation facilities in the study area. There are requirements for water in production of electrical power sources. The impacts of a reduced water supply on power generation, energy consumption, and power transmission are discussed in Appendix A, Section 4.5.

- **Recreation:** Water-based recreation is likely to be impacted by decreased flow in the Rio Grande, as indicated by deficits in summer months (Figure 2-19). Impacts with regard to land use and quality of life are also discussed in Appendix A, Section 4.4.

- **Flood Control Management:** Flows in the Rio Grande and the Santa Fe River are controlled by upstream reservoirs. Decreased flows that are expected under climate change conditions are unlikely to impact flood control management. If local runoff (downstream of the reservoirs) is significant, changes in the intensity of rainfall may impact transportation (e.g. culverts and bridges designed based on historical rainfall patterns). Other impacts to transportation are discussed in Appendix A, Section 4.6.

- **Fish and Wildlife Habitat:** Fish and wildlife habitat is likely to be impacted by decreased flow in the Rio Grande and the Santa Fe River, as indicated by deficits in summer months (Figure 2-19). Beyond decreases in water quantity, impacts to the ecosystem are discussed in more detail in Appendix A, Section 4.2.

- **Endangered, Threatened, or Candidate Species under ESA:** Aquatic and riparian species are likely to be impacted by decreased flow in the Rio Grande and the Santa Fe River, as indicated by deficits in summer months (Figure 2-19). Beyond decreases in water quantity, impacts to the ecosystem are discussed in more detail in Appendix A, Section 4.2.

- **Water Quality Issues (including salinity levels)**: Water quality impacts were not evaluated in this Basin Study.

- **Flow and Water Dependent Ecological Resiliency:** Aquatic and riparian species are likely to be impacted by decreased flow in the Rio Grande and the Santa Fe River, as indicated by deficits in summer months (Figure 2-19). Beyond decreases in water quantity, impacts to the ecosystem are discussed in more detail in Appendix A, Section 4.2.

Other climate change impacts that have been identified that are not only related to water supply are discussed further in Appendix A, Section 4.

2.7.3. Vulnerabilities Identified By the Community

Through an interactive, public workshop, the community and climate-change adaptation experts identified the vulnerabilities of water supply, ecosystems, agriculture, land use and quality of life, energy, transportation, and economic and sociological systems. The value of identifying vulnerabilities lies in finding adaptation actions that will address vulnerabilities and thereby increase the watershed's resiliency. A summary of the vulnerabilities are briefly described below:

Water supply: Decreased surface-water availability; increased water use; unsustainable groundwater use; insufficient storage to capture storm events; loss of storage capacity due to debris flows triggered by catastrophic-fire; degradation of water quality; more frequent restrictions under the Rio Grande Compact; increased competition over resource; less groundwater recharge.

Ecosystems: Vulnerability of forests to insects, fire, and desiccation; less available water; higher water needs; incursion of invasive species; habitat degradation from storms, flooding, erosion, and lack of water; loss of fisheries, upland forests, and grasslands.

Agriculture: Reduction in available water supply; increased crop water demand; greater divergence between timing of highest stream flows and greatest water need for irrigation; increased damage to crop from pestilence, high winds, violent rain storms, and flooding; rural/urban conflicts over water and water rights; failure of genetically engineered crops; reduction in viable grasslands for cattle; livestock mortality from extreme weather conditions.

Land Use and Quality of Life: Increased water needs for green spaces; increase of urban flooding; reduction in quality fishing opportunities; reduction in length of skiing and rafting seasons; diminished hiking, biking, and hunting opportunities due to fire; poorer air quality; increased heat stress in elderly, infirm, and infants from higher summer daytime and nighttime temperatures.

Energy: Increased competition for water with energy production; less hydropower production; reduction in solar production for increased temperature and air particulates; increased energy consumption during the summer and extreme cold weather events; reduced power and gas reliability during extreme conditions.

Transportation: Increased interruptions from dust storms, intense rains, and smoke; failure of infrastructure (paved roads, bridges, culverts, rails) designed for less extreme conditions; more difficult flying conditions under higher temperatures; decrease in fuel efficiency from increased heat and adverse conditions.

Economy: Tourism and population growth may decrease if climate conditions are unfavorable (e.g., too hot, not enough snow, smoky); insurance premiums may rise for services impacted by natural hazards; cost of energy and water may increase as each becomes more expensive to acquire and transmit.

Sociological Conditions: Limited local and regional governmental resources to provide emergency services for increased severe weather events; institutions inflexible maladaptive to rapidly changing conditions; disruption in cultural identities and traditions.

Chapter 3. Adaptive Strategies

A methodical decision process was used to compare and evaluate the alternatives for adapting to projected climate scenarios. The overall process has four steps:

- Identify adaptation strategies appropriate for the Santa Fe area water utilities
- Combine the adaptation strategies into adaptation portfolios
- Develop evaluation criteria and weight each criterion based on the relative importance of the criterion
- Rank the climate mitigation portfolios based how well they meet the criteria

This section presents the results of each step in the decision process and the selection of the climate mitigation portfolio that best meets water needs of the City and County of Santa Fe under projected climate change scenarios. More information on this process can be found in Appendix G.

3.1. Formulation of Adaptive Strategies

3.1.1. Community Suggested Adaptation Activities

An interactive workshop in March 2012 was hosted by Amy C. Lewis Consulting and the Institute for Social and Environmental Transition and informed the Preliminary Assessment. The Preliminary Assessment investigates how projected climate change impacts may influence some of the key natural and human systems in the Santa Fe Watershed. The assessment also explored the adaptive actions that stakeholders in the Santa Fe Watershed may consider implementing and details many of the ongoing activities that will increase the resiliency of the watershed and the community that it supports.

Participants in the Preliminary Assessment workshop were informed that, although uncertainty surrounds climate-change science, the experts in the field are confident in projecting, at a minimum, the following impacts to the Santa Fe watershed:

- Increased temperatures
- Diminished snowpack and earlier spring melt of existing snowpack
- Reduced stream flow due to greater evaporation rates and water use by plants
- Earlier stream flow peak (from earlier snowmelt) and dampened peak flows
- Drier mid- to late-summers
- More severe and frequent droughts
- Increased fire activity and risk of catastrophic fire
- More intense precipitation events resulting in increases to peak storm flows, greater magnitude and frequency of flooding, higher erosion rates, and more sediment transport by storm flows

Stakeholders at the Preliminary Assessment Workshop identified the following adaptation actions to increase the resilience of the Santa Fe Watershed and the communities that it supports to the impacts of a changing climate.

- Provide incentives and programs to reduce water use
- Allow limited-term transfers of water from agriculture to urban use during drought
- Adjudicate Santa Fe basin water rights
- Augment potable water supplies with reclaimed wastewater
- Improve ecosystem biodiversity

- Manage and plan restoration holistically
- Design or modify bridges and culverts to handle higher-intensity runoff events
- Incorporate urban agriculture in water and land use planning
- Cultivate climate-appropriate crops
- Require pervious pavement, where appropriate
- Decentralize energy infrastructure
- Municipalize energy system
- Install solar panels over parking lots to reflect heat and produce energy
- Establish a climate-change target monitoring system
- Appoint an artist-in residence dedicated to the Santa Fe River

3.1.2. City and County Adaptation Strategies

Representatives of the City and County identified adaptation strategies for meeting water demands under climate change scenarios. The adaptation strategies identified are appropriate for the arid climate and landscape of the Santa Fe region. For example, water storage is an important strategy that is still being considered by the City and County, but building additional storage reservoirs was not considered an appropriate adaption strategy for this study because of the high evaporation losses from reservoirs and the limited areas available for constructing storage reservoirs. Instead, underground storage of water through an aquifer storage and recovery system is included for this study because evaporation losses are negligible and the surface land area required is small compared to a traditional surface reservoir. The adaptation strategies selected for the Santa Fe Basin Study are summarized in Table 3-1.

Table 3-1. Adaptation Strategies for the Santa Fe Basin Study Area

Adaptation Strategy	Description	Infrastructure Components
Direct/Indirect Reclaimed Water Reuse	Use reclaimed water from the City wastewater treatment plant to meet contract obligations; remaining reclaimed water for potable reuse or return flow credits for pumping.	New conveyance for reclaimed water from wastewater treatment plant to existing Buckman Regional Water Treatment Facility and distribution system or new conveyance to the Rio Grande for return flow credits.
Water Conservation	Reduce water use on a per person per day basis.	None
Direct Injection for Aquifer Storage and Recovery	Inject treated water into the aquifer in wet and normal years for use in dry years.	Construction and operation of injection well(s); withdrawal using existing wells and distribution system.
Infiltration for ASR in the Santa Fe River	Maintain flow in the Santa Fe River to induce infiltration into the aquifer for use in dry	Withdrawal using existing wells and distribution system.
Additional Surface Water Rights	Additional surface water would be diverted at the Buckman Direct Diversion and treated at the Buckman Regional Water Treatment Facility.	Existing diversion, conveyance, treatment, and distribution systems

3.1.3. Objectives and Constraints

The primary objective of this Basin Study is to identify adaptation strategies and portfolios that will provide adequate water supply under climate change conditions, hence the primary requirement of the adaptation strategies is that they provide a reliable water supply to a growing population. Reliability criteria were developed and the adaptation portfolios were screened against these reliability criteria. Only those portfolios that provide a reliable water supply in 2055 were evaluated further against performance criteria.

The gaps between water supply and demand under the climate change scenarios if no adaptation strategies are implemented are summarized in Table 3-2. A water supply gap of about 5,000 AFY in the year 2055 is projected to occur under simulated historic climate conditions (stationarity assuming that climate similar to historic), but the magnitude of the water supply gap increases under any of the three climate change scenarios.

Table 3-2. Santa Fe Basin Projected 2055 Water Supply Gap

	Climate Change Scenario			
	Simulated Historic (no climate change)	Central Tendency	Warm Wet	Hot Dry
Total Demand - Average Annual (AFY)	21,643	22,925	22,646	23,299
Total Supply - Average Annual (AFY)	16,488	15,550	16,304	13,976
Water Supply Gap – Difference between Demand and Supply (AFY)	**(5,155)**	**(7,375)**	**(6,342)**	**(9,323)**

The reliability criteria are:

1. **Average Buckman Well Field pumping does not exceed the management target by more than 500 AFY on average:** The current management target for the Buckman Well Field is 3,000 AFY but water rights equal 10,000 AFY. It was determined that a 500 AFY increase in average pumping was acceptable for this planning-level analysis.

2. **Deficit in any year does not exceed 2,000 AFY:** Based on the assumption that in emergency situations conservation of 10 gpcd is realistic and would fill a temporary gap of 2,000 AFY in 2055.

3. **No more than 10 percent probability of deficits over 100 AFY:** Based on the assumption that the system can accommodate small deficits that cannot be reliably simulated with the model. To account for model noise, over 10 percent probability of deficits are accepted if they are less than 100 AFY.

Each of these criteria were assessed for the Central Tendency climate change scenario as it is considered to be the most appropriate for planning purposes. Reliability results were then analyzed for all the climate scenarios when further assessing performance.

3.1.4. Approach to Adaptive Strategy Identification

The adaptive strategies developed and included in adaptive portfolios were summarized in Table 3-2 above and described below. Even though the planning horizon target is the 2050s, all the adaptive portfolios use current conditions and constraints as the starting point.

3.1.4.1. Direct Reclaimed Water Reuse

Reclaimed water is currently used in the City as described in the RWRP (City of Santa Fe 2013), which outlines specific allocations for reclaimed water use. Simulated reclaimed water supply (including seasonal demands and infrastructure constraints) from the City of Santa Fe wastewater treatment plant that is not used by one of the reclaimed water contracts is considered as new beneficial uses for reclaimed water as follows:

- Treatment at the Buckman Regional Water Treatment Facility for potable supply
- Return flow credits for discharges to the Rio Grande

Discharge from the Quill wastewater treatment plant, owned and operated by Santa Fe County, was not included in the Santa Fe Basin Study but will represent an additional source of reclaimed water in the study area.

3.1.4.2. Water Conservation

The City began a Water Conservation Program in 1997, building a comprehensive and effective program which has resulted in Santa Feans reducing per capita water consumption by more than 39 percent since consistent tracking began in 1995. Reducing the water use is one measure of success for any water conservation program, and Santa Fe is a leader in the Southwest. For the purposes of this study, the annual unit water demand used is 114 gpcd gallons per capita per day (gpcd), as determined from monthly 2002-2010 City water production data. This gpcd does not include the reuse of reclaimed wastewater. For this adaptation strategy, the maximum conservation realistically achievable was considered to be a decrease of 20 gpcd.

3.1.4.3. Direct Injection for Aquifer Storage and Recovery

This adaptation strategy would inject and store treated excess water from one of the City or County’s other sources into an aquifer that has been developed by the Partners for water supply (e.g., Buckman Well Field) and later use the water in a process commonly referred to as aquifer storage and recovery (ASR). The ASR process uses water from above ground to recharge groundwater. ASR can be achieved by active means, usually direct injection, or through passive methods, primarily infiltration.

Large scale implementation of ASR through direct injection wells is not currently in widespread use in New Mexico. However, it has the advantage that most of the water injected into the aquifer can be recovered under a permit from the New Mexico Office of the State Engineer (OSE). Also, direct injection minimizes the amount of land required for implementation. This adaptation strategy would use surface water rights in excess of current demand or require acquisition of additional surface water rights, treat the water at the Buckman Regional Water Treatment Facility to drinking water standards, and directly inject the water in the aquifer at or near existing water supply wells. It is assumed that the water rights used for this strategy can be permitted by the OSE with dual purposes: they can be used as needed for meeting groundwater pumping offsets or can be recovered for direct use.

Withdrawal of water through existing water supply wells and conveyance through the existing distribution system is assumed under this adaptation strategy. Water would be injected in normal to wet years or if acquired water rights are in excess of demand and would build up over time. The water could be withdrawn and used in normal to dry years. A maximum cap of 5,000 AFY of accumulated storage is assumed for this adaptation strategy.

3.1.4.4. Infiltration in the Santa Fe River Channel for Aquifer Storage and Recovery

ASR using passive methods through natural or engineered infiltration systems have been implemented on large scales at numerous locations in the United States, including two in New Mexico. This adaptation strategy takes advantage of flow in the Santa Fe River as a natural infiltration system that recharges the aquifer. This process occurs whenever water is flowing in the Santa Fe River, but this adaptation strategy would entail satisfying the requirements of both the Ground Water Storage and Recovery Act, New Mexico Statutes Annotated 1978, §72-5A-2 and the New Mexico Underground Storage and Recovery Regulations to be able to withdraw the water that has infiltrated.

Permits to pursue ASR through infiltration in the Santa Fe River could be sought for two areas: the upper Santa Fe River where releases from upstream reservoirs maintain flow in the river and the lower Santa Fe River where flow in the river is maintained by discharge from the City Wastewater Treatment Plant.

The “infiltration rate” is that portion of stream flow that is assumed to infiltrate the upper Santa Fe River stream bottom and recharge the aquifer. For this adaptation strategy, the infiltration rate was assumed to be up to 70 percent of stream flow (similar to an estimate for the City of Albuquerque). Withdrawal of water under this adaptation strategy would be realized via existing water supply wells and conveyed through the existing distribution system. There is projected to be sufficient water for flow in the Santa Fe River in wet to normal years and the stored water from infiltration is projected to accumulate during wet years so that it could be withdrawn and used in normal to dry years. A maximum cap of 2,000 AFY of accumulated storage was assumed for this adaptation strategy.

For the lower Santa Fe River, the flow of water released from the City's wastewater treatment plant to the Santa Fe River is presumed to be available for the ASR project. The amount of flow in this portion of the Santa Fe River is constrained by the amount of reclaimed water used to supply reclaimed water contracts or for direct use. The maximum infiltration rate (70 percent) and cap of accumulated water storage (2,000 AFY) are modeled in the same way as for the upper Santa Fe River infiltration adaptive management strategy.

3.1.4.5. Acquisition of Additional Surface Water Rights

This adaptation strategy requires acquiring additional surface water rights and using the Buckman Direct Diversion infrastructure to divert, convey, and treat the water. The treated water could be directly distributed through the water distribution system or could be injected for ASR.

The City and County link new development to water. In the City, development projects with new water demand are required to either purchase water conserved by customers (for example through the water conservation rebate program) or to transfer existing (or newly acquired) water rights to the City. In the County, development projects either acquire water rights or pay a water right acquisition fee. The amount of additional surface water rights expected to be available through the City's Water Right Transfer Program is expected to be a maximum of about 35 AFY each year, based on historical trends in the program.

The adaptations considered included both non-structural and structural changes. The non-structural adaptation strategies identified are conservation and acquiring additional water rights within the Buckman Direct Diversion current diversionary capacity. The remaining adaptation strategies require upgrading or building new infrastructure to implement as described in Section 3.1.5.

3.1.5. Adaptive Strategies Considered

The portfolios are summarized in Table 3-3. The systems model WaterMAPS was used to simulate each portfolio to determine if they could meet demands under climate-change conditions. Portfolios 1, 2, and 3 use a single adaptive strategy, but they will not reliably provide sufficient water supply under conditions projected for 2055. Portfolios 4 through 8 combined adaptive strategies to create portfolios with different emphases to compare and contrast the impacts of varying levels of each adaptation strategy in order to provide clear direction for the City and County long-range water supply planning.

Table 3-3. Santa Fe Basin Study Portfolios and Simulated Supply

	Simulated Supply from Adaptation Strategy (AFY)					
	Direct Reclaimed Water Reuse	Conservation	Direct Injection Aquifer Storage and Recovery	Infiltration Santa Fe River Aquifer Storage and Recovery	Additional Water Rights	**Portfolio Simulated Supply**
Portfolio 1: Conservation Only		4,005				**4,005**
Portfolio 2: Direct Reuse Only	4,024					**4,024**
Portfolio 3: Additional Water Rights Only					1,400	**1,400**
Portfolio 4: More Conservation & Water Rights (Reuse to Potable)	2,224	4,005	559	149	1,400	**8,337**
Portfolio 5: More Conservation & Water Rights (Reuse to Offsets)	2,224	4,005	559	149	1,400	**8,337**
Portfolio 6: More Infiltration ASR		3,003	0	2,841	1,400	**7,244**
Portfolio 7: More Direct Reuse (to Potable)	3,243	2,002		148	920	**6,313**
Portfolio 8: More Direct Reuse (to Return flow credits)	3,243	2,002		148	920	**6,313**

It is important to understand that WaterMAPS employs several constraints that may reduce the supply available for a particular adaptation strategy within a portfolio. These include capacity, water rights, and available wet water during the water year or season in question, and conditions based on season or hydrology
(wet, dry, normal year) constraints. Additional constraints are then applied based on individual adaptation strategies as indicated in the following sections. Note that some of the gap for these portfolios is met with Buckman pumping in excess of the management target (See Appendix G, Section 3 for more information).

The following sections describe how the portfolios were modeled and the reliability results compared to the criteria used for screening each portfolio. If the portfolio did not meet the reliability criteria for Central Tendency, it was not further analyzed for other climate scenarios. Therefore, portfolios that do not meet the reliability criteria only show the annual deficit probability for Central Tendency.

3.1.5.1. Portfolio 1: Conservation Only

Portfolio 1 consisted solely of conservation and tests whether the projected effects of climate change could be ameliorated by conservation alone. This portfolio is based on a 20 gpcd decrease in water use. This portfolio could be implemented with an increase in water conservation education, on-site plumbing changes, and enforcement of restrictions. No new infrastructure would be required. The simulated supply created by this level of conservation is 4,005 AFY. The supply from Buckman pumping in excess of the management target is 2,674 AFY. In the absence of climate change, Portfolio 1 would close the gap between supply and demand, but significantly more groundwater pumping would be needed. The cumulative probability of annual deficits under the Central Tendency climate change scenario for Portfolio 1 is shown in Figure 3-1. Figure 3-1 shows that the maximum annual deficit is 1,372 AFY and at that an annual deficit of 391 AFY is expected to be exceeded 10 percent of the time.

Portfolio 1 does not meet two of the three reliability criteria as shown in Table 3-4. Additional analysis of this portfolio shows that conserving 40 gpcd would result in a portfolio that would meet the reliability criteria. However, the ability of the City and County to consistently reduce demand by 40 gpcd is too uncertain to use this conservation goal in water supply planning. The goal itself remains as part of utility management efforts and conservation outreach.

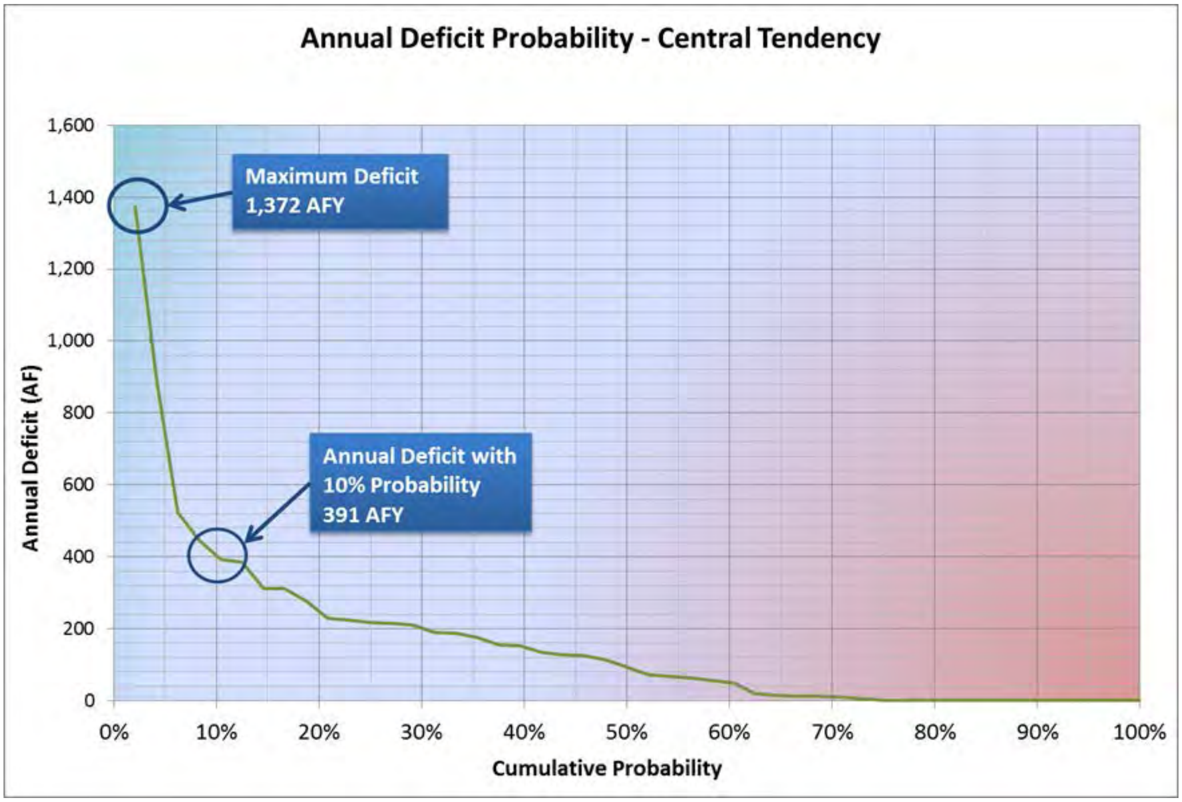


Figure 3-1. Santa Fe Basin Portfolio 1 annual deficit probability curve under central tendency climate scenario.

Table 3-4. Performance of Portfolio 1 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	**Maximum Annual Deficit <2000 AFY**	**Annual Deficit at 10% probability > 100 AFY**
Portfolio 1: Conservation Only	NO (exceeds by 2,674 AFY)	YES (1,372 AFY maximum annual deficit)	NO (391 AFY annual deficit at 10% probability)

3.1.5.2. Portfolio 2: Direct Reuse Only

Portfolio 2 consists solely of the direct reuse of reclaimed water. Similar to Portfolio 1, the purpose of Portfolio 2 is to assess if the projected 2055 water supply gap could be filled by reuse of reclaimed water alone. The portfolio assumes that effluent from the City Wastewater Treatment Plant is conveyed by new infrastructure to the Buckman Regional Water Treatment Facility. The reclaimed water would be treated to drinking water standards and delivered for potable use through the existing distribution system. Alternatively, new piping could be installed to deliver the treated water to the Rio Grande for return flow credits.

Portfolio 2 assumes that 1,734 AFY of the 3,489 AFY of existing non-potable reclaimed water contracts is delivered (about 50 percent; the portion allocated to public projects). The remainder is returned to the Buckman Regional Water Treatment Facility and treated for potable reuse. The simulated average annual supply for Portfolio 2 is 4,024 AFY. Supply from Buckman pumping in excess of the management target is 2,225 AFY. In the absence of climate change, Portfolio 2 can close the gap between supply and demand, but significantly more groundwater pumping would be required. Figure 3-2 illustrates that the maximum annual deficit is 1,159 AFY and the annual deficit at 10 percent probability is 378 AFY.

Portfolio 2 does not meet two of the three reliability criteria as shown in Table 3-5. Additional analysis of this portfolio showed that if the reuse was assumed to be 6,696 AFY, the resulting portfolio that would meet the reliability criteria. However, this would mean that most of the existing reclaimed water contracts would not be honored and there would be no discharge to the Santa Fe River. Considering the reliance on reclaimed water by downstream users (both human and ecological), this level of direct reuse was considered unacceptable.

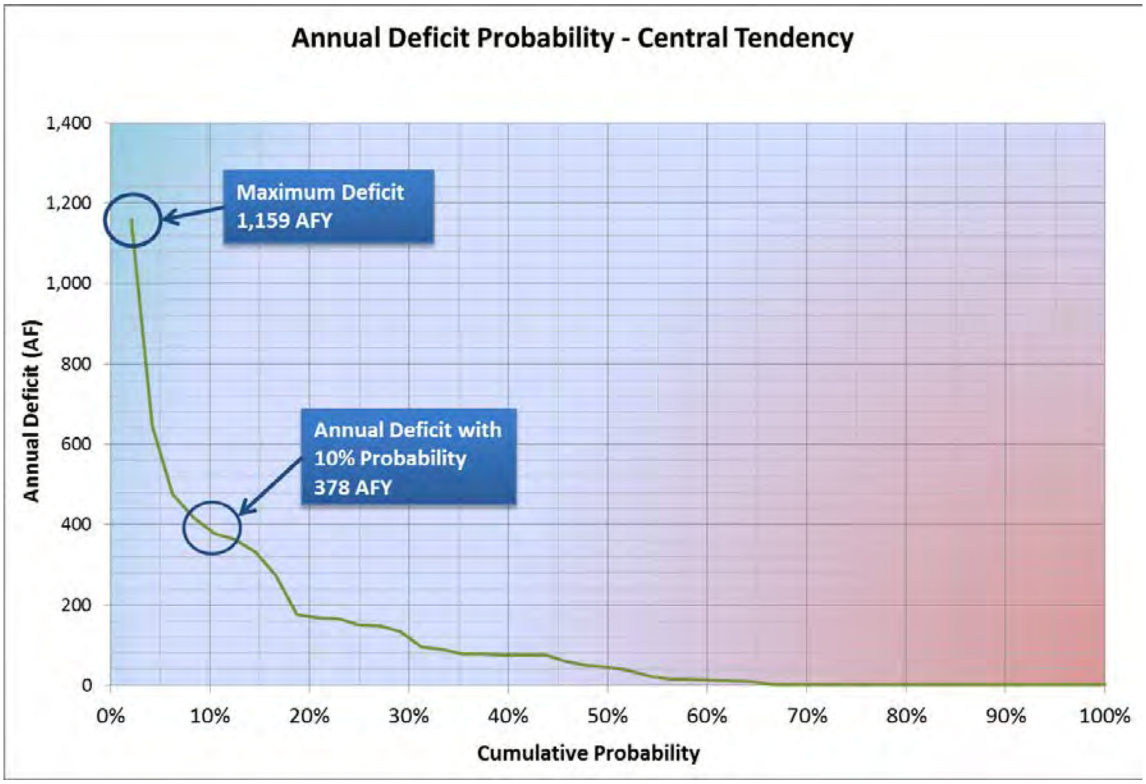


Figure 3-2. Santa Fe Basin Portfolio 2: Direct Reuse Only annual deficit probability curve under central tendency climate scenario.

Table 3-5. Performance of Portfolio 2 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	**Maximum Annual Deficit <2000 AFY**	**Annual Deficit at 10% probability >100 AFY**
Portfolio 2: Direct Reuse Only	NO (exceeds by 2,225 AFY)	YES (Maximum deficit is 1,159 AFY)	NO (Annual deficit at 10% is 378 AFY)

3.1.5.3. Portfolio 3: Additional Water Rights Only

Portfolio 3 consists solely of acquiring additional Rio Grande surface water rights from within the Middle Rio Grande valley between Otowi Gage and Elephant Butte Reservoir. Similar to Portfolios 1 and 2, the purpose of Portfolio 3 was to assess if the projected 2055 water supply gap could be filled by obtaining additional surface water rights alone. The portfolio assumes that the Water Rights Transfer Program acquires 35 AFY each year of new surface water rights or a total of 1,400 AFY over the 40-year planning period. The simulated average annual supply for Portfolio 3 is 1,400 AFY. Supply from Buckman pumping in excess of the management target is 4,451 AFY. In the absence of climate change, Portfolio 3 can close the gap between supply and demand, but significantly more groundwater pumping above the management target would be required. The additional surface water obtained for this portfolio would be diverted, conveyed, treated and delivered through the existing Buckman Direct Diversion Project, and it is assumed that no new infrastructure would be required for 1,400 AFY. Figure 3-3 illustrates that the maximum annual deficit is 3,978 AFY and the annual deficit at 10 percent probability is 2,363 AFY.

Portfolio 3 does not meet any of the three reliability criteria as shown in Table 3-6. Additional analysis of this portfolio showed that over 7,000 AFY in new surface water rights would be required to meet the reliability criteria. Acquiring this amount of new water rights is unrealistic considering the relative scarcity of water rights for purchase and the impact to Middle Rio Grande valley of such an acquisition.

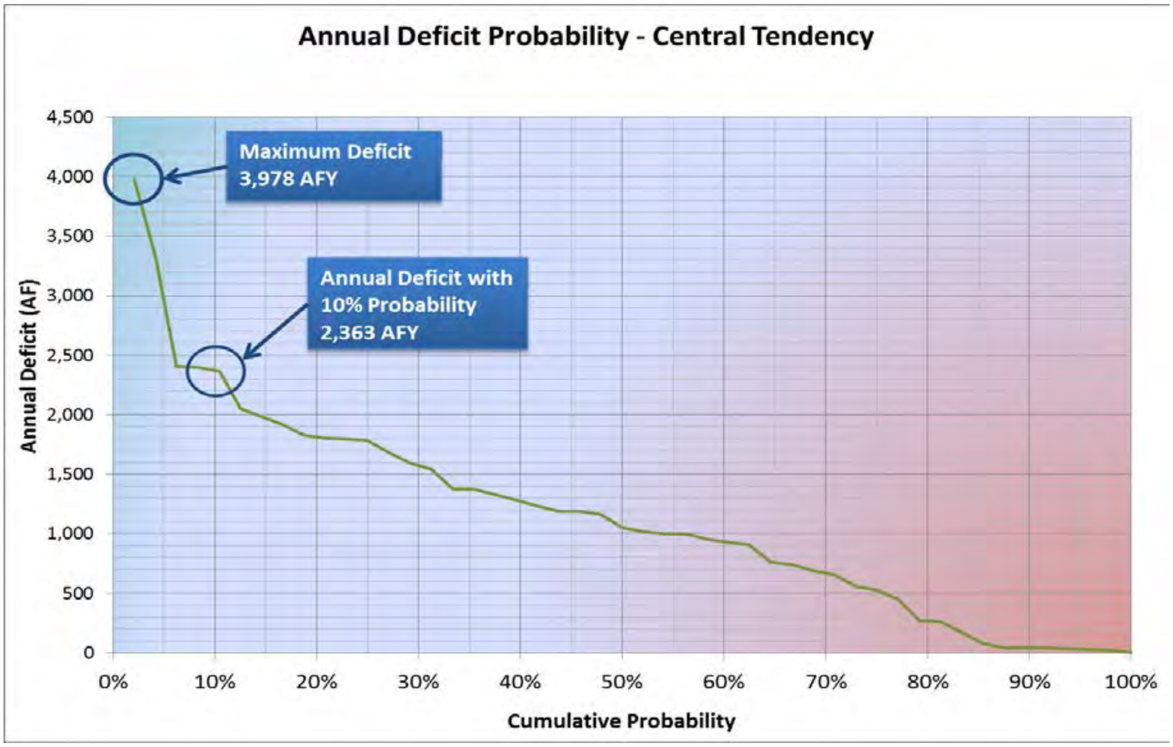


Figure 3-3. Santa Fe Portfolio 3: Additional Water Rights Only annual deficit probability curve under central tendency climate scenario.

Table 3-6. Performance of Portfolio 3 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	Maximum Annual Deficit <2000 AFY	Annual Deficit at 10% probability >100 AFY
Portfolio 3: Additional Water Rights Only	NO (exceeds by 4,451 AFY)	NO (Maximum deficit is 3,978 AFY)	NO (Annual deficit at 10% is 2,363 AFY)

3.1.5.4. Portfolio 4: More Conservation & Water Rights (Reuse to Potable)

Portfolio 4 and the remaining four portfolios combine supply and demand strategies to meet the reliability criteria.

Portfolio 4 has the following components:

- **Direct Reuse:** Deliver 2,250 AFY to reclaimed water contracts, 1,239 AFY to potable use
- **Conservation:** Reduce demand by 20 gpcd
- **Direct Injection ASR:** 640 AFY up to a maximum of 5,000 AF of storage
- **Infiltration ASR in Santa Fe River:** infiltration in upper Santa Fe River (30 percent of river flow)
- **Additional Water Rights:** 1,400 AFY

This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new infrastructure required)
- Treat to drinking water standards at the Buckman Regional Water Treatment Facility and distribute to customers (use existing infrastructure)
- Construct injection well(s) or modification of wells to act as injection well (new infrastructure required)
- Convey water from Buckman Regional Water Treatment Facility to injection well (new infrastructure required)

- Withdraw water from wells and distribution to customers (use existing infrastructure)

Buckman pumping is reduced to below management targets for this portfolio. Figure 3-4 illustrates that the maximum annual deficit is 57 AFY and the annual deficit at 10 percent probability is zero. Portfolio 4 meets all of the three reliability criteria as shown in Table 3-7. Further, Portfolio 4 meets the reliability criteria under all 3 climate scenarios, with the exception of the hot-dry scenario where the annual deficit at 10% probability is greater than 100 AFY (Figure 3-4). Portfolio 4 was carried on for evaluation with respect to the performance criteria.

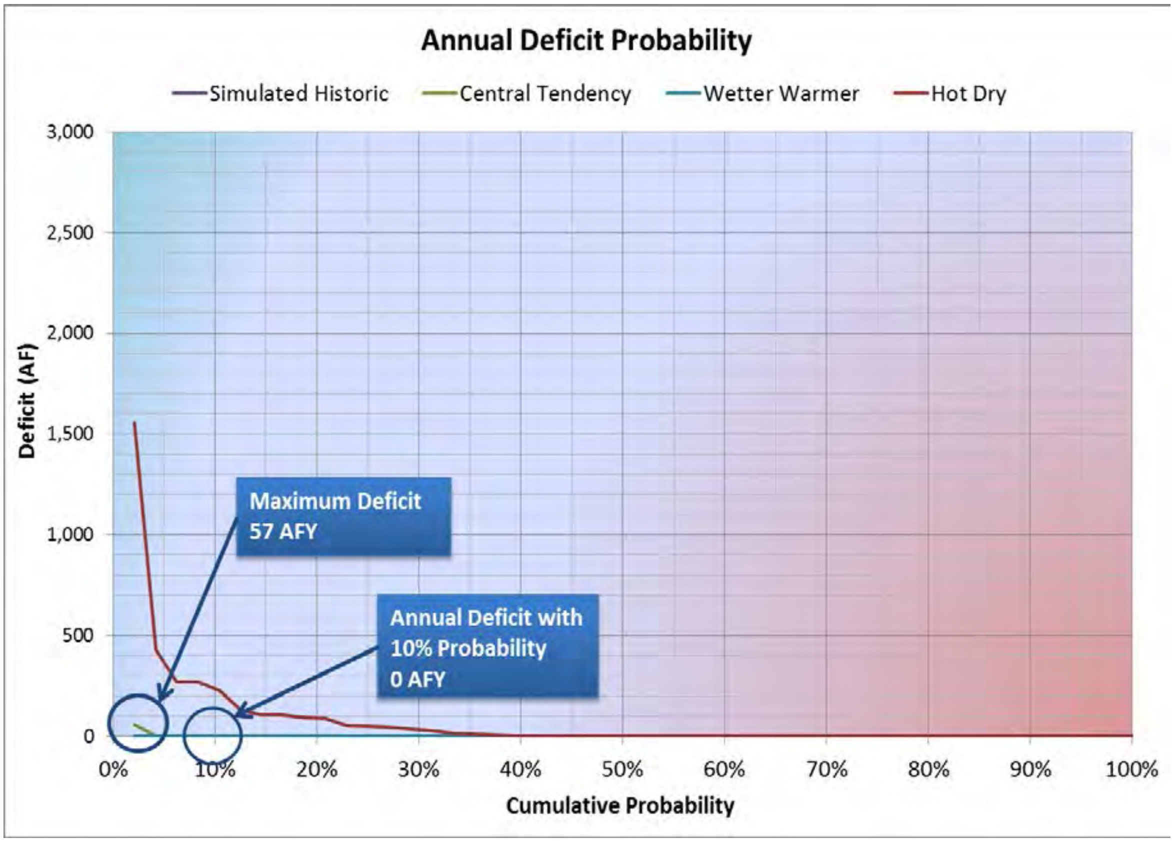


Figure 3-4. Santa Fe Portfolios 4 and 5: More Conservation and Water Rights (Reuse to Potable) annual deficit probability curve under central tendency climate scenario.

Table 3-7. Performance of Portfolios 4 and 5 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	**Maximum Annual Deficit <2000 AFY**	**Annual Deficit at 10% probability >100 AFY**
Portfolios 4 and 5: More Conservation and Water Rights	YES (does not exceed)	YES (Maximum deficit is 57 AFY)	YES (Annual deficit at 10% is 0 AFY)

3.1.5.5. Portfolio 5: More Conservation & Water Rights (Reuse to Return Flow Credits)

Portfolio 5 is exactly the same as Portfolio 4 except the treated water is returned to the Rio Grande for return flow credits rather than for potable use. Therefore, the reliability results (Figure 3-4 and Table 3-7) are the same for these two portfolios.

Portfolio 5 meets all of the three reliability criteria as shown in Table 3-7. Further, Portfolio 5 meets the reliability criteria under all 3 climate scenarios, with the exception of the Hot-Dry scenario where the annual deficit at 10 percent probability is greater than 100 AFY (Figure 3-4). Portfolio 5 was carried on for evaluation with respect to the performance criteria.

3.1.5.6. Portfolio 6: More Infiltration Aquifer Storage and Recovery

Portfolio 6 emphasizes infiltration ASR, with moderate conservation and less acquisition of water rights. Portfolio 6 has the following components:

- **Conservation:** Medium reduction in demand (15 gpcd)
- **Direct Injection ASR:** 640 AFY to a maximum of 3,500 AF of storage
- **Infiltration ASR:** infiltration in both upper and lower Santa Fe River (70 percent of flow)
- **Additional Water Rights:** 1,400 AFY

This portfolio would require the following infrastructure components:

- Convey water from Buckman Regional Water Treatment Facility to injection well (new infrastructure required)
- Withdraw water from wells and distribution to customers (use existing infrastructure)

Buckman groundwater pumping exceeds the management target by 291 AFY. One notable result of this portfolio is in regards to the direct injection ASR. The model uses water first to fulfill required offsets for groundwater pumping, and any remaining water is used for direct injection. Portfolio 6 does not include direct reuse, so there is only enough water to meet offset requirements, and there is not enough to inject for ASR. Figure 3-5 illustrates that the maximum annual deficit is 553 AFY and the annual deficit at 10 percent probability is 161 AFY. Portfolio 6 meets two of the three reliability criteria as shown in Table 3-8, although the portfolio is very close to meeting all the criteria. Portfolio 6 was carried on for the performance criteria evaluation.

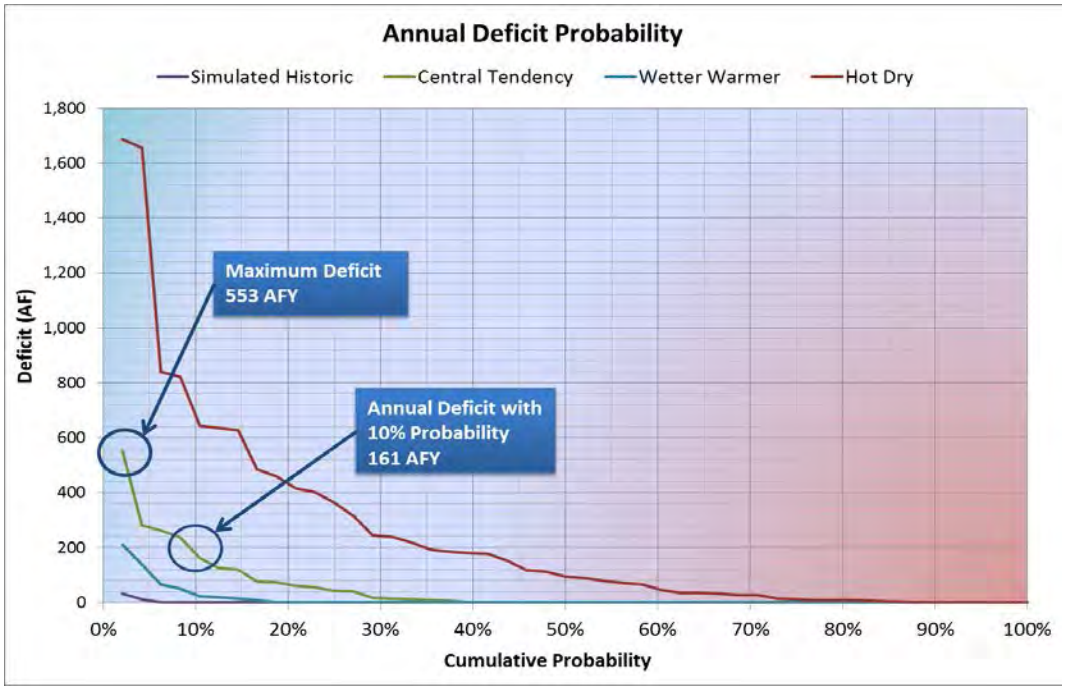


Figure 3-5. Santa Fe Basin Portfolio 6: More ASR annual deficit probability curve under central tendency climate scenario.

Table 3-8. Performance of Portfolio 6 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	**Maximum Annual Deficit <2000 AFY**	**Annual Deficit at 10% probability >100 AFY**
Portfolio 6: More ASR	YES (exceeds by 291 AFY)	YES (Maximum deficit is 553 AFY)	NO (Annual deficit at 10% is 161 AFY)

3.1.5.7. Portfolio 7: More Direct Reuse (Potable Use)

Portfolio 7 emphasizes direct reuse with the smallest decrease in conservation. Portfolio 7 has the following components:

- **Direct Reuse:** Meet 1,734 AFY of reclaimed water contracts, remainder to potable use
- **Conservation:** Small reduction in demand (10 gpcd)
- **Infiltration ASR in Santa Fe River:** infiltration in upper Santa Fe River (30 percent of river flow)
- **Additional Water Rights:** 920 AFY (assuming less water rights are available)

This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new infrastructure required)
- Treat water to drinking water standards at the Buckman Regional Water Treatment Facility and distribute to customers (use existing infrastructure)
- Withdraw water from wells and distribute to customers (use existing infrastructure)

Buckman groundwater pumping exceeds the management target by 323 AFY. Figure 3-6 illustrates that the maximum annual deficit is 211 AFY and the annual deficit at 10 percent probability is 32 AFY. Portfolio 7 meets two of the three reliability criteria as shown in Table 3-9, although the portfolio is very close to meeting the remaining criteria. Portfolio 7 was carried on for evaluation with respect to the performance criteria.

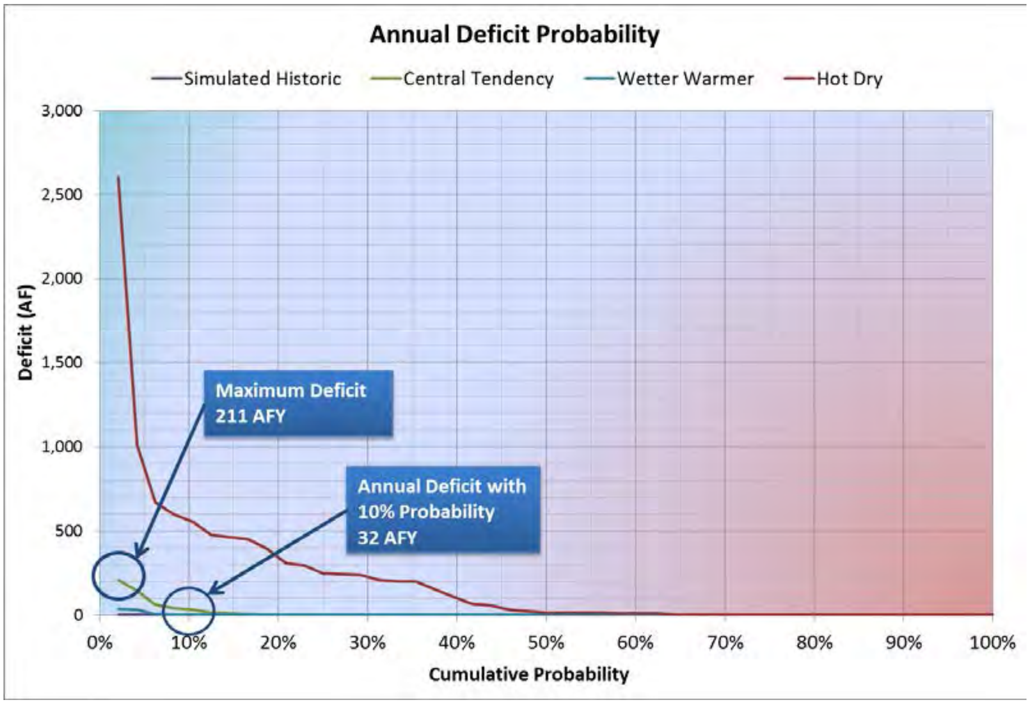


Figure 3-6. Santa Fe Basin Portfolios 7 and 8: More Direct Reuse annual deficit probability curve under central tendency climate scenario.

Table 3-9. Performance of Portfolios 7 and 8 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target <500 AFY	Maximum Annual Deficit <2000 AFY	Annual Deficit at 10% probability >100 AFY
Portfolios 7 and 8: More Direct Reuse	YES (exceeds by 323 AFY)	YES (Maximum deficit is 211 AFY)	YES (32 AFY annual deficit at 10% probability)

3.1.5.8. Portfolio 8: More Direct Reuse (Return Flow Credits)

Portfolio 8 is the same as Portfolio 7 except the treated water is returned to the Rio Grande for return flow credits. Therefore, the reliability results (Figure 3-4 and Table 3-7) are the same for these two portfolios.

Portfolio 8 meets all three of the three reliability criteria as shown in Table 3-9. Portfolio 8 was carried on for evaluation with respect to the performance criteria.

3.2. Evaluation and Comparison of Adaptive Strategies

The five combination portfolios (Portfolios 4 through 8) that meet or nearly meet the threshold of the reliability criteria were moved through the next step of the assessment process: evaluation with respect to the performance criteria. For consistency, the overall performance criteria are largely the same as those used for the Santa Fe Long-Range Water Supply Plan (City of Santa Fe 2008 [Water]), although they have been simplified for this Basin Study.

The performance criteria address multiple aspects of the water supply system and are both quantitative and qualitative. For each criterion, there is a corresponding performance measure that describes the metric that will be used to evaluate that criterion. Further, all criteria are not of equal importance. The method used to indicate the relative importance of the criteria is by assigning each a weight, as discussed in Section 3.2.6. Criteria Weighting.

3.2.1. Cost Considerations

This criterion addresses the cost of each portfolio. Developing cost estimates was not part of this Basin Study, so the cost considerations are qualitative estimates based on the amount of new infrastructure that would be required to implement the portfolio and the complexity of the operations for the portfolio. This criterion is the sum of three sub-criteria:

- **Capital costs**, which are the cost of construction and must be accounted for in the Capital Improvement Plan (CIP). Estimated based on number and type of new infrastructure required.

- **Operation and maintenance (O&M) costs** are an indication of the long-term costs of a portfolio, estimated based on complexity of the infrastructure components.

- **Potential for Cost Share** evaluates the degree to which the portfolio would be eligible for state or federal funding. Estimated based on features such as reuse and regionalization.

3.2.2. Reliability and Sustainability

This criterion applies to how well the portfolio performs with respect to providing water supply under different climate conditions and impact to groundwater supplies. Portfolios 4 through 8 met (or nearly met) the initial reliability criteria because of their performance under the Central Tendency climate scenario. This criterion looks at the performance of each portfolio under the Hot-Dry climate scenario to identify the portfolio that provides water supply under the range of projected climate conditions.

- **Drought Supply** measures the ability of a portfolio to supply adequate water under the Hot-Dry climate scenario. This is determined from the annual deficit probability curves produced by WaterMAPS.

- **Groundwater Use** assesses the impact of pumping groundwater. WaterMAPS provides the amount of water pumped from the Buckman Well Field, which is presented as the percentage above the management target and maximum pumping constraint.

3.2.3. Acceptance

This criterion is an expectation of the public acceptance of each portfolio. Two aspects of acceptance are provided: regulatory complexity and willingness of the public to accept the portfolio. Risk to human health is often correlated to regulatory complexity: low risk activities (e.g., pumping water) have simpler regulatory requirements than do high risk activities (e.g., treating reclaimed water for potable use). Public acceptance is broader, because it includes health and safety concerns (e.g., reclaimed water on athletic fields) as well as quality of life concerns (e.g., conservation at a 20 gpcd reduction).

- **Regulatory Compliance Complexity** assesses the effort, cost, and time to achieve and maintain regulatory compliance for a portfolio. This is a qualitative estimate based on the number of activities requiring regulatory permits in each portfolio.

- **Public Acceptance** assesses the perception of the public regarding the different components of each portfolio. This is a qualitative estimate based on national, regional, and local trends.

3.2.4. Environmental/Cultural

This criterion considers the impacts to the environment and cultural properties or practices associated with each portfolio. The criterion is made up of two sub-criteria: flow in the Santa Fe River and in the Rio Grande. The discharge from the City of Santa Fe wastewater treatment plant has provided flow in the Santa Fe River. Irrigators downstream of the plant depend on flow in the river. The riparian habitat is also supported by flow in the river. The Rio Grande has special species considerations so the impact of the portfolios on flow in the Rio Grande is included as a sub-criterion.

- **Flow in the Santa Fe River** is a measure of the extent to which a portfolio accommodates maintaining flow in the river below the wastewater treatment plant. WaterMAPs provides the projected flow after all modeled inflows and outflows.

- **Flow in the Rio Grande** assesses whether the flow in the Rio Grande is affected by the portfolio. This is a qualitative appraisal based on the inflows and outflows directly to the Rio Grande.

3.2.5. Technical Implementability

This criterion considers the extent to which the portfolios include commonly used technologies that are well understood, reliable, have accepted designs, and proven operational track records. Technologies that meet these standards are easier and less expensive to implement. For example, potable reuse scores lower than return flow credits for technical implementability because new or better technology may be needed to treat wastewater effluent to drinking water standards, and this technology will likely be more difficult to implement. This criterion is also intended to consider the appropriateness of the technologies for the climate and landscape of the Santa Fe area. Extent of infrastructure requirements and aging infrastructure were not considered as part of this criterion as these are mostly considered as part of the cost.

- **Technology Viability** is a measure of the robustness of the technologies incorporated in each portfolio. It is based on the qualitative assessment of the balance of established (easier to implement) versus newer (more difficult to implement) technologies in each portfolio.

3.2.6. Criteria Weighting

In any decision-making process, evaluation criteria are not all equally important and some criteria may be more relevant for a decision-maker than others. As an example, for a given individual, costs may be more important than the environmental/cultural considerations of an alternative. These relative weightings vary from person to person and community to community, reflecting different values, experiences, and opinions. Thus, weighted criteria representing the perspectives of a cross-section of the effected population are valuable as they reflect the range of values and preferences present in the community and customize the decision-making process for that community.

The weights were developed on a consensus basis by the City, County, and Reclamation. The criteria, performance measures, and weights are shown in Table 3-10.

Table 3-10. Performance Criteria, Performance Measures, and Criteria Weight

Performance Criteria	Performance Measure	Criteria Weight
Cost Considerations		**15%**
Capital Cost	Qualitative: estimate	40%
O&M Cost	Qualitative: estimate	40%
Potential for Cost Share	Qualitative	20%
Reliability and Sustainability		**25%**
Drought Supply	Quantitative: assessment of annual deficit probability curves	50%
Groundwater Use	Quantitative: average and maximum pumping compared to management target	50%
Acceptance		**10%**
Regulatory Compliance Complexity	Qualitative	50%
Public Acceptance	Qualitative	50%
Environmental/Cultural		**30%**
SF River Flows	Quantitative: flow in Santa Fe River	50%
Wetland Preservation	Qualitative	50%
Technical Implementability		**20%**
Technology Viability	Qualitative	100%

Chapter 4. Findings

Findings include the ultimate result of the analysis conducted for this Basin Study: a preferred adaptation portfolio to be used as a guide for working toward for addressing water supply deficits due to an increase in demand and impacts due to predicted climate change. This was accomplished by scoring and ranking the different water supply portfolios according to the criteria presented in Section 3.2. The scoring and ranking result is discussed in this next section followed by next steps and future considerations.

4.1. Scoring and Ranking of Water Supply Portfolios

The ranking process for the Santa Fe Basin Study was based on scoring each climate adaptation portfolio with respect to each of the performance criteria. A team composed of City and County staff, Reclamation, and CDM Smith completed scoring at a workshop and each score represents the consensus of the team.

All of the criteria were scored from 1 to 5:

- "1" equals worst, virtually impossible, infeasible, undesirable, highest cost
- "5" equals best, most easily implemented, most desirable, lowest cost

The weighted sum of the criteria was compared for each portfolio. The higher the score, the better the portfolio meets the cumulative criteria. The ranking of the portfolios, based on the consensus scoring and the criteria weighting, is displayed in Figure 4-1 and summarized in Table 4-1.

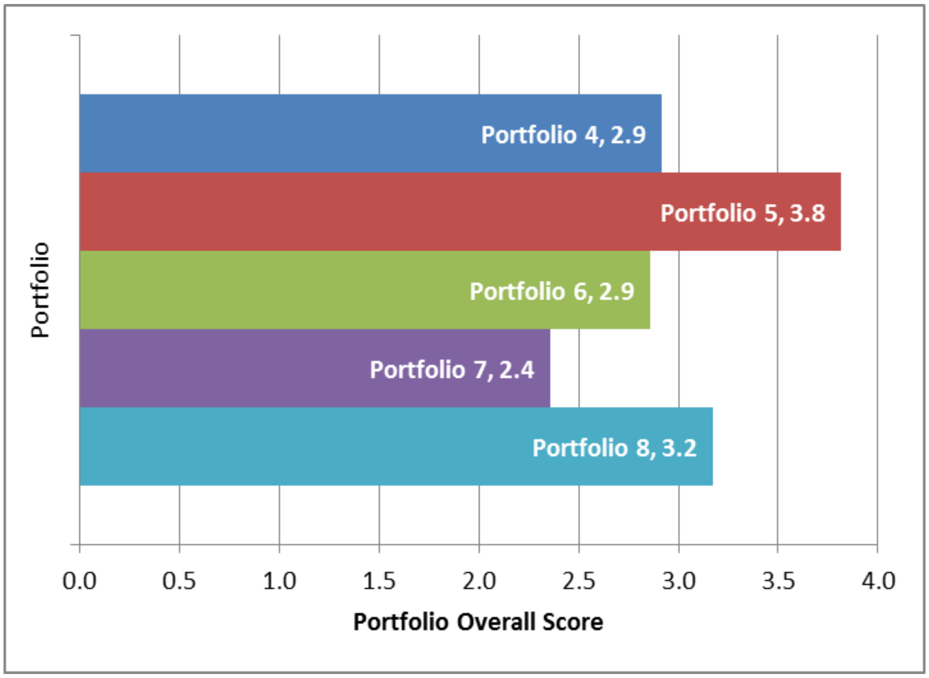


Figure 4-1. Ranking of Santa Fe Basin Study Portfolios.

Table 4-1. Scoring of Adaptation Portfolios

Criteria	Criteria Weights	4	5	6	7	8
		More Conservation & Water Rights (Reuse to Potable)	More Conservation & Water Rights (Reuse to Offsets)	More Infiltration ASR	More Direct Reuse (to Potable)	More Direct Reuse (to Return flow credits)
Cost Considerations	**15%**	**0.5**	**0.5**	**0.6**	**0.6**	**0.4**
Capital Cost	40%	3.7	3.7	3.8	3.5	3.5
O&M Cost	40%	3.9	3.5	3.5	3.8	3.1
Potential for Cost Share	20%	2	1	4	4	1
Reliability and Sustainability	**25%**	**1.3**	**1.3**	**0.5**	**0.5**	**0.5**
Drought Supply	50%	5	5	1	2	2
Groundwater Use	50%	5	5	3	2	2
Acceptance	**10%**	**0.2**	**0.5**	**0.3**	**0.2**	**0.5**
Regulatory Compliance Complexity	50%	1	5	2	1	5
Public Acceptance	50%	2	5	4	2	5
Environmental/Cultural	**30%**	**0.6**	**0.6**	**0.9**	**0.8**	**0.8**
Santa Fe River Flow	50%	2	2	4	2	2
Rio Grande Flow	50%	2	2	2	3	3
Technical Implementability	**20%**	**0.4**	**1.0**	**0.6**	**0.4**	**1.0**
Technology Viability	100%	2	5	3	2	5
Results		**2.9**	**3.8**	**2.9**	**2.4**	**3.2**

A relatively simple sensitivity analysis for the criteria weights was conducted because there was concern that costs were not weighted heavily enough compared to the other criteria. Portfolio 5 is the most highly ranked, and this analysis showed that the weight of the cost criterion does not change that outcome. This is true even when the cost criterion is increased to 50 percent or reduced to zero. This result provides confidence that Portfolio 5 best meets the criteria, whether costs are considered or not.

The ranking of the portfolios clearly shows that Portfolio 5, with an overall score of 3.8, meets the performance criteria better than the other alternatives (Figure 4-1). Portfolios 4 and 5 scored highly in Reliability and Sustainability because they provide an adequate water supply under the Hot-Dry climate scenario while maintaining groundwater pumping near the management target. However, Portfolio 5 scored higher for Acceptance and Technical Implementability because the reclaimed water is used for return flow credits rather than potable use as in Portfolio 4. The second ranked portfolio, Portfolio 8, did not perform well in Reliability and Sustainability, but it scored higher in Environmental/Cultural and Acceptance because it includes use of reclaimed water for return flow credits, which would augment the flow in the Rio Grande in the short-term while allowing for additional groundwater pumping.

One common element of the three highest ranked portfolios is increased use of reclaimed water. This suggests that the City and County focus efforts to use reclaimed water from both the City wastewater treatment plant and the County's Quill wastewater treatment plant. The three highest ranked portfolios also use the maximum number of adaptive strategies, demonstrating the value of a multi-faceted approach to achieving climate change mitigation goals for the Santa Fe region.

4.2. Current and Ongoing Activities

The Santa Fe community is collectively engaging in a number of actions that have already increased the ability of the collective watershed- humans included- to respond and adapt to projected changes. These current or ongoing actions include:

Water Management

Reclaimed water use

Storm-water management

Emergency response capacity

Conjunctive use of water

Water for ecosystems

Improved water quality

Domestic well restrictions
Storm water retention

Education and Planning

Water supply planning

Education and outreach

Public involvement

Regional cooperation

Water conservation

Monitoring

Art-inspired actions

Aquifer storage / recovery

Drought management plans

Energy-wise building codes

Local and renewable energy

Land and Agriculture

Forest thinning

Riparian restoration

Seed sovereignty

Small-scale land shaping

Urban forests

Land preservation

Irrigation efficiency

Locally-sourced food

Urban gardening

Arroyo stabilization

Preservation of green spaces

Rangeland improvements

4.3. Next Steps and Future Considerations

The City and County will continue to work together to develop future water supplies to fill the water supply gap identified as part of this study. Reliability results from the modeling and the performance assessment indicate that Portfolio 5 should be further investigated and potentially pursued. Portfolio 5 includes the following adaptation strategies:

- Use of reclaimed water (potentially in the form of return flow credits)
- Water conservation
- Direct injection and infiltration ASR
- Obtain additional water rights

One of the primary adaption alternatives is to “augment potable water supplies with reclaimed wastewater” as described in the report, Climate Change and the Santa Fe Basin: A Preliminary Assessment of Vulnerabilities and Adaptation Alternatives Bureau of Reclamation WaterSMART Program Initiative (February, 2013) and the RWRP for the City (April, 2013) which identified potential alternatives to using reclaimed water as a supply source. City Council Resolution 2013-55 was enacted and approved and directs City Staff to pursue opportunities to evaluate and implement engineering and cost analysis of using reclaimed water alternatives to supplement water supplies.

In addition, the City and County were awarded a grant through Reclamation’s Title XVI Program to conduct a water reuse feasibility study in June, 2014. The water reuse feasibility study will evaluate ways to cost-effectively use its reclaimed wastewater in a more efficient manner and will consider both potable and non-potable alternatives to meet water demand requirements while better balancing environmental conditions in the watershed This is the next necessary step to accomplish City and County water management goals of diversifying its supply portfolio and build in greater system resiliency.

Chapter 5. Disclaimers

While the best available information and consistent methodology was used in developing this Basin Study, projections into the future require many assumptions and result in inherent uncertainty. While this is necessary and appropriate for planning-level analyses, additional, more detailed feasibility- and design-level studies are required when implementing some of the adaptation strategies identified. The purpose of this study is to provide a reasonable path forward based on the best information available. Some specific items to note are discussed below:

- Climate change impacts on groundwater supply were not explored for this Basin Study. The analysis accounted for likely reductions in groundwater supply through the use of management targets, which are significantly less than actual water rights.

- Water rights, management targets, and capacity constraints are changing annually and must be verified before utilizing in future studies or planning of projects.

- The predicted water supply gap is sensitive to population projections, which were not closely studied as part of this Basin Study. The future water service area for the County is not well known. Previous studies and input from the project team members was relied upon for this information.

The Santa Fe Basin Study was funded jointly by Reclamation, the City of Santa Fe and Santa Fe County, and is a collaborative product of the study participants as identified in Section 1.4. Coordination and Participants. The purpose of the study is to assess current and future water supply and demand in the Santa Fe Basin and other basins providing water to the City and County, and to identify a range of potential strategies to address any projected imbalances. The study is a technical assessment and does not provide recommendations or represent a statement of policy or position of Reclamation, DOI, or the funding partners. The study does not propose or address the feasibility of any specific project, program or plan. Nothing in the study is intended, nor shall the study be construed, to interpret, diminish, or modify the rights of any participant under applicable law. Nothing in the study represents a commitment for provision of Federal funds. All cost estimates included in this study are preliminary and intended only for comparative purposes.

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July 11, 2012

Preliminary Assessment Report: Climate Change and the Santa Fe Watershed

Bureau of Reclamation WaterSMART Program Initiative

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Bureau of Reclamation **City of Santa Fe** ***Santa Fe County***

Prepared by:

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Executive Summary

Under a Bureau of Reclamation (Reclamation) WaterSMART Program Initiative, the City and County of Santa Fe have collaborated with Reclamation to conduct a preliminary assessment of system vulnerabilities to climate change in the Santa Fe Watershed and consider alternatives for creating a more resilient watershed. To understand the systems that are relevant in the Santa Fe watershed, members of the community were invited to learn about the impacts from climate change that are predicted for the area and to provide their insight into how the predicted changes may affect the systems that they are most concerned with. This report captures the expertise of the authors and presenters, as well as the information gathered at a one-day workshop held in Santa Fe on March 6, 2012 with 120 participants.

Predicted impacts for the watershed include:

- Reduced stream flow due to greater evapotranspiration and thus less runoff;
- Diminished snowpack, and earlier spring melt of existing snowpack;
- Earlier peak snowmelt runoff and lower peak flows;
- Drier mid- to late-summers;
- More severe and more frequent droughts; and
- More intense precipitation events that increase peak storm flows, with an accompanying potential for more sediment transport and erosion and further degradation of the Santa Fe River.

Participants worked in small groups to describe physical, biological and socio-economic systems within the Santa Fe Watershed, particular vulnerabilities of those systems, and solutions for creating more resilient systems, and ultimately, a more resilient watershed. The systems range from forest ecosystems to farms to transportation and energy systems. The vulnerabilities are numerous, including the increased risk of catastrophic fire, flooding, and erosion.

Fortunately, the Santa Fe Watershed has benefited from numerous projects that will enhance the system resilience under climate change. These projects, such as forest thinning, riparian restoration, and storm water management, could be mapped in order to highlight and prioritize the areas needing additional restoration or treatment.

1 Purpose

The purpose of this report is to preliminarily assess the vulnerabilities of systems in the Santa Fe watershed to climate change based on input obtained during a March 6, 2012 workshop and from research conducted by the authors. This Preliminary Assessment Report identifies "qualitative climate-change impacts on water supply sources, ecosystems, quality of life, agriculture and local food production, landscapes, land use and water demand" as directed by a Memorandum of Agreement between the partners (Reclamation et al., 2011). It is part of a larger Basin Study under Reclamation's WaterSMART Program, and as such evaluates the extent to which changes in the water supply will impact fish and wildlife habitat, listed endangered species, water quality, and flow- and water-dependent ecological resiliency, in partial fulfillment of the requirements in Element 2 of Reclamation's Basin Study Framework.

> ***"Deep, crushing cycles of drought are part of the natural history of the Southwest and, for all practical purposes, they always have been. Building resilience against drought into the region's water systems and cultural practices would be a wise course, irrespective of the cause or timing of the next emergency. Perhaps the dangers now arising from anthropogenic climate change will goad us into doing the things we should have been doing all along… to strive for resilience,--the capacity of an ecosystem to experience disturbance without losing its essential character and becoming something else."***
>
> ***Bill deBuys, 2011***

1.1 Introduction

Climate change may alter many aspects of life in the Santa Fe basin, including the availability of water to the city and county, as well as the health of forests and other ecosystems. To prepare for these changes, the City of Santa Fe, Santa Fe County and the Bureau Reclamation are partnering on a Basin Study through the US Department of Interior Bureau of Reclamation Water SMART Initiative Basin Studies Program (Reclamation, 2011). Through the Santa Fe Basin Study, of which this report is one component, the partners seek to:

1. assess the projected impacts of climate change on the Santa Fe watershed and on the City and County's water supplies;
2. quantify the potential impact of climate change on the potentially available water supply from each of the three sub-basins that supply surface water to the City and the County (the Santa Fe River Basin, the Upper Rio Grande, and several tributaries to the San Juan); and

3. assess the vulnerability and possible shortcomings of the current long-range water supply strategies; and
4. evaluate new mitigation and adaption strategies and integrate them into the region's water supply plan as necessary.

The results of this study will be presented to the Public Utilities Commission in the hope that the information gathered can inform efforts to create a more resilient community. The initial part of this study calls for public input and the preparation of a preliminary assessment report of qualitative climate change impacts on water supply sources, ecosystems, quality of life, agriculture and local food production, landscapes and land use, and water demand.

> ***"It stands to reason that a grassland with a diversity of grasses--some that flourish with fourteen inches of rain, some that prosper with just eight--will fare better through fluctuating conditions than will a monoculture of a single species."***
>
> ***Bill deBuys, 2011***

To seek stakeholder input, the project partners sponsored an interactive workshop, held on March 6, 2012 in Santa Fe, in which federal, state, local, private, and non-profit groups and individuals were invited to contribute to and gather information for this preliminary assessment report. Workshop goals were to identify vulnerabilities in human and non-human systems and to assess how climate change may affect these systems. . The focus of the workshop was primarily on system resilience and adaptation, versus mitigation measures. The Santa Fe River watershed was specified as the system boundary, which allows for a more holistic approach to the analysis of system impacts and the development of potential solutions. The use of a systems approach to the analysis of vulnerabilities and adaptations allowed consideration of impacts and solutions in smaller units and scales; although it was recognized that interconnections and overlap between systems may not be completely captured. Climate-change experts provided the foundation for the workshop by giving a summary of climate-change projections for the Santa Fe Watershed, the southwestern forest response to drought and the historical and sociology impacts of climate change.

Breakout groups provided input on a range of climate-change impacts of various physical, biological and socio-economic systems within the Santa Fe Watershed. Groups were asked to identify how climate change may threaten a system of concern, begin prioritizing how those risks should be responded to, and brainstorm initial adaptation actions that can be taken at the city and county-level to build resilience to those systems in the face of those impacts.

This report also summarizes the many present and past activities in the watershed that are already building resilience in our watershed. It is our hope that this report will also serve as an educational tool for decision makers and the public of the ways that a community might prepare for climate change.

1.2 Background

The Santa Fe River originates near Lake Peak at an elevation of 12,408 ft. in the Sangre de Cristo Mountains and flows to the west through the City of Santa Fe and down to the Rio Grande at 5,220 ft. elevation (Figure 1). The Santa Fe Watershed is approximately 256 square miles and includes many ephemeral channels such as the tributaries of Arroyo Hondo, Arroyo de los Chamisos and Arroyo Mascaras.

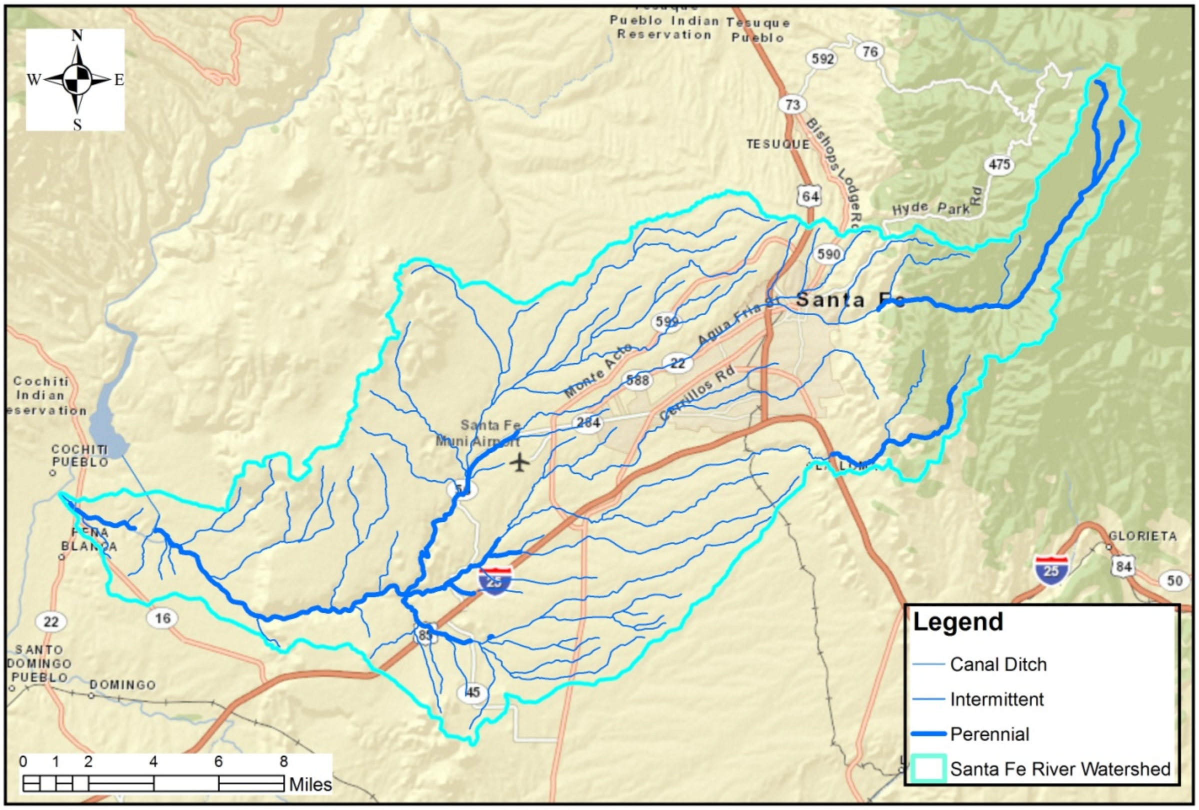

Figure 1. Aerial view of the Santa Fe Watershed.

1.3 Relationship to Other Planning Efforts

This assessment is intended to complement numerous other planning efforts in the Santa Fe community that seek to enhance sustainability or resilience. In the city and county of Santa Fe, such efforts include the City's Sustainable Santa Fe Commission and the County's Sustainable Growth Management Plan.

The City adopted a Sustainable Santa Fe Plan (SSFC, 2008) in 2008, which is associated with the U.S. Mayors Conference on Climate Change, and identifies ways that community could prepare for the effects of global warming. While the focus of the Sustainable Santa Fe Plan is on community and municipal actions to reduce carbon emissions (mitigation), the Plan has an insightful list of potential adaptation actions, including local food production. The Annual report of 2010 Activities highlights progress in establishing more local food production, in part through new community gardens, and increased education and outreach.

The Santa Fe County Sustainable Growth Management Plan (SFCO, 2010) was developed to provide direction for future growth and sustainable development through the adoption of goals and policies. One of the key issues identified is the environmental impacts and resource scarcity that is likely to result from shifting climate patterns. With limited acreage (about 15,000 acres) of irrigated land within Santa Fe County, several strategies were developed to enhance food security, protection of water resources and greenhouse gas management were adopted to improve the potential for local and economic sustainability. Efforts and other incentives that promote efficient water uses and farming techniques and protection of indigenous food sources which are resilient to drought are key strategies adopted by Santa Fe County.

Santa Fe County established the Office of Renewable Energy and Energy Efficiency in the spring of 2011 (http://www.santafecountynm.gov/public_works/energy). Through investment in renewable energy and energy efficiency education and technical assistance, Santa Fe County proposes to reduce energy use and greenhouse gas emissions. Additionally, an energy-efficient green building code will promote energy efficiency, water conservation and renewable energy improvements to existing and proposed developments.

Definitions

Systems – include both infrastructure (e.g. food supply, water supply, transportation, energy, shelter, communication, health, education, finance) and ecosystems (e.g. agricultural land, parks, wetlands, rivers, range land, forests) that provide services or functions for humanity.

Vulnerability – the underlying fragility or weakness in a system that leaves it open to harm or damage; for example, a drinking water system serviced only by surface water supplied from one small river is highly vulnerable to drought.

Resilience – the capacity of a system to absorb disturbances, and still have the same basic structure and ways of functioning OR to elegantly anticipate and move to a new a way of functioning. A resilient system is flexible and modular (e.g. a forest can be made more resilient through thinning and/or prescribed burns which reduce the stressors that could cause it to fail during a wildfire). In people, resilience is the ability to cope with stress and adversity.

Adaptation – taking action to minimize the impact of, take advantage of, or cope with changes that are occurring or are expected to occur.

Mitigation - an act that lessens the intensity or force of something unpleasant; the act of making a condition or consequence less severe. In relation to climate change, mitigation usually refers to actions to decrease greenhouse gas emissions.

2 Climate Change: What the Science Says

There is no longer any doubt that our climate is changing.

Human activities are increasing concentrations of greenhouse gasses such as carbon dioxide and methane in the atmosphere, and these gases are trapping increasing heat near the Earth's surface. In response, global average air temperatures near the Earth's surface are rising, oceans are warming and expanding, land-based ice is melting, sea ice is thinning and permafrost is melting, precipitation patterns are shifting, and plants and animals are growing, migrating, and responding in different ways, places and times. The evidence for climate change that is being documented in the world around us is concordant with the climate science and physics captured in global modeling; there is no longer any doubt that our climate is changing. A detailed description of the climate science is provided in Appendix C.

The releases of greenhouse gasses that have occurred to date commit us to a certain degree of climate change, regardless of future emissions.

The greenhouses gasses that have been released to date commit us to a certain degree of climate change, regardless of future emissions; and, currently, global emissions are accelerating rather than decreasing, and therefore we are committing ourselves to increasing warming. This means that, in addition to working to limit future emissions and associated warming, we will need to adapt to existing and at least near-future climate changes.

The goal of the Preliminary Assessment Workshop was to introduce climate change and its potential impacts in the Santa Fe Basin to a broad group of local stakeholders, and to solicit from those stakeholders their primary areas of concern and their initial thoughts about how to take action. This section discusses the impacts climate change is likely to have on the Santa Fe Basin.

2.1 Climate Change Projections for Santa Fe Basin

Climate change is already occurring in the Santa Fe Basin, as evidenced by measured temperature increases. Average temperatures in the watershed have risen about 2 ^{o}F since 1900. Continuing CO_2 emissions around the world will trap additional heat near the Earth's surface, so that temperatures will continue to rise for the foreseeable future, in the Santa Fe watershed and elsewhere. Global climate models (called General Circulation Models, or GCMs) project that air temperatures in the Santa Fe Basin could increase an additional 5.5 to 6.5 ^{o}F by 2100 (Figure 2).

Increasing temperatures impact the circulation of moisture in the atmosphere, which it turn impacts precipitation patterns. Though models suggest that the amount of precipitation that falls in the Santa Fe watershed may remain relatively unchanged, when and how it falls is likely to shift. The combination of increasing temperatures and changes in precipitation patterns will significantly impact Santa Fe and surrounding communities, lands and ecosystems.

There are three primary elements of climate change that will have direct impacts on, and associated implications for, water resources in the Santa Fe Basin: 1) rising temperatures, 2) changes in precipitation patterns, and 3) increases in climate variability.

These changes are not going to be smooth, steady changes over time. Instead, climate change is expected to increase the variability of our already extremely variable climate. Currently, record wet spells can be followed by record droughts; record hot-summers followed by record winter cold-spells. Climate change is likely to bring even more variability, with even higher high temperatures and with more variability within and between seasons and from year to year. Spring and fall weather may become even more mercurial, with implications for plant survival and growth. Individual precipitation events may become more intense, while dry periods become longer and hotter. These impacts will exacerbate the already formidable water-management challenges in the Santa Fe basin, and may also create new water challenges.

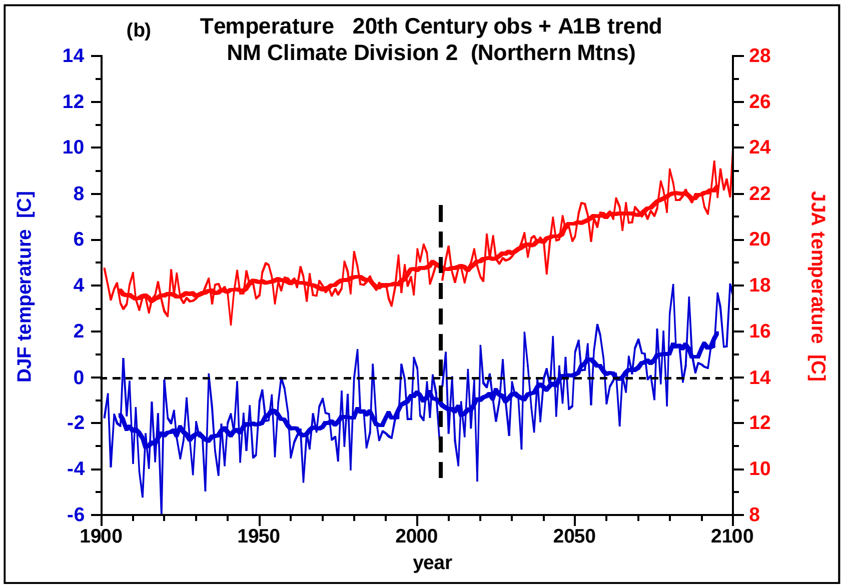

Figure 2. Temperature for winter and summer seasons, 1900 to 2100.

2.2 Climate Change Impacts to Santa Fe Basin Hydrology

Projected changes in temperature and precipitation will have implications for summer aridity, for winter precipitation (increasingly falling as rain rather than snow), and for spring snowmelt runoff timing and volume (Figure 3).

Global climate models project a transition to a much more arid climate in the Southwest by the mid-21st Century, primarily due to increasing rates of evaporation and increasing water use by plants, which will result from the projected higher temperatures. Evaporation and plant water use are directly related to surface temperature; warmer air holds more moisture. If precipitation remains relatively constant and evaporation and plant water use increase, then surface runoff and groundwater recharge will decrease. Irrigation water demand and riparian water consumption will increase, and non-irrigated vegetation will likely become water stressed.

All systems that depend on water are vulnerability to water availability, changes in the timing of water availability, sensitivity to high or highly variable

Higher temperatures will also impact winter snowpack depth and spring snowmelt timing and volume. Climate models project decreases in snowpack throughout the western mountains because, as temperatures increase, more winter precipitation is expected to fall as rain rather than snow. By mid-century, the Southern Rocky Mountains are projected to experience a 20 to 70% reduction in snowpack.

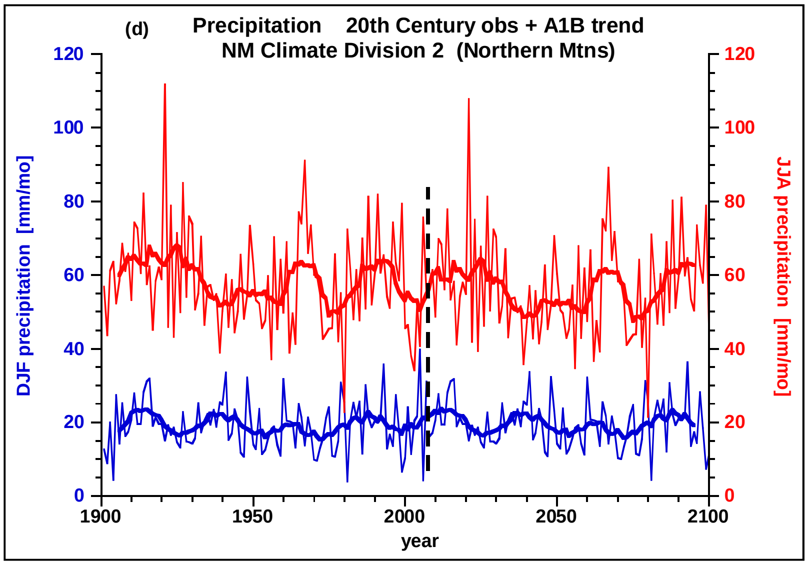

Figure 3. Annual precipitation for winter and summer seasons, 1900-2100.

What snow does fall will melt earlier, due to higher spring temperatures, rain falling on snow, or intense spring windstorms blowing dust onto the snow, making it absorb more sunlight and melt faster. By 2050, spring runoff could be 15 to 35 days earlier than it was under pre-development conditions. This much-earlier peak runoff date, driven by warmer temperatures, may also have lower peak flows, due to less snow. This earlier runoff may fill McClure and Nichols reservoirs over a relatively brief period and then overflow the reservoirs and continue downstream. Therefore, even if the total runoff were comparable to average historic supply, much of this water may become unavailable, and therefore may cause the Santa Fe water supply to be short more often.

Snowpack currently feeds a late-spring flood pulse on the upper Rio Grande and its tributaries. In their 2008 paper, Hurd and Coonrod found that in the warmer climate projected for New Mexico; there would be an earlier and smaller snow-fed flood pulse, and a reduced total stream-flow volume, especially in the late spring to early summer. Their projected reductions in flow for the Middle Rio Grande are (Hurd and Coonrod, 2008):

- 2030: 4 - 14% reduction
- 2080: 8 - 29% reduction

Santa Fe River stream-flow projections are similar to those for the Middle Rio Grande. Cox et al., in their 2011 modeling analysis, project an annual decrease in stream flow above McClure Reservoir of 11-18% by 2060 compared to the historic record from 1950 to 1999. These temperature and precipitation projections, and their associated impacts to snowpack, snowmelt, stream flow, evaporation and plant water use, have significant implications for virtually all water-related systems in New Mexico. Reservoir storage and river operations will be impacted by changes in volume and timing; these in turn will impact water availability for urban, agricultural and ecosystem use. Changes in precipitation intensity and snowpack may further impact groundwater recharge. As a result, all systems that depend on water will need to be evaluated for their vulnerability to reduced water availability and changes in the timing of water availability, and for their sensitivity to high or highly variable temperatures, aridity, and drought.

"Potential Effects of Climate Change on New Mexico", Technical State Agency Working Group, State of NM, 2005

The projections of future New Mexico climate presented below rely heavily on the evaluation of climatologists with expertise in southwestern climate (Gutzler 2005, Overpeck 2005). These projections are for the late 21st century and are based on the assumption that global anthropogenic emissions of greenhouse gases continue to increase in a "business as usual" fashion, with no measures undertaken to reduce emissions globally:

Temperature

- Average New Mexico air temperature substantially warmer
- Greater warming of winter temperatures, nighttime minimum temperatures, and higher-elevation temperatures
- More episodes of extreme heat
- Fewer episodes of extreme cold
- Longer annual frost-free periods

Precipitation

- A higher proportion of winter precipitation falling as rain; earlier snowmelt where snow still accumulates
- More extreme events (torrential rain, severe droughts)
- Potential exacerbation of historical patterns of wet and dry cycles, including likely recurrence of multiyear drought (like the 1950s)

2.3 Case Study: Southwestern US Forest

> ***"By 2050, average summer temperatures may equal those of the worst drought years that the Southwestern U.S. has experienced in the past 1,000 years."***
>
> **Dr. Park Williams**

A particularly arresting example of the potential for cascading impacts of climate change is the predicted effect of increasing temperatures on Southwestern forests. Dr. Park Williams, who spoke at the workshop, has been studying how forest fires correlate with rates of water use by plants, winter snowpack, drought indices, and pine beetle outbreaks. He has found that all of these factors are strongly correlated; dry winters coupled with dry, hot summer conditions stress the trees, making them more susceptible to pine beetles and more prone to forest fires.

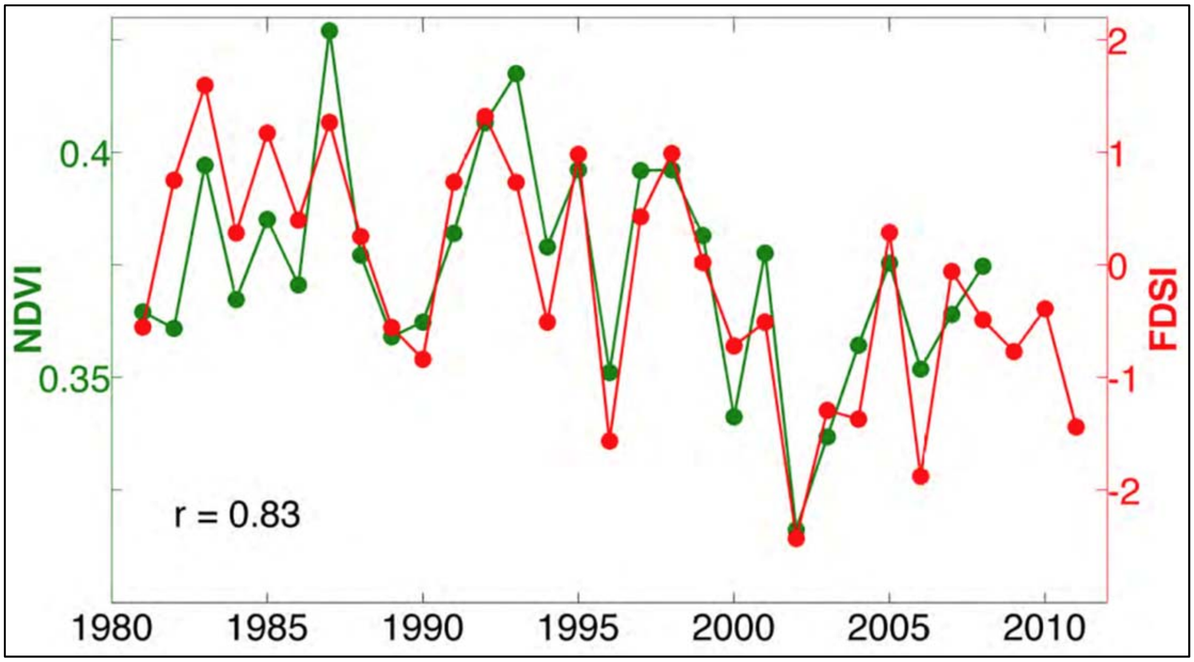

Figure 4. Correlation between summer vegetation greenness index (NDVI) and the Forest Drought-Stress Index (FDSI) (Williams, 2012).

Dr. Williams used this information, combined with historical data from tree rings, to develop a "forest drought stress index" (Figure 4). Low index values indicates conditions prime for forest fires. The index was particularly low in northern New Mexico in 2002, 2006, and 2011, all years with particularly high fire damage in this region. New Mexico experienced the worst fire season on record in 2011, when the Los Conchas fire burned 150,000 acres in the Jemez Mountains. The Pacheco fire burned about 10,000 acres in June 2011 and came within two miles of the Santa Fe Watershed.

If climate models are correct, by the 2050s average drought stress will equal that of the worst drought years that the Southwestern U.S. has experienced in the past 1000 years.

Drought-induced forest fires are normal in New Mexico. For example, tree-ring data suggest that regionally extensive droughts in the late 1200s and late 1500s caused increased forest fires throughout the Southwestern U.S., also periods for which Dr. Williams' calculated the forest drought severity index to be low. However, climate projections suggest index values will become more negative in the future. By about 2050, Dr. Williams predicts that forest drought stress index values for even the wettest, coolest years will equal or exceed the values experienced during the 1200 and 1500 "mega-droughts", the 1950s drought, and the recent 2002, 2006 and 2011 summers. By 2050, average conditions will equal that of the worst drought years that the Southwestern U.S. has experienced in the past 1000 years (Figure 5).

In the near future, forest fires are likely to become more frequent, and possibly larger (depending on how we manage our forests). These forest fires in turn affect the stability of the landscape. The more intense rainstorms that are expected are likely to increase erosion, and cause the accumulation of ash and sediment in our rivers. As we saw in 2011 with the severe erosion following the Los Conchas fire, these changes can prevent the use of surface water for drinking by communities such as Santa Fe for many months.

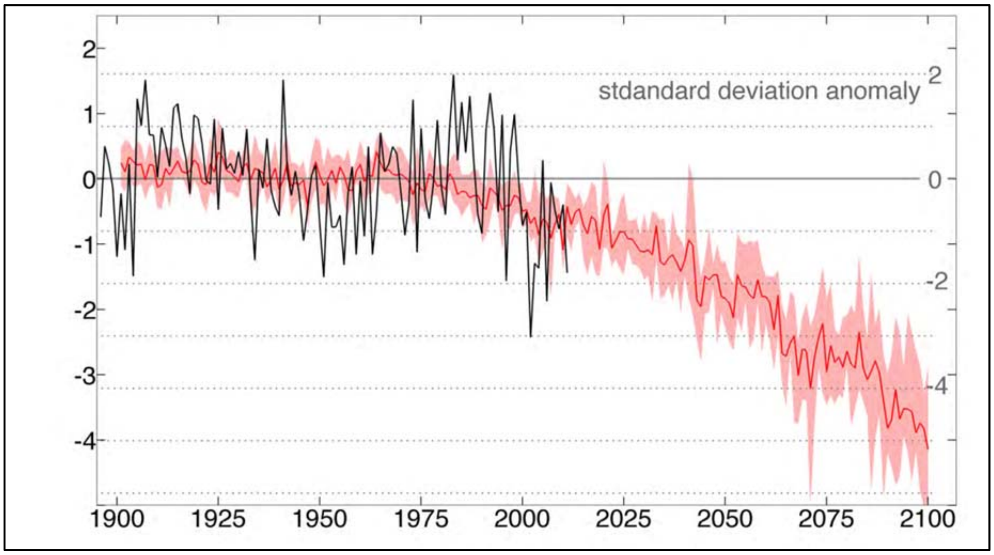

Figure 5. Projected and historic FDSI derived from measured data (black).

Within a few decades, maintaining ecosystems as forests, rather than allowing conversion to scrublands or grasslands, may only be possible in wetter or otherwise milder climatic niches. Other areas will convert to non-forest vegetation types.

2.4 So What Next?

The projected impacts of climate change include:

- Lower stream flows due to both less runoff and greater water use by plants;
- Diminished snowpack, and earlier snowmelt of existing snowpack;
- Drier spring seasons, with earlier peak runoff and lower peak flows;
- Drier mid- to late-summers;
- More severe droughts;
- More intense precipitation events, with an accompanying potential for more sediment transport and erosion and for declining aquifer recharge; and
- Loss of ponderosa and mixed-conifer forest ecosystems.

All of these impacts are primarily temperature driven, and are expected to occur even if there are no significant changes in annual precipitation. These impacts are virtually certain; however, because climate modeling provides us with **projections**, not **predictions,** we are not able to specifically predict the impacts or their timing.

Global circulation models are mathematical representations of our best understanding of the critical processes that drive our climate. The models are run for a series of greenhouse-gas emissions scenarios that we think are plausible potential futures. The result is a range of model outputs that we hope capture the conditions we are likely to experience in the future. However, since the future greenhouse-gas emissions will be determined by human and societal behavior, we cannot say with certainty where, within that range we will fall. Nor can we say whether we have captured the full range of possible futures.

So, we are left with irresolvable uncertainty. And, because much of this uncertainty is dependent on which future pathway humanity chooses, we will be unable to fully resolve it. However, the level of uncertainty around climate is no greater than uncertainty around population projections, economic forecasts, and technological changes, and yet we regularly conduct planning dependent on those variables. We have enough information about future climate to begin planning for and addressing it.

Bill deBuys describes the temptation to sink into despair when faced with the reality of climate change in the Southwest. In deBuys' book *A Great Aridness* (deBuys, 2011) he describes the work of numerous researchers and their study of the impacts of climate change that are already being felt in the Southwest. He says that we may already be in a mega drought, and can only know after several decades have passed, and:

"In a way, our decisions for the future should be the same, no matter whether we are a few years inside a mega drought or lucky enough to have decades of relative abundance ahead of us. Deep, crushing cycles of drought are part of the natural history of the Southwest and, for all practical purposes, they always have been. Building resilience against drought into the region's water systems and cultural practices would be a wise course, irrespective of the cause or timing of the next emergency. Perhaps the dangers now arising from

anthropogenic climate change will goad us into doing the things we should have been doing all along… to strive for resilience,--the capacity of an ecosystem to experience disturbance without losing its essential character and becoming something else. It stands to reason that a grassland with a diversity of grasses--some that flourish with fourteen inches of rain, some that prosper with just eight--will fare better through fluctuating conditions than will a monoculture of a single species."

"There is only the age-old duty to extend kindness to other beings, to work together and with discipline on common challenges, and to learn to live in the marvelous aridlands without further spoiling them."

3 Public Participation

The daylong workshop generated an inspiring amount of interest and engagement from a broad cross-section of community members. Within 24 hours of the workshop announcement, registration was half-full, and it was full, with a waiting list, a week before the event. Event attendance was capped at 120 participants, to ensure that all attendees could be engaged in and actively contribute to small-group breakout discussions and large-group conversations. Participants were from a wide range of backgrounds, with 40 percent from state, tribal, federal and local governments, 26 percent from non-profit organizations, and the remainder private citizens or environmental consultants. The participant list is included as Appendix B.

3.1 Engagement & Small-Group Discussion

The community in Santa Fe has thought extensively about both water and climate change. Most attendees came to the workshop with at least some background knowledge about climate change, potential climate change impacts, and possible responses. They also came with prior knowledge and concerns about water, water demands, and potential solutions for current water issues. Workshop organizers capitalized on this expertise and experience, setting an ambitious agenda for the day.

The workshop asked a lot of participants: to learn new technical information; to work in small groups along with people they did not know; to break water basin management down into components that were unfamiliar; and then, to collaborate to identify and prioritize possible solutions. Attendees' ongoing engagement throughout the day indicated commitment, interest and concern about the issues of water management and climate change.

The day began with a series of presentations about climate change, ranging from the big-picture projections of impacts to Santa Fe, to a fairly technical picture of how climate change could impact local forest ecosystems that illustrated how climate science is conducted, to a broad overview of the social ramifications and ways that we, as individuals, might choose to engage with what is perhaps humanity's greatest challenge.

Following the early-morning plenary presentations, participants chose themed breakout groups in which to participate. There were two sessions of small group conversation: in the first, participants chose between breakout groups themed around water or ecology; in the second, participants chose between land use; quality of life and agriculture; and food security. Themes were intentionally broad to allow participants to explore the issues they found most relevant. Within the breakout groups, participants were further divided into tables of about 10. Table groups were asked to work together to identify key systems of interest, current vulnerabilities of those systems, how vulnerabilities would be intensified or change in response to climate change, and key thresholds at which, under the strain of climate change, those systems would be stressed to a point of lasting damage. Because attendees came from diverse professional and personal backgrounds, they came with a variety of interests, agendas and expectations of the event. The small-group conversation offered an opportunity for participants to speak to what their own interests were, and to listen to the particular interests that others brought to the table. Through the opportunities in small-group conversation, participants quickly identified that there were many, and diverse, competing interests and agendas for water management. The comprehensive experience of the small groups exposed the challenges inherent in reducing complex systems to their component parts.

The breakout groups demonstrated an impressive capacity to engage in high-level mapping of water management as a complex, adaptive system. Conversations in break-out groups repeatedly highlighted that important systems are interrelated and that a reductionist approach, identifying singular points of action without taking into account holistic interactions, would be doomed to fail. The groups expressed an expectation that resilient water management be holistic, and indicated the capacity of the community to collaborate and learn.

Two themes came clearly through the reflection on systems: that comprehensive, holistic approaches to watershed management are essential; and that social, cultural and political change is critical to achieving the physical system changes that are needed. Workshop participants were clearly comfortable with the idea that change will need to be facilitated at individual, group, and community scales and encompass both behavioral changes and learning. Participants were enthusiastic and supportive of suggested solutions that hinged on innovative learning, the growth of Santa Fe as a community, and a change in the community's relationship to water.

3.2 Generation and Prioritization of Solutions

Following two rounds of themed breakout sessions, the workshop closed with a plenary session in which participants were asked to discuss solutions and identify priority actions. Attendees enthusiastically offered a wide and creative range of approaches to diverse problems associated with water management. The more readily actionable solutions are presented and discussed in Section 5; the full list of proposed activities is included as Appendix D.

During this brainstorming and prioritization of solutions, it became clear that there is a lot of work already underway at different levels in the community around climate change, sustainability, resilience and water. Much could be accomplished through collaboration and communication between these efforts, and any that grow out of the workshop, to develop and share emerging solutions. Chapter 5 describes potential solutions that were suggested in the workshop, along with efforts that are already underway.

Overall, the workshop demonstrated that there is great energy and potential for sustainable change in the Santa Fe community. A common interest was expressed in working toward a future that reflects that sustainability, along with an understanding that getting there will require collaboration, education, and ongoing engagement.

3.3 Workshop Follow-up

Responses from one-on-one conversations during the workshop, from workshop evaluation forms, and from emailed feedback from participants paints a picture of a community with core capacities for managing change and a willingness to engage the challenges of the future. Throughout the workshop, participants willingly learned from each other. Many participants offered feedback that they had a better understanding of the complexity involved in engaging different perspectives and managing competing agendas than they did at the beginning of the day. From the presentations in the morning, participants shared that they enhanced their understanding of the urgency, and imminent reality of the drastic changes in the environment that are likely to result from changing climate. Though the day was challenging, by the end of the day people also expressed the strength of their convictions and commitment to continue to work towards greater resilience for the watershed, and shared the sense that everyone was in it together. Participants wanted to learn what others were doing, what projects are underway or planned for implementation, and what opportunities for engagement and learning are being generated.

4 Systems and their Vulnerabilities

The Santa Fe Watershed consists of multiple small, basin-scale systems embedded within a larger, regional system. In the workshop, we asked participants to share and explore systems of interest and/or concern to them. This section summarizes and expands on the systems explored at the workshop.

Systems Include:

Infrastructure: food supply, water supply, transportation, energy, shelter, communication, health, education, finance

Ecosystems: agricultural land, parks, wetlands, rivers, range land, forests.

While this discussion segregates the various physical, biological and socio-economic systems within the Santa Fe Watershed these systems are interconnected and are part of a complex whole. This disaggregation allows for examination of the aspects of climate change that will prove challenging or threatening to each system. This, in turn, allows for better anticipation of the timing and nature of the impacts that will need to be addressed. Re-aggregation then allows us to combine activities that can benefit multiple systems simultaneously, reducing the vulnerability of one system by reducing the vulnerabilities of associated systems.

Vulnerability – the underlying fragility or weakness in a system that leaves it open to harm or damage

Vulnerability to climate change is defined by the IPCC as “the degree to which geophysical, biological and socio-economic systems are susceptible to and unable to cope with, adverse impacts of climate change” (Pg. 783 of IPCC, chapter 19, Schneider et al., 2007). The purpose of defining the vulnerabilities is to assess how to make each system less vulnerable and thus, more resilient.

The following discussion of systems, though extensive, is not comprehensive.

4.1 Water Supply Systems

Water supply systems include surface and groundwater sources and the human demand for water. There are also water supply implications for ecosystems; these are discussed in section 4.2.

4.1.1 Surface Water

The Santa Fe River, which supplies surface water for Santa Fe and Santa Fe Basin acequias, is vulnerable to several aspects of climate change. First, the availability of water could be greatly compromised if the forest in the upper watershed experienced a high-intensity fire; as explained by Park Williams at the workshop, the risk of catastrophic fire increases with the projected drier climate. As observed in other parts of the Rocky Mountains and Jemez Mountains, a severe thunderstorm following a catastrophic fire could result in debris flows; sediment accumulation in the municipal reservoirs, and flooding of the downstream valley (e.g. downtown Santa Fe). Sediment and ash in the runoff could compromise the operation of the water treatment plant.

Second, increasing temperatures will decrease the amount of available water because of increasing evaporation and increasing water use by plants, which will result in decreasing runoff and decreasing groundwater recharge. Cox et al. (2011) estimates that the average yield of the Santa Fe River into McClure reservoir will decrease by 11 to 18 percent by 2060 below the historic average from 1950-1999.

Third, also as a result of increasing temperatures, an increasing percentage of winter precipitation is projected to fall as rain, rather than snow, reducing snowpack water volume. Remaining snowpack is projected to melt earlier, potentially impairing Santa Fe's capacity to store the runoff for use at a later time, if inflow comes off too fast and exceeds the capacity of the reservoirs. Santa Fe's water rights are greater than the storage capacity of the reservoirs and the ability to divert the city's water right is dependent on both stored water and inflowing water. If more of the annual runoff occurs over a shorter time period (i.e. a few weeks) the reservoirs could fill and spill. This could be followed by very little inflow to the reservoirs from the Santa Fe River the remainder of the year.

Like the Santa Fe River, the Rio Grande and Reclamation’s San Juan-Chama Project water systems are vulnerable to fire, reduced flow, reduced snowpack, and earlier snow melt. They are susceptible to water-quality degradation from intense thunderstorms that carry nutrients, sediments, pathogens and toxins into the Rio Grande from Los Alamos National Laboratories and other communities upstream. Increased temperatures will affect the self-purification capacity of these rivers by reducing the amount of oxygen that can be dissolved and used for biodegradation, also impacting aquatic life. Increased precipitation event intensity can trigger flash flood events and escalate erosion.

All of the city and county's surface water sources, including the Santa Fe River, the Rio Grande and Reclamation's San Juan-Cham project, are subject to interstate compacts. In particular, Santa Fe’s right to store water is limited when New Mexico is under Article VII restrictions under the Rio Grande Compact, which occurs when supplies for Reclamation’s

Rio Grande Project (the irrigation project downstream of Elephant Butte Reservoir) falls below specified thresholds. Under the Compact terms, the City can divert water at a rate equal to the inflow to McClure Reservoir until reservoir storage reaches the pre-compact rights of 1,061 ac-ft. Subsequent stream flow must either be diverted by the City of Santa Fe, by-passed or “purchased” by exchange. Climate Change projections suggest that Article VII of the Compact will be in effect much more frequently under future, drier conditions. Theoretically, Santa Fe County's rights to native water of the Rio Grande could be curtailed to support deliveries under the Rio Grande Compact, although this has not yet happened. San Juan Chama waters supply can be curtailed if the supply is insufficient, or if the supply is constrained under the Colorado River Compact.

4.1.2 Groundwater Supply

The vulnerability of groundwater supply is less well understood than surface water vulnerabilities because the mechanisms and timing of recharge are more difficult to quantify. Climate change projections suggest future precipitation may be delivered in fewer, more intense events giving the above-ground flow less time to infiltrate into the aquifer. Groundwater recharge generated from snowmelt will also likely be reduced as a result of a smaller snowpack area and shorter melt season. Both factors would contribute to a lowering of the water table and a reduction of water storage in the aquifers in the Santa Fe watershed.

4.1.3 Water Use

Water use for all human sectors is expected to increase with higher temperatures – from a greater need for irrigation (unless different crop types and irrigation techniques are implemented) to greater demand for domestic and commercial, urban and rural uses. Outdoor watering and use of swamp coolers will likely increase with higher temperatures. Cooling demands for power plants, industry, and businesses will increase. Parks and green spaces within the city will require more water, unless vegetation types are transitioned or replaced. Even artificial turf, which has been installed for over a decade in many city parks and schools, may require water to reduce the heat of the surface.

4.2 Ecosystems

Climate change will pose increased or new stresses for virtually all Santa Fe Basin ecosystems (Figure 6). The Santa Fe Watershed ecosystems and habitat are controlled most significantly by elevation and water availability. From the alpine conditions above tree line at 12,400 ft. elevation to the wetlands where the Santa Fe River discharges to the Rio Grande (5200 ft.) all systems are predicted to be subjected to the predicted climate changes. Further detail is provided in the following subsections on possible impacts on specific ecosystems, including forest habitat, grassland habitat, riparian habitat, aquatic habitat, and wildlife habitat. The Nature Conservancy (Robles and Enquist, 2011) rated the Middle Rio Grande Watershed, which includes the Santa Fe Watershed, as "most vulnerable" based on the predicted temperature increase and the number of species of concern.

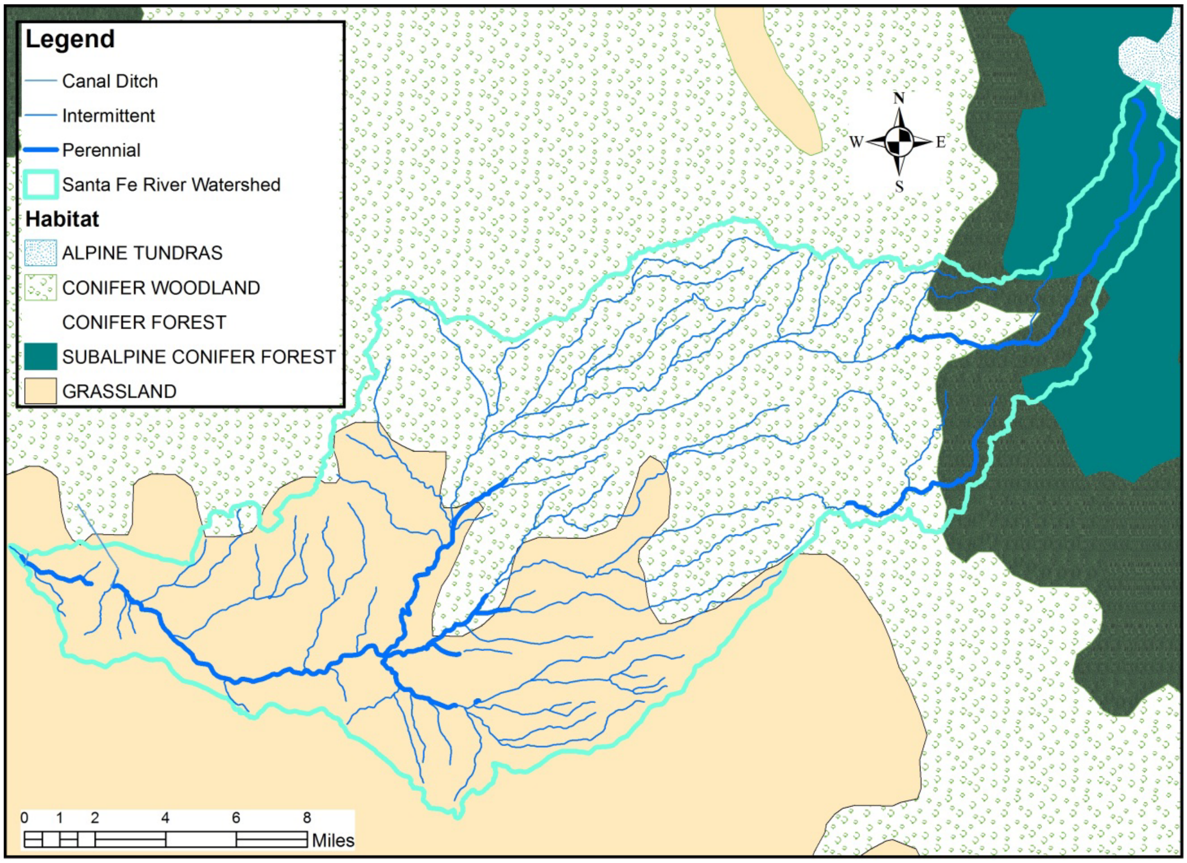

Figure 6. Habitats in the Santa Fe Watershed (TNC, 2012)

4.2.1 Forest Habitat

The Santa Fe watershed forests at the higher elevations are composed of Douglas fir and aspen, mixed-conifer zones, which progress to ponderosa pine and Gambles oak at about 10,000 feet, and then to piñon pine and juniper at the elevations below about 7,500 feet . Forest habitat is vulnerable to both decreases in cold-season precipitation and increases in warm-season vapor pressure deficit (Williams, 2012; see section 2.2.1). Stress from either of these factors leave forests increasingly susceptible to insects and forest fires. At the same time, increased minimum temperatures increase insect survivability and increased maximum temperatures increase fire risk. Even relatively healthy sections of forest may be impacted or lost to catastrophic fires started in other areas. Conifer woodlands are projected to decrease from a total area of 10 percent to 1 percent in the Middle Rio Grande Valley by 2030 (Click et al., 2011).

4.2.2 Grassland habitat

At elevations below about 6,500 feet, the non-developed land transitions from piñon-juniper savanna to native grasslands with nutrient-rich grasses of blue gramma and ring muhly. Increased temperatures will favor grassland habitat pests and invasive species, which have a high germination rate and start growing before native grasses. These non-native grasses will quickly out-compete native perennial vegetation, which will put native grasslands at higher risk. Decreases in soil moisture and increases in plant water use will stress grasses, leading to subsequent die-off and contributing to erosion. The resulting topsoil losses may lead to further grassland degradation, creating a negative feedback loop. Grassland degradation would result in a transition from native, nutrient-rich grasses to invasive species such as cheat grass and buffel grass, which lack the nutrients needed by native wildlife. Semi-desert grasslands are predicted to decline from 38 percent to 25 percent with a complete loss of plains grasslands by 2030 (Glick et al., 2011).

4.2.3 Riparian Habitat

Riparian habitats occur along streams and areas beyond the channel confines where flooding occurs, and includes perennial and ephemeral reaches. The riparian habitats thrive in the perennial reaches of the Santa Fe River above Nichols reservoir and below the wastewater treatment plant, and in Arroyo Hondo upstream of the intersection with I-25 (Figure 1). The riparian habitat is vital to many species, including beaver, migratory birds, the listed endangered species southwestern willow flycatcher, and the northern leopard frog, which is designated as a sensitive species under the Endangered Species Act. Riparian habitat along intermittent reaches of streams is vulnerable to vegetation loss from droughts and longer-term reduction in overall stream flow. Intense runoff events may rework the riparian channel, leading to down-cutting and incision and/or deposition of sediment. The riparian habitat around the springs at La Cienega could be impacted by a reduction in groundwater recharge, which, along with continued pumping of the aquifer, could reduce the flow into and the area of wetlands.

The riparian habitat along ephemeral reaches is vulnerable to climate change. Increased runoff volumes will have a scouring effect on ephemeral streams, leading to increased bank erosion and channel degradation. The increasing frequency and force of bank erosion and overbank flows will threaten adjacent property and infrastructure, undermining trails, wells, roads, bridges, fences, and buildings. Intermittent dry spells will lead to the die back of plants along ephemeral streams, causing soils on banks and terraces to be more susceptible to erosion. As a result, heavy flows will transport more sediment and deposit sediment in flat and wide channel section or upstream from bridges and other obstacles in the channels. Altered sedimentation patterns will most likely exacerbate bank erosion and undermining of structures adjacent to sediment plugs. There will be an increasing need to update FEMA maps that indicate flood prone areas and flood risks to structures, even for ephemeral streams.

4.2.4 Aquatic Habitat

The aquatic habitat in the Santa Fe watershed includes the cold-water fishery in the reach above Nichols reservoir, where Rio Grande cutthroat trout and rainbow trout enjoy a nearly pristine habitat. The 12.7-mile reach below the wastewater treatment plant is designated as a marginal cold-water fishery and warm-water fishery, which provides habitat for the Rio Grande sucker, a listed sensitive species (BLM, 2010). Aquatic habitat is highly sensitive to water supply and quality, but also to temperature. The thresholds for aquatic habitat are defined as “warm water fisheries” or “cold water fisheries” because of the species supported by these habitats. Water temperatures above 20 ^{o}C (68 ^{o}F) impair the quality of a cold-water fishery, making it unsuitable for many of the native trout; thus aquatic habitat will be directly impacted by increased temperatures.

4.2.5 Wildlife Habitat

Wildlife, such as bears, mountain lions, elk, deer, beaver, squirrels, rabbits, hares, foxes, bobcats, antelope and a wide variety of birds, are abundant in the Santa Fe watershed. Wildlife habitat, which includes the forest, riparian, and aquatic habitats, will become increasingly stressed as water and food supplies diminish. As temperatures rise, the number of hours in a day when a species may be active will likely be reduced, thereby reducing their ability to forage and hunt. If habitat area diminishes due to vegetation loss and ecosystem degradation as a result of warmer temperatures and human activities, migration pathways (i.e. the connections between habitats) become smaller, placing an additional burden on animals already stressed by development and highways. Piñon Jays nest mainly in stands of piñon-juniper and their population trend in the Santa Fe National Forest is downward due to the wide-scale loss of piñon associated with drought and Ips beetle infestation (BLM, 2010). Some animals, such as the Abert's squirrel in the upper Santa Fe Watershed, live in forests with ponderosa pine trees, which serve as their sole source of food; a drastic reduction of ponderosa forests would therefore have a big impact on the Abert's squirrel. Species reliant on non-forest ecosystems may prosper, however. For instance, reduced snow pack could allow elk to forage at elevations they were previously unable to reach, though because elk eat woody plants; their access to new areas could cut into nesting habitat for birds that rely on deciduous environments (Hagner, 2012).

An assessment of the Middle Rio Grande valley found that five out of nine of the amphibian species are vulnerable to climate change (Glick et al., 2011). They also identified the southwestern willow flycatcher, the western yellow-billed cuckoo and the common yellowthroat, birds that depend on riparian habitat, to be among the most vulnerable to climate change. Of the 36 mammals assessed, they found that five are the most vulnerable: New Mexico meadow jumping mouse, beaver, woodrat, hoary bat and black bear because of their reliance on riparian areas, dense vegetation or specific vegetation. The jackrabbit and desert shrew populations are expected to increase due to expansion of their habitats.

Clearly, there are opportunities for some wildlife species and drawbacks for others. Whether any particular species thrives or declines will depend on the specific habitat needs of the species and the impact of climate change on the habitat, food chain or ecosystem upon which the species depends.

4.3 Agriculture and Food Security

Agriculture in the Santa Fe watershed includes 720 acres (Longworth et al., 2008) most of which are in the La Cienega area, with a few small farms located throughout the urban area. The vast majority of food is imported rendering high food security vulnerability. There is a growing regional emphasis on shifting the community's dependence on the global food market to more local supplies. Impacts to local agriculture and food security are growing concerns as climate change is projected to reduce water supply and effect additional stresses (environmental and economic) to the crops and livestock.

4.3.1 Acequias and Farming

Acequias and farming in the Santa Fe watershed are vulnerable to many aspects of projected climate change. First, climate change is expected to increase water stress on crops. The projected earlier snowmelt may result in the majority of runoff occurring before peak growing season. Then, during the peak growing season, when less water is available, increased temperatures will increase crop water demand. Currently, most of the agriculture within the Santa Fe River Watershed is spring fed or supplied by treated City of Santa Fe effluent from the municipal wastewater plant. Agriculture that is currently spring fed may not be adequately supplied if groundwater recharge rates are reduced due to changes in precipitation and temperature. The four acequias in the urban area benefit from the storage capacity of the city’s two reservoirs.

Second, increased weather variability during the growing season will stress crops. Projected increased thunderstorm intensity, amplify the risk of higher winds, larger hail, and more flooding to crop production. The projected larger diurnal temperature fluctuations may make growing crops more difficult.

Third, the growing urban demand for water has already resulted in the transfer of water rights from agriculture to other uses in the Santa Fe watershed. The increased difficulty of crop viability described above will likely place additional pressure on farmers to sell their water rights. This transfer of additional water rights to urban or domestic use may threaten the long-term viability of small scale, acequia agriculture.

And fourth, genetically engineered crops, now prevalent in the basin, may be maladaptive. “Genetic engineering and biotechnology have developed strains of crops with improved yield and/or pest and weed resistance under current climatic conditions, but it is unclear whether they will prove as resilient as native seeds to climatic extremes the future may bring. Cross-pollination of the genetically engineered crops with native crops is threatening seed sovereignty for farmers in the region, who believe native seeds can tolerate drought much better (Ralph Vigil, personal communication at workshop). Additionally, pesticide-resistant "super bugs" and herbicide-resistant "super weeds", which have evolved in response to the genetically engineered crops, will place additional stress on the crops.

It is possible climate change will benefit some crops in the short term. Increased temperatures could improve growing conditions for crops at the cold-limit of their range, and increased CO2 could increase growth rates for some crop types. However, if "business as usual" climate change progresses beyond the next few decades, most studies suggest these short-term benefits will be overwhelmed by new or intensified existing stressors discussed above.

4.3.2 Ranching

In the Santa Fe watershed, ranching is primarily focused on the high desert plains of the Caja del Rio mesa and in the grasslands northwest of the City. Ranching will likely experience reduced grassland quality due to increased water use by the plants on which the livestock depends, and increased frequency and severity of drought. This will reduce the carrying capacity of the land. Longer, drier summers will also limit natural filling of stock ponds and speed stock-pond drying. More extreme winter and spring weather could increase calf mortality. Hotter, drier summers may increase cattle heat stress, which could increase mortality and/or reduce growth rates.

4.3.3 Food Security

Currently, and at first glance, Santa Fe's overall food supply is not particularly vulnerable to local climate change due to its very limited local production. Only a small percentage of the food consumed in Santa Fe is grown within a 200-mile radius. Without a detailed mapping of the origins of the majority of locally-consumed food, it is difficult to identify the food security risk climate change poses for the Santa Fe Basin. An increased commitment to local food production may increase the basin's overall water demand, thus shifting a benefit in the food system to vulnerability in the water supply system.

4.4 Land Use and Quality of Life

Human activities and enjoyment of living in the Santa Fe Watershed are at risk of impairment by climate change. Thoughtful decisions and actions will need to be taken to maintain and improve quality of life.

4.4.1 Recreation

Recreational activities dependent on the lands and waters in and around the Santa Fe watershed will be impacted by climate change. The ski season will be reduced, and eventually may be too short for ski resorts to be viable. Rafting on rivers near our basin will be impacted in part depending on how reservoir operation and storage are handled in the future; rafting during peak-flow season will shift earlier in the year, and potentially for shorter periods of time. Changes to water quality and water temperatures will impact aquatic species mortality and morbidity, potentially impacting recreational fishing opportunities. The hunting season will be impacted as species shift and are stressed by changes to forest ecosystems. Wildfires or the threat of fires may increasingly impact hiking trails and campgrounds.

However, the projected changes may have some recreational benefits. For example, warmer winter temperatures may increase winter visits to parks, improve winter camping conditions, and expand the opportunity for cool-season rafting.

4.4.2 Landscaping and Parks

Landscaping and parks will be vulnerable to increased temperatures and will require more water. Water shortages may result in limits to outdoor watering. With warming temperatures, the parks may be used for more days of the year. Perhaps Santa Fe is less vulnerable because of its leadership in low-water intensity parks and green spaces; this may prove to be a skill-set that can be exported to other communities both in- and out-of-state.

4.4.3 Air Quality

Air quality may be impaired by wildfire, drought, and higher winds associated with more intense storms, which accelerate the distribution of smoke, dust, pollen and other particulates. Heat also tends to intensify the impacts of urban air quality contamination (Patricia Romero-Lankao, NCAR). Reduced air quality may result in increased allergic and respiratory issues for local citizens.

4.4.4 Streetscapes and Urban Habitat

Streetscapes and urban habitat are vulnerable to the projected increase in storm intensity and higher temperatures. More intense storms may result in short-term urban flooding, with impacts to commons areas, homes, businesses and transportation routes. Higher temperatures, particularly summer heat waves and increases in nighttime high temperatures, may place increased stress on urban dwellers, particularly the elderly, infirm, and infants, and on urban vegetation. Increased temperatures will also place greater stress on streets and pavement, resulting in the buckling and cracking of concrete and/or blacktop surfaces during heat waves. Decreases in urban vegetation in response to potential water limitations may increase the city heat-island effect. The effect could be mitigated, to some degree, through the planting of shade trees. But if these are not low-water-use trees, this planting may increase overall water use.

4.5 Energy Systems

Santa Fe is powered primarily by electrical power and natural gas, and in rural parts of the County, propane and rural electric cooperatives. New Mexico Gas Company provides the natural gas. Electrical power is primarily supplied by the Public Service Company of NM (PNM), who generates and purchases power from a mix of sources (EPA, 2012)

- Coal-fired power plants - 38.6 percent;
- Natural gas powered plants – 35.7 percent,
- Nuclear power - 16.5 percent;
- Hydropower - 6.1 percent; and
- Renewables (solar and wind) - 3.1 percent.

4.5.1 Power Generation

With the exception of wind and solar power, the electrical power sources listed above requires some amount of water for their functioning, either for cooling or turbine driving. Water demands for thermal power plants (e.g. coal and natural gas-fired) increase with increasing air and water temperatures. Increases in ash or sediment in water supplies may also impact generation capacity and potentially lead to increasing energy costs.

Hydropower generation is particularly susceptible to climate impacts to water availability. In particular, the City's 93 kW turbine-generator unit powers the treated water distribution. Power generation will be reduced if less surface water is available. Local solar power production could be impacted by smoke and dust accumulation on panels during forest fires and drought. Solar power generation efficiency is reduced as temperature increases. Local power production and energy availability will also be impacted by climate events distant from New Mexico. For example, coastal storms coupled with sea level rise will increasingly disrupt offshore extraction and coastal refining of fuel, reducing power plant and automotive fuel availability and increasing prices.

4.5.2 Energy Consumption

Consumption of energy is affected by temperature changes. Across the U.S., projected temperature increases will increase warm-season cooling demand (from 8 to 35%) and decrease cool-season heating demand (5 to 35%) (U.S. Climate Change Science Program, 2008). In the Santa Fe Basin, where a majority of warm-season cooling is via evaporative coolers or non-existent, increased cooling demand will increase both household water and electricity consumption.

4.5.3 Power Transmission

Power transmission can be impacted by extreme low-temperature events, intense precipitation, and wildfires. In February 2011, very low temperatures (-20 °F) dramatically increased gas and electrical demand in New Mexico and Texas. Simultaneously, the increased electrical demand exceeded supply, triggering rolling brown-outs that shut down natural gas compressor stations, disrupting gas transmission (Aaboe, 2012). In summer 2011, a Lubbock, Texas gas well-field lost power for two weeks when a wildfire burned the power lines.

High temperatures can impact pipelines handling supercritical fluids, and electrical reliability can be affected by high soil temperatures and soil dryness (U.S. Climate Change Science Program, 2008). Infrastructure, particularly pipelines, can be impacted by intense precipitation events, cold-extremes causing unexpected freezing, and heat and drought extremes causing cracking and buckling of soil and pipes. While Santa Fe basin may not contain all of the impacted infrastructure, effects elsewhere will likely propagate into the power-supply grid within the region.

4.6 Transportation Systems

Climate change will impact ground and air transportation through increased temperatures, high winds, intense rains, smoke and dust, resulting from increased droughts, dust storms and wildfires. Bridges and culverts are generally designed for threshold flood events; flood events exceeding those design specifications will result in flooding and possible infrastructure damage. Similarly, thermal expansion of expansion joints in bridges, paved surfaces, runways and railroad and light rail rails may exceed design specifications with increased warming, causing buckling. Increasing dust storms during droughts and/or with high wind events, and smoke due to wildfires, may dramatically impair visibility. Fuel usage in cars is also increased, by 12% at highway speeds, with the use of air-conditioners.

Increasing temperatures also impact air transportation uniquely: warmer air is less dense, requiring longer runways, more speed, and more fuel to lift planes off the ground (TRB, 2008). For some airports, this could eventually require longer runways or limit the usage of larger planes to cooler seasons.

4.7 Economic Systems

Climate change will pose interesting new demands on existing economic systems. Whether these demands are vulnerabilities or opportunities will depend on how we respond to them, and will vary for different economic sectors. For example, sectors that will see new challenges include insurance and tourism. The insurance sector has been very proactive to date around the changing risk-frequencies of damaging events. This has led to increases in premiums as well as refusals to provide insurance in areas where risks are increasing, such as for homes in areas of increased wildfire risk or in floodplains. Such limitations to insurance coverage may become even more widespread in the future.

Tourism will be heavily influenced by global and national economics and by local recreational opportunities (see Section 4.4.1). Global and national economics, and consequently tourist travel and spending, will be impacted by politics as well as climate change, and are therefore even more uncertain that climate change alone. The tourism sector is probably best advised to broaden its client base, tourism activities, and seasons to build resilience.

More broadly, local businesses may see increasing energy and cooling costs, and may be impacted by flooding and air quality concerns. Local households will also see these impacts, as well as increased food costs as both global and national agriculture will be impacted by changing climate coupled with increasing global energy costs and growing global population. Local households and businesses could also be impacted if climate change and water scarcity leads to reduced property values due to reduction in quality of life, though increases in growth management to address limited water supply could just as likely boost property values.

4.8 Sociological (body politic/community)

Government, community, and cultural institutions may become stressed while facing the challenges posed by climate change. Some institutions will be able to evolve to deal with fluctuating climate conditions and societal expectations around climate; others will not.

Citizens expect their governments, whether local or national, to provide certain services, serve particular functions, create and modify laws, and enforce particular visions of "society". Within much of the U.S., local governments are expected to maintain critical infrastructure like road networks or parks, and to provide the framework within which utilities or other companies can provide services. As described earlier, increased temperatures and greater precipitation variability will stress Santa Fe's infrastructure. If the frequency of infrastructure disruption and destruction increases, the local government might find its ability to repair infrastructure in a timely manner greatly compromised.

Additionally, local governments are expected to make land use decisions and develop and enforce building codes. Santa Fe's local governments may need to grapple with balancing resource supply with increasing urban development. How the policy makers handle growth in the next 10-20 years will greatly influence how vulnerable the watershed might be to various aspects of climate change.

Governments are also in charge of managing and adjudicating property rights – in the Southwest, water is one of the most highly contested types of property. As climate variability and change alter the Santa Fe Basin hydrology, and economic preferences shift between agriculture, ranching, and urban demands, existing water rights systems may no longer be appropriate. Water rights and associated supporting legal structures will become more contentious in the future, challenging the ability of governments to adjudicate and balance demands.

Beyond water rights and land use/ infrastructure decisions, many local and state governments are also charged with emergency management and response during and after disasters. Wildfires, such as the 2011 Las Conchas fire, or extreme weather events can quickly overwhelm the capacity of local governments to respond and deal with the aftermath. National governments are increasingly being called upon to provide monetary, personnel, and equipment resources to local and state governments during and post-disaster. As discussed earlier, climate change is likely to increase both the frequency and intensity of certain types of hazards for New Mexico, particularly wildfires and drought.

Cultural and community institutions may also be impacted by the projected increases in temperature and precipitation variability. New Mexico and Santa Fe are home to varied communities with many rich cultural traditions, – from the traditional acequia-grounded agricultural communities, to the diverse Pueblos. The identities and cultural traditions of such communities have historically been linked to water, seasons, and associated cropping cycles. Reductions in water supply and changes in crop viability associated with climate change will alter cultural identities and community institutions throughout the Southwest, potentially leading to the collapse of small farming communities. Many communities' identities and traditions are evolving already due to changing economic and demographic conditions; climate change has the potential to exacerbate changes to such institutions.

5 Potential Solutions and Current Actions

Santa Fe Watershed stakeholders have been very active in efforts to create a more resilient community and watershed for many years. Under the historical climate, the watershed has periodically faced drought, water quality impairment, erosion and down-cutting of the river from urban development, and massive piñon pine die-offs (in 1950 and again in 2002), all of which are projected to increase in frequency and/or severity with climate change (Williams, et al., 2010). Likewise, the risk of wildfire has become very clear as residents of the Santa Fe Watershed have witnessed catastrophic fires to the west in 1996 (Dome Fire), 2000 (Cerro Grande Fire) and the Conchas Fire, which burned over 150,000 acres in 2011. Because of this history and experience of dealing with drought, pests and catastrophic forest fires, Santa Feans have been working to make the watershed more resilient.

In people, resilience also includes responsiveness, resourcefulness, and the capacity to learn.

Workshop participants eagerly shared their thoughts and ideas on actions that local governments and citizens could take to create a more resilient Santa Fe watershed. A long list of potential solutions to the projected of impacts of climate changes was identified from the workshop (Appendix D), as well as a long list of actions that is already well underway. We have sifted through those ideas to consolidate the suggestions and summarize what is being or has been done and what remains to be implemented. In this way we can provide clear guidance for the next steps for improving the resilience of the various systems.

We use “resilience” to mean the ability to absorb disturbances (including climate variability and extremes), to change or adjust, and then to re-organize and still have the same basic structure and ways of functioning OR to anticipate and elegantly move to a new way of functioning. Resilient systems are flexible, modular, and, if they fail, can fail safely. Thus, our goal is not simply to predict specific effects of climate change and address them one by one, but to strengthen the entire watershed, its component systems, and its inhabitants in ways that provide more flexibility in the face of an uncertain future. Further, we want to do this in ways that build on current efforts and concerns, so that the Santa Fe Basin continues to build more resilient systems in ways that respond to today’s climate, but that will also be resilient in the future.

The following proposed solutions are organized in the order of the systems discussed in Section 4, where appropriate. However, no solutions were proposed for the transportation or economic systems (perhaps because climate change is not predicted to have a significant impact on these sectors) and some of the proposed solutions either overlap with multiple systems (i.e. education) and we have presented those at the end of this section. We present the proposed solutions (represented with an arrow) followed with a summary of the current actions that are already underway (represented with an open bullet or discussion).

5.1 Water Supply Systems

Actions proposed for water supply systems were focused on water management strategies and demand reduction.

5.1.1 Water Management

Water management is a top priority for addressing the impacts of climate change. Here is what the workshop participants stressed:

- ➢ Negotiate agriculture-to-urban water transfers of limited term, to be implemented in times of drought or other emergency.
- ➢ Limit domestic well use and permits for residential and commercial groundwater pumping.
- ➢ Complete Santa Fe River Adjudication of water rights.
- ➢ Promote aquifer recharge/develop infrastructure and programs for aquifer storage and recovery: using excess surface water rights-or runoff that cannot be captured in the upstream reservoirs.
- ➢ Create task force to preserve/protect water freed up by conservation.

Conjunctive Use Plans in Place:

Conjunctive use strategies, which optimize the balance between groundwater and surface-water use, have been adopted by Santa Fe County and the City of Santa Fe. These strategies seek to maximize the use of renewable surface water when it is available, and save groundwater resources for use in times of drought. The Santa Fe County Conjunctive Management Plan for the Santa Fe Basin, adopted in 2009 (Ross, et al, 2009), created a policy with the benefits of 1) protecting local water resources, 2) enhancing the reliability of supply, 3) protects acequia water rights, 4) optimizes public asset through a multi-year rolling average for groundwater use, that reduce the number of local groundwater rights needed by the County, 5) reduced impact to other water rights holders by shifting the predominant source of supply from local groundwater to Rio Grande surface supplies, and 6) reducing depletions to springs and the Santa Fe River.

To address potential contamination from storm water entering the Rio Grande, an early warning system for contaminants has been coupled to an auto shutoff of Buckman Direct Diversion. The City and County have the Buckman wellfield as a backup supply to use when the surface water is not available due to drought or contamination.

Existing Limits on Individual wells:

The City of Santa Fe passed an ordinance to prohibit new domestic wells within 300 feet of an existing water line and the State of New Mexico regulations limit the installation of new domestic wells within 200 feet of an existing water system. Residents meeting these criteria are instead required to connect to the municipal supply.

Existing Drought Plans:

The City of Santa Fe currently has a comprehensive drought preparation and management approach, including:

- emergency water regulations (i.e., demand management),
- conjunctive use of surface and groundwater,
- long-term sustainability of the groundwater resources and
- a long-term water supply plan to meet future drought (City of Santa Fe, 2010).

Adjudication of Water Rights:

The Office of the State Engineer is responsible for adjudicating water rights in the State of New Mexico. The Santa Fe River adjudication (Anaya v. Public Service Company of New Mexico, Santa Fe County Cause No. 43, 347) was filed in 1971. The Office of the State Engineer intervened in 1975 and completed a Hydrographic Survey in 1978. Most of the subfiles recognizing individual rights have been completed, but the inter-se period, in which parties to the settlement can object, will not begin until the Office of the State Engineer has sufficient resources to commit to the adjudication (Singer, 2012).

Aquifer Storage and Recovery:

While no official aquifer storage and recovery projects have been implemented in the Santa Fe watershed, the City's in-stream flow program for the Santa Fe River will help to replenish the aquifer.

Use of Reclaimed Wastewater:

The City of Santa Fe has reused wastewater since 1940s, and today 28% of municipal wastewater is reclaimed and used for irrigation of parkland, playing fields, golf courses, as well as for dust control and wildlife/livestock watering. The City of Santa Fe is in the process of updating the 1998 Treated Effluent Management Plan with the Reclaimed wastewater use plan which explores the best approaches to maximizing the use of wastewater.

5.1.2 Demand Reduction

Water conservation is one way to reduce the stress on water resources and build resilience to predicted reductions in water supply. However, as Bill deBuys pointed out in his presentation at the workshop, if water saved from reductions in per capita water use is used to support housing development and local population growth, it can lead to demand hardening, in which a higher proportion of the water supply is used for essential uses, and there is less flexibility during drought. Water management plans (discussed under 5.10) can be used to establish policies that avoid demand hardening. Workshop participants stressed the need for public recognition that water is a scarce resource and that our community should continue to promote water conservation through:

- Tiered water rate structure - cheaper rates for those who use less.
- Incentives for addressing water leaks.
- Strengthen programs for water reclamation and reuse.
- Use municipal wastewater to augment water supply.

Santa Fe is a Leader in Water Conservation:

The City and County both have tiered municipal-water rate structures that promote water conservation. The City of Santa Fe adopted a water conservation ordinance in 1996 to reduce per capita demand through a tiered rate structure. Its water conservation programs include:

- a toilet retrofit program (see photo),
- rebate programs for water efficient appliances,
- a pre-rinse spray nozzle program for dishwashers,
- moisture sensors and evaporation controllers for landscape watering systems,
- a gray-water code that promotes use of some household wastewater for landscape watering, and
- Free water audits to check for leaks.

Through these programs, and a leak detection and repair program for the water distribution system, the City has reduced per-capita demand from 168 gallons per capita per day (gpcd) in 1995 to 104 gpcd in 2010 (www.santafenm.gov/index.aspx?NID=168).

Santa Fe County has a strong policy on water conservation which is implemented by ordinance to require water conservation measures for all new residential and commercial development within Santa Fe County. Additionally, property owners seeking to subdivide land or zoning changes are required to have water restrictive covenants limiting the amount of water a residence or development may use. Santa Fe County is exploring options for improving water conservation within existing small public water systems through a survey of these systems and their water use. This project is funded by the Bureau of Reclamation and includes multiple partners. The City of Santa Fe has adopted a water-harvesting element in its green building code. Santa Fe County has a code requiring rooftop harvesting for roof areas greater than 2,500 ft^2.

5.2 Ecosystems

Ecosystem strategies were primarily focused on forests and rangeland health and riparian restoration.

5.2.1 Forests and Rangeland Health

Foremost on the minds of workshop participants was the risk of catastrophic wildfire in the upper watershed and in the urban-forest interface. The Santa Fe River has provided the City of Santa Fe with a significant portion of its water supply, averaging about 40%. The source of this supply is the 17,000 acres of forest above Nichols and McClure reservoirs. The awareness of the risk of fire has developed over the past 15 years as Santa Fe residents have seen the great plumes of smoke from catastrophic fires in neighboring forests. The understanding of this risk was only heightened by Dr. Park Williams' presentation about the predicted decline of forests in the southwest (Appendix C). Here's what the participants recommended:

- Continue to treat the Santa Fe River upper watershed forests with prescribed fire, when conditions are favorable, to reduce the risk of catastrophic fires.
- Develop contingency plans and budgets for responding to large-scale fires in the Santa Fe watershed, with consideration for flood protection, recovery of water systems, and rehabilitation of reservoirs.
- Improve biodiversity in the watershed: convert the forests of the upper watershed from a near monoculture of ponderosa pine to a more diversion forest; promote a greater variety of ground cover throughout the basin; and protect grasslands.

Completed and Pending Forest Treatments:

In 2000, the City of Santa Fe and the USFS began thinning the Upper Santa Fe Watershed in the vicinity of the reservoirs. This work was initiated due to a growing recognition that the forest ecosystem was out of balance, with a high density of small diameter trees and a low density of desirable grasses, and thus vulnerable to a high severity fire. To date, 7,270 acres have been treated and an additional 2,900 acres are proposed for treatment to reduce the risk of a catastrophic wildfire. The treatments have increased the biodiversity and resilience of the forest to drought and fire.

The City of Santa Fe's Wildland Urban Interface (WUI) program provides information and assistance to homeowners about proper landscaping and methods to reduce the risk of fire in areas near the surrounding forests. The Santa Fe Fire Department has a full-time position dedicated to WUI issues. The City of Santa Fe's Fire department adopted the International Fire Code and the Wild Land Urban Interface Code that requires indoor sprinkler systems for homes built where access is limited and fire hydrants are not available.

New Mexico State Forestry, a division of the Energy Minerals and Natural Resources Department, joined with leadership from the City of Santa Fe and Santa Fe County as well as the State Cooperative Extension Service, to develop and implement a coordinated response to the bark beetle crisis and its impact on the community (www.emnrd.state.nm.us/fd/santafetrees/background.html).

The Santa Fe Piñon Initiative Steering Group has taken action to help educate the public about forest health and management of dead piñon trees. This group has produced a fact sheet for homeowners on how to reduce the risk of fire on their property (www.emnrd.state.nm.us/fd/santafetrees/pdf/firefacts.pdf.)

Forest Fire Emergency Response Plan:

The US Forest Service has a BAER (Burned Area Emergency Response) team in place to quickly evaluate the severity of a fire and propose treatments. The City is fortunate to have two reservoirs to help protect the city from flood and debris flows that often follow a catastrophic fire, but the storage capacity may not be sufficient to retain debris and sediment from a high-severity fire.

Initiatives to Improve Biodiversity of Rangelands:

The following Initiatives are underway to Improve Biodiversity of Rangelands:

- Santa Fe Conservation Trust works with landowners to retire development rights and keep land in its natural state.
- The Caja del Rio project was funded in 1999 through the New Mexico Environment Department's "319 Program" (a program to address non-point source pollution under Section 319 of the Clean Water Act) to restore grasslands, manage livestock, build water tanks, improve fences, and manage the watershed through controlled burns.

5.2.2 Riparian Restoration

The Santa Fe Watershed Association was established in 1997 and the Santa Fe River Commission was established in 1984 and reformed in 2007 as a standing committee of the City (resolution 2007-14). Due largely to the actions of these groups, the Santa Fe River has received a great deal of care over the past 15 years, from the headwaters in the Sangre de Cristo Mountains down to the Rio Grande. Some of these efforts are described here. The following are additional recommendations made at the workshop:

- Continue efforts to restore riparian areas; consider the impacts of restoration on the rest of the watershed (for example, on availability of water downstream, flood risk, and risk of debris plugging infrastructure)
- Employ best management practices to manage runoff, especially runoff from dirt roads, prevent erosion and gullying, and reduce runoff turbidity.
- Modify/design bridges and culverts to handle higher intensity runoff events, consider installing bottomless culverts.

Water for Ephemeral Reaches of the Santa Fe River:

The City of Santa Fe recently dedicated up to 1000 acre-feet per year from its Santa Fe River water supply to support in-stream flows in the urban reach of the Santa Fe River. The water will be released from Nichols Reservoir in pulses. One of the stated goals of the pulses is to “irrigate the trees and other vegetation along the river corridor to support the typical spring time activities within tree/plant (and faunal) annual life cycles as plants are beginning to draw water, beginning to produce buds and leaves” (Administrative Procedures for Santa Fe River Target Flows).

Riparian Restoration:

Many projects (Figure 7) have been funded through the NMED 319 Program (a program to address non-point source pollution under Section 319 of the Clean Water Act), which have included riparian restoration and other projects, all of which have help improve the resilience of the watershed.

The Canyon Preservation Trust, Randal Davey Audubon Center and US Fish & Wildlife Service have partnered with private landowners to address the riparian health between the old Two-mile dam site and the Acequia Madre head gate. The project, which began in 1996, involved mapping and restoring degraded areas (Grant, 2002).

The Santa Fe Watershed Association obtained a grant from NMED's Surface-Water Quality Bureau (SWQB) River Ecosystem Restoration Initiative (RERI) for Habitat Restoration along the Upper Santa Fe River. The project involved re-routing the river to its natural channel in the reach below Nichols Dam. Native vegetation was planted along the reach, and a river drop/fish ladder structure was constructed at Stone Dam. A second grant was provided by NMED SWQB RERI to construct erosion control structures; remove exotic species, thin vegetation to reduce fire hazard and plant native species at Aztec Springs and the Santa Fe River below Nichols Dam.

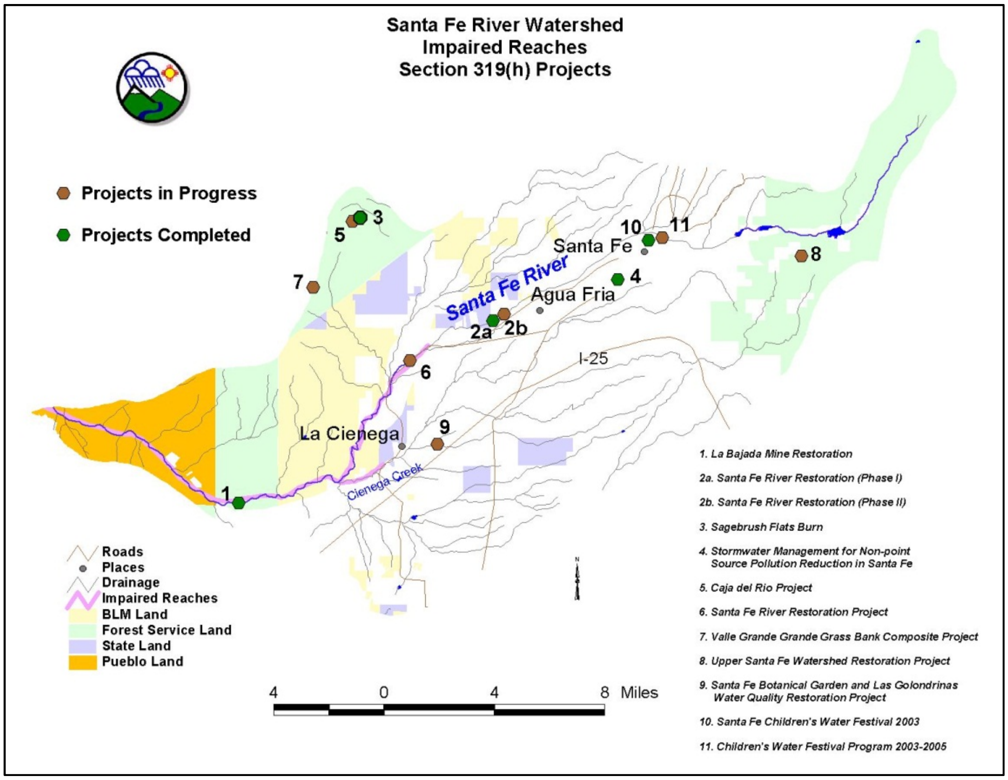

Figure 7. Santa Fe River Watershed Impaired Reaches Section 319(h) Projects (Franklin, 2012).

The Santa Fe River Corridor Master Plan was adopted in 1995, and included channel stabilization and trail system development between Patrick Smith Park and Frenchy's Park. The City of Santa Fe obtained a NMED SWQB RERI grant in 2009 for restoring riparian vegetative cover, improving infiltration and sinuosity, and stabilizing the channel and banks of the Santa Fe River along the 3.1 mile reach from Camino Alire to Frenchy's Park (Drypolcher, 2012). The grant also includes the re-design of the San Jose Road storm drain and planting of the area with native vegetation to stabilize river channel, improve hydrologic function, and provide wildlife habitat.

The City of Santa Fe and the Santa Fe Watershed Association are completing an assessment of the status of ephemeral stream (arroyos) in Santa Fe with a view to the needs for future repair, management, and stewardship. The City has developed a priority list for arroyo repair and maintenance, which was part of the adopted 2011 Bond Issue for public works projects.

The City of Santa Fe Public Works Department has undertaken a number of projects to keep traffic out of the river and prevent erosion and further down-cutting of the channel. These actions include:

- Construction in 2009 of a bridge at Siler Road that will keep traffic out of the river channel.
- Closure to traffic in 2009 of the crossing at Camino de Carlos Rael.

Santa Fe County Public Works built an improved crossing at San Ysidro in 2003 that protects the river from erosion and further down cutting. The County also installed a bank stabilization structure at Lopez Lane Bridge.

The State Land Office conducted river restoration on a reach 1 mile upstream of the State Road 599 crossing on State lands. This project was funded by NMED 319 Project funds.

The restoration of La Bajada Uranium Mine by the US Forest Service and Bureau of Land Management between La Cienega and the Village of La Bajada has also helped to restore the riparian habitat.

Water Quality Improvements on the Santa Fe River:

The Santa Fe River water quality downstream of the wastewater treatment plant has improved significantly over the past decade due to concentrated efforts of WildEarth Guardians, the City of Santa Fe, Santa Fe County, the Santa Fe Botanical Gardens, private landowners, the Santa Fe Soil and Water Conservation District and the Surface Water Quality Bureau of the New Mexico Environment Department (Guevara, 2011). The 12.7 mile-long reach was not meeting standards for pH, sediment and dissolved oxygen. Stock ponds have been built on the Caja del Rio to remove cattle from the stream, levees have been removed to enhance floodplain connection, wetlands have been constructed and cottonwoods have been planted. Water quality has improved and the stream is now meeting the water quality standards.

While the water quality has improved, the projects described above are not without controversy. This reach of the river is an artificial wetland created by the discharge of wastewater effluent. Some do not consider this reach to be “restored”, but instead to be an artificially created habitat that does not reflect historic conditions.

Comprehensive Wetland Restoration and Protection has been undertaken in Arroyo Hondo, Santa Fe County, with funding from the U.S. Environmental Protection Agency through the New Mexico Environment Department – Surface Water Quality Bureau, Wetlands Program.

The grant provided funding to prepare a wetlands action plan and improve the wetlands in Arroyo Hondo downstream of I-25 near an old dam site. In 2012, this same program funded a project that will produce a Wetlands Action Plan for the Santa Fe County area, a geo-hydrological analysis of surface and ground water flows into the wetlands in La Cienega, a technical field guide on wetland management, a series of pilot wetland restoration projects in the Cañada de los Alamos, Arroyo Hondo reservoir, San Marcos Arroyo, and Escalante Arroyo (Cerrillos Hills), and wetland planning and policy recommendations for local government agencies and landowners.

5.3 Agriculture and Food Security

To address additional stresses on the agricultural sector and food security from reduced water supply, earlier runoff, increased pests and more severe storms events participants at the workshop recommended the following:

- Incorporate urban agriculture in planning; encourage small farms in the city and county and food-scapes in commons areas to respond to the significant interest in increasing locally sourced food (less than 100 miles) that does not require shipping and supports local ecosystems and community members.
- Encourage cultivation of climate-appropriate crops by developing guarantees for seed sovereignty through buffer zones for genetically engineered crops.
- Improve irrigation infrastructure efficiency where such actions would not impair ecosystems and senior water rights.

Abundant Interest in Locally Sourced Food:

- The Farm to Table is a non-profit organization dedicated to promoting locally based agriculture through education, community outreach and networking (www.farmtotablenm.org). Farm to Table enhances marketing opportunities for farmers; encourages family farming, farmers' markets and the preservation of agricultural traditions; influences public policy; and, furthers understanding of the links between farming, food, health and local economies.

- Earth Care launched a Youth Food Cadre Program with nonprofit, school, and government partners leveraging federal funds to create AmeriCorps positions for young adults working to develop school and community gardens that provide food and health education, and support local producers and food organizations
- The Southwest Grass-fed Livestock Alliance SWGLA is an alliance of producers, consumers, land managers, conservationists, and researchers that seek to improve human, ecological and animal health, and strengthen local agricultural communities by educating producers, and the public about grass fed livestock products.
- Two new community gardens were opened in City Parks (SSFP Update, 2011).
- Farmers markets are held 7 days a week- Rail yard and Santa Fe Place in Santa Fe, El Dorado, La Cienega, and at the Flea Market.
- Further support the growing school garden program in Santa Fe and the integration of locally grown and school-grown food in school lunch programs. Schools with gardens include: SF High, Eldorado Community School, Monte del Sol Charter School, Acequia Madre Elementary, Salazar Elementary, Amy Biehl Community School, and others.

Current Actions to Protect Seed Sovereignty:

The New Mexico Food & Seed Sovereignty Alliance, with core members from the Traditional Native American Farmers' Association (TNAFA) and the New Mexico Acequia Association (NMAA) have a joint mission to "continue, revive, and protect our native seeds, crops, heritage fruits, animals, wild plants, traditions, and knowledge of our indigenous, land- and acequia- based communities in New Mexico for the purpose of maintaining and continuing our culture and resisting the global, industrialized food system that can corrupt our health, freedom, and culture through inappropriate food production and genetic engineering"(NMAA, 2012). The Alliance was successful in passing Senate Joint Memorial 38 and House Memorial 84 in the 2007 State of New Mexico Legislature, a Memorial that recognizes the importance of indigenous agricultural and native seeds to the food security of New Mexico as well as farmers' rights to keep their seeds free from GE contamination.

Santa Fe County Resolution No 2006-150 was adopted to commit the County to work towards the cultivation and preservation of "Chimayo Chile".

Efforts to Improve Irrigation Efficiency:

Santa Fe County, with funding from the Bureau of Reclamation, is currently assessing agricultural lands in the region to assess irrigation efficiency and whether an increase in efficiency would be beneficial to the system overall. Decreases in the consumptive use of irrigation or evaporation losses from the field that do not also result in negative impacts on crop yields can stretch the available surface-water supply so that it is available for more uses. However, decreases in water delivery that simply decrease the losses to the groundwater system can decrease the availability of water to wells or drains, which other users might rely on, and can negatively impact riparian habitat.

Because the agricultural sector has already been subjected to the stress of economic hardship and the expansion of urban areas, local have implemented measures to preserve agricultural lands and the food security that they can provide to the community. In 2006, Santa Fe County passed Resolution No 2006-184, which committed the County to protection of agricultural lands in production and the attendant water rights. In 2010, Santa Fe County passed Resolution No 2010-23, which committed the County to encourage and assist landowners who choose to voluntarily protect the open space character of their agricultural land in perpetuity. This resolution recognizes the benefits of conservation easements, the state income tax credits and the federal income tax deductions for those landowners that voluntarily decide to protect and support these agricultural lands.

Various land trust organizations, such as Santa Fe Conservation Trust, New Mexico Land Conservancy, Trust for Public Land, and The Nature Conservancy are active in Santa Fe to offer advice and broker conservation easements for the preservation of agricultural land.

Additionally, Santa Fe County's Open Lands, Trails, and Parks program has a mandate to protect and when desirable, purchase agricultural lands of conservation value for the community and has done so in the past, and may do so again if/when funds are made available.

The State of New Mexico has existing policies that support the protection of agricultural land, including:

- The New Mexico Land Use Easement Act (NMSA §§ 47-12-1 through 47-12-6), which aids landowners who wishes to donate a land use easement that specifies agricultural use in perpetuity.
- The New Mexico Property Tax Code (NMSA § 7-36-20 and 3.6.5.27) provides for tax relief for agricultural properties.
- The US government has policies that support the protection of agricultural land including:
  - The Federal Farm and Ranchland Protection Program which provides matching funds to help purchase development rights to keep productive farm and ranchland in agriculture.
  - The Federal Farmland Protection Policy Act which commits the federal government to the goal of conserving farmland in carrying out its public works and other development projects.
  - The Federal Internal Revenue Code that provides significant tax breaks for preservation of farmland.

5.4 Land Use and Quality of Life/Parks and Urban Landscaping

Parks and residential landscaping provide opportunities to address multiple climate change vulnerabilities on a small, but significant scale. Workshop participants stressed:

- Mulch, soil preservation, and other permaculture actions, such as landscape contouring to enhance storm water capture, slow down runoff, improve moisture retention, improve soils, and reduce water demand.
- Improve urban forests: Plant and maintain healthy trees within city limits to "cool" cities.
- Incorporate edible vegetation or "food scapes" in public landscaping.
- Provide tax incentives for green properties (infrastructure that is cooler, captures runoff, increases infiltration, is energy efficient, incorporates passive or active renewable energy, etc.).

- Require pervious pavement.
- Provide green-waste bins to residents and city/county composting.
- Allow limited, appropriate development in hazard-prone areas, such as the urban-forest interface, in balance with economic diversity and the availability of water supply

Small-scale storm water management activities:

Numerous projects have been funded through the New Mexico Environment Department's (NMED's) "319 Program" (a program to address non-point source pollution under Section 319 of the Clean Water Act) to reduce impacts from storm water runoff. These include:

- Contour swales, gabion check dams, splash pads, and tree and shrub planting at EJ Martinez Elementary School.
- Contour swales at numerous private residences.
- Contour swales and check dams at Alta Vista and 2nd street by Santa Fe Southern Railway.
- Contour swales, gabion check dams and splash pads at Calle Lorca Park.
- Erosion control structures and storm water filter structures in Arroyo de los Chamisos between Camino Carlos Rey and Avenida de las Campanas (with additional funding from the Santa Fe Community Foundation and the City of Santa Fe and in-kind support from local businesses).(picture from the Santa Fe New Mexican, May 18, 2010).
- Restoration of the Arroyo de los Piños at Museum Hill, which involved installing permeable pavement to reduce urban runoff and increase groundwater recharge, and channel restoration work in the headwaters of the Arroyo de los Piños at Museum Hill (with additional funding from Santa Fe Botanical Garden).
- Erosion control structures in Arroyo Saiz (Grant, 2002) by private land owners
- A gabion check dam, splash pad and French drains at the Llano St Pool/La Farge Library.
- Large scale, well-designed rock cascade structures at stormwater outflows in Arroyo Mascaras along north Paseo de Peralto, and into SF River along Santa Fe River Street.

The City of Santa Fe, Santa Fe County and the Cerro Gordo Ditch Association have adopted storm water ordinances. The City of Santa Fe’s Storm Water Management ordinance works with the EPA regulations to reduce pollutants from storm water by requiring best management practices (BMPs) at construction sites. The City also provides guidance for landscape design and methods to harvest runoff and reduce erosion through swales and check dams. Specific storm water related projects funded by the city include:

- El Parque del Rio (2012): a project that will capture stormwater along the Santa Fe River from St. Francis to Palace Avenue and redirects it to river corridor vegetation. Prior to this project, storm water bypassed the vegetation through traditional drop inlets, which over time lowered the water table and increased the channelization of the river. The El Parque del Rio project is utilizing Oxbow swales to allow water to infiltrate and in large rain events exit and continue to another swale or traditional storm water outlet. The project also utilizes the existing stone curbing near Old Santa Fe Trail to intentionally allow "leaking" under the sidewalk and hydrate the cottonwood canopy downtown.
- Various stormwater infiltration garden, rock run-downs, and spill pads along the Arroyo de los Chamisos between Santa Fe High School and Richards Avenue (by Earth Works Institute 2007-2011)
- Stormwater management in the Arroyo de los Pinos for the establishment of the Santa Fe Botanical Garden (funded by City of Santa Fe, managed by SF Botanical Garden; implemented by Earth Works Institute 2006-2010)
- Restructuring of existing storm-water drain exits to increase infiltration capacity on river benches, and
- Replacing asphalt parking areas near the river with permeable pavestones.

Improve Urban Forests

The Santa Fe Residential Green Building Code encourages planting of trees that are native or appropriate for local growing conditions and for species and locations that will, when the trees are mature, provide summer shading of streets, parking areas, and buildings to moderate temperatures.

Santa Fe Botanical Garden (www.santafebotanicalgarden.org) manages the Leonora Curtin Wetland Preserve and the Ortiz Mountains Educational Preserve and will soon begin construction of Santa Fe Botanical Garden at Museum Hill, which will join the two preserves as a lovely and serene space to experience nature. Santa Fe Botanical Garden celebrates, cultivates and conserves the rich botanical heritage and biodiversity of our region, and provides education and community service.

5.5 Energy Systems/Production and Consumption

While this report does not address ways to reduce CO_2 emissions, reducing energy production and use helps make our community more resilient. Workshop participants had many of the same recommendations for energy as they did for food security, basically to create more energy locally and reduce the expenses and vulnerabilities in transportation. Specific recommendations included:

- Decentralize energy infrastructure and produce more renewable energy locally.
- Introduce greater incentives for energy efficiency and renewable energy conversion (including incentives for such actions as improving insulation and installing solar panels and keeping them clean).
- Require more energy efficient buildings with passive cooling features.
- Municipalize city energy system.
- Install solar panels over parking lots to reflect heat and generate energy.

Current Local Production of Renewable Energy:

Santa Fe City and County have both invested in renewable energy infrastructure for the community. Renewable energy projects in the Santa Fe watershed include:

- The City of Santa Fe has a small hydropower plant (93 kW turbine-generator) powered by gravity-fed pressure in treated water pipes.
- The City of Santa Fe has a 1 Megawatt solar facility at the wastewater treatment plant
- The City and County have a1 Megawatt solar facility at Buckman Direct Diversion (BDD), and are planning another 1 Mw solar facility along the BDD raw water pipeline

Current Incentives for Local Energy Production

Residents currently receive incentives for installing solar photovoltaic and solar thermal systems. PNM has a Solar Energy Customer Program that allows customers to receive payment for renewable energy credit. Under this program, PNM pays the customer for the energy produced by their system, regardless of whether the customer consumed all of the energy produced. The costs of the systems receive a Federal income tax credit of 30% and a state tax credit of 10%.

Existing Building Codes for Energy Efficiency

The City of Santa Fe adopted a residential green building code on March 11, 2009 (Ord. 2009-09) with revisions dated January 11, 2012. (http://www.santafenm.gov/DocumentView.aspx?DID=9873). The green building code requires that all new homes meet stringent standards specified in the Home Energy Rating System (HERS) according to the size of the home. The City's energy efficiency standard for new construction is one of the most aggressive in the country. Santa Fe County is also in the process of adopting a green building code.

5.6 Sociological Systems/Public Engagement & Policy Change

Workshop participants were very passionate about the need for our community to be ready to respond to the cumulative impacts of climate change on the various systems. Suggestions included:

- Increase incentives for actions that address climate change.
- Highlight models of successful projects happening now.
- Foster inclusive discussions incorporating all components of community (including discussion of uncomfortable topics such as population growth and appropriate development).
- Enhance regional governance – connect government agencies across watershed.
- Build capacities of local governments for handling weather-related hazards.

What's Happening Now?

The Sustainable Santa Fe Commission is dedicated to creating a strong, resilient Santa Fe for current and future generations (http://sustainablesantafenm.ning.com). The Sustainable Santa Fe Commission is comprised of citizen volunteers with expertise in a variety of areas that advise the City Council on issues of sustainability

5.7 Monitoring

Monitoring of vulnerable systems to collect appropriate data is critical to furthering our understanding and their response to changes. In order to develop the appropriate adaptive management, monitoring should be established to evaluate the effectiveness of management activities. It is important to examine existing historic data to assess how local species and systems have already responded to climate change.

- Develop a monitoring plan that defines the appropriate location, timing, parameters, equipment and responsible party
- Monitoring equipment should be established before impacts occur

Current and future monitoring

Stream flow monitoring in the Santa Fe River began in 1913 with a USGS stream gage in the upper watershed. In 1998, the City of Santa Fe established more monitoring on the Santa Fe River (Lewis and Borchert, 2009). A series of monitor wells were historically monitored by the USGS and that monitoring is currently being conducted by contractors to the Office of the State Engineer. Monitoring of water quality is performed routinely by the New Mexico Environment Department Drinking Water Bureau on public water systems.

A monitoring plan was developed as part of the EIS for the forest treatments in the Santa Fe Watershed (USDA, 2001). This plan involved monitoring the impact of forest treatments on bird population, tracking the actual changes in vegetation density (overstory, ground cover and litter cover) and impacts to turbidity during the treatments. The Interstate Stream Commission is monitoring the impact of forest treatments on the water budgets in a paired basin study in the Santa Fe Watershed.

Santa Fe County has received grant funding to install surface and groundwater monitoring equipment in the La Cienega and La Cienguilla areas of the lower watershed. The goal is to monitor changes in spring and stream discharge along with groundwater levels to create a baseline of current hydrological conditions.

5.8 Education

Education can be used to increase awareness of the sensitivity of various systems to climate change and to provide information on actions individuals can take to improve the resilience of systems. Workshop participants suggested:

- City/county classes and public school curricula and demonstration on growing food, composting, conservation, xeric gardening, and rainwater harvesting.
- Tours of the water (Buckman Direct Diversion) and waste-water treatment plants, to educate residents and school children on the need for water conservation and the life cycle of municipal water.
- A Central clearinghouse for the community of water conservation information.

Educational Opportunities Abound:

Numerous non-profit organizations in the Santa Fe area have dedicated many volunteer hours educating the public and involving school children. The principal non-profit organization addressing climate change in the Santa Fe watershed is the Sustainable Santa Fe Commission, which is devoted to educating Santa Fe on and ways to reduce the community's carbon footprint and improve the resilience of our ecosystems (www.santafenm.gov/index.aspx?NID=685). Other organizations devoted to implementation of many of the educational outreach efforts include the Forest Guardians, the Santa Fe Conservation Trust, the Santa Fe Watershed Association, the Randall Davey Audubon Center and the NM Chapter of the Audubon Society, The Nature Conservancy, Quivera Coalition, and until recently, Earth Works Institute.

The City of Santa Fe works with the Santa Fe Watershed Association on an extensive education and outreach effort to provide education on forest and riparian ecology, water issues and ecosystems services. This outreach effort has included the development of an educational video, public hikes in the watershed, and environmental monitoring programs with middle and high school students. The city and the Santa Fe Watershed Association are also collaborating on the Climate Masters' program, a 10-week training program on climate mitigation and adaptation (www.santafewatersehd.org). The Santa Fe Watershed Association and Southwest Urban Hydrology collaborate to provide educational events in the community. For example, in May 2012, these organizations sponsored: 1) *Urban Watershed and Green Infrastructure*, a presentation on the impacts of a growing urban landscape on watershed functions, and 2) *Bio-retention Basin Workshop*, a hands-on workshop to implement bio-retention basins. . Both events provided instruction on the benefits of Green Infrastructure as a means to prevent local flooding, storm water pollution, urban heat-island effects, and habitat loss in urban watersheds.

The City of Santa Fe's Water Conservation Division of the Water Utility has a xeric demonstration garden, and several programs for education. These education programs include the Children's Poster Contest, Water Fiesta, and the River Xchange program (coordinated with Santa Fe County), in which 5th graders explore key water resource concepts through a year-long curriculum which includes focused field trips and hands-on activities . The City of Santa Fe, in 2002, also developed a handbook: "Storm Water as a Resource, how to Harvest and protect a dryland treasure in 2002.

The New Mexico Environment Department (NMED) developed a handbook for restoring riparian areas called "Healthy Streamside Wetlands, A guide to good stewardship for southwestern bosque and riparian wetlands" (www.nmenv.state.nm.us/swqb/Wetlands/HSW/index.html).

The Quivera Coalition has an annual workshop and numerous publications to educate ranchers and the public about rangeland management (www.quiviracoalition.org). The Quivera Coalition's publications include: *Let the Water Do the Work: Induced Meandering, an Evolving Method for Restoring Incised Channels* (Zeedyk and Clothier, 2012).

5.9 Visionary

Santa Fe residents understand the power of visual and artistic expression of ideas to create change. Here are a few visionary ideas suggested by the workshop participants:

- Appoint an Artist in Residence dedicated to the Santa Fe River to create images that foster respect for the resource
- Create sacred space around water, including a physical reminder, such as a table or alter, at meetings to remind people that water sustains life for all and should not be considered a commodity

One example of a visionary action:

Mayor David Coss named 2012 "Love Your River Year" and environmental artists Bobbe Besold and Dominique Mazeaud along with Santa Fe poet laureate Valerie Martinez have initiated a project called "River Runs through Us". The project engages the community to walk the 46-mile length of the river, and along the way to plant native species, listen to music and poetry and other activities to celebrate the river. The four-day journey in May 2012, was an exploration of the Santa Fe Watershed and is designed to create art, promote awareness, engage community, and illuminate our relationship with river systems, earth and water (http://riversrunthroughus.net).

5.10 Implementation

Initial steps that could enhance the effective implementation of the recommendations presented in this report include:

- More regional governance
- More communication and collaboration across government levels, beginning with the city and county
- Long-term ,rather than short-term, thinking
- Planning, including
  - Tools to optimize decision-making (which will be needed because climate change will leave us with less room for error)
  - Prioritization of actions

  - Integrated implementation of plans
- A diversity of decision-makers, coupled with deep community engagement

6 Next Steps

This preliminary assessment captures many of the vulnerabilities that the Santa Fe watershed may face under projected climate changes, as well as potential adaptation strategies to address these vulnerabilities and create a more resilient watershed. It also describes numerous projects that are ongoing in the watershed to enhance sustainability and resilience. Under the second phase of the Santa Fe Basin Study, the partners will quantify the potential impact of climate change on the available water supply from the watersheds that provide water to the City and County (the Santa Fe River Basin, the Upper Rio Grande and several tributaries in the San Juan), assess the vulnerability and possible shortcomings of the existing water plans, and develop strategies to address the concerns.

Below are additional strategies that local, regional or state governmental organizations and concerned citizens may consider as next steps to begin to adapt to the impacts that climate change will have in our region.

- Develop a GIS-based watershed-wide map for tracking of existing action in all sectors or systems. The map may be helpful in identifying the areas where further action is a priority.
- Develop and/or coordinate community-based, watershed-wide, technical advisory committees that focus on specific sectors or systems. These committees may develop more detailed visions, strategies and recommendations, implement activities, and/or track progress. To increase communication and coordination, we recommend that these advisory committees work closely within existing ‘umbrella’ organizations like the Sustainable Santa Fe Commission, and other existing planning and emergency groups.
- Increase communication and coordination among existing efforts to enhance effectiveness.
- Monitor key climate-change impacted parameters (temperature, precipitation, temperature extremes, and storm events) so that the picture of impacts and emerging trends can be identified.
- Implement the water-related recommendations from Phase 2 of the Santa Fe Basin Study.

- Enhance interagency and intergovernmental communication, planning and emergency preparedness coordination.
- Develop comprehensive public education program to teach the community, agency staff, and elected officials about the potential impacts of climate change and provide opportunity for collaborative citizen engagement.
- Seek funding opportunities to implement recommendations made in this report.

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Appendix A. Workshop agenda

Santa Fe Watershed Climate Change Workshop

Santa Fe Community Convention Center, March 6, 2012

Agenda		
Time	Activity	Location
8:00-8:30	Sign-in	Sweeny F
8:30-8:45	Introduction **Councilor Bushee/Claudia Borchert City of Santa Fe** **Dagmar Llewellyn, Bureau of Reclamation** **Commissioner Vigil/Karen Torres Santa Fe County**	Sweeny F
8:45-10:30	Setting the Stage **David Gutzler**, UNM climate change expert – *Summary of climate change projections for the* *Santa Fe Watershed and the Southwest* **Park Williams**, Los Alamos National Lab ecologist – *Southwestern forest response to drought* **Bill deBuys**, author and conservationist – *Historical/sociology impacts of climate change*	Sweeny F
10:30-10:45	**Break**	Sweeny F
10:45 – 11:30	What can we do with this information? Karen MacClune, Institute for Social and Environmental Transition	Sweeny F
11:30-12:30	Parallel Breakout Session 1	
	Water	Milagro
	Ecology	Peralta
12:30-1:15	**Working Lunch**	Sweeny F
1:15-1:45	Parallel Breakout Session 1 continued	Return to group
1:45-3:15	Parallel Breakout Session 2	
	Land Use/Quality of Life	Milagro
	Agriculture and Food Security	Peralta
3:15-3:30	**Break**	Sweeny F
3:30-5:00	Break out session results and Next Steps	Sweeny F

David Gutzler Ph.D., University of New Mexico: Dr. Gutzler's interests include interactions between the atmosphere and land surface processes, especially energy and moisture fluxes. He hopes to contribute to the interesting research being done putting surface systems together with atmospheric systems. Dr. Gutzler has taught: Meteorology (a non-mathematical intro to weather science); Climatology (an upper- division undergrad survey of climate processes); Global Climate Change (upper level science & policy mix), and Physical Climatology (grad-level climatology course).

William deBuys, Author and Conservationist: Mr. deBuys has authored seven books his most recent being *"A Great Aridness: Climate Change and the Future of the American West* "(released by Oxford University Press, Nov. 2011). He was a 2008-2009 Guggenheim Fellow. As a conservationist, he has helped protect more than 150,000 acres in New Mexico, Arizona, and North Carolina. From 2001 to 2005, he served as founding chairman of the Valles Caldera Trust, which administers the 89,000 acre Valles Caldera Preserve. He lives and writes on a small farm in northern New Mexico.

Park Williams, postdoctoral researcher at Los Alamos National Laboratory: Dr. Williams' research focuses on how global climate variability influences drought in places where water is a limiting resource for life such as forests in the Southwestern United States. Using tree-ring records, he has determined how Southwestern forests have responded to drought, wildfires and bark beetles for the past 1000 years and has forecast how Southwestern forests should respond to climate change in the next several decades. He received a Ph.D. from the University of California, Santa Barbara in the Geography Department in 2009.

Karen MacClune, **ISET** has been engaging for over 5 years with cities around how to utilize climate change information in city planning processes to build resilience to potential climate impacts. ISET has been supporting communities to understand potential, local climate hazards and how their nature might evolve under climate change, to develop vulnerability and risk assessments to explore the potential direct and indirect impacts of those climate hazards, and to develop resilience plans which identify and prioritize mitigation, adaptation, and resilience building activities to be taken within the context of daily policy and operating concerns. As part of this work, ISET has created and continues to refine a resilience building curriculum to systematically walk communities through the steps involved in developing resilience plans. Dr. MacClune also has a PhD in Geophysics from the University of Colorado and extensive experience with New Mexico water issues, having worked for SS Papadopulos & Associates, Inc. for 8 years, with particular focus on work for the Interstate Stream Commission on surface water, groundwater, and water operations issues.

Artwork: 1st through 6th grade students in Santa Fe

Since 2003, The City of Santa Fe Water Conservation Office has hosted an annual poster contest. All public, private and charter elementary schools in Santa Fe are invited to participate. Participants range from 1st grade to 6th grade. Over 350 classrooms were invited to design a poster with a water conservation message. A first, second, and third place winner will be selected from each grade, for a total of 18 winners.

The artwork represented here is a sample of the posters both winning and non-winning that were received in 2011 and 2010. The posters represent children's interpretation of the future of water.

Appendix B. Participants in the Santa Fe Watershed Climate Change Workshop on March 6, 2012

First	Last	Company	City
Joni	Arends	Concerned Citizens for Nuclear Safety	Santa Fe
Talitha	Arnold	The United Church of Santa Fe	Santa Fe
Pete	Balleau	Balleau Groundwater, Inc.	Albuquerque
Reid	Bandeen	Truchas Hydrologic Associates, Inc.	Placitas
Beth	Bardwell	Audubon New Mexico	Las Cruces
Rita	Bates	NM Environment Department, Air Quality Bureau	Santa Fe
Athena	Beshur	Seeds of Wisdom, LLC	Santa Fe
Bobbe	Besold	Littleglobe	Santa Fe
Consuelo	Bokum		Santa Fe
Claudia	Borchert	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
Angela	Bordegaray	NM Interstate Stream Commission	Santa Fe
David	Breecker	Santa Fe Innovation Park	Medanales
Felicity	Broennan	Santa Fe Watershed Association	Santa Fe
Melvin	Buchwald		Santa Fe
Elva	Busch	Santa Fe Garden Club	Santa Fe
Patty	Bushee	City of Santa Fe	Santa Fe
Darcy	Bushnell	Utton Center, UNM School of Law	Albuquerque
Mitch	Buszek	Public Advocates	Santa Fe
Nichole	Carnevale	Nambe Pueblo, Environmental and Natural Resources	Nambe Pueblo
Rick	Carpenter	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
Margaret	Chavez	Eight Northern Indian Pueblos	
Christine	Chavez	Los Alamos County Utilities	Los Alamos
Juliana	Coles	We Are People Here	Santa Fe
Betsy	Conover		Santa Fe
Jennifer	Cramer	Santa Fe National Forest	Santa Fe
Susan	Dean	Self-Employed	Santa Fe
William	DeBuys		Chamisal
Bill	Dempster	Institute of Ecotechnics	Santa Fe
Carolyn	Donnelly	Bureau of Reclamation	Albuquerque
Paul	Drakos	Glorieta Geoscience, Inc.	Santa Fe
Brian	Drypolcher	City of Santa Fe, Public Works	Santa Fe
Gary	Durrant	City of Santa Fe, Buckman Direct Diversion	Santa Fe
Dave	Englert	New Mexico Environment Department	Santa Fe
Emily	Geery	NMED, Drinking Water Bureau	Santa Fe
Pamela	Gilchrist	ElderGrace Cohousing	Santa Fe
Tim	Glasco	Los Alamos County Utilities	Los Alamos
Lindsey	Grant	Self Employed	Santa Fe
David	Gutzler	University of New Mexico	Albuquerque
Anna	Hamilton	Tetra Tech, Inc.	Santa Fe
David	Harrington	Squash Blossum Farm	La Bajada
Steve	Harris	Rio Grande Restoration	Embudo
Kathleen	Holian	Santa Fe County	Santa Fe
Alan	Hook	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
John	Horning	WildEarth Guardians	Santa Fe
Melissa	Houser	Santa Fe Conservation Trust	Santa Fe
OrorJonne	Hower	Bureau of Reclamation	Salt Lake City

Appendix B. Participants in the Santa Fe Watershed Climate Change Workshop on March 6, 2012

First	Last	Company	City
Bruce	Hutchison	Self Employed	Santa Fe
Nancy	Hutchison	Self Employed	Santa Fe
Jan-Willem	Jansens	Ecotone	Santa Fe
Richard	Jennings	Earthwrights Designs	Santa Fe
Peggy	Johnson	New Mexico Tech, NMBGMR	Socorro
Brandon	Johnson	United Church of Santa Fe	Santa Fe
Mike	Johnson	New Mexico Office of the State Engineer	Santa Fe
Aaron	Kauffman	Southwest Urban Hydrology	Santa Fe
Dave	Kite		Santa Fe
Jerzy	Kulis	NM Environment Department Hazardous Waste Bureau	Santa Fe
Judith	Lawson		Santa Fe
Amy	Lewis	ACL Consulting	Santa Fe
Mark	Licht	NMLA	Santa Fe
Andrew	Lieuwen	ABCWUA	Albuquerque
Dagmar	Llewellyn	Bureau of Reclamation	Albuquerque
William A	Loeb	OSFA	Santa Fe
Larry	Logan	Edison Electric Institute	Washington
Dale	Lyons	City of Santa Fe, Sangre de Cristo Water Division	SANTA FE
Karen	MacClune	ISET	Boulder
Ken	Margolis	GEOS Institute	Santa Fe
Marcos	Martinez	City of Santa Fe, Attorney	Santa Fe
Dominique	Mazeaud	Heartist	Santa Fe
Laura	McCarthy	The Nature Conservancy	Santa Fe
Annie	McCoy	John Shomaker and Associates	Albuquerque
Betsy	Millard	Southeast Neighborhood Association	Santa Fe
Mark	Miller	Daniel B. Stephens & Associates, Inc.	Albuquerque
Hvtee	Miller	Santa Fe County	Santa Fe
Beth	Mills	Santa Fe County, Open Trails	Santa Fe
Katherine	Mortimer	Public Utilities, City of Santa Fe	Santa Fe
Andy	Novak	retired	Santa Fe
Charlie	Nylander	EBRIF	Santa Fe
Charlie	O'Leary	Santa Fe Conservation Trust	Santa Fe
Erin	Ortigoza	Environmental Services	Santa Fe
Louise	Pape	ClimateToday	Santa Fe
Francois-Marie	Patorni	Santa Fe Watershed Association	Santa Fe
Jonathan	Phillips	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
Alex	Puglisi	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
Doug	Pushard	HarvestH2o	Santa Fe
Anna	Rael Delay	Congressman Tom Udall Office	Santa Fe
Daniel	Ransom	City of Santa Fe, Sangre de Cristo Water Division	Santa Fe
Jesse	Roach	Sandia National Laboratories	Albuquerque
Maria	Rotunda	Earthprints	Santa Fe
Steven	Rudnick	University of New Mexico	Santa Fe
Rich	Schrader	River Source	Santa Fe
Chris	Shaw	New Mexico Interstate Stream Commission	Santa Fe
Sigmund	Silber	S.Silber&Associates	Santa Fe

Appendix B. Participants in the Santa Fe Watershed Climate Change Workshop on March 6, 2012

First	Last	Company	City
Duncan	Sill	Santa Fe County Economic Development	Santa Fe
John Miles	Smith	Santa Fe Basin Water Association	Santa Fe
Dependable	Strongheart	Santa Fe Water Conservation Committee	Santa Fe
Mark	Sundin	Bureau of Land Management	Taos
Ryan	Swazo-Hinds	Pueblo of Tesuque, Environment Dept.	Santa Fe
Enid	Tidwell	Santa Fe Garden Club	Santa Fe
Karen	Torres	Santa Fe County	Santa Fe
Laurie	Trevizo	Sangre de Cristo Water Division, City of Santa Fe	Santa Fe
Kari	Tyler	ISET	Boulder
Arnold	Valdez	Santa Fe County Planning	Santa Fe
Velimir	Vesselinov	LANL	Los Alamos
Ralph	Vigil	New Mexico Acequia Commission	Santa Fe
Susan	Waterman		Santa Fe
Natalie	Wells	Santa Clara County Valley Transportation Agency	Santa Fe
Park	Williams	Los Alamos National Laboratory	Los Alamos
Neil	Williams	Watershed West	Santa Fe
Charles	Wilson	Charles R. Wilson, Consultant	Santa Fe
Stephen	Wiman	Good Water Company	Santa Fe
Robert	Wood	City of Santa Fe, Parks Division	Santa Fe
Rick	Young	S. S. Papadopulos & Associates	Albuquerque
Risana	Zaxus	City of Santa Fe, Land Use	Santa Fe

Appendix C. Summary of Speaker Presentations

Human activities are increasing concentrations of greenhouse gasses such as carbon dioxide and methane in the atmosphere, and these gases are trapping increasing amounts of heat near the earth's surface. In response, global average air temperatures are rising, oceans are warming and expanding, melting of land-based ice is increasing, sea ice is thinning and permafrost melting, precipitation patterns appear to be shifting, and plants and animals are growing, migrating, and responding in different ways, places and times. The evidence for climate change that is being documented in the world around us is concordant with the climate science and physics captured in the global modeling; there is no longer doubt that our climate is changing.

The releases of greenhouses gasses that have occurred to date commit us to a certain degree of climate change, regardless of future emissions; and, currently global emissions appear to be accelerating rather than decreasing. This means that, moving forward, in addition to working to limit future emissions, we need to adapt to existing and at least near-future climate changes.

The goal of this workshop was to introduce climate change and its potential impacts in the Santa Fe Basin to a broad group of local stakeholders, and to solicit from those stakeholders their primary areas of concern and their initial thoughts about how to take action. This summary includes a review of the climate science presented at the workshop by Dr. David Gutzler, University of New Mexico and Dr. Park Williams, LANL, explores the implications of that science for water resources in the Santa Fe Basin, and closes with a call to action delivered by Bill deBuys.

C.1 Climate Change Impacts

Climate change has already occurred as evidenced by observed temperature increases; and forecasts predict that temperatures will continue to rise. The increasing temperatures impact the circulation of moisture in the upper atmosphere, thus impacting precipitation patters. A summary of the past and future changes is provided here.

C.1.1The Earth Is Getting Warmer

The earth is getting warmer – unequivocally. Beginning with the post-World War II boom, fossil fuel burning and land use change have had a noticeable and growing impact on global temperatures. Figure C-1 illustrates global mean temperature. The period from 1000 AD to 1860, obtained from temperature reconstructions, illustrates a variable but generally stable climate with temperatures lower than the reference level (the 0^{o}C line, which is based on the 10-year average of temperatures for the years 1995–2004). The period from 1860 to 2010 reflects measured temperatures; global mean temperature began warming rapidly around 1975 and current temperatures are higher than anything seen in the past 1000 years.

These global trends have clear corollaries in New Mexico; New Mexico is getting warmer – significantly. Over the past century, climate division 2, which encompasses the Santa Fe Basin, has warmed a degree Celsius. The growing season across the southwestern states, the period when average daily temperatures exceed 5^{o}C, increased by approximately 10 days between 1965 and 2008.

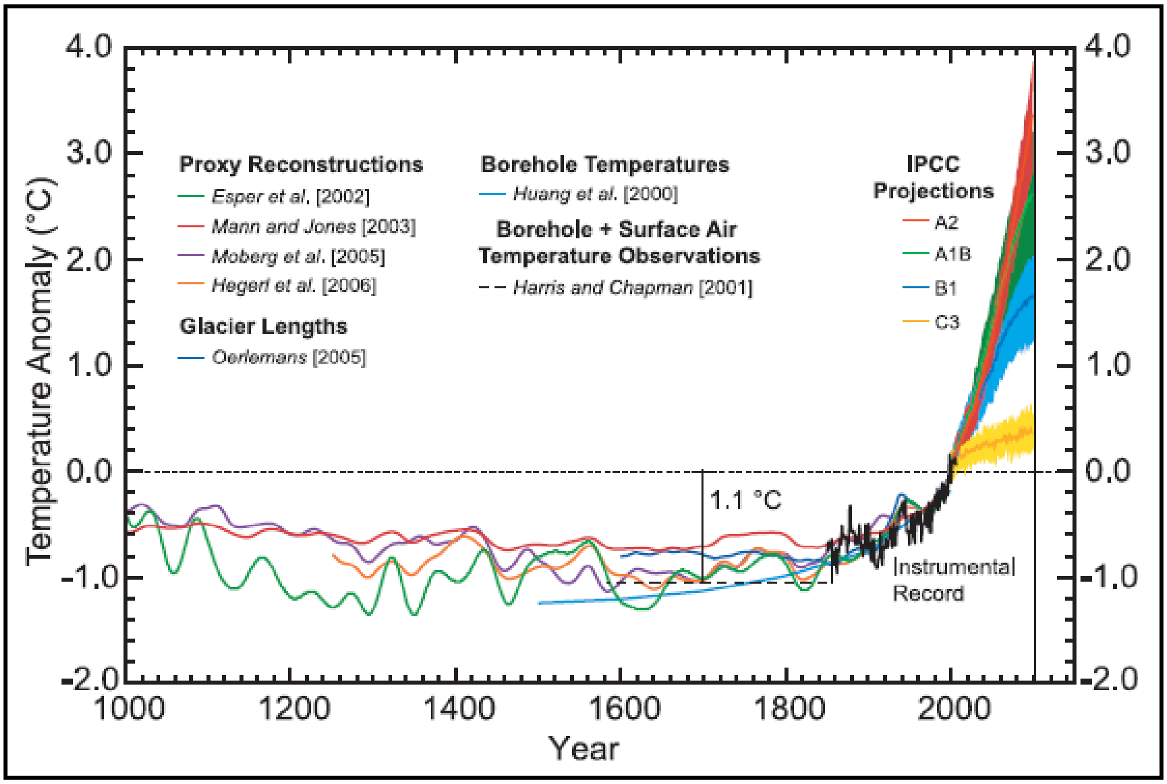


Figure C-1: ***Views of temperature change in the next century are informed by temperature changes in the past. For illustrative and educational purposes, three sets of surface temperatures have been assembled: 1000-year reconstructions of past temperature change based on proxies (tree rings, corals, etc.), glacier lengths, and borehole temperatures; the instrumental record; and Intergovernmental Panel on Climate Change (IPCC) projections for temperature change from 2000 to 2100. (Chapman and Davis, 2010)***

C.1.2 Climate Model Projections Indicate Further Warming

Climate model projections of 21st Century climate show large rates of warming. In Figure C-1, the period from 2010 to 2100 reflects global temperature projections for a variety of future land use, population, economic and emissions scenarios (C3, B1, A1B, A2) using the current suite of global circulation models (GCMs). The models illustrate that temperatures have the potential to dramatically increase in the next 100 years. Projected temperature changes under the A1B scenario are for 5.5 to 6.5 ^{o}F warming between 2000 and 2100.

However, there is a lot of uncertainty associated with the temperature projections. Uncertainty derives from:

- Which GCMs are used – each model represents earth systems with slightly different equations and divides the globe into slightly different boxes (grid cells and layers) in which to solve those equations; and,
- Which scenarios each GCM is run for – the scenarios make assumptions about population growth, energy usage, land use, and global economy to estimate emission rates. Each of

> those assumptions has implications for global greenhouse gas emissions and local impacts. Theoretically, each of the scenarios is as likely as another, although we are currently following some of the higher emission tracks.

Any value within the range of possible future temperatures is as likely as another. Consequently, in working with climate projections, it is important to consider the full range of modeled projections for a region.

It is also important to remember that climate projections are generally presented as the modeled range of **average** values for a given location, and do not take into account local climate variability. Gutzler and Robbins (2010) address this for New Mexico by combining historic temperatures and precipitation variability with projected temperate trends. Results are illustrated in Figures C-2 (temperature) and 3 (precipitation).

One of the striking elements of Figure C-2 is that, by 2100, projected low temperatures, even when combined with current variability, exceed all but the highest temperatures seen in the historic record. Even by 2050, winter temperatures are close to today's average temperatures. This would have significant implications for water availability, management, and demand.

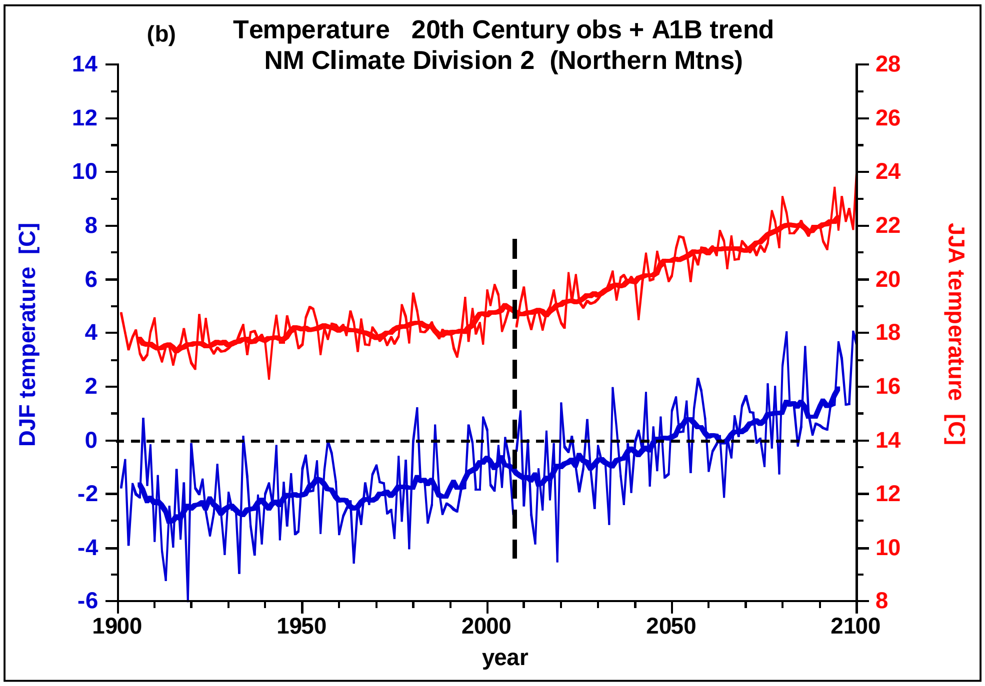


Figure C-2: Time series of annual temperature (°C) for the December-January-February (DJF) winter season (lower lines) and June-July-August (JJA) summer season (upper lines) for the twentieth and twenty-first centuries in New Mexico Climate Division 2. Thin lines show annual values; thick lines are 11-year running averages. For years 1901– 2007 (left of vertical dashed line), values are observed climate divisional data. For years 2008–2099 (right of dashed line), values are derived by adding twentieth century inter-annual variability to the twenty-first century simulated trend obtained by averaging 18 GCMs run for the A1B scenario. 21st century trends have values of +3.3°C/century in winter and +4.3°C/century in summer (Gutzler and Robbins, 2010).

Precipitation trends are less clear than temperature trends, both in the data and in model projections. Figure C-3 illustrates historic precipitation for NM Climate Division 2, and the projected precipitation under the A1B scenario, combined with historic variability. As can be seen, historic variability exceeds projected trends. Based on model results, future precipitation seasonal averages may be relatively indistinguishable from historic seasonal averages.

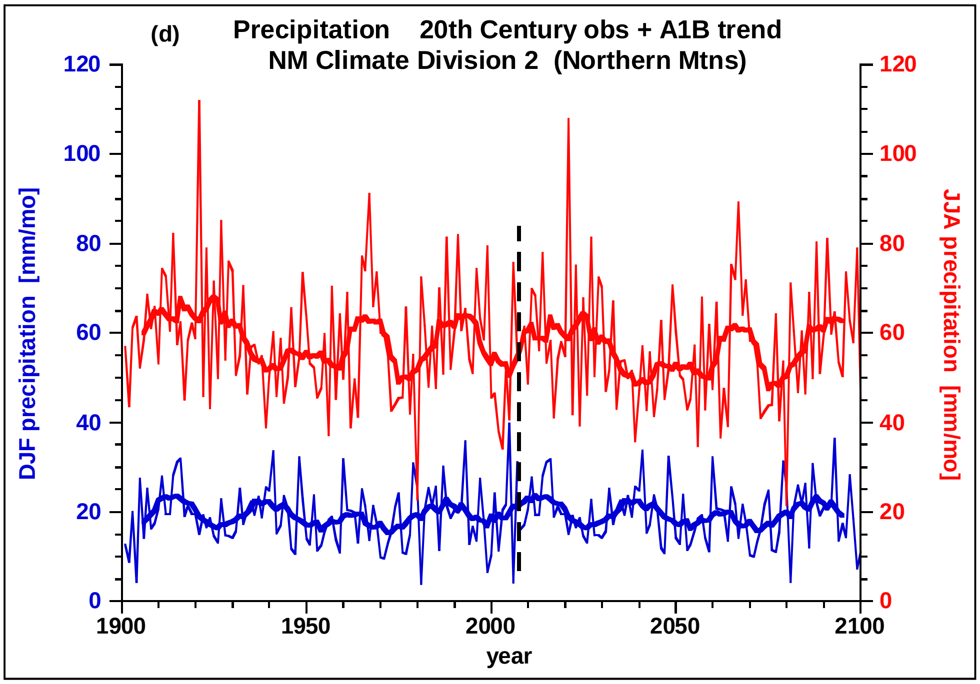


Figure C-3: Time series of annual precipitation (mm/mo) for the DJF winter season (lower lines) and JJA summer season (upper lines) for the twentieth and twenty-first centuries in New Mexico Climate Division 2. Thin lines show annual values; thick lines are 11-year running averages. For years 1901– 2007 (left of vertical dashed line), values are observed climate divisional data. For years 2008–2099 (right of dashed line), values are derived by adding twentieth century inter-annual variability to the twenty-first century simulated trend obtained by averaging 18 GCMs run for the A1B scenario. 21st century trends have values of -0.11 (mm/month)/century in winter and +1.6 (mm/month)/century in summer (Gutzler and Robbins, 2010).

This does not mean, however, that future daily precipitation will remain indistinguishable from historic precipitation events. Climate is projected to become more variable with climate change; future variability may exceed historical variability, with, for example, the lowest low temperatures remaining relatively unchanged but the high temperatures increasing dramatically. In particular, precipitation events are projected to become more intense (Figure C-4). This implies that, though seasonal precipitation totals may remain relatively unchanged, they are likely to be delivered in fewer, more intense rainfall events.

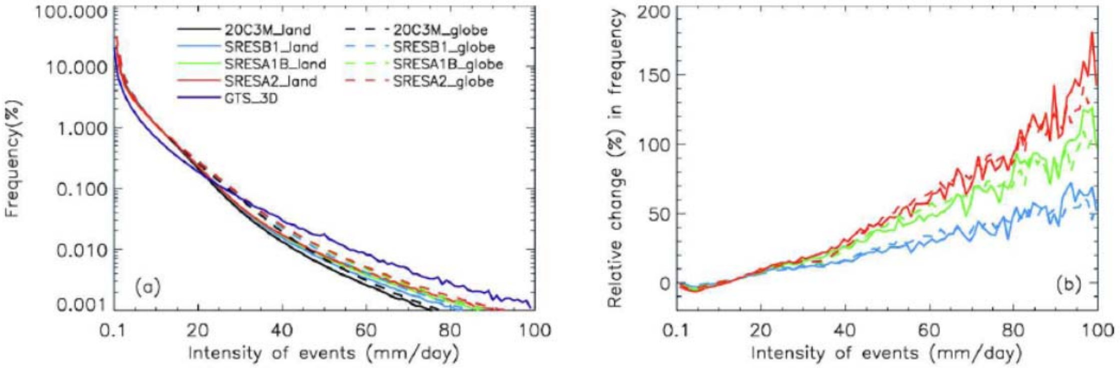


Figure C-4: Compared to simulations of current climate, global models generate fewer, but more intense, a precipitation event, averaged globally, as the climate warms up (Sun et al., 2007).

C.1.3Hydrologic Implications of Climate Change

The projected changes in temperature and precipitation will have implications for summer aridity, for winter precipitation (increasingly falling as rain rather than snow), snowmelt, and, by association, for spring melt water runoff timing and volume. Global climate models project a transition to a much more arid climate in the Southwest by the mid-21st Century, as a result of both the lack of increase in overall precipitation and the increased evaporation and evapotranspiration resulting from higher temperatures. Evaporation and evapotranspiration (E) are a strong function of surface temperature; warmer air holds more moisture. If precipitation (P) holds relatively constant, then available water (runoff and groundwater recharge), P-E, becomes consistently negative (drier surface) by the latter half of this century in model simulations. This means the dry season becomes even more intensely dry, with implications for irrigation needs for irrigated crops, and negative impacts to non-irrigated vegetation.

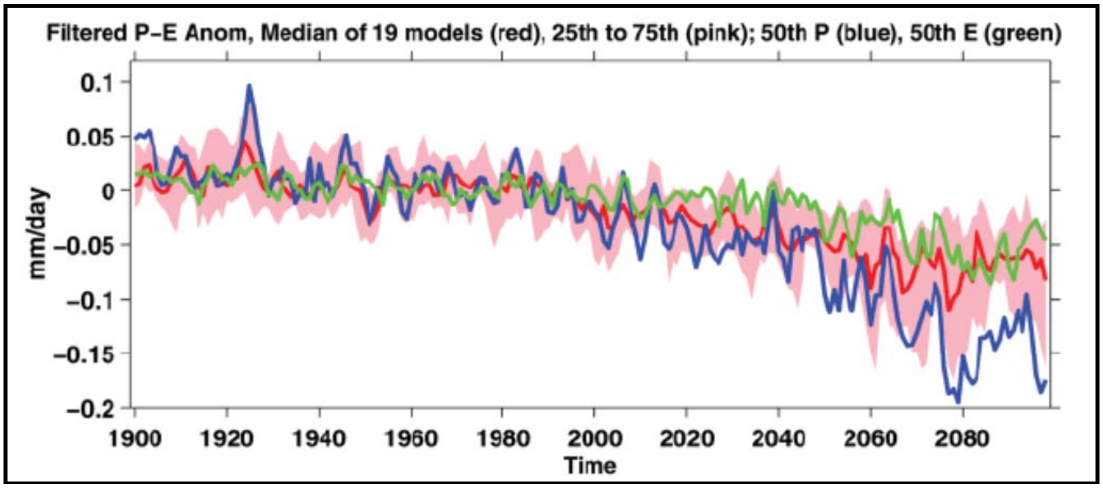


Figure C-5: Modeled change in annual mean Precipitation-Evaporation for the Southwestern US (Seager et al., 2007). The historical period used known and estimated climate forcings, and the projections used the SResA1B emissions scenario. Anomalies (Anom) for each model are relative to that model's climatology from 1950–2000. The model-ensemble mean P − E in this region is around 0.3 mm/day.

The predicted future winter climate will show changes in snowpack depth and snowmelt. Driven primarily by temperature changes, decreases in snowpack throughout the western mountains are seen in climate model simulations. The decreases are due principally to temperature change, with winter precipitation falling as rain rather than snow. By mid-century, projected changes for the Southern Rocky Mountains range from a 20 to 70% reduction in snowpack (Figure C-6).

What snow does fall will melt earlier, due to higher spring temperatures? Figure C-7 suggests that by mid-century, spring runoff could be 15 to 35 days earlier. This much earlier peak runoff date, driven by warmer temperatures, may also have lower peak flows, due to less snow. This clearly has significant implications for spring irrigation, mid- to late-summer flows, and reservoir storage.

Snowpack currently feeds a late-spring flood pulse on the upper Rio Grande and its tributaries, providing base flow for both the middle and lower river. In their 2008 paper, Hurd and Coonrod found that in the warmer climate projected for New Mexico, there would be an earlier and smaller snow-fed flood pulse, and a reduced total stream flow volume, especially in late spring/early summer. Their projected reductions in flow for the Middle Rio Grande are (Hurd and Coonrod, 2008):

- 2030: 4 - 14% reduction
- 2080: 8 - 29% reduction

Santa Fe River stream flow projections are similar to those for the Middle Rio Grande. Cox et al., in their 2011 paper, project an annual decrease in stream flow above McClure Reservoir by 2060 of 11-18%.

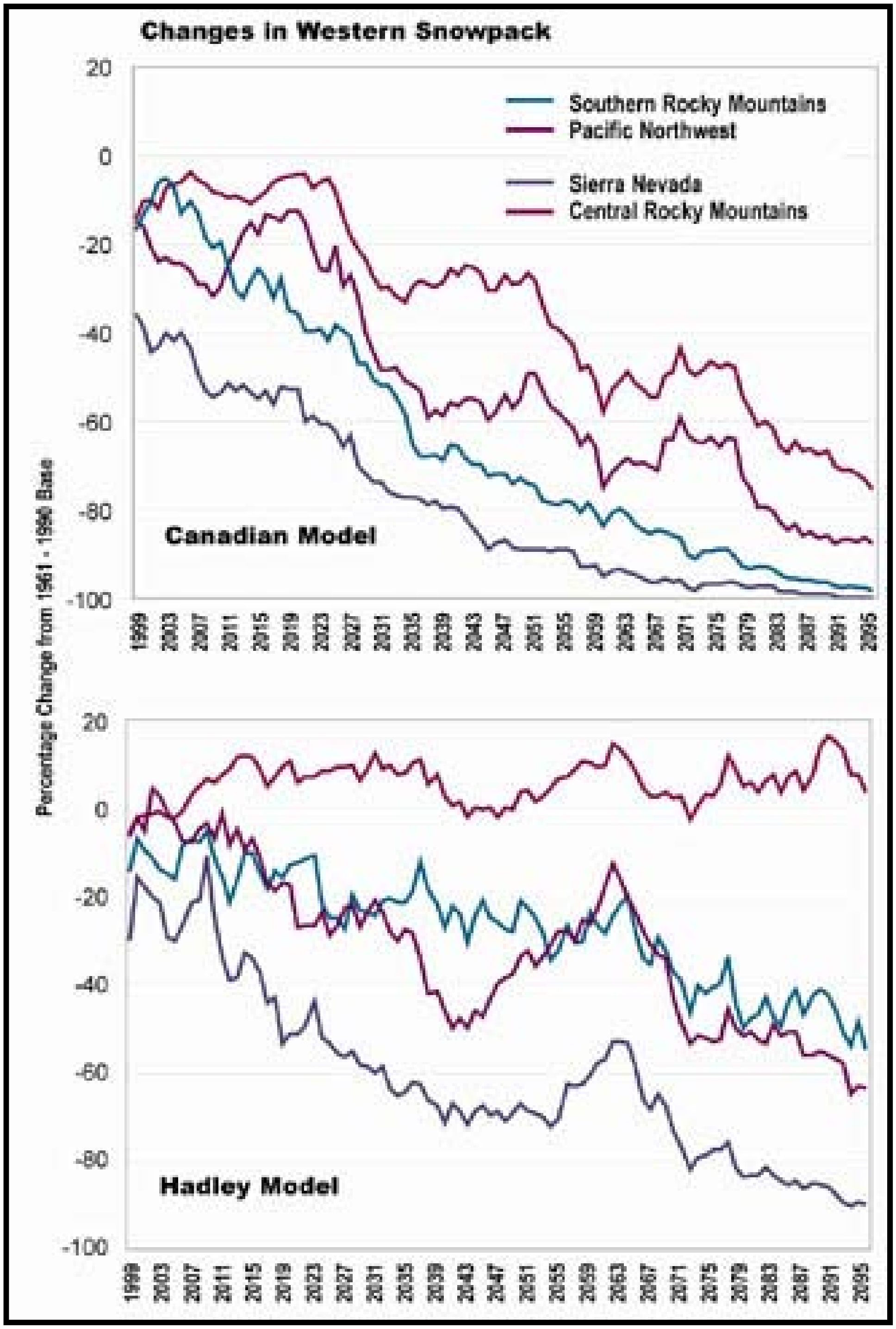


Figure C-6: Percentage change in the April 1 snowpack from the 1961-90 baseline in four areas of the western US as simulated for the 21st century by the Canadian and Hadley global circulation models. April 1 snowpack is important because it stores water that is released into streams and reservoirs later in the spring and summer. The sharp reductions are due to rising temperatures and an increasing fraction of winter precipitation falling as rain rather than snow. The largest changes occur in the most southern mountain ranges and those closest to the warming ocean waters. (NAST, 2000).

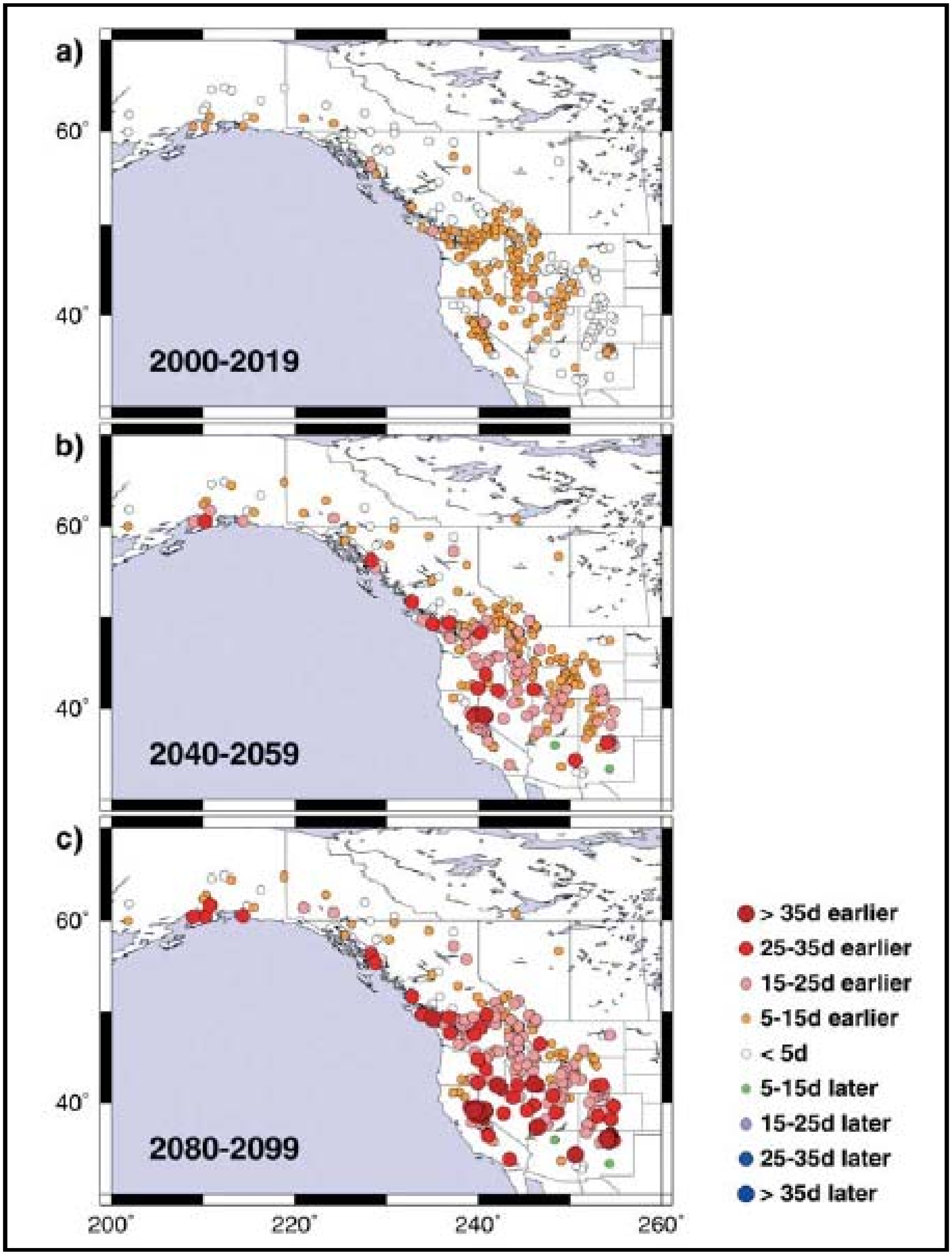


Figure C-7: Projected change in snowmelt runoff timing for western North America (Stewart et al., 2004)

C.2. Potential Secondary Effects

The temperature and precipitation projections, and their associated impacts to snowpack, snowmelt, stream flow, and P-E anomaly, have significant implications for virtually all water-related systems in New Mexico. Reservoir storage and river operations will be impacted by changes in volume and timing; these in turn will impact water availability for urban, agricultural and ecosystem use. Changes in precipitation intensity and snowpack may impact groundwater recharge rates. As a result, all systems that depend on water need to be evaluated for their vulnerability to reduced water availability, changes in the timing of water availability, and/or sensitivity to aridity and drought.

The second speaker at the workshop, Dr. Park Williams, LANL, delivered a case study on potential climate change impacts to forest ecosystems of New Mexico. This study provides significant insight into the types of cascading impacts that climate change may bring to New Mexico and the Santa Fe Basin.

C.2.1 Past, Present, and Future Impacts of Drought on Forests in the Southwestern USA

Dr. Williams initially analyzed how temperature (relative to precipitation) impacts regional forest productivity and mortality in the Southwestern USA. However, he quickly realized that temperature impacts forests via vapor pressure deficit. **Vapor Pressure Deficit** (**VPD**) is the difference (deficit) between the amount of moisture in the air and how plants draw more water from their roots. VPD has a simple, nearly straight-line relationship to the rate of evapotranspiration.

The growth of piñon pine, ponderosa pine and Douglas fir trees in New Mexico and the Southwestern U.S. is limited by moisture availability. During seasons and years of optimal climatic conditions, annual growth rings are wide; during drier years, thinner rings develop, on average with the thinnest rings during the driest years. Breaking the year down into seasons, and assessing both precipitation and vapor pressure deficit, Williams and colleagues found that winter (Nov-Mar) precipitation and summer (Aug-Oct of previous year and May-July of current year) account for 91% of the year-to-year variability in tree-ring width. Warm season vapor pressure deficit accounts for 56% of this correlation, and cold-season precipitation for 44%. Williams used this to develop a "Forest Drought-Stress Index", FDSI:

FDSI = 0.44 [zscore(cold-season precipitation)] – 0.56 [zscore(warm-season VPD)]

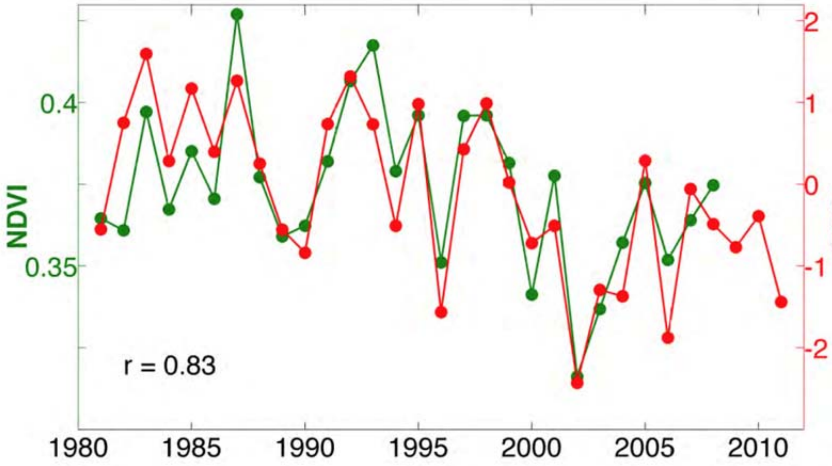
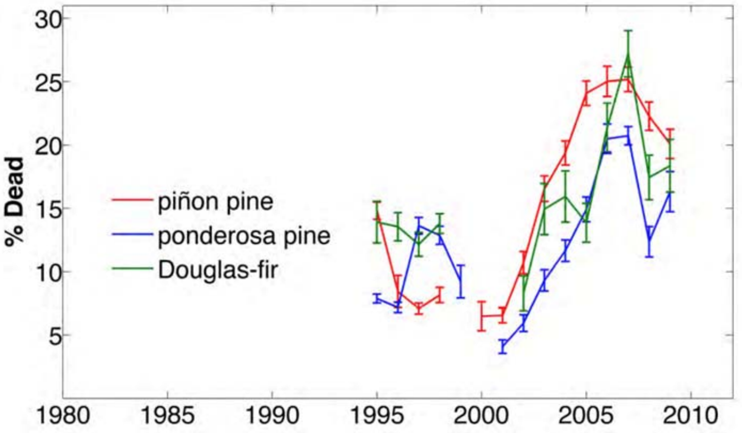


Figure C-8: Correlation between NDVI (summer vegetation greenness index derived from AVHRR satellite imagery) and the Forest Drought-Severity Index (FDSI).

The FDSI is strongly correlated (0.83) with summer vegetation greenness (NDVI) derived from AVHRR satellite imagery, as is illustrated in Figure C-8.The NDVI dropped significantly in 2002 and remained lower, for the rest of the 2000s, than in the 1980s and 1990s. This drop coincided with a period of high tree die-off in response to bark beetle outbreaks, as shown in Figure C-9. Between 1997 and 2010 bark beetles were responsible for the death of 8% of the forests in the Southwest; the number of dead trees roughly doubled between 2001 and 2006.

Figure C-9: Number of dead piñon pine, ponderosa pine and Douglas fir, USFS Forest Inventory & Analysis (FIA) data.



The bark beetle outbreaks, in turn, corresponded with drought. Drought-induced stress made trees more susceptible to beetle infestation. Figure C-10 illustrates the strong inverse correlation (0.84) between the forest area impacted by bark beetles (left axis) and the 2-year running-average FDSI (right axis; more negative values, corresponding with higher drought, are at the top of the axis).

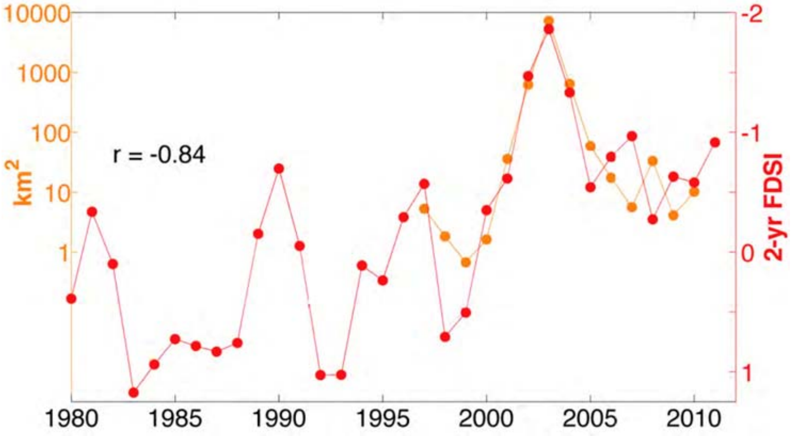


Figure C-10: Inverse correlation between forest area impacted by bark beetles (left axis; Forest Health Technology Enterprise data) and the 2-year running-average Forest Drought-Severity Index (FDSI, right axis).

Drought-induced stress also left forests more susceptible to wildfires, which further contributed to the reduction in NDVI. 2002, 2006 and 2011 all saw large areas in the Southwest burn. As with bark beetle impact, total burned area is strongly inversely- correlated with the FDSI, as shown in Figure C-11; 2002, 2006 and 2011 are all years when the FDSI was lower than -1.

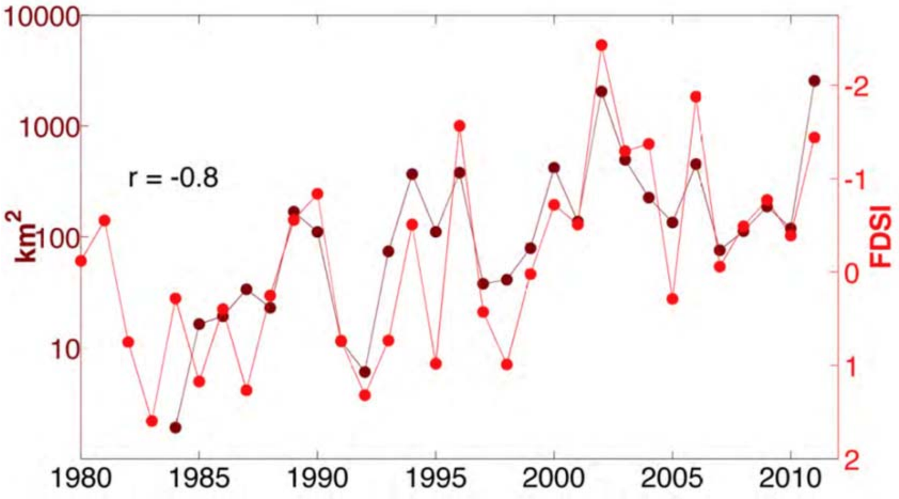


Figure C-11: Inverse-correlation between forest burned area (left axis) and FDSI (right axis). More negative values of FDSI correspond to deeper drought conditions.

Drought-induced forest mortality is normal in New Mexico. For example, tree-ring data suggest that regionally extensive droughts in the late 1200s and late 1500s caused increased tree mortality throughout the Southwestern U.S. More recently, mortality of many southwestern tree species occurred during the severe drought of the 1950s. In general, the risk of widespread tree mortality dramatically increases for FDSI values below -1. However, climate projections suggest FDSI values will become more negative in the future. By about 2050, FDSI values for even the wettest, coolest years will equal or exceed the FDSI values experienced during the 1200 and 1500 "mega-droughts" and the 1950s drought.

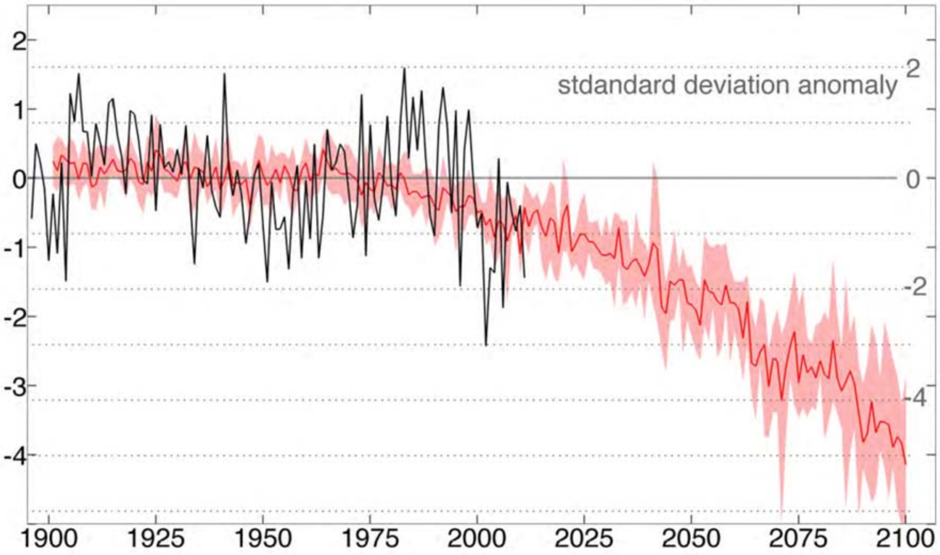


Figure C-12: Projected FDSI (dark red line is average; light red shading is range) vs. historic FDSI derived from measured data (black).

This means that, if climate models are correct, by the 2050s average drought stress will equal that of the worst drought years that the Southwestern U.S. has experienced in the past 1000 years.

C.2.2Case Study Implications

It is generally accepted that current drought and elevated temperatures have contributed to the recent increase in widespread fires and bark-beetle outbreaks in the Southwestern US. At least 8 to 11% of southwestern forest and woodland area was affected by extensive tree mortality due to bark beetles from 1997 through 2008. Another approximately 3.0% of forest and woodland area was affected by stand-replacing fire with moderate to severe burn severity from 1984 through 2006. Together, fire and bark beetles have caused high levels of mortality in 14–18% of southwestern forest areas (excluding woodlands) over the past two decades.

This suggests that, with only two more recurrences of drought/die-off similar to that of the past 20 years, Southwest forest area could be reduced by more than 50% over 1980s coverage. And, given the projections for warming and the associated increase in vapor pressure deficit and FDSI, two more recurrences similar to or worse than the past 25 years seem likely. Clearly, this is a broad simplification that ignores self-limiting effects, regeneration, and other complexities; there is considerable uncertainty about how forests will respond to increasing stress over the coming decades. Nonetheless, this science should inform the debate around how to build forest resilience.

Appendix D. Solutions Proposed At Workshop

This appendix contains the full list of climate change actions and solutions proposed at the workshop, 62 in all. Actions are divided into categories, as for sections 5 and 6 of the report, for ease in cross-referencing.

D.1 Water Supply Systems

Water: Management

1. Storm water management by neighborhood
2. Coordinated water quality / water quantity management
3. Local, community-based water board
4. Aquifer recharge/ aquifer storage and recovery: using surplus rainwater and snowmelt, landscape contouring to enhance storm water capture, arroyo catchment systems, etc.
5. Negotiate agriculture to urban water transfers of limited term with MRGCD, to be implemented in times of drought or other emergency.

Water: Demand Reduction

1. Tiered water billing - cheaper rates for those who use less
2. Strengthen water and wastewater reuse; explore cleaning wastewater to drinking water standard
3. Clearinghouse for city conservation programs

D.2 Ecosystems

1. Improve urban forests using carbon credits
2. Conduct more prescribed fires in winter
3. Thin Santa Fe River watershed (healthy forests)
4. Develop contingency plans for responding to large-scale fires in the Santa Fe watershed, including consideration of flood protection, recovery of water systems, rehabilitation of reservoirs, and budgets required to implement

D.3 Agriculture and Food security

1. Guarantee seed sovereignty
2. Buffer zones for GE crops
3. Encourage small farms in the city and county
4. Annual budget from Santa Fe County Commission to support healthy food systems
5. Urban planning to incorporate a wide variety of urban agriculture techniques, including urban farming and food-scapes in commons areas

D.4 Land Use and Quality of Life

Parks and Landscaping

1. Use compost and mulch in all commons areas
2. Plant trees w/in city limits to “cool” cities
3. Manage city parks to harvest and reduce runoff, reducing water demand

Urban Infrastructure/Green Infrastructure

1. Solar panels over parking lots to reflect heat and generate energy
2. Incentives for addressing water leaks
3. Tax incentives for green properties
4. Require pervious pavement
5. Free green-waste bin and city/county composting
6. Close 4-corners coal plant

Zoning/Development

1. Improve zoning to: preserve agricultural land, foster urban infill, and foster small (~150 people) neighborhoods
2. New development - zero-runoff requirement for storm water
3. Moratorium on new construction that draws from groundwater
4. Connect land and water planning
5. Explore policy options to address the tension between locals and second-homers – does Santa Fe want to encourage or discourage the growth of 2nd homes.

D.5 Energy Systems

1. Electric coop and/or municipal energy company
2. Create incentives to use renewable energy
3. Greater incentives for energy efficiency, coupled with funding help for individual households

D.6 Sociological Systems/Public Engagement/Policy Change

1. Start now: do what you can with what you have where you are
2. Provide more incentives for actions that address climate change
3. Highlight models of successful projects happening now
4. Foster inclusive discussions incorporating all components of community
5. Eliminate corporate personhood, starting locally and using this to leverage state and national change
6. Break down solutions between those that do and do not require financing
7. Open discussion of uncomfortable topics such as population growth
8. All citizens work annually for city water system, in exchange for a tax credit, to create more awareness

9. Build task force to manage conserved water to enhance resilience, avoid demand hardening or dedication to growth (task force to preserve/protect water freed up by conservation so that it doesn't go to support growth)
10. Create sacred space around water, including at meetings

D.7 Education

1. Free birth control, sex education in schools, and education on impacts of overpopulation
2. Free classes on growing food and composting
3. Conservation classes, participation rewarded through tax incentives
4. Xeric demonstration gardens
5. Demonstration rainwater harvesting systems
6. Install rainwater catchment systems in all schools, linked to gardens, food gardens, and trees
7. Require middle school water education and green education
8. Lessons learned – put into school buildings and curricula
9. Tours of WWTP to educate residents and school children on where waste-water goes
10. Tours of Buckman Direct Diversion (recognize cost)
11. School challenges to decrease carbon footprint within classrooms and school-wide, including quantification
12. Increase water resource outreach and education for all citizens

D.8 Visionary

1. Make imagination and possibility more seductive than scarcity and fear
2. Artist in Residence dedicated to Santa Fe River
3. Make conservation, both at individual and community level, a ritual
4. Water-free day each year to demonstrate how integral it is to our existence
5. "Year of water" – poets manage water for a year

D.9 Implementation

1. Regional governance – connect government agencies across whole watershed
2. More communication and collaboration across government levels, beginning with the city and county
3. A diversity of decision-makers, coupled with deep community engagement

Photo descriptions:

View of sunset from Santa Fe, June 2009. Photo by A. Lewis

One year after Las Conchas Fire, May 16, 2012. Photo by A. Lewis

Bill deBuys at Santa Fe River Climate Change Workshop, March 6, 2012. Photo by A. Lewis.

Santa Fe River Climate Change Workshop, March 6, 2012. Photo by A. Lewis

Breakout session during the Climate Change Workshop, March 6, 2012. Photo by A. Lewis

Blue gramma grass near Santa Fe, August, 2006. Photo by A. Lewis

High water use toilets on route to the landfill after being replaced through the City of Santa Fe's toilet retrofit program, December, 2006. Photo by A. Lewis

Las Conchas fire and fireworks, July 4, 2012. Photo by A. Lewis

Results of forest treatments in the Santa Fe Watershed near Nichols Reservoir, September, 2011. Photo by A. Lewis

Rangeland near Santa Fe, August 2007. Photo by A. Lewis

Domestic garden near Santa Fe, August, 2007. Photo by A. Lewis

Green chili roasting in Santa Fe, September, 2011. Photo by A. Lewis

Appendix B

Technical Memo on Development of Climate Change Hydrographs for WaterMAPS

Santa Fe Basin, New Mexico

Contents

This appendix provides the text of a technical memorandum from Jesse Roach, Ph.D, Earth Systems Analysis, to Claudia Borchet, Santa Fe County, dated September 6, 2013. The memo explains how hydrographs for the Water Management and Planning Simulation (WaterMAPS) were developed.

1 The CMIP3 GCM Runs

Phase 3 of the Coupled Model Intercomparison Project[1] (CMIP3) includes archived temperature and precipitation model output from 16 Global Climate Models (GCM) runs from 1950 through 2099 for three different emission scenarios and a variety of boundary conditions. The result is 112 different GCM runs numbered according to the framework shown in Table 1. The 112 CMIP3 GCM runs were spatially downscaled to $^1/_8$ degree resolution using statistical methods. The resulting "Bias Corrected Spatially Downscaled" (BSCD) projections are archived for public access.[2]

2 GCM Ensembles

The Hybrid-Delta Ensemble (HDe) method (Brekke, Pruitt and Smith 2010) was used to create hydrologic simulations for planning purposes that are limited in number and capture both the temperature and precipitation trends from the 112 GCM runs as well as historic variability of the Rio Grande System. This was accomplished as follows:

1. The Bureau of Reclamation's Technical Service Center (TSC) chose a representative area for the Upper Rio Grande basin as a rectangle extending from 31.6875 through 38.5625 degrees of latitude, and -07.9375 through -105.0625 degrees of longitude as shown in Figure 1.

2. A single average temperature and average precipitation was calculated for each of the 112 GCM runs for the spatial area shown in Figure 1 for the 1950-1999 historic simulation period (average of each month of data in each 1/8 degree pixel shown in Figure 1).

3. Another single average temperature and average precipitation value was calculated for each of the 112 GCM runs for the spatial area chosen during the 2040-2069 simulation period.

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[1] http://www-pcmdi.llnl.gov/projects/cmip/index.php
[2] http://gdo-dcp.ucllnl.org/

4. The difference between these values was defined as the “delta” temperature and the “delta” precipitation for each model run for the spatial extent and time periods selected.

5. The 112 temperature deltas were plotted against the 112 precipitation deltas, and the deltas were grouped according to rank. For the Santa Fe Basin study, and the accompanying Upper Rio Grande Impacts Analysis (URGIA), an activity of the West Wide Climate Risk Assessment,[3] the deltas were grouped as above or below the 50th percentile temperature delta and also above or below the 50th percentile precipitation delta. For the 112 runs, the 50th percentile occurs between the 56th and 57th delta. Thus, all points fell into one of four groups:

   - Above the 50th percentile for precipitation and temperature changes (“HotWet” or HW)

   - Above the 50th percentile for precipitation change and below the 50th percentile for temperature change (“WarmWet” or WW)

   - Below the 50th percentile for precipitation change and above the 50th percentile for temperature change (“HotDry” or HD)

   - Below the 50th percentile for precipitation and temperature changes (“WarmDry” or WD)

   Finally, an overlapping central group was defined as any point between the 25th and 75th percentile for both the change in precipitation and change in temperature (“Central” or C). The ensembles are shown in tabular form by index number (see Table 1) and graphically in Figure 2.

For the Santa Fe Basin Study, only the Warm Wet (WW), Hot Dry (HD), and Central (C) ensembles for the 2050s period are being used. The GCMs which define these ensembles for the2050s are listed in Table 2.

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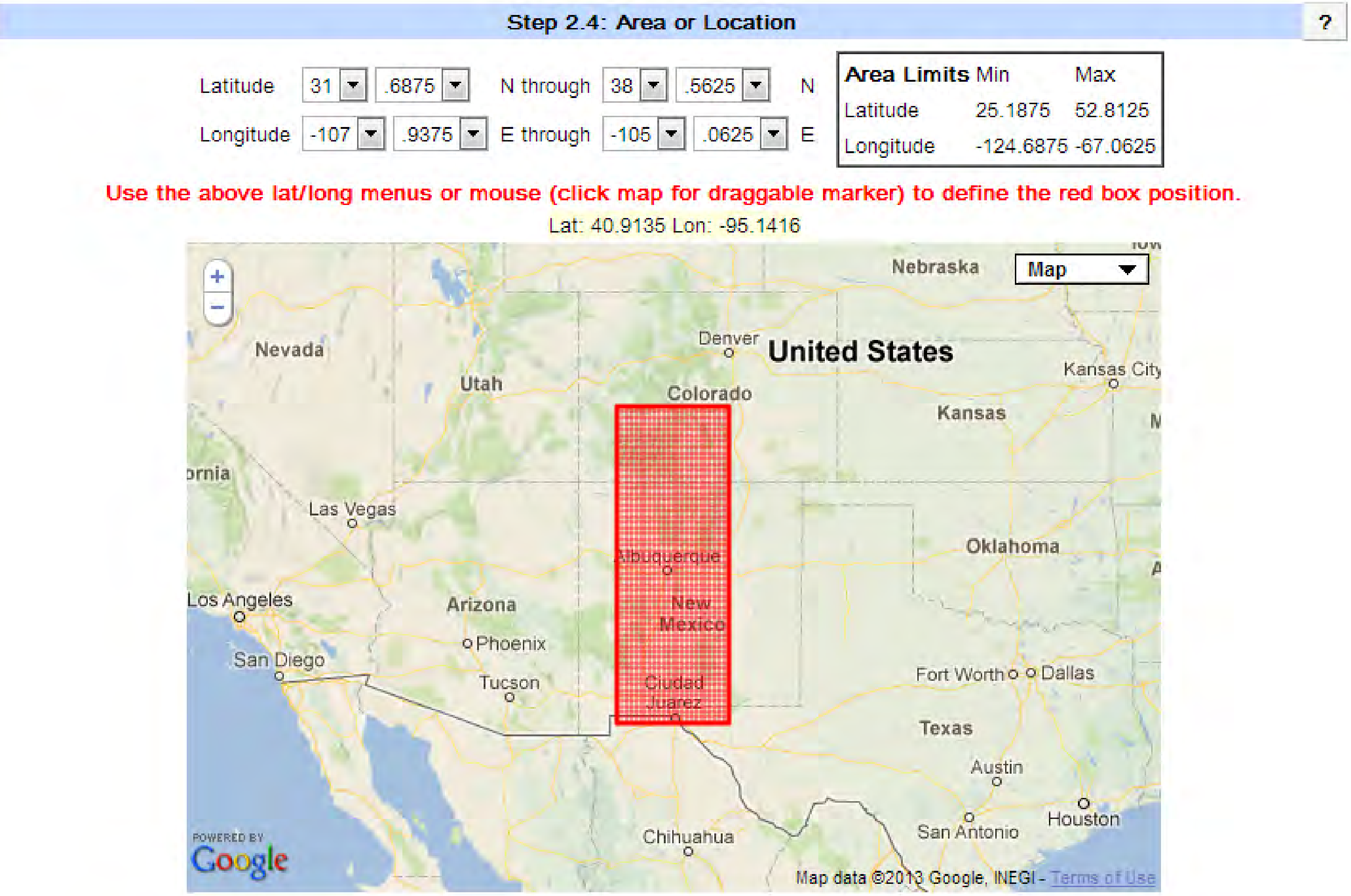
[3] http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf

[4] All temperature increases are positive for all models at all periods, thus the lower 50th percentile for temperature change is called Warm.

Table 1: The index values of the 112 CMIP3 GCM runs and the associated model and emission scenario.

	Emissions Scenarios																		
Climate Models:	**A1b**							**A2**					**B1**						
bccr_bcm2_0	1							40					76						
cccma_cgcm3_1	2	3	4	5	6			41	42	43	44	45	77	78	79	80	81		
cnrm_cm3	7							46					82						
csiro_mk3_0	8							47					83						
gfdl_cm2_0	9							48					84						
gfdl_cm2_1	10							49					85						
giss_model_e_r		11		12				50					86						
inmcm3_0	13							51					87						
ipsl_cm4	14							52					88						
miroc3_2_medres	15	16	17					53	54	55			89	90	91				
miub_echo_g	18	19	20					56	57	58			92	93	94				
mpi_echam5	21	22	23					59	60	61			95	96	97				
mri_cgcm2_3_2a	24	25	26	27	28			62	63	64	65	66	98	99	100	101	102		
ncar_ccsm3_0	29	30	31		32	33	34	67	68	69	70		103	104	105	106	107	108	109
ncar_pcm1	35	36	37	38				71	72	73	74			110	111				
ukmo_hadcm3	39							75					112						



Step 2.4: Area or Location

Latitude 31 .6875 N through 38 .5625 N

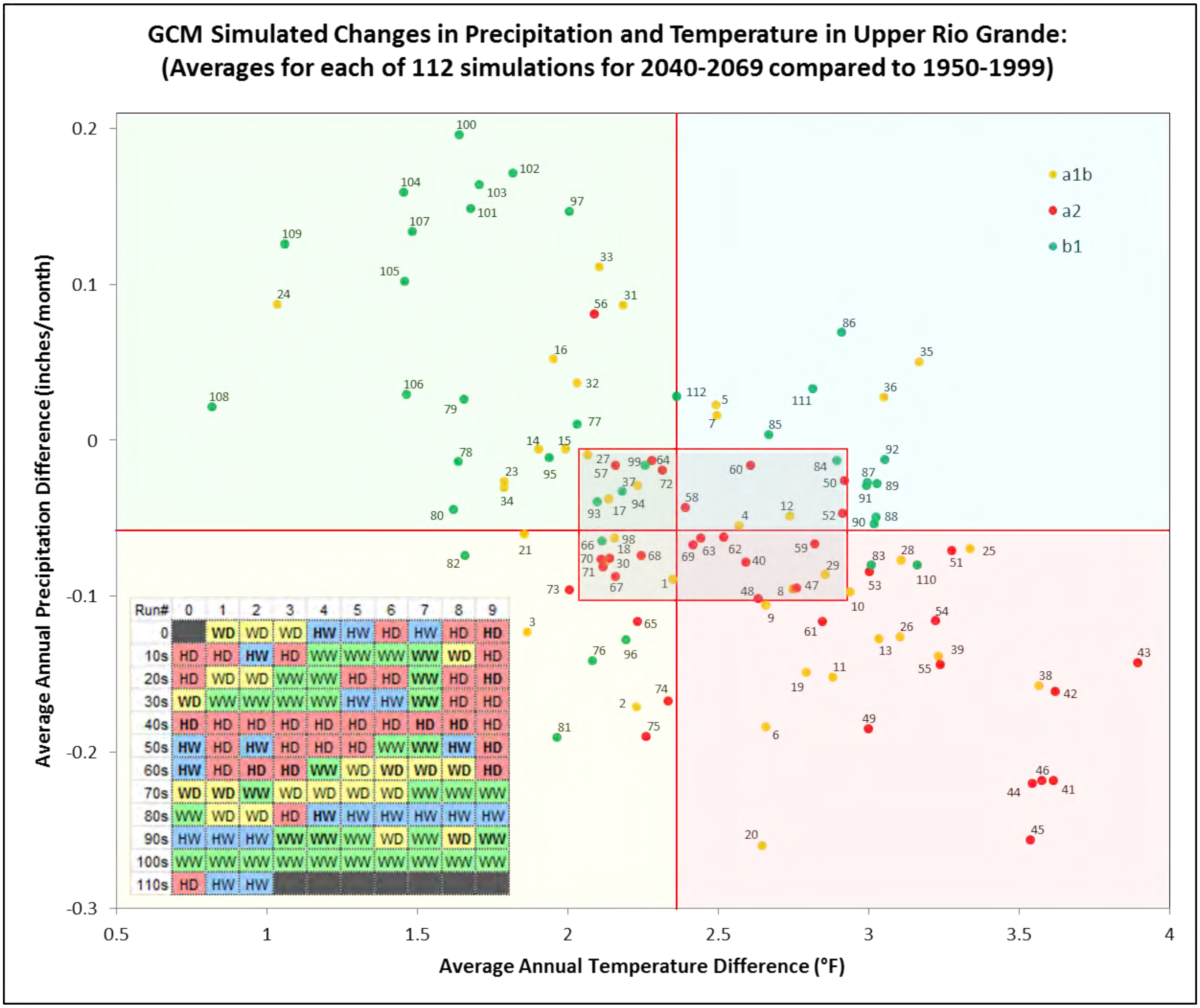
Longitude -107 .9375 E through -105 .0625 E

Area Limits	Min	Max
Latitude	25.1875	52.8125
Longitude	-124.6875	-67.0625

Use the above lat/long menus or mouse (click map for draggable marker) to define the red box position.

Lat: 40.9135 Lon: -95.1416

Figure 1: Spatial area used to define the average temperature and precipitation value for each GCM for a given time period. Extents are 31.6875 through 38.5625 degrees of latitude, and -107.9375 through -105.0625 degrees of longitude. Screen capture is from http://gdo-dcp.ucllnl.org.



Run#	0	1	2	3	4	5	6	7	8	9
0		WD	WD	WD	HW	HW	HD	HW	HD	HD
10s	HD	HD	HW	HD	WW	WW	WW	WW	WD	HD
20s	HD	WD	WD	WW	WW	HD	HD	WW	HD	HD
30s	WD	WW	WW	WW	WW	HW	HW	WW	HD	HD
40s	HD	HD	HD	HD	HD	HD	HD	HD	HD	HD
50s	HW	HD	HW	HD	HD	HD	WW	WW	HW	HD
60s	HW	HD	HD	HD	WW	WD	WD	WD	WD	HD
70s	WD	WD	WW	WD	WD	WD	WD	WW	WW	WW
80s	WW	WD	WD	HD	HW	HW	HW	HW	HW	HW
90s	HW	HW	HW	WW	WW	WW	WD	WW	WD	WW
100s	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW
110s	HD	HW	HW							

Figure 2: Plotting the temperature delta (X axis) against the precipitation delta (Y axis) to group the 112 GCMs into ensembles. The red lines represent the 50% values for each, and the red bounding square encompasses the 25% to 75% values.

Table 2: Ensemble summary table for the Santa Fe Basin study. See Table 1 to reference each number to a specific GCM run.

Warm Wet (upper left)	Hot Dry (lower right)	Central
14-17,23,24,27,31-34, 37,56,57,64,72,77-80, 93-95,97,99,100-109	6,8-11,13,19,20,25,26,28, 29,38-44,46-49,51,53-55, 59,61-63,69,83,110	1,4,9,12,17,18,27,29,30,37, 40,47,48,50,52,57-60,62-64, 66-72,84,93,94,98,99

3 From GCM Ensembles to Hydrographs

The average monthly changes in precipitation and temperature for each period and each ensemble are used to alter synthetic historic (Maurer et al. 2002) temperature and precipitation data for the 1951-1998 time period. This modified climate data is then used by TSC as inputs to a $^{1}/_{8}$ degree resolution macroscale land surface model known as the Variable Infiltration Capacity (VIC) Model (Liang et al. 1994) which generates runoff hydrographs at each $^{1}/_{8}$ degree computation cell, which is then routed through a river network. The VIC model application used for the Upper Rio Grande has been calibrated to some degree, but still generates flows significantly different from observed when forced by the Maurer et al. (2002) historic climate sequence. To handle this, the raw outflows are “bias corrected” in a post processing step that involves comparing the cumulative density function (CDF) of the historic simulated flows to the CDF of the historic observations to create a transformation of flows that is then used to transform all raw VIC output, both during the historic simulation and future scenario periods. For more information on this bias correction process, refer to the Upper Rio Grande Impact Assessment (Llewellyn et al. 2013). The end result of this process is 112 bias-corrected daily streamflow sequences for the study area.

4 From Hydrographs to Basin Scale Operations

The Upper Rio Grande Simulation Model (URGSiM) is a monthly timestep mass balance model that uses hydrologic and climatic inputs to simulate the movement of surface water and ground water through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico, including the Rio Chama and Jemez River tributary systems, and the Espanola, Albuquerque, and Socorro regional groundwater basins. URGSiM simulates operations in nine surface reservoirs, interbasin transfers from the Colorado River Basin to the Rio Grande Basin (via Reclamation’s San Juan-Chama project), and agricultural diversions and depletions in the Chama, Española, and Middle Rio

Grande Valleys. URGSiM requires hydrologic inflows at 21 locations corresponding to stream gaging stations with long-term historic records, as well as temperature and precipitation information at 21 different locations corresponding to climate measurement stations with long term historic records. For the HDe analysis, the hydrologic inflows at the 21 locations were generated by the bias corrected VIC model output described above. URGSiM simulated system behavior for the HDe scenarios is used to generate the inputs necessary to run WaterMaps, and thus evaluate the potential impacts of climate change on the Santa Fe Basin. The version of URGSiM run for this analysis reduces irrigated agricultural area in the Middle Rio Grande Valley to ensure that New Mexico meets required deliveries to Elephant Butte under the Rio Grande Compact, which impacts Santa Fe operations via Article VII conditions.

5 Data for WaterMaps

Four different time series data sets were delivered for each parameter needed by WaterMaps, the historic baseline, and the three ensembles shown in Table 2. Units are cubic feet per second (cfs), acre-feet (AF), thousand acre-feet (kAF), and inch/month (in/mo). The parameters being delivered are:

1. Rio Grande at Otowi [cfs]
    - Total flow at Otowi
    - Native flow at Otowi
    - San Juan Chama flow at Otowi
    - San Juan Chama flow at Otowi destined for direct diversion at Buckman.
    - San Juan Chama flow at Otowi destined for direct diversion by the Albuquerque Bernalillo County Water Utility Authority (ABCWUA).

2. Santa Fe River flow above McClure [cfs] (note, these data are directly from TSC)

3. San Juan- Chama percent allocation at Heron [%]

4. Abiquiu Reservoir related parameters
    - Total volume [AF]
    - Volume of Santa Fe City and County San Juan Chama water [AF]
    - Total evaporation [cfs]
    - Monthly evaporation rate [in/mo]

5. Article VII status [1 or 0 for in effect or not in effect respectively]

6. New Mexico Rio Grande Compact Balance [kAF]

The parameters are monthly from January 1951 through December 1998. This data is based on calendar years, and 1950 is lost because TSC processing occurred on a water year basis from October 1950 through September 1999, and the entire calendar years available after this processing are 1951 through 1998. A Microsoft Excel file named **Data4SFWaterMaps9.6.2013** includes the data discussed here and is available upon request. Five other Excel files, which include data for other Hybrid Delta Ensemble runs and are the source sheets for Figure 3 through Figure 13 (at the end of the next section) are also available:

- AbiquiuWaterMapsDynamic9.6.2013.xlsx
- ArticleVIIWaterMapsDynamic8.26.2013.xlsx
- OtowiWaterMapsDynamic8.26.2013.xlsx
- SFRiverWaterMapsDynamic9.06.2013.xlsx
- SJCAllocWaterMapsDynamic8.26.2013.xlsx

6 Analysis

Figure 3 shows native flow at Otowi as simulated by URGSiM. The lines lie on top of each other because they are all based on the historic simulation. It is easier to discern the overall differences between scenarios by looking at the cumulative flows shown in Figure 4. Interestingly, the 2050s "Warm Wet" (WW, which is less hot and more wet) ensemble resulted in more water in the system at Otowi compared to the Simulated Historic conditions, while the other ensembles show significantly less water. In general, the four scenarios from wettest to driest are: WW, Simulated Historic, C, and HD respectively.

Similar plots are shown for the Santa Fe River above McClure, San Juan Chama allocations, and Article VII status in Figure 5 through Figure 10. As with the Otowi data, differences between scenarios are most easily visualized with the cumulative plots. The 2050s WW scenario is approximately equal to the Simulated Historic scenario on the Santa Fe River from a total volume perspective, and the two are exactly alike with respect to San Juan Chama allocations where 100% allocation is made every year. Article VII conditions are least frequent under the WW scenario followed by the Simulated Historic, then the C and HD scenarios respectively. Abiquiu storage and evaporation related data are shown in Figure 11 through Figure 13. Total Abiquiu storage is generally highest for the WW scenario followed by the Simulated Historic, and then the C and HD scenarios respectively. Cumulative evaporation *depth* (Figure 12) is highest for the HD scenario followed by the C, and then—unlike the order seen in other variables, the WW and finally the Simulated Historic. This is because changes to evaporation depth are entirely a temperature effect, and the WW scenario is warmer than the Simulated Historic. Although evaporation rates in terms of depth rise with climate change, the overall effect at Abiquiu is controlled by the amount of water stored such that the total volume of water loss is least for the HD scenario followed by the C, the Simulated Historic, and finally the WW. Thus, despite increased evaporation demands as scenarios become hotter and drier with climate change, as supplies diminish, the reduced storage in the reservoir results in reduced overall evaporation.

New Mexico's Rio Grande Compact (Compact) Balance (Balance) for the four scenarios is shown in Figure 14. The largest Compact debit (under-delivery relative to Compact requirements) simulated for the four scenarios of interest was almost 300,000 AF, and the largest Compact credit (over-delivery relative to the Compact requirements) was almost 200,000 AF. For the first 30 years of the simulations (1950-1980), the Balance tends to be most positive for the Simulated Historic, followed by WW, C, and HD respectively, but as the wet years of the 1980s and 1990s set in, this order becomes less predictable. The specific reasons the relative Compact behavior becomes less predictable is beyond the scope of this analysis, but may have to do with the non-linear nature of Compact delivery requirements and the fact that in some cases, wetter years with high storage at Elephant Butte Reservoir can be more difficult for New Mexico in terms of meeting relatively higher delivery obligations.

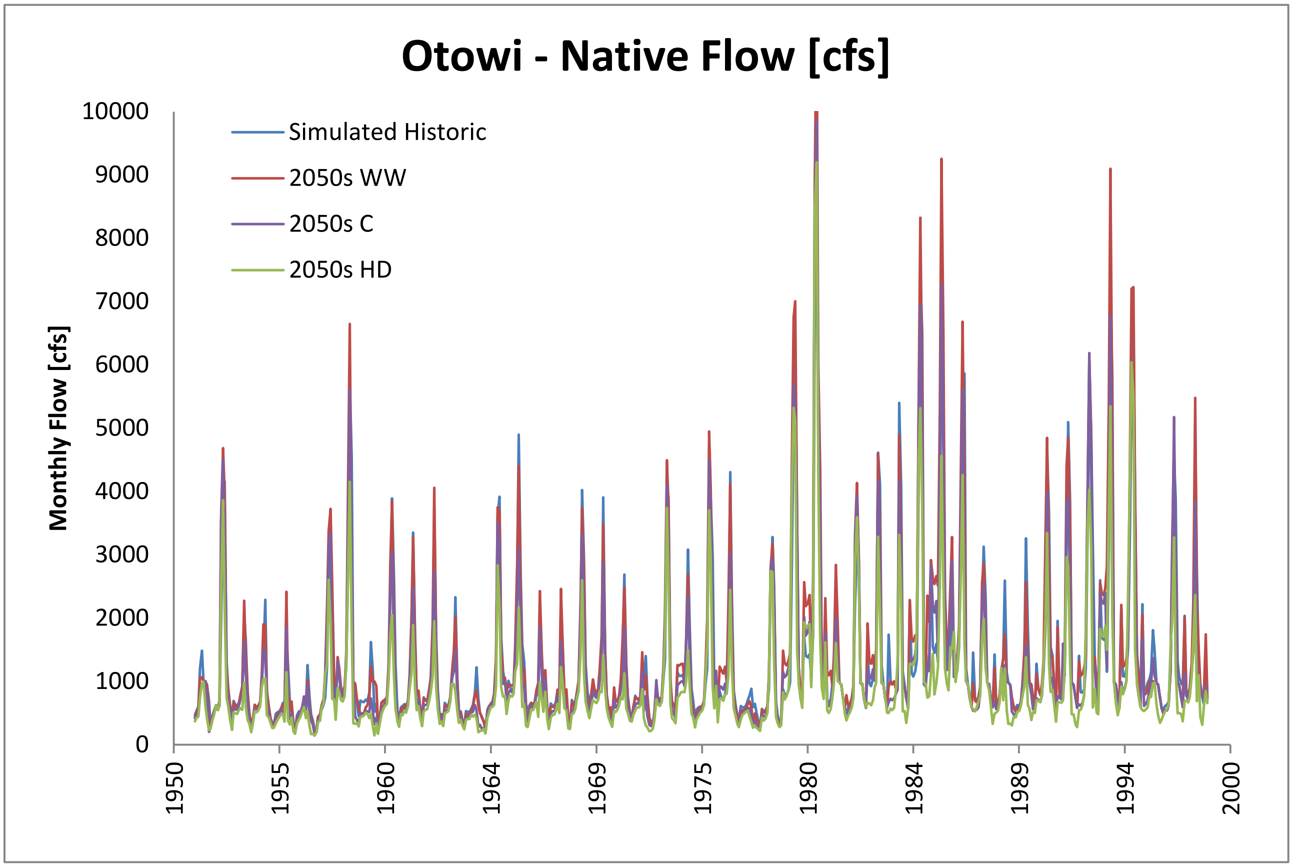


Figure 3: Native flow at Otowi for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

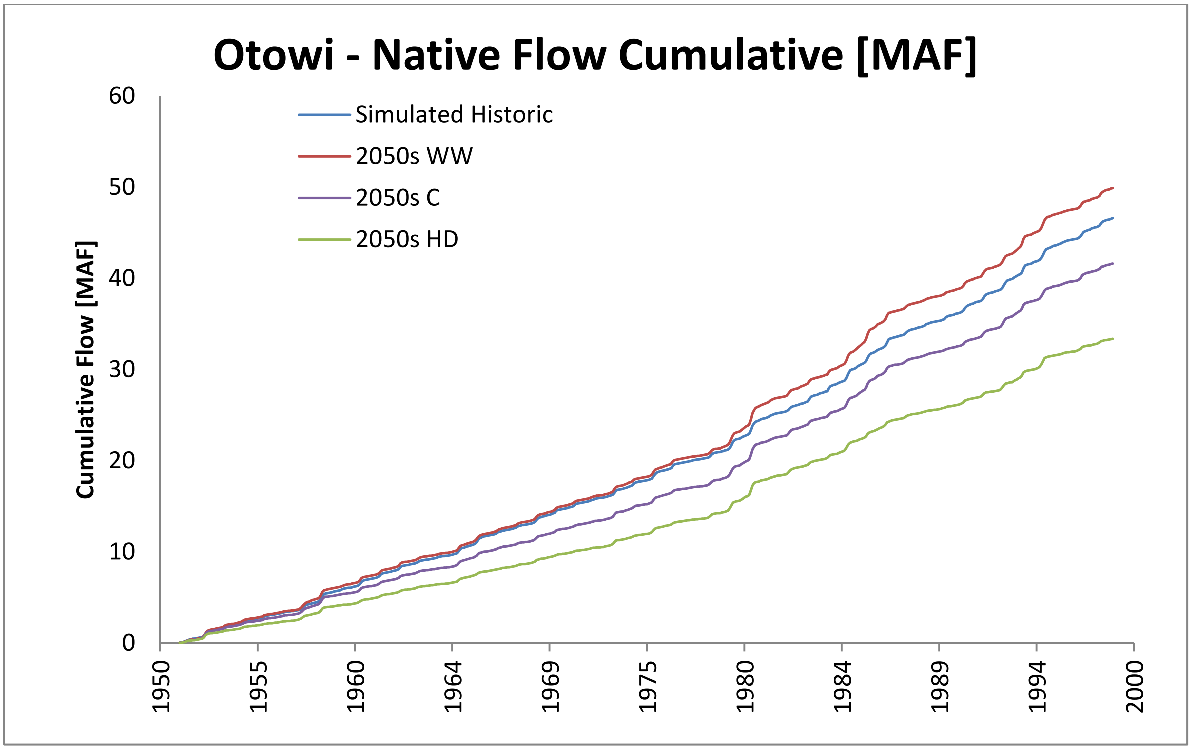


Figure 4: Cumulative native flow at Otowi for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

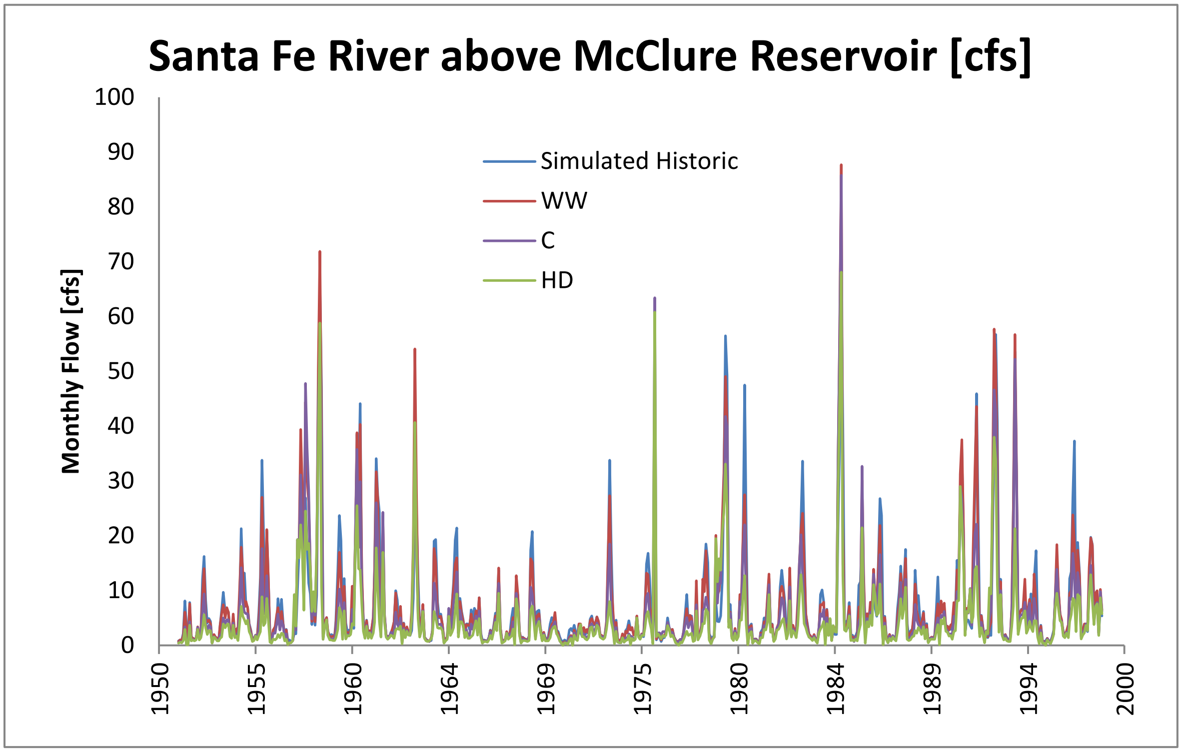


Figure 5: Flow of Santa Fe River above McClure reservoir for 2050s period analysis. Data from land surface model results from TSC.

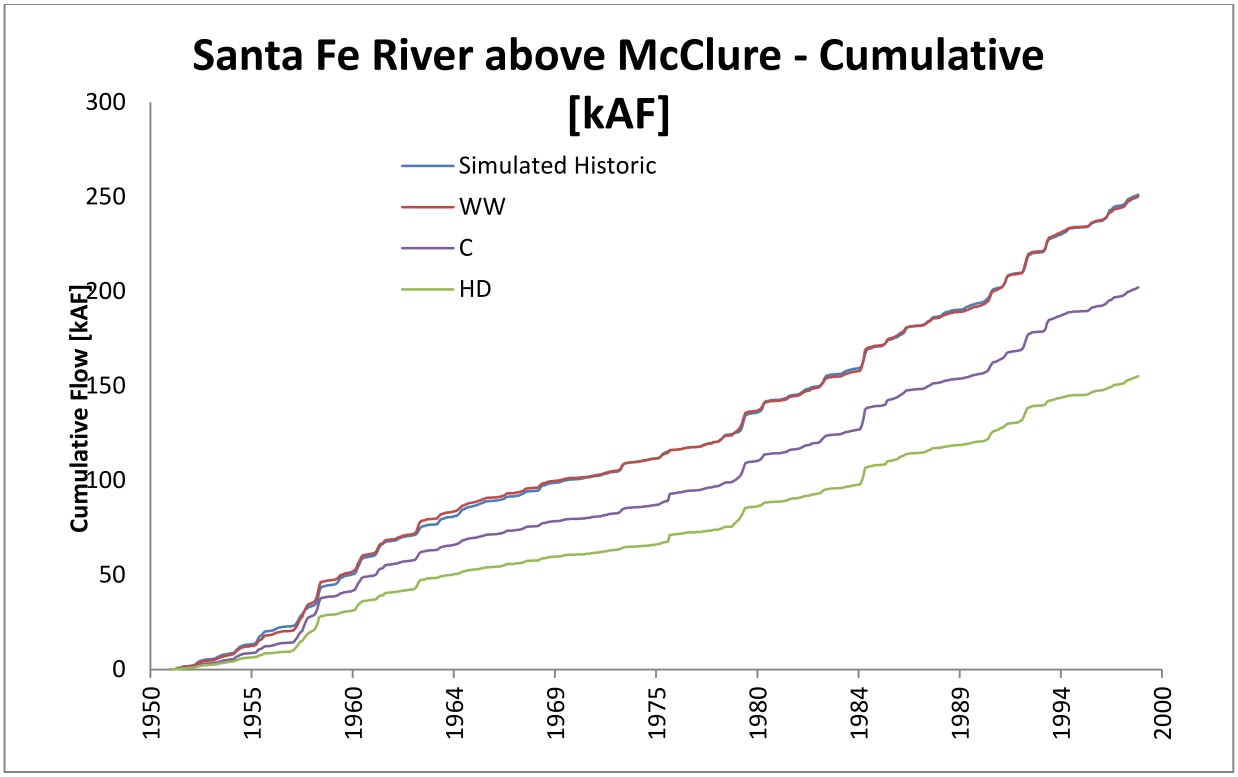


Figure 6: Cumulative flow of Santa Fe River above McClure reservoir for 2050s period analysis. Data from land surface model results by TSC

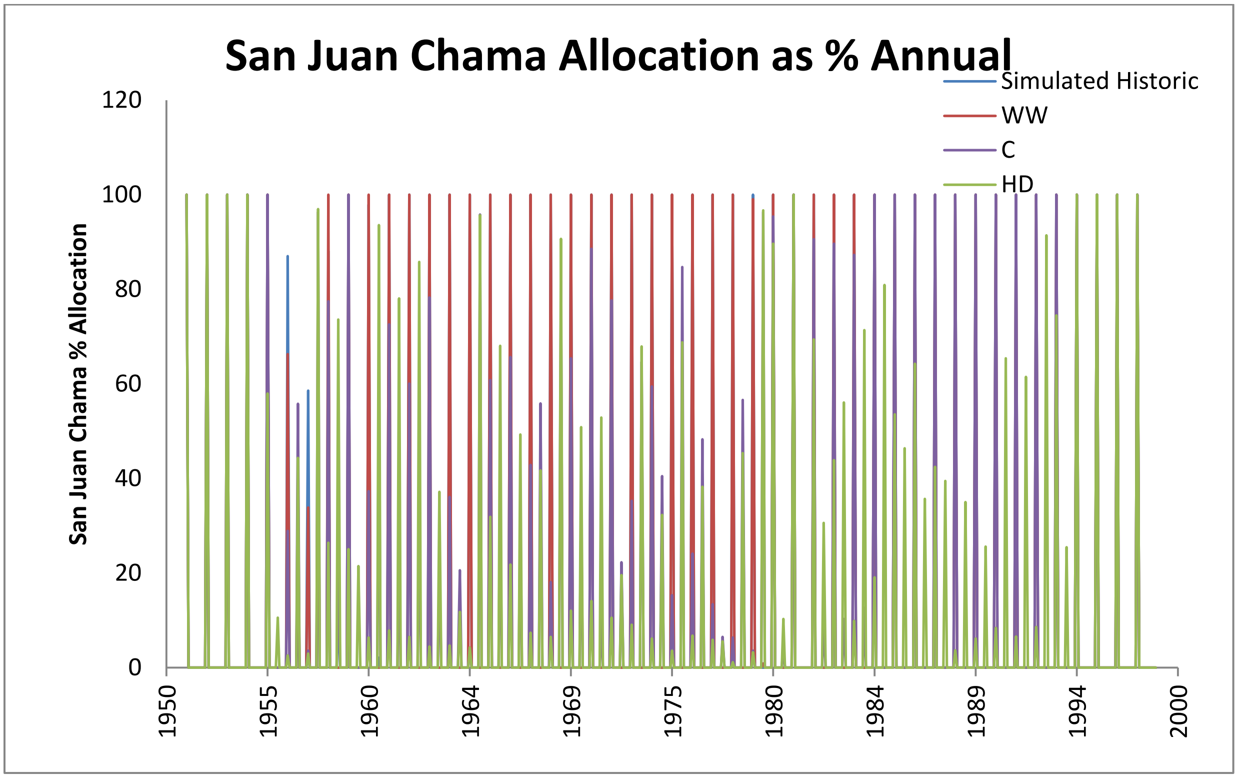


Figure 7: Monthly San Juan Chama allocations as a percent of annual allocation for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

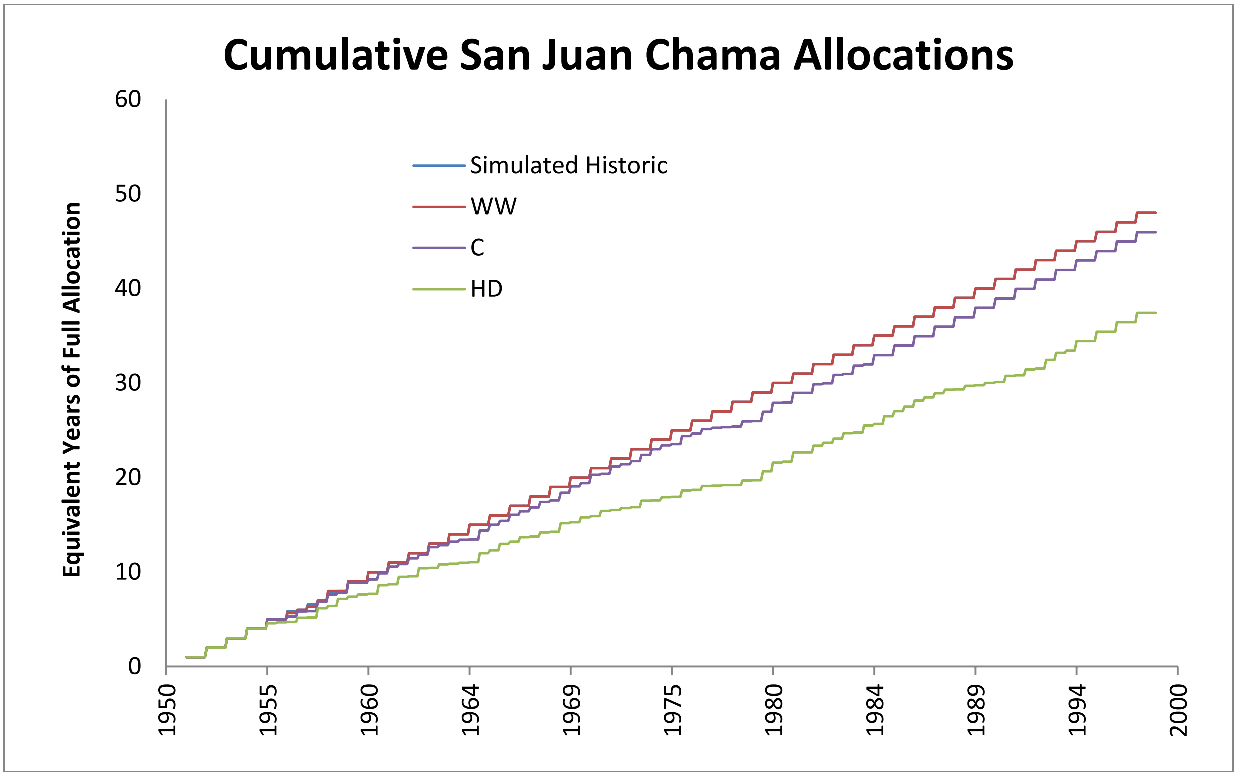


Figure 8: Cumulative San Juan Chama allocations as equivalent years of full allocation for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

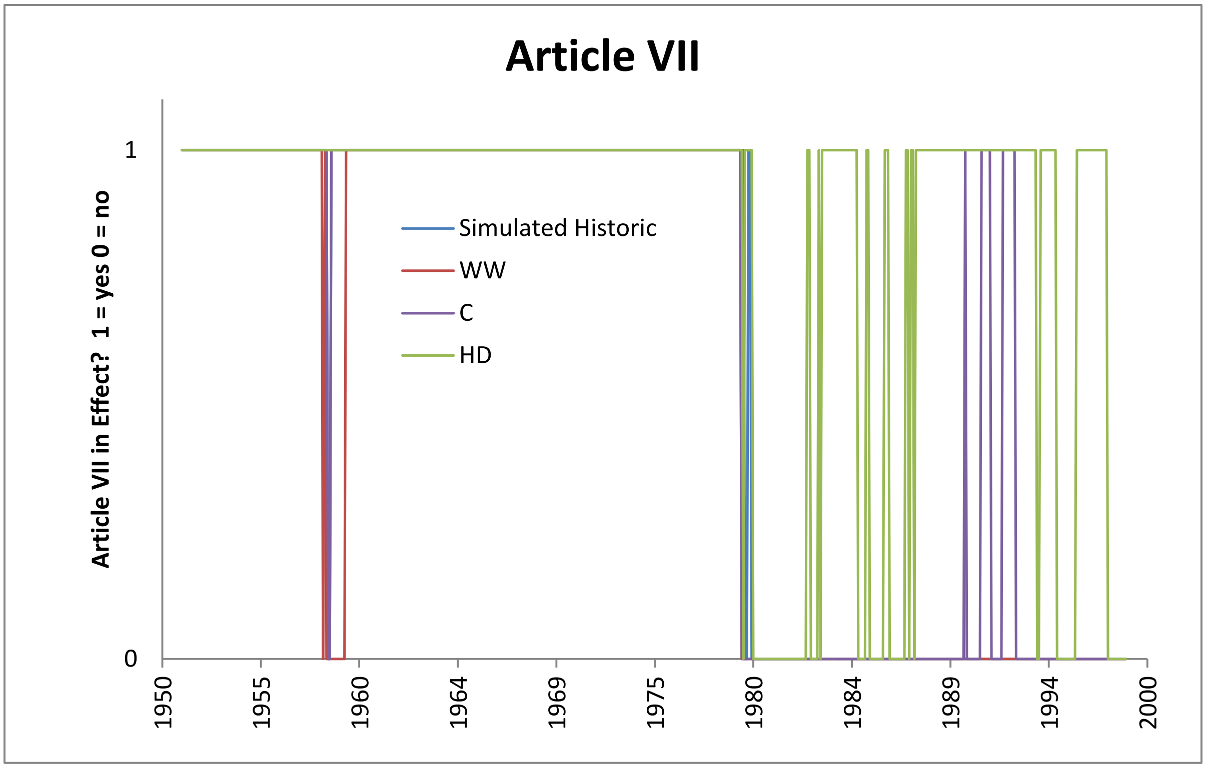


Figure 9: Article VII Rio Grande Compact conditions for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

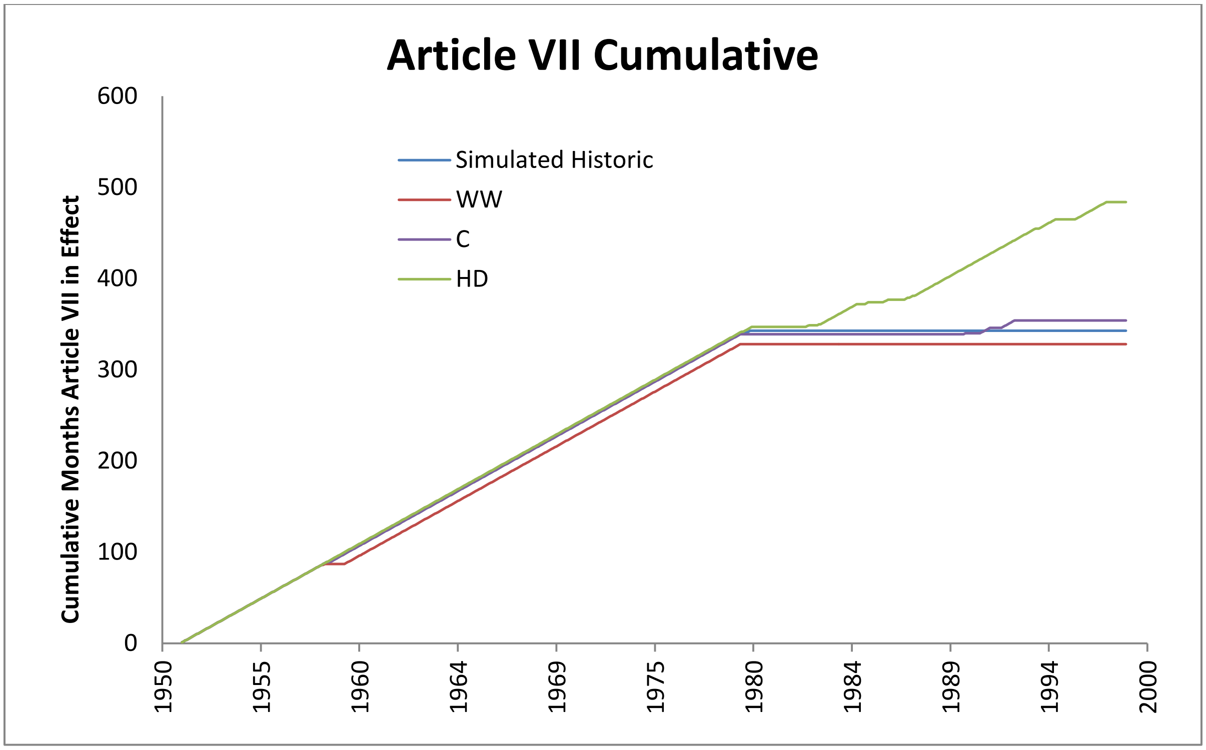


Figure 10: Cumulative Article VII Rio Grande Compact conditions (# months) for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

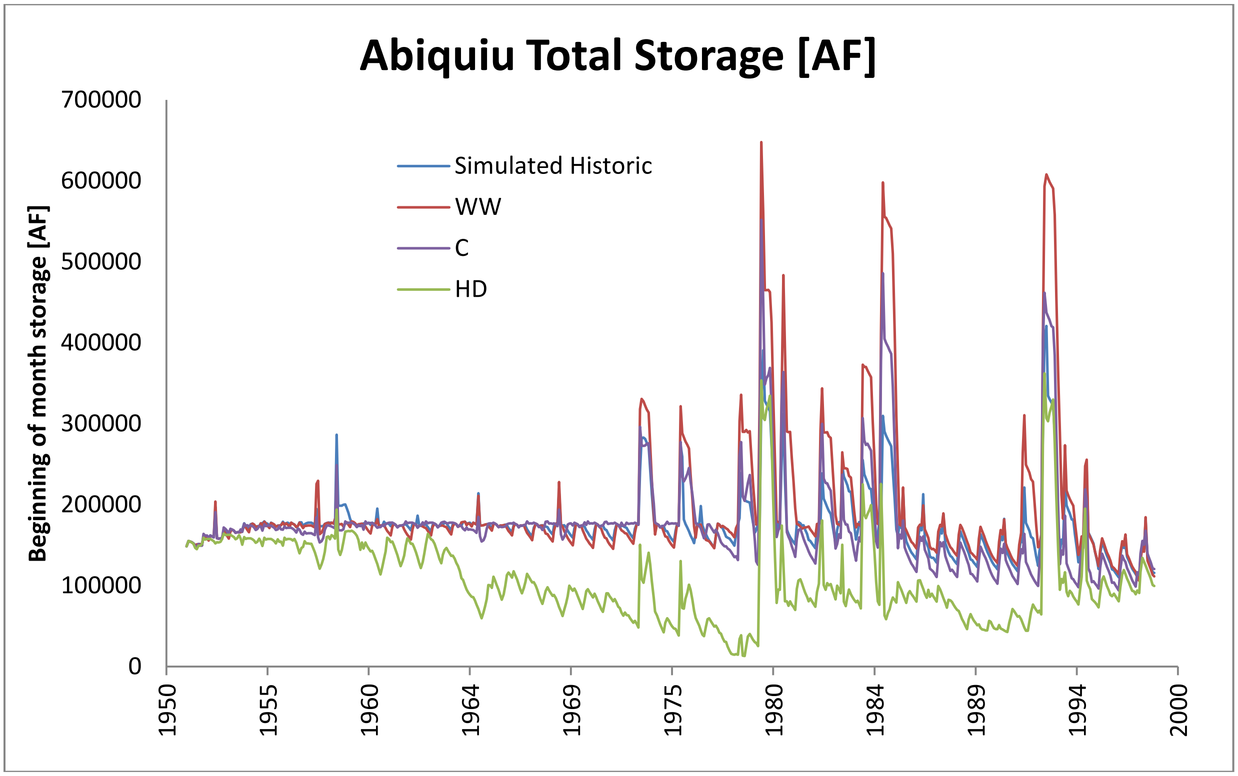


Figure 11: Abiquiu storage for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

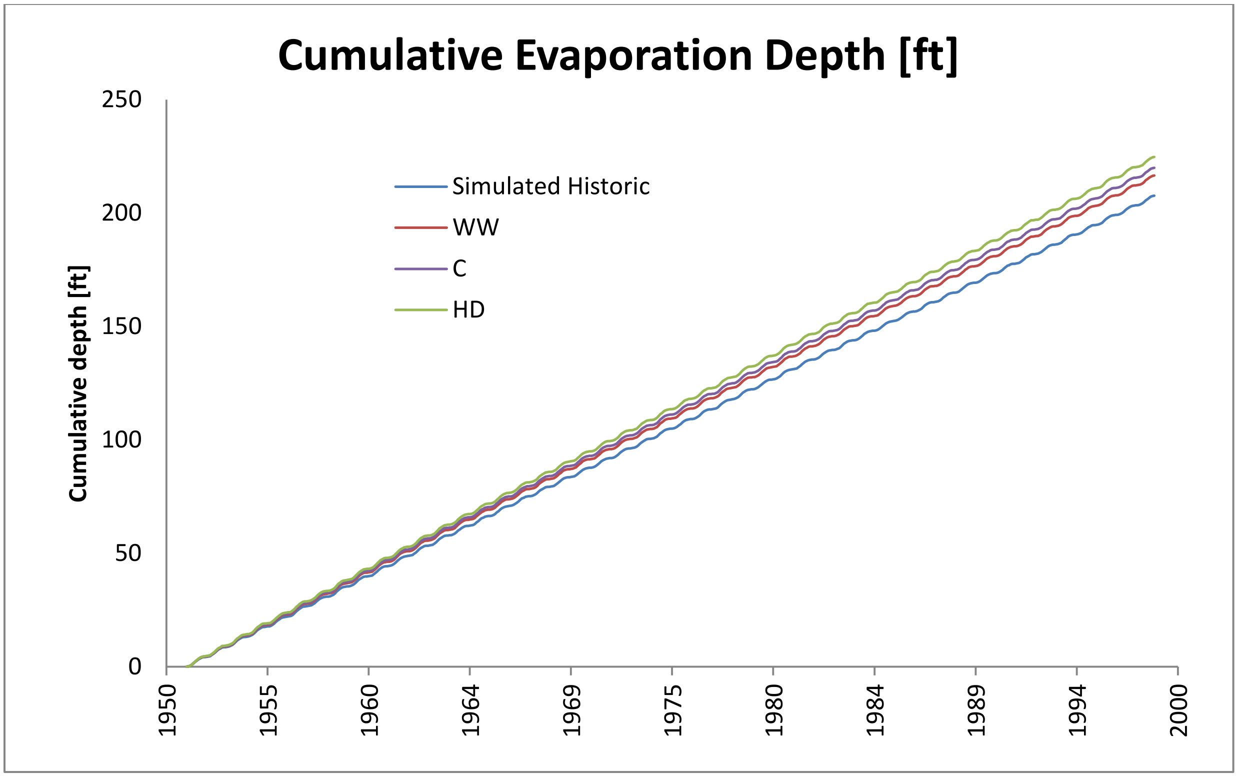


Figure 12: Abiquiu cumulative evaporation depth for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

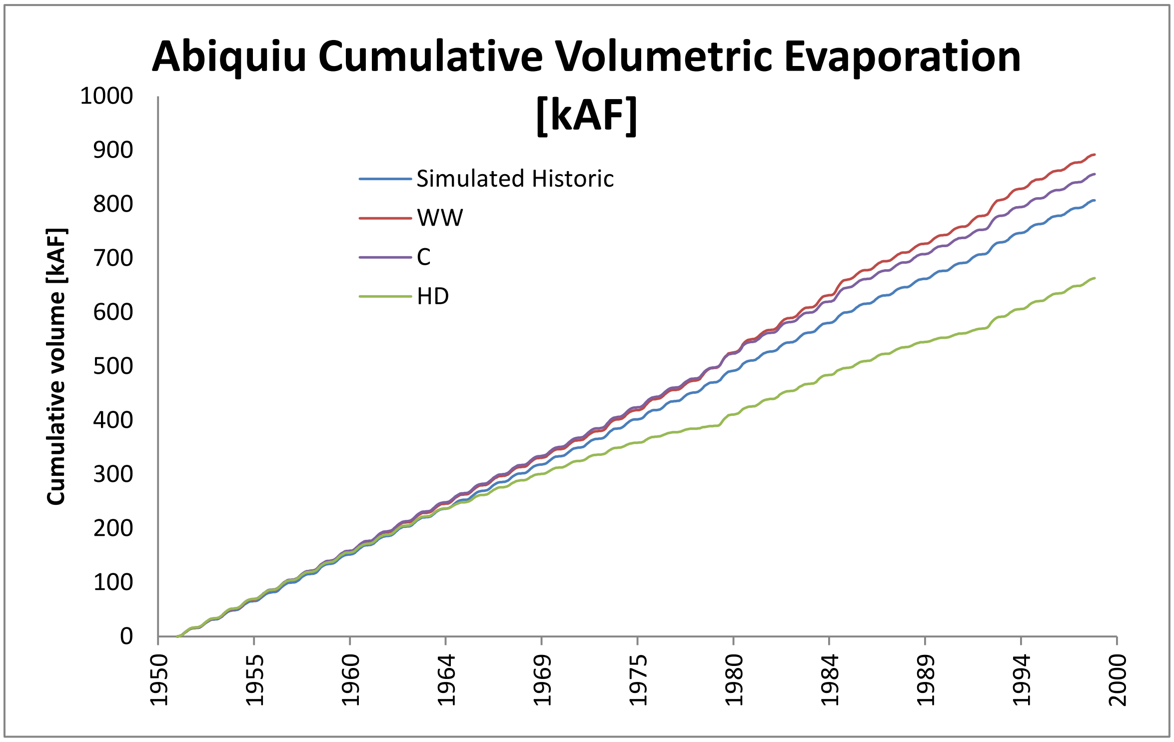


Figure 13: Abiquiu cumulative evaporation volume for 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

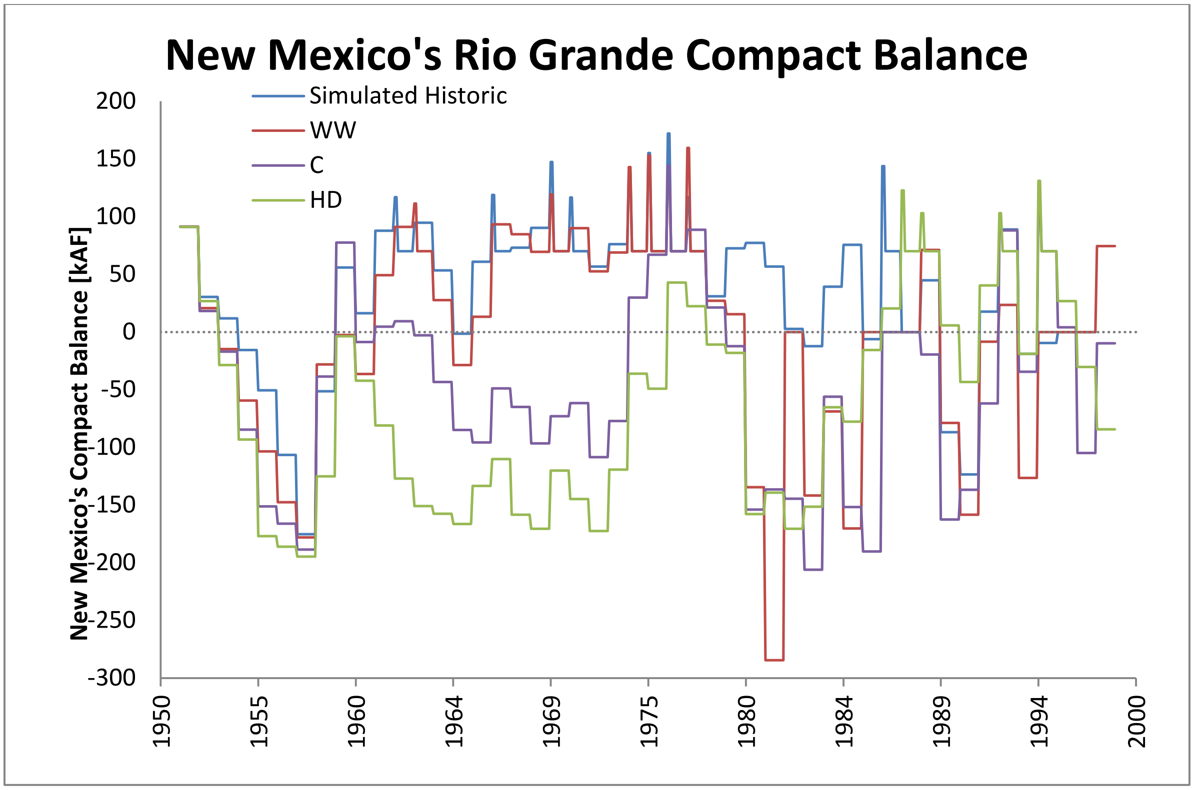


Figure 14: New Mexico's Rio Grande Compact Balance for the 2050s period analysis simulated by URGSiM-WWCRA.Hde.8.26.2013.

7 Works Cited

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Appendix C1

Temperature and Precipitation Data for Santa Fe Basin Study

Santa Fe Basin, New Mexico

Contents

This appendix provides the text of a technical memorandum from Jesse Roach, Ph.D, Earth Systems Analysis to Claudia Borchet, Santa Fe County, dated September 13, 2013. This memo describes the development of temperature and precipitation data for the City of Santa Fe, and Nichols and McClure reservoirs in the Santa Fe River watershed.

1 Background

Temperature and precipitation data were developed using the Hybrid-Delta ensemble method (HDe) in support of climate change impacts analysis being conducted by The City and County of Santa Fe with support from CDM Smith, the Bureau of Reclamation, and Sandia National Laboratories as part of the Santa Fe Basin Study. Refer to Appendix B for additional background information on the HDe method employed for this analysis.

2 Description of Data

The temperature and precipitation data delivered here are monthly averages for the two $^1/_8$ degree grid cells shown in Figure 1. As can be seen, the City of Santa Fe, and McClure Reservoir are centrally located in the two cells. Nichols Reservoir straddles the two. It will be up to the users of WaterMAPS to decide whether to assume that evaporation at Nichols is more closely described by the cell containing McClure, or an average of the two cells. For each of these spatial locations, there are data for three different parameters provided along with this memo:

1. Monthly average of daily maximum temperatures in Celsius (T_{max}) 1950-1999
2. Monthly average of daily minimum temperatures in Celsius (T_{min}) 1950-1999
3. Cumulative monthly precipitation in millimeters (P) 1950-1999

For each of these parameters, four different climate scenarios are provided (see Appendix B for additional details):

A. Maurer (Maurer et al. 2002). A spatially distributed synthetic dataset based on available historic point observations. This is a synthetic estimate of actual conditions at these locations from 1950-1999.

B. 2050-WW. Standing for 2050s warm-wet, this timeseries is the Maurer data, but altered according to the changes to precipitation and temperature represented in the difference between the historic simulation period (1950-1999) and the 2040-2069 (centered on 2055) simulation period for the warm-wet ensemble of general circulation models (GCM).

Figure 1: Two $^{1}/_{8}$ degree grid cells (note the lighter red vertical line that bisects the heavier red rectangle) that define the climatic conditions for the City of Santa Fe (left) and the Santa Fe River reservoirs (right). Nichols Reservoir, which is the smaller of the two blue water bodies visible actually straddles the cells, while McClure is centrally located in the more easterly cell. Image from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#Projections:%20Subset%20Request

C. 2050-HD. Analogous to 2050-WW, but for the hot-dry ensemble.

D. 2050-C. Analogous to 2050-WW, but for the central tendency ensemble.

These data were developed by the Bureau of Reclamation's Technical Service Center in Denver for 15 climate change scenarios (WW, HD, C and two other scenarios, each for three future time periods), of which only the three described in B-D above are being used in the Santa Fe Basin study. The data described here includes 24 time series (2 locations x 3 parameters x 4 scenarios). The Microsoft Excel workbook called MetDataSFBasinStudyStatic9.9.2013 delivered with this memo has three worksheets. The first two, called City and Reservoirs, contain the 24 timeseries of data, 12 on each sheet.

2.1.1 Reference ET

Reference evapotranspiration (ET) is defined as the potential ET for a reference crop (typically grass of a specific height, sometimes alfalfa) under a given set of climatic conditions. Reference ET can be directly measured with lysimeters, but is most typically calculated with empirical or semi-empirical equations calibrated to experimental results. There have been many such equations, but currently the industry standard, and the most commonly used equation (when good meteorological data exist) is a modified Penman-Monteith equation documented in FAO-56 (Allen et al. 1998) and adopted by the American Society of Civil Engineers as their standard reference ET equation (Task Committee on Standardization of Reference Evapotranspiration 2005). However, in addition to the maximum and minimum temperatures (T_{max} and T_{min}), this equation requires measurements of windspeed, relative humidity, and solar radiation. Without these data, and particularly for longer timesteps, the Hargreaves equation (Hargreaves and Samani 1985), a temperature and latitude based equation is arguably the best choice. Upper Rio Grande Simulation Model (URGSiM) uses the Hargreaves equation:

$$ET_o = 0.0023\ R_a\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} \qquad (1)$$

where R_a is extraterrestrial radiation expressed as a depth of evaporated water per time [L/T], and T_{mean}, T_{min}, and T_{max} are the mean, minimum, and maximum temperatures in Celsius. At a monthly timestep, T_{mean} is the average mean daily temperature for the month, and T_{min} , and T_{max} are the mean daily maximum and mean daily minimum temperatures for the month respectively. For more information on Reference ET equations, and why URGSiM uses Hargreaves instead of a more data intensive equation, refer to Appendix C2 and Roach (2012).

The Microsoft Excel workbook, called MetDataSFBasinStudyStatic9.9.2013, delivered with this memo has three worksheets. The first two, called City and Reservoirs, contain the temperature and precipitation data. A third sheet, called RefET, includes the calculations of Reference ET at each location (2) for each climate scenario (4) for each month from January 1950 through December 1999. The calculations on this sheet are dynamic so that if desired, the logic of the Hargreaves equation can be traced.

Thus, in addition to the 24 temperature and precipitation data timeseries, also included are 8 time series for Reference ET calculated with the Hargreaves equation. The cumulative values for these timeseries are shown in Figure 2 and Figure 3. Over the 50-year historical period, the range of annual average Reference ET is on the order of 3.3 to 3.7 feet per year for the grid cell encompassing the City of Santa Fe, and 3 to 3.4 feet per year for the grid cell encompassing McClure.

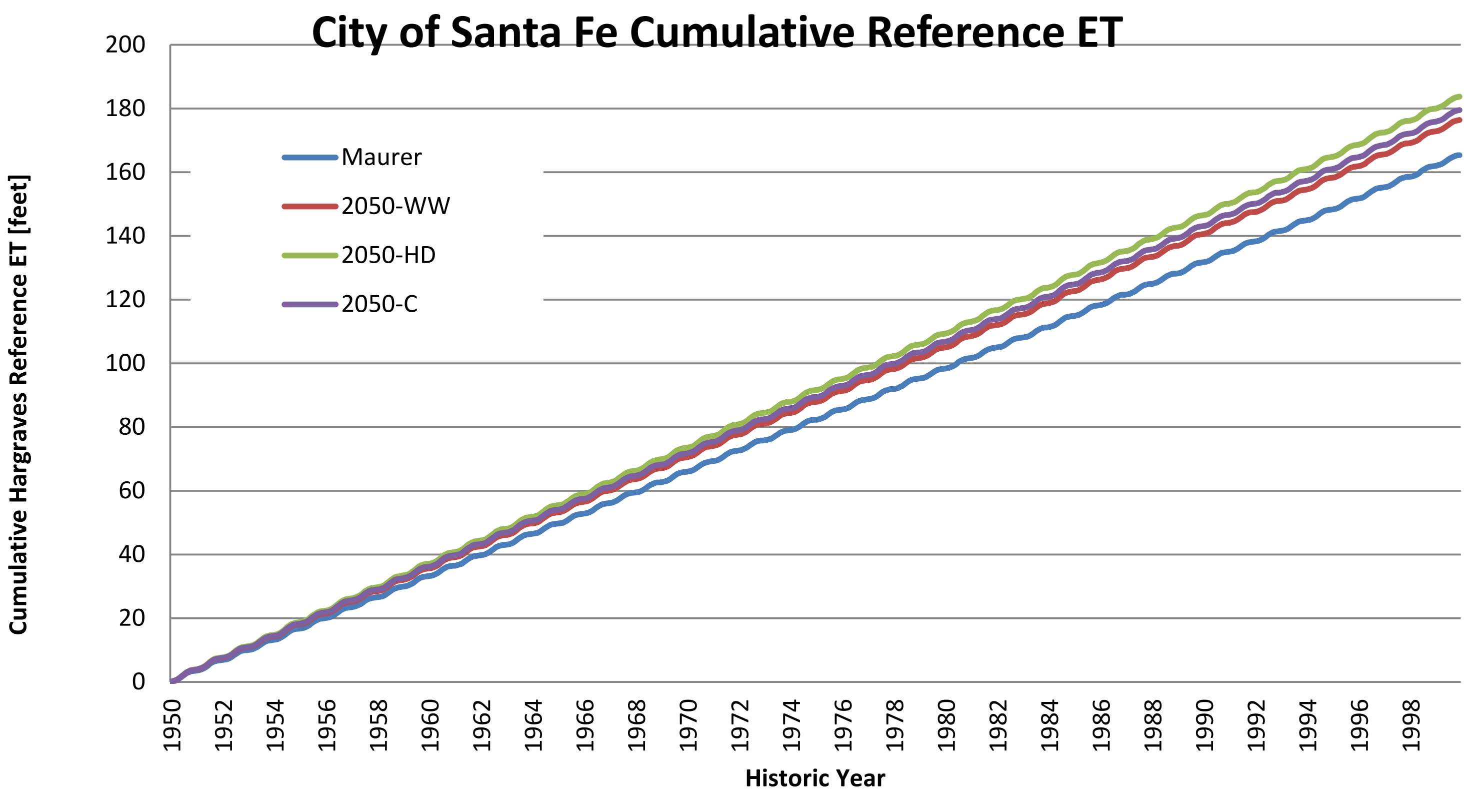

Figure 2: Cumulative Reference ET calculated using the Hargreaves equation for the temperature data associated with the grid cell encompassing the City of Santa Fe (see Figure 1).

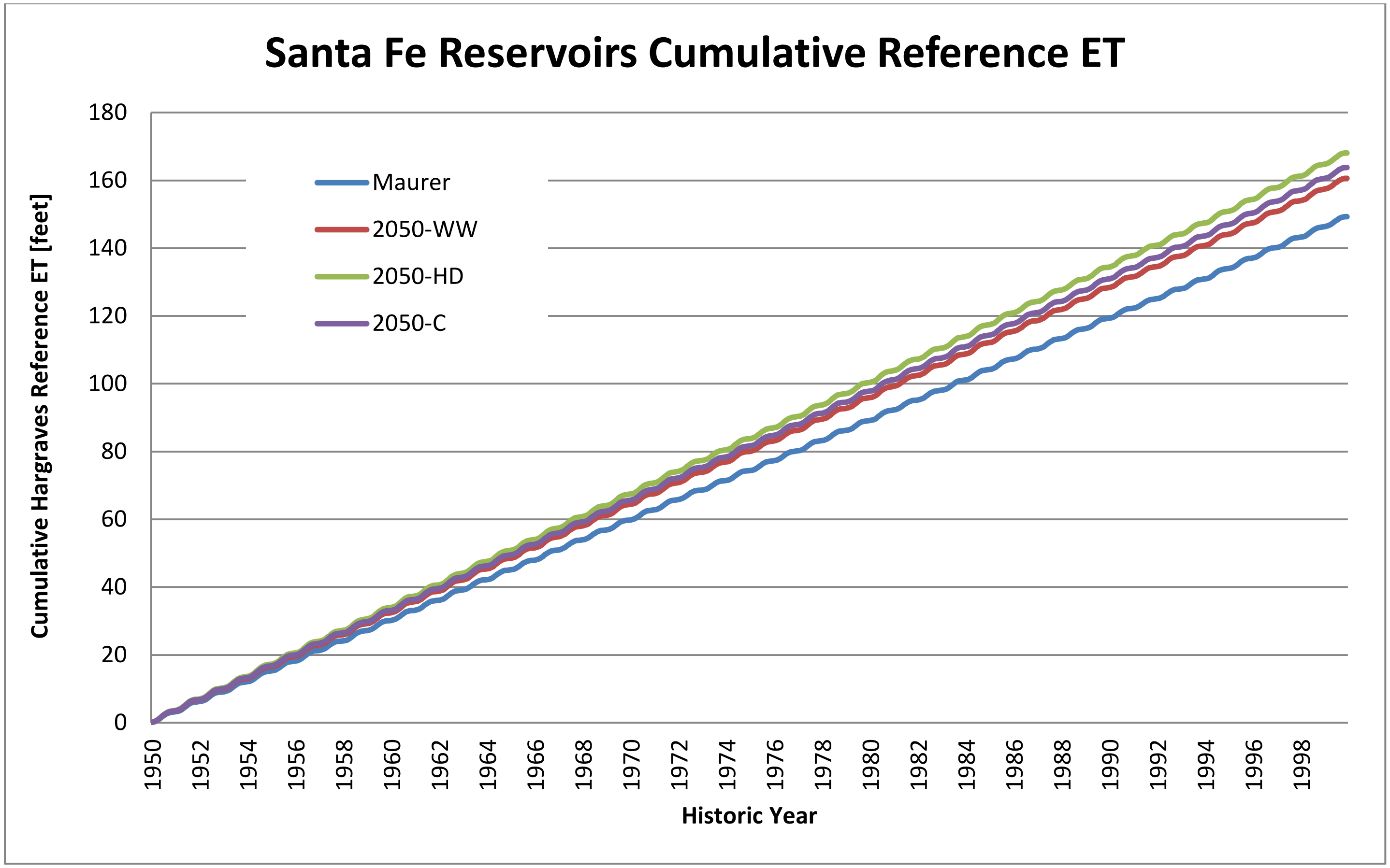

Figure 3: Cumulative Reference ET calculated using the Hargreaves equation for the temperature data associated with the grid cell encompassing McClure reservoir (see Figure 1).

2.1.2 Crop Coefficients

ET from a non-reference crop or open water evaporation can be estimated by adjusting the Reference ET with a “crop coefficient” which is an empirically determined factor that relates the ET in question to the Reference ET. URGSiM uses the open water evaporation coefficients shown in Table 1 to estimate reservoir evaporation with Reference ET.

Calculated Open Water Evaporation Coefficient by Month and Reservoir:												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
El Vado				0.9	0.9	0.9	0.8	0.8	0.8	0.8		
Abiquiu				1.2	1.2	1.1	1.0	1.0	1.0	1.2		
Cochiti				1.3	1.2	1.2	1.1	1.1	1.2	1.3		
Elephant Butte	1.3	1.3	1.6	1.6	1.6	1.4	1.3	1.2	1.3	1.4	1.5	1.3
Caballo	1.4	1.2	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.3	1.3	1.3

Table 1: Open water evaporation (crop) coefficients calculated from temperature and pan evaporation data measured at five reservoirs in New Mexico between 1975 and 2006.

These factors are derived based on comparison of Reference ET at each reservoir to 70% of observed pan evaporation at each reservoir. There are several conceptual problems with this approach to be noted. First, pan evaporation tends to overestimate actual reservoir evaporation because the water in the pan gets warmer than the top layer of the actual reservoir. As a result, a factor of 70% is applied to pan evaporation rate to estimate reservoir evaporation rate. In accounting in the Rio Grande, the 70% is applied to all reservoirs during all times of the year (unless the pan is frozen), regardless of size, or location. There is likely quite a bit of error in this blanket assumption, however, this is the approach used by the Rio Grande Compact accounting, and therefore by URGSiM and URGWOM. Second, ET is different, and arguably more complex than straight open water evaporation because it includes biologically mediated fluxes. URGSiM uses an equation derived to describe ET to estimate open water evaporation. This is warranted to some degree by the following statement from Chapter 4 of FAO- 56:

> *"Notwithstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ET_o* [Reference ET] *for periods of 10 days or longer may be warranted. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient"* (Allen et al. 1998).

Thus, it is reasonable to use monthly Reference ET to estimate monthly pan evaporation, and without additional information, this is a reasonable first step.

In future studies, a simpler or different equation could be used to estimate open water evaporation more accurately. Estimates of reservoir evaporation from Nichols and McClure using Reference ET rates and an URGSiM evaporation coefficient perhaps from El Vado (due to elevation) would be a reasonable approach, and perhaps most importantly would capture relative differences in evaporation between the different climatic scenarios.

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Appendix C2

Evapotranspiration Calculations in the Upper Rio Grande Simulation Model (URGSiM)

Santa Fe Basin, New Mexico

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

Contents

This appendix provides the text of a technical memorandum from Jesse Roach, Ph.D, Earth Systems Analysis, to Claudia Borchet, Santa Fe County, June 2, 2012.

I. Abstract

In 2011, the Upper Rio Grande Simulation Model (URGSiM) switched from a modified Penman based Reference Evapotranspiration (ET_o) equation with an associated growing degree day-based crop coefficient method and 20 vegetation types, to a Hargreaves based ET_o equation, FAO-56 based crop coefficients (Allen et al. 1998), and 5 vegetation types. These changes to URGSiM were made as part of ongoing model refinement (independent of the Santa Fe Basin Study) and for a variety of reasons, including unreliable results from the previous methods, sparse and unreliable historic weather data, and unnecessary complexity in previous vegetation classifications. This document summarizes the rationale for these changes and the implications in terms of simulated ET in the Upper Rio Grande between 1975 and 1999.

II. Reference evapotranspiration (ET) equations

URGSiM (Roach 2007 and Roach and Tidwell 2009) calculates a monthly mass balance in reaches of the Rio Grande in New Mexico from 1975 through 1999 in calibration mode, 2000 through 2009 in validation mode, and 2010 forward in scenario analysis mode. ET is one of the major terms in this mass balance, and is calculated as the smaller of potential ET and available water. For a given month, reach, and vegetation type this can be expressed mathematically as shown in Equation (1) below.

$$ET_a^{r,m,v} = \min(ET_p^{r,m,v}\ , H_2O_{available}^{r,m,v}) \qquad (1)$$

where $ET_a^{r,m,v}$ [L^3/T] is actual ET, $ET_p^{r,m,v}$ [L^3/T] is the potential ET, and $H_2O_{available}^{r,m,v}$ [L^3/T] is the water available for ET in reach *r* during month *m* for vegetation type *v*. Vegetation types include irrigated crops, riparian vegetation, or open water as discussed further in Section III.

In URGSiM, water availability is determined for irrigated crops as a fraction of monthly rainfall (effective precipitation) plus irrigation deliveries to the field, for riparian vegetation by the depth to groundwater, and for open water by river flow or reservoir volume. Potential ET is calculated as Reference ET (ET_o) multiplied by a crop coefficient and an area expressed mathematically in Equation (2) below.

$$ET_p^{r,m,v} = ET_o^{r,m} * K_c^{r,m,v} * A^{r,m,v} \qquad (2)$$

where $ET_o^{r,m}$ [L/T], the Reference ET, is the potential ET of a reference crop, either grass or alfalfa, in reach r during month m, $K_c^{r,m,v}$ [-] is a crop coefficient that relates the potential ET of crop v to the reference crop, and $A^{r,m,v}$ [L^2]is the area of vegetation v in reach r during month m. Estimation of vegetative area ($A^{r,m,v}$) although potentially uncertain, is straightforward. Estimation of $ET_o^{r,m}$ and $K_c^{r,m,v}$ on the other hand are uncertain and also ambiguous. A variety of equations and methods are available in the literature for calculation of ET_o, crop coefficients, or the product of the two. These range from highly localized pan evaporation observations to temperature and radiation based equations (e.g., Hargreaves 1985) to more general data intensive semi-empirical equations (e.g., Penman-Monteith).

A. Modified Penman ET_o problems

Prior to 2011, following the Bureau of Reclamation's ET Toolbox (Brower 2008), URGSiM used a version of the Penman equation modified by Dr. Ted Sammis (Sammis et al. 1985) to estimate ET_o and an associated growing degree day based crop coefficient estimation (ibid). In 2011, the ET Toolbox abandoned the Sammis modified Penman method for calculation of ET_o because of erroneously high results. ET_o for year 2007 Angostura weather station data[1] (Figure 1) was calculated with a variety of equations by Keller-Bliesner Engineering using software developed by Dr. Rick Allen called Ref-ET. According to this analysis, the annual cumulative ET_o calculated by the modified Penman equation was approximately 80 inches, some 20 inches or 33% greater than the approximately 60 inches calculated by the widely accepted FAO-56 (reference) or ASCE Standard (reference) methods. This result is not applicable quantitatively to all weather stations and all years, but follows a qualitative pattern of significant overestimate of ET_o by the modified Penman equation.

B. Choosing a new ET_o calculation

The results described above led to the abandonment of the legacy modified Penman equation as the default method of ET_o calculation by URGSiM, the Upper Rio Grande Water Operations Model (URGWOM), and the ET Toolbox. In choosing a new method for URGSiM, the availability and quality of historic data became of concern. Generally, two forms of the Penman-Monteith equation (FAO-56 (Allen et al. 1998), and the ASCE-Standard method (Task Committee on Standardization of Reference Evapotranspiration 2005)) are the current state of the art for calculating ET_o where sufficient high quality data exists. Penman-Monteith based equations such as these are weather data intensive however, requiring solar radiation, wind speed, temperature, and relative humidity data. If

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[1] http://www.usbr.gov/pmts/rivers/awards/Nm2/rg/PROD/wx/txt/archive/2007/ANGN.txt accessed 1/10/2012

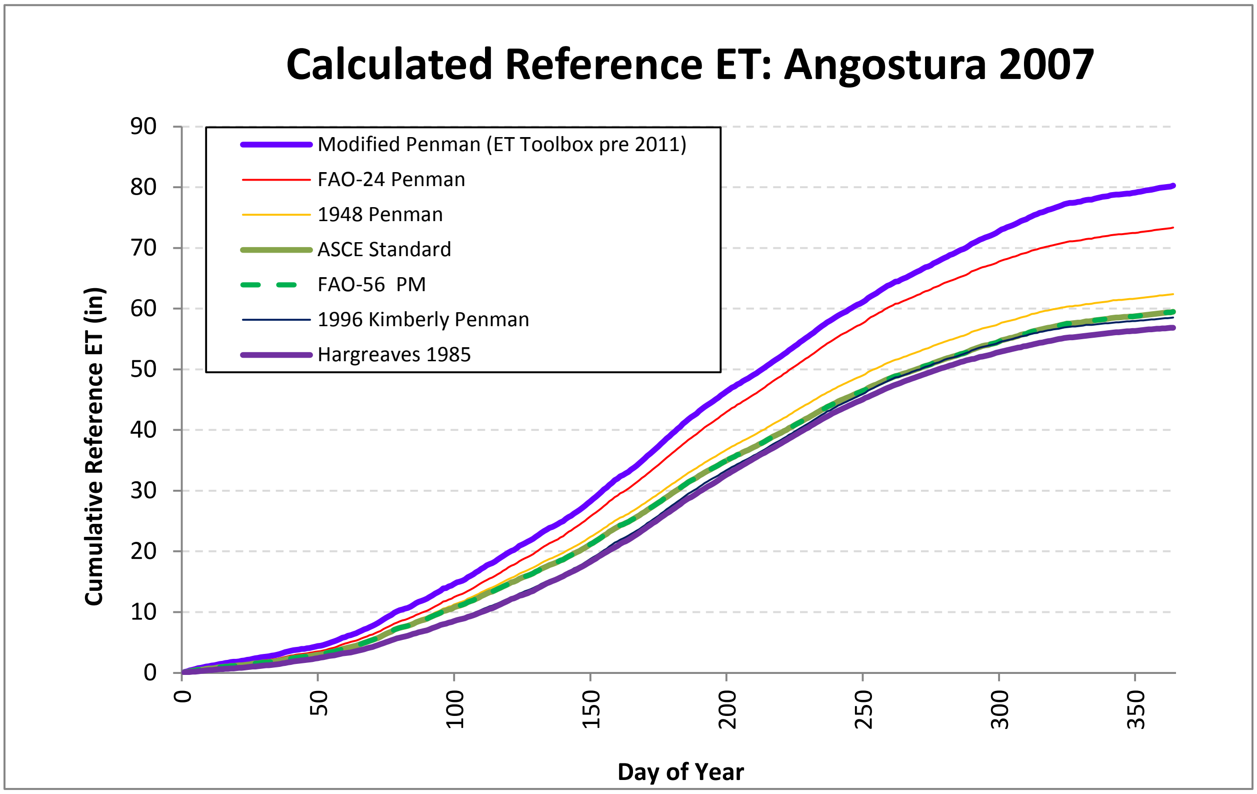

Figure 1: Cumulative Reference ET (ET_o) calculated at Angostura weather station during the year 2007 by a variety of ET_o equations. The modified Penman used previously by the ET Toolbox is erroneously high compared to all other methods. The other high outlier, the FAO-24 Penman has been superseded by the FAO-56 Penman-Monteith method. The FAO-56 and ASCE Standard methods are coincident for this data. The Hargreaves 1985 method requires temperature data only.

these data are not available, or of questionable quality, less data-intensive, temperature based methods such as the Hargreaves 1985 (Hargreaves and Samani 1985) may be more appropriate.

In the Rio Grande Valley in New Mexico upstream of Caballo Reservoir (the spatial extent of URGSiM), from 1975-1999 (the calibration period for URGSiM), full weather data including solar radiation, wind speed, and relative humidity measurements are spatially limited and of suspect quality. Temperature measurements, on the other hand, are more widely available and reliable. In addition, the monthly timestep of URGSiM reduces temporal variability that would be captured by a more complex and data intensive method, which reduces the advantage of the more complex method. Indeed, for timesteps longer than 5 days, the Hargreaves 1985 equation often compares very favorably to more complex methods (Hargreaves and Allen 2003). For all of these reasons, the relatively simple Hargreaves 1985 equation was adopted for use by URGSiM:

$$ET_o = 0.0023\ R_a\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} \qquad (3)$$

where R_a is extraterrestrial radiation expressed as a depth of evaporated water per time [L/T], and T_{mean}, T_{min}, and T_{max} are the mean, minimum, and maximum temperatures in Celsius. For URGSiM, at a monthly timestep, T_{mean} is the average mean daily temperature for the month, and T_{min} , and T_{max} are the mean daily maximum and mean daily minimum temperatures for the month respectively. Although the $(T_{max} - T_{min})^{0.5}$ term in equation (3) is not linear, monthly ET_o values calculated from monthly average inputs are almost identical to monthly averages of ET_o values calculated from daily inputs as shown in Figure 2 for daily Angostura weather station data from 2000 through 2011[2]. The choice to use Hargreaves 1985 is further supported by data availability and quality issues in the region explained in more detail in the next two subsections.

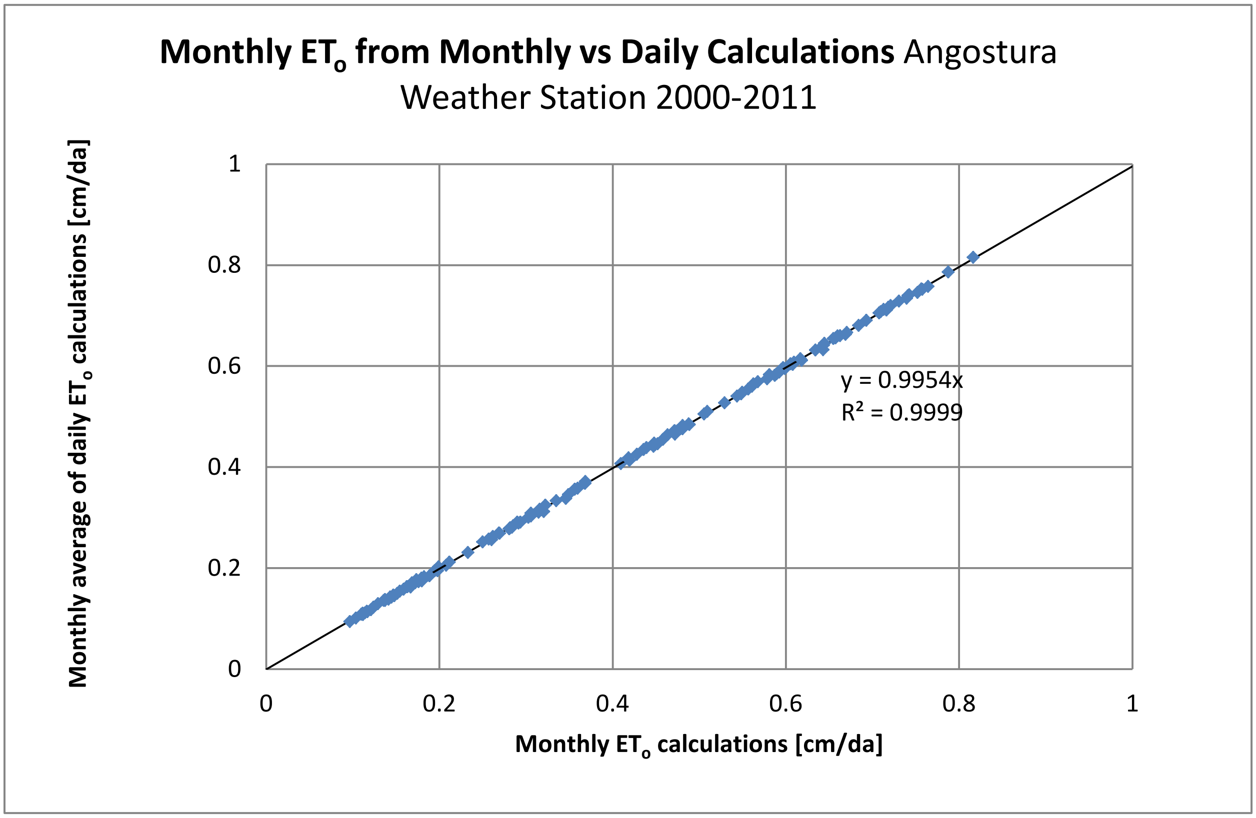

Figure 2: Comparison of monthly calculations of ET_o using the Hargreaves equation (x-axis) to monthly averages of daily calculations of ET_o using the same (y-axis) shows an almost imperceptible difference between the two methods for 12 years of Angostura weather station data. This stability of the non-linear $(T_{max} - T_{min})^{0.5}$ term in the Hargreaves equation for daily versus monthly calculations suggests that daily $(T_{max} - T_{min})$ in °C is relatively constant in any given month.

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[2] Daily data from ET Toolbox website downloaded 2/27/2012 http://www.usbr.gov/pmts/rivers/awards/Nm2/rg/PROD/wx/txt/archive/

1. Data availability issues

Within the spatial extent of URGSiM, full weather data (temperature, wind speed, relative humidity, and solar radiation) are available from 1985 to 1992 and 1993 to present at the Los Lunas and Alcalde data stations.[3] Weather data from additional locations became available starting in 2001; however, the 1975 to1999 calibration period is the period of focus for this analysis. Thus for the period of interest, full weather data are not available at all for 11 of 25 years and are only available in two useful locations for the remaining 14 years. Temperature data, however, is more widely available. Numerous temperature stations along the Rio Grande or Rio Chama within the URGSiM model extent have data available beginning in 1975 or earlier. The locations of some of these are shown in Figure 3 along with the two full weather data sites. It is clear from this figure that without better spatial and temporal data availability, the potential benefit of a data-intensive Penman-Monteith based Reference ET method is questionable, and a temperature based method makes the most sense for historic calculations.

2. Data quality issues

In addition to the spatial and temporal sparseness of the historic record for full weather data, preliminary analysis also suggests that the available historic data has not been carefully checked, and may not be reliable. Keller-Bliesner performed a high level analysis of weather data for the Alcalde Station from 1985- 2010, and found obvious issues with the solar radiation, relative humidity, and wind speed data. As seen in Figure 4, daily solar radiation values higher than theoretical maxima, relative humidity values greater than 100% or equal to 0%, and dramatic changes in wind sensor behavior in short periods of time were all noted in the data. In addition, Keller-Bliesner has noted one day shifts and a lack of quality control or assurance procedures associated with weather data from New Mexico State University sources (Brian Westfall, personal communication 7/1/2011). In general, a model is only as good as the data driving it, and this applies to Reference ET equations. As stated in Appendix D of the ASCE Standardized Reference Evapotranspiration Equation documentation (Task Committee on Standardization of Reference Evapotranspiration 2005):

> "***Weather data must be screened before use in any ET equation, including the standardized equation, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. When weather measurements are determined to be faulty, they can be adjusted or corrected using a justifiable and defensible procedure.***"

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[3] Downloaded from the New Mexico State University website: http://hydrology1.nmsu.edu/cgi-shl/cns/uberpage.pl?selected=2 Available online as of 1/10/2012

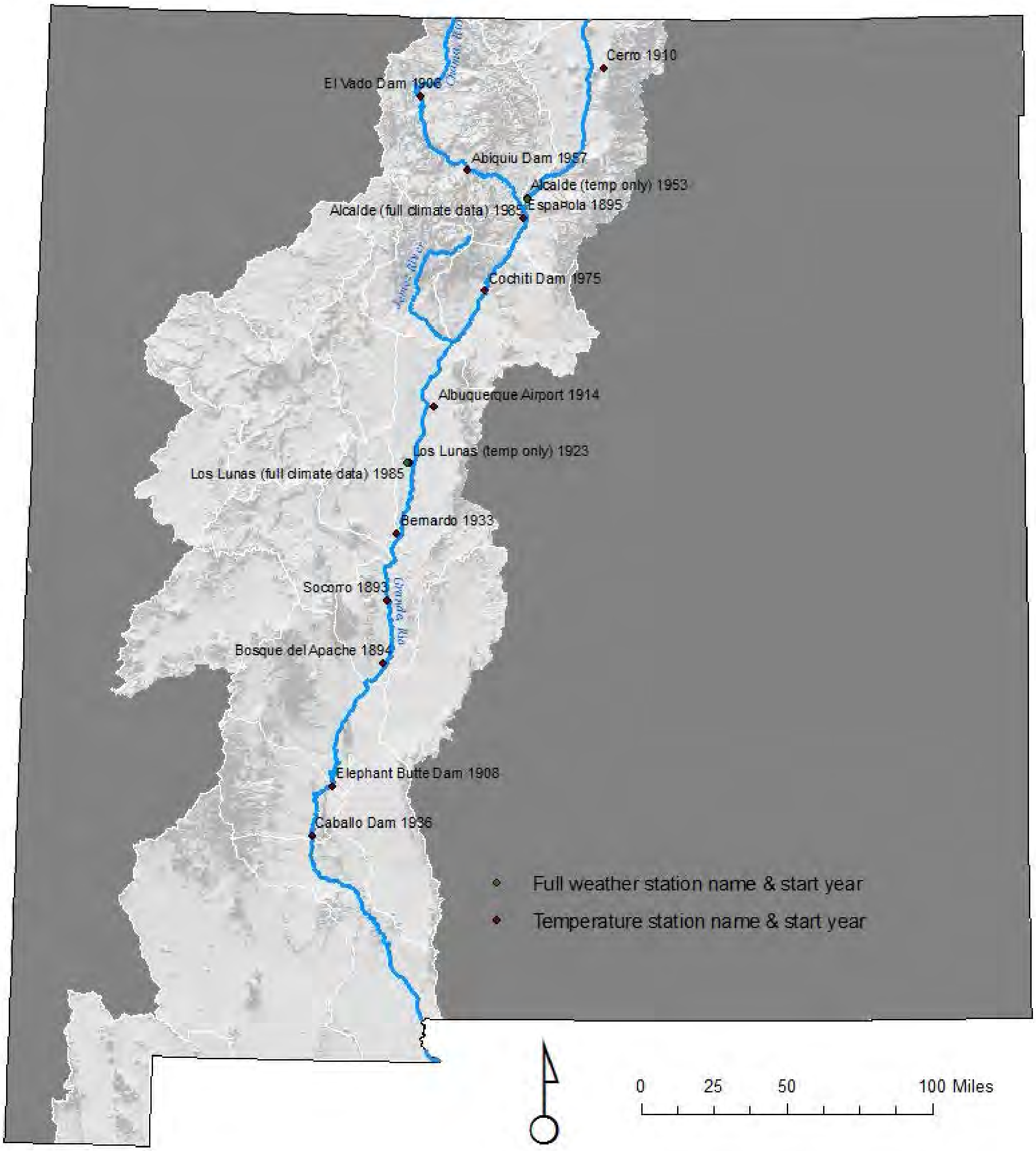
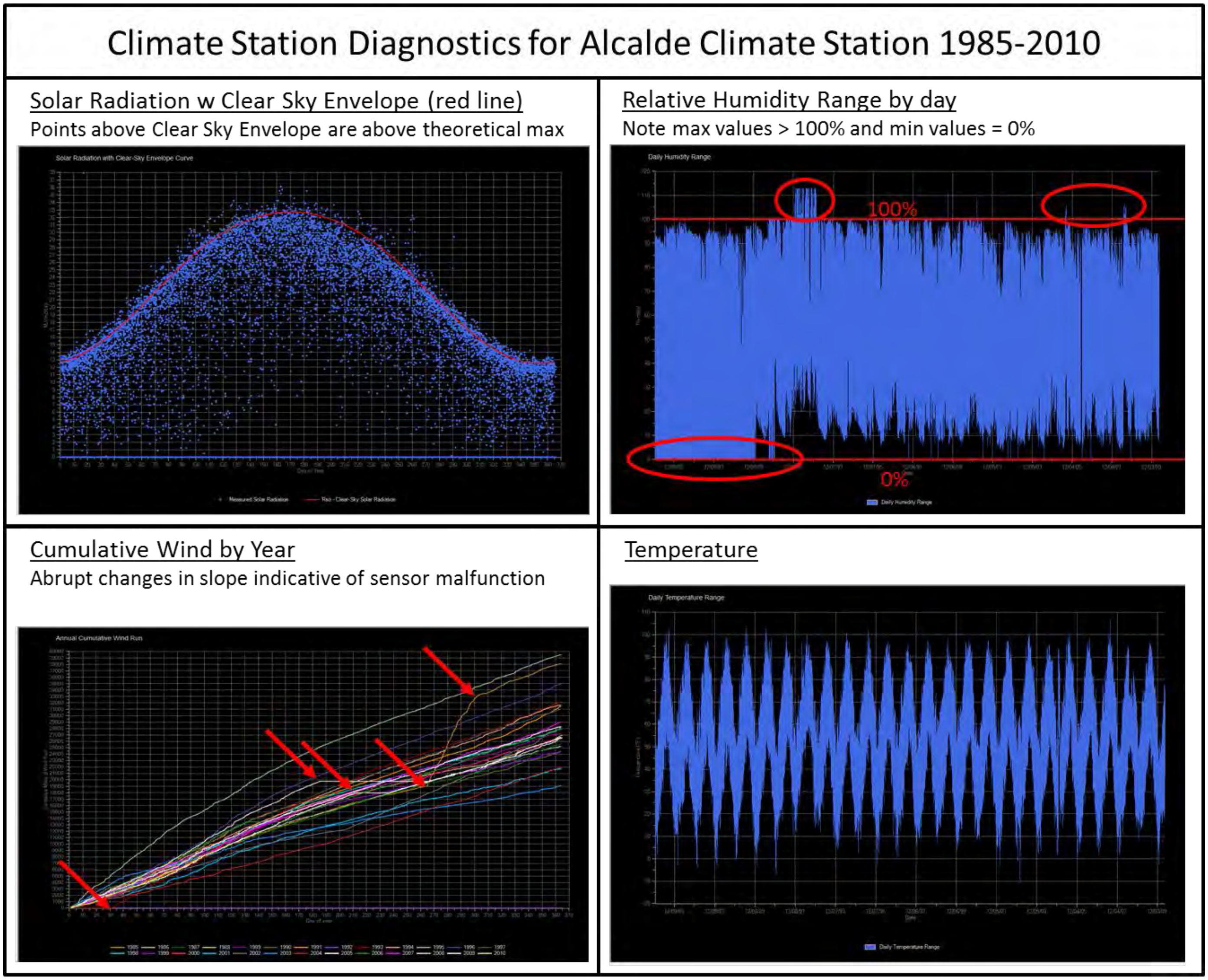


Figure 3: Weather station data available along river reaches within the URGSiM model extent with periods of record starting before the year 2000. Stations are labeled by period of record start year. Only two stations are available with long term full weather data (Alcalde and Los Lunas), while numerous stations are available with long term temperature data.



Climate Station Diagnostics for Alcalde Climate Station 1985-2010

Solar Radiation w Clear Sky Envelope (red line)

Points above Clear Sky Envelope are above theoretical max

Relative Humidity Range by day

Note max values > 100% and min values = 0%

Cumulative Wind by Year

Abrupt changes in slope indicative of sensor malfunction

Temperature

Figure 4: Weather station diagnostics for Alcalde weather station daily data between 1985 and 2010. Daily solar radiation values greater than theoretic maximum (upper left), maximum relative humidity values greater than 100% and minimum relative humidity values equal to 0% for years at a time (upper right), and dramatic shifts to the slope of cumulative wind plots in different years (lower left) are indicative of sensor problems. The daily temperature range (lower right) seems fine.

The limited availability of full weather data sets for the spatial and temporal extents of interest to URGSiM, coupled with the monthly timestep of the model, are sufficient to preclude use of a Penman-Monteith ET_o equation in the monthly timestep URGSiM. The apparent unreliability of the full weather data adds even more credence to the decision to use a temperature based method. Of the temperature based methods, the Hargreaves 1985 equation (Equation [3] above) is perhaps the most widely accepted and is now used in URGSiM for ET_o calculations.

III. Crop coefficients

Reference ET (ET_o) is by definition the potential evapotranspiration rate of a well-watered reference crop, in the case of Hargreaves 1985 and most other ET_o methods, a grass of specific properties. From this ET_o, which is a function of atmospheric conditions and reference crop physiology, the potential ET rates of other vegetation types can be inferred based on vegetation specific factors called crop coefficients as introduced in Equation (2) above. A crop coefficient of 0.9 for a given crop in a given time period means that the ET from that crop will be 90% of reference crop ET. Crop coefficients typically vary with time because of changes in the crop phenology. They can be defined as a function of month, position in growing season, or climatic factors depending on the level of detail desired.

A. Issues with the Sammis et al. (1985) crop coefficients

A significant factor in selection by the ET Toolbox of the modified Penman method as the default for estimation of ET_o was the existence of locally developed crop coefficients based on this specific ET_o formulation. Sammis et al. (1985) developed crop coefficients for alfalfa, cotton, corn, and sorghum at locations throughout New Mexico. The crop coefficients were calculated by comparison of ET estimates for the crop using a mass balance method (non-weighing lysimeter) to the Reference ET calculated from weather data using the modified Penman equation discussed in Section I.A. Rather than correlating the resulting crop coefficients to the day of year, however, the crop coefficient was correlated to the cumulative growing degree days. Growing degree days (GDD) are a proxy of expected cumulative plant growth calculated with daily temperature data and plant properties. Crop coefficients were calculated as a function of crop stage rather than date. Using this method, the crop coefficient for a given crop may vary on a given day from year to year based on antecedent temperature conditions to that point in the year. For example, in a cold year, alfalfa in June may be smaller and use less water than the same field of alfalfa in June of a warmer year.

1. Magnitude

It would be expected that an erroneously high ET_o from the modified Penman equation (as shown in Section II.A) would lead to erroneously low crop coefficients, and that in combination the errors would cancel and potential ET estimates would be useful. However, as shown in Figure 5 and Figure 6, the opposite is true, at least for Angostura 2007 data. Figure 5 shows that Sammis et al. crop coefficients for alfalfa at Angostura in 2007 are higher than alfalfa crop coefficients of the magnitude of FAO-56 recommendations, particularly during the peak of the summer when ET_o values are highest. When the effect of the GDD-based crop coefficients are combined with the effect of the high ET_o, the result, for the Angostura 2007 case, is potential ET estimates of 64 inches per year (which is almost 50% higher than the 43 inches per year estimated for the FAO-56 ET_o and crop coefficients case). Of this difference of 21 inches per year, 15 inches (over 70%) is due to the ET_o difference, and the remaining 6 inches is due to the crop coefficient difference. These results are shown in Figure 6.

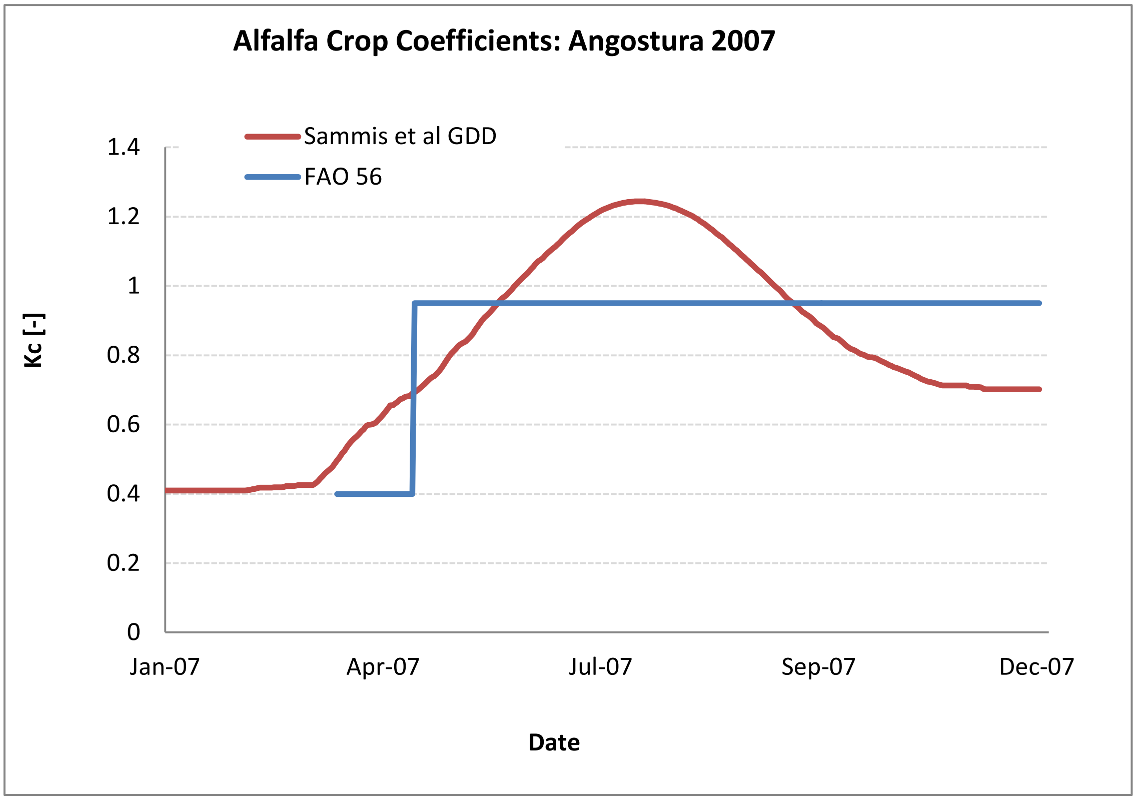


Figure 5: Crop coefficients calculated for alfalfa at Alcalde weather station using the Sammis et al. (1985) GDD method compared to simple FAO-56 based estimates of 0.4 for the first month of the growing season and 0.95 thereafter. The GDD method values are higher than the FAO-56 based values from May 21st through September 19th, a nearly 4 month period during which Reference ET will be at its greatest.

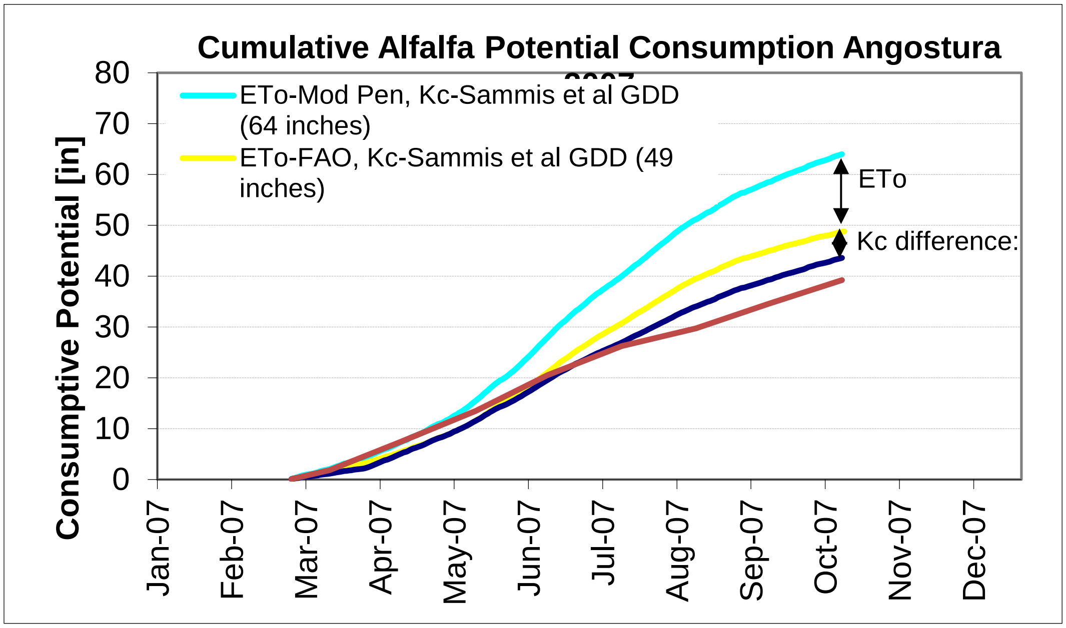


Figure 6: Cumulative potential ET estimates for alfalfa at Angostura in 2007 for different combinations of Reference ET (ET_o) equations (either modified Penman or FAO-56 Penman Monteith) and crop coefficients (K_c) (either Sammis et al. 1985 growing degree day (GDD) based method or FAO-56 based). The combination of modified Penman ET_o with Sammis et al. GDD K_c results in cumulative estimates 50% greater than the FAO combination.

Also shown in Figure 6 is cumulative *actual* ET estimated by an eddy covariance tower[4] for an alfalfa field in San Acacia, which is further south and at a lower elevation than Angostura. Potential ET assumes "standard" growing conditions, meaning a disease free, well-fertilized crop, grown in large fields under optimum soil water conditions (Allen et al. 1998). This situation typically represents an upper limit to ET, and thus actual ET is often less than potential ET. Thus, a direct comparison of potential ET at Angostura to actual ET at San Acacia is difficult in a quantitative sense. However, the fact that actual ET from a "well-watered" alfalfa field in San Acacia is on the order of 40 inches per year provides additional support for the notion that methods used previously by the ET Toolbox for calculation of ET_o and K_c that suggested more than 60 inches of potential ET at a more northerly location were anomalously high. A remaining question is why the potential ET values calculated by the Sammis crop coefficient method are so high when they were developed with field experiments. One possibility is that when Sammis et al. excavated and then refilled boxes in the field to create the non-weighing lysimeters, they created growing conditions that were not representative of the "standard" conditions simulated by the ET_o equation. Alfalfa yield data

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[4] Data downloaded 6/24/2010 from http://bosque.unm.edu/~cleverly/ALF/ALF.html . Website no longer available as of 1/10/201

shown in Table 1 support this hypothesis. Alfalfa yields from the five lysimeters were on average 174% of yields in the surrounding fields. Sammis et al's results might have been different if instead of calculating ET_o, they had measured ET_o with parallel lysimeters growing the reference crop.

			Alfalfa Yield [kg/ha]	
Location	ET_o [mm]	ET_a [mm]	Lysimeter	Field
Artesia	2140	1873	23400	13450
Clovis	2142	1786	15800	12780
Farmington	1582	1581	14700	6720
Las Cruces 1	1710	1715	21900	11430
Las Cruces 2	1893	1687	22600	12100
Average	**1893**	**1728**	**19680**	**11296**

Table 1: Reference ET (ET_o), actual ET (Et_a) in non-weighing lysimeters, and yields in the lysimeters and surrounding field crop yields reported by Sammis et al (1985) for Alfalfa. Note that lysimeter yields are significantly larger than field yields for all locations, with lysimeter yields averaging 174% of field yields. The non-weighing lysimeters were not representative of field conditions, and may not have been representative of "standard" conditions.

2. Growing degree day issues

Situations in which the GDD method begins to shut the plant down before the end of the growing season is another issue noted with using GDD to estimate riparian crop coefficients. This is illustrated when GDD are calculated using temperature data from the Bosque del Apache temperature station,[5] and then translated to Salt Cedar crop coefficients using the GDD based method in ET Toolbox (Brower 2008). The result, shown in Figure 7 is a crop coefficient that is zero before October[6] in every year between 2000 and 2008, before saltcedar is done transpiring (the ET Toolbox suggests a transpiration end date of November 15th

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[5] Data downloaded from the Western Regional Climate Center website: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1138 Available online as of 1/10/2012.

[6] These results are calculated at a monthly timestep using URGSiM. However, because GDD days are calculated as the midpoint between daily max and daily min temperatures less a base temperature, the sum of daily calculated GDD will be the same as a single calculation with monthly average min and monthly average max temperatures.

for Salt Cedar). The ET Toolbox GDD versus K_c curves shut down Salt Cedar and Cottonwood ET by the time they reach 1,600 Growing Degree Days, which is less than any other crop in the ET Toolbox for which GDD is used except spring barley. Alfalfa is still transpiring at 4,000 GDD, and Wheat at 3,000 to give some comparison. (The base temperature is higher for the riparian species than the other crops meaning the riparian species GDD will not accumulate as fast, so the comparison is not quite direct, but illustrative nonetheless). According to the ET Toolbox documentation (Brower 2008) page 34, the Salt Cedar and Cottonwood GDD to crop coefficient relationship are a result of “extensive field studies in 1999 at the Bosque Del Apache National Wildlife Refuge” by Dr. Salim Bawazir of NMSU. Interestingly, as can be seen in Figure 8, the year 1999 had low average temperatures at Bosque del Apache. especially in April, June, and July compared to 2000-2011. Thus defining GDD to crop coefficient relationships based on a single (relatively cool) year of data may explain why those curves end at 1,600 GDD, but GDD values exceeding this are reached at Bosque del Apache by October of all but one year between 2000 and 2009. Regardless of the reason, the GDD-based crop coefficients used previously by URGWOM and URGSiM can lead to obviously erroneous results for riparian vegetation in the (warmer) southern reaches of the Middle Rio Grande.

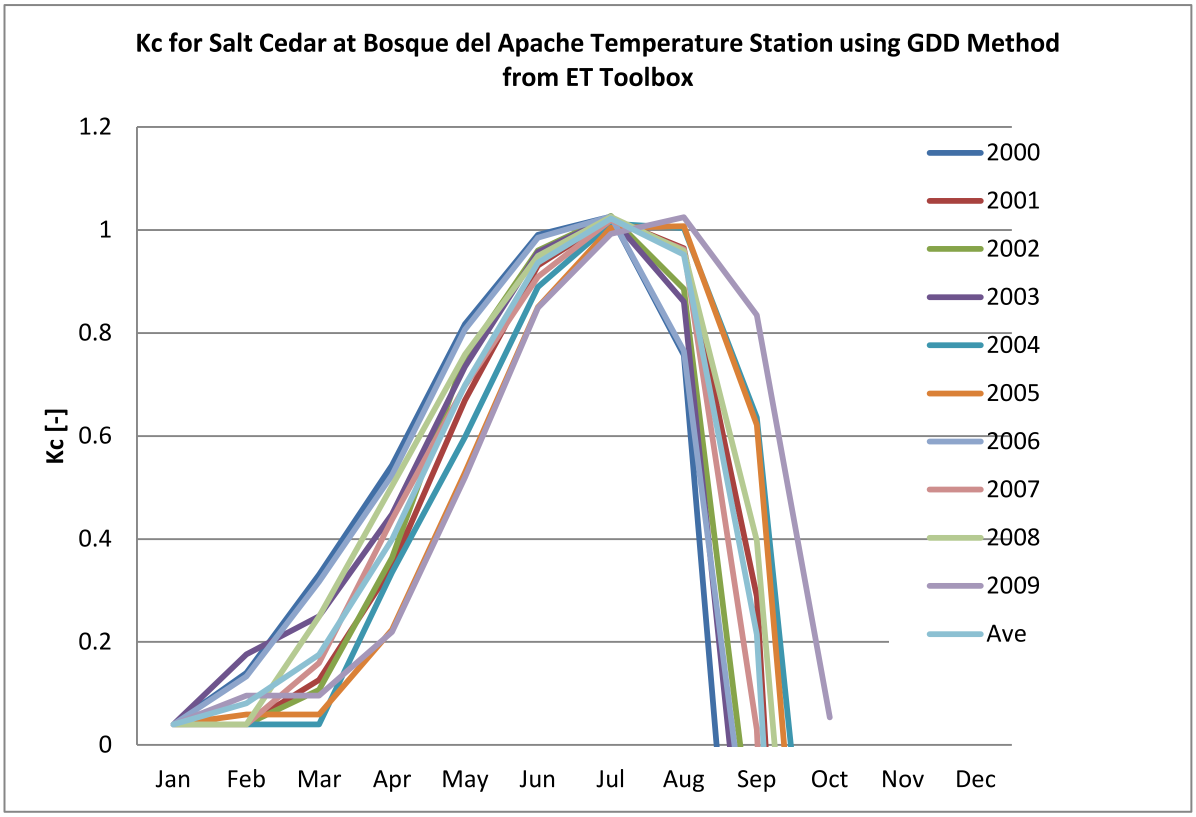


Figure 7: Crop coefficient (K_c) estimated for Salt Cedar at the Bosque del Apache temperature station[4] using a Growing Degree Method. Note that K_c comes down too quickly at the end of the summer mathematically shutting off ET prematurely before October of almost every year between 2000 and 2009.

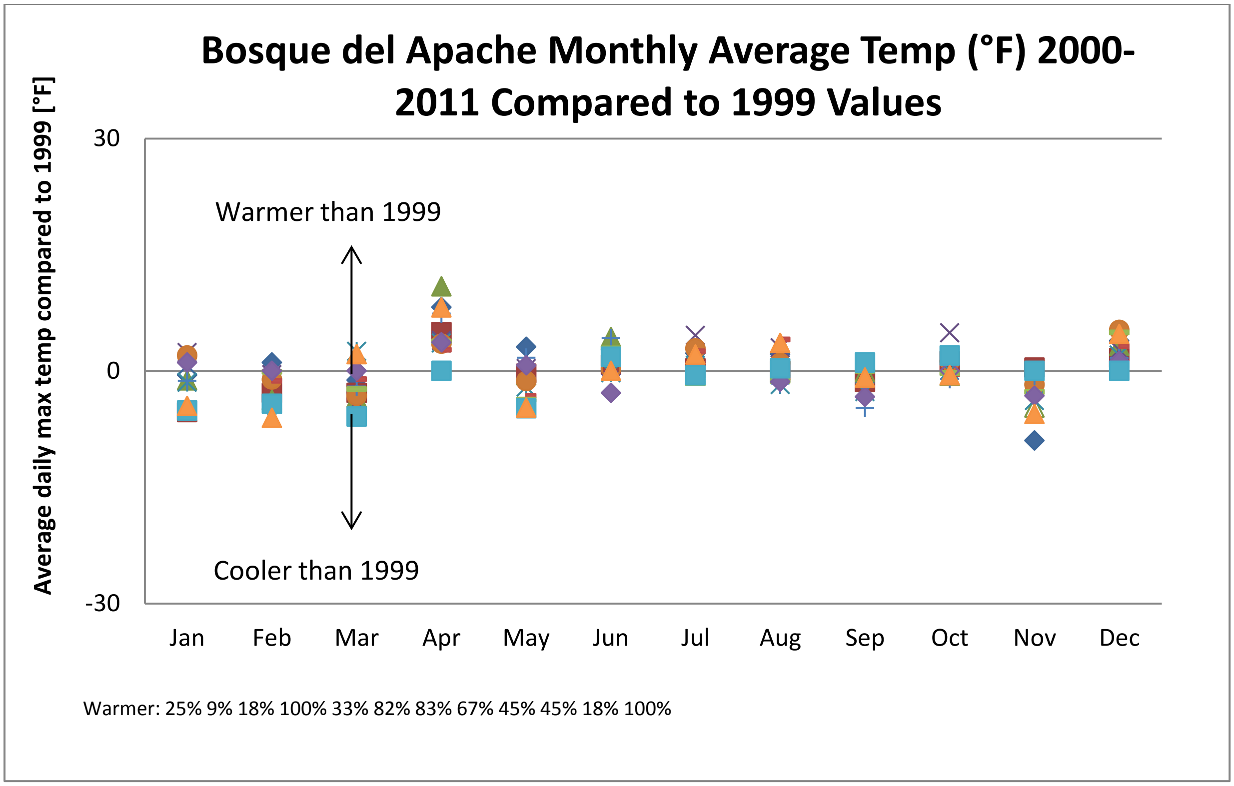


Figure 8: Monthly average temperature at the Bosque del Apache temperature station in 2000-2011 compared to the year 1999. Growing Degree Day based estimates of riparian crop coefficients in the ET Toolbox are based on 1999 field data from Bosque del Apache. 1999 was a cool summer in this location, especially in April, June, and July compared to 2000-2011. The "Warmer" percentages mean that, for example, 100% of Aprils between 2000 and 2011 had higher average temperatures than April of 1999.

B. Current crop coefficient methods

1. Irrigated agriculture

Irrigated agriculture in the URGSiM model extent has been dominated during recent history by alfalfa and pasture grass (see Section IV.A). To choose a new crop coefficient methodology for use in URGSiM, observed ET data from the eddy covariance tower over an alfalfa field near San Acacia (data seen previously in Figure 6) was compared to potential ET calculated with a Hargreaves ET_o method and alfalfa crop coefficients from three different sources: the Sammis et al. (1985) GDD method, the Middle Rio Grande Water Assessment (MRGWA) (Bureau of Reclamation, 1997) values, and FAO-56 (Allen, et al. 1998) based values. Results are seen in Figure 9. The actual ET is less than any of the potential ET values during the main growing season, but more than any method in October through December. The Sammis et al. (1985) GDD method results in the highest estimated potential ET while results from the MRGWA (reference) and FAO-56 (reference) crop coefficients are comparable. Based on this result, crop coefficient values based on FAO-56 were adopted for use in URGSiM for Alfalfa, Pasture Grass, Grains, and Fruits and Vegetables crop types. (The use of these four irrigated crop classifications is explained in Section III.) The crop coefficients used are shown in Figure 10.

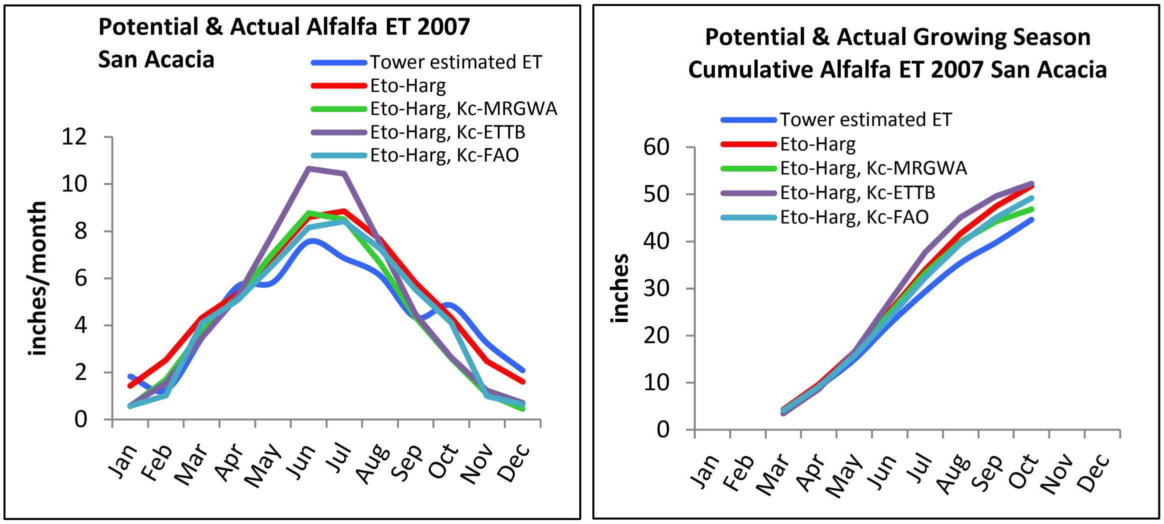
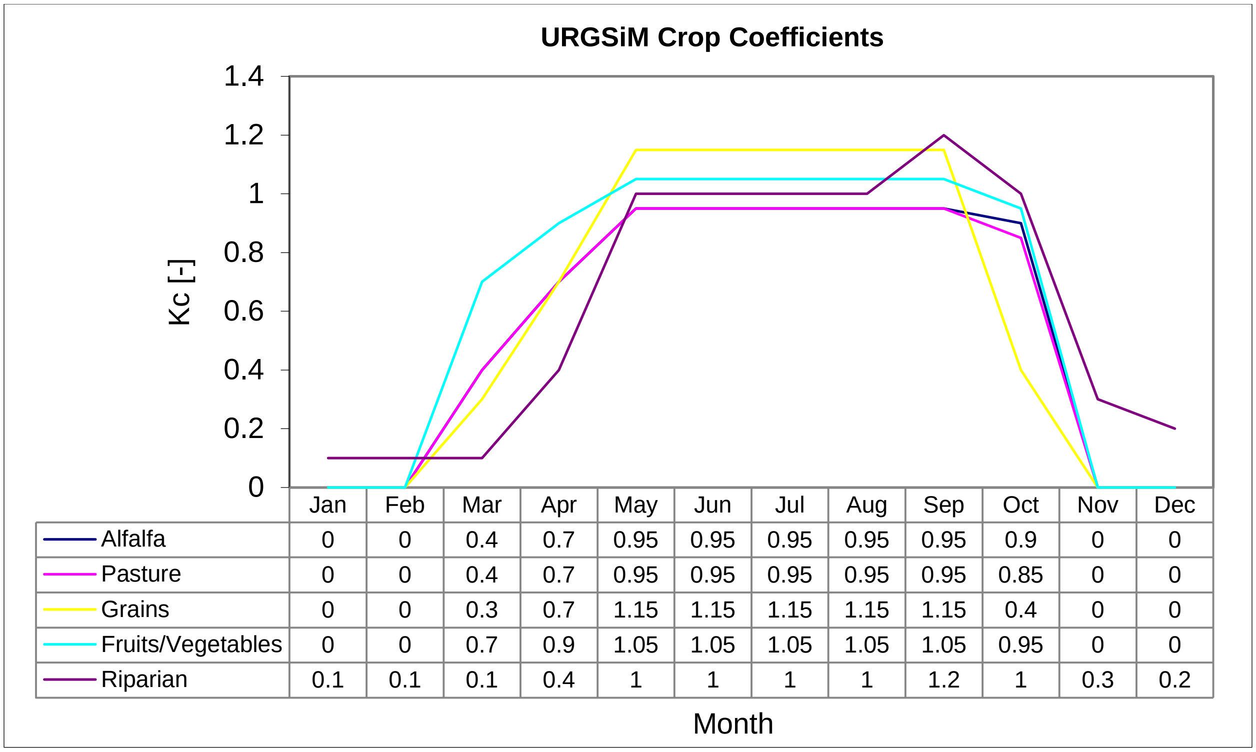


Figure 9: Estimates of potential ET for an alfalfa field near San Acacia during 2007. The blue line is an estimates of actual ET from an eddy-covariance tower (see footnote #3). The red line is calculated ET_o using the Hargreaves 1985 equation with observed temperature data from a temperature station next to the field. The remaining three lines are potential ET estimates resulting from multiplication of the ET_o value by a crop coefficient for alfalfa for the given month from either the Sammis et al. (1985) GDD method, the Middle Rio Grande Water Assessment (MRGWA), or FAO-56 (Allen et al. 1998) based values.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alfalfa	0	0	0.4	0.7	0.95	0.95	0.95	0.95	0.95	0.9	0	0
Pasture	0	0	0.4	0.7	0.95	0.95	0.95	0.95	0.95	0.85	0	0
Grains	0	0	0.3	0.7	1.15	1.15	1.15	1.15	1.15	0.4	0	0
Fruits/Vegetables	0	0	0.7	0.9	1.05	1.05	1.05	1.05	1.05	0.95	0	0
Riparian	0.1	0.1	0.1	0.4	1	1	1	1	1.2	1	0.3	0.2

Figure 10: Tabular and visual representation of crop coefficients utilized by URGSiM.

2. Riparian vegetation

Figure 10 also shows values used for riparian vegetation, which are explained here. Riparian vegetation is vegetation growing along the river corridor. For URGSiM, riparian vegetation is deep rooted vegetation that can obtain water from the shallow ground water system (i.e., trees but not grasses), and is not irrigated. Eddy covariance tower measurements of actual ET from riparian vegetation are available in the Middle Rio Grande valley from 2000 to 2004 (Cleverly et al. 2006). Eddy covariance derived ET data from three locations representing sparse Cottonwood, dense Cottonwood, and Salt Cedar vegetation types are shown in Figure 11.

Modeling ET from riparian vegetation is complicated by reductions in potential ET as groundwater levels drop. Groundwater models typically specify some relationship between depth to groundwater and potential ET. In their Albuquerque Basin MODFLOW groundwater model, McAda and Barroll (2002) specify groundwater deeper than 30 feet (extinction depth) as inaccessible to riparian vegetation, and a maximum riparian ET of 5 feet per year when groundwater levels reach the ground surface. Baird and Maddock (2005) use a relationship between *transpiration* and groundwater depth that reflects decreases in plant activity for very shallow groundwater situations due to root inundation. As water levels approach the surface and transpiration shuts down (as shown by the Baird

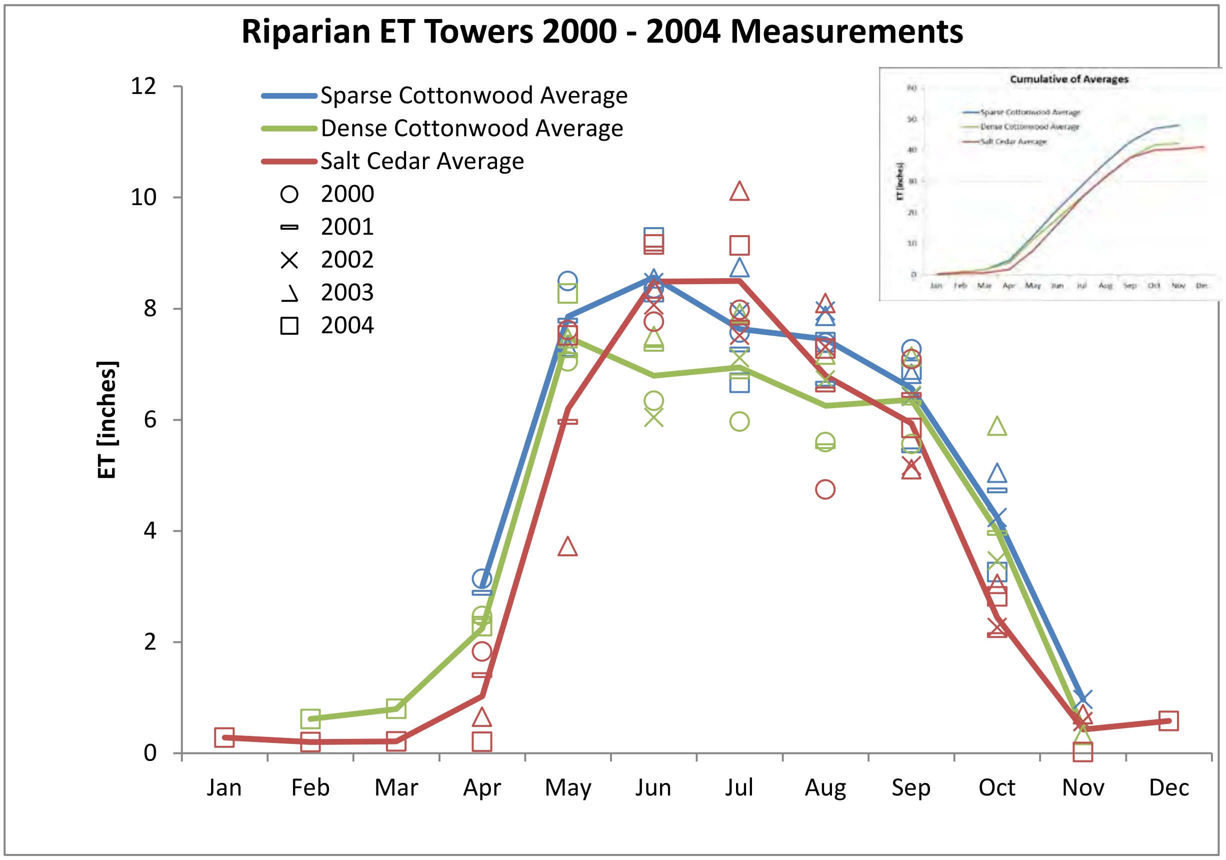


Figure 11: Eddy covariance tower based monthly ET estimates for sparse cottonwood (blue), dense cottonwood (green), and salt cedar (red) vegetation types from 2000 through 2004. Shapes indicate the year of measurement, colors indicate vegetation type, and the solid lines represent vegetation specific average values. Average cumulative annual values are approximately 41 inches for Salt Cedar, 42 inches for dense Cottonwood, and 48 inches for sparse Cottonwood.

and Maddock [2005] line), direct evaporation from the ground surface should increase. For a spatially distributed model, it might be possible to separate transpiration and ground surface evaporation components, but for the spatially lumped URGSiM model, it would be difficult. In order to capture the transpiration peak in the Baird and Maddock (2005) line while including the deep extinction depth and direct evaporation for very shallow groundwater from McAda and Barroll (2002), URGSiM uses a combination of the two. The URGSiM relationship is shown along with those from McAda and Barroll (2002) and Baird and Maddock (2005) in Figure 12. Finally, to use Reference ET information, URGSiM substitutes atmospheric potential ET for the absolute rates used by McAda and Barroll (2002) and Baird and Maddock (2005) (5 feet per year and 0.3 centimeters per day respectively). In this way, URGSiM combines both ground-water level and atmospheric condition information in calculating riparian ET.

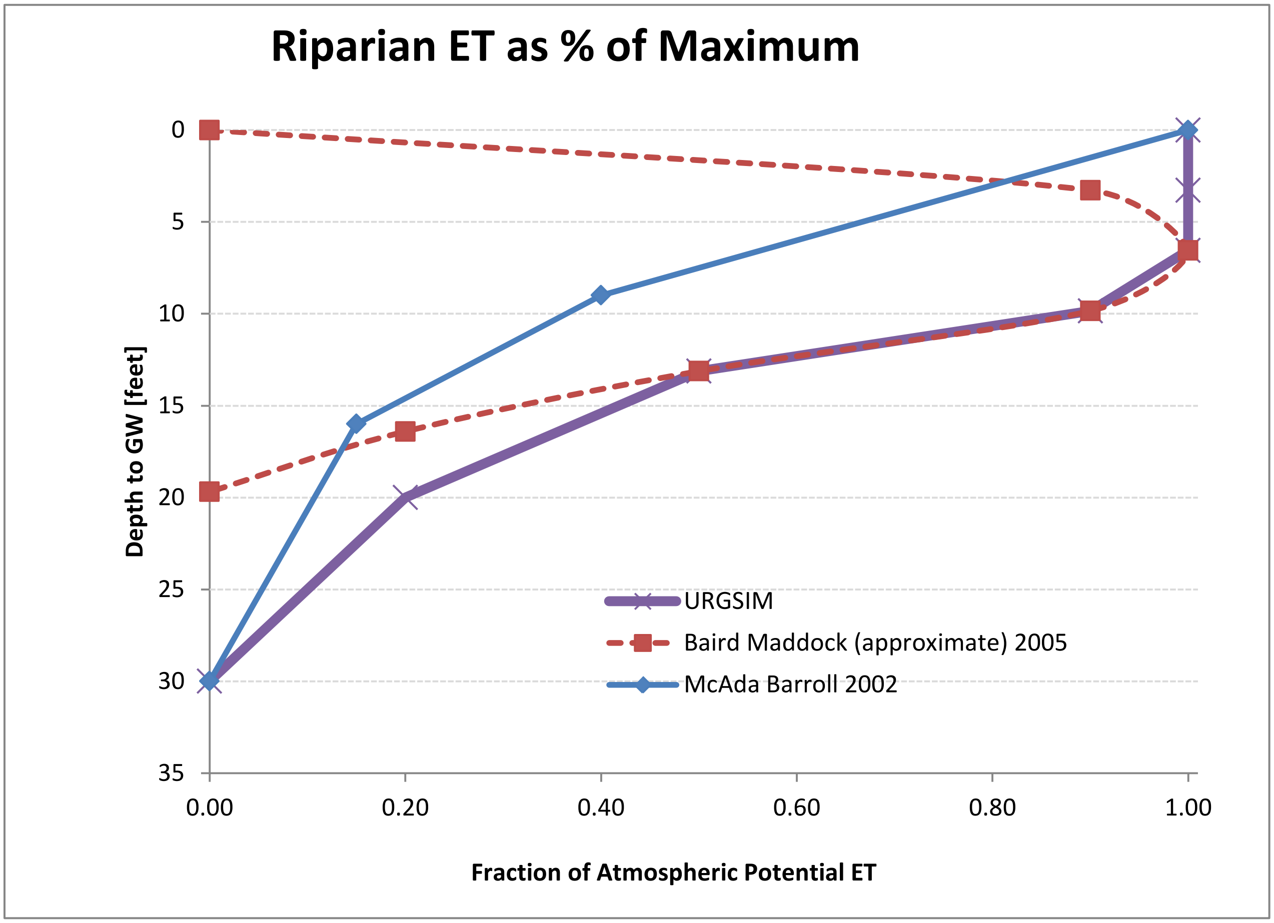


Figure 12: Relationship between depth to groundwater and atmospheric potential ET utilized by URGSiM. Atmospheric potential ET is defined as reference ET times the riparian crop coefficient. The McAda and Barroll (2002) and Baird and Maddock (2005) curves are defined with respect to absolute maximum ET rates of 5 feet per year and 0.3 centimeters per day respectively. By specifying these values as atmospheric potential, the URGSiM method normalizes the lines, and combines depth to groundwater and atmospheric conditions.

Adding the groundwater dependence to equation (2), we get

$$ET_p^{gwz,m,v} = ET_o^{r,m} * K_c^{m,v} * GW_c^{gwz,m,v} * A^{gwz,m,v} \tag{4}$$

where $ET_p^{gwz,m,v}$ [L^3/T] is evapotranspiration from riparian crop *v* in groundwater zone *gwz* during month *m*, $ET_o^{r,m}$ [L/T] is Reference ET in reach *r* during month *m*, $K_c^{m,v}$ [-] is the riparian crop coefficient, $GW_c^{gwz,m,v}$ [-] is the groundwater coefficient (percent of maximum ET due to groundwater depth) which is calculated with the depth to groundwater in groundwater zone *gwz* during month *m*, and the URGSiM relationship shown in Figure 12, and $A^{gwz,m,v}$ [L^2] is the area of riparian vegetation.

In URGSiM, Reference ET is calculated at a reach level while groundwater levels are calculated at a smaller spatial unit called a groundwater zone. Values can be rolled up from groundwater zone to reach or disaggregated from reach to groundwater zone depending on computational needs. Riparian vegetation crop coefficients adopted for use in URGSiM (Figure 10) are not spatially dependent, and so no reach or groundwater index has been added to the crop coefficient notation in equation (4).

If we divide both sides of equation (4) by the vegetation area, make the assumption that for groundwater-dependent vegetation's actual ET is equal to potential ET, and rearrange equation (4) to solve for crop coefficient, we get:

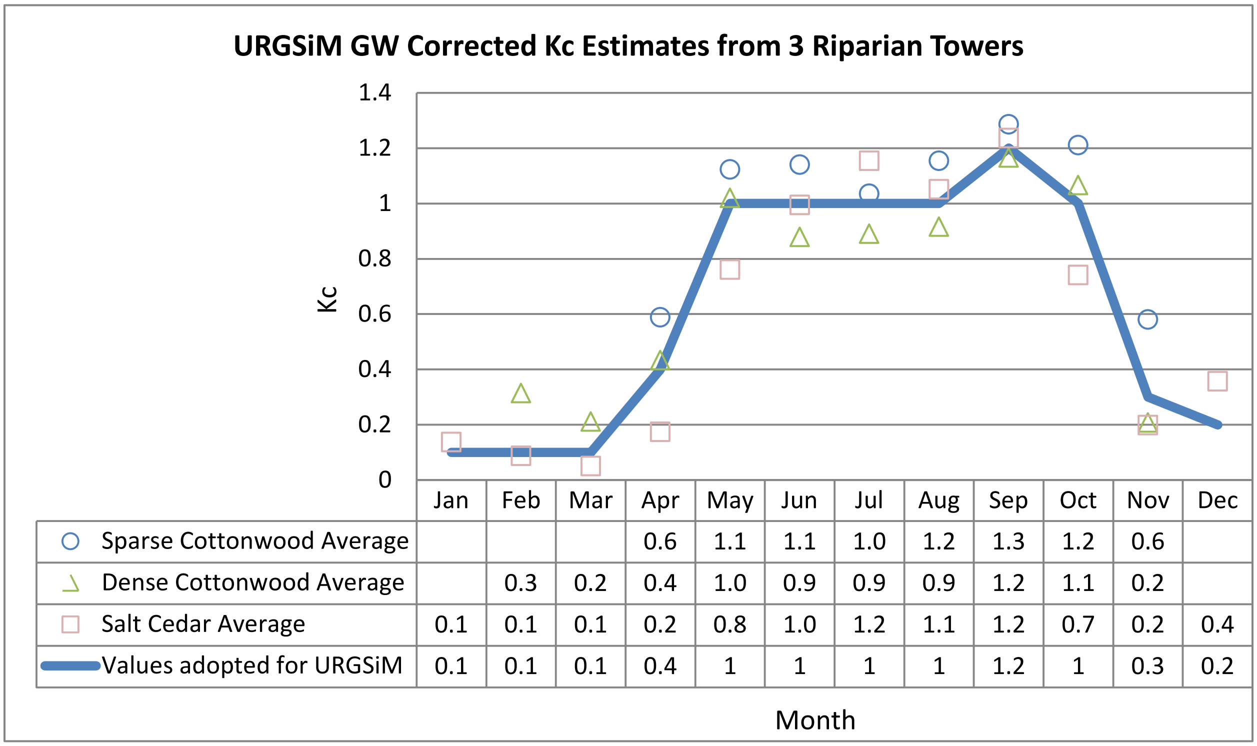
$$K_c^{m,v} = \frac{ET_{a-depth}^{m,ect}}{ET_o^{m,ect} * GW_c^{m,v,ect}} \tag{5}$$

where $ET_{a-depth}^{m,ect}$ is actual ET depth [L] measured at eddy covariance tower *ect*, and the Reference ET and groundwater depth (and thus groundwater coefficient) are based on weather data and groundwater depth measurements at the same eddy covariance tower *ect.* All terms on the right can be solved with data from a given eddy covariance tower.

Riparian vegetation in URGSiM is dominated by Cottonwood and Salt Cedar, and thus data from all three towers shown in Figure 11 were used to develop riparian crop coefficients. Reference ET was calculated with the Hargreaves 1985 equation, and the groundwater coefficient was calculated with the URGSiM relationship to groundwater depth shown in Figure 12. The resulting coefficients for each tower, as well as the average of the three towers are shown in Figure 13 below. Based on data overlap and relative consistency between the average data from the three different towers, the overall average crop coefficient was adopted for use throughout URGSiM.

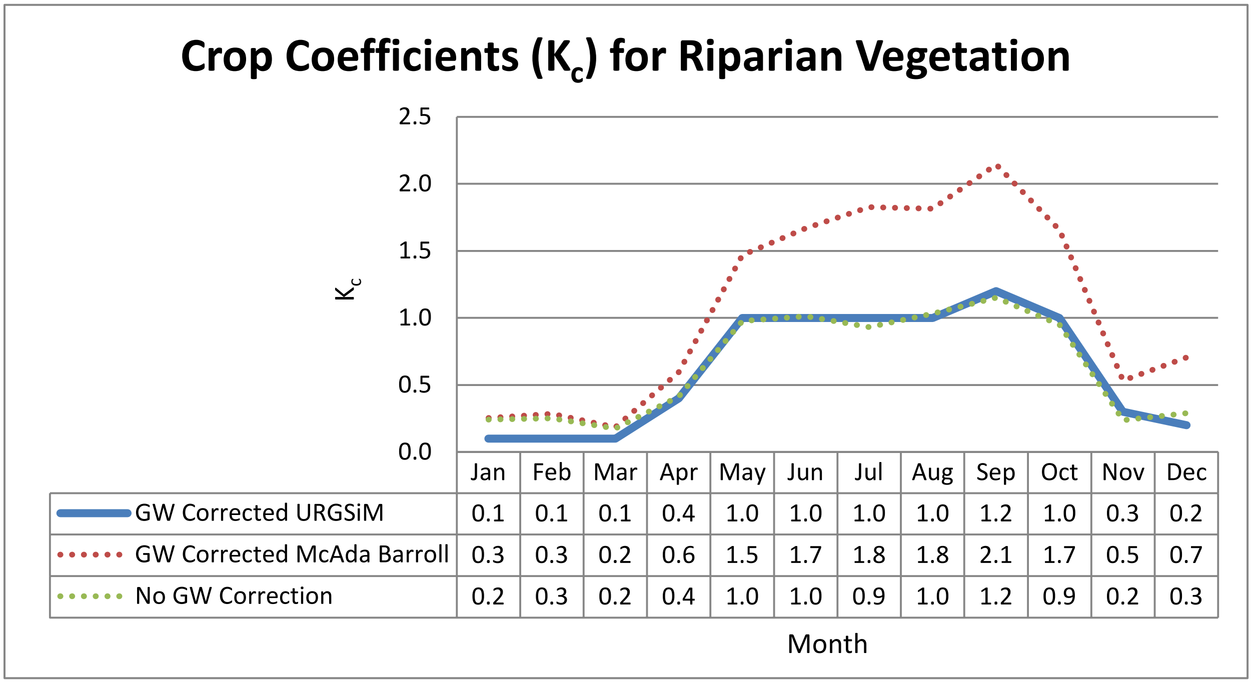
While the riparian vegetation crop coefficients derived here should be usable with Reference ET calculated with other accepted methods, they are specific to the relationship between depth to groundwater and maximum riparian ET used here and should not be used with other groundwater to maximum riparian ET relationships. Figure 14 shows the impact of the groundwater depth correction, and an alternate set of riparian vegetation crop coefficients that can be used without groundwater depth information, or with the McAda and Barroll (2002) relationship shown in Figure 12 above. The crop coefficient values calculated with the McAda and Barroll are extremely large as a result of groundwater depths on the order of 5 to 6 feet and actual cumulative riparian ET on the order of 3.5 to 4 feet in the areas where these measurements were made. The McAda and Barroll (2002) relationship would suggest only 2.5 to 3 feet of riparian loss for this situation without a K_c correction, and thus a high K_c is needed to reconcile the two. This results in values close to 100% of maximum for the URGSiM groundwater-potential ET percentage relationship (Figure 12), but sub-optimal values of 50% to 60% for the McAda Barroll relationship.

It is important to realize that estimates of ET from riparian vegetation without using groundwater depth implicitly assume some availability of water to the plant and thus some depth to groundwater. In the case of the groundwater independent crop coefficients shown in Figure 14, the implicit condition is the average depth to groundwater experienced by the vegetation when the eddy covariance tower measurements were made. For the eddy covariance data used here, the monthly average groundwater depth was less than 6.56 feet in 69% of measurements and between 6.56 and 9.84 feet in 21% of measurements where the riparian ET would be 100% and at least 90% of atmospheric potential respectively according to the URGSiM relationship between groundwater depth and atmospheric potential ET shown in Figure 12. Thus it is not surprising that the adopted riparian K_c value is close to the uncorrected groundwater value. Eddy covariance tower data and groundwater level data from areas where the depth to groundwater between 10 and 30 feet more often would make these results more robust. Put another way, if groundwater levels are always within 10 feet of the surface and if the URGSiM relationship between depth to groundwater and potential atmospheric ET shown in Figure 12 holds, then no groundwater correction would be necessary. Nonetheless, the K_c values shown in Figure 13 are adopted for use in URGSiM where there are areas with riparian groundwater deeper than 10 feet.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
○ Sparse Cottonwood Average				0.6	1.1	1.1	1.0	1.2	1.3	1.2	0.6	
△ Dense Cottonwood Average		0.3	0.2	0.4	1.0	0.9	0.9	0.9	1.2	1.1	0.2	
□ Salt Cedar Average	0.1	0.1	0.1	0.2	0.8	1.0	1.2	1.1	1.2	0.7	0.2	0.4
━ Values adopted for URGSiM	0.1	0.1	0.1	0.4	1	1	1	1	1.2	1	0.3	0.2

Figure 13: Monthly crop coefficients derived based on eddy covariance data in the Middle Rio Grande from 2000 - 2004 for specific vegetation types, and an overall average adopted for use in URGSiM.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GW Corrected URGSiM	0.1	0.1	0.1	0.4	1.0	1.0	1.0	1.0	1.2	1.0	0.3	0.2
GW Corrected McAda Barroll	0.3	0.3	0.2	0.6	1.5	1.7	1.8	1.8	2.1	1.7	0.5	0.7
No GW Correction	0.2	0.3	0.2	0.4	1.0	1.0	0.9	1.0	1.2	0.9	0.2	0.3

Figure 14: Monthly crop coefficients derived based on eddy covariance data in the Middle Rio Grande from 2000 - 2004 with different treatment of depth to groundwater as a constraint on potential ET. The values adopted use the URGSiM groundwater-ET relationship shown in Figure 12.

3. Open water

During the historic period, evaporation rates from the seven reservoirs modeled in URGSiM (Heron, El Vado, Abiquiu, Cochiti, Jemez, Elephant Butte, and Caballo) are calculated as 70% of measured pan evaporation. For climate change scenarios where impacts of changing temperature are to be evaluated with URGSiM, a temperature-based method of ET estimation is necessary.

The ET Toolbox (Brower 2008) includes open water evaporation coefficients from Jensen (1998) that are used to predict open water evaporation from ET_o. Because the Jensen coefficients were developed in the lower Colorado River, URGSiM does not use them and instead relies on coefficients calculated here based on pan evaporation rates observed at the Rio Grande reservoirs. Two notes of caution here:

- An equation like the Hargreaves 1985 reference equation designed to calculate evapotranspiration is set up to handle the physical differences between evaporation and transpiration, namely additional surface area and stomatal resistance associated with transpiration in plants compared to evaporation from a water or soil surface. To calculate open water evaporation, one might be better served by an early evaporation equation such as the Penman, which was developed more based on evaporation than transpiration. However, the data limitations described previously remain problematic. Therefore, despite this theoretic weakness, for reasons of practicality and simplicity, ET_o is used by URGSiM to predict open water evaporation.

- Pan evaporation can overestimate large and deep water body evaporation significantly largely because the temperature in the pan rarely matches that in the larger water body. As a result, the measured pan evaporation is multiplied by a calibration factor (70% in the case of URGSiM based on URGWOM methods) to account for some of this error. However, using the same factor of 70% at the relatively cool northern Heron reservoir (elevation ~7200 feet above mean sea level [amsl]) and the warmer southern Elephant Butte (elevation ~4300 amsl) as is done now in URGWOM and URGSiM may warrant some discussion. This issue will be seen in the calculations below.

Reference ET was calculated from 1975 through 2006 at the El Vado Dam,[7] Abiquiu Dam,[8] Cochiti Dam,[9] Elephant Butte Dam,[10] and Caballo Dam[11] temperature stations using the Hargreaves 1985 equation. For the same months, measured pan evaporation at each of these reservoirs was multiplied by the 70% factor, and this total then divided by the calculated reference ET to get an implied open water crop coefficient specific to a specific historic month and reservoir. This is shown in Equation (6) below which is a restatement of Equation (5) without any groundwater influence.

$$K_c^{m,res} = \frac{ET_{pan-depth}^{m,res}}{ET_o^{m,res}} \qquad (6)$$

Finally all values for a given month of year at a given reservoir were averaged and rounded to the nearest tenth to get estimated monthly open water evaporation coefficients for each of the five reservoirs as shown in Table 2. Empty cells from November through March at reservoirs upstream of Elephant Butte are a result of pan evaporation not being recorded during winter months at the northern reservoirs. URGSiM uses the April value for January through March, and the October value for November and December at these reservoirs. URGSiM uses El Vado values for Heron, and Cochiti values for Jemez reservoirs, and the value for the closest reservoir for direct river channel evaporation calculations.

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[7] Western Regional Climate Center: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm2837 Accessed 1/16/2012.
[8] Western Regional Climate Center: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm0041 Accessed 1/16/2012.
[9] Western Regional Climate Center: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1982 Accessed 1/16/2012.
[10] Western Regional Climate Center: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm2848 Accessed 1/16/2012.
[11] Western Regional Climate Center: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1286 Accessed 1/16/2012.

Calculated Open Water Evaporation Coefficient by Month and Reservoir:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
El Vado				0.9	0.9	0.9	0.8	0.8	0.8	0.8		
Abiquiu				1.2	1.2	1.1	1.0	1.0	1.0	1.2		
Cochiti				1.3	1.2	1.2	1.1	1.1	1.2	1.3		
Elephant Butte	1.3	1.3	1.6	1.6	1.6	1.4	1.3	1.2	1.3	1.4	1.5	1.3
Caballo	1.4	1.2	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.3	1.3	1.3

Table 2: Open water evaporation (crop) coefficients calculated from temperature and pan evaporation data measured at five reservoirs in New Mexico between 1975 and 2006.

It is clear in Table 2 that the coefficients increase in magnitude with distance south (and overall evaporative potential). In theory, climatic variability is handled by the reference equation, and thus the consistent spatial variability seen in Table 2 suggests a model weakness. This may be a result of either errors in the reference ET equation, the inability of reference ET to capture open water evaporation, or the actual evaporation estimate, or all three. Because of the trend towards increasing coefficients with increasing temperatures, it seems likely that this error is largely a result of assuming that 70% of pan evaporation is a reasonable approximation of actual reservoir evaporation at all reservoirs. These results could be explained by pan evaporation values that overestimate actual reservoir evaporation to a greater and greater degree as the air temperature at the reservoir, and thus presumably the difference in water temperature between pan and reservoir increases, a hypothesis that fits well with known deficiencies of pan evaporation measurements.

IV. Vegetation classifications

URGSiM was developed closely following URGWOM, and initially used riparian and irrigated agricultural areas from that model. Recently, the classifications of land types used have been simplified as explained in the next two subsections.

A. Irrigated agriculture

URGSiM uses estimates of irrigated area by reach and by crop type that were developed for URGWOM based on Middle Rio Grande Conservancy District (MRGCD) and Reclamation’s annual crop acreage reports. Values for 19 different crops for each year between 1975 and 1999 for each river reach between Cochiti and San Marcial are shown in Table 56 of the 2002 URGWOM model documentation (U.S. Army Corps of Engineers et al. 2002). Until recently, URGSiM used 20 crop types from the ET Toolbox (Brower 2008) that overlapped reasonably with the 19 crop types shown in the URGWOM documentation. However, the historic crop distribution is dominated by alfalfa and pasture grass such that additional crop types beyond these doesn't add much information to the model. As seen in Figure 15, URGSiM currently uses only four crop types: Alfalfa, Pasture Grass, Grains, and Fruits and Vegetables. Values for estimated irrigated crop area in the Middle Rio Grande from 1975 through 1999 are shown by crop type in Figure 16 and by reach in Figure 17. URGSiM also includes approximately 5,000 acres each in the Chama, Rio Grande above Otowi, and Jemez valleys, and 250 acres between San Acacia and San Marcial which are classified using the simplified four-crop classification.

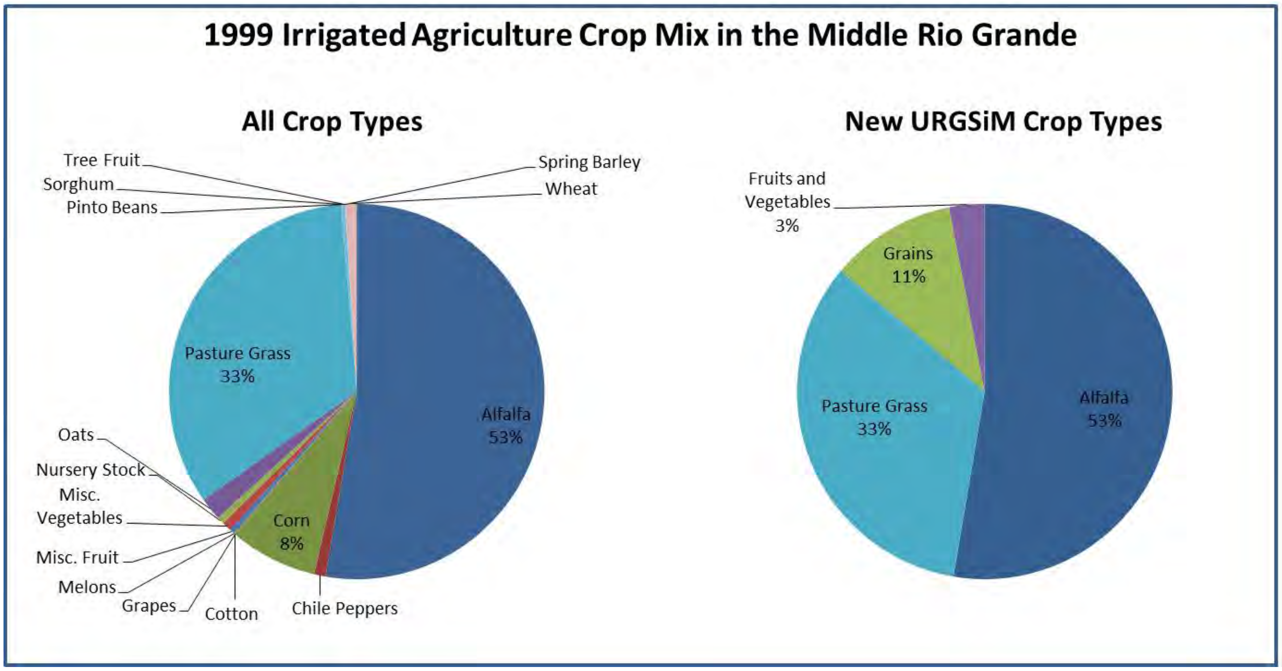

Figure 15: URGSiM crop type classifications and relative total percentages in the Middle Rio Grande in 1999. Left pie is the previous crop type classifications, and right pie is the current classifications. The crop types defined in the left pie are based on ET Toolbox classifications (Brower 2008). Alfalfa and pasture grass dominate irrigated area in the Middle Rio Grande.

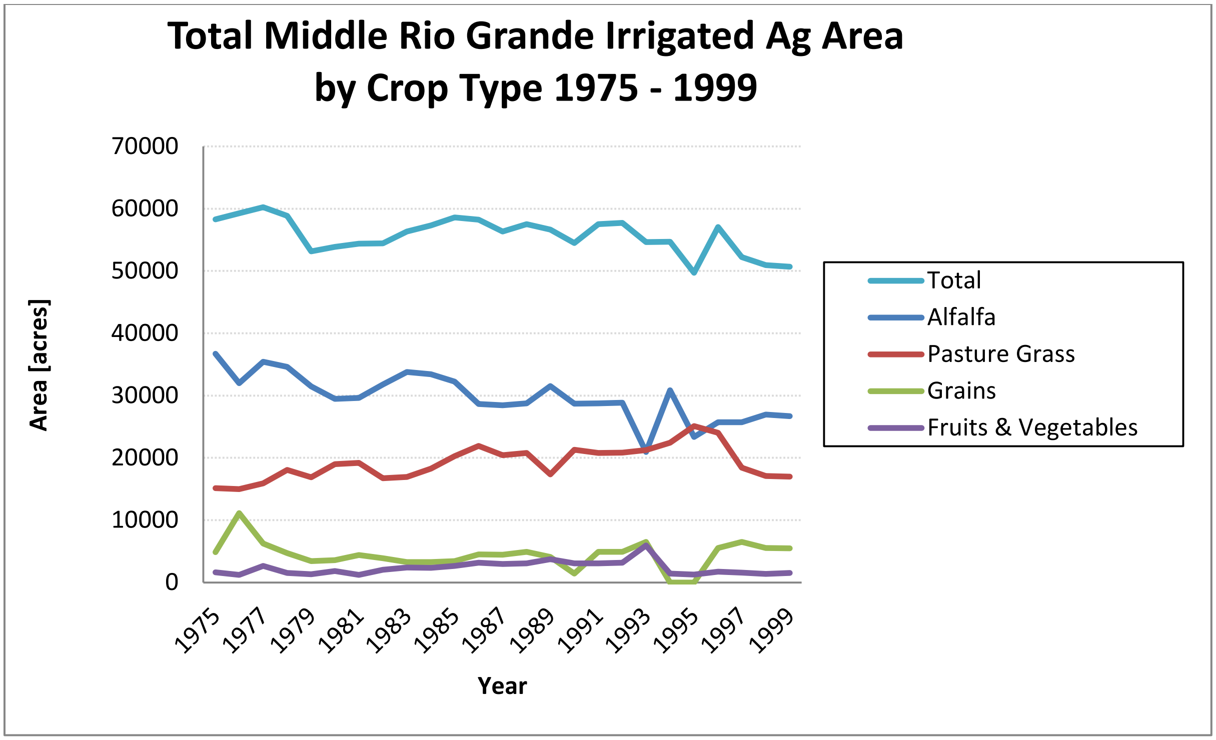

Figure 16: Irrigated area in the Middle Rio Grande from 1975-1999 by URGSiM crop type classification.

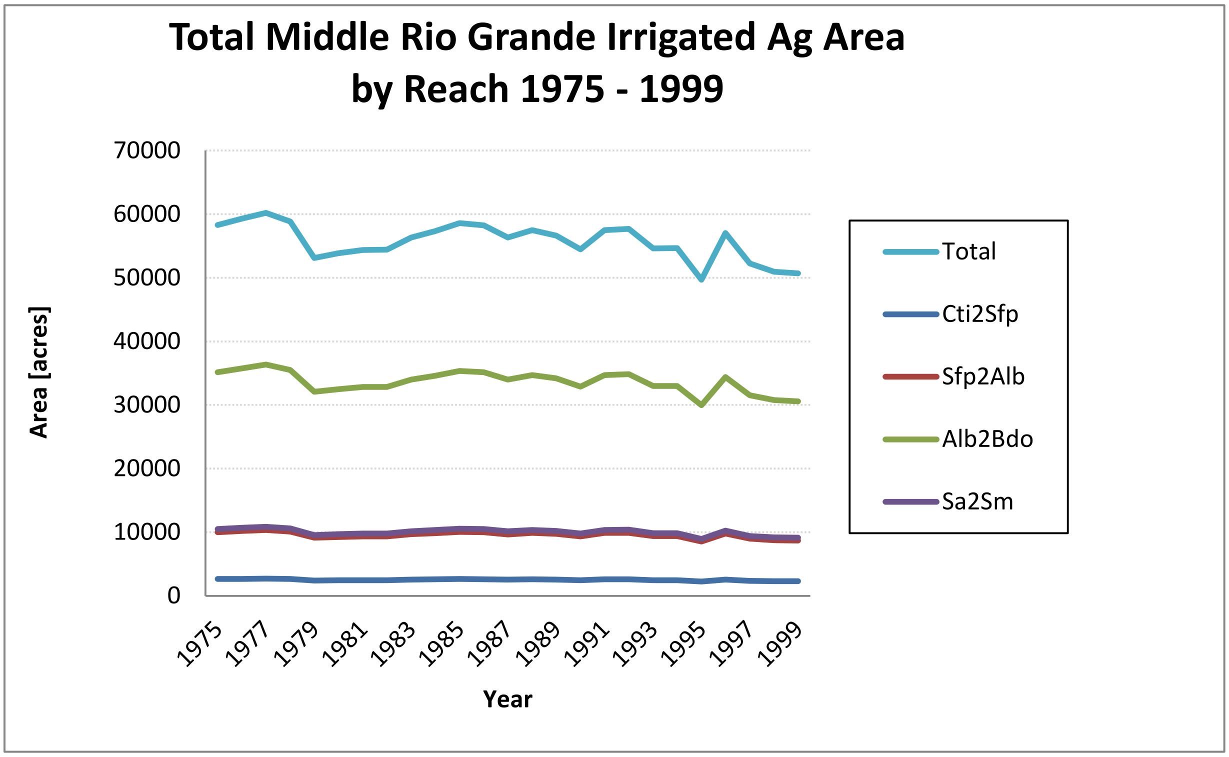

Figure 17: Irrigated area in the Middle Rio Grande from 1975-1999 by river reach. Cti2Sfp: Cochiti to San Felipe, Sfp2Alb: San Felipe to Albuquerque, Alb2Bdo: Albuquerque to Bernardo, Sa2Sm: San Acacia to San Marcial.

B. Riparian vegetation

Until recently, URGSiM used five riparian vegetation classifications based on data in the ET Toolbox (Brower 2008): Bosque (a mix of Cottonwood and Salt Cedar), Cottonwood, Marsh, Grass, and Salt Cedar. As seen in Figure 18, the estimates of areas of riparian vegetation in the Middle Rio Grande are dominated by Bosque and Salt Cedar. This makes the Cottonwood, Marsh, and Grass categories of questionable value to the model. As seen in Figure 11 and discussed in Section III.B.2, no significant difference between Cottonwood and Salt Cedar was evident from analysis of eddy covariance based estimates of ET. Thus, the model benefit of maintaining a difference between these is also questionable. As a result, URGSiM now uses only one riparian vegetation category. To get potential ET, total riparian vegetation area is multiplied by ET_o times the groundwater depth modified riparian crop coefficient discussed in Section III.B.2.

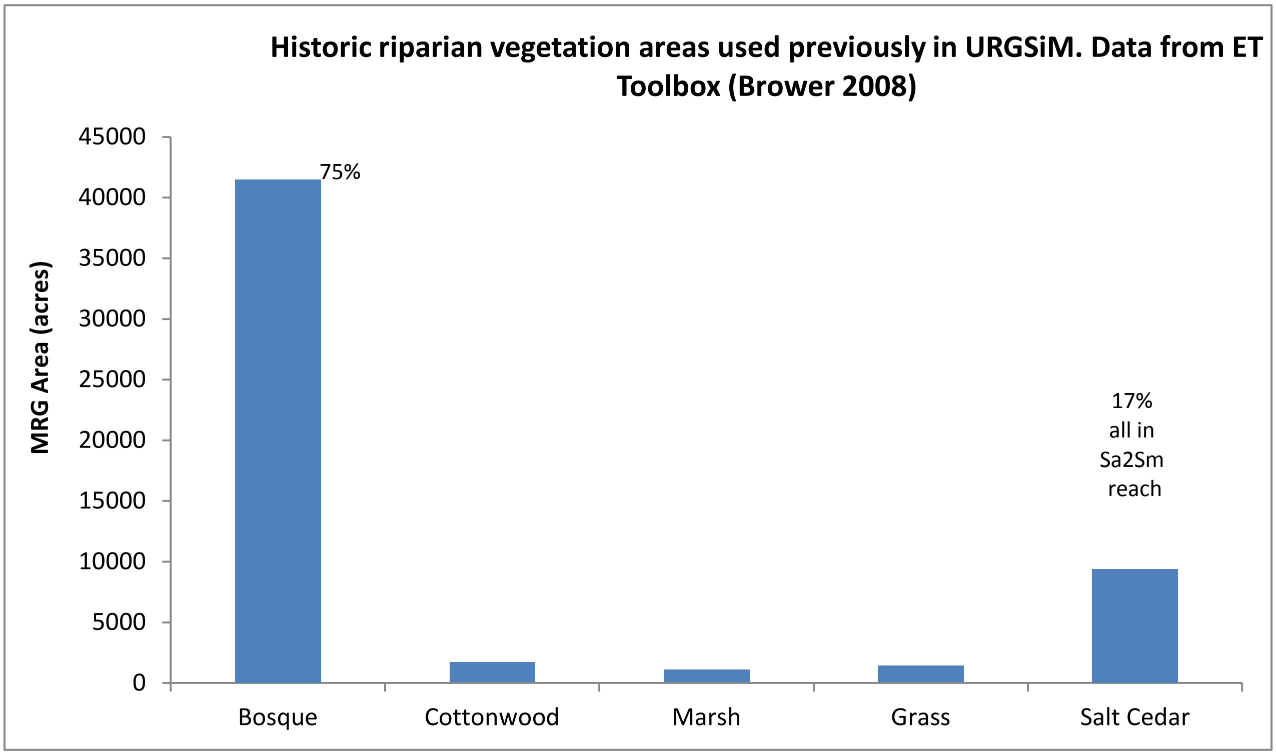

Figure 18: Riparian vegetation area by class in the Middle Rio Grande 1999. Area is dominated by Bosque (a mix of Cottonwood and Salt Cedar) with the exception of significant Salt Cedar area in the San Acacia to San Marcial (Sa2Sm) reach.

V. Effective precipitation

Effective precipitation is the portion of precipitation that can be used directly by a crop. It is calculated in URGSiM (and URGWOM) using a monthly average approach developed by the United States Department of Agriculture's Soil Conservation Service in their Technical Release no. 21 (United States Department of Agriculture 1970) often referred to as TR-21. According to the TR-21 method, monthly effective precipitation can be estimated as a function of total precipitation, depth of irrigation application, and crop consumptive use:

$$p_e = sf * (0.70917{p_t}^{0.82416} - 0.11556) * 10^{0.02426ET_p} \tag{7}$$

where $\boldsymbol{p_e}$ = effective precipitation in inches per month, $\boldsymbol{sf}$ is a soil storage factor determined by the depth of irrigation application as shown in Table 3 below, $\boldsymbol{p_t}$ is total monthly precipitation in inches per month, and $\boldsymbol{ET_p}$ is the crop potential ET ($ET_o * K_c$) also in inches per month. At each timestep, URGSiM calculates the net irrigation requirement as the crop potential ET less the effective precipitation.

Irrigation Application Depth [inches]	**Storage Factor *sf* [-]**
0.75	0.72
1	0.77
1.5	0.86
2	0.93
2.5	0.97
3	1
4	1.02
5	1.04
6	1.06
7	1.07

Table 3: Storage factor (*sf*) as a function of irrigation application depth used to estimate monthly effective precipitation with the TR-21 method (United States Department of Agriculture 1970).

VI. Implications of changed methods on historic mass balance

Evapotranspiration is calculated spatially and temporally in URGSiM, and ET is an important term in the hydrologic mass balance. Because it is part of a mass balance that was calibrated to get close to observed agreement at observation points (stream flow gages or reservoir stage gages), a 50% reduction (Figure 6) in ET_o does not necessarily result in a 50% reduction in modeled ET as other mass balance terms compensate to absorb changes to ET_o. As seen in Table 4, the new ET methods result in approximately 12% of total ET reduction between Cochiti and Elephant Butte in the recalibrated URGSiM model (665 cubic feet per second (cfs) to 586 cfs). The reach specific changes range from a 45% ET decrease for the for the Bernardo to San Acacia reach (29 cfs to 16 cfs), and a 34% ET decrease for the Jemez reach (42 cfs to 27 cfs) to a 3% increase between San Acacia and San Marcial (169 cfs to 175 cfs). The increase between San Acacia and San Marcial may be a result of the changes to riparian crop coefficient calculations correcting premature shutdown of riparian ET noted in southern reaches with the Growing Degree Day method (see Figure 7). In addition to changes in modeled ET,

Table 4 also shows changes to ungaged inflows because these are the main calibration term used in URGSiM for surface water reaches. Net changes to ungaged inflows offset much of the change to ET in the reaches from Cochiti to Bernardo. The remainder of the change is absorbed by other mass balance terms including surface water groundwater interactions and groundwater movement. Because the groundwater system ties certain reaches together, the net changes to ungaged inflows less ET are close to zero across all reaches associated with a given groundwater basin. Reaches between Cochiti and San Acacia overlie the Albuquerque groundwater basin and show a net decrease of less than 2 cfs across reaches for the ungaged inflows less ET term. The San Acacia to Elephant Butte reaches are associated with the Socorro groundwater basin, do not have any modeled ungaged inflows, and thus show no net change to ET across the two reaches.

The ET methods developed by Sammis et al. (1985) and used until 2011 in the ET Toolbox (Brower 2008), URGWOM (U.S. Army Corps of Engineers et al. 2002) and URGSiM have been shown to be unreliable as compared to current best available methods. The modified Penman Reference ET equation adopted by Sammis et al. overestimates ET_o when compared to other more widely accepted methods, and the associated growing degree day based crop coefficients appear to overestimate irrigated crop demand, and potentially underestimate riparian ET significantly in warm locations by shutting riparian vegetation down prematurely.

	Old ET methods			Current ET methods			Difference		
ET_o:	Modified Penman			1985 Hargreaves			Reduced ET_o		
Irrigated Crop K_c:	Growing Degree Day			FAO-56 Based			Reduced K_c		
Riparian K_c:	Growing Degree Day			From local data			Reduced K_c ?		
Effective Precipitation:	None considered			TR-21 (USDA 1970)			Less irrigation demand		
Irrigated Crop Types:	18			4			Reduced complexity		
Riparian Veg. Types:	5			1			Reduced complexity		
	Average Modeled Flux 1975-2000			Average Modeled Flux 1975-2000			Change		
	Ungaged inflows	ET	Net	Ungaged inflows	ET	Net	Ungaged inflows	ET	Net
Reach	[cfs]	[cfs]	[cfs]	[cfs]	[cfs]	[cfs]	[cfs]	[cfs]	[cfs]
Cochiti to San Felipe	16	39	-23	9	29	-20	-7	-10	3
Jemez Pueblo to Jemez Dam	45	42	4	36	27	9	-9	-14	5
San Felipe to Albuquerque	35	97	-62	10	75	-65	-25	-22	-3
Albuquerque to Bernardo	39	256	-217		237	-237	-39	-19	-20
Bernardo to San Acacia		29	-29		16	-16	0	-13	13
San Acacia to San Marcial		169	-169		175	-175	0	6	-6
San Marcial to Elephant Butte		33	-33		27	-27	0	-6	6
Total	135	665	-530	55	586	-531	-80	-79	-1

Table 4: Summary of changes to ET methods described in this document (rows above greyed out row), and resulting changes to total ET and ungaged inflows (model calibration term) for URGSiM reaches below Cochiti.

In terms of choosing a replacement method, the available historic weather data in the basin for solar radiation, relative humidity and wind speed are limited spatially and of suspect quality during the 1975-2000 URGSiM calibration period. This lack of quality solar, wind, and humidity data reduces the advantages of calculating ET_o with the widely accepted but more data intensive Penman-Monteith equations and has resulted in the decision to use the simpler temperature based Hargreaves 1985 method. Finally, irrigated crop types in the Rio Grande are dominated in the Rio Grande by alfalfa and pasture grass, and riparian vegetation types by the bosque classification, and thus irrigated crop and riparian vegetation classifications have been simplified to reduce unnecessary model complexity. In sum, these changes have resulted in a far simpler and more reliable method for estimating irrigated crop and riparian vegetation evapotranspiration demands as a function of climatic conditions.

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Appendix D

Projected Water Supply for Reclamation's San Juan-Chama Project

Santa Fe Basin, New Mexico

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Sandia
National
Laboratories

Contents

1 Imported Water: The San Juan-Chama Project

Reclamation's San Juan-Chama Project brings a portion of New Mexico's allocation under the Colorado River Compact (Compact) into the Rio Grande system. The system (Figure 1) diverts water from tributaries to the San Juan River, through the Azotea Tunnel and stores that water in Heron Reservoir, from where it is distributed. The San Juan-Chama Project supply depends on flows in three tributaries to the San Juan River: the Rio Blanco, the Little Navajo River, and the Navajo River. The project allocates 95,831 acre-feet of water per year (AFY) to its contractors (369 AFY of the 96,200 AFY firm yield is currently unallocated).

Analyses presented in this appendix are based on methods described in the Upper Rio Grande Impact Assessment (Llewellyn, et. al, 2013). These analyses use the Upper Rio Grande Simulation Model (URGSiM; Roach 2013), and the full suite of 112 150-year simulations developed from the General Circulation Model (GCM) runs included in the World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project Phase 3 (CMIP3) (Meehl et al. 2007). Input for the URGSiM simulations were developed from Reclamation's Bias-Corrected and Spatially Downscaled Surface Water Projections (Reclamation 2011), as processed through the Variable Infiltration Capacity (VIC) hydrologic model (see Appendix B and Llewellyn et. al. 2013). These projections did not use the Hybrid Delta ensemble projection sets that were used for the WaterMAPS modeling of the Santa Fe municipal water system described in this study.

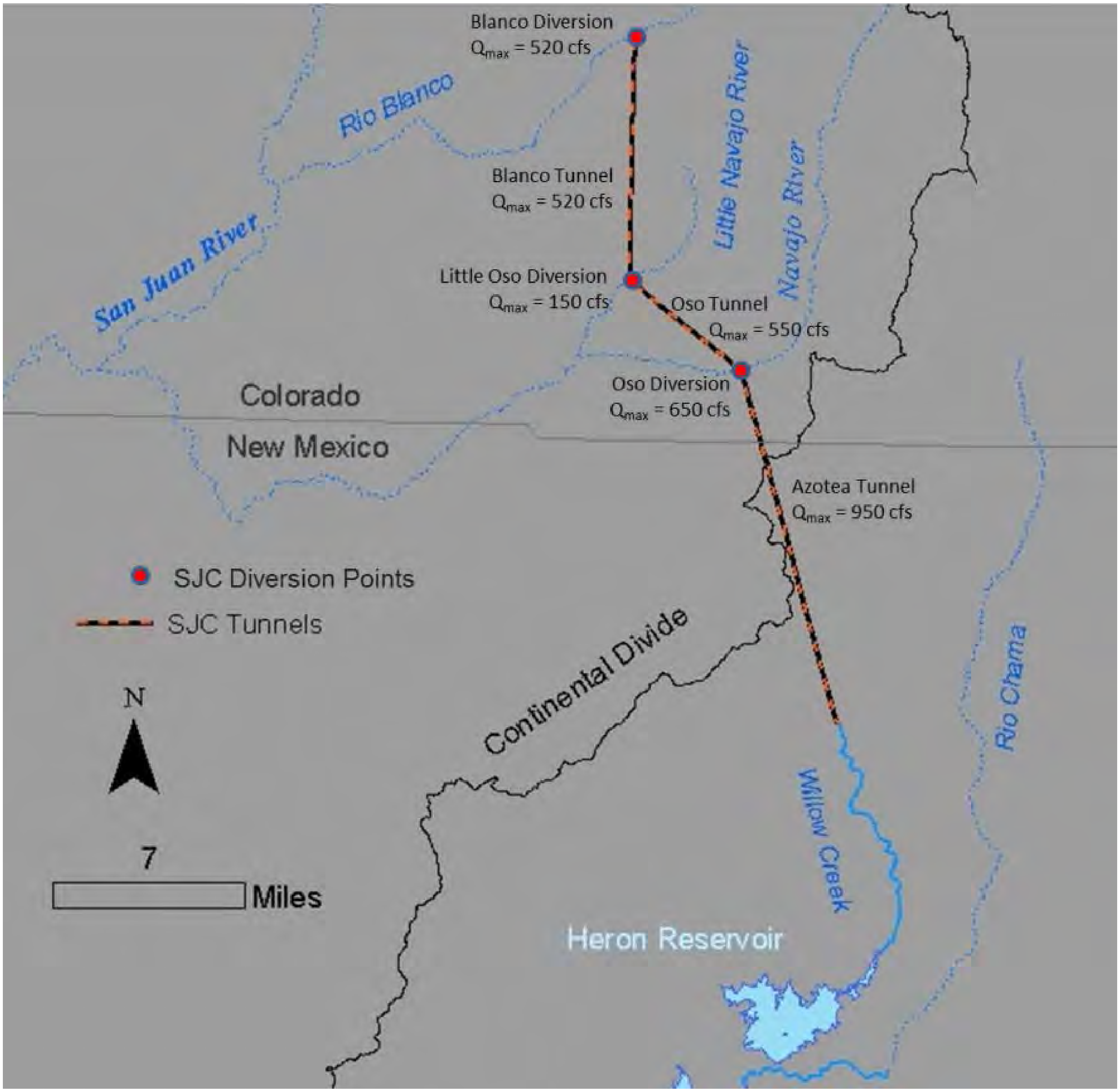

Figure 1.—Location and capacities in cubic feet per second (cfs) of San Juan-Chama Project diversions and tunnels.

2 Diversions

Figure 2 provides the URGSiM modeling results for the ensemble of projected flows through the three diversion locations: Oso Diversion on the Navajo River, Little Oso Diversion on the Little Navajo River, and Blanco Diversion on the Rio Blanco.

Projections show that:

- **Flows would decrease by one-quarter overall**. The sum of flows in the three tributaries to the San Juan River is projected to drop by only about one quarter between the historic simulation period (1950 through 1999) and the year 2100, which is less than the one-third reduction projected for native Upper Rio Grande flows. The five-year average of the median flow projection decreases from approximately 225 cfs between 1950 and 1999, to approximately 165 cfs in 2100 (Figure 2, Panel A).

- **Peak flows would shift to earlier in the year.** Total flows at the three diversion locations between February and April increase over the course of the century, as those between May and December decrease (Figure 2, Panel B). By the 2090s, almost 15 percent of simulated March and April flows are greater than any flow observed for those same months between 1950 and 1999 (Figure 2, Panel D).

3 Azotea Tunnel

Figure 3 provides the analysis results for the ensemble of simulations for projected flows through the Azotea Tunnel. Projections show that:

- **Flows would decrease by one-quarter overall**. The ensemble average trans-basin diversion decreases steadily from around 90,000 AFY during the historic simulation period (1950 through 1999) to between 70,000 and 80,000 AFY during the 2050 through 2099 period.

- **Flows would decrease in summer and increase in spring.** Overall, tunnel flows decrease with a larger portion of the flows occurring earlier in the year. The overall reduction in tunnel flows comes from large decreases in divertible flows from May through October even while divertible flows increase in March and April. The seasonality of the average tunnel flows is shown in Figure 3, Panel B.

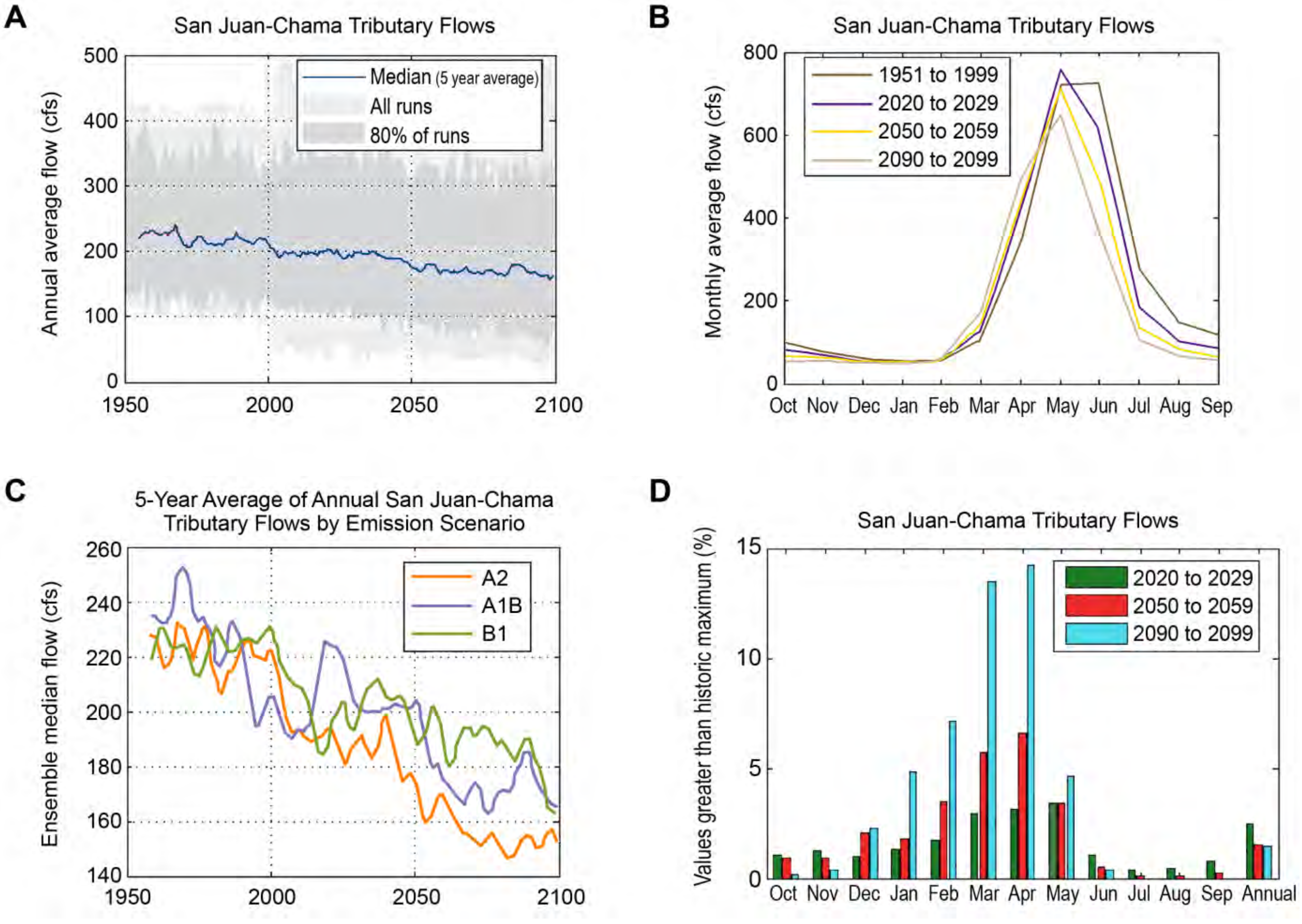

Figure 2.—Projections of total flows from the three San Juan-Chama Project diversion locations on the Rio Blanco, Little Navajo River, and Navajo River.

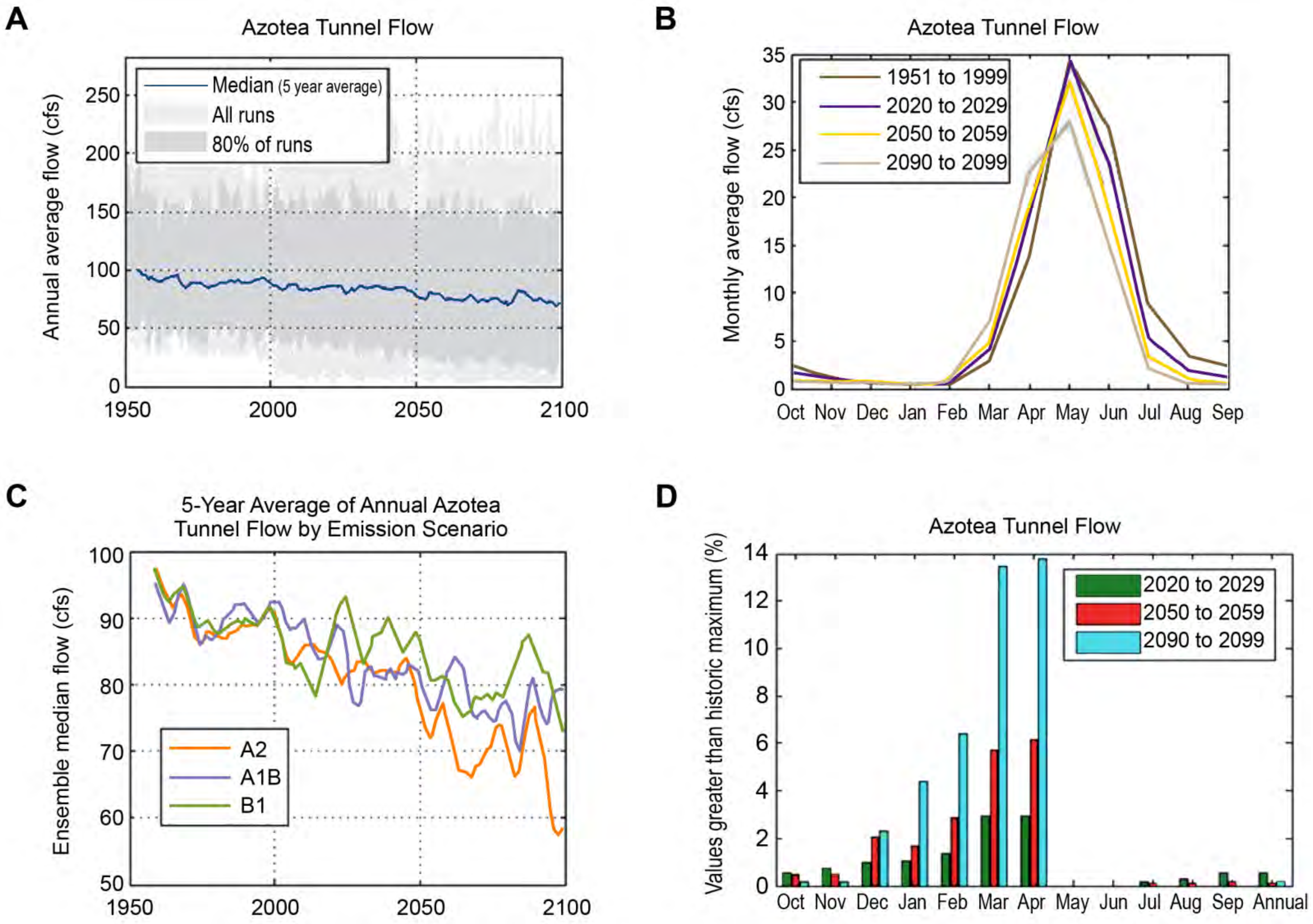

Figure 3.—Projected flows through the Azotea Tunnel of the San Juan-Chama Project.

The analyses on the availability of flows to the San Juan-Chama Project diversion tunnels were performed on a monthly basis. Therefore, these analyses do not capture potential changes to the volume or duration of snowmelt runoff at less than a monthly scale. Since snowmelt runoff is projected to occur earlier, and at potentially higher flow rates for a shorter period of time, the impacts on the San Juan-Chama Project's ability to divert could be larger than shown in this analysis. However, it is possible that the Federal government could decide to implement infrastructure changes to allow for a greater capture of short, high-discharge runoffs, so that these changes in runoff flows and timing do not significantly affect the San Juan-Chama Project's ability to divert sufficient water.

Also, it is important to note that, even if sufficient water is available in tributaries to the San Juan River for diversions to the San Juan-Chama Project, shortages within the Colorado River Basin could lead to priority calls or shortage-sharing agreements that would result in decreased supply to New Mexico under the Colorado River Compact. Such shortages could result in decreases in Reclamation's authorization to divert water to the San Juan-Chama Project, even if sufficient water is available locally.

4 Heron Reservoir

San Juan-Chama Project water is stored in the Heron Reservoir until it is moved downstream for storage or beneficial use. Heron Reservoir storage decreases significantly as the simulations progress, as shown in Figure 4, which displays Heron Reservoir storage on January 1st of each simulation year for the ensemble of simulations. As discussed in the next section, years when Heron Reservoir storage on January 1st is below 95,200 acre-feet result in a reduced initial allocation to San Juan-Chama Project contractors.

Projections show that:

- **Storage in Heron Reservoir would be reduced.** The reduction in storage seen in Figure 4 could be caused by a combination of the decreases in supply noted above and increases in use of San Juan-Chama allocations by contractors as temperature-driven demands in the Rio Grande basin (especially agricultural demands) rise as the simulations progress. However, as seen in Figure 5, San Juan-Chama Project releases from Heron are fairly constant through the first 100 years of simulation and don't show an increasing trend. This suggests that the reduction in storage in Heron Reservoir seen in Figure 4 is predominantly a result of decreased inflows and not as a result of increased outflows.

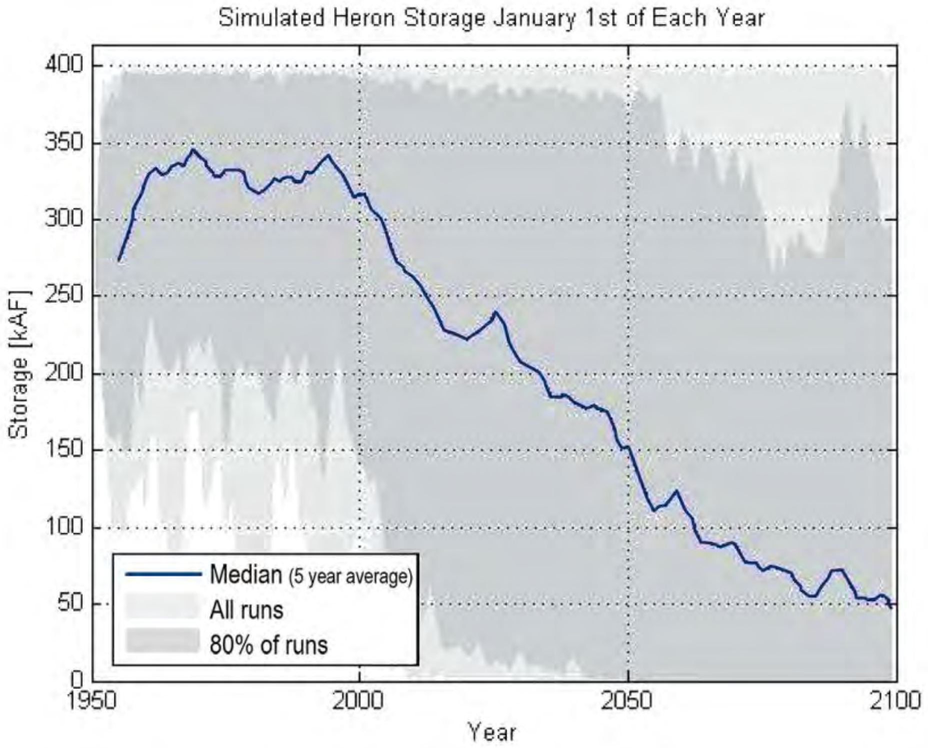

Figure 4.—Projected Heron storage on January 1st of each year.

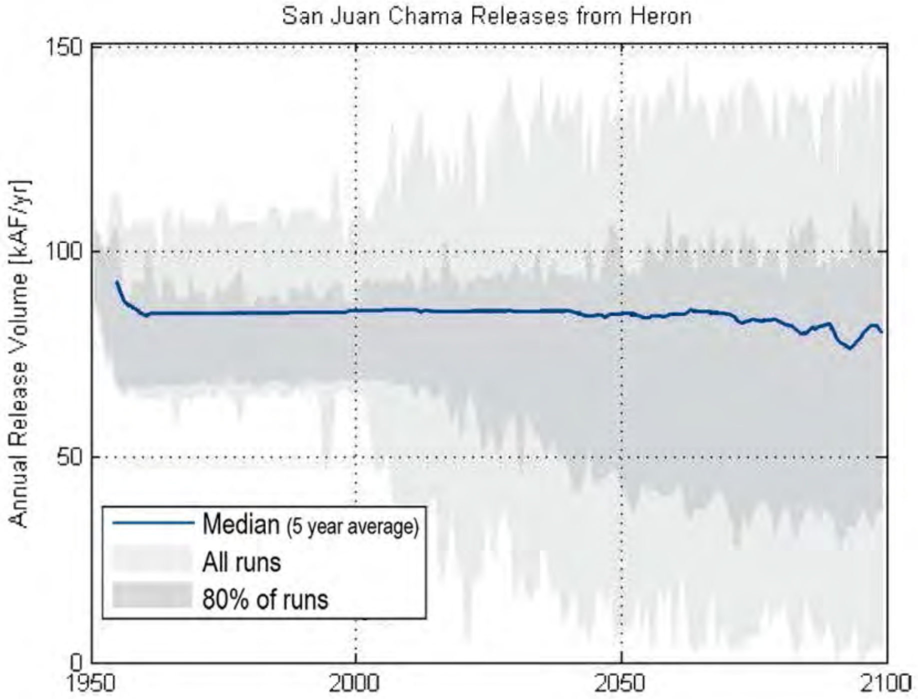

Figure 5.—Projected releases of San Juan-Chama Project water from Heron Reservoir.

5 Impact on Annual Allocations to Contractors

Heron Reservoir storage on January 1st (Figure 4) determines Reclamation's initial allocation of San Juan-Chama Project water to the contractors. If the initial allocation is less than 100 percent of the firm yield, a second allocation may be made on July 1st. This means that any water in storage on January 1st plus any water that can be moved through Azotea Tunnel between January 1st and July 1st can be allocated in a given year to San Juan-Chama contractors. As January 1st storage begins to drop in the simulations, the July allocation becomes more important to the total San Juan-Chama Project allocation.

Three time series showing the distributions of total, January, and July allocations are shown in the left side of Figure 6. As the flows through Azotea Tunnel become less reliable, the initial allocation also becomes less reliable, and the secondary allocation becomes more important. San Juan-Chama contractors receive a full allocation in 99 percent of simulated years from 1950 through 1999, 94 percent during the 2020s, 72 percent during the 2050s, and only 61 percent in the 2090s. At the same time, July allocations go from negligible during the 1950 through 1999 historic period to accounting for almost 40 percent of allocated water during the 2090s. Table 1 summarizes these trends quantitatively, and the right side of Figure 6 visualizes these trends as exceedance probability lines. This shows that the chances for a full allocation drop almost 30 percent and July allocations rise almost 40 percent.

Table 1.—San Juan-Chama allocations during different simulation periods

Period	Simulations with full San Juan-Chama allocation on January 1	Simulations with eventual full San Juan-Chama allocation (July 1)	Average total San Juan-Chama allocation	Average initial (January 1) allocation	Average secondary (July 1) allocation
1950 - 1999	98%	99%	99.95%	99.5%	0.45%
2020s	72%	85%	94%	81%	14%
2050s	51%	72%	88%	64%	24%
2090s	36%	61%	81%	49%	32%

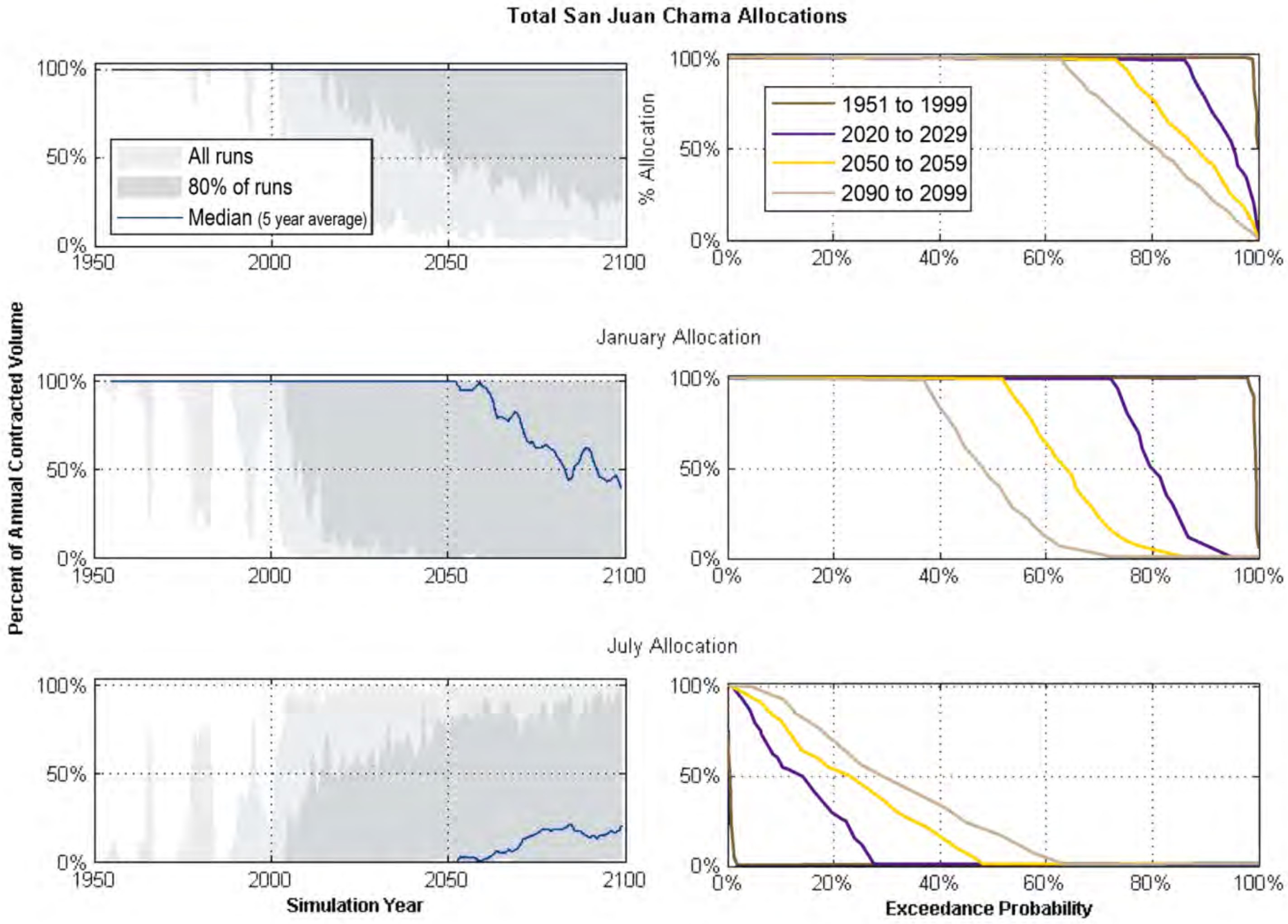

Figure 6.—Projected San Juan-Chama Project total annual allocations (top figures), January (initial) allocations (middle figures), and July (secondary) allocations (bottom figures).

6 Comparison to Previous Yield Estimates and Discussion

Reclamation has estimated the potential firm yield of the San Juan-Chama Project since the 1950s era design phase. By “firm yield,” these studies meant the yield at which there would rarely be a shortage. Reclamation studies since 1964 (Reclamation 1964, 1986, 1989 and 1999), each with a longer hydrologic analysis period than the last, set the firm yield of the project to 101,800; 94,200; 96,200; and 96,200 acre-feet, respectively.

More recently, Roach (2009) performed an analysis using 604 years of tree-ring records developed by Gangopadhyay and Harding (2008). This analysis tracked Heron Reservoir storage as it would have been if the San Juan-Chama Project had been in operation over that 604-year hydrologic sequence. Figure 23 shows the resulting distribution of January 1st storage values at Heron Reservoir. Once the influence of initial conditions wears off, the distribution of possible values is fairly constant. Once this state is reached (about simulation year 2040 in (Figure 7), there is approximately a 10 percent chance that Heron would start the year with less than 95,200 acre-feet in storage, and thus that the initial San Juan-Chama Project allocation would be less than the contracted amount less than 10 percent of the time.

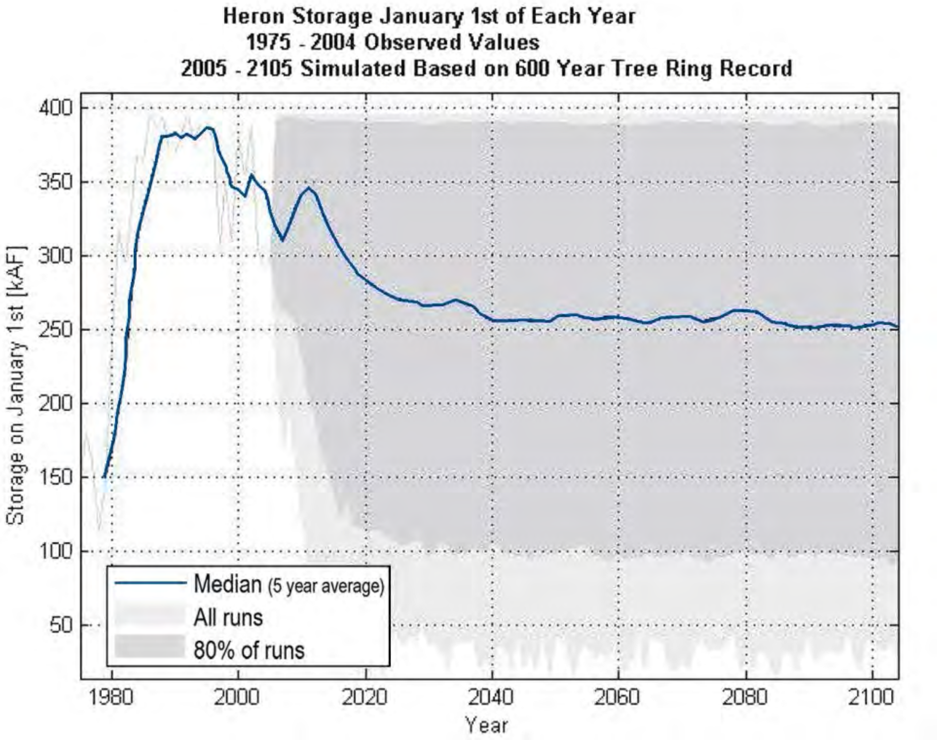

Figure 7.—Simulated Heron Storage on January 1st of a 150-year simulation representing the range of variability of a 600-year tree-ring record (simulated as if the San Juan-Chama Project was in operation for all of those 150 years).

In 2013, for the first time in the 42 years of operation of the San Juan-Chama Project, Heron Reservoir water supplies were insufficient on January 1st to support a complete initial allocation. Although Reclamation was able to provide a full supply July 1st, the supply is less certain for subsequent years. Whether this is just natural variability or a harbinger of things to come (as projected in the URGIA analysis) remains to be seen. This event may prompt an update of the firm yield calculations by Reclamation, and the added hydrologic record since 1999 (the last time the firm yield was evaluated) might itself result in a reduction in the firm yield calculation.

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Appendix E

Task 3: Update and Enhance WaterMAPS

Santa Fe Basin, New Mexico

Contents

This appendix provides the text of a technical memorandum from Kelly Collins, PG, BCES, CDM Smith, to Claudia Borchet, Santa Fe County, dated September 13, 2013. This memo summarizes Task 3: Update and Enhance WaterMAPS.

1 Introduction

To increase the sustainability of their water supplies, the City of Santa Fe (City) and Santa Fe County (County) water utilities have developed new surface-water sources. Like many surface waters in the arid Southwest, however, both existing (Santa Fe River) and new sources (Rio Grande and the tributaries to the San Juan River, the source of water for the San Juan-Chama Project) are vulnerable to climate-change-induced impacts. Through this Santa Fe Basin Study (Basin Study) the City, County, Bureau of Reclamation (Reclamation) and their consultants are working to better understand the future effects of and associated risks from climate change on surface water availability in three sub-basins: the Santa Fe River watershed, the upper Rio Grande watershed (upstream of Otowi stream gage), and the San Juan River watershed.

Tasks 1 and 2 of this Basin Study were related to preparing data for the Study and a Reclamation project conducting a firm-yield analysis of San Juan-Chama Project water supplies. These tasks were completed solely by the City, the County, and Reclamation. Task 3 of the Basin Study, and the topic of this memorandum, involves updating the City's Water Management and Planning Simulation (WaterMAPS) model to include the County as a partner entity and to enhance the model to include functionality to assess projected climate-change impacts. WaterMAPS is a tool that currently allows the City to manage their water supply portfolio from both water resources and water rights perspectives.

This technical memorandum describes the modifications and updates that were made to WaterMAPS under Task 3, as listed below:

- Incorporate climate-change projected stream flow hydrographs (Task 3a)
- Incorporate County supplies and demands and update other City data and management logic (Task 3c)
- Develop an algorithm to incorporate scaled demand projections according to climate change conditions (Task 3e)
- Incorporate adjustments to San Juan-Chama Project supplies (Task 3f)
- Develop and include climate-change-related evaporation rates for the Santa Fe municipal reservoirs and apply to WaterMAPS (Task 3g)

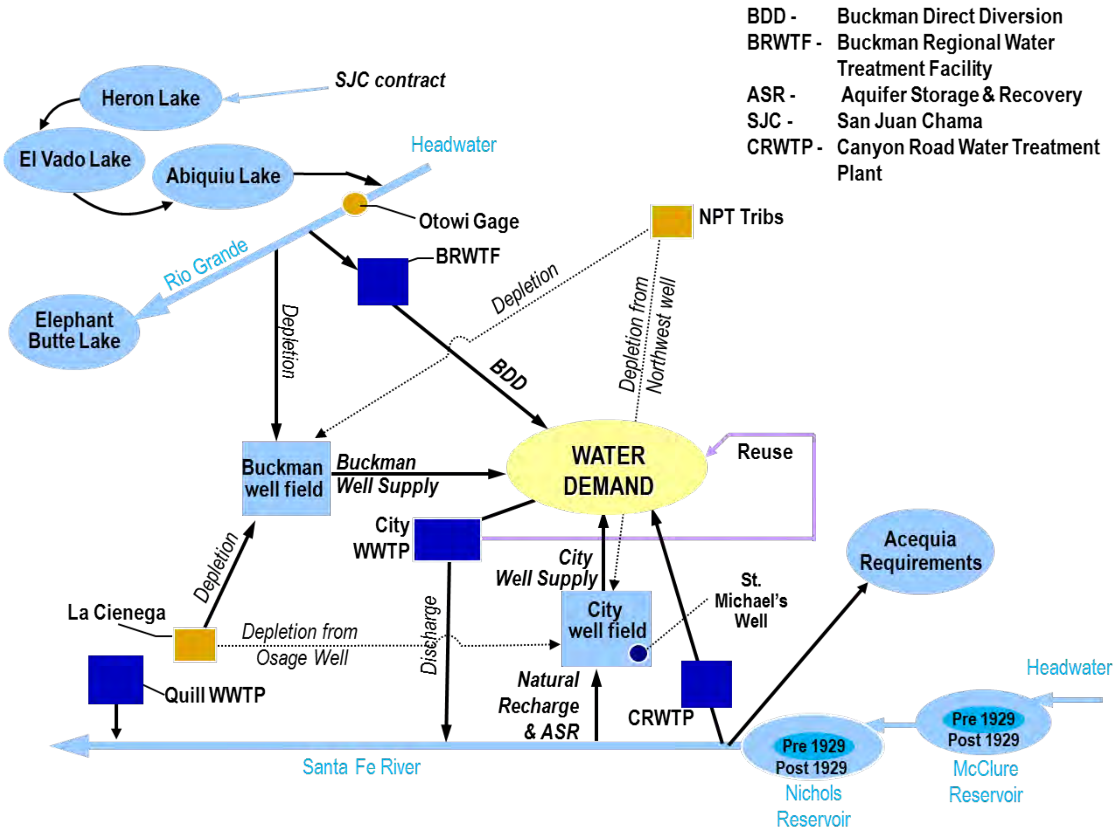
Note that the appendices referenced are the other technical appendices developed as part of the Santa Fe Basin Study Report.

2 WaterMAPS Background

WaterMAPS is a systems model built on the STELLA programming environment. STELLA (Systems Thinking Experimental Learning Laboratory with Animation), developed by Isee Systems, Inc. is a systems modeling industry standard. Figure 1 shows a schematic of the components of the water system that is modeled in WaterMAPS. The WaterMAPS model includes three different modes of simulation (the name in WaterMAPS is shown in parentheses):

- Short-term operational (Operational Simulation)
- Long-range, time-series planning (Forty Year Sequential Time Series Simulation)
- Long-range, probabilistic planning (Future Year Planning Simulation)

The Forty Year Sequential Time Series Simulation and the Future Year Planning Simulation are discussed further below.



BDD -	Buckman Direct Diversion
BRWTF -	Buckman Regional Water Treatment Facility
ASR -	Aquifer Storage & Recovery
SJC -	San Juan Chama
CRWTP -	Canyon Road Water Treatment Plant

Figure 1. WaterMAPS model schematic

The Basin Study uses the long-range, probabilistic planning simulation mode of the model, which is referred to as the Future Year Planning Simulation (Planning Year) mode, to estimate the impacts from climate change. This mode represents a single future planning year. A selected water supply portfolio is tested with the entire hydrologic period of record to determine the system performance for any type of hydrology condition recorded in a selected planning year. This type of simulation provides a probabilistic approach to planning decisions. For the Basin Study, climate change scenarios will be tested as part of Tasks 4 and 5 using the Planning Year mode for the planning year of 2055.

In order to use the Planning Year mode, the Forty Year Sequential Time Series Simulation (Forty Year) mode must be run because it sets up the conditions necessary for the Planning Year simulation. The Forty Year mode represents a forty year sequential time series, with increasing demands over time. The supply portfolio is tested with forty-year hydrology sequences that were selected from the historical hydrology data. The purpose of this type of simulation is to model the impacts of groundwater pumping on aquifer drawdown, reservoir storage, offsets, and stream depletions over time. This simulation also gives a starting point, with regards to groundwater pumping, for the Planning Year simulation.

An important element of the Santa Fe system is the groundwater-surface water interaction and the surface water depletions caused by pumping of some wells. To solve for the effects of pumping in groundwater and surface water, the Forty Year mode uses an additional model, the Stream Unit Response Function Solver (SURFS) SURFS, developed in Excel, works in tandem with STELLA. SURFS is also a stand-alone tool that can be used to solve simple groundwater pumping scenarios for depletions and drawdown.

Note that the details of WaterMAPS are only discussed here as they relate to the updates that were made for the Basin Study. Additional details of the model are available in the WaterMAPS Model manual developed in 2005.

3 Climate Change Modeling Background

WaterMAPS was updated to include climate-change impacts to assist with updating the City and County long-term water supply plans, which will now address the water supply needs of the City/County region. The process of developing the inputs that represent the changes in climate was described in detail in Appendix B and is summarized here. The hydrologic data used in this project was developed from an analysis of 16 Global Climate Models (GCM) run under 3 greenhouse gas emissions scenarios and a variety of starting conditions resulting in 112 GCM runs. The Hybrid-Delta Ensemble (HDe) method (Brekke, Pruitt, and Smith 2010) was used to combine the 112 GCM runs in a way that captures the range of temperature and precipitation trends. The HDe method resulted in four climate change simulation groups that can be described as follows:

- Hot-Wet: above the 50th percentile for precipitation and temperature changes

- Warm-Wet: above the 50th percentile for precipitation change and below the 50th percentile for temperature change

- Hot-Dry: below the 50th percentile for precipitation change and above the 50th percentile for temperature change

- Warm-Dry: below the 50th percentile for precipitation and temperature changes

An overlapping group was defined as being between the 25th and 75th percentile for both the change in precipitation and change in temperature and is referred to here as Central Tendency. Figure 2 provides a visual representation of these groups.

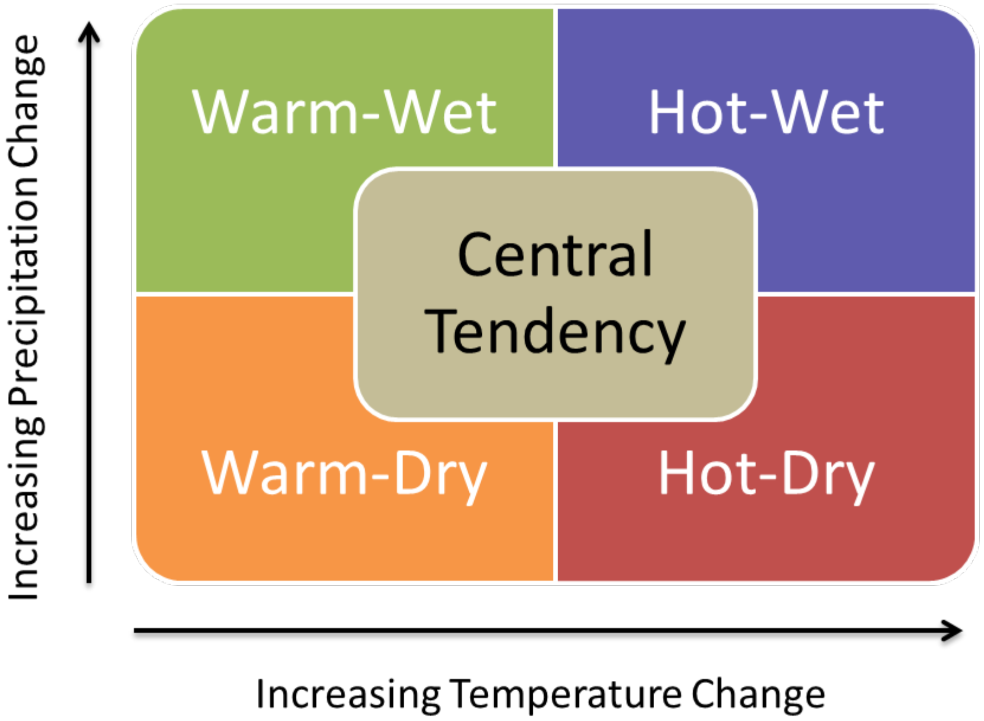


Figure 2. Hydrid-Delta ensemble (HDe) scenarios

For the Basin Study, three of the HDe simulation groups were selected for simulating climate change impacts in WaterMAPS:

- Warm-Wet
- Hot-Dry
- Central Tendency

These three were chosen because they have a greater number of observations from the GCM simulations and they represent the extremes of predicted temperature and precipitation changes.

The HDe climate scenarios were then used as inputs in a land surface model known as the Variable Infiltration Capacity (VIC) model. The VIC model generates the runoff hydrographs that can then be routed through a river network. As discussed in Appendix B, it was necessary to correct biases in the VIC model for use in the Upper Rio Grande basin modeling.

Hydrologic inflows at 21 locations were generated by the bias-corrected VIC model output for use in the Upper Rio Grande Simulation Model (URGSiM). URGSiM is "a monthly timestep mass balance model that uses hydrologic and climatic inputs to simulate the movement of surface water and ground water through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico, including the Rio Chama and Jemez River tributary systems, and the Española, Albuquerque, and Socorro regional groundwater basins" (Roach 2013). URGSIM also simulates reservoir operations, interbasin transfers, and agricultural diversions and depletions.

Dr. Jesse Roach, formerly of Sandia National Laboratories, was contracted by the Bureau of Reclamation to use URGSiM with the selected HDe scenarios and VIC model results to generate the surface water flow inputs necessary for WaterMAPS to evaluate the potential impacts of climate change on the Santa Fe Basin. This work was described in more detail in Appendix B.

4 Task 3 of the Basin Study

Task 3 of the Basin Study incorporates the three selected HDe simulation groups plus a baseline simulation that represents the temperature and precipitation conditions with no climate change. The baseline simulation is described as a simulation of the historic climate. It uses current infrastructure and operations with synthetic historic climate and inflows. Actual historic climate data could not be used because the rainfall runoff models require spatially distributed data that are not available directly but can be produced synthetically. This baseline simulation is referred to as the "simulated historic" scenario.

The result is four scenarios that are simulated in WaterMAPS to assess climate-change-induced impacts. For simplicity in explanation throughout this memorandum, these four scenarios will be referred to as the "climate-change scenarios," although one of the scenarios is the baseline used for comparison.

4.1 Task 3a: Climate-Change Projected Stream Flow Hydrographs

The climate-change-projected stream flow hydrographs used in WaterMAPS were generated by the URGSiM model. The output related to this sub-task includes:

- Stream flow into the Santa Fe Basin above McClure Reservoir (Santa Fe River Flow)
- Stream flow in the Rio Grande at Otowi Bridge
- Parameters related to Abiquiu reservoir

Each of the above items is provided as a time series representing the variability in climate. Four time series are provided for each parameter.

The stream flow into the Santa Fe Basin is used to simulate the amount of water in the McClure and Nichols Reservoirs. The climate-change scenarios result in different stream hydrographs that impact the water supply available in these reservoirs. The impact of climate change on the evaporation rates for these reservoirs is discussed in Section 4.5.

The stream flow in the Rio Grande at the Otowi gage limits the amount that can be diverted via the Buckman Direct Diversion (BDD). Logic in WaterMAPS was updated according to an environmental impact assessment (United States Department of the Interior 2007). The report outlines the conditions under which diversions should be curtailed.

Abiquiu Reservoir was the only San Juan-Chama Project reservoir for which climate-change scenario data were provided. Evaporative losses out of Abiquiu Reservoir are applied to any San Juan-Chama Project water stored there. Evaporative losses as simulated by URGSiM are based on the entire reservoir volume. Because WaterMAPS only simulates the storage of San Juan-Chama Project water for the City and County in Abiquiu Reservoir, the simulated evaporative losses could not be applied directly. Instead, the evaporative losses were converted to a percent loss that could then be applied specifically to the San Juan-Chama Project water for the City and County. Remaining mass balance data (stream flows, evaporation, withdrawals, etc.) were not provided for the reservoirs that transfer and store the San Juan-Chama Project water, as this system of reservoirs is not specifically modeled in WaterMAPS or used for water resource management. This is discussed in detail in Section 4.4.2.

Because WaterMAPS uses a percent loss to simulate evaporative losses out of Abiquiu Reservoir, percent losses were developed for each of the climate change scenarios as part of the Basin Study. The annual average percent loss due to evaporation out of Abiquiu Reservoir for each of the climate change scenarios is shown in Figure 3. As expected, the Hot-Dry scenario results in the greatest percent loss to evaporation.

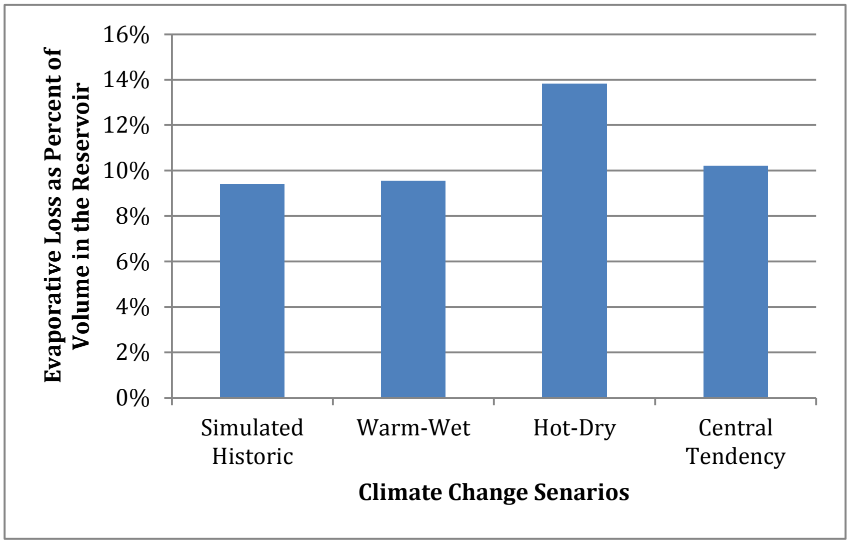


Figure 3. Evaporative loss as a percentage of San Juan-Chama Project simulated water in Abiquiu Reservoir

4.2 Task 3c: Update Model Data and Logic

This Basin Study encompassed several WaterMAPS updates, which applied to different model aspects. Most of these updates apply to the three simulation modes, but some may only apply to simulations with the climate change scenarios. The water supply priorities, water supply constraints, water demand, and reclaimed water demand and use apply to all simulation modes of WaterMAPS. However, changes made regarding water accounting and the Santa Fe River Target Flows only apply to the Planning Year simulation mode when simulating climate change scenarios at this time. Each update is described in the following sections.

4.2.1 Water Supplies and Priorities

The primary water supplies available are outlined below in order of priority:

- San Juan-Chama Project water and Rio Grande native water diverted via the Buckman Direct Diversion
- Local surface water from the Santa Fe River watershed
- Groundwater from the City Well Field along the Santa Fe River
- Groundwater from the Buckman Well Field near the Rio Grande

San Juan-Chama Project water and Rio Grande native water: The Buckman Direct Diversion is used to divert water from the Rio Grande. This includes both San Juan-Chama Project water and native Rio Grande water that can be diverted via the Buckman Direct Diversion. San Juan-Chama Project water is described in more detail under Section 4.4.

Local surface water from the Santa Fe River watershed: This is water released from the McClure and Nichols Reservoirs and treated at the Canyon Road Water Treatment Plant (CRWTP).

City Well Field along the Santa Fe River: This supply includes the Osage well, Northwest well, St. Michael's well, and "Other City wells." The Osage, Northwest, and St. Michael's wells are modeled as individual sources of supply. The "Other City wells" are grouped together as a single supply source and include Agua Fria, Torreon, Alto, Ferguson, Santa Fe, and Hickox wells.

Buckman Well Field near the Rio Grande: This supply includes 13 wells near the Rio Grande. Use of the Buckman Well Field results in depletions from the Rio Grande, Rio Pojaque, Rio Tesuque, and La Cienega (calculated in WaterMAPS). These river depletions are re-paid with Rio Grande surface water rights for depletion offsets and dedicated portions of the San Juan-Chama Project water, if necessary. Such depletions also apply to the Northwest and Osage Well fields, but the depletions are minimal in comparison.

Water rights, management targets, and capacity constraints (discussed in Section 4.2.2) require that the primary supplies discussed above be modeled in further detail. The detailed supply sources in the model are prioritized as follows:

- Minimum Buckman Pumping (for operational purposes)
- Buckman Direct Diversion (BDD)
- Canyon Road Water Treatment Plant (CRWTP)
- Osage Well Supply
- St. Michael's Well Supply
- Northwest Well Supply
- Other City Wells Supply
- Additional Supply from Buckman Wells

Water conservation and use of reclaimed water to offset potable demands will be included as part of Task 5 for this Basin Study, which analyzes ways to fill the water supply gap. These sources, when included, are considered as first-priority supplies (i.e., before minimum Buckman pumping in the list above). Note that reclaimed water is simulated in the model and meets specific reclaimed water contracts for non-potable use. This is discussed more under Section 4.2.4 - Reclaimed Water Demand and Use.

The minimum pumping of the Buckman wells is required as a first priority due to water rights constraints and is portrayed that way in WaterMAPS. During the beginning months of the year, the Buckman Direct Diversion, CRWTP, and City wells have the capacity to meet projected demands without much supplemental supply from the Buckman wells. However, water rights constraints limit the availability of the CRWTP and City wells, potentially leaving only the Buckman Direct Diversion and Buckman wells to meet demands at the end of the year, which results in shortages due to capacity constraints rather than actual supply constraints. In order to prevent overuse of the CRWTP and City well field at the beginning of the year, a minimum Buckman pumping is provided as a supplemental source of supply throughout the year, thereby reducing shortages caused by source prioritization assumptions and water rights constraints.

4.2.2 Water Supply Constraints

The water supply sources are subject to various regulatory, management targets, and capacity constraints. Some of these constraints were updated as part of this Basin Study. Additionally, water rights values were added for the County and Las Campanas Co-Op. The system capacity constraint is an automatic physical constraint, but the water rights and management targets are management objectives. WaterMAPS allows the user to select one of the following constraint scenarios when simulating future planning years:

- Water Rights (i.e., supply) and Capacity Constraint
- Management Target and Capacity Constraint
- Capacity Constraint Only

The Management Target and Capacity constraint will primarily be used for the Basin Study. The other constraints may be explored as needed. These constraints for each supply are shown in Table 1.

Expansion of WaterMAPS to include the County involves inclusion of the County's water supply sources. Although the City does not have native Rio Grande water rights, the County does, so these were added to WaterMAPS. This supply required some changes to the model logic because the City only has San Juan-Chama Project water; therefore, Buckman Direct Diversion water and San Juan-Chama Project water were previously modeled as one. With the addition of the County supply, there is supply from the Buckman Direct Diversion that is not

San Juan-Chama Project water. This is significant to note because this source of supply has different constraints on its diversion than does the San Juan-Chama Project water. As modeled for this study, this supply will be used by both the City and County.

It is important to note that the City and County demands and supplies in WaterMAPS are not accounted for separately. The City and County supplies and demands are added to WaterMAPS as separate inputs, but the logic and routing of WaterMAPS adds these values together, after which they cannot be separated. This study will capitalize on all water rights owned by the City and County, which means that supply deficits cannot be separated as a City or County deficit without additional post processing.

4.2.3 Water Demand

Water demand was updated in WaterMAPS as part of this project to determine the impact of climate change, but it was also updated in general for use in other simulation scenarios available in WaterMAPS. The demand components that were updated include: population projections, annual unit demands, and seasonal variability factors. Additionally, County demands were added. Note that all of the water demand calculations that are presented in this section are based on City data. Assumptions regarding County water demands were made as described below because water demand data were not provided by the County.

Population Projections

The City population projections are based on the City of Santa Fe (2008) Long Range Water Supply Plan, Appendix D. For this study, the population projection was shifted by six years because 2006 projected water demand in the Water Supply Plan matched the demand estimated for 2012. The population projections used in WaterMAPS are from 2015 to 2055.

The County water service area population was estimated based on Water Transmission and Storage System Master Plan (Brown and Caldwell 2009) developed for the City of Santa Fe. The master plan includes water demand projections for the County because the City must have capacity to deliver maximum day demands to the County as part of a water service agreement. Maximum day demand was converted to population by first converting the maximum day demand to an average day demand. The average day to maximum day peaking factor is two (Brown and Caldwell 2009). The average day demand was then divided by the current gallons per capita per day (gpcd) calculated for the City.

Table 1. Water Supply Constraints Included in WaterMAPS for the City and County (Including Las Campanas)

Source	Water Rights (AFY)			Management Target (AFY)			Capacity Constraint		
	SF County	City of SF	Las Campanas Co op	SF County	City of SF	Las Campanas Co op	SF County (mgd)	City of SF (mgd)	Capacity[12] (AFY)
SF River (CRWTP + St. Mike's Well)	0[3]	5040[6]		0	TBD[8]		0	8	8,961
St. Mike's Well alone					241			0.62	694
Relinquishment Pool Water		7000			0				
City Well Field (without NW Well)		4215[7]			3000			2.89[9]	
Northwest Well		650			500			1.4	1,568
Osage Well		96			96			0.36	403
County Wells	153[4]			153			0		
Buckman Well Field		10000			3000		0	8.9[10]	9,969
Buckman Well Offset[2]		1200	100		1200	100			
BDD (Native Rio Grande)	1325[5]			1325			15[11]		16,802
BDD (SJCP)	375	5230		375	5230				
BDD (Native Partner Exp.)[1]	590	590		590	590				

Notes:

1. Does not exist today, but is assumed to be in place for the future planning simulation year of 2055.
2. Supply can only be used to satisfy surface water depletions from groundwater pumping.
3. Santa Fe basin, in-basin surface water rights is 23 AFY. Assumed to be out of Santa Fe River. Amount is small and not included in model.
4. Santa Fe basin, in-basin groundwater rights is 153 AFY. Wells do not currently exist for this right; therefore, this supply is added to the City Wells in WaterMAPS
5. Imported Middle Rio Grande water (2% carriage loss to be subtracted from this number)
6. CRWTP and St. Mike's operate together untill cumulative production reaches 3500 AFY. Then St. Mike's shuts down and CRWTP has an additional 1540 AFY.
7. If NW well is used, the total water rights for City Wells and Northwest Well are 3257 AFY. May change after NW well hearing. Other City Wells, Osage, NW and St. Mikes are modeled as separate sources.
8. TBD based on Santa Fe River target flows
9. Capacities in previous model are from a 2001 report (about 3 mgd). Latest report from B&C (2009) has updated capacities that can be broken down by well as needed (pg 2-2 to 2-4). Total max hydraulic capacity is 3.87 mgd excluding NW well. Excluding St. Mike's and Osage reduces it to 2.89 mgd.
10. Accounts for improvements made as part of the BDD project
11. Capacity of potable system is 15 mgd. Max capacity is 28.2 cfs (18.2 mgd) but this includes Las Campanas at 5 cfs (3.2 mgd).
12. This is only capacity converted from mgd to AFY to be able to compare to the water rights. It does not represent any permit limits.

The County maximum day water demand projections extend only to 2030. From 2030 to 2055, it was assumed that the demand would increase at a similar rate as from 2010 to 2030. The resulting growth rate for the County water service area is fairly constant from 2015 to 2055.

The resulting County water service area population projection was compared to the total County population projection from the Santa Fe County Sustainable Growth Management Plan (Sustainable Growth Plan) adopted in 2010 (Santa Fe County 2010). This projection includes the City of Santa Fe. While the actual population growth rate for the entire County will decrease over time, it is reasonable to assume that the County water service area will increase at a constant rate. This accounts for existing population and new population connecting to the County water system in the future.

The City water service, County water service, total water service (City plus County), and total County population projections are shown in Figure 4. The 2020, 2030, 2040, and 2050 population values are shown in Figure 4. The difference between the total County population and the total water service population represents the population that is not served water by either the County or City water systems. The ultimate 2055 populations used for the climate change analysis and for development of the water supply plan are 125,019 for the City water service area and 44,673 for the County water service area.

Unit Water Demand and Seasonal Demand Factors

The current annual unit water demand in terms of gallons per capita per day was determined from monthly water production data provided by the City and the City population data from 2002 to 2010. The unit per capita potable water demand calculated for each year is shown in Figure 5. The data from 2004 was assumed to be not representative; therefore, was excluded from the calculated average of 114 gpcd.

To be consistent in our analysis, the data used in Task 3e and the data used to develop the annual unit water demands had to be the same; therefore, the base demand calculated here may not exactly correspond to the 2012 Santa Fe Annual Water Report (2012 Water Report). The 2012 Water Report discusses unit demand calculated using a specific methodology. These values could not be exactly reproduced with the water production data provided and used as part of the demand variability task discussed under Section 4.3 in this memorandum.

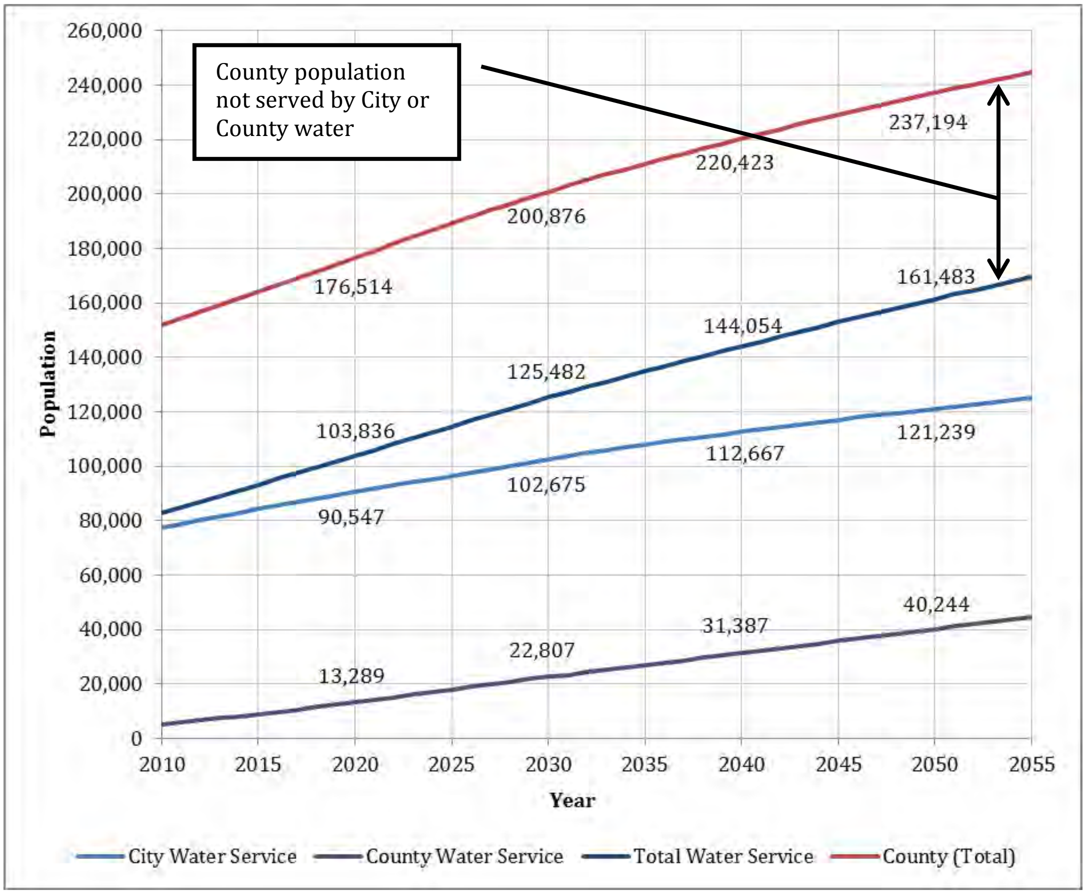


Figure 4. Population projections (labeled values are for 2020, 2030, 2040, and 2050)

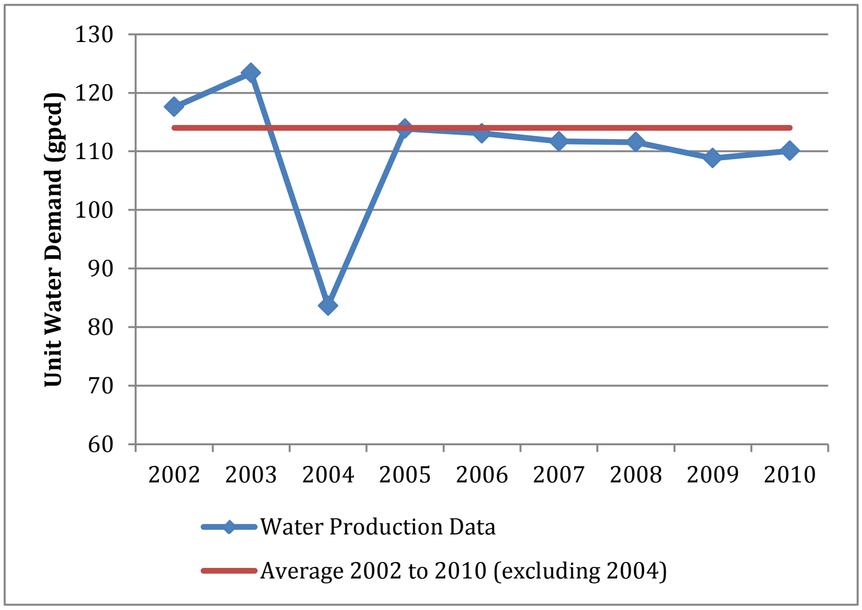


Figure 5. Unit demand data for the City of Santa Fe

Two demand scenarios were programmed in WaterMAPS as part of the Basin Study. Each is described below:

- **Status Quo (SQ)**: The unit demand is assumed to stay the same as it is today, which was calculated as 114 gpcd. As population increases, total water demand will increase, but the unit demand will remain at 114 gpcd. This scenario represents the baseline demands that will be used to identify the potential water supply gap.

- **Use Less (UL)**: The unit demand will decrease such that as population increases, the total water demand will stay the same. This was calculated to be 73 gpcd. This scenario will be included as an option to incorporate more aggressive water conservation measures.

The seasonal demand factors were updated in WaterMAPS. The seasonal demand factors are multiplied by the unit demands described above to get the unit water demand for a particular month. The demand factors previously modeled were based on water production data from 1981 to 2002. The updated demand factors are based on data from 2002 to 2010. Each demand factor curve is shown in Figure 6. The difference in the curves is most notable in April (decrease) and August (increase), which indicates a shift in the time when water is needed.

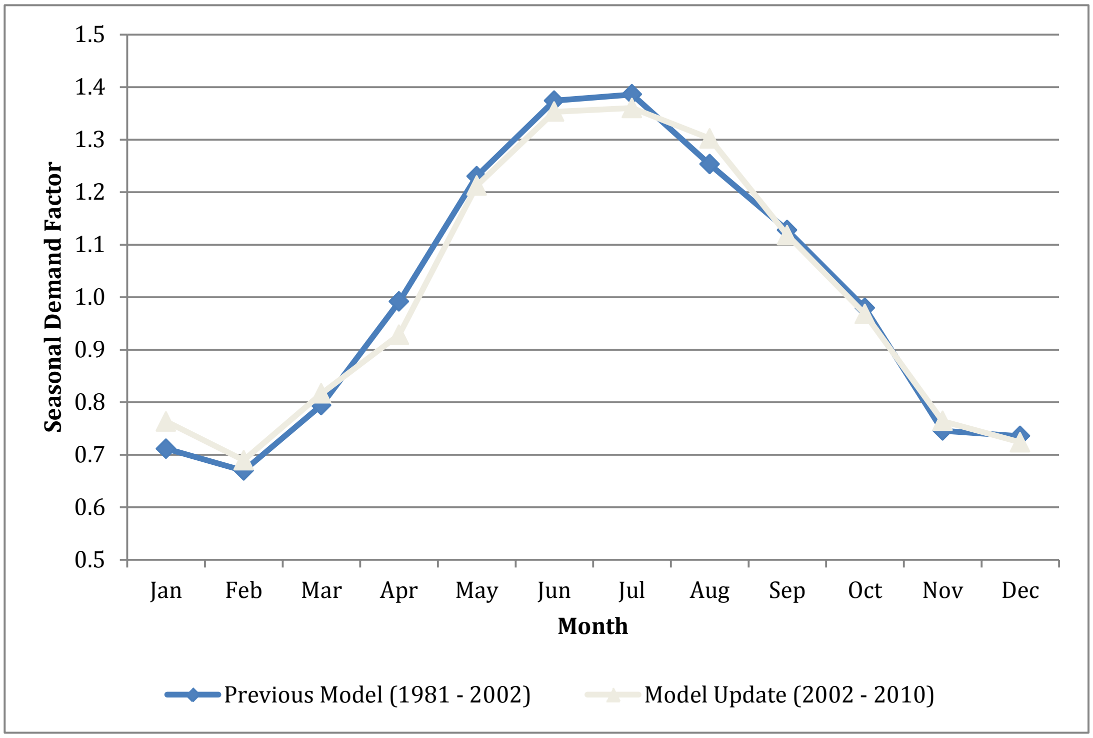


Figure 6. Comparison of seasonal demand factor curve from the previous model to the updated model

Note that the seasonal demand factor is not used as part of the climate change impacts for this Basin Study. Demand for those scenarios is specifically varied based on the predicted temperature and precipitation as discussed in Section 4.3. The seasonal demand factor information was updated and provided for informational purposes only.

Other Water Demands

Other water customers previously included in WaterMAPS include the Acequia Madre and Cerro Gordo irrigation systems, and the Las Campanas community. The Acequia Madre and Cerro Gordo water demand is assumed to be the same as the court order right of 70 and 25.4 acre-feet per year (AFY), respectively. This is similar to previous programming in WaterMAPS. One change that was made was to apply a seasonal demand factor similar to reclaimed water seasonal use, because the use is mostly for irrigation. The same demand factor curve was applied as shown in the next section. In the future, this demand may be met by reclaimed water, but currently it is assumed as a potable water demand. Las Campanas is a wholesale customer of the County, and so the demand is assumed to be included as part of the calculated County water demand.

4.2.4 Reclaimed Water Demand and Use

Demand on reclaimed water was updated per the City of Santa Fe Reclaimed Wastewater Resource Plan (City of Santa Fe 2013) (RWRP). The RWRP outlines specific allocations for reclaimed water use. Table 2 lists the different allocations, their annual amounts, and the anticipated maximum monthly demand. The option “Upstream Santa Fe River” (i.e., “living” river option) was removed from the total demand programmed in WaterMAPS as instructed by the City, because they are re-considering this use. Note that this option is not the same as the Santa Fe River target flows, which are currently met by releases from the reservoir. This option specifically pumps reclaimed water upstream to run through the City. The option “Future Potable Supply” was also removed because this will be calculated separately according to the dynamics of the model to be included as a potential supply option to be analyzed as part of Task 5. Finally “Santa Fe Equestrian Center” was removed because potable supply is ranked as a higher priority; therefore, the demand SF Equestrian will be met when supply is available, but it is not necessary to include in this analysis. The total annual reclaimed water demand modeled in WaterMAPS, excluding the above three options, is 3,489 AFY.

Table 2. Reclaimed Water Allocations from RWRP

Option ID (from Reclaimed Wastewater Resource Plan)	**Option Name**	**Annual Use (Acre Feet per Year)**	**Maximum Monthly Use (Acre Feet per Month)**
14	USFS Livestock Water	6.14	1.24
11	NM Game & Fish	6.14	0.62
12	Landfill	18.41	4.04
3	Southwest Activity Node (SWAN) Park	58.31	11.20
10	On-demand Sales	95.14	13.69
13	Buckman Well Field Permit Compliance	101.27	8.56
2	Downs of Santa Fe	135.03	24.27
4	SW Irrigated Parks	147.31	30.49
1	Municipal Recreation Complex (MRC)	165.72	33.92
8	Santa Fe County Club Golf Course	398.96	78.10
7	Marty Sanchez Golf Course	515.57	83.70
5	Downstream SF River	1841.33	289.37
	TOTAL OF ABOVE	**3489.33**	
6	Upstream Santa Fe River	543.19	45.74
9	Santa Fe Equestrian Center	125.82	38.58
15	Future Potable Supply[1]	2200.40	NA

[1] To be included in later analysis as a potential supply

As discussed in the RWRP, it is expected that most of the allocated reclaimed water will be used in the next 5 to 7 years. By the 2020s, the City expects to use reclaimed water as a potable supply. Infrastructure is needed to make use of these supplies, but the amount of reclaimed water currently produced is not expected to increase. Given that current supply of reclaimed water is already enough to meet the total demand expected (i.e. the sum of the allocations listed in Table 2), it was assumed that the current demand for reclaimed water modeled in WaterMAPS would be the full amount for any future year simulated from now until 2055.

The demand for reclaimed water varies monthly. Historical monthly use of reclaimed water was used to update the seasonal demand factors used in WaterMAPS. Data from 2007 to 2012 was used to develop the average demand factor curve shown in Figure 7.

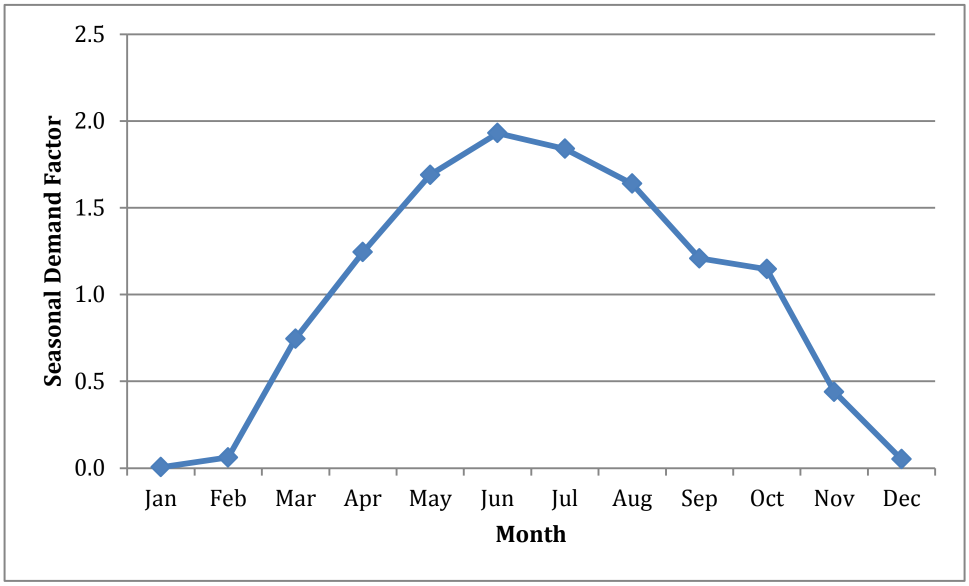


Figure 7. Reclaimed water monthly demand factors

For this Basin Study, it was not necessary to vary the demand for reclaimed water based on the climate change scenarios. The sum of the allocated amounts is what is expected to be used.

The RWRP discusses the anticipated supply of reclaimed water that will be available. WaterMAPS calculates this dynamically, and the supply will adjust according to the demand scenario simulated. The supply available is based on indoor water use, which does not change significantly in any given month nor is it expected to change significantly with climate change. Therefore, the supply is based on the demand scenario multiplied by a return factor. The return factor is the expected return of water to the wastewater treatment plant given the amount of water produced. The return factor reported in the RWRP and used in WaterMAPS is 62 percent (i.e., 62 percent of water produced returns to the wastewater treatment plant and 38 percent is consumed).

Water discharged from the wastewater treatment plant that is not used by one of the reclaimed water contracts shown in Table 2 is considered as additional supply that may be used as follows:

- Direct potable supply
- Additional reclaimed water contracts
- Discharged to Santa Fe River (some of this flow will recharge the aquifer)
- Credits for return flow to the Rio Grande

These options will be reviewed in more detail as part of Task 5.

4.2.5 Water Accounting Logic

The water accounting module of WaterMAPS is one of the most complex components in the system. Storage in the Canyon reservoirs (Nichols and McClure) is subject to several management strategies and conditions. The available water accounting pools to which Canyon reservoir storage may be allocated include the Pre-Compact Pool, the Post-Compact Pool (subject to storage restrictions according to the Rio Grande Compact), the San Juan Chama pool, and the Relinquishment Pool. These are not physical pools of water. Instead they represent volumes of water that are tracked on paper for accounting purposes.

Each pool is described below:

- ***Pre-Compact Pool***: This pool stores water in storage space constructed before the Rio Grande Compact (Compact) went into effect, and it is not subject to Compact restrictions. Storage limit is 1,061 acre-feet (AF).
- ***Post-Compact Pool***: This pool holds native water and is subject to Compact restrictions. There is no limit on the storage volume for this pool other than the capacity of the Canyon reservoirs.
- ***San Juan-Chama Pool***: The volume in this pool represents water that has been exchanged for San Juan-Chama Project water. Storage in this pool is not restricted by the Compact, but all increases in daily storage in this pool must be paid for with releases of San Juan-Chama Project water. There is no limit on the storage volume for this pool other than the capacity of the Canyon reservoirs.

- ***Relinquishment Pool***: This pool holds native water stored under the terms of the 2003 Relinquishment Agreement between New Mexico and Texas. Storage in this pool is not restricted by the Compact, but all increases in daily storage in this pool must be paid for with a portion of the credit assigned to Santa Fe.

Daily increases and decreases in the Canyon reservoirs are assigned to one of these four pools.

Changes made in WaterMAPS regarding the water accounting logic were made specifically based on aspects of the Rio Grande Compact, which include:

- New Mexico's credit or debit status
- If Elephant Butte Reservoir has over or under 400,000 AF in storage (i.e., status of Article VII, storage restrictions)

These aspects dictate when water can be stored in the Post-Compact Pool and if water can be moved from the Post-Compact Pool to other pools. WaterMAPS uses an assumed priority logic for determining which inflows are assigned to pools, the order in which outflows are assigned to pools, and when to transfer water from the Post-Compact Pool to other pools.

The Rio Grande Compact settings are usually static in the WaterMAPS simulations, meaning that the status of each is selected for a particular simulation and remains the same throughout the simulation. However, the URGSiM simulations that provide input to WaterMAPS determine the status of Rio Grande Compact settings for each month. The Bureau of Reclamation provided the status of each condition for each month as an input to WaterMAPS for the climate-change scenarios to be simulated in the Basin Study.

4.2.6 Santa Fe River Target Flows

An ordinance and associated administrative procedure (City of Santa Fe, New Mexico, Ordinance No. 2012-10 and City of Santa Fe, *Administrative Procedures for Santa Fe River Target Flows and City of Santa Fe*) was adopted in February of 2012 to provide 1,000 AFY to the Santa Fe River. The purpose of the Santa Fe River Target Flow is to increase water flow in the river below the City's reservoirs in order to maintain a "living river," except under emergency conditions. The administrative procedure outlines specific hydrographs for daily releases throughout the year based on the expected annual yield. For normal and wet years, the annual target is 1,000 AFY. This target decreases in dry and critical years according to the percent of normal annual yield expected. Figure 8 shows how the Santa Fe River Target Flow decreases based on the annual yield.

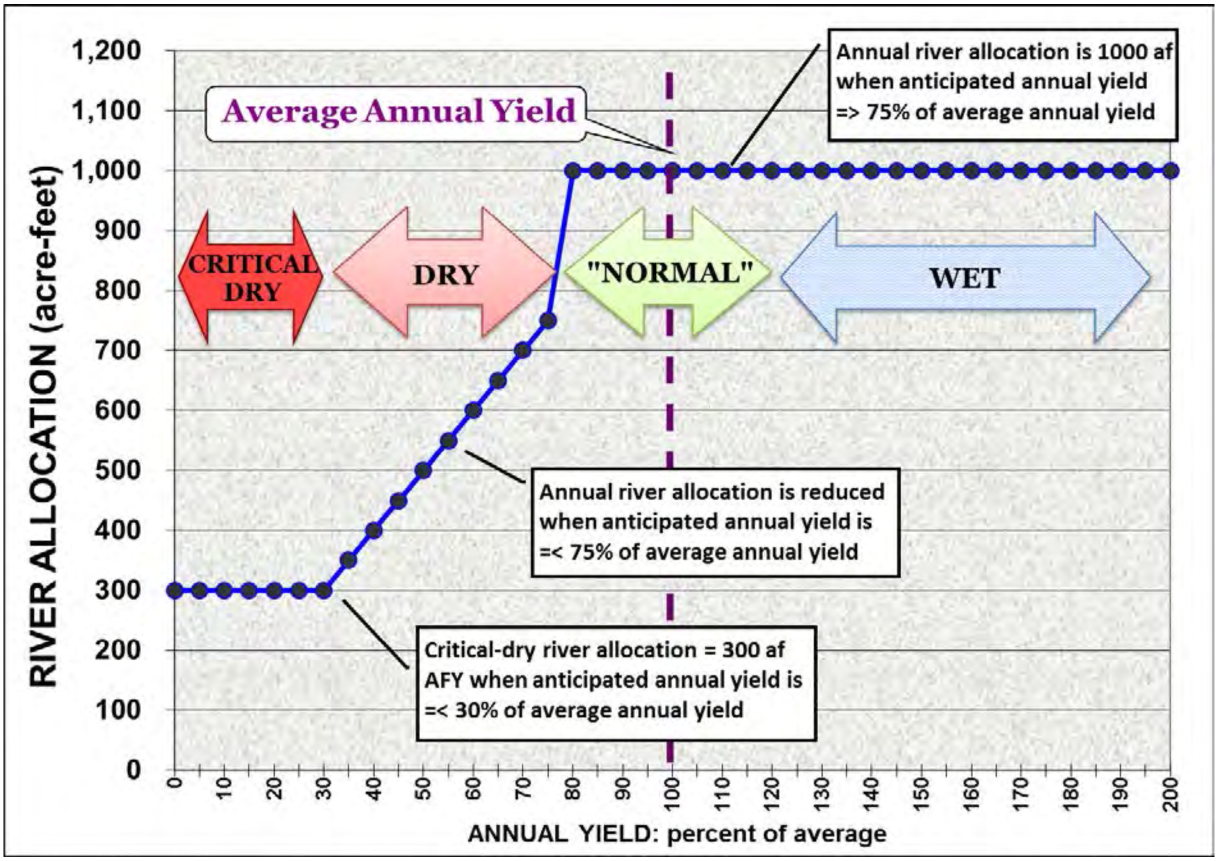


Figure 8. Santa Fe River Target Flow Allocation as a function of annual yield (City of Santa Fe, 2012)

To model the Santa Fe River Target Flow in WaterMAPS, the hydrographs representing daily releases required to meet the desired target flow were summarized into monthly releases. These summarized hydrographs are shown in Figure 9. Each hydrograph is different, based on the percent of normal expected annual yield (e.g. "Dry – 70%" means the expected annual yield is 70 percent less than normal). If the expected annual yield is 30 percent or less of normal, then the "Critical-Dry" hydrograph is used. This means that even under drought conditions, the City plans to release at least 300 AFY to support in-stream flows in the Santa Fe River.

The hydrographs of releases shown in Figure 9 were applied in WaterMAPS according to the projected stream flow hydrographs for each of the climate change scenarios. The average annual yield of stream flow in the Santa Fe River according to gage data from 1914 to 2007 is 4,909 AFY (as stated in the administrative procedure). This value represents "normal" conditions.

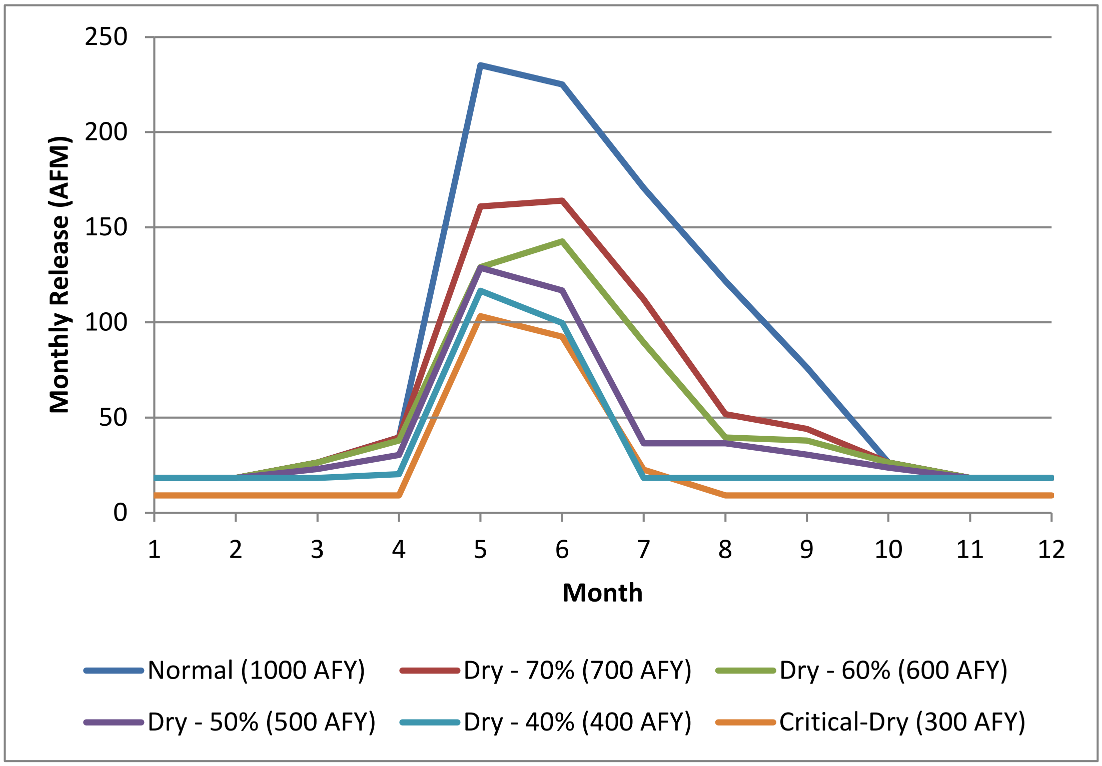


Figure 9. Santa Fe River Target Flow monthly releases hydrographs

The hydrograph associated with the percentage of normal from Figure 9 was applied to each year to create the Santa Fe River Target Flows to be simulated in WaterMAPS. These target flows are simulated as releases from Nichols Reservoir and they are tracked through the model.

The average annual yield for each year simulated and each climate change scenario was developed from the projected stream flow hydrographs. These yearly averages were compared to the normal annual yield of 4,909 AFY to determine the percent of normal. The variation of flow as a percentage of the normal annual yield for each climate change scenario is shown in Figure 10. The frequency of average annual flow being above and below normal is shown in Figure 11.

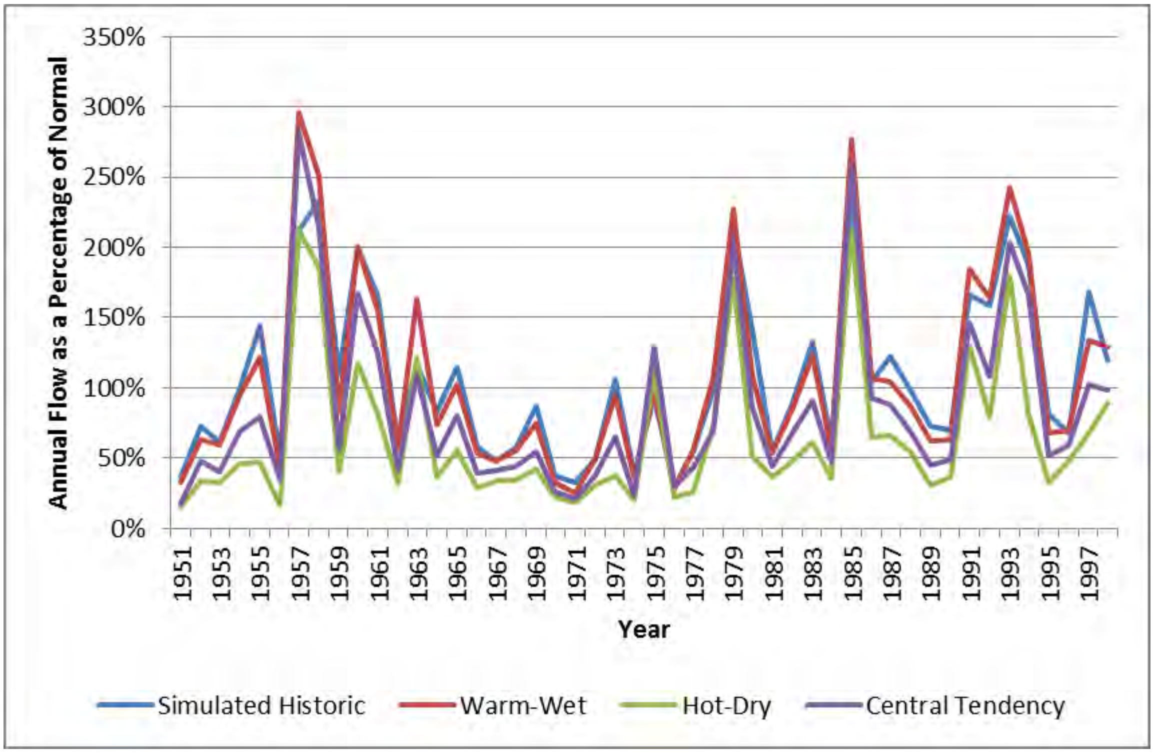


Figure 10. Santa Fe River projected annual yield as a percent of normal (4,909 AFY) by climate change scenario

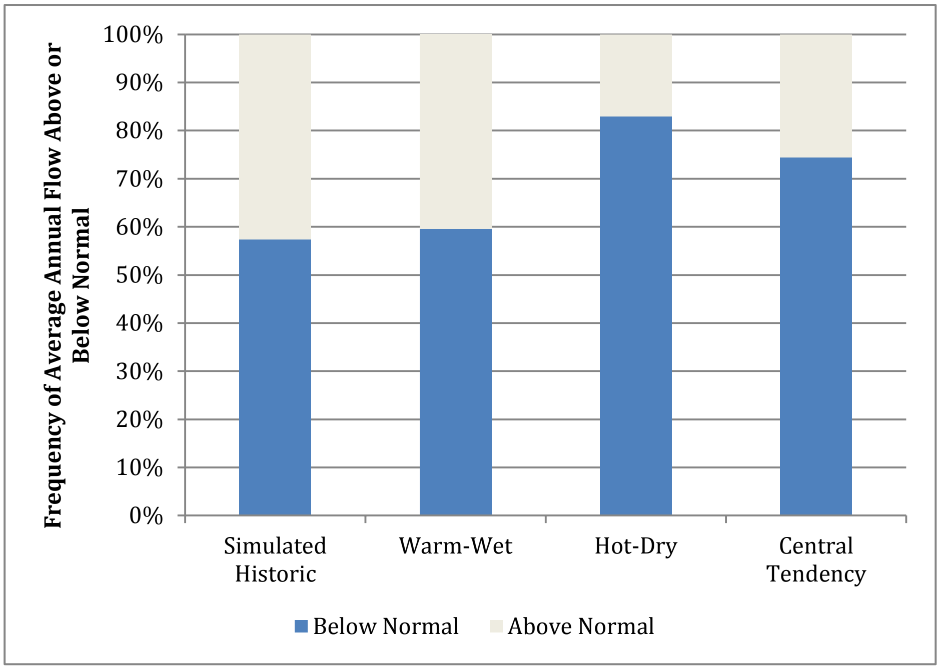


Figure 11. Frequency of years below and above normal Santa Fe River flow conditions, for each climate change scenario

4.3 Task 3e: Water Demand Variability

The objective of this analysis was to provide a means of varying future water demand estimates for the City and County of Santa Fe given future weather conditions projected under the climate change scenarios. This variability in demand was applied to the WaterMAPS model.

Monthly water production, monthly average maximum daily temperature, and monthly total precipitation were obtained for January 2002 through December 2010 for the City of Santa Fe. Annual population of the City was used to convert the water production values from million gallons per month to monthly estimates of gallons per day per capita (monthly gpcd).

The variation in monthly gpcd is strongly correlated with the average of maximum daily temperatures in the month (max. temp.) as shown in Figure 12. The relationship between monthly estimates of gpcd and monthly precipitation is not as clearly defined as shown in Figure 13. Also notable in Figure 12 and Figure 13 is that the gpcd data for the year 2004 are abnormal. This may be due to reporting or data formatting errors. Therefore, observations for the year 2004 are removed from this analysis.

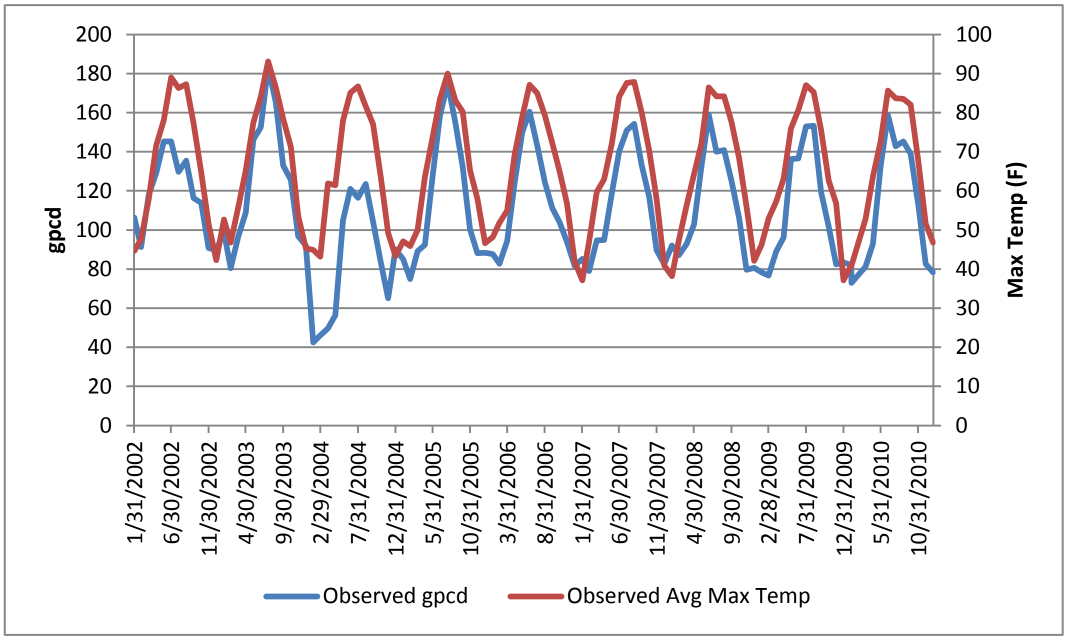


Figure 12. Monthly observed gpcd and average maximum daily temperature for the City of Santa Fe

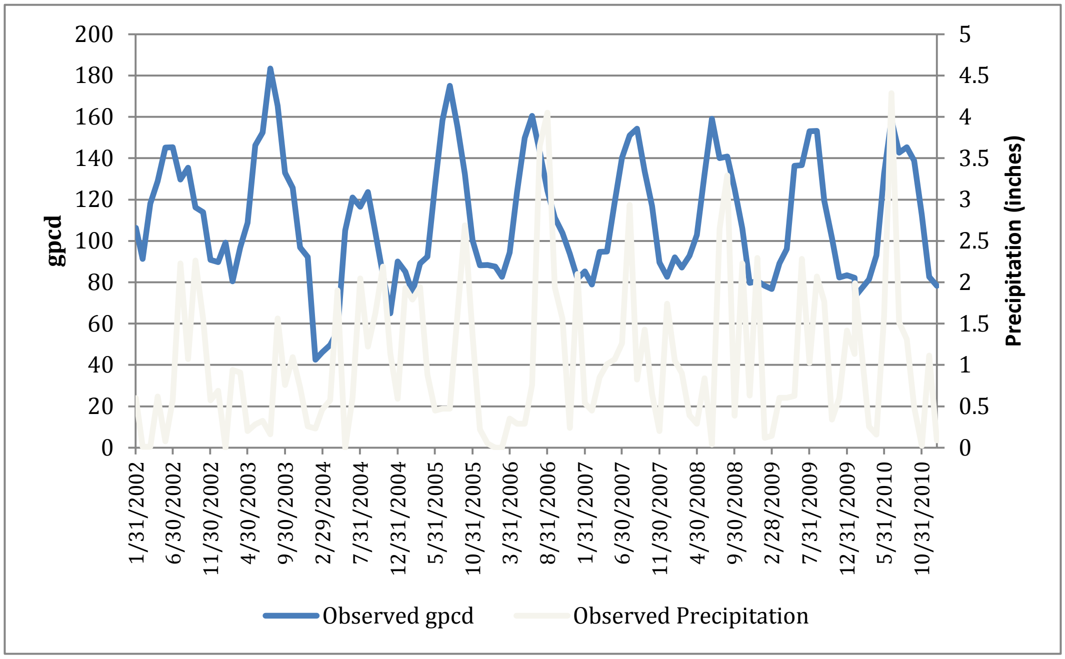


Figure 13. Monthly observed gpcd and precipitation for the City of Santa Fe

A number of regression models were tested in which the monthly gpcd is the dependent variable and monthly maximum temperature and monthly precipitation are tested as independent variables. As expected by the overlapped time series shown in Figure 12 and Figure 13, the regression coefficients for monthly average maximum temperature were highly significant while coefficients estimated for monthly precipitation were not significant. Models were tested in both linear and log forms. The advantage of the log model is that the estimated coefficient can be directly interpreted as the elasticity of demand to the variable and represents the percent change in demand given a percent change in the variable. Model 1 and 2 show the estimated relationships between gpcd and maximum temperature in linear and log form, respectively.

- Model 1:
  $\text{gpcd} = 6.6316 + 1.6316 \text{ x (avg max temp)}$ $R^2 = 0.856$

- Model 2:
  $\text{gpcd} = e^{1.092753} \text{ x (avg max temp)}^{0.869574}$ $R^2 = 0.869$

The R^2 values represent goodness of fit and range from 0 to 1. In Model 2, the elasticity of maximum temperature of 0.8695 indicates a 0.87 percent increase in gpcd for every 1 percent increase in maximum temperature. This relationship can be used to adjust estimates of future water demand (in gpcd) for theoretical changes in monthly average maximum daily temperature.

Model 3 (below) shows the addition of monthly precipitation as an additional variable to Model 2 above.

- Model 3:
  $\text{gpcd} = e^{1.09341} \text{ x } (\text{avg max temp})^{0.869298} \text{ x } (\text{precip} + 1)^{0.00078}$ $R^2 = 0.824$

There is a very negligible shift in the estimated elasticity for average maximum temperature, and the estimated elasticity for monthly precipitation is 0.00078. It is expected that the precipitation elasticity would be negative (i.e. a decrease in precipitation would lead to an increase in demand), but given the data, the result was a positive elasticity. Given that the value is so small compared to the elasticity for temperature, the effect of precipitation is considered to be statistically insignificant. Thus, variations in precipitation during this period show no effect on per capita water use. Note that the model is in log form, and one cannot take the log of zero, but some months have zero precipitation. To address this, a value of one is added to all monthly precipitation values before they are transformed into log values. This has no impact on the relationship between precipitation and gpcd.

The average annual demand for the City of Santa Fe from 2002 to 2010 (excluding 2004) is about 113.8 gpcd. This value can be used in conjunction with projections of future population for the City and the County to derive estimates of average future water demand. The average value for monthly average maximum daily temperature for this time period is 65.66 °F and the average value for monthly precipitation is 1.04 inches. These values may be considered as representative of "normal" conditions. Deviation from these "normal" values can be calculated and used to adjust the average gpcd for the month. Thus monthly per capita water demand with adjustments for variation in monthly weather can be estimated as:

- $\text{Predicted gpcd} = 113.8 \text{ x } (\text{max temp}/65.66)^{0.869298} \text{ x } ((\text{precip}+1)/(1.04+1))^{0.00078}$

Figure 14 shows the results of using this formula to estimate historical monthly gpcd from the historical monthly weather values relative to the observed historical gpcd.

This same formula can be used to assess the impacts of alternative climate change scenarios on future water demand for the City and County. Reclamation has provided temperature and precipitation data for the climate change and simulated historic scenarios. These data are for the same time period as the other climate change scenario provided and discussed as part of Task 3a. The development of this data was described in a memorandum from Dr. Jesse Roach (Appendix C). Temperature and precipitation projections were provided for two 1/8 degree grid cells, referred to as the "City" and "McClure Reservoir" grid cells.

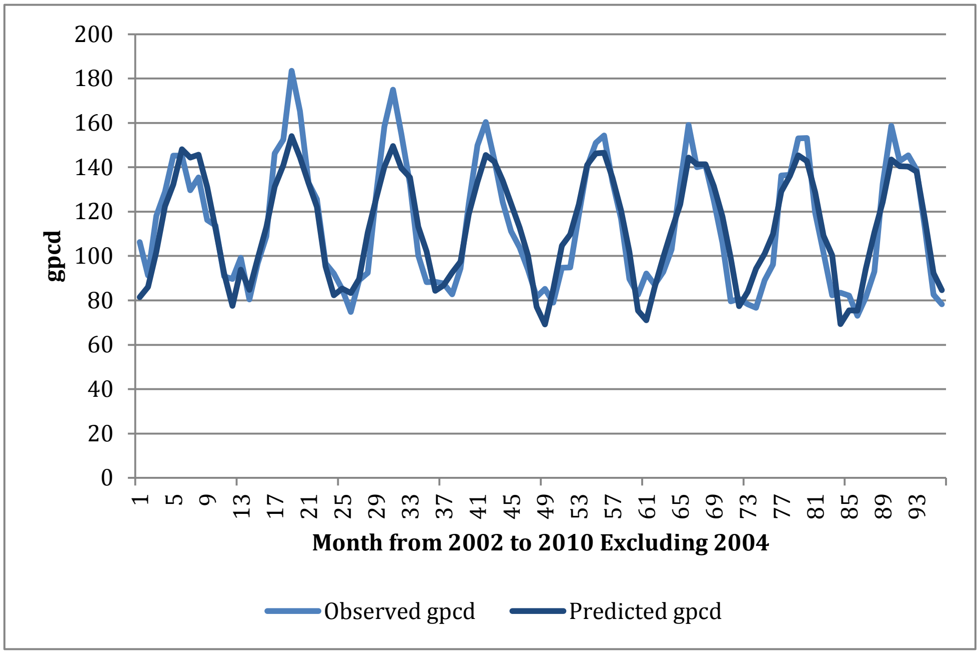


Figure 14. Monthly observed gpcd and predicted gpcd (excluding 2004 data)

The City of Santa Fe falls in the middle of the City grid cell. The temperature and precipitation projections developed for the City grid cell were used for projecting demand. The McClure Reservoir grid cell covers an area where there is less population and demand for water, and therefore was not used to predict demand. The temperature and precipitation projections were also used in the development of the evaporation projections for McClure and Nichols Reservoirs, as is discussed further in later sections of this memorandum.

The climate change scenarios include an estimation of simulated historic weather as a basis for determining the change in climatic patterns. The simulated historic weather does not align precisely with observed historic weather. Therefore, the long-term averages of monthly daily maximum temperature and monthly total precipitation were calculated from the simulated historic period and substituted into the above formula for predicted gpcd. Thus, the adjusted formula shown below is calibrated to the same historic period averages as the climate change scenarios.

Simulation Formula: $\text{gpcd} = 114 \text{ x } (\text{max temp}/63.08)^{0.869298} \text{ x } ((\text{precip}+1)/(1.41+1))^{0.00078}$

The above formula is used with temperature and precipitation time series in the climate change scenarios to predict water demand in WaterMAPS simulations. Two demand scenarios are considered, as previously discussed: status quo and use less. For status quo (SQ), the above formula is used as is. For the use less demand scenario (UL), 114 gpcd is replaced with 73 gpcd. The average and maximum monthly gpcd simulated for each climate change scenario and under the status quo and use-less demand scenarios are shown in Figure 15 and Figure 16, respectively. The labels in these figures indicate the unit demand value for Synthetic Historic and the percent increase from the Synthetic Historic unit demand for each of the climate change scenarios.

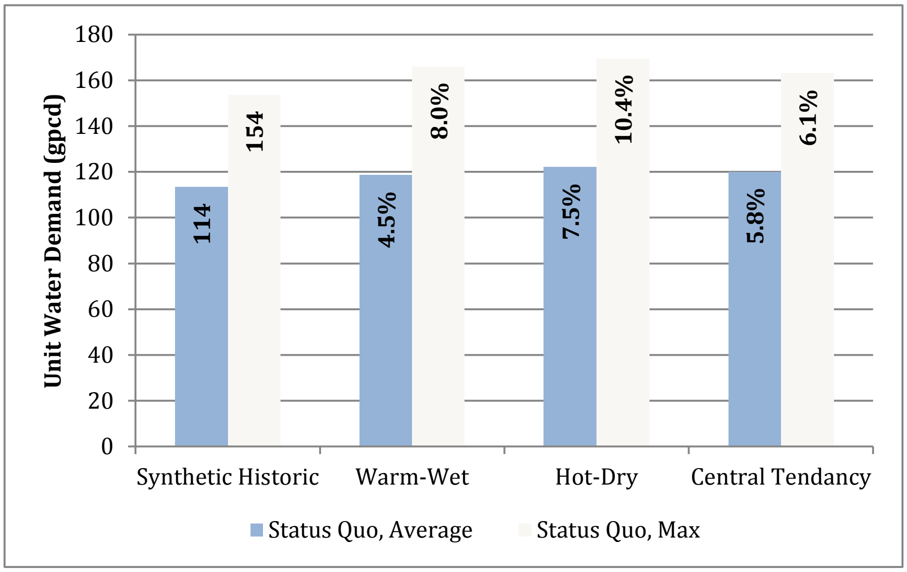


Figure 15. Average and maximum monthly gpcd simulated, status quo

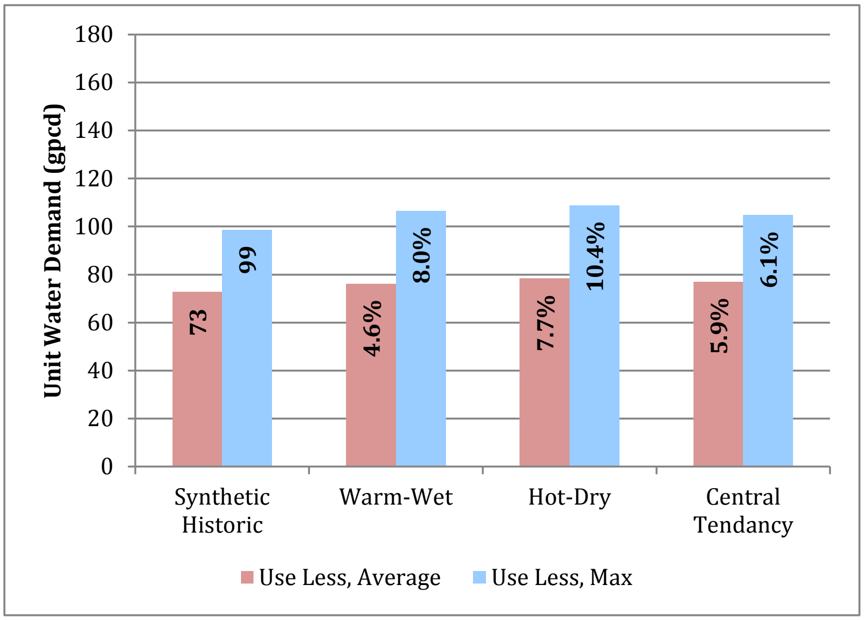


Figure 16. Average and maximum monthly gpcd simulated, use less

4.4 Task 3f: San Juan Chama Project Adjustments

The objective of this task was to incorporate the impacts of climate change on expected firm yield water deliveries from the San Juan-Chama Project into WaterMAPS. When WaterMAPS was first developed, it was assumed that San Juan-Chama Project water would always be available to the full permitted amount. Shortages in recent years have shown that this is not the case.

4.4.1 Understanding of San Juan-Chama Project Percent Allocation

Using URGSiM, Reclamation has provided the percent allocation expected at the beginning of each simulated year for the climate change scenarios. If the allocation for a given year in the simulation is not 100 percent starting in January, there is the potential for revision to the allocation in July. For example, if the total allocated amount of annual of San Juan-Chama Project water for an entity is 100 AFY, but based on URGSiM results, only 25 percent is predicted to be available at the beginning of the year, only 25 AFY can be delivered. Starting in July, if URGSiM determines that an additional 50 percent of the annual allocated amount can be used, then an additional 50 AFY are delivered. This means for that year, a total of 75 AFY can be used, but the model cannot account for the additional 50 AFY until July.

4.4.2 San Juan-Chama Project Water Delivery System

An understanding of how San Juan-Chama Project water is delivered to the Rio Grande for diversion at the Buckman Direct Diversion (BDD) is necessary for explaining how the San Juan-Chama Project system and deliveries were modeled in WaterMAPS. Below is an outline of how San Juan-Chama Project water is delivered and the limitations on the water’s availability for diversion:

- San Juan-Chama Project water is diverted from tributaries to flow by gravity to Heron Reservoir. The amount and frequency of diversion is based on the flow of the tributaries and the temperature (i.e., the diversion does not occur under freezing conditions). This aspect is modeled in URGSiM. Note that other entities in addition to the City and County of Santa Fe have rights to San Juan-Chama Project water.

- The City and County call for their portion of San Juan-Chama Project water, from Heron Reservoir as needed on a daily basis.

- As needed, the City and County transfer water from Heron Reservoir to Abiquiu Reservoir. From Abiquiu, water is released into the Rio Grande for diversion at the Buckman Direct Diversion.

- The City and the County are allowed to store water in Abiquiu until there is a need for use or until storage capacity exceeds storage contract rights. Evaporative losses apply to water stored in Abiquiu. Any unused waterstored in Heron Reservoir is lost to Reclamation at the end of the year unless the contractor obtains a waiver (as Santa Fe has done in recent years). However, any losses due to evaporation in Heron Reservoir are absorbed by Reclamation.

- As discussed in OSE Permit SP-2847-E (New Mexico Office of the State Engineer 2006), which allows for direct diversion of San Juan-Chama Project water via the Buckman Direct Diversion, "the amount of the permittees' San Juan-Chama Project water available for diversion at the Buckman Direct Diversion on a particular day shall be calculated as the amount of water released from either Heron or El Vado Reservoir two days prior to diversion at the Buckman Direct Diversion, less a 2 percent conveyance loss…" This conveyance loss is to account for losses due to evaporation and infiltration as the water is transported. If water is to be released directly from Abiquiu, the conveyance loss is reduced to 0.9 percent and is calculated one day prior to diversion.

4.4.3 WaterMAPS Simulation of San Juan-Chama Project Water Delivery System

The system of reservoirs and daily calls for water discussed above is complex. The San Juan-Chama Project system of reservoirs and delivery of water was modeled in a simplified manner in WaterMAPS as described below:

- San Juan-Chama Project water is delivered on a monthly basis to Heron according to the percent allocation data predicted by URGSiM for the different climate change scenarios. It is assumed that the allocated amount is divided over the twelve months of the year for the first six months. Then if the allocation is increased in July, the remaining annual amount is divided evenly over the last six months.

- If the monthly amount of San Juan-Chama Projectwater delivered to Heron is less than the demand for such water in any given month, the water passes through the reservoirs. No evaporative losses due to storage are incurred, but the 2 percent carriage loss is applied.

- If the monthly amount of San Juan-Chama Project water delivered to Heron is greater than the demand for such water in any given month, water is stored in Abiquiu according to storage limits. Related to this is the following:
  - Evaporative losses are applied to stored water in Abiquiu.
  - If the storage limit for Abiquiu is exceeded, water is stored in Heron. No evaporative losses are applied to Heron, but any water remaining in Heron at the end of the year is lost.

  - The 2 percent carriage loss is applied when the water is used.

- Simulation of the San Juan-Chama Project reservoirs in WaterMAPS does not include any flows or storage amounts other than San Juan-Chama Project water for the City and County and evaporative losses at Abiquiu Reservoir. Evaporative losses at Abiquiu are applied as a percentage of the San Juan-Chama Project amount that is stored for the City and County. Those percentages were developed as described under Section 4.1.

This simplification of the system is considered adequate because WaterMAPS only tracks water for the City and County of Santa Fe. San Juan-Chama Project water transferred for other entities is not relevant for the Basin Study nor is it useful for the City or the County.

WaterMAPS does not consider the 0.9 percent carriage loss for use of water that has been stored in Abiquiu. For the purposes of this project, which looks at the impact of climate change on the system in 2055, water is seldom stored in Abiquiu in the modeled scenarios. As a high priority source, it is likely that it will be completely used before other sources. The additional modeling complication of including this loss was, therefore, not included. The 2 percent loss is applied across the board for all water used.

4.5 Task 3g: Evaporation Rates for the Santa Fe Municipal Reservoirs

Evaporation rates for Nichols and McClure Reservoirs were developed for the climate change scenarios for simulation in WaterMAPS. Appendix C discussed the development of the temperature and precipitation data that were used to calculate reference evapotranspiration. Additional detail on the evapotranspiration calculations is presented in a report on the Upper Rio Grande Simulation Model (United States Department of the Interior et al. 2013) that has also been provided in Appendix C2.

As discussed in Appendix C2 and under Section 4.3, temperature and precipitation data were developed for two grid cells in the downscaled climate projections. The two grid cells centrally encompass the City of Santa Fe and McClure Reservoirs, so the evaporation data developed for the McClure Reservoir grid cell could be used directly. Nichols Reservoir straddles the grid cells; therefore, the evaporation data for Nichols Reservoir is based on the average evapotranspiration developed for the two grid cells.

Reference evapotranspiration is converted to reservoir evaporation using open water evaporation coefficients, developed for each month, as discussed in Appendix C2. Such coefficients are not available for McClure and Nichols Reservoirs; therefore, open water evaporation coefficients for a reservoir nearest in elevation to McClure and Nichols was used. Although Heron Reservoir is nearest in elevation, a lack of historic temperature data prevented the development of such coefficients. The next reservoir nearest in elevation is El Vado. The open water evaporation coefficients for El Vado were used to convert reference evapotranspiration to reservoir evaporation for each of the municipal reservoirs.

A time series of evaporation was calculated for each reservoir and for each of the climate change scenarios to be simulated in WaterMAPS. Evaporation was simulated in feet per month. This is multiplied by the dynamically simulated area of each reservoir to get a volume of water lost from the reservoirs.

In addition to evaporation, precipitation was included in the simulation, but only as an amount that falls directly on the reservoir. The inflow hydrographs account for precipitation that falls on the watershed. Precipitation was simulated in feet per month. This is multiplied by the simulated area of each reservoir to get a volume of water gained from the precipitation.

5 WaterMAPS Functionality

The functionality of WaterMAPS, given the changes described in this memorandum, is checked as part of Task 4, which is an examination of the results given the climate change scenarios. The results presented in the Task 4 memorandum are checked against the average annual estimate of supply and demand to determine if the results are reasonable.

Significant changes were made to WaterMAPS as part of this Basins Study, including additional supplies and demands from the County. These improvements to the model prevent a direct comparison to previous WaterMAPS results. Although final results cannot be directly validated, specific programming in the model was checked with regard to the functionality of each of the updates discussed in this memorandum.

6 References

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Appendix F

Task 4: Assessment of Adequacy of Current Water Supplies in Meeting Future Demand under Projected Climate-Change-Induced Conditions

Santa Fe Basin, New Mexico

CDM Smith

Contents

This appendix provides the text of a technical memorandum from Kelly Collins, PG, BCES, CDM Smith, to Claudia Borchet, Santa Fe County, dated September 5, 2014. This memo summarizes Task 4: Assessment of Adequacy of Current Water Supplies in Meeting Future Demand under Projected Climate-Change-Induced Conditions. This memorandum is not a stand-alone document. An understanding of the information presented in Appendix E is important for comprehending the results shown here.

1. Background Information

In this section, a brief summary of the water supply, future demand, and modeling approach are provided as background for the gap analysis. Additional information can be obtained in Appendix E.

2. Water Supply and Future Demand

A brief summary of the climate-change scenarios, City and County water supplies, demand projections, and demand variability are discussed below:

- Four water supply scenarios under future climate-change-projected conditions were selected to represent the range of projected conditions and are described in detail in Section 3 of Appendix E. These include:
  - Simulated historic (baseline simulation)
  - Warm-wet
  - Central tendency
  - Hot-dry

The primary water supplies available, in order of priority, are:

  - San Juan Chama Project (SJCP) water and Rio Grande native water diverted via the Buckman Direct Diversion (BDD)
  - Local surface water from the Santa Fe River watershed
  - Groundwater from the City Well Field along the Santa Fe River
  - Groundwater from the Buckman Well Field near the Rio Grande

- The water supply sources are subject to various regulatory limits, management targets, and capacity constraints. The constraints for each supply are described in Appendix E.

- The ultimate 2055 populations used for the climate change analysis and for development of the water supply plan are 125,019 for the City water service area and 44,673 for the County water service area (Appendix E). By comparison, 2015 populations for the City and County are 96,578 and 18,048, respectively.

- The demand scenario selected for analysis is based on the current average annual unit demand, which was calculated from City records as 114 gallons per capita per day (gpcd).

With regard to seasonal demand factors, monthly demand is specifically varied based on the predicted temperature and precipitation for the respective climate change scenarios. The average and maximum monthly gpcd simulated for each climate change scenario is shown in Figure 1 and is described in detail in Section 4.3 of Appendix E.

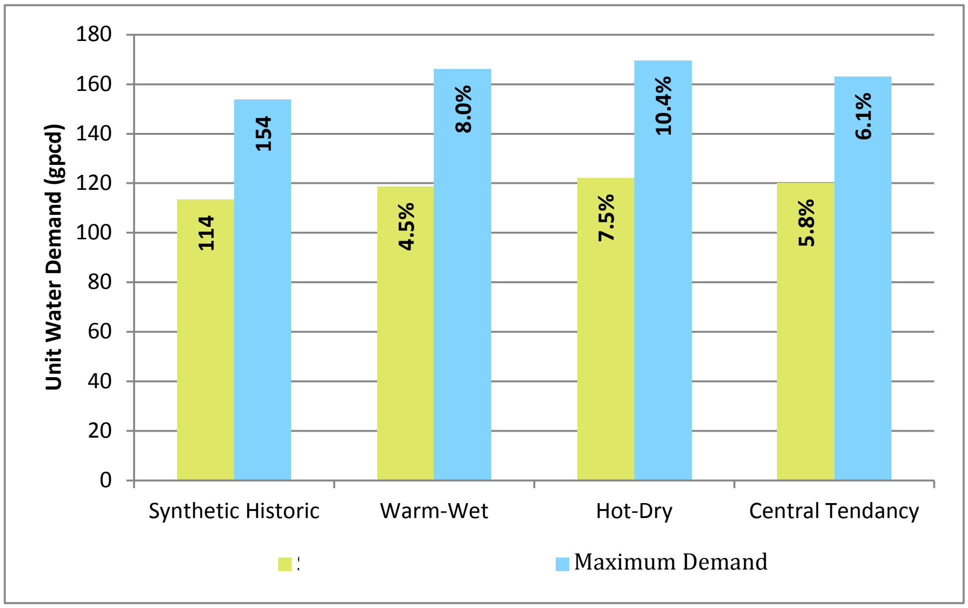


Figure 1. Average and Maximum Monthly Simulated Water Demand (gpcd)

3. Modeling Approach

In addition to the information presented below, detailed information concerning the model setup is provided in Section 4.2 of Appendix E. Concerning the model setup, several parameters remain constant among the simulations:

- Supplies are constrained by the management targets (rather than water rights, which are greater) determined by the City and County as shown in Table 1. For the supplies shown in Table 1, surface water supplies are impacted by climate change while groundwater supplies are not for this study. While climate change conditions may impact groundwater in reality, this was not considered in the study. The management targets are used to represent possible depletions in the availability of groundwater in the future.
- Maximum Buckman Well Field pumping is 5,000 acre-feet per year (AFY). This applies to designated dry years.
- The initial storage condition for McClure, Nichols, El Vado, and Abiquiu reservoirs is 25 percent full, representing an approximation of recent conditions.

Table 1. Management Targets for Selected Water Supply Sources.

Source	**Management Target (AFY)**	
	County	City
Groundwater Supply		
Buckman Wells	-	3,000
City Wells	-	3,000
Northwest Well	-	500
St. Mike's Well	-	241
Osage Well	-	96
Surface Water Supply		
Canyon Road WTP	0	Varies based upon SF River flows (3,630)
Native Rio Grande Rights	1,915	590
San Juan-Chama Project Water	375	5,230

Additionally, a preliminary simulation (the Forty Year Sequential Time Series Simulation) is required to determine groundwater pumping offsets that will need to be met with water rights (either specific water rights for offsets or other rights) in the future.

WaterMAPS was used to simulate the demand on supply given climate change and the above conditions. The results were then used to evaluate how well the City and County will be able to meet future water supply objectives under the four climate change scenarios.

4. Gap Analysis Results for Climate Change Impacts

Results from the simulations include quantitative estimates from WaterMAPS on the gap between expected demand in 2055 and available supply for each of the three climate-change scenarios. As noted in Task 3, the simulated historic scenario serves as a baseline; therefore, the results from the respective simulation can be compared to the baseline.

The performance measures of the results include:

- Need for and frequency of mandatory demand restrictions or additional supply
- Extent to which non-Buckman Direct Diversion water supply (Santa Fe River water and groundwater) is needed.

To compare the performance measures among all climate change scenarios, the following results were developed:

- Annual and monthly deficit probability: the likelihood that there will be a water shortage of a certain extent in any given year or month.

- Monthly deficit probability for both summer and winter months: the likelihood of deficits under summer and winter conditions
- Annual average supply mix: the extent to which each supply is used on an average annual basis
- Monthly supply mix: the extent to which each supply is used on a monthly basis

The monthly supply mix displays eight water sources and is determined for four conditions based on the simulated historic Santa Fe River flow. The four conditions are:

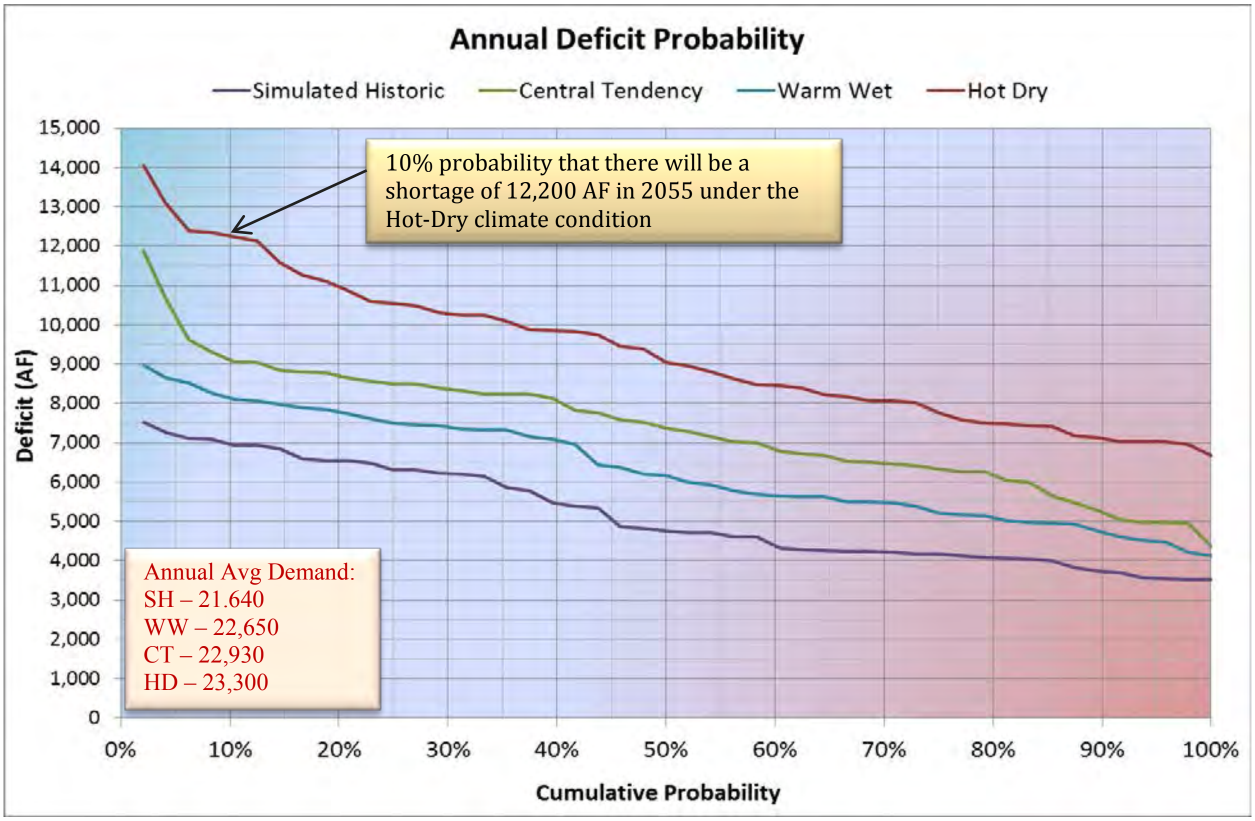
- Average Annual – all time steps are taken into account
- Normal Year – one year in the time series where flow in the Santa Fe River represents the median flow
- Dry Year – one year in the time series where flow in the Santa Fe River represents the 10th percentile (low flow condition)
- Wet Year – one year in the time series where flow in the Santa Fe River represents the 90th percentile (high flow condition)

Note that the dry and wet years were chosen to be representative of dry and wet years and do not necessarily represent the “worst” and “best” case scenarios for water supply.

5. Deficit Probability

Part of the WaterMAPS output is the probability of deficits (or water shortages) on an annual basis and on a monthly basis. The output graphs show the percent likelihood of a deficit of a particular amount in any given year based on the simulation results.

Figure 2 shows the annual deficit probability for each climate change scenario. Each line represents a climate change scenario and the range of deficits predicted. An example of how to interpret the graph is shown in Figure 2, which indicates that there is a 10 percent probability that there will be an annual deficit of 12,200 acre-feet (AF) under the Hot-Dry climate condition. For reference, the projected average annual demand under this climate condition is approximately 23,300 acre-feet per year (AFY).



10% probability that there will be a shortage of 12,200 AF in 2055 under the Hot-Dry climate condition

Annual Avg Demand:
SH – 21.640
WW – 22,650
CT – 22,930
HD – 23,300

Figure 2. Probability Curves for the Annual Deficit for each Climate Change Scenario

From Figure 2, all climate change scenarios (including the baseline) encompass an annual deficit ranging between 3,500 acre-feet (AF) and 14,000 AF. To compare the climate change scenarios, the Hot-Dry scenario has the highest maximum annual deficit, about 14,000 AF while the Warm-Wet scenario has the lowest maximum annual deficit, falling just below 9,000 AF. The annual deficit probability curve for the Central Tendency scenario falls in between the Hot-Dry and Warm-Wet probability curves.

Based on these results, it is very likely that there will be an annual deficit greater than 3,500 AF in the year 2055 unless adaptive strategies are implemented to reduce demand or supplement supply. It is important to understand that these results not only indicate climate change impacts, but also reflect the combination of City and County supply and demand, which has not been studied previously. The combined result is much greater demand without a commensurate increase in supply. Also, groundwater pumping is being restricted by the management targets; the most restrictive of which is the Buckman Well Field limitation of 3,000 AFY.

Figure 3 shows the monthly deficit probability for each climate change scenario. Similar to Figure 2, each line represents a climate change scenario and the range of deficits predicted. An example of how to interpret the graph is shown in Figure 3, which indicates that there is a 10 percent probability that there will be a monthly deficit of 1,300 AF in any given month of 2055 under the Hot-Dry climate condition.

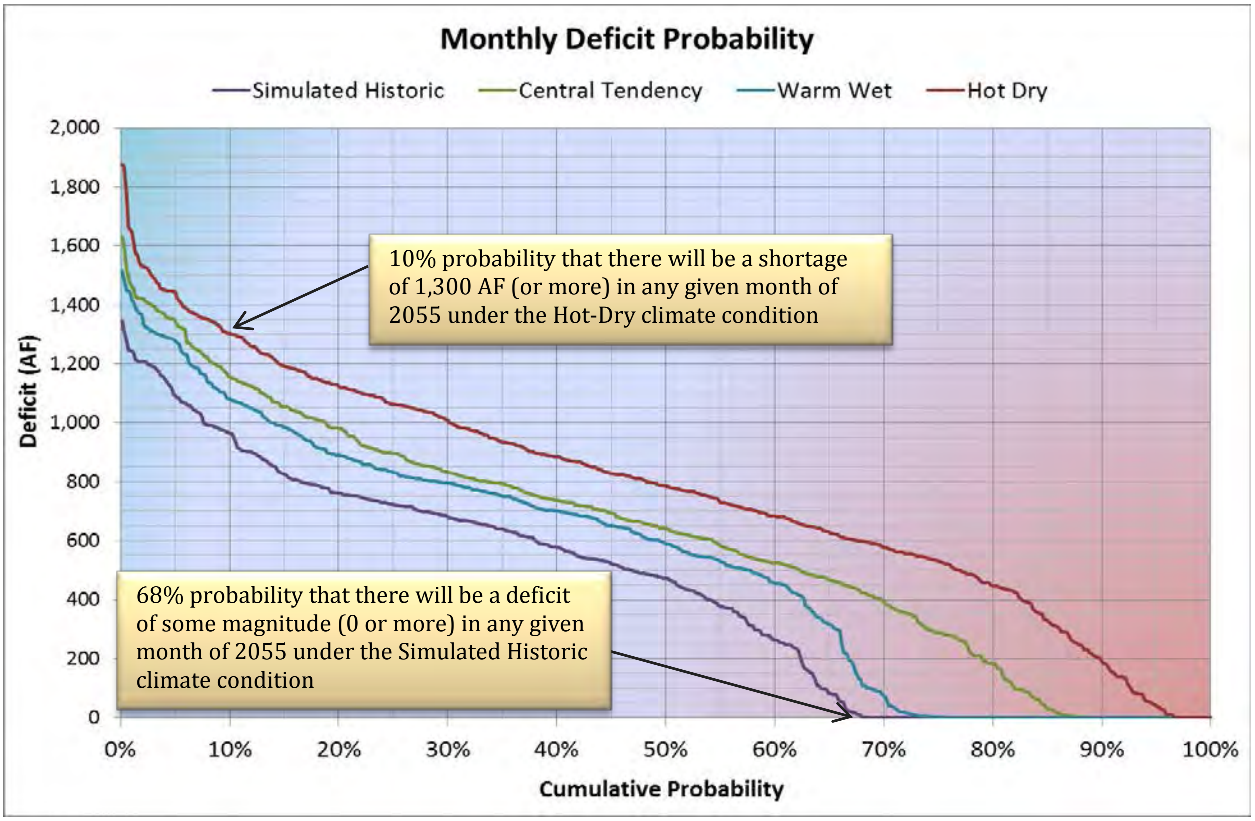
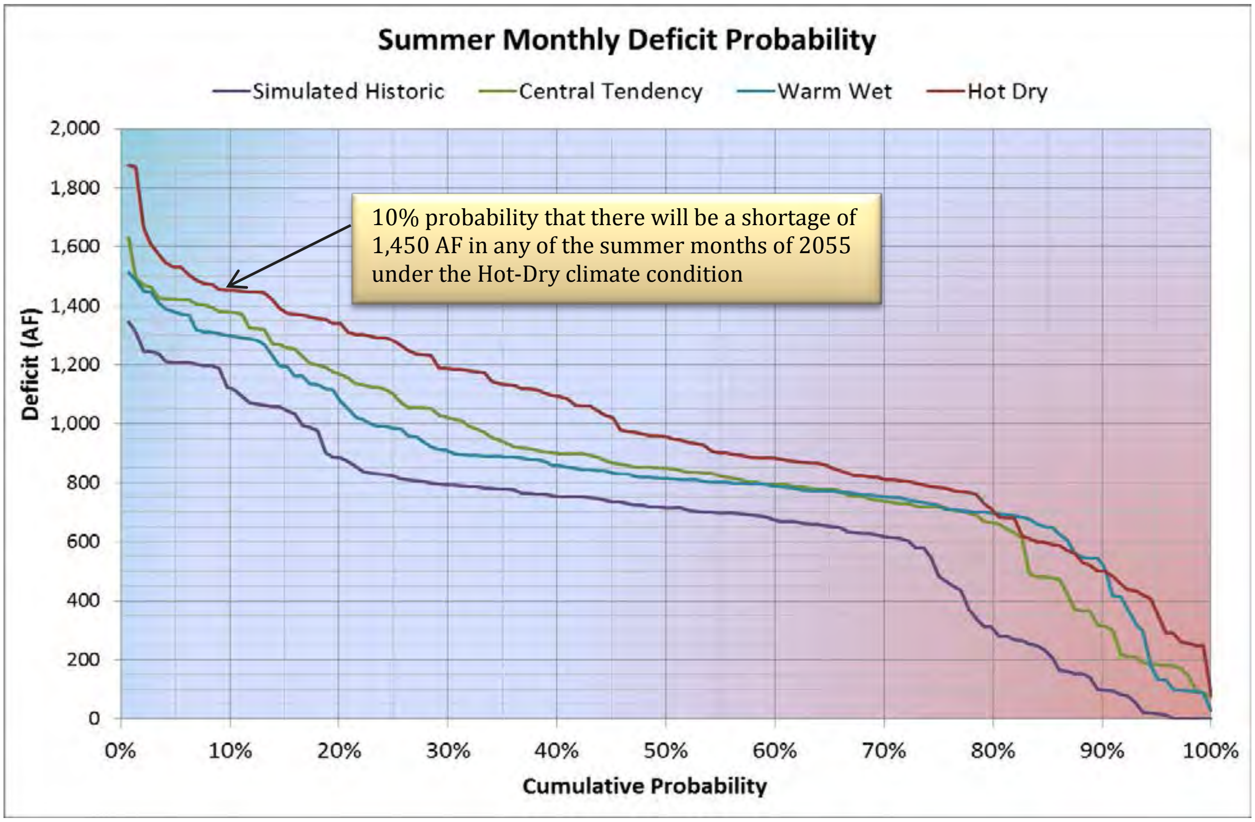


Figure 3. Probability Curves for the Monthly Deficit for each Climate Change Scenario.

As shown in Figure 3, a monthly deficit ranging from zero to 2,000 AF is likely for all climate change scenarios, including the baseline. The Hot-Dry climate change scenario has the highest maximum monthly deficit of approximately 1,900 AF while the Warm-Wet scenario has the lowest maximum monthly deficit of about 1,500 AF. It is important to understand that these graphs represent the probability of deficits of a particular magnitude and not the probability of no deficits. For example, under the Simulated Historic climate conditions, it cannot be said that there is a 68 percent chance of no deficits. It can only be said that there is a 68 percent chance of deficits between 0 and 1,350 AF. To state the probability of any deficit, the cumulative probability should be inverted (i.e., the probability of no deficits for Simulated Historic in 2055 is 32 percent).

As with the annual deficit, the monthly deficit probability curve for the Central Tendency scenario falls in between the Hot-Dry and Warm-Wet probability curves. Based on these results for monthly deficit, there is a 68 to 95 percent chance that there will be a water supply shortage in any given month by year 2055.

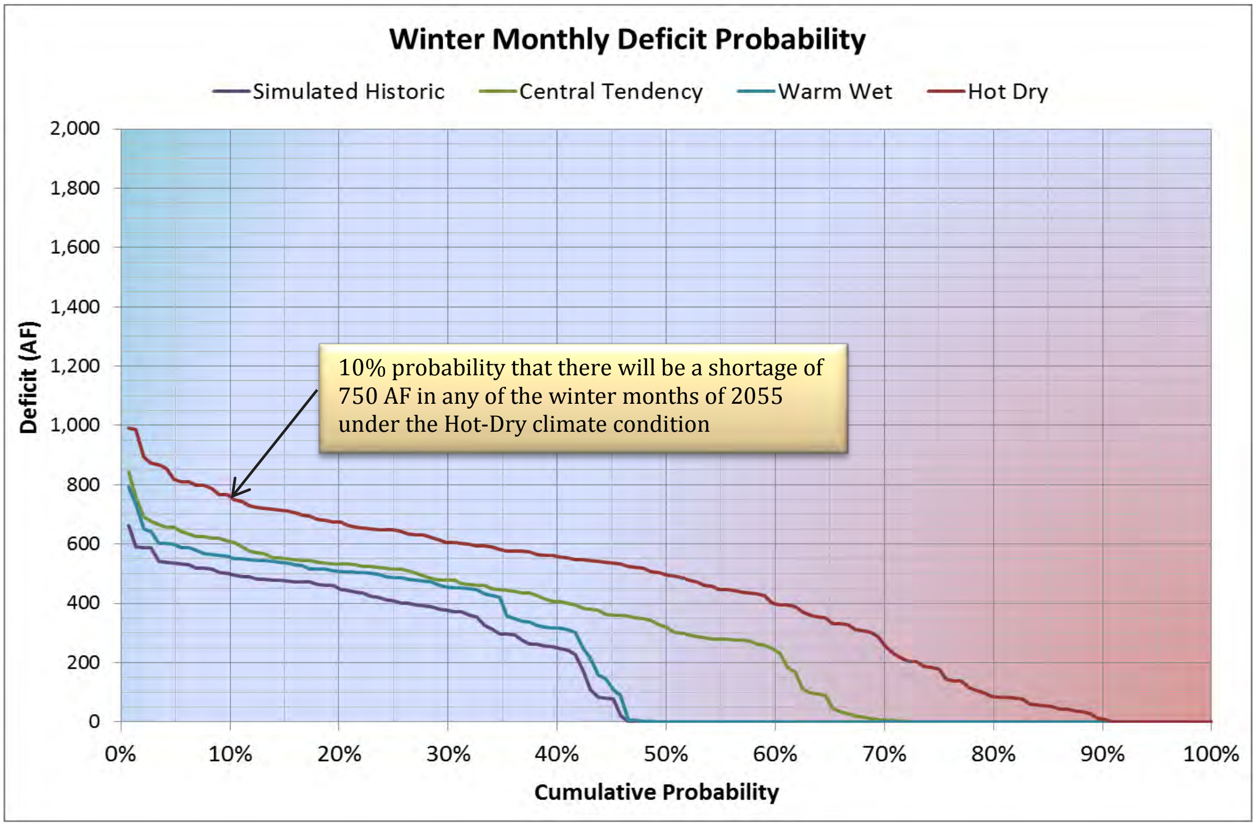
To better understand the seasonality of deficits, the summer and winter monthly probability curves for each climate change scenario were developed (Figure 4 and Figure 5). The summer months were designated as June, July, and August while the winter months are December, January, and February.



10% probability that there will be a shortage of 1,450 AF in any of the summer months of 2055 under the Hot-Dry climate condition

Figure 4. Probability Curves for the Summer Monthly Deficit for each Climate Change Scenario.

As expected, the summer months show a greater magnitude and frequency of deficits for all climate change scenarios. Within the summer months, the largest deficit occurs in the Hot-Dry scenario as compared to the Central Tendency and Warm-Wet scenarios. The summer monthly deficit ranges from zero to 1,900 AF over all climate change scenarios. As anticipated, the maximum deficit seen in the summer months is the overall maximum monthly deficit. Overall, it is very likely that there will be a monthly deficit during the summer by the year 2055. Therefore, adaptive strategies will be the most important in the summer months.



10% probability that there will be a shortage of 750 AF in any of the winter months of 2055 under the Hot-Dry climate condition

Figure 5. Probability Curves for the Winter Monthly Deficit for each Climate Change Scenario

During the winter months, the largest deficit occurs in the Hot-Dry scenario and is approximately 1,000 AF, considerably less than the summer maximum monthly deficit. The Central Tendency and Warm-Wet scenarios have a maximum deficit in the winter months of about 850 AF and 800 AF, respectively. The difference between the maximum deficits for each climate change scenario in the winter months is minimal. The significant difference in probability occurs when deficits of less than 400 AF occur. The monthly deficits predicted to occur during the winter are low in comparison to the summer months and annual deficits.

As mentioned previously, the supply gap and average annual supply mix was determined for each climate change scenario and includes eight water supply sources (Figure 6). These sources, in order of priority, include the San Juan-Chama Project supply, Native Rio Grande (RG) Rights, Canyon Road Water Treatment Plant (WTP), Osage Well, St. Mike's Well, Northwest (NW) Well, City Wells, and Buckman Wells. The Canyon Road WTP represents surface water supplies for the Santa Fe River reservoirs. The Osage Well, St. Mike's Well, and Northwest Well are also considered as part of the City Well field, but those supplies are tracked separately in Water Management and Planning Simulation (WaterMAPS) and thus are shown separately here.

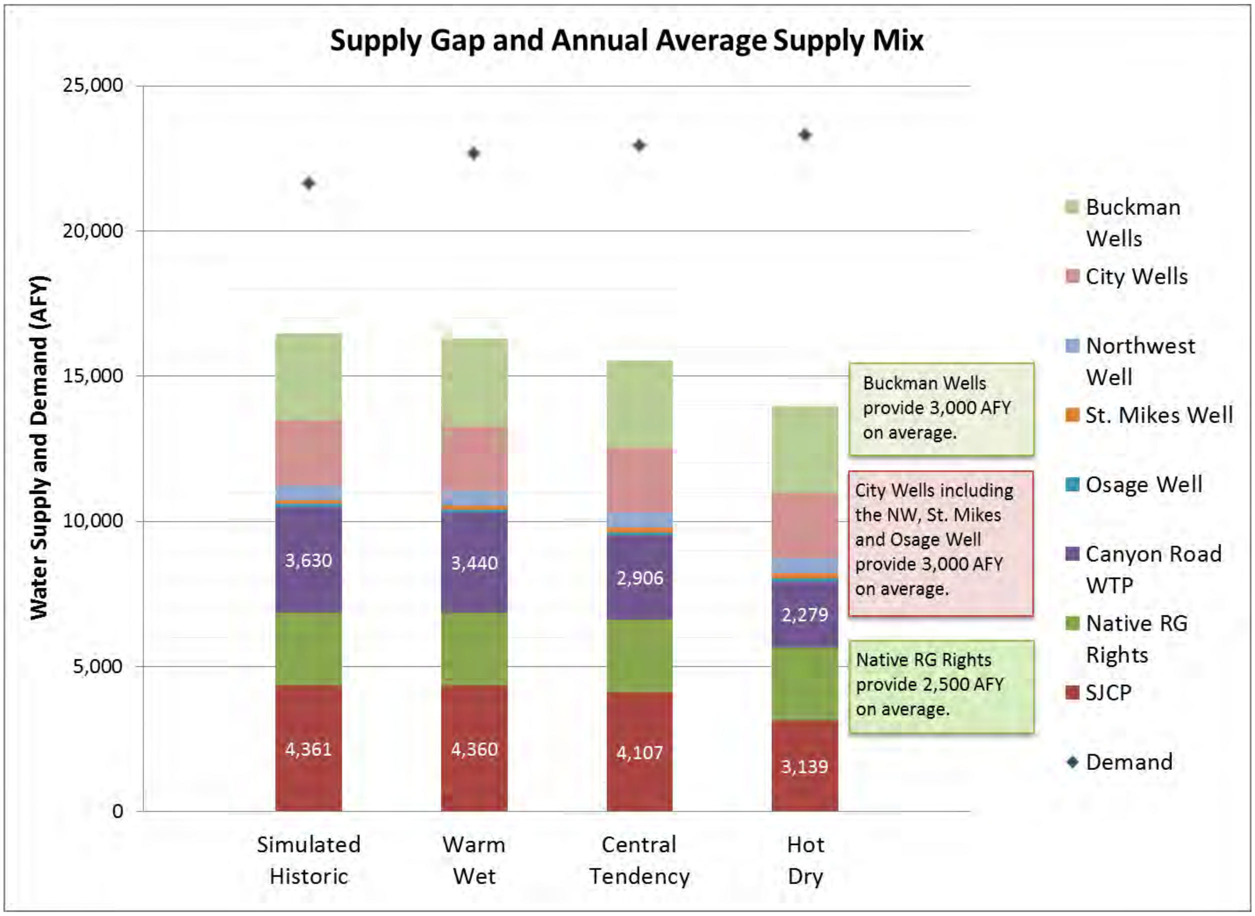


Figure 6. Supply Gap and Average Annual Supply Mix for each Climate Change Scenario

The largest water supply gap based on the annual average supply mix occurs in the Hot-Dry scenario and is approximately 9,300 AFY. The water supply gap for the Central Tendency and Warm-Wet scenarios are 7,400 AFY and 6,300 AFY, respectively. The water supply gap for baseline conditions (simulated historic), is 5,100 AFY.

Climate change was not applied to the supply from Native RG Rights, Osage Well, St. Mike’s Well, NW Well, City Wells, and Buckman Wells; therefore, they do not vary amongst the climate change scenarios. As an alternative, the management targets were used to restrict the groundwater supply due to their indeterminate availability in the future. The combined average annual supply from these sources is approximately 8,500 AFY. The San Juan-Chama Project water and Canyon Road WTP are significantly impacted by climate change conditions. As shown in Figure 6, the Hot-Dry scenario significantly impacts the Canyon Road WTP supply as well as the San Juan-Chama Project supply, which is expected as both of these supplies are dependent upon surface water availability.

Note that all the scenarios show a significant decrease in the availability of San Juan-Chama Project water from the annual right of 5,605 AFY (City and County total rights). There are two reasons for this. First, some of the San Juan-Chama Project water is being used to meet groundwater pumping offsets that could not be completely met by current offset water rights. Because these simulations assume no demand restrictions due to drought and no additional supplies being added over time, the system relies heavily on groundwater supplies. This results in greater offsets that need to be met. In reality, it is likely that the City and County would apply water-saving strategies or new surface supplies over time, which would reduce the use of groundwater on an average basis. This would, in turn, reduce groundwater pumping offsets that would need to be met and increase the San Juan-Chama Project water available for use.

The second reason for the reduction in San Juan-Chama Project supply is the climate-change-predicted availability of San Juan-Chama Project water in the future. This information was provided by Reclamation using the Upper Rio Grande Simulation Model (URGSiM) as described in Appendix B and programmed into WaterMAPS.

As mentioned, the monthly supply mix for each climate change scenario was developed for four conditions based on the Santa Fe River Flow: average annual, normal year, dry year, and wet year. Figures 7, 8, 9, and 10 show each of these conditions for the Simulated Historic, Warm-Wet, Central Tendency, and Hot-Dry climate change scenarios, respectively.

Figure 7a. Average annual monthly supply mix for simulated historic.

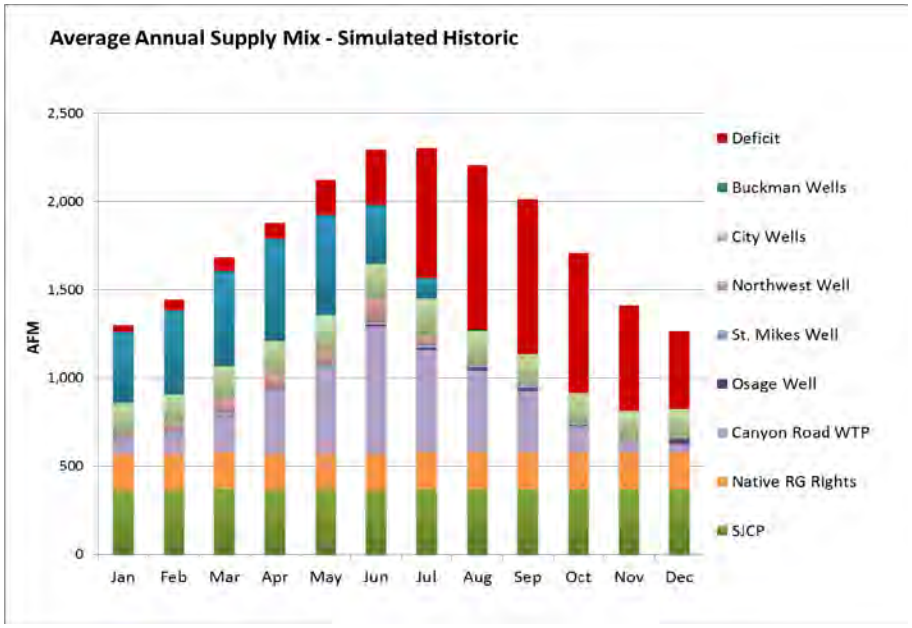


Figure 7b. Monthly supply mix for simulated historic during a normal year.

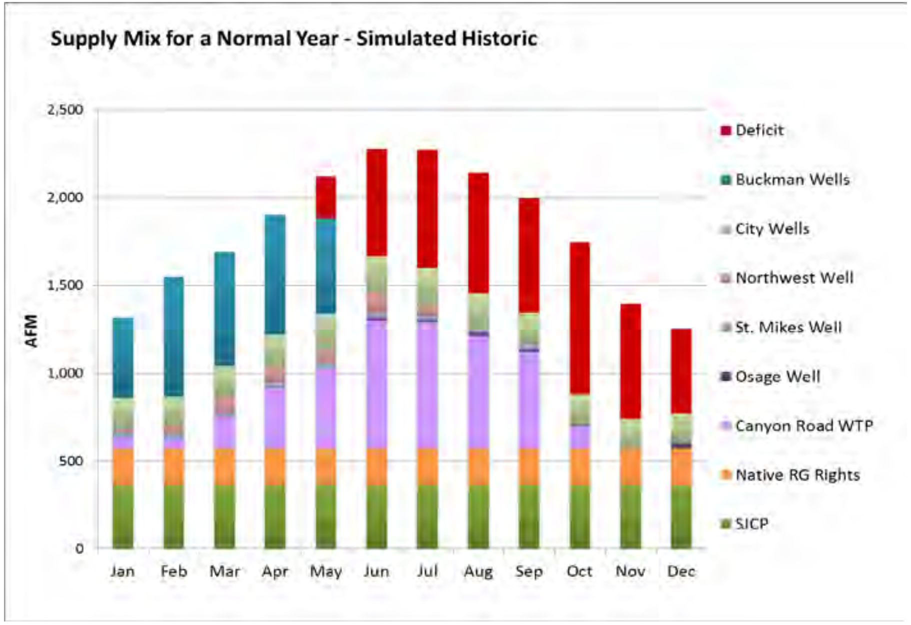


Figure 7c. Monthly supply mix for simulated historic during a dry year.

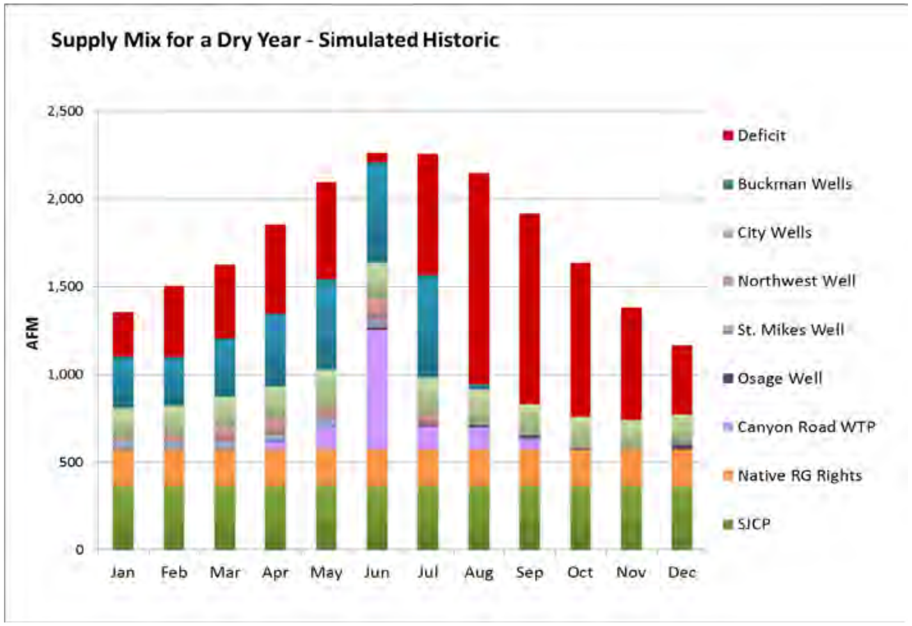


Figure 7d. Monthly supply mix for simulated historic during a wet year.

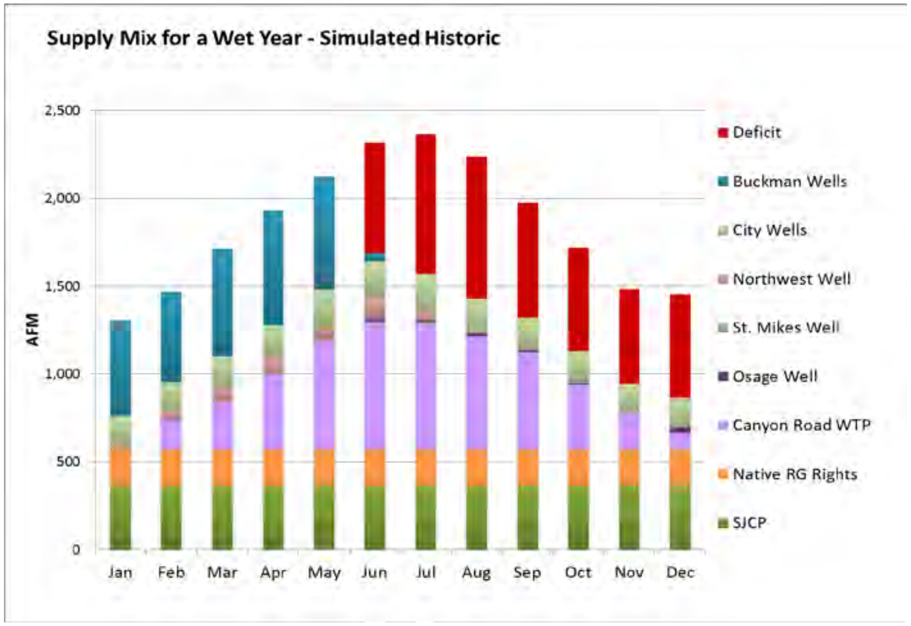


Figure 8a. Average annual monthly supply mix for warm-wet.

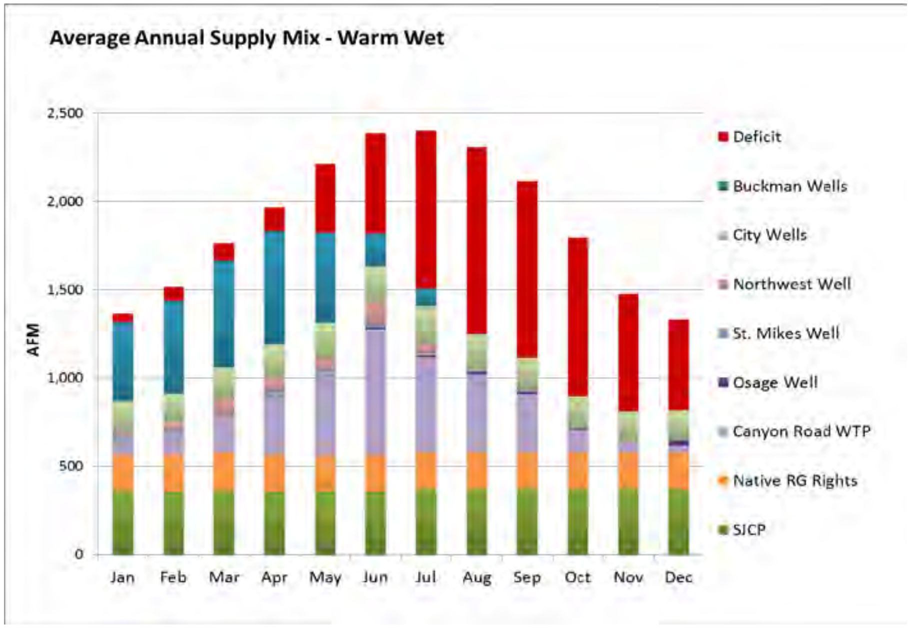


Figure 8b. Monthly supply mix for warm-wet during a normal year.

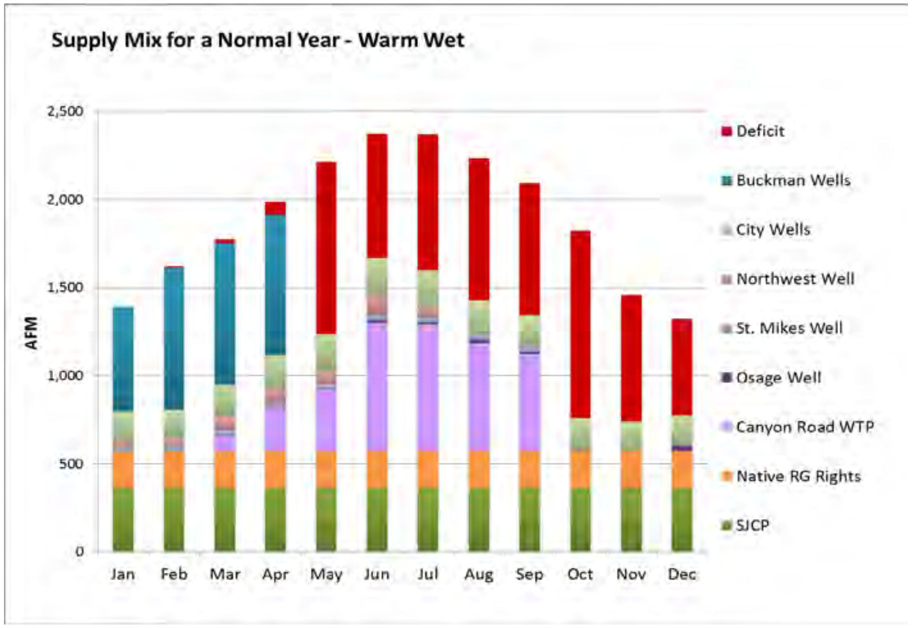


Figure 8c.Monthly supply mix for warm-wet during a dry year.

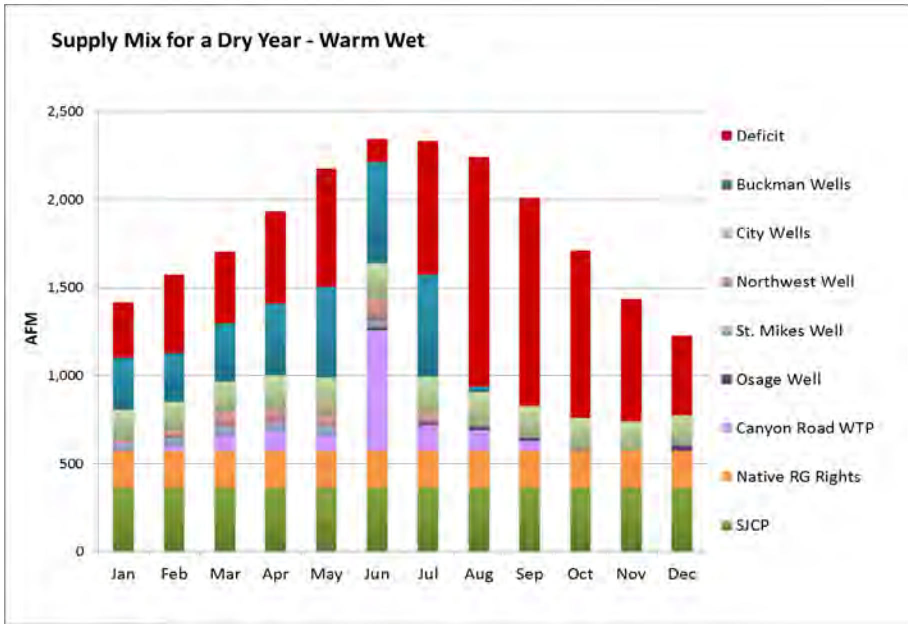


Figure 8d. Monthly supply mix for warm-wet during a wet year.

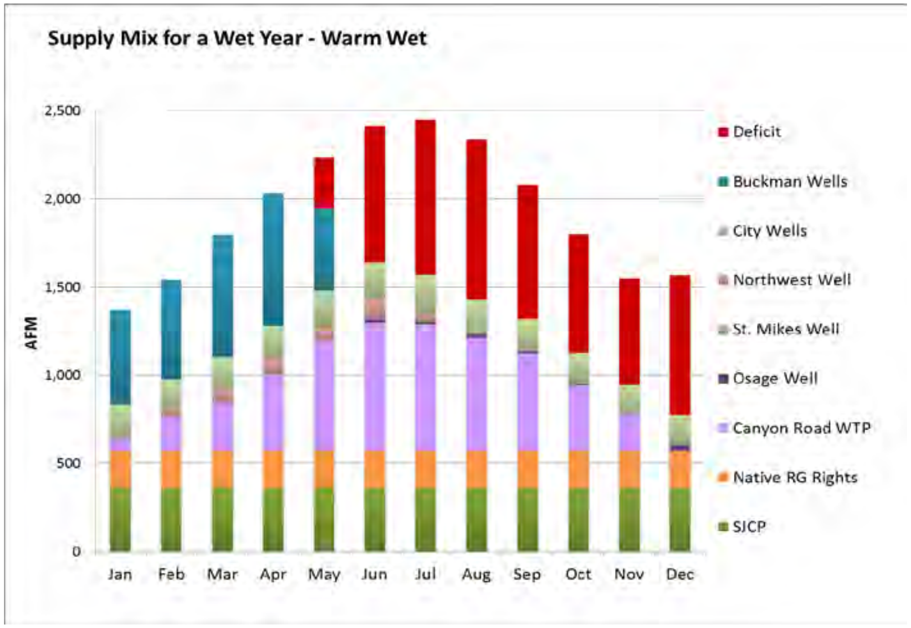


Figure 9a. Average annual monthly supply mix for central tendency.

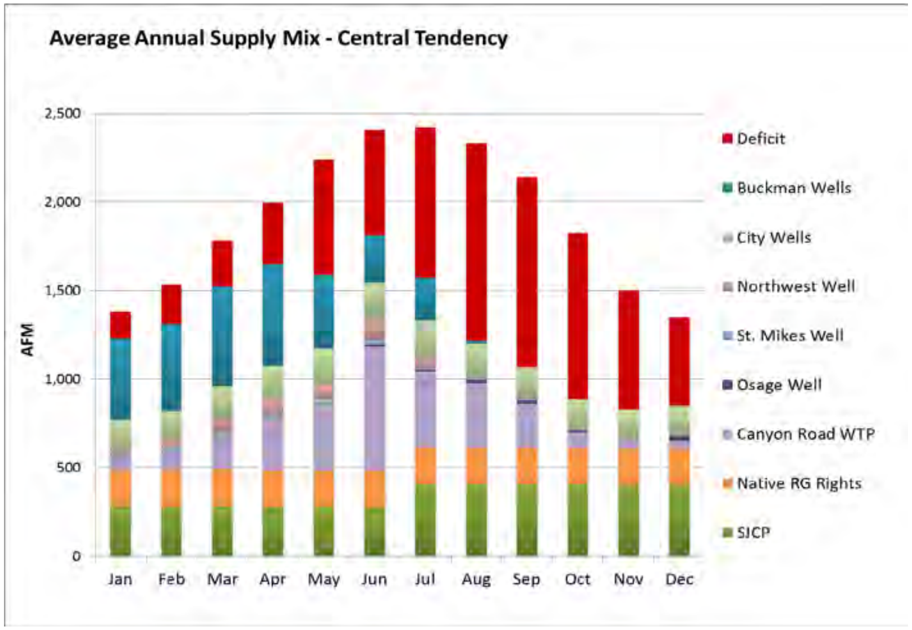


Figure 9b. Monthly supply mix for central tendency during a normal year.

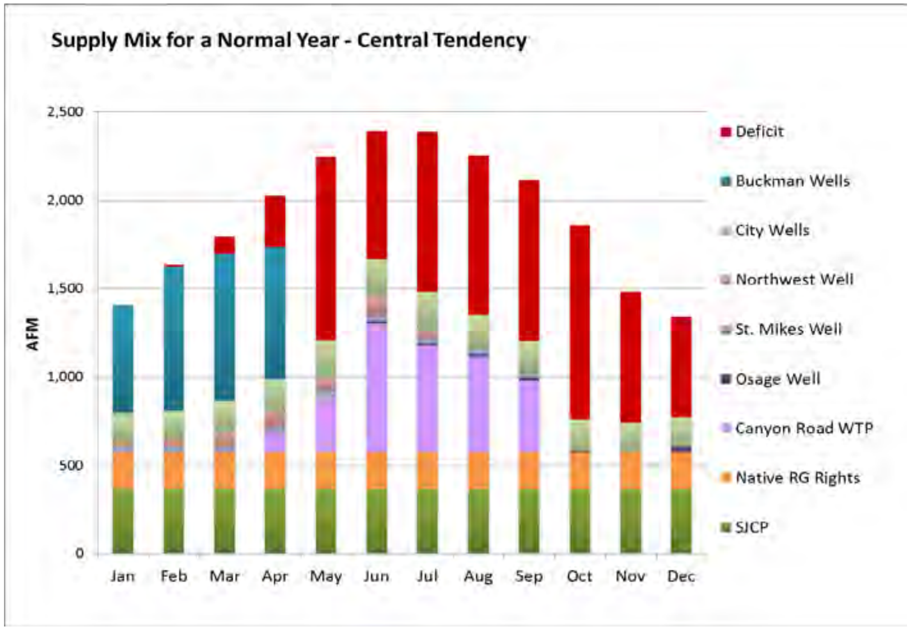


Figure 9c. Monthly supply mix for central tendency during a dry year.

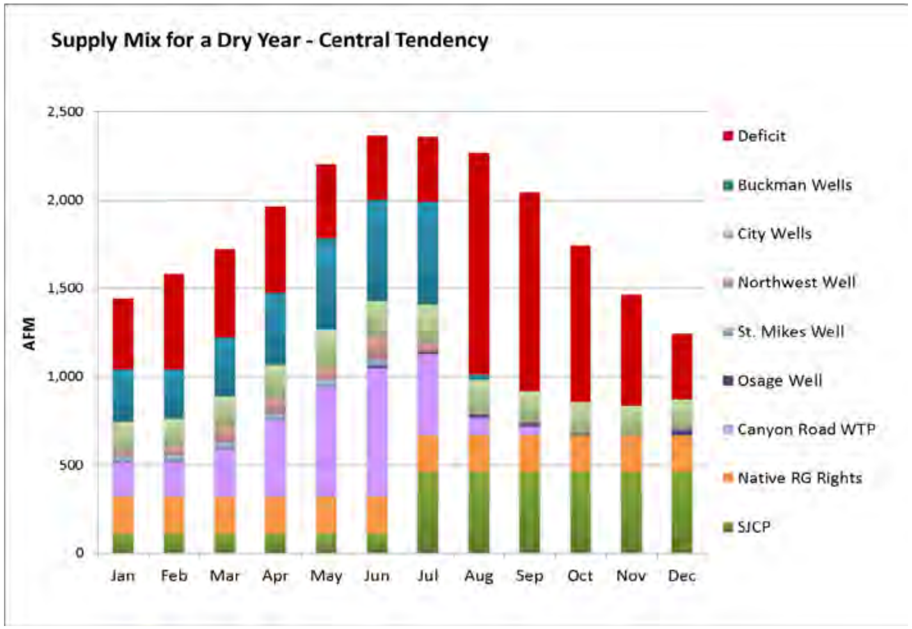


Figure 9d. Monthly supply mix for central tendency during a wet year.

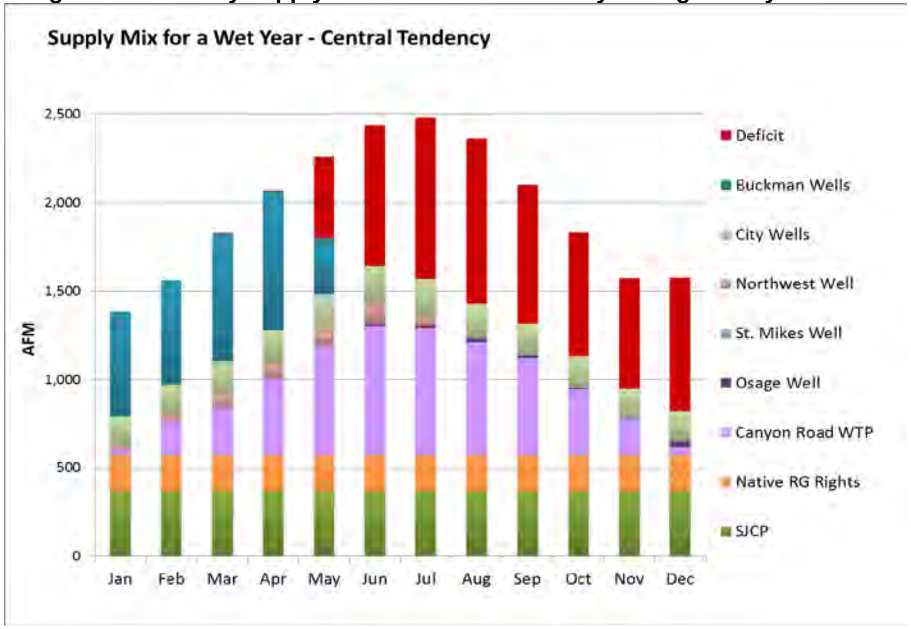


Figure 10a. Average annual monthly supply mix for hot-dry.

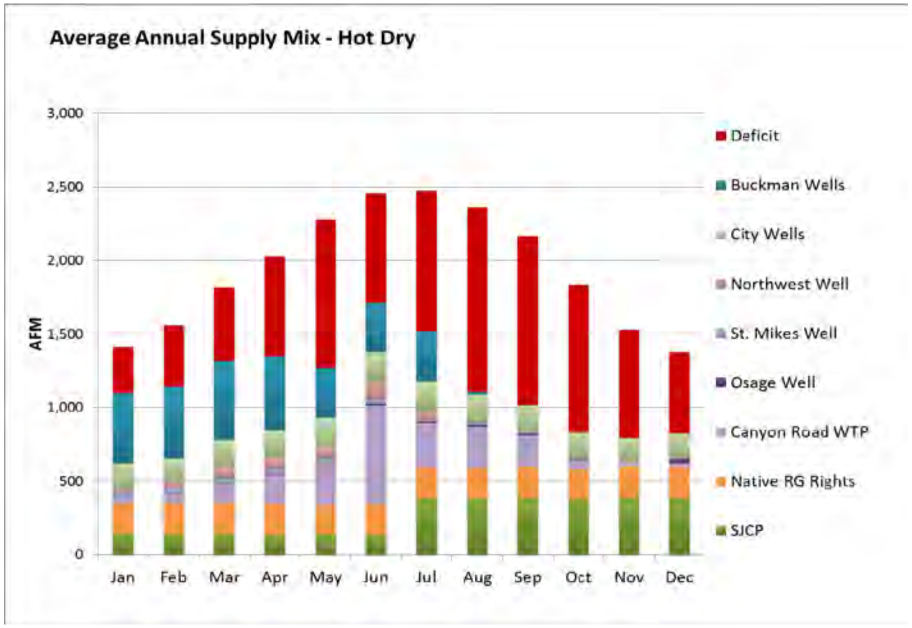


Figure 10b. Monthly supply mix for hot-dry during a normal year.

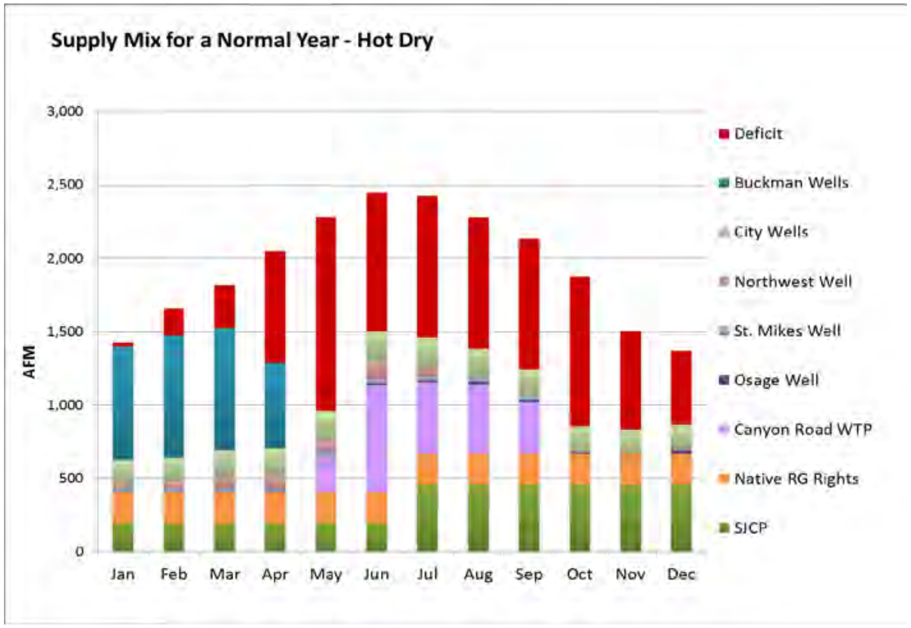


Figure 10c. Monthly supply mix for hot-dry during a dry year.

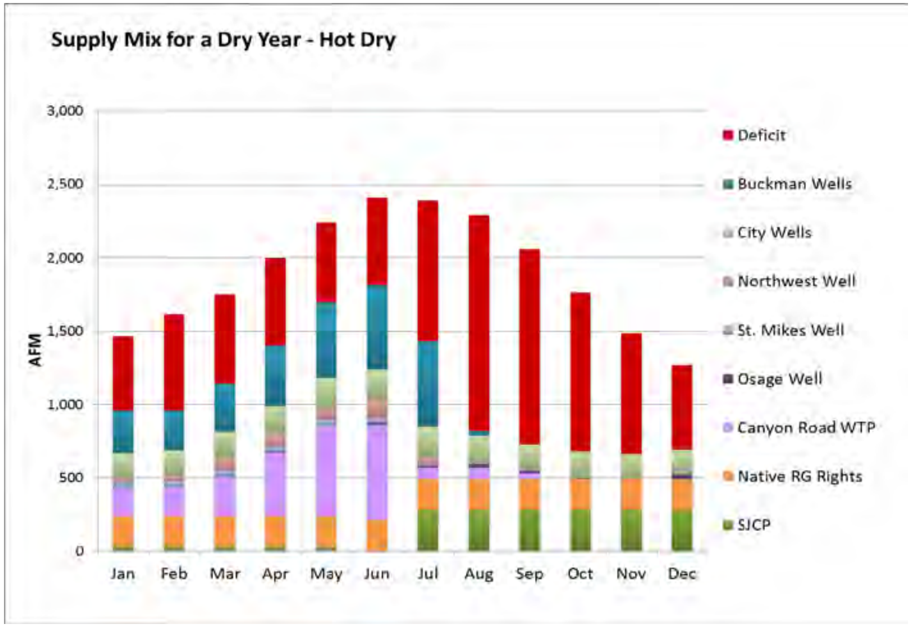
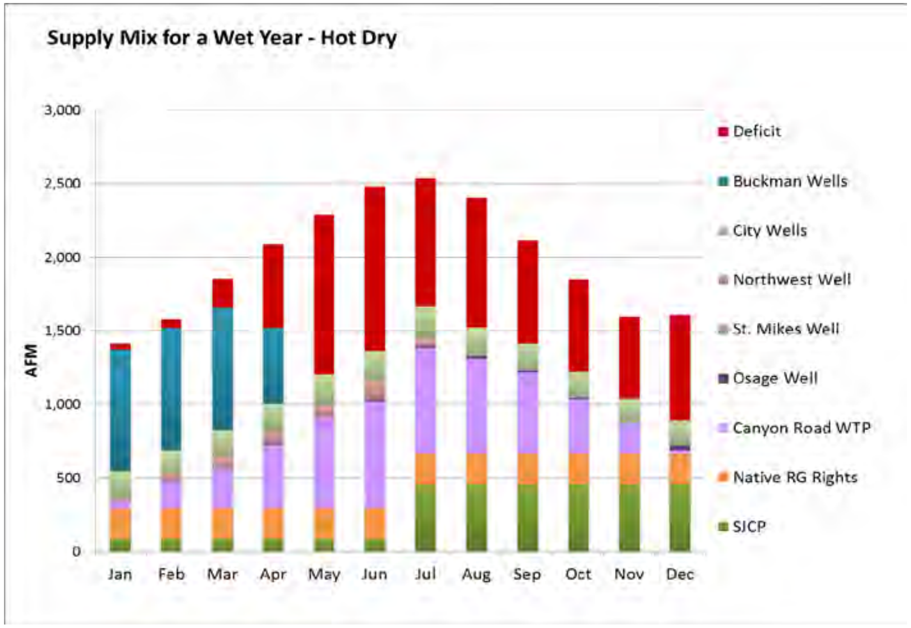


Figure 10d. Monthly supply mix for hot-dry during a wet year.



The supply mix graphs show the impacts of climate change on some of the supplies and the impact of some of the WaterMAPS programming with regards to the Buckman Well Field. In the Central Tendency and Hot-Dry scenarios (Figures 9 and 10), there are significant declines in the Canyon Road WTP supply (purple bar). This supply reduction is also seen during the dry year conditions for all scenarios (Figures 7c, 8c, 9c, and 10c). Because this supply depends on surface water availability, it is expected that climate change impacts would be substantial.

Also observed in the Central Tendency and Hot-Dry scenarios, the first six months of the year show a reduction in available San Juan-Chama Project water (green bar). This reduction is due to the climate-change-predicted availability of San Juan-Chama Project water that was provided by URGSiM and programmed into WaterMAPS. Note that the change occurs in six-month increments because that is how URGSiM produces the percent availability (see Appendix E, Section 4.4.1).

The Buckman Well Field (blue bar) also shows interesting results. WaterMAPS was programmed to employ different pumping schemes, depending upon whether the simulated year was considered dry, normal, or wet. For normal and wet years, water can be pumped from the Buckman Well Field up to the capacity of the system in any month, but it is then restricted by water rights or a management target for the year. For example, in Figure 10b, there are still deficits in January, February, and March because the capacity of the system was reached before the supply for the year was used. For dry years, the maximum pumping limit is subject to seasonality factors that distribute the maximum pumping limit over the entire year. These pumping schemes work well when there is enough supply in most years to cover demand. Because demand is significantly greater than supply, even wet and normal years have significant deficits.

The dry year results for the Buckman Well Field (Figures 7c, 8c, 9c, and 10c) also show that even though the pumping scheme is supposed to distribute the supply over the year, the supply barely lasts till August. This is because the management target established for this study (3,000 AFY) is less than the 5,000 AFY maximum pumping that was set as part of the simulation run. During a dry year, WaterMAPS applies a seasonal distribution based on 5,000 AFY, but then the 3,000 AFY maximum is reached before the year is over. This is an impact of the programming that was rectified as part of simulating the adaptation strategies discussed in Appendix G.

Monthly supply mix results show that the SJCP water, Native RG Rights, Canyon Road WTP, and City Wells including Osage, St. Mike's, and NW Wells with supplemental supply from the Buckman wells do not provide enough supply to meet projected demands. Management target constraints limit the supply that could be available from groundwater sources. Model runs were conducted to see if demands could be met if groundwater pumping was allowed up to the full amount of water rights available instead of being restricted by the management targets. Deficits were reduced significantly, but they could not be eliminated. For the Central Tendency and Hot-Dry scenarios, deficits were still greater than what could be managed without implementing additional adaptive strategies.

In summary, for all climate change scenarios there is a clear need for adaptive strategies that result in demand reductions and additional supply. The City and County are exploring different adaptive strategies including water conservation, water reuse, and aquifer storage and recovery (ASR) in addition to obtaining additional surface water rights.

Appendix G

Task 5: Develop and Analyze Adaptation Strategies

Santa Fe Basin, New Mexico

RECLAMATION
Managing Water in the West

County of Santa Fe · State of New Mexico · 1852 ·

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Sandia National Laboratories

CDM Smith

Contents

This appendix provides the text of a technical memorandum from Kelly Collins, PG, BCES, CDM Smith, to Claudia Borchet, Santa Fe County, dated September 12, 2014. This memo summarizes Task 5 of the Santa Fe Basins Study, which entails developing adaptation strategies to be used in the evaluation of alternatives for meeting demands under projected climate conditions.

1 Introduction

A methodical decision process was used to compare and evaluate the alternatives for adapting to projected climate scenarios. The overall process has four steps:

1. Identify adaptation strategies appropriate for the Santa Fe area
2. Combine the adaptation strategies into alternative climate mitigation portfolios
3. Develop evaluation criteria and weight each criterion based on the relative importance of the criterion
4. Rank the climate mitigation portfolios based how well they meet the criteria

This memo presents the results of each step in the decision process and the selection of the climate mitigation portfolio that best meets water needs of the City and County of Santa Fe under projected climate change scenarios.

2 Identify Adaptation Strategies

Representatives of the City and County identified the adaptation strategies for meeting water demands under climate change scenarios, which are appropriate for the arid climate and landscape of the Santa Fe region. For example, water storage is an important adaptation strategy, but building additional storage reservoirs was not considered an appropriate adaption strategy because of the high evaporation losses off of reservoirs and the limited areas available for constructing storage reservoirs. Instead, underground storage of water through an aquifer storage and recovery (ASR) system is considered appropriate because evaporation losses are negligible and the surface land area required is small compared to a traditional surface reservoir. The adaptation strategies selected for the Santa Fe Basin Study are summarized in Table 1 and described in the following sections.

Table 1: Adaptation Strategies for Santa Fe Region

Adaptation Strategy	Description	Infrastructure Components
Direct Reclaimed Water Reuse	Use reclaimed water from the City wastewater treatment plant to meet contract obligations; remaining reclaimed water for potable reuse or return flow credits for pumping	New conveyance for reclaimed water from wastewater treatment plant to existing Buckman Regional Water Treatment Facility and distribution system or new conveyance to the Rio Grande for return flow credits
Water Conservation	Reduce water use on a per person per day basis	None
Direct Injection for Aquifer Storage and Recovery	Inject treated water into the aquifer in wet and normal years for use in dry years	Construction and operation of injection well(s); withdrawal using existing wells and distribution system
Infiltration for Aquifer Storage and Recovery in the Santa Fe River Channel via Aquifer Storage and Recovery	Maintain flow in the Santa Fe River to induce infiltration into the aquifer for use in dry years	Withdrawal using existing wells and distribution system.
Additional Surface Water Rights	Additional surface water would be diverted at the Buckman Direct Diversion and treated at the Buckman Regional Water Treatment Facility	Existing diversion, conveyance, treatment, and distribution systems

2.1 Direct Reclaimed Water Reuse

Reclaimed water is currently used in the City as described in the City of Santa Fe Reclaimed Wastewater Resource Plan (Santa Fe 2013) (RWRP). The RWRP outlines specific allocations for reclaimed water use. The total annual contracted reclaimed water demand is about 3,489 acre-feet per year (AFY). For this Basin Study, it was not necessary to vary the supply of reclaimed water based on the climate change scenarios because reclaimed water is from indoor water use, which is not expected to vary significantly in response to climate change.

Water discharged from the City of Santa Fe wastewater treatment plant that is not used by one of the reclaimed water contracts, about 6,000 AFY by 2055, is considered as an additional supply. Due to the seasonality of demands and constraints set in WaterMAPS regarding the infrastructure and how this source is utilized, the ability to use the full supply under current reclaimed water use practices is significantly reduced. The simulated supply is presented in later sections. This study considered two new beneficial uses for reclaimed water:

- Treatment at the Buckman Regional Water Treatment Facility for potable supply

- Return flow credits for discharges to the Rio Grande

Discharge from the Quill wastewater treatment plant, owned and operated by Santa Fe County, was not included in the Santa Fe Basin Study, but represents an additional source of reclaimed water in the study area.

2.2 Water Conservation

The City began a Water Conservation Program in 1997, building a comprehensive and effective program which has resulted in Santa Feans reducing per capita water consumption by more than 39 percent since tracking began in 1995. Reducing gallons per capita per day (gpcd) is one measure of success for any water conservation program, and Santa Fe is a leader in the Southwest. The current annual unit water demand averages 114 gpcd, as determined from monthly water production data provided by the City and the City population data from 2002 to 2010.

For this adaptation strategy, the maximum conservation realistically achievable was considered to be a decrease of 20 gpcd, to a unit demand of 92 gpcd. Water demand under the climate change scenarios was specifically varied based on the predicted temperature and precipitation.

2.3 Direct Injection for Aquifer Storage and Recovery

This adaptation strategy would inject treated water from one of the City’s other sources into an aquifer that has been developed by the City for water supply (e.g., Buckman Well Field) for storage and later use of the water in a process commonly referred to as aquifer storage and recovery (ASR). The ASR process uses water from above ground to recharge a groundwater aquifer. ASR can be achieved by active means, usually direct injection, or through passive methods, primarily infiltration.

Large scale implementation of ASR through direct injection wells is not currently in widespread use, but ASR is assumed for this adaptation strategy because all of the water injected into an aquifer can be withdrawn under a permit from the New Mexico Office of the State Engineer and it minimizes the amount of land required for implementation.

ASR projects must comply with the requirements of the Ground Water Storage and Recovery Act, NMSA 1978, §72-5A-2 and the New Mexico Underground Storage and Recovery Regulations and Underground Injection Control (UIC) regulations.

The Ground Water Storage and Recovery Act is the legal mechanism for aquifer storage and recovery. In enacting the Act, the Legislature specifically found that the “conjunctive use and administration of both surface and ground waters are essential to the effective and efficient use of the state’s limited water supplies” and that ground water recharge, storage and recovery have the potential to reduce the rate of aquifer decline, promote conservation, serve public welfare, and lead to more effective use of water resources. Water stored pursuant to the Act is exempt from forfeiture (NMSA 1978, §72-5A-8). The amount of water that can be recovered is only the amount of water recognized and approved by the State Engineer that has reached the aquifer, remained within the area of hydrologic effect, and may be recovered without impairment to water rights or harm to land owners within the area of hydrologic effect. These constraints on the amount of water that can be recovered from the aquifer must be quantified by the pilot/demonstration testing described below. The determination of the amount of water that can be recovered will be an important factor in decisions regarding the extent to which direct injection ASR is appropriate in the Santa Fe Basin.

Water can be stored pursuant to this statute only by permit, and a number of criteria must be met before a permit will be issued (NMSA 1978, §72-5A-6). The State Engineer has adopted Underground Storage and Recovery regulations (19.25.8.1 NMAC). These regulations govern the application process; the hydrologic, technical and financial capability report requirements; and the permit terms and conditions authorized under the Act.

The application procedure for an Underground Storage and Recovery Permit is a two-step process:

1. **Pilot/Demonstration Project:** This step is intended to collect and evaluate technical information to determine the feasibility of a full-scale, long-term project. An application for a Pilot/Demonstration Project Permit must include a complete description of the pilot/demonstration project, a Capability Report for the pilot/demonstration project, and a preliminary description of the full-scale project (including an estimate of the area of hydrologic effect and the scope and purpose of the full-scale project).

2. **Full-Scale Project:** This step includes the permit application for the full-scale project and must include a complete description of the full-scale project, findings from the pilot/demonstration project, and a Capability Report for the full-scale project that is based on the information gathered during the pilot/demonstration project (Step 1).

Storage of water under the Act would also have to comply with all requirements of New Mexico's Underground Injection Control (UIC) Program, as implemented through the Water Quality Act (NMSA 1978, §74-6-1 et seq.) and the UIC regulations (20.6.2.5000 NMAC). The UIC regulations control discharges from UIC wells to protect groundwater that has an existing concentration of 10,000 mg/L or less of TDS. Groundwater management injection wells used to replenish water in an aquifer are considered Class V UIC. Pursuant to the UIC regulations, a groundwater discharge permit must be obtained from the New Mexico Environmental Department (NMED) prior to use of a groundwater management injection well.

A Groundwater Discharge Permit application must include the methods or techniques that will be used to ensure compliance with groundwater quality regulations (Sections 20.6.2.3000 through 20.6.2.3999 NMAC and Sections 20.6.2.5000 through 20.6.2.5006 NMAC).

This adaptation strategy would use water made available through the acquisition of additional surface water rights through the City's Water Rights Transfer Program (Section 2.5), treat the water at the Buckman Regional Water Treatment Facility to meet drinking water standards, and directly inject the water in the aquifer at or near existing water supply wells. It is assumed that the water rights used for this strategy can be permitted by the OSE with dual purposes: it can be used for meeting return flow credits and for ASR. The concept of water rights permits with dual purposes has been discussed with the Office of the State Engineer, but no dual purpose permits have been applied for or issued to date.

It is possible that an existing well(s) could be modified to act as an injection well. A study previously conducted for the City found that hydrogeologic conditions at Buckman wells 11 through 13 are suitable for ASR. Modeling results showed that approximately 500 gallons per minute (gpm) of water could be injected into each Buckman 11 and 13 on a seasonal basis or for several years at a time. Buckman 12 is limited to an injection rate of 250 gpm. A new injection well(s) could also be constructed for this adaptation strategy.

Withdrawal of water under this adaptation strategy is assumed to be through existing water supply wells and conveyed through the existing distribution system. Water would be injected in wet to normal years and would build up over time. The water could be withdrawn and used in normal to dry years. A maximum cap of 5,000 AFY of accumulated storage was assumed for this adaptation strategy.

2.4 Infiltration for Aquifer Storage and Recovery in the Santa Fe River Channel via Aquifer Storage and Recovery

Large scale implementation of ASR using passive methods of ASR through natural or engineered infiltration systems have been implemented in at numerous locations in the United States. This adaptation strategy takes advantage of flow in the Santa Fe River as a natural infiltration system that recharges the aquifer. This process occurs whenever water is flowing in the Santa Fe River, but this adaptation strategy would entail satisfying the requirements of both the Ground Water Storage and Recovery Act, NMSA 1978, §72-5A-2 and the New Mexico Underground Storage and Recovery Regulations and UIC regulations (as described in Section 2.3) to be able to withdraw the water that has infiltrated.

An ordinance and associated administrative procedure (City of Santa Fe, New Mexico, Ordinance No. 2012-10 and City of Santa Fe, Administrative Procedures for Santa Fe River Target Flows) was adopted in February 2012 to provide for releasing 1,000 AFY from the City's Nichols Reservoir to the Santa Fe River. The purpose of the Santa Fe River Target Flow is to increase water flow in the river below the City's reservoirs in order to maintain a "living river," except under emergency (i.e., drought) conditions. The administrative procedure outlines specific hydrographs for daily releases throughout the year based on the expected annual yield. For normal and wet years, the annual target is 1,000 AFY. This target decreases in dry and critical years according to the percent of normal annual yield expected (see Appendix E, Section 4.2.6 for more information).

ASR through infiltration in the Santa Fe River would be permitted for two areas:

- The upper Santa Fe River where releases from upstream reservoirs maintain flow in the river

- The lower Santa Fe River where flow in the river is maintained by discharge from the City Wastewater Treatment Plant

The amount of water expected to be available for ASR is a percentage of the released water flowing in the Santa Fe River. In the upper Santa Fe River, the Santa Fe River Target Flow was modeled using Water Management and Planning Simulation (WaterMAPS), based on hydrographs representing daily releases required to meet the desired target flow. Each hydrograph is different based on the percent of normal expected annual yield (e.g. "Dry – 70%" means the expected annual yield is 75 percent of normal). If the expected annual yield is 30 percent or less of normal, the "Critical-Dry" hydrograph is used. This means that even under drought conditions, the City plans to release at least 300 AFY to support in-stream flows in the Santa Fe River.

The "infiltration rate" is that portion of stream flow that is assumed to infiltrate the stream bottom and recharge the aquifer. The assumed infiltration rate is in line with the rate granted by the State Engineer for a similar project in Albuquerque, the Bear Canyon Arroyo. Also, the rate is not inconsistent with infiltration studies completed for the Santa Fe River. For this adaptation strategy, the infiltration rate was assumed to be up to 70 percent of stream flow. Withdrawal of water under this adaptation strategy is assumed to be through existing water supply wells and conveyed through the existing distribution system. There is projected to be sufficient water for flow in the Santa Fe River in wet to normal years and the stored water from infiltration is projected to accumulate over time. The water could be withdrawn and used in normal to dry years. A maximum cap of 2,000 AFY of accumulated storage was assumed for this adaptation strategy.

For the lower Santa Fe River, the flow of reclaimed water released from the City's wastewater treatment plant to the Santa Fe River is used to estimate infiltration. The amount of flow in this portion of the Santa Fe River is constrained by the amount of reclaimed water used to supply reclaimed water contracts or for direct use (Section 2.1). The maximum infiltration rate (70 percent) and cap of accumulated water storage (2,000 AFY) are the same as for the upper Santa Fe River infiltration adaptive management strategy.

2.5 Additional Surface Water Rights

This adaptation strategy is based on obtaining additional surface water rights and using the Buckman Direct Diversion Project infrastructure to divert, convey, and treat the water. The treated water could be directly distributed through the water distribution system or could be injected for ASR.

The City has established the Water Right Transfer Program, which links new development to water. Large scale development projects are required to purchase water rights from outside of the City system and to transfer those rights to the City in order to offset the increased demand associated with their projects. Future water from conservation provides dual benefits: as a decrease in demand and an increase in supply. The amount of additional surface water rights expected to be available through the Water Right Transfer Program is expected to be a maximum of about 35 AFY each year, based on historical trends in this program. This value is quite small relative to other adaptation strategies evaluated in this study.

3 Alternative Climate Mitigation Portfolios

The adaptation strategies described in Section 2 were used to develop portfolios of strategies that, if implemented, could mitigate the impact of climate change on the water supply for the Santa Fe area:

Single adaptive strategies:

Portfolio 1: Conservation Only
Portfolio 2: Direct Reuse Only
Portfolio 3: Additional Water Rights Only

Combined adaptive strategies:

Portfolio 4: More Conservation & Water Rights (Reuse to Potable)
Portfolio 5: More Conservation & Water Rights (Reuse to Return Flow Credits)
Portfolio 6: More Infiltration Aquifer Storage and Recovery
Portfolio 7: More Direct Reuse (Potable Use)
Portfolio 8: More Direct Reuse (Return Flow Credits)

The adaptive strategies in each portfolio were varied with ranges that were considered realistic by the planning team. For example, conservation was varied between maximum, moderate, and smallest decrease in water use. The gap between water supply and demand under the climate change scenarios is described in detail in Appendix F and is summarized in Table 2, below. A water supply gap of about 5,000 AFY in 2055 is projected to occur under simulated historic climate conditions (assuming a climate similar to historic), but the magnitude of the water supply gap increases under any of the three climate change scenarios: the smallest gap under the warm-wet scenario and largest gap under the hot-dry scenario. The Central Tendency climate change scenario represents future conditions between warm-wet and hot-dry scenarios. The Central Tendency climate change scenario is considered to be the most appropriate for planning purposes.

The systems model WaterMAPS was used to simulate each portfolio to determine if they could meet demand under climate-change conditions. It is important to understand that WaterMAPS employs several constraints that may reduce the supply available for a particular adaptation strategy within a portfolio. These include capacity, water rights, seasonal, and hydrologic condition (wet, dry, or normal year) constraints. Additional constraints are then applied based on the individual strategy as discussed in Section 2.

Table 2: Santa Fe Basin Projected 2055 Water Supply Gap (Annual Average)

	Climate Change Scenario			
	Simulated Historic (no climate change)	Central Tendency	Warm Wet	Hot Dry
Total Demand - Average Annual (AFY)	21,643	22,925	22,646	23,299
Total Supply - Average Annual (AFY)[1]	16,488	15,549	16,304	13,976
Water Supply Gap – Difference between Demand and Supply (AFY)	**(5,155)**	**(7,376)**	**(6,343)**	**(9,323)**

1. Supply based on simulation in WaterMAPS with groundwater use limited by management targets, which are less than the water rights.

In developing the results for the portfolios, groundwater pumping management targets used to develop Table 2 were found to be too restrictive, causing a high frequency of shortages that could be easily managed by allowing more pumping in some years. To alleviate this, groundwater pumping was allowed to be used up to the available water right. With the Buckman Well Field representing the last priority supply, the supply was only used when and up to the extent it was needed. The average Buckman pumping then becomes part of the performance criteria used to evaluate each portfolio, which will be described in Section 4. The portfolios and the simulated supply, including groundwater pumping beyond the management target, are summarized in Table 3.

Table 3 – Santa Fe Basin Study Portfolios and Simulated Supply

Simulated Supply from Adaptation Strategy	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6	Portfolio 7	Portfolio 8
	Conservation Only	Direct Reuse Only	Additional Water Rights Only	More Conservation & Water Rights (Reuse to Potable)	More Conservation & Water Rights (Reuse to Offsets)	More Infiltration ASR	More Direct Reuse (to Potable)	More Direct Reuse (to Return flow credits)
Direct Reclaimed Water Reuse (AFY)		4,024		2,224	2,224		3,243	3,243
Conservation (AFY)	4,005			4,005	4,005	3,003	2,002	2,002
Direct Injection Aquifer Storage and Recovery (AFY)				559	559	0		
Infiltration Santa Fe River Aquifer Storage and Recovery (AFY)				149	149	2,841	148	148
Additional Water Rights (AFY)			1,400	1,400	1,400	1,400	920	920
Buckman Well Field Pumping Beyond 3,000 AFY	2,674	2,225	4,451	0	0	291	323	323
Portfolio Simulated Additional Supply (AFY)	**6,679**	**6,249**	**5,851**	**8,337**	**8,337**	**7,535**	**6,636**	**6,636**

Each portfolio was evaluated to determine if the portfolio met basic reliability criteria. The reliability criteria were established to ensure that only portfolios that can reliably provide water supply were considered further. The reliability criteria are:

1. ***Average Buckman Well Field pumping does not exceed the management target by more than 500 AFY on average*** –The current management target for the Buckman Well Field is 3,000 AFY but water rights equal 10,000 AFY. It was determined that a 500 AFY increase in average pumping was acceptable for this planning-level analysis.

2. ***Deficit in any year does not exceed 2,000 AFY*** **–** Based on the assumption that in emergency situations conservation of 10 gpcd is realistic and would fill a temporary gap of 2,000 AFY in 2055.

3. ***No more than 10 percent probability of deficits over 100 AFY*** **–** Based on the assumption that the system can accommodate small deficits that cannot be reliably simulated with the model. To account for model "noise," over 10 percent probability of deficits are accepted if they are less than 100 AFY.

Performance criteria (Section 4) were also developed to further evaluate only the portfolios that meet the reliability criteria above.

Each portfolio is presented in the following sections with results from WaterMAPS. Note that because of the change from constraining groundwater pumping by management targets to water rights, the supply gap is reduced by both the portfolio and the additional groundwater pumping over the management target. The management target for the Buckman Well Field is 3,000 AFY.

3.1 Portfolio 1: Conservation Only

Portfolio 1 consisted solely of conservation to see if the projected effects of climate change could be ameliorated by conservation alone. This portfolio is based on a 20 gpcd decrease in water use, to a total of 94 gpcd. This portfolio could be implemented with an increase in water conservation education and enforcement, but no new infrastructure would be required. The simulated supply created by this level of conservation is 4,005 AFY. Supply from Buckman pumping in excess of the management target is approximately 2,674 AFY. In the absence of climate change, Portfolio 1 can meet the gap between supply and demand but significantly more groundwater pumping is needed. The cumulative probability of annual deficits under the Central Tendency climate change scenario for Portfolio 1 is shown in Figure 1.

The annual deficit probability curve in Figure 1 shows that the maximum annual deficit is 1,372 AFY and at 10 percent cumulative probability the annual deficit is 391 AFY. Portfolio 1 does not meet two of the three reliability criteria as shown in Table 4. Additional analysis of this portfolio showed that conservation of 40 gpcd (total of 74 gpcd) would result in a portfolio that would meet the reliability criteria. However, the ability of the City and County to consistently reduce demand by 40 gpcd is too uncertain to use this conservation goal in planning. The goal itself remains as part of utility management efforts and conservation outreach.

Table 4 – Performance of Portfolio 1 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	Maximum Annual Deficit < 2000 AFY	Annual Deficit at 10% probability < 100 AFY
Portfolio 1: Conservation Only	NO (exceeds by 2,674)	YES (1,372 AFY maximum annual deficit)	NO (391 AFY annual deficit at 10% probability)

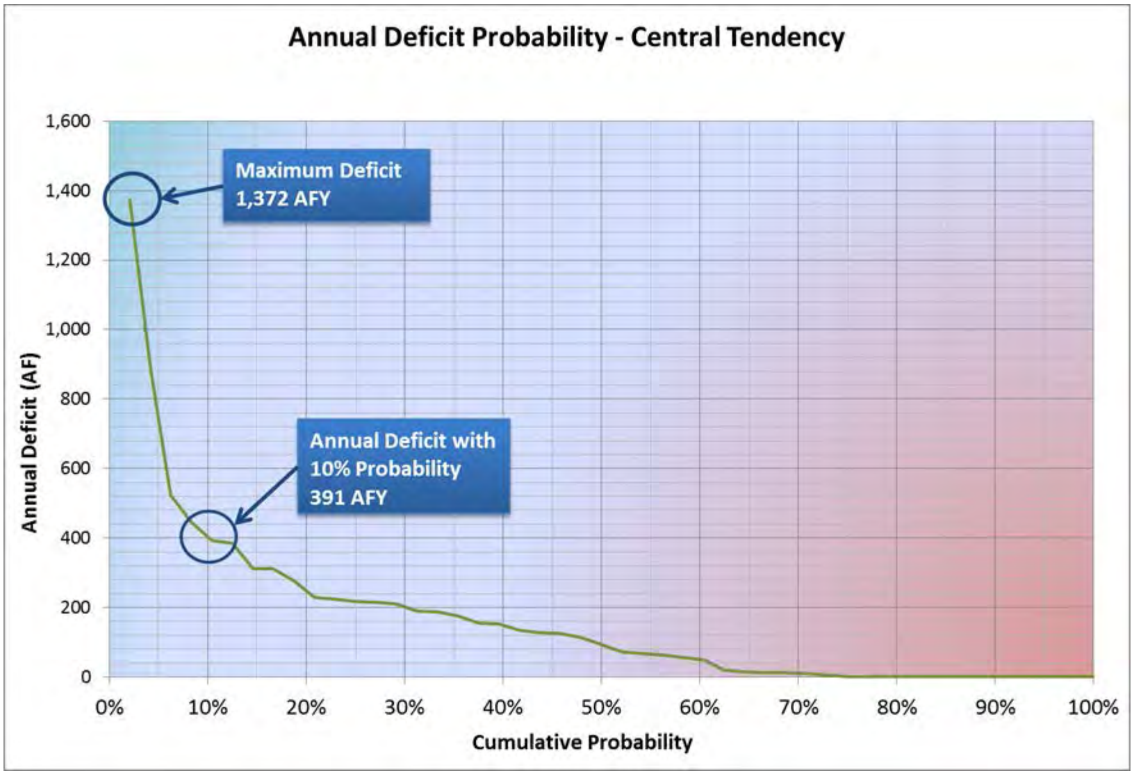


Figure 1: Santa Fe Basin Portfolio 1 Annual Deficit Probability Curve under Central Tendency Climate Scenario

3.2 Portfolio 2: Direct Reuse Only

Portfolio 2 consists solely of the direct reuse of reclaimed water. Similar to Portfolio 1, the purpose of Portfolio 2 was to assess if the projected 2055 water supply gap could be filled by reuse of reclaimed water alone. The portfolio assumes that effluent from the City Wastewater Treatment Plant is conveyed by new infrastructure to the Buckman Regional Water Treatment Facility. The reclaimed water would be treated to drinking water standards and delivered for potable use through the existing distribution system. Alternatively, new piping could be installed to deliver the treated water to the Rio Grande for return flow credits.

Portfolio 2 assumes that 1,734 AFY (about 50%) of the 3,489 AFY existing reclaimed water contracts is delivered. The remainder is delivered for potable reuse. The simulated average annual supply for Portfolio 2 is 4,024 AFY. Supply from Buckman pumping in excess of the management target is approximately 2,225 AFY. In the absence of climate change, Portfolio 2 can meet the gap between supply and demand but significantly more groundwater pumping is needed. Figure 2 illustrates that the maximum annual deficit is 1,159 AFY and the annual deficit at 10 percent probability is 378 AFY.

Portfolio 2 does not meet two of the three reliability criteria as shown in Table 5. Additional analysis of this portfolio showed that if the reuse was assumed to be 6,696 AFY, the resulting portfolio that would meet the reliability criteria. However, this would mean that most of the existing reclaimed water contracts would not be honored and there would be no discharge to the Santa Fe River. Considering the reliance on reclaimed water by downstream users (both human and ecological), this level of direct reuse was considered unacceptable.

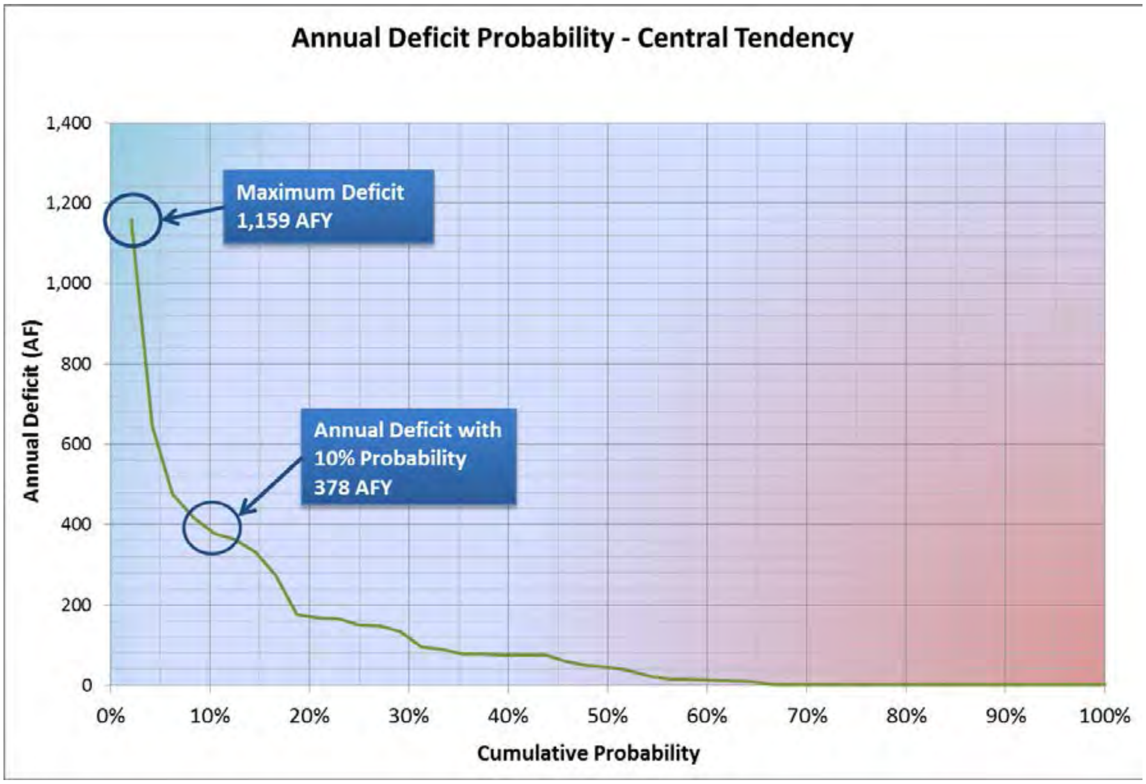


Figure 2 – Santa Fe Basin Portfolio 2: Direct Reuse Only Annual Deficit Probability Curve under Central Tendency Climate Scenario

Table 5 – Performance of Portfolio 2 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	Maximum Annual Deficit < 2000 AFY	Annual Deficit at 10% probability < 100 AFY
Portfolio 2:Direct Reuse Only	NO (exceeds by 2,225 AFY)	YES (1,159 AFY maximum annual deficit)	NO (378 AFY annual deficit at 10% probability)

3.3 Portfolio 3: Additional Water Rights Only

Portfolio 3 consists solely of acquiring additional surface water rights. Similar to Portfolios 1 and 2, the purpose of Portfolio 3 was to assess if the projected 2055 water supply gap could be filled by obtaining water rights alone. The portfolio assumes that the Water Rights Transfer Program acquires 35 AFY each year of new surface water rights or a total of 1,400 AFY over the 40-year planning period. The water would be diverted, conveyed, treated and delivered through the existing Buckman Direct Diversion Project and would require no new infrastructure. The simulated average annual supply for Portfolio 3 is 1,400 AFY. Supply from Buckman pumping in excess of the management target is approximately 4,451AFY. In the absence of climate change, Portfolio 3 can meet the gap between supply and demand but significantly more groundwater pumping is needed. Figure 3 illustrates that the maximum annual deficit is 3,978 AFY and the annual deficit at 10 percent probability is 2,363 AFY.

Portfolio 3 does not meet any of the three reliability criteria as shown in Table 6. Additional analysis of this portfolio showed that over 7,000 AFY in new surface water rights would be required to meet the reliability criteria. Acquiring this amount of new water rights is unrealistic considering the relative scarcity of water rights for purchase.

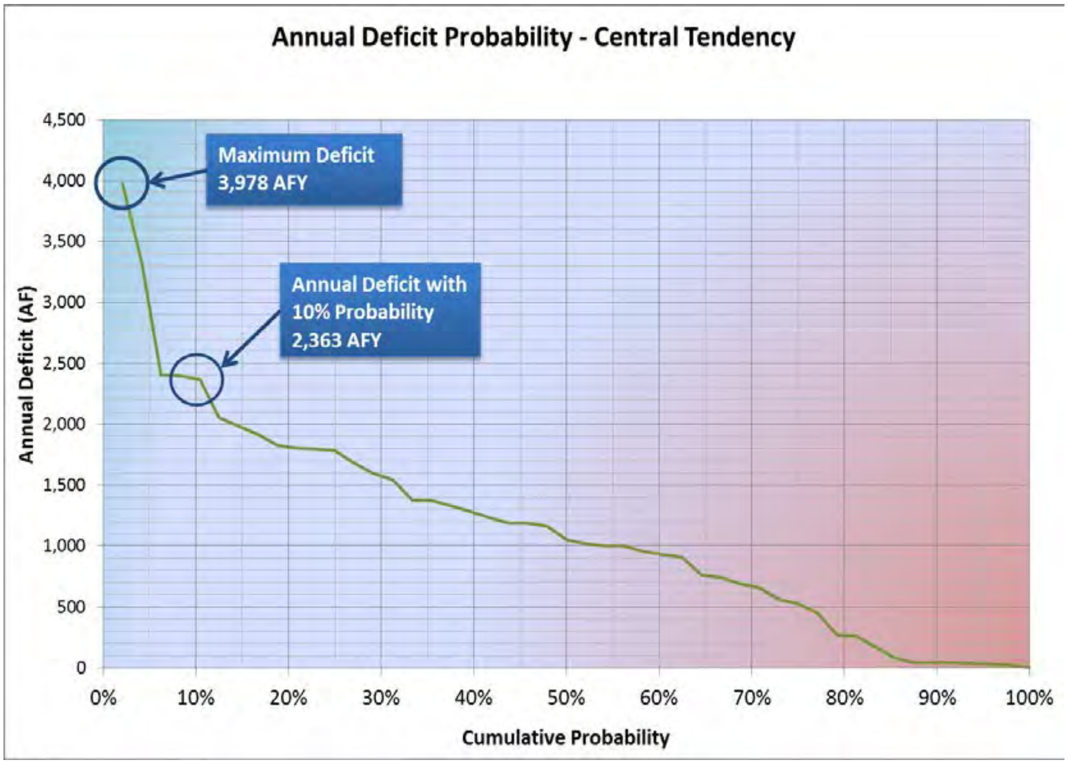


Figure 3: Santa Fe Portfolio 3: Additional Water Rights Only Annual Deficit Probability Curve under Central Tendency Climate Scenario

Table 6 – Performance of Portfolio 3 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	**Maximum Annual Deficit < 2000 AFY**	**Annual Deficit at 10% probability < 100 AFY**
Portfolio 3: Additional Water Rights Only	NO (exceeds by 4,451 AFY)	NO (3,978 AFY maximum annual deficit)	NO (2,363 AFY annual deficit at 10% probability)

3.4 Portfolio 4: More Conservation & Water Rights (Reuse to Potable)

Portfolio 4 and the remaining four portfolios are a combination of adaptive strategies. The purpose of these combination portfolios is to develop source and demand strategies that meet the reliability criteria. It is clear from Portfolios 1, 2, and 3 that a single adaptive strategy will not reliably provide sufficient water supply under conditions projected for 2055. Portfolios 4 through 8 combined adaptive strategies to create portfolios with different emphases so that when the portfolio that best meets the performance criteria was selected, it would provide clear direction for the City and County long-range water supply planning. Portfolio 4 has the following components:

- **Direct Reuse:** Deliver 2,250 AFY to reclaimed water contracts, 1,239 AFY to potable use.
- **Conservation:** Reduce demand by 20 gpcd.
- **Direct Injection ASR:** 640 AFY up to a maximum of 5,000 AF of storage.
- **Infiltration ASR:** Infiltration from upper Santa Fe River (30 percent of river flow).
- **Additional Water Rights:** Acquisition of 1,400 AFY of water rights.

This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new).
- Treat to drinking water standards at the Buckman Regional Water Treatment Facility and distribute to customers (existing).
- Construct injection well(s) or modification of wells for use as injection well (new).
- Convey water from Buckman Regional Water Treatment Facility to injection well (new).
- Withdraw from wells and distribute to customers (existing).

Buckman pumping is reduced to below management targets for this portfolio. Figure 4 illustrates that the maximum annual deficit is 57 AFY and the annual deficit at 10 percent probability is zero. Portfolio 4 meets all of the three reliability criteria as shown in Table 7. Further, Portfolio 4 meets the reliability criteria under all 3 climate scenarios, with the exception of the hot-dry scenario where the annual deficit at 10 percent probability is greater than 100 AFY (Figure 4). Portfolio 4 was carried on for evaluation with respect to the performance criteria (Section 4).

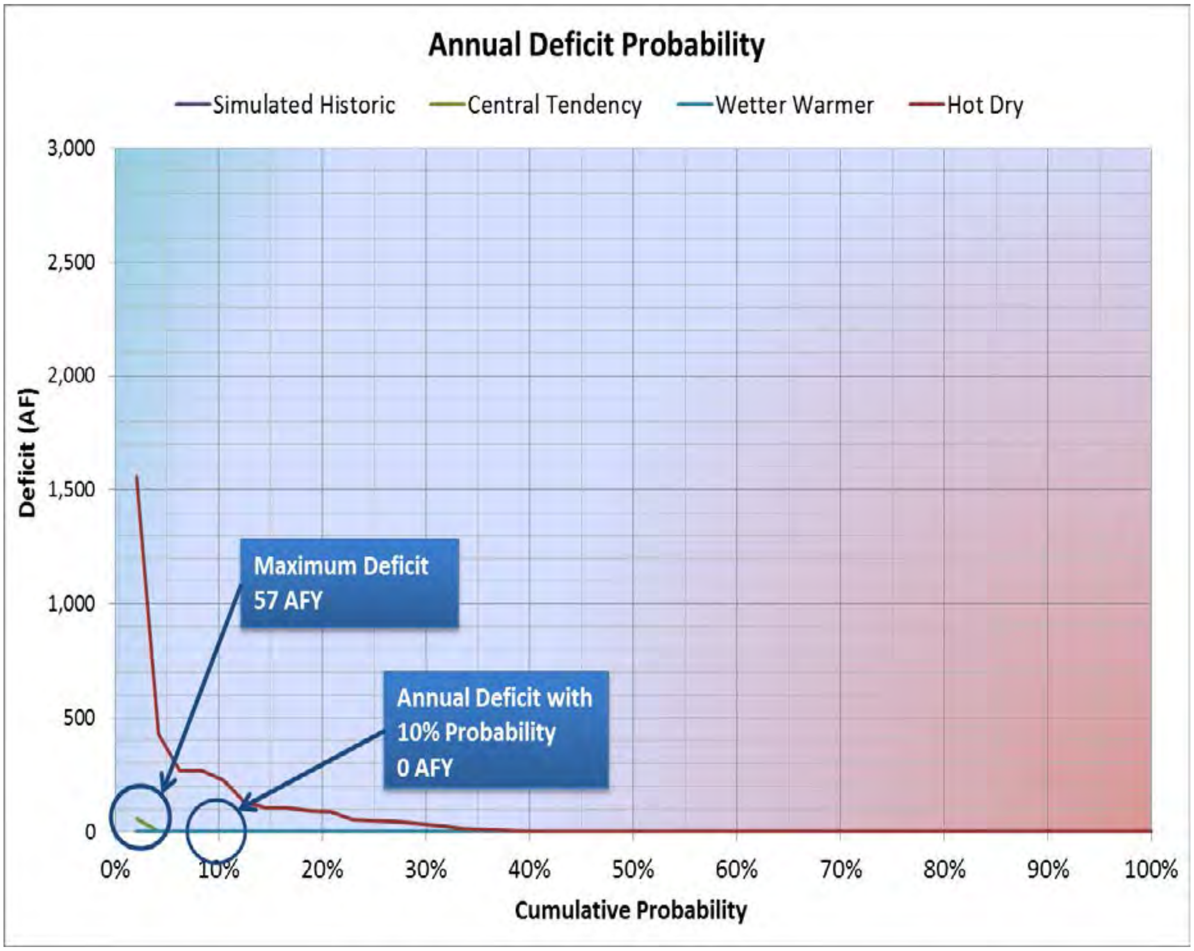


Figure 4: Santa Fe Portfolios 4 and 5: More Conservation and Water Rights (Reuse to Potable)

Table 7 – Performance of Portfolios 4 and 5 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	Maximum Annual Deficit < 2000 AFY	Annual Deficit at 10% probability < 100 AFY
Portfolios 4 and 5: More Conservation and Water Rights	YES (does not exceed)	YES (57 AFY maximum annual deficit)	YES (0 AFY annual deficit at 10% probability)

3.5 Portfolio 5: More Conservation & Water Rights (Reuse to Return Flow Credits)

Portfolio 5 is exactly the same as Portfolio 4 except the treated water is returned to the Rio Grande for return flow credits rather than for potable use. Portfolio 5 has the following components:

- **Direct Reuse:** Deliver 2,250 AFY to reclaimed water contracts, 1,239 AFY to the Rio Grande for return flow credits.
- **Conservation:** Reduce demand by 20 gpcd.
- **Direct Injection ASR:** 640 AFY up to a maximum of 5,000 AF of storage.
- **Infiltration ASR:** Infiltration in upper Santa Fe River (30 percent of river flow).
- **Additional Water Rights:** Acquisition of 1,400 AFY of water rights.

This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new).
- Treat to drinking water standards at the Buckman Regional Water Treatment Facility (existing).
- Convey reclaimed water to Rio Grande for return flow credits (new).
- Construct injection well(s) or modification of wells to act as injection well (new).
- Convey water from Buckman Regional Water Treatment Facility to injection well (new).
- Withdraw from wells and distribute to customers (existing).

Buckman pumping is reduced to below management targets for this portfolio. Figure 4 illustrates that the maximum annual deficit is 57 AFY and the annual deficit at 10 percent probability is zero. Portfolio 5 meets all of the three reliability criteria as shown in Table 7. Further, Portfolio 5 meets the reliability criteria under all 3 climate scenarios, with the exception of the hot-dry scenario, where the annual deficit at 10 percent probability is greater than 100 AFY (Figure 4). Portfolio 5 was carried on for evaluation with respect to the performance criteria (Section 4).

3.6 Portfolio 6: More Infiltration Aquifer Storage and Recovery

Portfolio 6 emphasizes infiltration ASR, with moderate conservation and less acquisition of water rights. Portfolio 6 has the following components:

- **Conservation:** Medium reduction in demand (15 gpcd).

  Direct Injection ASR: 640 AFY to a maximum of 3,500 AF of storage.

- **Infiltration ASR:** Infiltration in both upper and lower Santa Fe River (70 percent of flow).

- **Additional Water Rights:** Acquisition of 1,400 AFY of water rights.

Table 3 lists the simulated additional water supply from Portfolio 6. This portfolio would require the following infrastructure components:

- Convey water from Buckman Regional Water Treatment Facility to injection well (new).

- Withdraw from wells and distribute to customers (existing).

Buckman groundwater pumping exceeds the management target by 291 AFY. One notable result of this portfolio is in regards to the direct injection ASR. The order in which water is used is to fulfill required offsets for groundwater pumping first and any remaining water is used for direct injection. Portfolio 6 does not include direct reuse, so there is only enough water to meet offset requirements and there is not enough to inject for ASR. Figure 5 illustrates that the maximum annual deficit is 553 AFY and the annual deficit at 10 percent probability is 161 AFY. Portfolio 6 meets two of the three reliability criteria as shown in Table 8, although the portfolio is very close to meeting all criteria. Portfolio 6 was carried on for evaluation with respect to the performance criteria (Section 4).

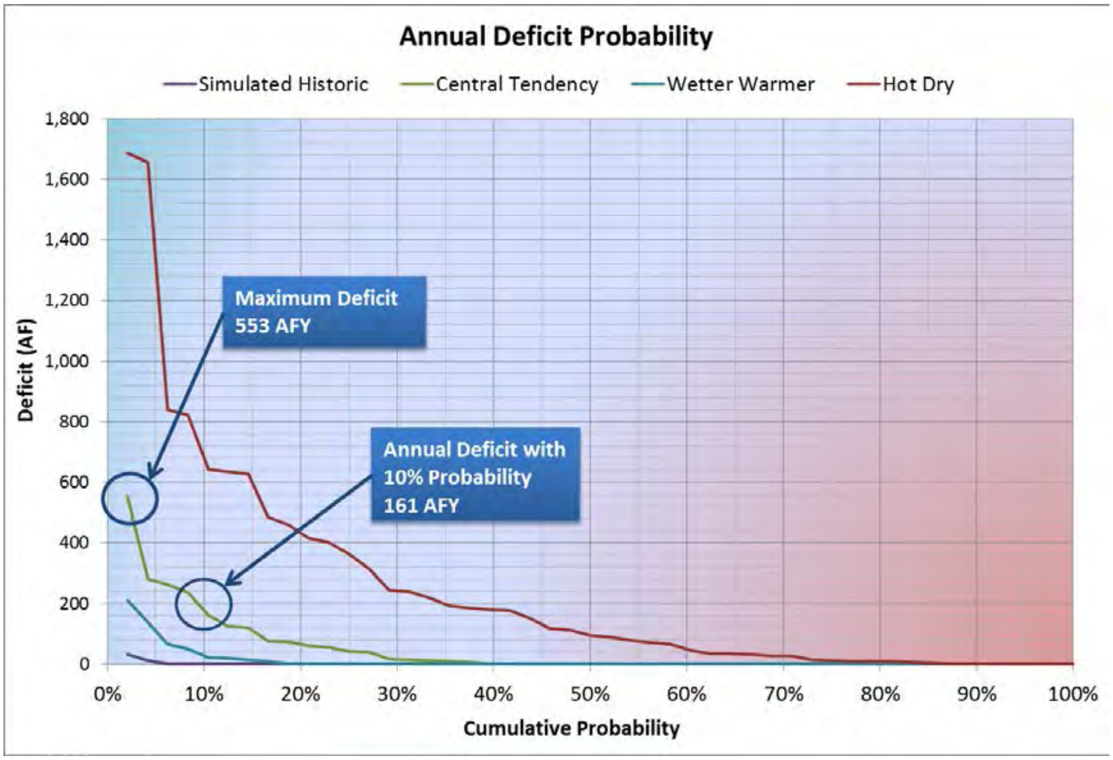


Figure 5: Santa Fe Basin Portfolio 6: More ASR Annual Deficit Probability Curve

Table 8 – Performance of Portfolio 6 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	Maximum Annual Deficit < 2000 AFY	Annual Deficit at 10% probability < 100 AFY
Portfolio 6: More Conservation and Water Rights	NO (exceeds by 291 AFY)	YES (553 AFY maximum annual deficit)	NO (161 AFY annual deficit at 10% probability)

3.7 Portfolio 7: More Direct Reuse (Potable Use)

Portfolio 7 emphasizes direct reuse with the smallest decrease in conservation. Portfolio 7 has the following components:

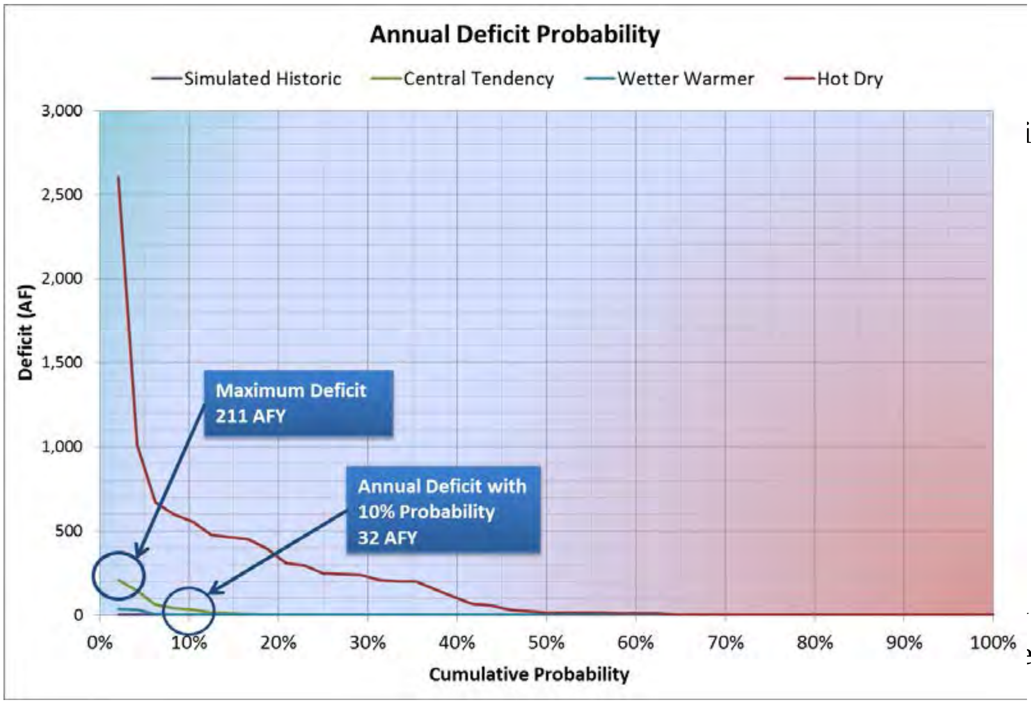
- **Direct Reuse:** Meet 1,734 AFY of reclaimed water contracts, remainder to potable use.
- **Conservation:** Small reduction in demand (10 gpcd).
- **Infiltration ASR:** Santa Fe River infiltration in upper Santa Fe River (30 percent of river flow).

Table 3 has the simulated additional water supply from Portfolio 7. This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new).

- Treat to drinking water standards at the Buckman Regional Water Treatment Facility and distribute to customers (existing).
  Withdraw from wells and distribute to customers (existing).

The simulated average additional annual supply for Portfolio 7 is 6,313 AFY, and Buckman pumping that exceeds the management target adds approximately 323 AFY. This portfolio is 763 AFY short of closing the water supply gap of 7,376 AFY. Figure 6 illustrates that the maximum annual deficit is 211 AFY and the annual deficit at 10 percent probability is 32 AFY. Portfolio 7 meets all three reliability criteria as shown in Table 9, although the portfolio is very close to meeting the remaining criteria. Portfolio 7 was carried on for evaluation with respect to the performance criteria (Section 4).



Maximum Deficit 211 AFY

Annual Deficit with 10% Probability 32 AFY

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Figure 6: Santa Fe Basin Portfolios 7 and 8: More Reuse Annual Deficit Probability Curve

Table 9 – Performance of Portfolios 7 and 8 Relative to Reliability Criteria

	Reliability Criteria		
	Avg Buckman Pumping in Excess of Target < 500 AFY	Maximum Annual Deficit < 2000 AFY	Annual Deficit at 10% probability < 100 AFY
Portfolios 7 and 8: More Direct Reuse	YES (exceeds by 323 AFY)	YES (211 AFY maximum annual deficit)	YES (32 AFY annual deficit at 10% probability)

3.8 Portfolio 8: More Direct Reuse (Return Flow Credits)

Portfolio 8 is the same as Portfolio 7 except the treated water is returned to the Rio Grande for return flow credits. Portfolio 8 has the following components:

- **Direct Reuse:** Meet 1,734 AFY of reclaimed water contracts, remainder to potable use
- **Conservation:** Small reduction in demand (10 gpcd)
- **Infiltration ASR:** Upper Santa Fe River
- **Additional Water Rights:** Acquisition of 920 AFY of water rights

Table 3 has the simulated additional water supply from Portfolio 8. This portfolio would require the following infrastructure components:

- Convey reclaimed water to the Buckman Regional Water Treatment Facility (new)
- Treat to drinking water standards at the Buckman Regional Water Treatment Facility (existing)
- Convey to Rio Grande for return flow credits (new)
- Withdraw from wells and distribute to customers (existing)

Buckman groundwater pumping exceeds the management target by 323 AFY. Figure 6 illustrates that the maximum annual deficit is 211 AFY, and the annual deficit at 10 percent probability is 32 AFY. Portfolio 8 meets all three reliability criteria as shown in Table 9. Portfolio 8 was carried on for evaluation with respect to the performance criteria (Section 4).

4 Evaluation Criteria

The five combination portfolios (Portfolios 4-8) that meet or nearly meet the threshold of the reliability criteria were moved through the next step of the decision process: evaluation with respect to the performance criteria. For consistency, the overall performance criteria are largely the same as those used for the Santa Fe Long-Range Water Supply Plan in 2008, although they have been simplified for this Basin Study.

4.1 Performance Criteria

The performance criteria address multiple aspects of the water supply system and are both quantitative and qualitative. For each criterion, there is a corresponding performance measure that describes the metric that will be used to evaluate that criterion. Further, all criteria are not of equal importance. The method used to indicate the relative importance of the criteria is by assigning each a weight. The weights were developed on a consensus basis by the City of Santa Fe, Santa Fe County and the Bureau of Reclamation. The criteria, performance measures, and weights are shown in Table 10 and are described in the following sections.

Table 10 Santa Fe Basin Study Performance Criteria, Performance Measures, and Weights

Performance Criteria	Performance Measures	Criteria Weights
Cost Considerations		**15%**
Capital Cost	Qualitative: estimate	40%
O&M Cost	Qualitative: estimate	40%
Potential for Cost Share	Qualitative	20%
Reliability and Sustainability		**25%**
Drought Supply	Quantitative: assessment of annual deficit probability curves	50%
Groundwater Use	Quantitative: average and maximum pumping compared to management target	50%
Acceptance		**10%**
Regulatory Compliance Complexity	Qualitative	50%
Public Acceptance	Qualitative	50%
Environmental /Cultural		**30%**
Santa Fe River Flows	Quantitative: flow in Santa Fe River	50%
Rio Grande Flow	Qualitative	50%
Technical Implementability		**20%**
Technology Viability	Qualitative	100%

4.1.1 Cost Considerations

This criterion addresses the cost of each portfolio. Developing cost estimates was not part of this basin study, so the cost considerations are qualitative estimates based on the amount of new infrastructure that would be required to implement the portfolio and the complexity of the operations for the portfolio. This criterion is the sum of three sub-criteria listed below:

- **Capital costs,** which are the cost of construction and must be accounted for in the Capital Improvement Plan (CIP). Estimated based on number and type of new infrastructure required.

- **Operation and maintenance (O&M) costs,** are an indication of the long-term costs of a portfolio, estimated based on complexity of the infrastructure components.

- **Potential for cost share,** the degree to which the portfolio would be eligible for State or Federal funding. Estimated based on features such as reuse and regionalization.

4.1.2 Reliability and Sustainability

This criterion applies to how well the portfolio performs with respect to providing water supply under different climate conditions and impact to groundwater supplies. Portfolios 4 through 8 met (or nearly met) the initial reliability criteria because of their performance under the Central Tendency climate scenario. This criterion looks at the performance of each portfolio under the hot-dry climate scenario to identify the portfolio that provides water supply under the range of projected climate conditions.

- **Drought Supply:** the measure of the ability of a portfolio to supply adequate water under the Hot-Dry climate scenario. This is determined from the annual deficit probability curves produced by WaterMAPS.

- **Groundwater Use:** assesses the impact of pumping groundwater. WaterMAPS provides the amount of water pumped from the Buckman Well Field, which is presented as the percentage above the management target and maximum pumping constraint.

4.1.3 Acceptance

This criterion is an expectation of the public acceptance of each portfolio. Two aspects of acceptance are provided: regulatory complexity and willingness of the public to accept the portfolio. Risk to human health is often correlated to regulatory complexity: low risk activities (e.g., pumping water) have simpler regulatory requirements than do high risk activities (e.g., treating reclaimed water for potable use). Public acceptance is broader, because it includes health and safety concerns (e.g., reclaimed water on athletic fields) as well as quality of life concerns (e.g., conservation at 94 gpcd).

- **Regulatory Compliance Complexity:** is an assessment of the effort, cost, and time to achieve and maintain regulatory compliance for a portfolio.

This is a qualitative estimate based on the number of activities requiring regulatory permits in each portfolio.

- **Public Acceptance:** assesses the perception of the public regarding the different components of each portfolio. This is a qualitative estimate based on national, regional, and local trends.

4.1.4 Environmental/Cultural

This criterion is intended to consider the impacts to the environment and cultural properties or practices associated with each portfolio. The criterion is made up of two sub-criteria: flow in the Santa Fe River and in the Rio Grande. The discharge from the City of Santa Fe wastewater treatment plant has provided flow in the Santa Fe River. Irrigators downstream of the plant depend on flow in the river. The riparian habitat is also supported by flow in the river. The Rio Grande has special species considerations so the impact of the portfolios on flow in the Rio Grande is included as a sub-criterion.

- **Flow in the Santa Fe River:** is a measure of the extent to which a portfolio accommodates maintaining flow in the river below the wastewater treatment plant. WaterMAPs provides the projected flow after all modeled inflows and outflows.

- **Flow in the Rio Grande:** assesses whether the flow in the Rio Grande is affected by the portfolio. This is a qualitative appraisal based on the inflows and outflows directly to the Rio Grande.

4.1.5 Technical Implementability

The purpose of this criterion is to consider the extent to which the portfolios include commonly used technologies that are well understood, have accepted designs, and proven operational track records. It is also intended to consider of the appropriateness of the technologies for the climate and landscape of the Santa Fe area.

- **Technology Viability:** is a measure of the robustness of the technologies incorporated in each portfolio. It is based on the qualitative assessment of the balance of established versus newer technologies in each portfolio.

4.2 Criteria Weighting

In any decision-making process, evaluation criteria are not all equally important, and some criteria may be more relevant for the decision-maker than others. As an example, for a given individual, costs may be more important than the environmental/cultural considerations of an alternative. These relative weightings vary from person to person and community to community, reflecting different values, experiences, and opinions. Thus, weighted criteria representing the perspectives of a cross-section of the effected population are valuable as they reflect the range of values and preferences present in the community and customize the decision-making process for that community.

The performance criteria described in Section 4.1 reflect the weights that were developed for the Santa Fe Long-Range Water Supply Plan in a process that involved input from the public and government officials. The weights assigned to the evaluation criteria and sub-criteria were presented in Table 11.

5 Rank the Climate Mitigation Portfolios

The ranking process for the Santa Fe Basin Study was based on scoring each climate mitigation portfolio with respect to each of the criteria described in Section 4. A team composed of representatives of the City, County, Bureau of Reclamation and CDM Smith completed scoring at a workshop and each score represents the consensus of the team. All of the criteria were scored from 1 to 5:

- “1” equals worst, virtually impossible, infeasible, undesirable, highest cost
- “5” equals best, most easily implemented, most desirable, lowest cost

The weighted sum of the criteria were compared for each portfolio. The higher the score, the better the portfolio meets the cumulative criteria. The ranking of the portfolios, based on the consensus scoring and the criteria weighting, is summarized in Table 11 and illustrated on Figure 7.

A relatively simple sensitivity analysis of the criteria weights was conducted because there was concern that costs were weighted low compared to the other criteria. This analysis showed that the weight of the cost criterion does not change that Portfolio 5 is the most highly ranked. This is true even when the cost criterion weight is increased to 50 percent or reduced to zero. This result provides confidence that Portfolio 5 best meets the criteria, whether costs are considered or not.

Table 11 Portfolio Assessment

Criteria	Criteria Weights	4 More Conservation & Water Rights (Reuse to Potable)	5 More Conservation & Water Rights (Reuse to Offsets)	6 More Infiltration ASR	7 More Direct Reuse (to Potable)	8 More Direct Reuse (to Return flow credits)
Cost Considerations	**15%**	**0.5**	**0.5**	**0.6**	**0.6**	**0.4**
Capital Cost	40%	3.7	3.7	3.8	3.5	3.5
O&M Cost	40%	3.9	3.5	3.5	3.8	3.1
Potential for Cost Share	20%	2	1	4	4	1
Reliability and Sustainability	**25%**	**1.3**	**1.3**	**0.5**	**0.5**	**0.5**
Drought Supply	50%	5	5	1	2	2
Groundwater Use	50%	5	5	3	2	2
Acceptance	**10%**	**0.2**	**0.5**	**0.3**	**0.2**	**0.5**
Regulatory Compliance Complexity	50%	1	5	2	1	5
Public Acceptance	50%	2	5	4	2	5
Environmental/Cultural	**30%**	**0.6**	**0.6**	**0.9**	**0.8**	**0.8**
Santa Fe River Flow	50%	2	2	4	2	2
Rio Grande Flow	50%	2	2	2	3	3
Technical Implementability	**20%**	**0.4**	**1.0**	**0.6**	**0.4**	**1.0**
Technology Viability	100%	2	5	3	2	5
Results		**2.9**	**3.8**	**2.9**	**2.4**	**3.2**

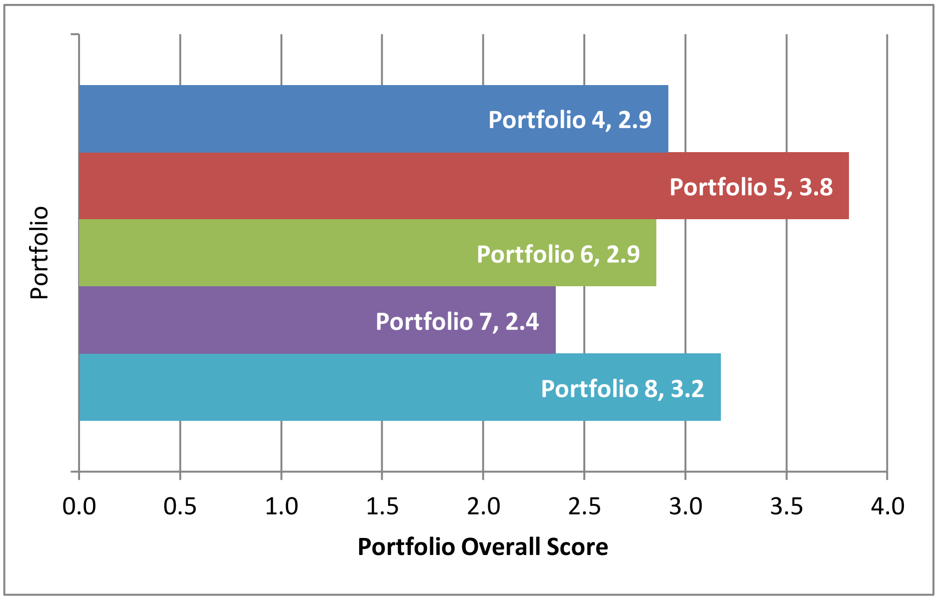

Figure 7 Ranking of Santa Fe Basin Study Portfolios

The ranking of the portfolios clearly shows that Portfolio 5 with an overall score of 3.8 meets the performance criteria better than the other alternatives (Figure 7). Portfolios 4 and 5 scored highly in Reliability and Sustainability because they provide an adequate water supply under the Hot-Dry climate scenario while maintaining groundwater pumping near the management target. However, Portfolio 5 scored higher for Acceptance and Technical Implementability because the reclaimed water is used for return flow credits rather than potable use as in Portfolio 4. Portfolio 5 also scored higher for Public Acceptance because the reclaimed water is used for return flow credits rather than potable use as in Portfolio 4.

The next ranked portfolio, Portfolio 8, did not perform well in Reliability and Sustainability, although it was slightly higher in Environmental/Cultural and Public Acceptance because it uses reclaimed water for return flow credits, which would augment the flow in the Rio Grande in the short-term while allowing for additional groundwater pumping.

One common element of the three highest ranked portfolios is increased use of reclaimed water. This suggests that the City and County focus efforts to use reclaimed water from both the City wastewater treatment plant and the County's Quill wastewater treatment plant. The three highest ranked portfolios also use the maximum number of adaptive strategies demonstrating the value of a multi-faceted approach to achieving climate change mitigation goals for the Santa Fe Region.

6 References

City of Santa Fe, New Mexico, 2013. Reclaimed Wastewater Resource Plan. http://www.santafenm.gov/document_center/document/794

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City of Santa Fe, New Mexico, Ordinance No. 2012-10 and City of Santa Fe, Administrative Procedures for Santa Fe River Target Flows, February of 2012.