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## Recommended Citation

Demint, Ann. "Integrating a GIS-produced, Reach-based Hydrologic Analysis into a Dynamic Surface Water Model of the Middle Rio Grande, New Mexico." (2010). https://digitalrepository.unm.edu/wr_sp/145

# Integrating a GIS-produced, Reach-based Hydrologic Analysis into a Dynamic Surface Water Model of the Middle Rio Grande, New Mexico

by

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**Publication No. WRP-12**
December 2005

NOTE:  This publication is the Professional Project report of Ann D. Demint, submitted in partial fulfillment of the requirements for the Master of Water Resources degree at the University of New Mexico (December 2005).  The project was supervised and approved by the following committee: Dr. Julia E. Allred Coonrod, Department of Civil Engineering, UNM (Chair); Dr. Janie Chermak, Department of Economics, UNM; and Dr. Michael E. Campana, Water Resources Program and Department of Earth and Planetary Sciences, UNM.

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## Acknowledgements

I would like to thank the following people and organizations for the data, information, and support they provided. Without their help, this project would not have been possible.

| | |
|---|---|
| Christy Jones | GIS data for Middle Rio Grande: reach outlet points, definition of contributing sub-basins, and digital elevation models for sub-basins |
| Jesse Roach | Extensive data on Middle Rio Grande |
| Dr. Vince Tidwell | Sandia National Laboratory Powersim models on the Middle Rio Grande, data, and modeling concepts |
| Dr. Janie Chermak | Economic demand equation for water demand in Albuquerque |
| Dr. James Cleverly | Summary of extensive data on riparian evapotranspiration in the Middle Rio Grande |
| Dr. Francisco Olivera | ArcView 3.2 Avenue script for combining land use and soils coverage into curve number grid for hydrologic analysis |
| Julie Anderson | Ground water data for Middle Rio Grande basin |
| Dr. Julia Coonrod | Overall technical assistance, especially with ArcGIS 9 |
| Dr. Michael Campana | Overall technical assistance and editing |
| U.S. Army Corps of Engineers (URGWOM) | Extensive data on Middle Rio Grande |
| S.S. Papadopulos & Associates, Inc. | Extensive data on Middle Rio Grande |

## Acronyms

| | |
|---|---|
| AF | Acre-feet |
| cfs | cubic feet per second |
| ET | Evapotranspiration |
| gpcd | gallons per capita per day |
| LFCC | Low Flow Conveyance Channel |
| MRG | Middle Rio Grande |
| MRGCD | Middle Rio Grande Conservancy District |
| SNL | Sandia National Laboratories |
| USBR | United States Bureau of Reclamation |
| USGS | United States Geological Survey |

# Abstract

Using the Powersim™ software platform, a dynamic systems model was built to explore the surface water supply in the Middle Rio Grande in New Mexico from Cochiti Dam to Elephant Butte Dam. A number of similar models exist but do not include a spatial component and/or attempt to model terms with a great deal of uncertainty, such as riparian evapotranspiration, ungaged tributary inflow, and effective precipitation. This model simulates the Middle Rio Grande in six reaches, extending from Cochiti Dam to Elephant Butte Dam, a distance of approximately 175 miles. Ungaged tributary inflow and effective precipitation are successfully included through the use of an ArcGIS-based hydrologic analysis and precipitation profiles built with paleoprecipitation reconstructions for New Mexico over the last 1000 years. The simulation results are compared to gaged river flows over the past 50 years through a probabilistic distribution analysis. Generally, probabilistic analysis indicates the model may be optimistic in its estimation of river flows, although not in the year to year variability of those flows. Thus, either the inflows are overestimated by the model relative to the last 50 years, or the outflows are underestimated, or a combination of both. However, comparison of the distribution of the precipitation profile data source (1000 years long) and the model precipitation profiles indicate inflows are appropriately simulated. Alternatively, the model seems to represents the last 50 years fairly well in the upper reaches, but has difficulty in the lower reaches. Nevertheless, the model can provide useful information when comparing simulation results to each other. Year to year variability is very high and clearly maintained from gage to gage. Not surprisingly, the very dry climate is the “worst” climate scenario, with a lowest average flow at San Marcial of 691 cfs. The “best” scenario was the moderately wet and consistent climate with an average flow of 1053 cfs at San Marcial. When considering compliance with the Rio Grande Compact, the average consistent climate was the worst, generating 38 years of accrued debit status and 18 years of annual debits. A correlation analysis indicated gage flows for each reach have a positive 1 to 1 correlation with sub-basin runoff. Open water evaporation was positively correlated to a moderate extent with gage flows, reflecting the influence of surface area on evaporation. In addition to these analyses, the simulation results revealed the effects of the price of water by using an economic demand equation. A “conservation” price path was designed to meet Albuquerque’s goals of 150 gpcd by 2014 and 130 gpcd by 2040. This path and a 2.5 percent annual increase price path caused immediate reductions in the total demand volume and reductions in the San Juan-Chama diversion by 2014. However, the conservation price path led to a rebound in the diversion, with full diversion again occurring by 2038 even though per capita use was only 132 gpcd. The 2.5 percent price path began to rebound in 2032 when per capita use reached the imposed lower limit of 75 gpcd. More moderate price increases of 1.25 percent and 1.5 percent reduced the San Juan-Chama diversion in 2042 and 2030, respectively. No rebound occurred and per capita use reached a low of 75 gpcd and 101 gpcd by 2053. The 1.5 percent or 2.5 percent annual price increases converged in 2053 at a maximum reduction of the San Juan-Chama diversion at almost 62,000 AF per year, with per capita use of 75 gpcd. While reduction of the San Juan-Chama diversion led to increases in the flow at the Albuquerque gage, declines in per capita use resulted in decreases at the Bernardo gage, caused by declines in wastewater return flows in that reach. The simulated drop in the Bernardo gage flow was small, less than an annual average of 45 cfs at its maximum. Although the model produced simulation results with a “wetter” distribution than the past 50 years, it provides a platform for exploring the relative impact of management alternatives. Interestingly, the averages are not as far apart as the probabilistic distribution. Thus, “average” is a dangerous word for the Middle Rio Grande and may misrepresent future climates and river flows.

# Integrating a GIS-produced, Reach-based Hydrologic Analysis
# into a Dynamic Surface Water Model of the Middle Rio Grande

## 1. INTRODUCTION

In the semi-arid southwest United States, water has always been a critically scarce resource. This is nowhere more true than along the Middle Rio Grande in New Mexico, where the increasing water demand of a burgeoning human population combined with traditional irrigation farming has caused the allocation of water to become a contentious issue. In 2002, Texas appropriated $6.2 million to sue New Mexico about water deliveries (Gaume 2002). A legal requirement to supply water for ecological needs has also been recently introduced, further aggravating the delicate act of balancing competing uses. As an additional complication, many experts believe the area is entering an extended drought cycle. The drought year of 2002 was one of the worst hydrologic droughts on record (Papadopulos 2002, Liles 2002) with the Rio Grande possibly at its lowest level on record and the Elephant Butte reservoir lower than it has been in decades (Turney 2002).

To deal with these sensitive issues, water planning has become more prevalent and various alternative solutions are being investigated. However, water systems and their watersheds are complex systems and competing uses are often difficult to equitably fulfill.

To explore alternative solutions to the fair allocation problem, the interaction between the river, its inflows and outflows, and competing uses must be carefully studied. One method for linking all these components is the computer-based dynamic systems model. This type of model can represent a complex system where factors change over time, making it ideal for analyzing the effects of different management alternatives. Such a model can thus provide information to water planners on probable long-term impacts of alternatives.

Accordingly, a dynamic reach-based surface water model of the Middle Rio Grande was built to investigate the effects on surface water availability of changes in demand levels and climate. The model separates the river into six individual reaches and reports the annual values of river flows at several locations as well as the values of other elements of the river system. It also includes six agricultural reaches whose extents mirror the six river reaches. Simulations of several alternatives were performed, with results presented and discussed later.

The model is structured to allow other users to operate it. A user interface is included, supplying the user with a choice of numerous parameters to change such as the price of water or the type and amount of crop or riparian acreages. The report interface provides the user with information on the effects of those changes on the river. Full documentation of sources and explanation of concepts and equations are directly included in the model structure.

## 2. STUDY AREA

The Middle Rio Grande basin, for the purposes of this project, encompasses the Middle Rio Grande in New Mexico from Cochiti Dam downstream to the Elephant Butte Reservoir. This portion of river is roughly 175 miles long (Papadopulos 2004) with the outlet point defined as the Elephant Butte Dam. The Middle Rio Grande is partitioned into six reaches, corresponding to the Upper Rio Grande Water Operations Model (URGWOM) reaches, except for URGWOM reach 5 which includes both reach 5 and part of reach 6 of this project. Each reach is defined by an inflow gage at the top of the reach and an exit gage at the bottom. Figure 1 defines the reaches and their contributing sub-basins while Figure 2 illustrates the location of diversions and tributaries relative to the gages.

Table 1 summarizes key information for each reach, including identification of the inlet and outflow gages. Not mentioned in the table is the Low Flow Conveyance Channel (LFCC), which is an artificial channel built by the U.S. Bureau of Reclamation (USBR) in the 1950's for "the purpose of reducing consumption of water, providing more effective sediment transport, and improving valley drainage" (Gorbach 1999). It begins at the San Acacia diversion immediately prior to Reach 5, but is modeled as beginning in Reach 5.

The LFCC carried the majority of flows in the 1960's and 1970's, but heavy sedimentation of the LFCC and river channel began in the 1980's and diversions into LFCC ceased in March 1985. The artificial channel was repaired and improved in the 1980's and now serves as the main drainage outlet for seepage flows and irrigation return flows. It also provides the Bosque del Apache with its main water supply. Future diversions of entire river flow, like the 60's, are considered to be unlikely. The LFCC continues through this reach and enters the Elephant Butte reservoir directly (Gorbach 1999).

Elephant Butte Reservoir is included in the model, although only the north portion is directly modeled. The reservoir can be separated into two major portions by the area known as the Narrows (Papadopulos 2004). The volume of the entire reservoir is calculated, based on the northern portion volume, in order to drive the calculations that determine compliance with the Rio Grande Compact.

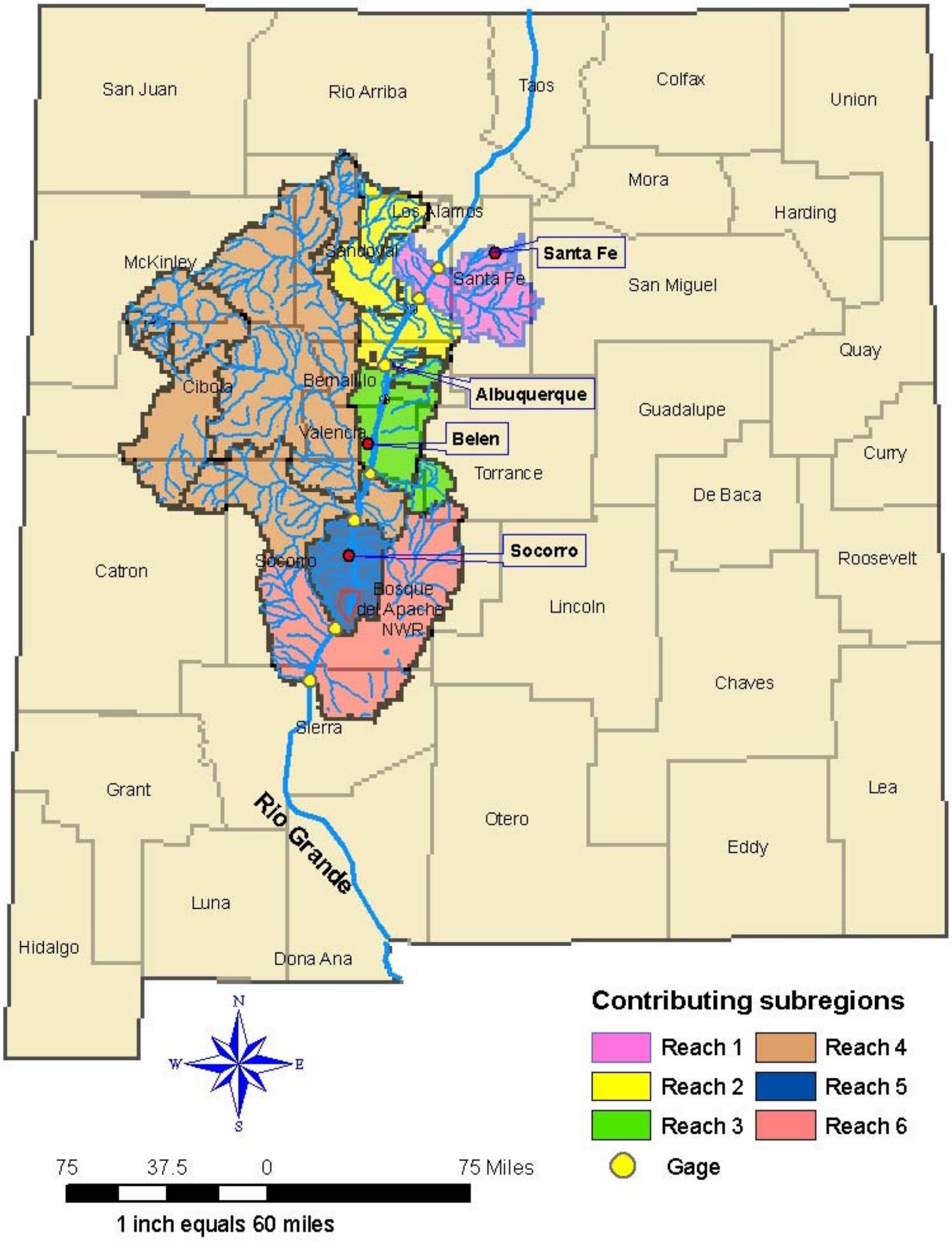


**Figure 1.** The Middle Rio Grande of New Mexico: modeling six river reaches and their contributing sub-regions.

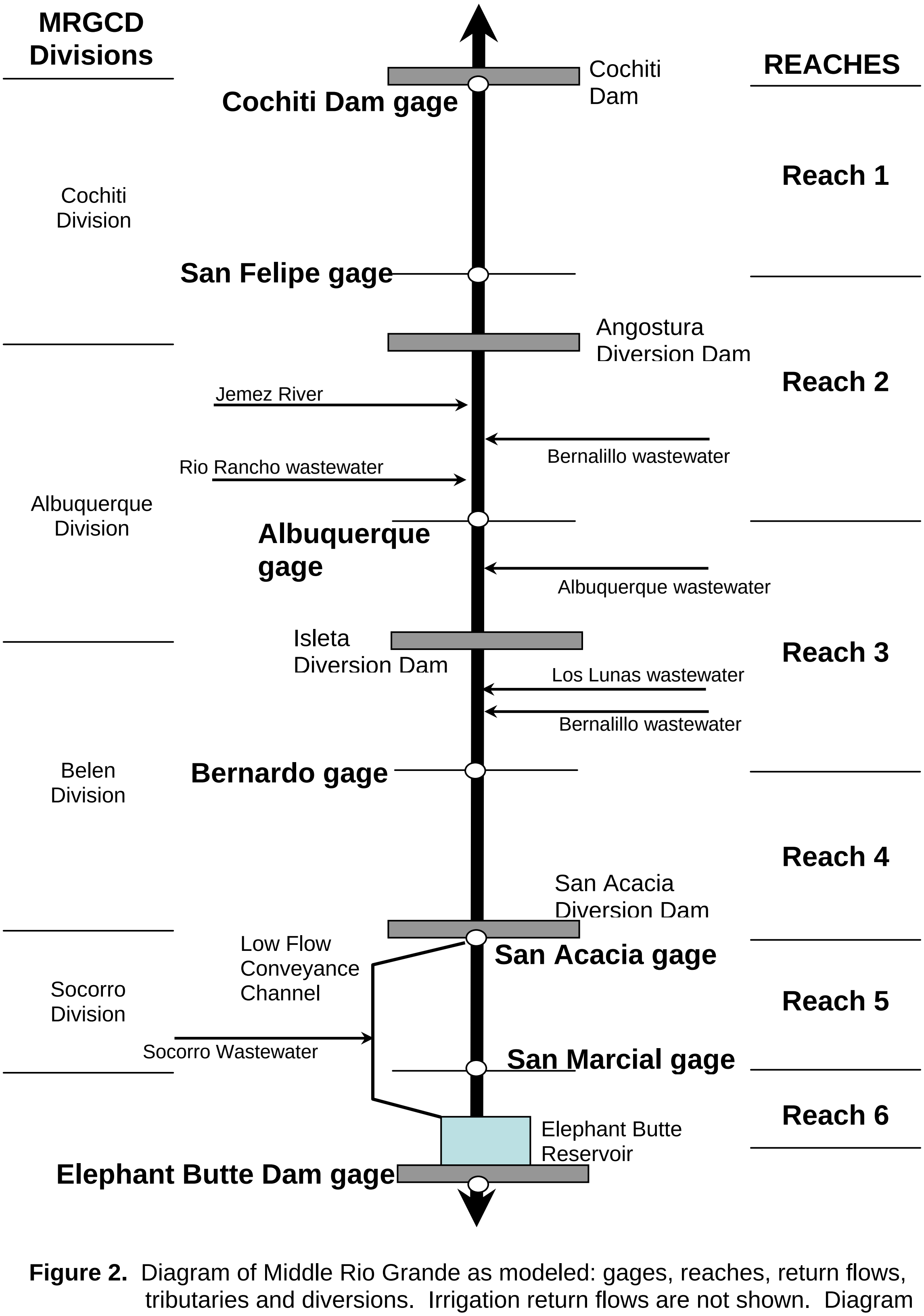


**Figure 2.** Diagram of Middle Rio Grande as modeled: gages, reaches, return flows, tributaries and diversions. Irrigation return flows are not shown. Diagram is not to scale. East-West orientation is notional only.

**Table 1.** Key information for Middle Rio Grande reaches

| Reach ID | Inflow gage | Outlet gage | Tributaries and Inflows | Diversions | Relevant municipalities |
|---|---|---|---|---|---|
| 1 | Cochiti Dam | San Felipe | Galisteo Creek | -- | -- |
| 2 | San Felipe | Albuquerque | Jemez River,<br>Bernalillo wastewater,<br>North Floodway Channel,<br>Rio Rancho wastewater | Angostura | Bernalillo,<br>Rio Rancho,<br>Albuquerque |
| 3 | Albuquerque | Bernardo | Albuquerque wastewater,<br>South Diversion Channel,<br>Tijeras Arroyo,<br>Los Lunas wastewater,<br>Belen wastewater | Isleta | Albuquerque,<br>Los Lunas,<br>Belen |
| 4 | Bernardo | San Acacia | Rio Puerco,<br>Rio Salado | San Acacia | -- |
| 5 | San Acacia | San Marcial | Socorro Wastewater | -- | Socorro |
| 6 | San Marcial | Narrows at Elephant Butte | -- | -- | |

## 3. BACKGROUND

The Rio Grande Compact governs the distribution of Rio Grande flows between Colorado, New Mexico and Texas. Decades of conflict over the allocation of widely varying flows led to signing of the agreement in 1938. The Compact dictates interstate delivery obligations between these 3 states under a variety of flow conditions. Of particular interest in the Middle Rio Grande are the quantified required deliveries to Texas, based on annual native flows at the Otowi gage upstream of Cochiti Dam. While New Mexico can deplete as much water above Otowi as it did in 1938, the amount allocated to Middle Rio Grande users is controlled by inflow to the river at Otowi.

Downstream of Otowi, the Cochiti Dam gage defines the river inflow for the Middle Rio Grande model. Other inflow includes runoff from precipitation on the contributing watersheds carried by tributaries, arroyos, and overland flow. Most of the tributaries are ephemeral, except for the Jemez River. Wastewater and irrigation return flows are other sources of water to the river. Ground water exchange is sometimes a source of inflow, although the model generally evaluates the exchange as a loss to the river on an annual basis. Also, the San-Juan Chama project imports water into the Middle Rio Grande from the San Juan basin.

Authorized by Congress in 1962, the San Juan-Chama Project is a trans-mountain diversion project that takes water from the upper tributaries of the San Juan River in the Colorado River Basin and transfers it to the Rio Grande Basin. A volume of 110,000 acre-feet (AF) is added to the Rio Grande stream flow (via the Rio Chama). 96,200 AF are definitively allocated among various entities along the Rio Grande, although not all entities currently use their allocation.

As mentioned above, all these inflows are not committed solely to the users in the Middle Rio Grande Basin. In fact, when the stream flow at the Otowi gage exceeds 1.1 million acre feet per year, the Middle Rio Grande users’ share is capped by the Rio Grande Compact at approximately 405,000 acre-feet per year. The remainder must pass through to downstream users such as Texas and Mexico. Furthermore, at half that Otowi inflow, the Middle Rio Grande region’s share is only 214,000 acre-feet (Papadopulos 2004).

Whether 405,000 or 214,000 acre-feet, this limited amount of water must be shared between numerous users throughout the Middle Rio Grande. One large user is the Middle Rio Grande Conservancy District (MRGCD). Created in 1923, the MRGCD stretches about 150 miles from Cochiti Dam to the north boundary of the Bosque del Apache National Wildlife Refuge, almost the entire project reach. The irrigation system utilizes gravity flow with mostly unlined ditches, laterals, and drains. Drains collect ground water and farm runoff. This water and tailwater from conveyance canals are eventually returned to the river through wasteways or delivered to a downstream reach (Papadopulos 2002).

Irrigation efficiencies vary among the 4 regional divisions of the MRGCD. The 2 lower divisions have the highest efficiency. Urbanization in and near Albuquerque (second division) has decreased efficiency and many people now irrigate lawns. The efficiency of the northernmost division is the lowest, “due to the provision of water 24 hours a day to satisfy pueblo customs” (Papadopulos 2002).

Several other water users rely on MRGCD diversion and conveyance facilities, including the a number of historical “acequias” (community irrigation districts, one of the largest being La Joya Acequia Association), four New Mexico Department of Game and Fish refuges (the Belen, Casa Colorado, Bernardo and La Joya Waterfowl Areas), the U.S. Fish and Wildlife Service (USFWS) Sevilleta National Wildlife Refuge (Sevilleta), and the USFWS Bosque del Apache National Wildlife Refuge. Bosque del Apache, the largest of these water users, is located just downstream of the MRGCD and diverts water from MRGCD canals carrying water diverted at San Acacia and from the LFCC (Papadopulos 2002).

The MRGCD has permits to deliver 3.0 acre feet of river water per irrigated acre annually over a maximum of 90,000 acres, although the average irrigated acreage between 1991 and 1998 was only about 53,000 acres (Papadopulos 2004). However, “the quantity of water that MRGCD diverts is very large compared to the acreage that it irrigates—two or more times as much water per acre as the other irrigation and conservancy districts in New Mexico” (Papadopulos 2004). Recent drought has caused problems for MRGCD irrigators and in 2002, MRGCD used over 180,000 acre-feet of water from upstream reservoirs. The reservoir storage was depleted, invoking specific requirements of the Rio Grande Compact for the first time in 23 years, such that El Vado Reservoir was not allowed to be refilled with native Middle Rio Grande waters for MRGCD use in 2003 (Papadopulos 2004).

MRGCD also supplies water for irrigation at several Indian pueblos, who have primary and paramount rights in New Mexico’s priority system of water rights (Turney 2002). This means they have senior water rights, but the quantity of those rights has not been identified. Many of the pueblos are pursuing economic development such as golf courses and resort hotels and the exact amount of their rights have become an issue.

Another important user of surface water is the riparian ecosystem. Riparian ecosystems are important in the semi-arid and arid regions of western North America because they are especially productive and dynamic (Farley et al. 1994, Ellis et al. 1998, Scott et al. 1999). Also, western riparian areas have a disproportionately high biodiversity compared to the dry uplands

(Farley et al., 1994; Ellis et al., 1998; Scott et al., 1999). Unfortunately, these valuable riparian areas have already been degraded by the invasion of exotics and river management practices of the past. The problem of riparian degradation is compounded by the high water use of some exotic species. For instance, salt cedar has been replacing native trees and is thought to use more water for evapotranspiration (ET) than the native species. Zavaleta (2000) estimates that salt cedar's high use of water has resulted in an annual loss of irrigation water across the West in the amount of $38 million to $131 million (1998$), with $3-9 million in New Mexico, Texas, and the Great Basin alone.

Limited supplies, increasing uses, and flow changes due to river management practices have also caused problems for the aquatic ecosystem. Many fish species have been extirpated and in 1994, the silvery minnow (*Hybognathus amarus*) was federally listed as endangered under the Endangered Species Act (USFWS 1994). The minnow historically survived the drying of some reaches due to its widely spread population and its ability to migrate to wetter stretches. However, dams have blocked migration and population numbers have declined. As a result, critical habitat designation for the silvery minnow was established in 2003, extending from Cochiti Dam downstream to the utility line crossing the river in Socorro County (USFWS 2003). Continuing drought has exacerbated the situation with several downstream reaches going dry, resulting in a large number of minnow deaths. However, the number or percentage of the population killed is unknown (USFWS 2003).

Conflict over the minnow and in-stream flows reached a peak in 2003 when the10th Circuit Court of Appeals ruled 2-1 that the Bureau of Reclamation "must consider reducing allocations to contractors, if necessary, to meet the required water flows for the endangered Rio Grande silvery minnow" (USBR undated). Parties to the litigation appealed the decision and the 10th Circuit recently vacated the earlier decision as moot (USBR undated). This issue is so important that New Mexico has spent $1 to 1.5 million for a minnow breeding and rearing facility to raise 50,000 minnows. 25,000 of those minnows will be placed in the river (Turney 2002). The city of Albuquerque is also involved, providing funds up to $165,000 per year (USBR 2004).

The minnow-killing intermittency of flow in these reaches would be aggravated if not for the waters of the San Juan-Chama Project, mentioned previously. One of the primary San Juan-Chama water right holders is the city of Albuquerque. Its unused water right of 48,200 acre-feet has helped keep the river wet and the minnow alive in previous years. However, Albuquerque has plans to begin using its allocation in the immediate future to alleviate the drawdown on the aquifer, which has been the primary source of water for the city (USFWS 2003). Santa Fe intends to begin using its allocation in the near future also (Santa Fe 2005).

In addition to urban and irrigation uses, human uses include recreation. For instance, recreation-generated income is a key component of the local economy in Sierra County (Stephens 2003).

This precarious balance of inflows and uses will be complicated in the future by a changing climate. Although most assume this climate change is global warming with a resulting drier climate, Gleick (2000, cited in Papadopulos 2001) indicates that average precipitation over the continental United States has increased by about 10 percent since 1910. In New Mexico during the last 200 years, the amount and duration of above normal rainfall has been greater than during any period since the seventh century, with a steady increase since the early 1700's (Grissino-Mayer 1996; cited in Papadopulos 2004).

On the other hand, San Marcial gaged flow data for 1896 to 1964 indicates a declining trend in flow levels. This may be a result of greater diversions during that time, but Otowi gaging data, above significant diversions, for the same period also indicates a declining trend. So the declining trend may be a result of decreased snow-pack due to increased temperatures (Liles 2002). Long-term proxy (tree-ring) data indicates this decline is not unusual. Gaged flow at San Marcial from 1896 to 1964 averaged 940,417.4 acre-feet per year, but a more long term average, derived from proxy (tree-ring) data, may be as low as 832,193 acre-feet per year, 13 percent below the gaged average (Ackerly 1999).

Nevertheless, the past 50 years have demonstrated the great variability inherent in the Southwest climate, with periods of both extreme drought (1950's) and the greatest moisture (1978-1992) on record (Papadopulos 2004). The variability may increase even further, as some experts think global warming will amplify extremes, meaning more severe droughts and wetter wet periods (Liles 2002).

In addition to the changing and highly variable climate, an increasing population and further urbanization will further complicate the balance between water supply and use in the Middle Rio Grande basin. Clearly, to ensure the most effective allocation of water while meeting legal obligations, the basin keenly needs exceptional water planning efforts. Fortunately, there is an on-going regional water planning process, with different agencies and organizations involved. One of the important parts of the process is which management alternatives are "better."

Finding answers is critical, but they must be more than "best guesses." A dynamic systems model provides an analytical method for evaluating climate change and management alternatives. This type of model simulates the impact of changing human activities on a water system over a long period of time, integrating hydrology, ecology, and demography into one model. In this way, the long-term effect of changes in policy that drive urban and irrigation demands can be reviewed in combination with changes to natural factors, such as climate or endangered species requirements, even for a large river with several users.

In fact, just such a dynamic systems model has previously been built by Sandia National Laboratories. The Sandia National Laboratories (SNL) Middle Rio Grande (MRG) dynamic simulation model examines the hydrology, ecology, and demography of the basin, allowing analysis of the impacts of management decisions. It has a user-friendly interface that allows it to be presented to the public for education purposes. As such, it enhances the multi-agency and community-based water planning process currently underway. However, the current model is a lumped parameter model, treating the entire basin as a single entity and determining only one value for the annual volume of water in the river. It does not consider the variable characteristics of different reaches of the river or the contributing sub-basins, as does the model presented in this report.

Also, Papadopulos (2004) has completed a water supply study, providing information on water supply and demand for the Middle Rio Grande. However, several model terms used by Papadopulos included a great deal of uncertainty, such as riparian evapotranspiration. And the study was not able to quantify the uncertainty in ungaged tributary inflow and effective precipitation (Papadopulos 2004). In this model, ungaged tributary inflow and effective precipitation are effectively included through the use of an ArcGIS-based hydrologic analysis which is included in a Powersim™-based dynamic systems model.

## 4. MODEL DESCRIPTION

The Middle Rio Grande basin is a dynamic system, with numerous complex components which change continuously over time and interact to influence the surface water flow in the Rio Grande. The components, such as surface water flow volume, sub-basin runoff, ground water exchange and surface water evaporation, can be considered complex sub-systems in themselves.

The Powersim Studio™ modeling software is designed to analyze such complex systems. Using the systems dynamics modeling methodology developed at Massachusetts Institute of Technology, Powersim allows the investigator to observe patterns of behavior within the system by providing the numerical results of interactions between the variables. Then the investigator can discern the causes and effects through Powersim’s visual representation of the system structure, including the causal links and the mathematical relationships.

This powerful software platform was used to build a dynamic simulation model of the Middle Rio Grande. The model includes Rio Grande flow volumes over time with inflows and outflows of water to the river. Inflows are both natural (runoff from precipitation and tributary baseflow) and anthropogenic (wastewater and irrigation return flows). Outflows are termed uses and losses, again with natural parts (evaporation) and human-caused (irrigation diversions). Some outflows are naturally-occurring, but strongly influenced by human activity. The effect of ground water pumping on leakage to ground water and the increase in overall evaporation by the building of reservoirs are two examples.

These inflows and outflows and Middle Rio Grande can be studied as one large lumped system, as in the early SNL models. Or the river can be divided into reaches, with inflows and outflows for each reach. This brings into play the spatial distribution of the components and allows the identification of areas in the river that tend to be dry. It can also serve to pinpoint high priority physical locations for data collection, since the majority of the data varies spatially. For instance, both evaporation and leakage can vary greatly with location. However, the model utilizes annual values for all components. Further refinement would include the study of temporal variation over the months of the year.

As mentioned, the river is divided into six reaches and flow volumes are determined at established physical gage locations. The agricultural system of canals and drains is separately analyzed from the river and is itself broken into six reaches that mirror the river reaches. The agricultural system interacts with the river system via irrigation diversions and return flows. Another surface water system is the artificial Low Flow Conveyance Channel (LFCC), which begins in Reach 5, carries through Reach 6, and enters Elephant Butte Reservoir.

As each river and agricultural reach has the same sort of inflows and outflows (but with different values), they are constructed to be visually similar. The model structure for Reach 2 (Figure 3) illustrates the basic structure of each reach, although it does not include the LFCC. Each reach has several inflows and outflows, represented in the model as variables and designated by flow symbols in Figure 3. The reach is represented by a blue box, called a level in Powersim. Levels accumulate and lose quantities of the item of interest - a volume of water in this model. Thus, for this model, a level is like pouring water into a bucket with a spigot for letting water out. But in a surface water model of a river, it is the flow (volume per unit time) which is of interest. Also, due to the nature of the integration used by Powersim to calculate variable values, an unacceptable time delay is induced if the reach levels are used in calculations. For this reason, they are simply visual representations of each reach.

## Reach 2: San Felipe gage to Albuquerque gage

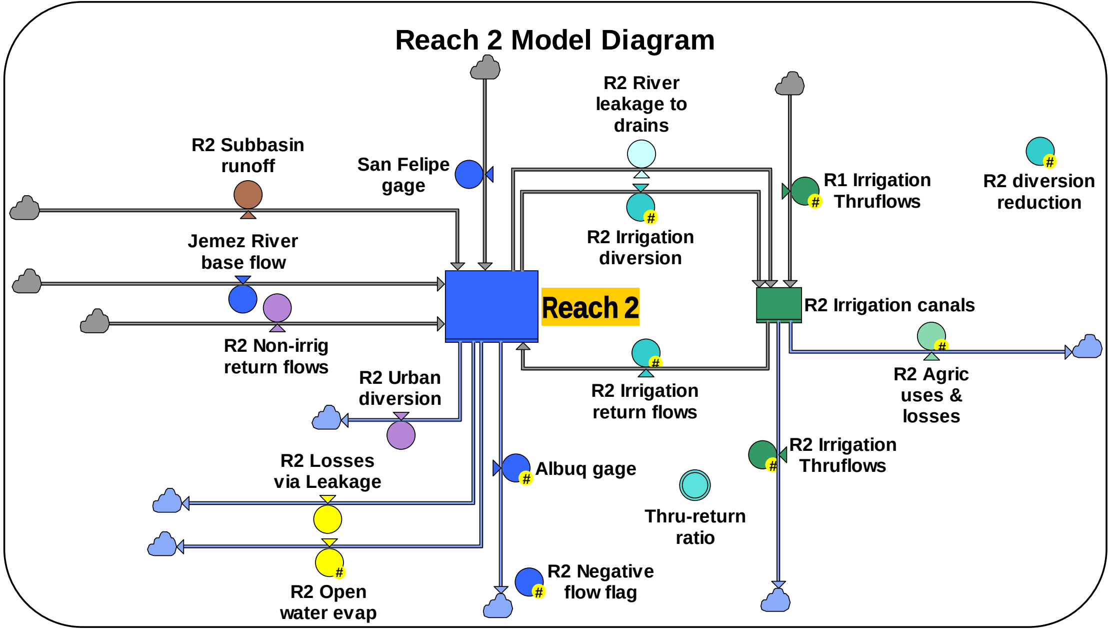
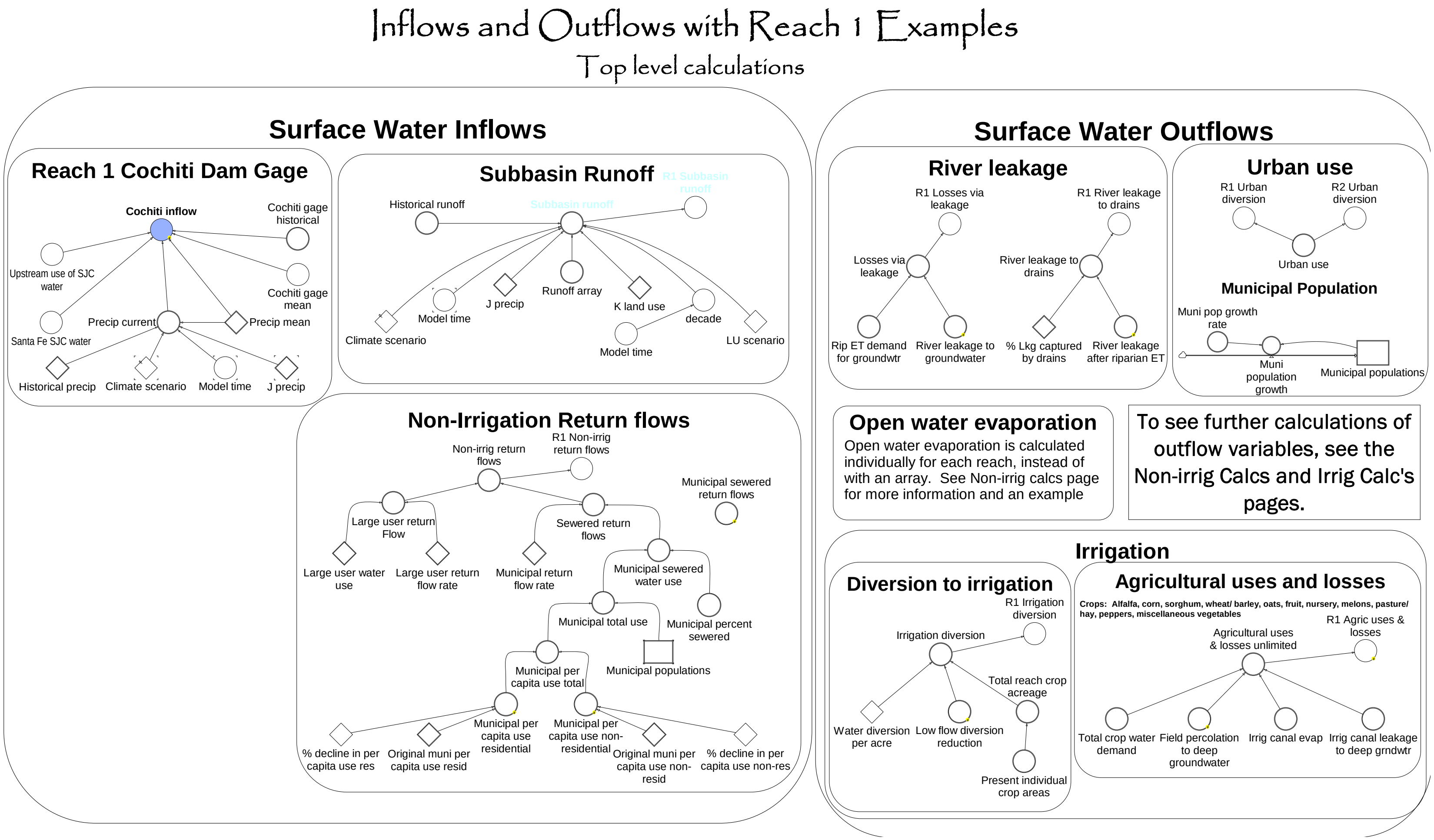


**Figure 3.** Model diagram for Reach 2.

The underlying determination of the value of each inflow and outflow, as well as the interaction between them, is controlled by equations representing these physical relationships. These equations are contained on other pages of the model for simplicity of understanding but are linked to the flow symbols in Figure 3. Figure 4 identifies the model page showing top level variables for inflows and outflows.

Basically, the inflows to each reach include the river flow at the top gage and runoff from the contributing sub-basins. In some reaches, tributary baseflow and non-irrigation (wastewater) return flows are additional inflows. The river flow at each bottom gage serves as the top gage for the next reach. Since it is assumed there is no storage in the river, the flow at the bottom gage of each river reach is determined by subtracting the sum of the outflows from the sum of the inflows. All bottom gage flows are controlled for negativity. If outflows exceed the calculated inflows in a reach, that reach's outflow is set to zero and a negative flow flag is set for that reach. The flag indicates that the outflow values for that year and reach are over-valued.

The inflow to Reach 1 is handled different by the model since there is no upper reach. Reach 1 is initialized by the stream flow at the gage below Cochiti Dam. This inflow is based on the mean historical flow and varied each year by the ratio of that year's precipitation value to the



Open water evaporation is calculated individually for each reach, instead of with an array. See Non-irrig calcs page for more information and an example

To see further calculations of outflow variables, see the Non-irrig Calcs and Irrig Calc's pages.

**Figure 4.** Model diagram for top level inflows and outflows.

average precipitation value for Reach 1. Each reach's average precipitation value is the spatially averaged value from the mean annual precipitation raster (Daly and Taylor 2005).

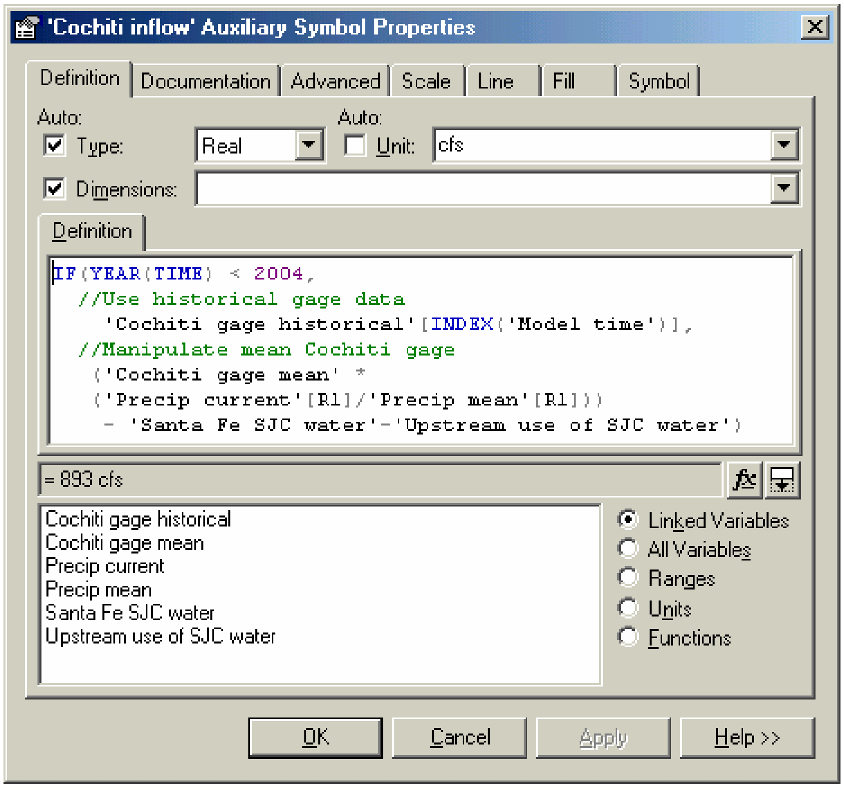
Upstream use of San Juan-Chama water is also accounted for in this variable with an assumed start date of 2013 for Santa Fe (8730 acre-feet (AF) per year) and 2035 for Los Alamos, Espanola, Taos, Jicarilla Apache Nation, and San Juan Pueblo (total of 11,100 AF per year) (USBR undated). The actual Santa Fe water right for San Juan Chama water is 5605 AF per year. However, the Papadopulos (2004) study makes reference to native water rights and states that Santa Fe's Buckman diversion will be 8730 AF per year.

The model "definition" for Cochiti inflow incorporating the above information is shown in Figure 5 as an example of how equations are written in the model. Each variable is also fully documented with explanatory information and data sources within the model to assist future users in understanding and replicating the model (Figure 6). Additional information on this variable and all variables can be found in Appendix C, Detailed model description.

Another inflow is runoff generated by precipitation. It is assumed there is no continual snowpack. Runoff values for each reach were pre-determined for a range of precipitation values over the contribution sub-basins. The reaches' sub-basins were previously established by Jones (2002).

The terrain varies greatly within each reach, from high mountainous terrain to high desert, resulting in widely varying precipitation across a sub-basin as well as between reaches. The variance in precipitation is captured in spatial precipitation distributions (rasters of 4 kilometer cells). Using ArcGIS 9.0 and 3.2 software, the precipitation rasters were combined with digital elevation models (rasters of 100 meter cells), detailed soils spatial files (coverages), and land use/land cover classification (coverages) based on Landsat imagery,in a hydrologic analysis of each contributing sub-basin to produce the runoff values. This GIS-produced runoff alleviates the issues of ungaged tributary inflow and effective precipitation common in many other models such as URGWOM and the Papadopulos (2004) water study. This procedure is described in Appendix D, ArcGIS procedures.

The spatially averaged precipitation value and corresponding runoff for a particular year are selected by the model in accordance with the user-chosen climate scenario. There are ten available climate scenarios (Table 2), drawn from an analysis of Ni et al.'s (2002) paleoprecipitation reconstruction for New Mexico climate division 5 and PDO cycles. The precipitation reconstruction data covers the time period 1000 A.D. to 1988 and all New Mexico climate divisions, but climate division 5 predominates along the Middle Rio Grande. For more



Auto: ☑ Type: Real

Auto: ☐ Unit: cfs

☑ Dimensions:

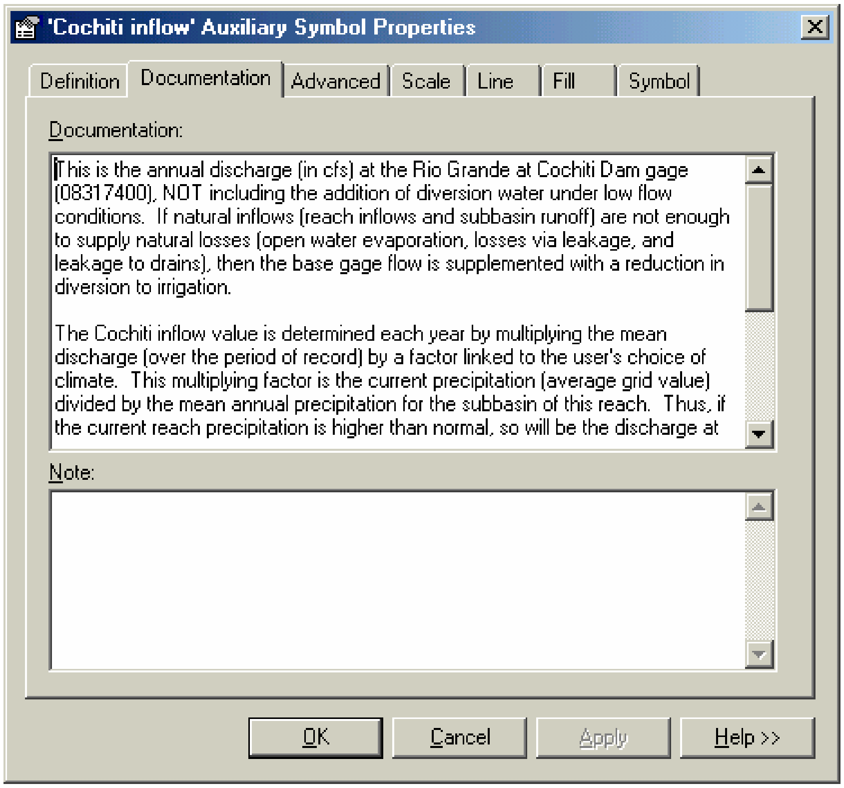
```
IF(YEAR(TIME) < 2004,
  //Use historical gage data
    'Cochiti gage historical'[INDEX('Model time')],
  //Manipulate mean Cochiti gage
   ('Cochiti gage mean' *
   ('Precip current'[R1]/'Precip mean'[R1])
    - 'Santa Fe SJC water'-'Upstream use of SJC water')
```

= 893 cfs

Cochiti gage historical
Cochiti gage mean
Precip current
Precip mean
Santa Fe SJC water
Upstream use of SJC water

● Linked Variables
○ All Variables
○ Ranges
○ Units
○ Functions

**Figure 5.** Powersim definition dialog for Cochiti inflow variable.



Documentation:

This is the annual discharge (in cfs) at the Rio Grande at Cochiti Dam gage (08317400), NOT including the addition of diversion water under low flow conditions. If natural inflows (reach inflows and subbasin runoff) are not enough to supply natural losses (open water evaporation, losses via leakage, and leakage to drains), then the base gage flow is supplemented with a reduction in diversion to irrigation.

The Cochiti inflow value is determined each year by multiplying the mean discharge (over the period of record) by a factor linked to the user's choice of climate. This multiplying factor is the current precipitation (average grid value) divided by the mean annual precipitation for the subbasin of this reach. Thus, if the current reach precipitation is higher than normal, so will be the discharge at

Note:

**Figure 6.** Powersim documentation dialog for Cochiti inflow.

**Table 2.** Mean normalized precipitation values for climate scenarios and reaches

| | Very dry | Dry & consistent | Dry & variable | Moderately dry & consistent | Moderately dry & variable | Average & consistent | Average & variable | Moderately wet & consistent | Moderately wet & variable | Very wet |
|---|---|---|---|---|---|---|---|---|---|---|
| Reach | 1050 - 1100 | 1750 - 1800 | 1200 - 1250 | 1850 – 1900 | 1250 - 1300 | 1775 - 1825 | 1150 - 1200 | 1600 - 1650 | 1825 - 1975 | 1800 - 1850 |
| | % | % | % | % | % | % | % | % | % | % |
| 1 | 0.917 | 0.926 | 1.070 | 0.928 | 1.032 | 0.936 | 0.937 | 1.156 | 1.027 | 1.050 |
| 2 | 0.884 | 0.928 | 1.010 | 0.937 | 1.007 | 0.968 | 0.965 | 1.137 | 1.054 | 1.106 |
| 3 | 0.816 | 0.933 | 0.889 | 0.954 | 0.956 | 1.030 | 1.022 | 1.115 | 1.108 | 1.218 |
| 4 | 0.885 | 0.937 | 0.999 | 0.926 | 1.017 | 0.982 | 0.984 | 1.127 | 1.074 | 1.126 |
| 5 | 0.816 | 0.933 | 0.889 | 0.954 | 0.956 | 1.030 | 1.022 | 1.115 | 1.108 | 1.218 |
| 6 | 0.816 | 0.933 | 0.889 | 0.954 | 0.956 | 1.030 | 1.022 | 1.115 | 1.108 | 1.218 |
| Ave | 0.856 | 0.932 | 0.958 | 0.942 | 0.987 | 0.996 | 0.992 | 1.127 | 1.080 | 1.156 |

information on the precipitation rasters, climate scenarios, and precipitation profiles, see the Model Data section and Appendix B, Supporting data.

Inflows to some reaches also include human-generated flows such as wastewater return flows (called non-irrigation return flows in the model) and irrigation return flows (discussed later). Wastewater returns are typically 50 percent of sewered water use, which is a portion of the total water use. Total water use is determined by per capita use and municipal populations. Per capita use can be established by a default, by user choice, or by an economic demand equation.

All these variables are arrays. Powersim allows the use of arrays for variables, which can simplify the model structure and reduce the number of variables. For example, the variable Municipal populations is an array with 1 dimension, called Municipalities (Bernalillo, Rio Rancho, Albuquerque, Albuquerque area, Los Lunas, Belen, and Socorro). The majority of the variables in the model are arrays, with 2 dimensions being common, such as reaches and crop types for agricultural acreage. Thus, all the acreages for each crop type and reach are specified in one single variable. A few variables have 3 dimensions.

A final inflow for discussion is the Jemez River base flow in Reach 2. A base flow of 0.35 cubic feet per second (cfs) was included based on analysis of monthly gage data for the Jemez River below Jemez Canyon Dam gage. All other tributaries are considered to be ephemeral.

All the variables that support calculations of inflows are included in the model page shown in Figure 4, along with top level outflow variables. Additional supporting variables for non-irrigation outflow calculations are displayed on the model page shown in Figure 7.

One non-irrigation outflow is leakage from the river to ground water. While some reaches may have gaining stretches, overall every reach is a losing reach (USACE 2002). Water leaves the river where part is consumed by riparian vegetation as evapotranspiration (ET) and lost to the system. The model divides the remaining leakage into the volume captured by drains and the volume lost to deep ground water, with first priority given to capture by drains. The leakage captured by drains becomes an inflow to the agricultural sub-system and some or all may return to the river. For presentation, the model lumps riparian ET and leakage to deep ground water as a single outflow variable in each reach.

The model calculations for riparian ET are based on analysis of actual data collected by Dr. James Cleverly et al. (2005) of the University of New Mexico at 5 sites along the Middle Rio Grande with a focus on exotic species. Further information on the analysis can be found in the Model Data section; essentially, the analysis introduces inter-reach variability and stochastic variation. The collection of dominant species at each data collection site was used to assign each site's data to one of 5 model categories: salt cedar and natives, monotypic salt cedar, cottonwood and exotics, cottonwood and natives, and Russian olive and natives. The model uses a sixth riparian category of marsh, but the Cleverly (2005) data did not include this type. Consequently, the marsh ET is calculated by multiplying an index value by the reference ET value based on a modified form of the Penman-Monteith equation (Sandia 2003a).

The ET values, in units of depth per time per acre, are translated into volumes by multiplying them by riparian acreage data obtained from the 1991 U.S. Bureau of Reclamation's Middle Rio Grande Database (MRGDB) of riparian land use contained in an ArcGIS shapefile and processed with ArcGIS 9 into the model's riparian vegetation categories.

Then the model converts the riparian ET into a demand for the water supplied by the river leakage to ground water. First, the ET is capped at the available ground water, meaning the model gives first priority on the use of leakage to riparian ET. Then this limited value is reduced by the low flow scaling ratio which recognizes the stress encountered by riparian vegetation during drought. The low flow scaling ratio was introduced into the model as part of the calibration process and is discussed in that section.

Returning to the computation of the leakage volume, the underlying variable for leakage is static leakage values from URGWOM (USACE 2002) for each reach. These are modified over time in accordance with predictions from the Papadopulos (2004) water study about the

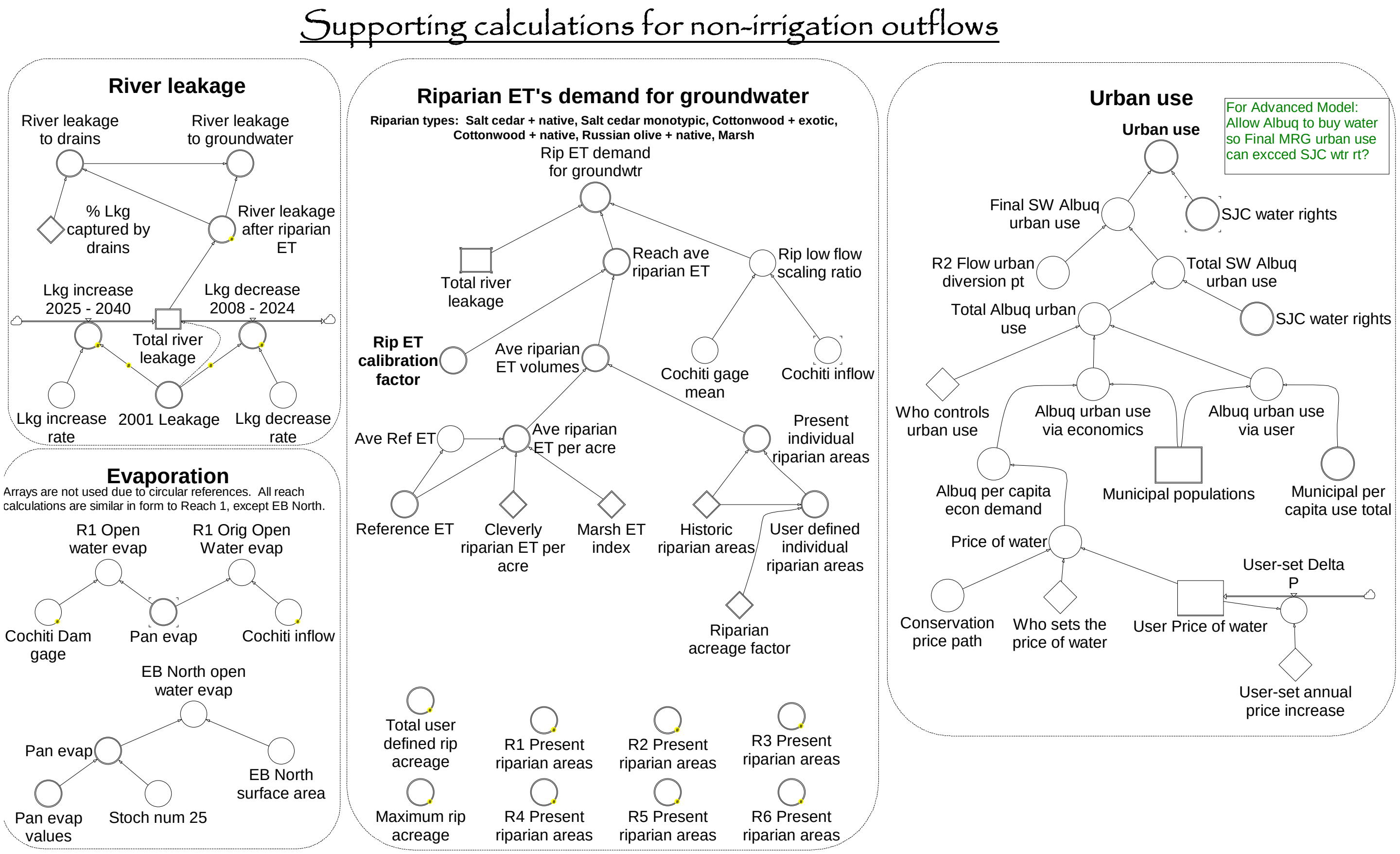


**Figure 7.** Model diagram for non-irrigation outflow variables.

impact of reduced pumping of ground water by Albuquerque. It is generally accepted that unsustainable pumping by Albuquerque and other users has lowered the aquifer and increased the leakage. Albuquerque intends to reduce use of ground water once it begins diverting its San Juan-Chama water. However, population pressure will drive ground water use up and Papadopulos (2004) predicts total leakage will be approximately 96 percent of the 2000 value by 2040.

Albuquerque's diversion of the San Juan-Chama water is calculated in the model by first determining the total water use by Albuquerque. The diversion is equal to the total use or twice the city's San Juan Chama water right, whichever is less. Albuquerque's water right is 48,200 acre-feet per year, but the city has approval to divert 96,400 acre-feet because the average wastewater return flow of 55,000 acre-feet per year will constitute the "return flow" that brings the city's consumptive use in line with the actual water right (USBR 2004). While Albuquerque's use will be 48,200 acre-feet per year from a legal perspective, it will be 96,400 acre-feet from the silvery minnow's and the river's perspective.

This method of "accounting" is ignored for the other municipalities owning San Juan Chama water rights and it is assumed they will use only their water right. Bernalillo (Reach 1) has a water right of 400 acre-feet per year and an assumed start date of 2025, while Los Lunas and Belen (both Reach 3) have an assumed start date of 2015 and water rights of 400 and 500 acre-feet, respectively. Los Lunas and Belen were given earlier start dates due to their rapid growth in recent years and expected growth rates of almost 4 percent and 2 percent per year (BBER 2004). Also, Bernalillo is physically constrained in its growth by Rio Rancho, Albuquerque, and the Santa Ana Indian reservation.

Returning to Albuquerque's water use, the city's total water use is calculated in two possible ways, either by an economic demand equation where demand is a function of price or by user-controlled annual decreases in per capita use. If the user chooses to have economics determine the water use, s/he can then choose to let the price path over time be established by Albuquerque's stated water conservation goals or by setting annual increases in price.

The model assumes Albuquerque will only supply this water to city residents in order to provide a scenario where decreased demand would decrease the urban diversion. In reality, Albuquerque already supplies water to non-residents and is likely to extend services to more non-residents in the future (Draft 2000). Thus, it is likely the city will always divert its full amount. The only time the diversion is reduced is when flows are low. There are two criteria levels, 260 cfs and 130 cfs, but these are daily or monthly values. While the model incorporates these criteria, it is extremely rare for Reach 2 to experience an average annual flow that low.

Furthermore, due to the extreme variability of the flows, it is not possible to estimate an annual value that would correspond to such a monthly or daily average.

Water not taken from the river by humans is subject to evaporation, which occurs from surface water and saturated sand bars in the river channel. Each reach's evaporation volume is calculated with a different empirical equation obtained from the URGWOM documentation (USACE 2002). The equations, discussed further in the Model Data section, treat evaporation as a function of flow levels and pan evaporation values. The pan evaporation values are varied stochastically among 25 possible values for annual pan evaporation, differing from reach to reach. There are actually 2 different equations for each reach: the first is valid for discharge less than bankfull discharge. The second is valid for discharges over bankfull discharge (when sandbars are submerged).

Another source of outflow in many reaches is irrigation diversion to the agricultural sub-system. The supporting variable structure for the agricultural sub-system can be seen in the model page in Figure 8. The New Mexico State Engineer has informed the MRGCD that they should not need more than 7.2 AF of diversion per acre of irrigated land per year. Diverting more than 7.2 acre-feet per acre of irrigated land per year could be considered wasteful (Turney 2001, cited in Papadopulos 2002). Thus, the model uses 7.2 AF per acre as the default diversion rate. However, past MRGCD diversions have ranged from eight to twelve AF per acre, while the Elephant Butte Irrigation District diverts only six AF per acre, on average (Papadopulos 2002). So the user is given the choice of setting the diversion rate higher or lower than 7.2 AF per acre. Diversions occur before Cochiti Dam gage (driven by Reach 1 irrigated acreage), below San Felipe gage (Angostura diversion, driven by Reach 2 acreage), in the middle of Reach 3 (Isleta diversion, driven by Reach 3 and Reach 4 acreage), and immediately before the San Acacia gage (San Acacia diversion, driven by Reach 5 acreage).

Diversions may be reduced from this "planned" amount in two ways if low flow conditions exist. This represents the assumption that MRGCD and irrigators will recognize and respect the need to preserve in-stream flows (not common in the past). The first reduction method considers the impact of Cochiti inflow on the entire system. If the inflow is equal to or more than 50 percent of the mean historical Cochiti inflow, then there is no reduction. If the Cochiti inflow is equal to or greater than 45 percent of the mean, then the flow is reduced slightly. If the flow level drops below 45 percent of the mean, a greater reduction is taken.

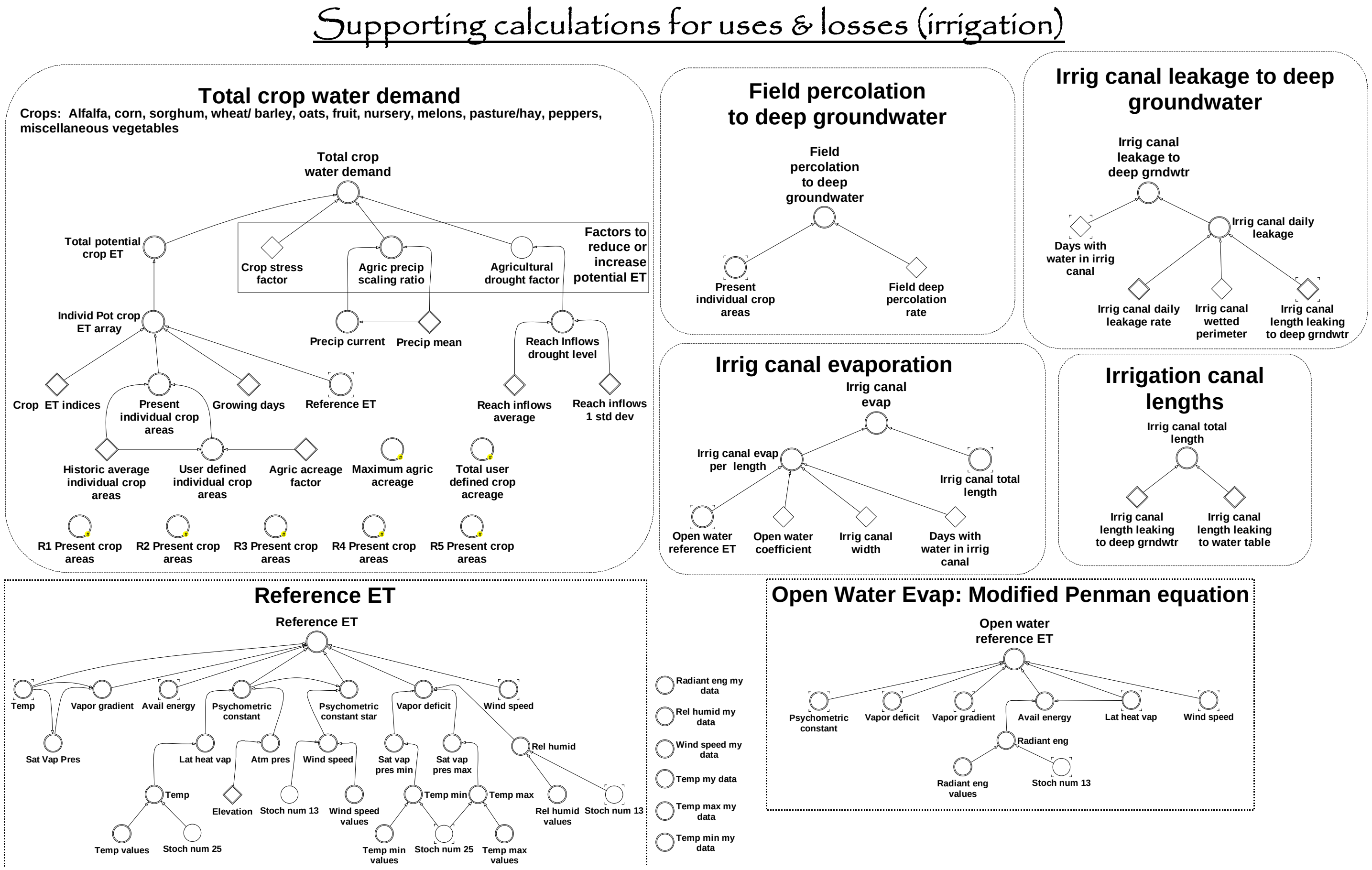


**Figure 8.** Model diagram for irrigation variables.

The second method individually considers the need for additional flow in each reach. If a reach's inflows are not enough to supply its uncontrolled outflows plus support an irrigation diversion, then the diversion is reduced or eliminated. Uncontrolled outflows are riparian ET, leakage to ground water and drains, open water evaporation, and urban diversions. This assumes urban diversions have priority over irrigation uses.

In addition to diversions, another inflow to the agricultural sub-system is river leakage via capture by drains, as mentioned previously. Also, each reach receives through flow from its upstream reach. Through flow is a portion of the excess water remaining after crop water demand via evapotranspiration (ET) and irrigation losses (field percolation to deep ground water, canal evaporation, and canal leakage to deep ground water).

The potential (maximum) crop ET is calculated by multiplying individual crop indices by the reference crop ET, based on a modified form of the Penman-Monteith equation (Sandia 2003a). Each crop index expresses the ET for that specific crop as a percentage of the ET of the reference crop. The underlying parameters for reference ET are varied stochastically, inducing variation in reference ET and therefore crop ET. Potential crop ET, expressed like precipitation as depth per unit time, is converted to a volume by multiplying by the crop acreage variable, which specifies acreage for each crop type and reach.

The user has the choice of varying the acreage of each crop and the model introduces the change according to an exponential decay function with a time constant of ten years. Each step of these calculations is expressed by multiple variables in the model, seen as a cascading structure on the supporting calculations pages (Figures 4, 7, and 8). This allows the user to easily modify equations and values to study their contribution to system behavior.

The translation of potential crop ET into crop water demand is accomplished by reducing the potential ET by scaling factors for drought, environmental crop stress, and precipitation. That water demand is then combined with the irrigation losses to calculate each reach's agricultural uses and losses (crop water demand and irrigation losses). These are compared to the available inflows to that reach and limited to the available water if necessary. Then the model analyzes the limited agricultural uses and losses to determine the extent of crop failure.

The irrigation losses are subtracted from the limited uses and losses variable to determine the amount of water available to supply crop water demand. The ratio of the limited crop water demand to unlimited water demand determines the percentage of crop failure. This assumes a farmer will recognize the limited water supply and limit his/her acreage so s/he can adequately supply the remaining crop's needs.

Each reach's agricultural uses and losses are subtracted from that reach's inflows to the agricultural sub-system to determine the excess water. That water is divided into return flow to the river and through flow to the next reach in the same proportions as occurred in 2001 in the MRGCD divisions. The locations of the MRGCD divisions relative to the river reaches are shown in Figure 2.

Another sub-system in the model is the artificial Low Flow Conveyance Channel (LFCC). The LFCC is divided into its own reaches in river Reaches 5 and 6. Although the LFCC serves as a canal for the agricultural sub system in Reach 5, the model treats the two separately, dividing the Reach 4 through flow between the two. Figure 9 shows the model structure for Reach 5. River flow is no longer diverted into the LFCC and recent historical flows have been extremely low (USGS undated), so a very minimal flow was assigned to the entry to the LFCC channel (LFCC wasteway), calculated as 10 percent of the irrigation through flow from Reach 4.

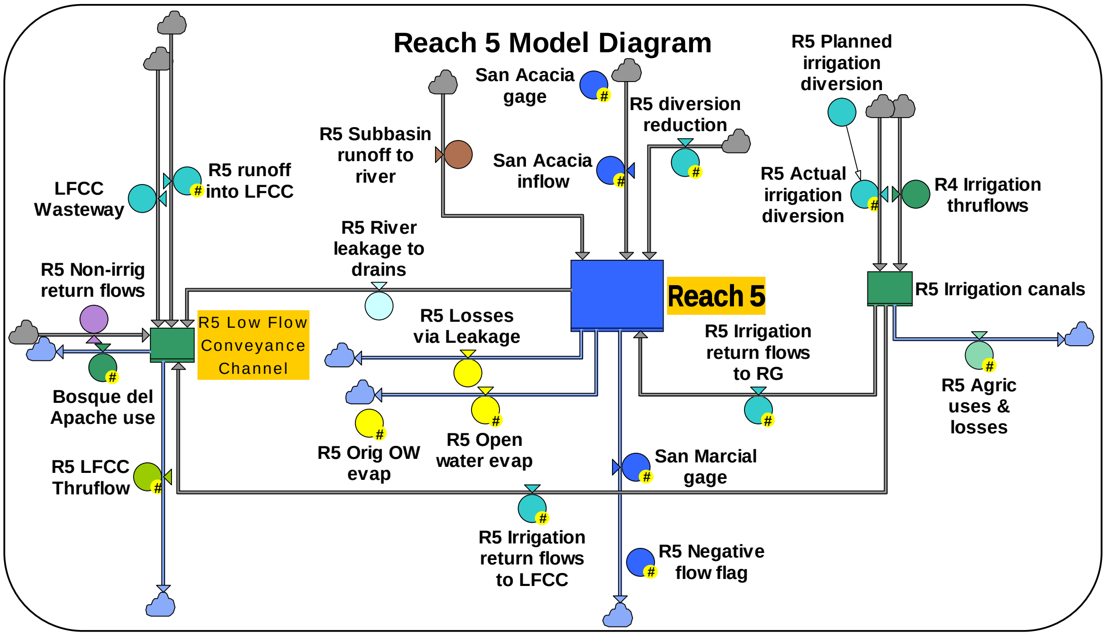

Reach 5: San Acacia gage to San Marcial gage

**Figure 9.** Model diagram for Reach 5.

Other gains to the LFCC include wastewater return flows from the city of Socorro in Reach 5, the capture of river leakage by irrigation drains in Reaches 5 and 6, and a portion of sub-basin runoff in Reach 5. Sub-basin runoff in Reach 6 is simply assigned to Elephant Butte because the LFCC outflow to Elephant Butte after San Marcial (the beginning of Reach 6) has not been gaged.

The outflow from the LFCC in Reach 5 is diversion by the Bosque del Apache National Wildlife Refuge for irrigating crops for consumption by birds, ponding, and other wildlife habit enhancements (Papadopulos 2002). The consumptive use water right by Bosque del Apache per the State Engineer's direction is 8691 AF/year, according to Papadopulos (2002). The remaining LFCC flow becomes through flow to the Reach 6 LFCC (gaged as the LFCC at San Marcial). There are no outflows from the Reach 6 LFCC except the flow into Elephant Butte.

Elephant Butte is included in the model, although only the northern portion of the reservoir is directly modeled. Since the Reach 6 was defined by Jones (2002) with the outlet point at the gage called the Rio Grande at the Narrows in Elephant Butte Reservoir, the northern lake is included in Reach 6 (Figure 10). Papadopulos (2004) refers to a north basin of Elephant Butte, separated by the Narrows, with a surface area of 14,196 acres. Elephant Butte North (the model name) is modeled as a reservoir, which in Powersim means a level that cannot be depleted below zero. Thus, the model calculates the volume of Elephant Butte North using a first order Euler integration, based on an initial volume and annual inflows and outflows. As mentioned previously, the reach levels are not operative and so the reach flow volumes are calculated via entered equations, not with an Euler integration.

The surface area and length of the north lake, relative to the total Elephant Butte surface area and length, were determined using a GIS land use shapefile. Then geometry and thinking of the lakes as right triangle pyramids provided the relationship between the Elephant Butte North volume and the total volume. It is assumed this relationship remains constant over a variety of volumes, so the model is able to calculate a total volume for Elephant Butte each year based on the Elephant Butte North volume. The initial volume for Elephant Butte North was determined using a total volume of 1,460,738 AF, the average volume for 2000, which was a moderately dry year (Palmer Drought Severity Index = -0.04).

Another inflow to Elephant Butte North is the precipitation directly on the lake. This is simply the depth of precipitation times the surface area. The surface area is determined with a graphical surface area – volume relationship provided by Roach (2004).

A major outflow from Elephant Butte North is loss from open water evaporation. This is also a simple calculation, multiplying the Reach 6 pan evaporation value by the surface area of the lake and the evaporation coefficient (0.7). This coefficient accounts for pan effects, relating the pan evaporation value to the actual evaporation rate over the lake (WRCC undated).

## Reach 6: San Marcial gage to Narrows at Elephant Butte gage

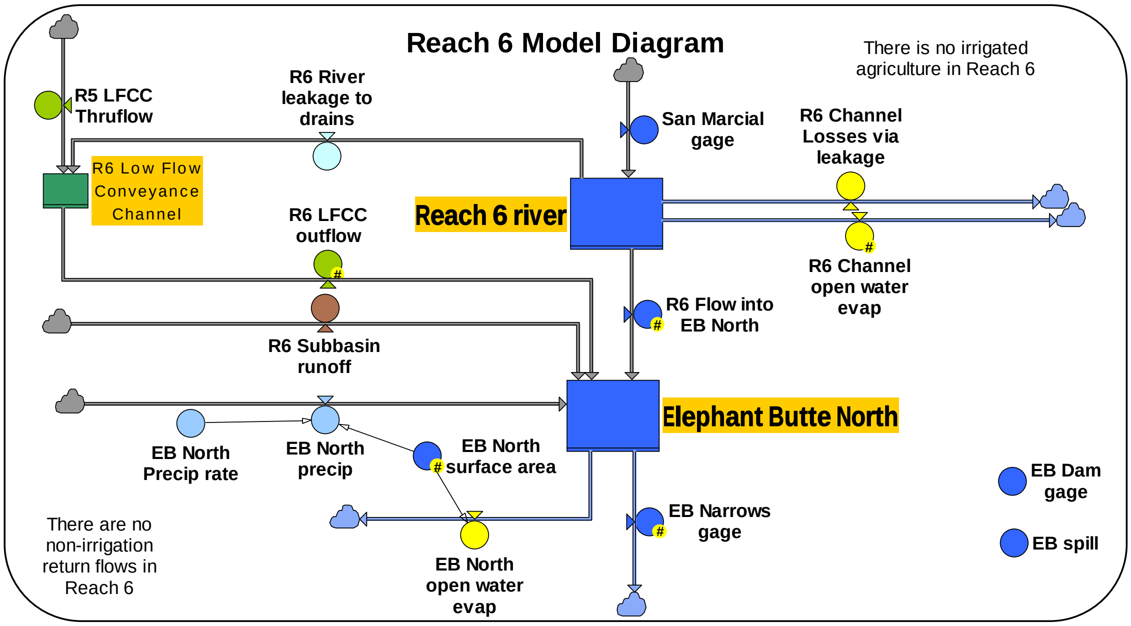


**Figure 10.** Model diagram for Reach 6.

The final outflow from the model is the releases from Elephant Butte, measured by the Elephant Butte Dam gage, the endpoint of the entire model. Unlike the flows at the bottom gage of each river reach, the flow volume at Elephant Butte Dam gage is not determined by subtracting outflows from inflows. Instead, it is determined by convoluted "rules" based on the Rio Grande Compact requirements and historical flows and volumes. Generally, the model releases are calculated to maintain consistent flow values and to assure Compact compliance.

If the annual Elephant Butte volume goes above 1,700,000 AF or below 400,000 AF, the annual release is increased to avoid flooding and incurring annual debits. Being in accrued debit status is allowed, but the model attempts to keep accrued debits above -200,000 AF. Since 1969, the accrued debit hasn't been below -200,000 AF except for one year, 1980 (Gorbach 1999). Greater accrued debits are not completely prohibited though. According to Mutz (1999), the lowest accrued debit since 1940 was 529,000 AF at the end of 1956. This is extremely difficult to model correctly on an annual basis due to the complexity of the rules and because real world releases are made continuously throughout the year and adjusted, based on present volume and weather predictions.

For instance, determining the occurrence and volume of spills can be complicated. In the real world, spills are avoided and so releases can be increased early in anticipation of spill conditions (when the reservoir volume exceeds maximum capacity). But complete anticipation is not possible and spills do occur in reality. So the model rules governing the flow at Elephant Butte Dam gage must minimize the chance of a spill but allow for occasional spills of various amounts.

The excess water cannot just be "emptied out," because the exact amount of the spill volume, as well as the release volumes, is needed for the model to determine compliance with the Rio Grande Compact. As with all variables, more information on the supporting data can be found in the Model Data section and detailed explanatory information and equations can be found in Appendix C, Detailed model description. The model structure for the variables containing the rules and Elephant Butte Dam gage can be seen in Figure 11.

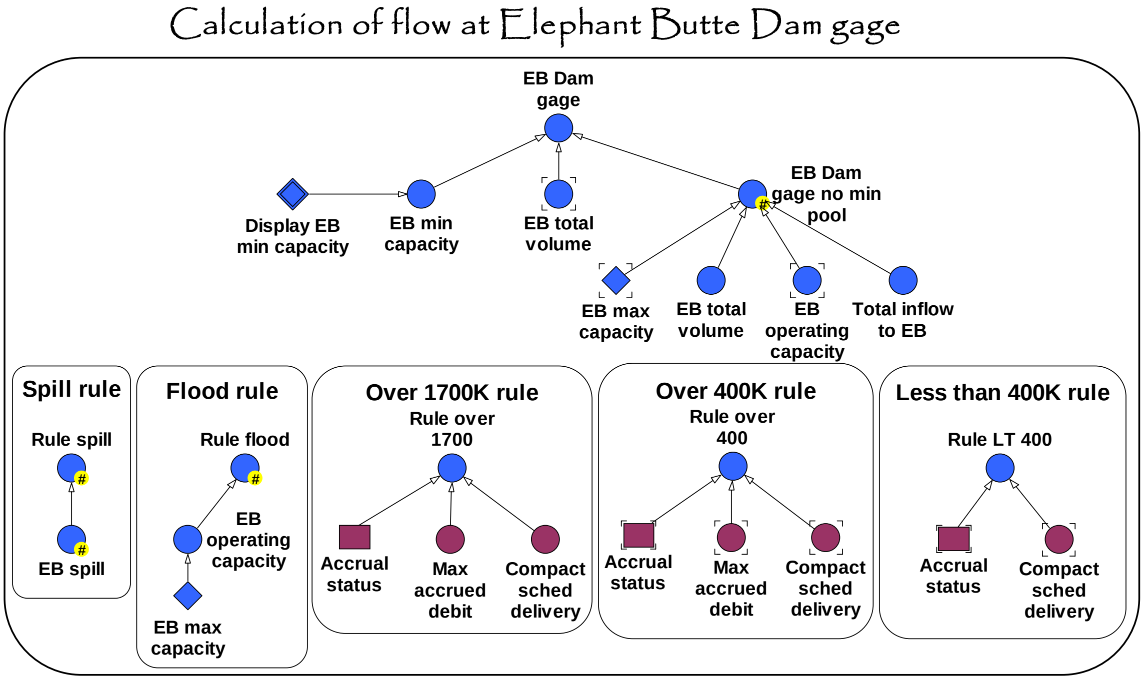


**Figure 11.** Model diagram for Elephant Butte variables.

As mentioned previously, the Rio Grande Compact is a legal agreement between Colorado, Texas, and New Mexico governing the apportionment of flow volumes in the Rio Grande. Pertinent to the model, the Compact dictates quantified deliveries from Elephant Butte by New Mexico to Texas, based on annual native flows at the Otowi gage (Otowi index supply). To determine each year's required delivery, the model uses a graphical representation of the delivery schedule and computes values between the defined points by a third order polynomial interpolation.

Since this is crucial to both states, score is carefully and intricately kept in accordance with terms specified in the Compact. In accordance with those terms, if the annual flow at Elephant Dam gage exceeds the scheduled delivery, the model computes annual credits equal to the difference between the two and vice versa for annual debits. The accrual of credits and debits is tracked by the model in a level, but modeling Compact compliance is highly complicated: there are limits to the annual credit and debit amounts, changes to debit amounts based on changes in storage in several real-world reservoirs in New Mexico, losses due to evaporation must be accounted for, and the occurrence and volume of spills affects the accrual status. Figure 12 displays the model variable structure used for these computations.

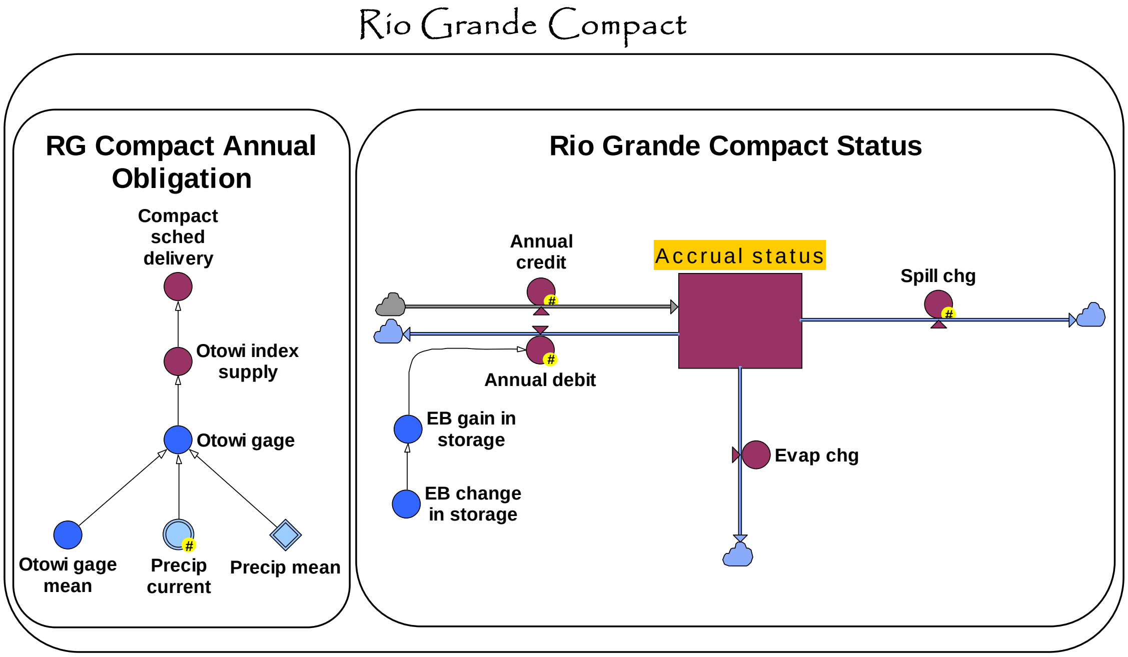


**Figure 12.** Model diagram for Rio Grande Compact variables.

Finally, the model allows the user to modify several variables, solely or in combination, so the user can run a simulation of these changes and see the effects on the river flow at each gage point. Figure 13 shows the main user controls page, by which the user accesses the individual controls. The user can choose between the 10 different climate scenarios which drive the year to year value of precipitation and runoff. As mentioned, the user can also choose to calculate Albuquerque's total water use by an economic demand equation with the user's choice

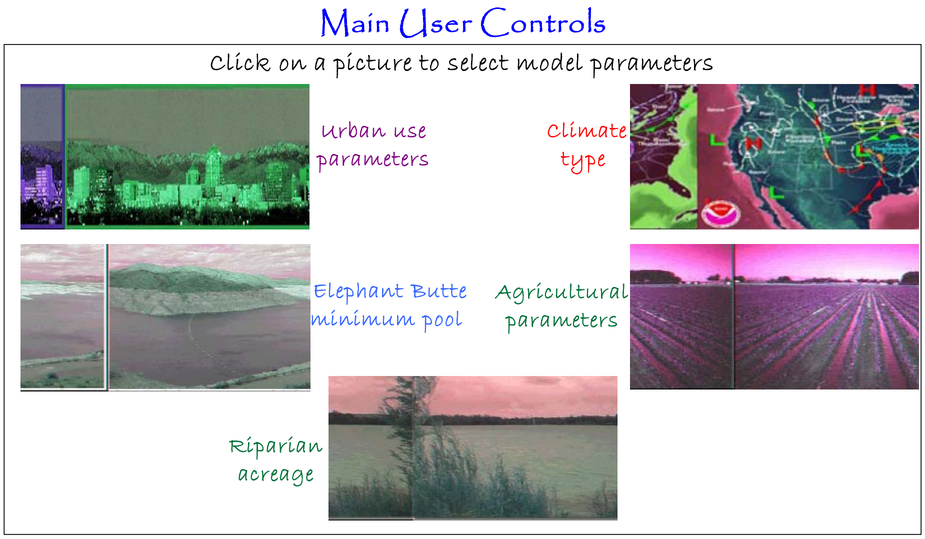


**Figure 13.** Model diagram for main user controls.

of price paths or by a user-selected decline in per capita usage. The user can also establish the start date for use of San Juan-Chama water upstream from Cochiti Dam.

Another area of choice for the user is the agricultural sub-system. The user can alter the diversion rate. Also, the user can alter crop composition and the acreage for each crop. This choice is applied equally to each reach because giving the user a choice of individually modifying the reaches would be overwhelming, with 66 (11 crops in each reach) selections to be made.

Conversely, the user is allowed to individually alter the riparian vegetation composition and acreage in each reach. The last user option is to alter the Elephant Butte minimum volume, which has a default value of 300,000 AF. There is an authorized 50,000 minimum pool for recreation, created with San Juan-Chama water (USACE 2002), but the reservoir volume didn't drop below 1,000,000 AF between 1982 and 2000. On the low end, the volume has been lower than 100,000 AF only 3 months of the 312 months of record (since 2000), 200,000 AF only 15 months and 300,000 AF only 30 months (Roach 2004). More recently, the volume has dropped significantly. The monthly average for September 2004 was only 96,000 AF and as of 6 October 2004, the volume was 336,350 AF. However, many people think 350,000 AF is too low for Elephant Butte, given today's uses (Liles 2002).

## 5. KEY MODEL DATA

### *5.1 Sources*

While several sources were used for supporting data for this model, five sources were primary. The first source, three Sandia National Laboratory (SNL) Middle Rio Grande models provided both data and concepts for the model construction. The second source was the Upper Rio Grande Water Operations Model (URGWOM) website (USACE 2002), which supplied concepts, data and equations. The third source was S. S. Papadopulos and Associates, Inc. who have prepared several technical documents about the Middle Rio Grande basin for the U.S. Army Corps of Engineers, New Mexico Office of the State Engineer and Interstate Stream Commission.

Another highly useful source of ideas and data was the Powersim version of the URGWOM model built by Jesse Roach, a graduate student at the University of Arizona, for SNL. Finally, the reach definition and delineation of their contributing sub-basins was accomplished and provided in GIS format by Christy Jones, a graduate student at the University of New Mexico. Additional sources can be found in Appendix A, Data dictionary.

### *5.2 Various data for each reach*

Copious amounts of data were needed to build the model. Some of that data is summarized in Tables 3 and 4. The mean precipitation values in Table 3 are spatially and temporally averaged values. Table 5 contains data pertinent to municipal areas that affect the Middle Rio Grande by urban diversions and/or wastewater return flows. Detailed information on this and other data can be found in Appendix B, Supporting data.

**Table 3.** Various data for reaches

| Reach ID | Mean precip for 1971 – 2000 (inches/year) | Leakage (cfs) | Average pan evaporation (inches/year) | Total riparian acreage | Total irrigated agriculture (acres) |
|---|---|---|---|---|---|
| 1 | 14.5 | 13.2 | 90.83 | 3,985 | 2,392 |
| 2 | 15.7 | 408.75 | 99.03 | 5,951 | 9,128 |
| 3 | 12.8 | 324.5 | 73.13 | 10,550 | 32,147 |
| 4 | 12.3 | 126 | 69.59 | 9,046 | 802 |
| 5 | 11.4 | 29 | 80.81 | 21,306 | 9,127 |
| 6 | 12.4 | 53 | 100.30 | 7,306 | 0 |
| | Daly and Taylor (1998). | USACE (2002) | WRCC (undated-a) | RGIS website (undated-c). | USACE (2002), Papadopulos (2004), Roach (2004) |

**Table 4.** Evaporation empirical equations for reaches (USACE 2002).

| Reach ID | Bankfull discharge (cfs) | Bankfull surface area (acres) | For Q < bankfull discharge | For Q >= bankfull discharge |
|---|---|---|---|---|
| 1 | 5650 | 625 | $L = Pan_e (111 Q^{.20}) + 0.25 Pan_e (625-111 Q^{.20})$ | $L = Pan_e (111 Q^{.20})$ |
| 2 | 4820 | 2718 | $L = Pan_e (84 Q^{.41}) + 0.25 Pan_e (2718-84 Q^{.41})$ | $L = Pan_e (84 Q^{.41})$ |
| 3 | 4820 | 5175 | $L = Pan_e (124 Q^{.44}) + 0.25 Pan_e (5175 -124 Q^{.44})$ | $L = Pan_e (124 Q^{.44})$ |
| 4 | 4000 | 1054 | $L = Pan_e (13 Q^{.53}) + 0.25 Pan_e (1054 - 13 Q^{.53})$ | $L = Pan_e (13 Q^{.53})$ |
| 5 | 9100 | 2913 | $L = Pan_e (158 Q^{.32}) + 0.25 Pan_e (2913 - 158 Q^{.32})$ | $L = Pan_e (158 Q^{.32})$ |
| 6 | 2400 | 166 | $L = Pan_e (60 Q^{.13}) + 0.25 Pan_e (166 - 60 Q^{.13})$ | $L = Pan_e (60 Q^{.13})$ |

Where:
$Q$ = Mean daily discharge at the upstream end of the reach, in cfs;
$L$ = Loss from water surface evaporation and wetted sands in the reach, in acre-ft/day; and
$Pan_e$ = Pan evaporation data for the site nearest to the reach under consideration, in ft/day.

**Table 5.** Municipal data

| Municipality | 2000 population (persons) | Time frame | Population growth rate (%) | Sewered water use return flow rate (%) | San Juan Chama water right (AF/year) |
|---|---|---|---|---|---|
| Bernalillo | 6,611 | 2000 – 2005: | 1.04 | 50 | 400 |
| | | 2006 – 2010: | 0.88 | | |
| | | 2011 – 2015: | 0.78 | | |
| | | 2016 – 2020: | 0.69 | | |
| | | 2021 – 2025 | 0.60 | | |
| | | 2026 – 2055: | 0.53 | | |
| Rio Rancho | 51,765 | 2000 – 2005: | 4.77 | 35 | 0 |
| | | 2006 – 2010: | 4.04 | | |
| | | 2011 – 2015: | 3.58 | | |
| | | 2016 – 2020: | 3.14 | | |
| | | 2021 – 2025 | 2.75 | | |
| | | 2026 – 2055: | 2.43 | | |
| Albuquerque | 448,607 | 2000 – 2005: | 1.30 | 50 | 48,200 |
| | | 2006 – 2010: | 1.17 | | |
| | | 2011 – 2015: | 1.06 | | |
| | | 2016 – 2020: | 0.96 | | |
| | | 2021 – 2025 | 0.87 | | |
| | | 2026 – 2055: | 0.79 | | |
| Albuquerque area | 63,753 | 2000 – 2005: | 1.36 | 50 | 0 |
| | | 2006 – 2010: | 1.22 | | |
| | | 2011 – 2015: | 1.11 | | |
| | | 2016 – 2020: | 1.00 | | |
| | | 2021 – 2025 | 0.91 | | |
| | | 2026 – 2055: | 0.83 | | |
| Los Lunas | 10,034 | 2000 – 2005: | 3.73 | 50 | 400 |
| | | 2006 – 2010: | 3.39 | | |
| | | 2011 – 2015: | 3.13 | | |
| | | 2016 – 2020: | 2.83 | | |
| | | 2021 – 2025 | 2.52 | | |
| | | 2026 – 2055: | 2.26 | | |
| Belen | 12,702 | 2000 – 2005: | 1.88 | 50 | 500 |
| | | 2006 – 2010: | 1.71 | | |
| | | 2011 – 2015: | 1.58 | | |
| | | 2016 – 2020: | 1.43 | | |
| | | 2021 – 2025 | 1.27 | | |

| Municipality | 2000 population (persons) | Time frame | Population growth rate (%) | Sewered water use return flow rate (%) | San Juan Chama water right (AF/year) |
|---|---|---|---|---|---|
| | | 2026 – 2055: | 1.14 | | |
| Socorro | 8,877 | 2000 – 2005: | 0.72 | 57 | 0 |
| | | 2006 – 2010: | 0.65 | | |
| | | 2011 – 2015: | 0.59 | | |
| | | 2016 – 2020: | 0.52 | | |
| | | 2021 – 2025 | 0.45 | | |
| | | 2026 – 2055: | 0.40 | | |
| Citation | US Census Bureau (undated). | -- | BBER (2004), Gregory (1996), Rio (undated), Water (undated). | SNL (2002), Papadopulos (2004), Stephens (2003) | USBR (undated) |

### *5.3 Climate scenarios and precipitation profiles*

The future climate in New Mexico, as in other locations, is often a source of strong debate. Many think the last 50 years was very wet in comparison to the last 1000 years and the state should expect less precipitation and lower stream flows in the 21st century. For instance, 1978-1992 was the third wettest period in the last 1,371 years (Papadopulos 2004). Table 3 shows the mean precipitation values for 1971 – 2000, while Figure 14 maps the distribution of the precipitation across the sub-basins.

But the past century also saw record dry conditions. A severe drought occurred in the 1950's, with a precipitation deficit of 24 inches over a seven year period. This drought lasted from 1945-1963 and was the 3rd most severe drought over the last 1,371 years. Certainly, drought seems to be a normal condition for the state. From 1896 to 2002, New Mexico experienced drought conditions 55 percent of those years (Liles 2002).

On the other hand, perhaps precipitation is showing an increasing trend for New Mexico. Grissino-Mayer (1996, cited in Papadopulos 2004) states "A long-term, above normal rainfall pattern began ca. AD 1791 and has lasted into the current century. The reconstruction shows that two short-term drought periods occurred during AD 1890-1904 and AD 1945-1958. In general, however, rainfall during the last 200 years has been above normal, and has been steadily increasing since the early1700s." Some think this increased precipitation is a result of global warming and could continue in the future. But warmer temperatures will mean less snowpack, which is critical to stream flow. Also, global warming will amplify extremes, meaning more severe droughts and wetter wet periods (Liles 2002).

More recently, the New Mexico precipitation deficit was six inches over a 3 year period (as of September 2002) (Liles 2002). The 2002 drought was similar to the 1950's drought in intensity (PDSI lower than -3), but it was much shorter. Yet stream flows were at record lows in 2002, with annual average flows at Cochiti Dam gage 45 percent of the mean, probably due to

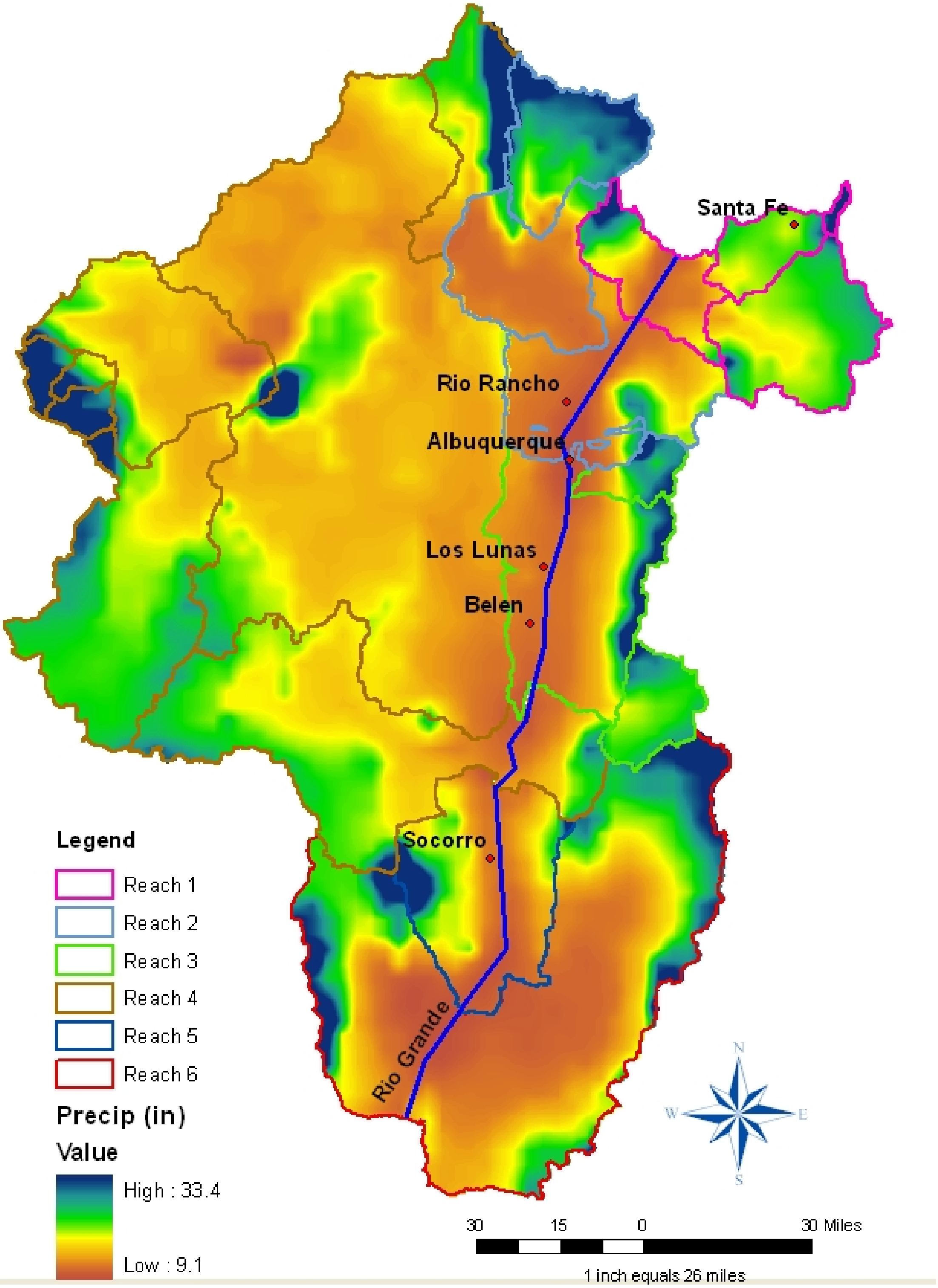


**Figure 14.** Mean annual precipitation for contributing sub-basins.

increased demand and anthropogenic changes to the river. In 2003, precipitation was even less and the Cochiti Dam flow was only 40 percent of the mean (USGS undated). This presents a foreboding picture, with less severe droughts likely to cause controversial water allocation issues more often (Liles 2002).

Thus, the model's climates and corresponding precipitation profiles should include wet and dry periods, with a great degree of variability. Rather than create the precipitation profiles from scratch, it was decide to use cool season (November – April) paleoprecipitation reconstructions from tree ring data produced by Ni et al. (2002). The values were normalized by dividing by the mean for the entire period. This allows the assumption that a dry cool season indicates a dry year and vice versa. The reconstructions included precipitation values for 1000 AD to 1988 for all New Mexico climate divisions.

Climate division 5 (Figure 15) is the dominant division among the Middle Rio Grande sub-basins, so its values were analyzed in 50 year time periods, beginning every 25 years (e.g., 1000 - 1050, 1025 - 1075, etc). A mean normalized precipitation values was calculated for each period. The "driest" 50 year period, with a mean normalized precipitation of 0.816, was 1050 - 1100. Table 2 shows each climate scenario's time period and mean normalized precipitation for each reach.

"Dry" was then defined as being less dry, i.e., having a normalized mean precipitation close to 0.90. Papadopulos (2004) also defines "wet" and "dry" as being 10% above the mean for the period of record. Time periods with this approximate value were visually analyzed for the pattern within the time period. It was decided to use 2 time periods for each approximate normalized value - one that had consistent climate for longer periods of time and one that was more variable over a shorter period of time. Greater variability over a very short period of time was the goal for this more variable climate scenario, to reflect the predicted impact of global warming on New Mexico. Figures 16 and 17 compare precipitation profiles for some consistent and variable climates for Reaches 1 and 5.

This method was repeated for the rest of the climate scenarios. "Moderately dry" was defined as having a normalized mean precipitation close to 0.95. Average was defined as having a normalized value of 1, of course. The wettest time period was chosen next. 1325 - 1375 had a normalized value of 1.336. However, this seemed very wet, with only one other similar 50 year time period (1300 - 1350). This was seen as anomalous or occurring at very large time intervals. Thus, the second wettest 50 year period was chosen to be the "wettest" climate scenario for the model. This was 1800 - 1850, the wettest period since 1650 with a

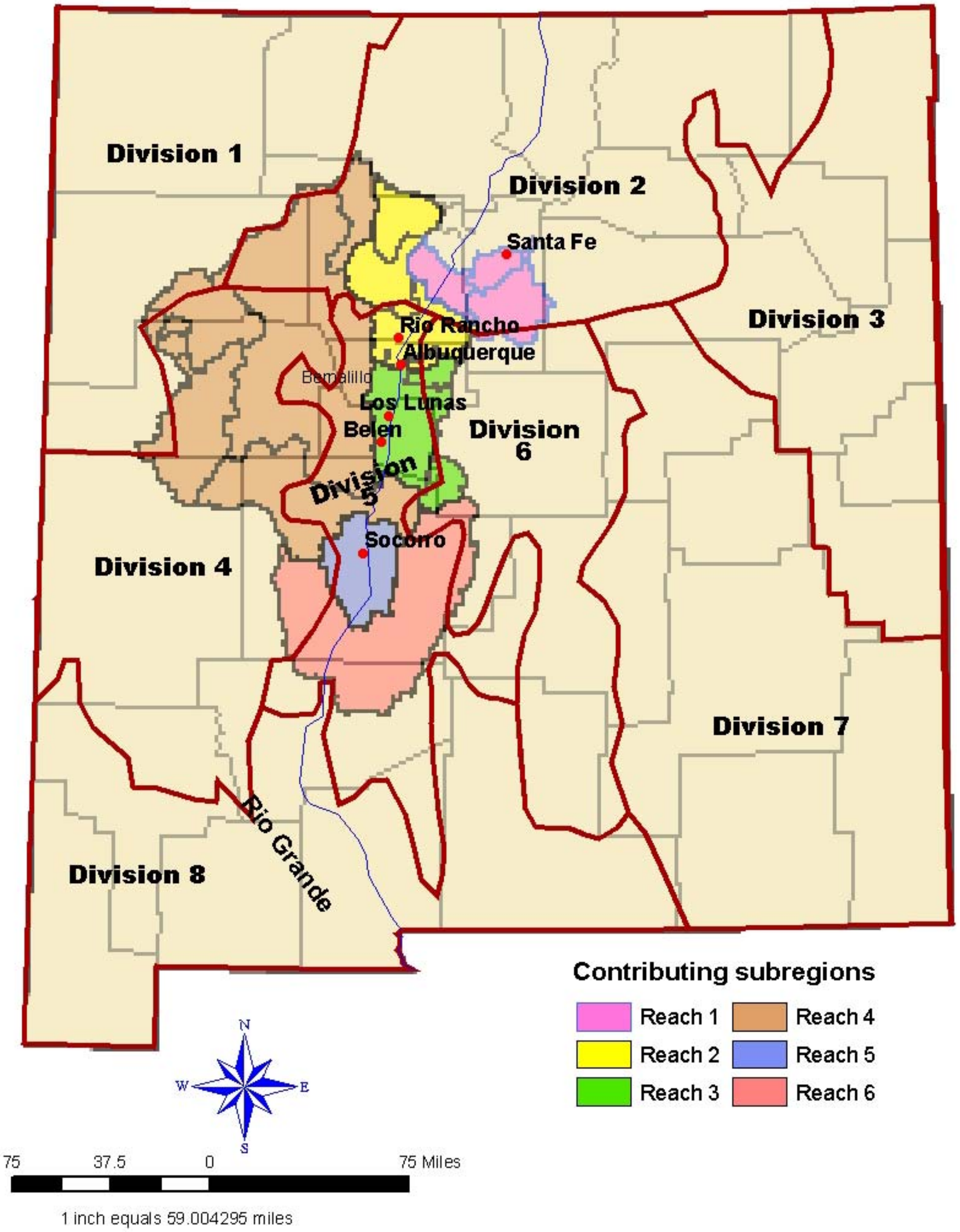


**Figure 15.** Climate divisions in New Mexico.

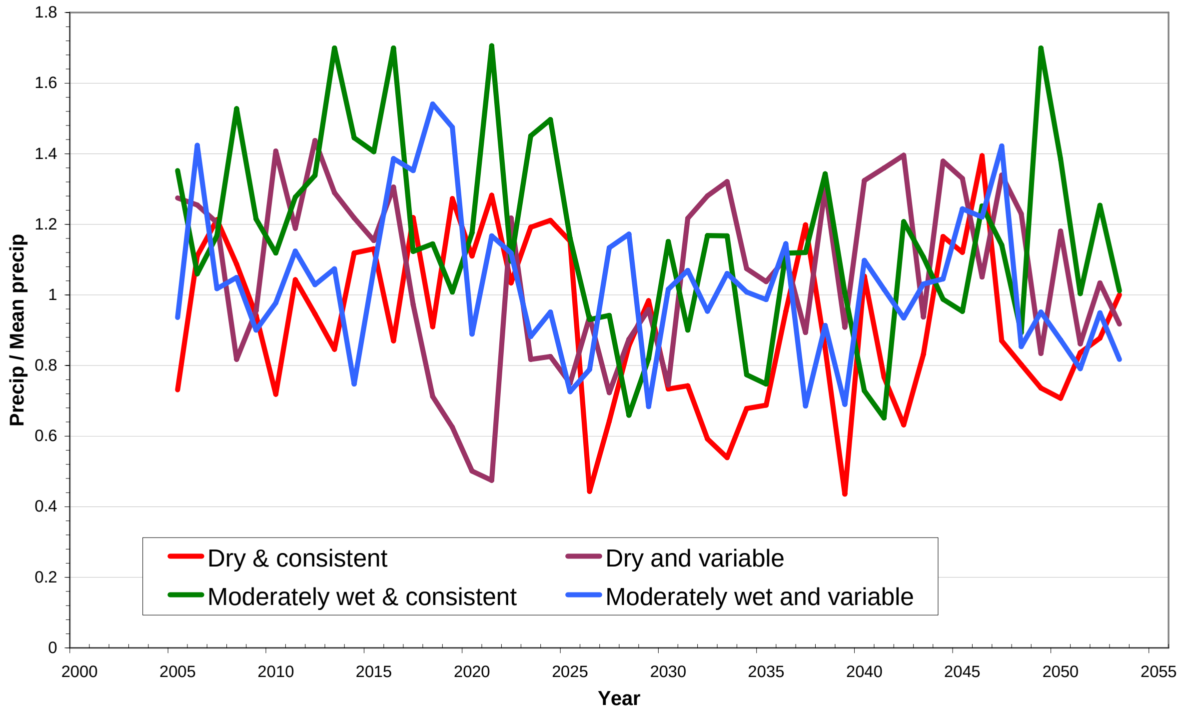


**Figure 16. Consistent and variable climate scenarios: normalized precipitation for Reach 1**

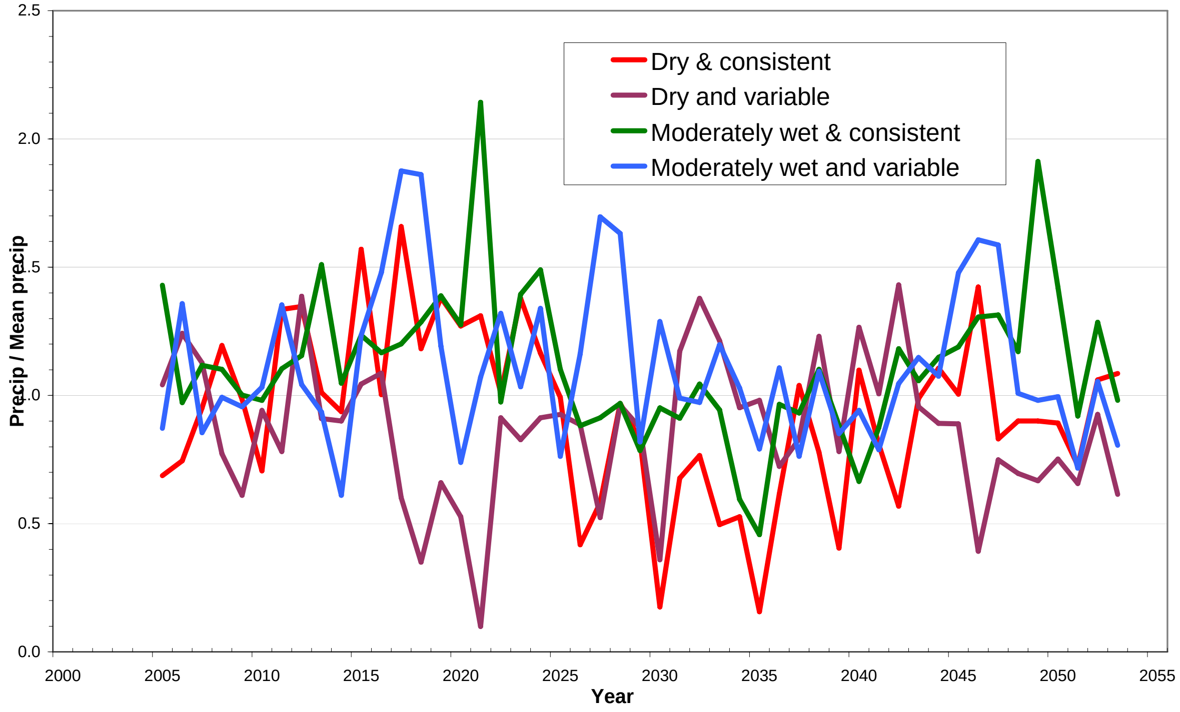


**Figure 17. Consistent and variable climate scenarios: normalized precipitation for Reach 5**

mean normalized precipitation value of 1.22. "Moderately wet" was then defined as having half the normalized value of the wettest period, or roughly 1.10.

Each chosen period was then used to create a normalized precipitation 50 year sequence for each reach, based on which climate division each reach was in. This maintained the inter-reach variation in precipitation although only division 5 was analyzed to pick the 50 year periods. Reach 1 is entirely within climate division 2. Reach 2 is mostly in division 2 with some area in division 5, so each year's value was calculated as being 2/3 the division 2 value and 1/3 the division 5 value. These proportions were based on visual analysis of ArcGIS shapefiles of the divisions and reaches. Reaches 3, 5, and 6 are entirely within climate division 5. Reach 4 is similar to Reach 2, located in multiple climate divisions. The proportions were 1/2 division 4, 1/4 division 2, and 1/4 division 5. The entire 50 year precipitation profiles for each climate and reach can be found in Appendix B.

The variability in the 50 year time periods was high, with the normalized precipitation ranging from 0.1 to 2.4 in most reaches and time periods. Thus, roughly 24 precipitation rasters were created for each reach by multiplying the 1971 – 2000 mean precipitation raster (Figure 14) by the normalized precipitation values. This maintains the variability of the long-term record and wetter trend of the last 3 centuries. Therefore, approximately 144 possible sub-basin runoff values are included in the model.

### *5.4 Economics*

If the economics option is chosen by the user, the Albuquerque per capita water use is calculated with an economic demand equation (per capita water use as a function of price). The form of the demand equation was obtained from Chermak (2003). Using a per unit price of water of $1.20, total per capita use of 200 gal/person/day, and an elasticity of -0.51, she derived a demand equation of

$$Q = 147.4 - 41.48 P$$

where

Q = per capita water demand

P = Price per water unit. A water unit equals 748 gallons.

The model equation was derived using the same procedure and per unit price of water for 2003 of $1.1934 (Customer 2004), total per capita use of 204 gal/person/day (Papadopulos 2004) and an elasticity of -0.51. That equation is:

$$Q = 150.32 - 42.54 P$$

The model incorporates a lower limit of 75 gallons per person per day. This reasonable but low number is comprised of 50 gallons per person per day for residential use and 25 gallons per person per day for non-residential use. According to Karpiscak et al. (1990), a residential use of 50 gal/person/day of municipally-supplied water was achieved by families living in an experimental house in Arizona for 3 years without lifestyle changes. The current non-residential use of 72 gallons per person per day for Albuquerque was reduced in the same proportion, for just over 25 gallons per person per day. The sum of these two is 75 gallons per person per day.

The price of water used in this equation for each year's demand can be calculated by the model in two ways. If the user chooses the model option, the model uses a price path over time created to meet Albuquerque's water conservation goals (based on the demand equation and the 2004 price of $1.2294/unit (Customer 2004) as the initial price). The city intends to reduce water demand by 40 percent from the 1995 baseline by 2014 (150 gallons per person per day) (USBR 2004). The 2040 goal is 130 gallons per person per day (Papadopulos 2004). These two data points were combined with the demand equation to create annual prices necessary to achieve the desired water demands.

Since only 3 data points were available, linear interpolation was used to calculate additional data points for 2023 and 2032. Then the model uses Powersim's graphical function with these 5 data points to determine the price between these points. It is assumed that the 2040 conservation goal (and hence the price) will be valid until 2050. The GRAPH function accomplishes this past 2040 by computing the output value by horizontal extrapolation. The user may also choose to set an annual price increase, which then drives the demand equation.

### *5.5 Riparian evapotranspiration data*

The riparian ET values used by the model are shown in Table 6. The dominant vegetation community for each site from Cleverly (2005) and the assigned model riparian categories are listed in Table 7. Cleverly's (2005) data was averaged over the 5 years of collection and assumed to represent average ET for each riparian type over the entire Middle Rio Grande. This may not be a valid assumption, but this was the only actual data available on riparian ET for this region. Then the riparian ET was modified to vary between reaches in accordance with the inter-reach variation of reference ET. This also introduced stochastic variation in the riparian ET because reference ET varies stochastically.

**Table 6.** Average riparian ET by vegetation community

| Vegetation community | ET (cm/yr) |
|---|---|
| Salt cedar and native | 78.8 |
| Salt cedar monotypic | 109.2 |
| Cottonwood and exotics | 125.6 |
| Cottonwood and natives | 108.5 |
| Russian olive and natives | 108.5 |

**Table 7.** Riparian ET data collection sites and assigned model riparian categories

| Site | Dominant vegetation community | Riparian category for model |
|---|---|---|
| South Valley in Albuquerque (SHK). | Cottonwood, salt cedar, Russian olive | Cottonwood and exotics |
| Belen (BLN | Cottonwood, seep willow, and coyote willow | Cottonwood and natives |
| Sevilleta (SEV) | Salt cedar and saltgrass, with saltbush, coyote willow, and mesquite also present | Salt cedar and natives |
| Bosque del Apache (BDAS). | Dense monotypic salt cedar | Salt cedar monotypic |
| La Joya (LARO). | Russian olive and willow | Russian olive and natives |

## 6. MODEL CALIBRATION

Using runoff values generated from precipitation rasters for 2000 to 2003, the model was calibrated with actual gaged flows for those years. These historical flows are shown in Table 8. Results of the simulation using the uncalibrated model are shown in Table 9. Generally, flows were too low, so variables were modified to increase flow as needed. After several iterations, the changes listed in Table 10 were incorporated into the calibrated model.

Variables with uncertainty as to their accuracy were changed first. For instance, leakage from the Rio Grande is still being studied. The accepted leakage values are being refined but there are no definitive values. Also, with only 5 data points for riparian ET, the assumption that these values could represent an average ET might not be entirely realistic. Therefore, riparian ET values were reduced.

Next, it was noticed the difference in flow values were usually greater in 2002 and 2003, which were particularly dry years. Due to the importance of the in-stream flows to endangered

**Table 8.** Gaged flows for 2000 to 2003

| | Cochiti Dam | San Felipe | Albuquerque | Bernardo | San Acacia LFCC | San Acacia | San Marcial LFCC | San Marcial | Elephant Butte dam |
|---|---|---|---|---|---|---|---|---|---|
| | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs |
| 2000 | 893 | 920 | 773 | 516 | 0.37 | 598 | 258 | 340 | 1081 |
| 2001 | 937 | 983 | 815 | 550 | 35.5 | 545 | 231 | 378 | 1084 |
| 2002 | 628 | 723 | 485 | 232 | 1.73 | 359 | 141 | 191 | 1144 |
| 2003 | 566 | 631 | 440 | 210 | 0 | 299 | 107 | 172 | 499 |

**Table 9.** Simulation results for 2000 to 2003 using uncalibrated model

| | Cochiti | San Felipe | Albuquerque | Bernardo | San Acacia LFCC | San Acacia | San Marcial LFCC | San Marcial | Elephant Butte dam |
|---|---|---|---|---|---|---|---|---|---|
| | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs |
| 2000 | 893 | 918 | 731 | 489 | 4 | 475 | 120 | 386 | 956 |
| 2001 | 937 | 952 | 767 | 527 | 5 | 515 | 125 | 429 | 956 |
| 2002 | 628 | 641 | 456 | 263 | 4 | 291 | 74 | 201 | 805 |
| 2003 | 566 | 572 | 396 | 198 | 3 | 210 | 69 | 116 | 288 |

**Table 10.** Calibration changes

| Parameter changed | Affected reaches | Change |
|---|---|---|
| 2001 Leakage | Reaches 1 - 4 | Reaches 1 & 2 were reduced by 20%, R3 by 35%, and R4 by 50% |
| 2001 Leakage | Reach 5 | Increased by 300% |
| Average riparian ET volume | Reaches 1, 4, and 5 | Reach 1 was reduced by 20%, Reach 4 by 10% and Reach 5 by 50% |
| Riparian ET demand for ground water | All reaches | After capping by available leakage, demand is reduced when Cochiti flows are less than 45% of the historical mean (1406 cfs):<br>Reduction = (Cochiti inflow / mean flow) + 0.45 |
| Irrigation diversions | All reaches | A low flow reduction variable was created for Cochiti inflows less than 50% of the historical mean:<br>For flows more than 45% of the mean: Reduction = (Cochiti inflow / mean flow) + 0.45<br>For lower flows: Reaches 1-3 and 5-6: Reduction = (Cochiti inflow / mean flow) + 0.25<br>Reach 4: For flows over 20%, Reduction = (Cochiti inflow / mean flow) - 0.20<br>For flows < 20% of the mean, the diversion is eliminated |
| Reach 4 Sub-basin | Reach 4 | Increased by 30% |

| Parameter changed | Affected reaches | Change |
|---|---|---|
| runoff | | |
| Ratio of through flow to return flow | Reach 4 | Original value multiplied by 0.85 (increases return flow) |
| Irrigated acreage | Reach 5 | Total acreage reduced from 9574 ac to 9217 ac (1999 value – Roach (2004)) |
| Drain capture rate | Reach 5 | Increased from 68% to 100% |
| LFCC Wasteway | Reach 5 | The proportion of R4 irrigation through flow into the LFCC wasteway was reduced from 25% to 10% |
| Irrigation return flow | Reach 5 | The proportion of return flow to the river and the LFCC was changed from 2/9 and 7/9 to 5% and 95%, respectively. |
| Reach 5 Runoff into LFCC | Reach 5 | 60% of the Reach 5 sub-basin runoff was sent to the LFCC |

species, irrigation should be reduced in dry years. A diversion reduction for each reach was already in place that compared inflows and outflows. It reduced diversions when inflows are inadequate to supply non-irrigation outflows. But apparently, for very dry years, irrigation was reduced prior to impending problems. So an additional irrigation diversion reduction was added to take into account incoming flows to the system. Thus, when the model's Cochiti inflow was less than 50% of flows are reduced. Specifically, if the flow level is equal to or greater than 45% of the mean, then the flow is reduced slightly. If the flow level drops below 45% of the mean, a greater reduction is taken. These reductions are applied equally to each reach.

It was decided to also reduce riparian ET during these low flow periods with a scaling ratio. The ET is slightly reduced when Cochiti inflow is less than 45% of the mean. These changes worked well in the upper reaches, but Reaches 4 and 5 were not yet calibrated. San Acacia was too low, but San Marcial was too high, except for 2003. Also, the LFCC at San Marcial was drastically low. So additional flow was needed for Reach 4 and flow in Reach 5 needed to be transferred from the river to the LFCC. Therefore, the next changes focused on these reaches.

To increase San Acacia flows, the low flow diversion reduction was increased at the San Acacia diversion, which is located immediately upstream of the San Acacia gage. Also, sub-basin runoff and the proportion of return flow to through flow were increased in Reach 4. To transfer flow in Reach 5, the drain capture rate was increased and riparian ET was reduced to 50% of its value to provide more leakage for drain capture. A portion of the Reach 5 sub-basin runoff was sent to the LFCC. Also, the Reach 5 irrigation return flow to the LFCC was increased and conversely, the return flow to the river was reduced.

The gage flows resulting from these final changes are shown in Table 11 with the differences between the model flows and the historical gaged flows shown in Table 12. The changes brought the flow differences to close to ten percent for all gages except San Acacia, so the model was considered to be calibrated. Elephant Butte Dam gage was not calibrated because of the complexity of the rules governing its value combined with the fact that only 4 data points were available for calibration. Observations about the implications of these calibration changes are included in the Discussion section.

**Table 11.** Simulation results for 2000 to 2003 using calibrated model

| | Cochiti cfs | San Felipe cfs | Albuquerque cfs | Bernardo cfs | San Acacia LFCC cfs | San Acacia cfs | San Marcial LFCC cfs | San Marcial cfs | Elephant Butte dam cfs |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | 893 | 917 | 728 | 483 | 4 | 460 | 116 | 371 | 956 |
| 2001 | 937 | 951 | 764 | 521 | 5 | 501 | 121 | 415 | 956 |
| 2002 | 628 | 641 | 453 | 259 | 4 | 251 | 95 | 163 | 769 |
| 2003 | 566 | 571 | 394 | 194 | 3 | 170 | 92 | 78 | 272 |

**Table 12.** Differences in flow between historical values and simulation results for calibration model, expressed as a percentage of historical values

| | Cochiti % | San Felipe % | Albuquerque % | Bernardo % | San Acacia LFCC % | San Acacia % | San Marcial LFCC % | San Marcial % | Elephant Butte dam % |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | 0 | 0.31 | 5.89 | 6.32 | -1102.70 | 23.09 | 55.13 | -9.19 | 11.56 |
| 2001 | 0 | 3.22 | 6.24 | 5.20 | 86.96 | 8.15 | 47.71 | -9.89 | 11.80 |
| 2002 | 0 | 11.39 | 6.55 | -11.75 | -108.67 | 30.00 | 32.50 | 14.43 | 32.80 |
| 2003 | 0 | 9.51 | 10.54 | 7.46 | 0.00 | 42.99 | 14.25 | 54.44 | 45.53 |
| Average | 0 | 6.11 | 7.30 | 1.81 | -374.81 | 26.06 | 37.40 | 12.45 | 25.42 |

## 7. SIMULATION RESULTS

The results presented herein must be caveated to ensure proper interpretation and use. Papadopulos (2004) puts it best, “Model results are presented as a distribution of possible outcomes, such as range of agricultural demand, or range of Compact delivery Credit/Debit status, under the specified development condition and climatic variability. The results can not be compared to conditions experienced in New Mexico over the past decade or 50 years, nor can they be used to predict conditions for any given year or span of years in the future. The study results, instead, describe the range of conditions that could be experienced either currently or in 2040."

A summary of the simulations is shown in Table 13. The first simulations were designed to explore the sensitivity of certain variables. Then the user control options were used to explore system behavior under a variety of climate and price conditions.

**Table 13.** Simulation run summary

| Focus of simulation | Parameter changed | Variation | Effect Variables |
|---|---|---|---|
| Sensitivity | Pan evaporation | Value * 0.75, 0.90, 1.10, 1.25 | Gage flows<br>Open water evaporation |
| Sensitivity | Total volume for Riparian ET (uncapped) | Value * 0.75, 0.90, 1.10, 1.25 | Gage flows<br>Riparian ET demand for ground water |
| Sensitivity | 2001 Leakage value | Value * 0.75, 0.90, 1.10, 1.25 | Gage flows<br>Riparian ET demand for ground water<br>Leakage to drains and ground water |
| Effect of climate | Climate scenario | All 10 climates | Gage flows<br>Sub-basin runoff<br>Rio Grande Compact status<br>Crop failure |
| Effect of price | Price of water | Conservation price path and price increases of 0%, 1.25%, 1.50%, 2.5% | Gage flows<br>Price paths<br>Total Albuquerque water use<br>Reach 2 urban diversion |

### *7.1 Sensitivity*

Sensitivity analyses were performed for pan evaporation, riparian ET, and the base leakage value (2001 value), with values that were 75%, 90%, 110%, and 125% of the base value. The very dry climate scenario and full use of the San Juan-Chama water were used for all sensitivity runs.

The sensitivity of open water evaporation volumes and gage flows to pan evaporation values are listed in Table 14. The evaporation volumes display a consistent effect, but little sensitivity was seen in the river flow, although the sensitivity increases downstream.

To analyze the sensitivity of river flow to riparian ET values, the riparian ET data based on Cleverly's (2005) data and the marsh ET index were varied as mentioned previously. The results are shown in Tables 15 and 16. Both the unlimited and capped riparian ET values are directly affected, except in Reach 1. However, gage flows are unaffected, with the same slight downstream increase.

**Table 14.** Sensitivity analysis of pan evaporation values: Average differences in gage flow and open water evaporation from the base case values, expressed as a percent of the base values

|  | Gage flows |  |  |  |  | Open water evaporation |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Modification factor | 0.75 | 0.90 | 1.10 | 1.25 |  | 0.75 | 0.90 | 1.10 | 1.25 |
| San Felipe | -0.10% | -0.04% | 0.04% | 0.10% | Reach 1 | 25.00% | 10.00% | -10.00% | -25.00% |
| Albuquerque | -0.67% | -0.27% | 0.27% | 0.67% | Reach 2 | 24.98% | 9.99% | -9.99% | -24.96% |
| Bernardo | -1.68% | -0.67% | 0.67% | 1.68% | Reach 3 | 25.07% | 10.01% | -10.00% | -24.97% |
| San Acacia | -1.87% | -0.75% | 0.73% | 1.83% | Reach 4 | 24.84% | 9.90% | -9.86% | -24.56% |
| San Marcial | -2.71% | -1.08% | 1.07% | 2.66% | Reach 5 | 25.25% | 10.08% | -10.05% | -25.07% |
| Elephant Butte Dam gage | -3.44% | -1.31% | 1.37% | 4.18% | Reach 6 | 24.76% | 9.89% | -9.87% | -24.62% |
| Elephant Butte | -4.32% | -1.58% | 2.05% | 6.52% | Elephant Butte | 22.70% | 8.97% | -8.40% | -19.17% |

**Table 15.** Sensitivity analysis of riparian ET data: Average differences in gage flow from the base case value, expressed as a percent of the base value

| Modification factor | 0.75 | 0.90 | 1.10 | 1.25 |
|---|---|---|---|---|
| San Felipe | 0.00% | 0.00% | 0.00% | 0.00% |
| Albuquerque | -0.46% | -0.18% | 0.18% | 0.46% |
| Bernardo | -1.15% | -0.46% | 0.46% | 1.14% |
| San Acacia | -1.62% | -0.65% | 0.64% | 1.59% |
| San Marcial | -1.85% | -0.74% | 0.73% | 1.81% |

**Table 16.** Sensitivity analysis of riparian ET data: Average differences in riparian ET demand for ground water and reach total riparian ET (unlimited) from the base case values, expressed as a percent of the base values

| Reach | Rip ET demand for gndwtr |  |  |  | Reach ave rip ET |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | 0.75 | 0.90 | 1.10 | 1.25 | 0.75 | 0.90 | 1.10 | 1.25 |
| Reach 1 | 0.79% | 0.00% | 0.00% | 0.00% | 25.00% | 10.00% | -10.00% | -25.00% |
| Reach 2 | 25.00% | 10.00% | -10.00% | -25.00% | 25.00% | 10.00% | -10.00% | -25.00% |
| Reach 3 | 25.11% | 10.05% | -10.05% | -25.11% | 24.99% | 10.00% | -10.00% | -24.99% |
| Reach 4 | 25.11% | 10.04% | -10.04% | -25.11% | 24.98% | 9.99% | -9.99% | -24.98% |
| Reach 5 | 25.25% | 10.10% | -10.10% | -25.25% | 24.97% | 9.99% | -9.99% | -24.97% |

Presented next in Tables 17 and 18 is the river's sensitivity to leakage values. The base variable studied in these simulations was 2001 leakage was. There is no effect on riparian ET demand for ground water except in Reach 1, but the leakage to drains and ground water clearly see a large effect. While still not large, a greater sensitivity in the gage flows is evident, with the same downstream increase.

**Table 17.** Sensitivity analysis of leakage data: Average differences in gage flows and riparian ET demand for ground water from the base case values, expressed as a percent of base values

| Gage | Gage flows | | | | Riparian ET demand for ground water | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.75 | 0.9 | 1.1 | 1.25 | 0.75 | 0.9 | 1.1 | 1.25 |
| San Felipe | -0.21% | -0.08% | 0.08% | 0.21% | 25.00% | 10.00% | -10.00% | -24.84% |
| Albuquerque | -4.04% | -1.62% | 1.62% | 4.04% | 0.00% | 0.00% | 0.00% | 0.00% |
| Bernardo | -8.82% | -3.52% | 3.50% | 8.73% | 0.00% | 0.00% | 0.00% | 0.00% |
| San Acacia | -9.79% | -3.92% | 3.80% | 9.38% | 0.00% | 0.00% | 0.00% | 0.00% |
| San Marcial | -13.38% | -5.29% | 5.17% | 12.79% | 0.00% | 0.00% | 0.00% | 0.00% |

**Table 18.** Sensitivity analysis of leakage data: Average differences in leakage to drains and ground water from the base case values, expressed as a percent of the base values

| Gage | River leakage to drains | | | | River leakage to ground water | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.75 | 0.9 | 1.1 | 1.25 | 0.75 | 0.9 | 1.1 | 1.25 |
| San Felipe | 25.00% | 10.00% | -10.00% | -34.84% | 25.00% | 10.00% | -10.00% | -34.84% |
| Albuquerque | 28.20% | 11.28% | -11.28% | -28.20% | 28.20% | 11.28% | 0.00% | -11.28% |
| Bernardo | 32.83% | 13.13% | -13.13% | -32.83% | 32.83% | 13.13% | -13.13% | -32.83% |
| San Acacia | 58.83% | 23.53% | -23.53% | -58.83% | 58.83% | 23.53% | 0.00% | -23.53% |
| San Marcial | 66.68% | 26.67% | -26.67% | -66.68% | 0.00% | 0.00% | 0.00% | 0.00% |

### *7.2 Effect of climate on gage flows*

Following the sensitivity analysis, the effect of climate on sub-basin runoff, crop failure, and gage flows was explored. Also included in the analysis was the status of compliance with the Rio Grande Compact. These simulations were made with full use of San-Juan Chama water every year after use was initiated. The average sub-basin runoff volumes for each reach and climate scenario are displayed in Table 19. The range in average runoff volumes for each gage across the climate scenarios ranges from just under 7,000 AF per year to over 44,000 AF per year. Expressed as a percentage of the average runoff across the climates, the ranges vary from 27 percent of the reach-climate average for Reach 1 to 50 percent for Reach 5, showing a good deal of variability. Table 20 shows the minimum and maximum occurring runoff volumes for each reach and climate.

**Table 19.** Average sub-basin runoff volumes for climate scenarios and reaches

| Climate Scenario | Reach 1 AF/year | Reach 2 AF/year | Reach 3 AF/year | Reach 4 AF/year | Reach 5 AF/year | Reach 6 AF/year |
|---|---|---|---|---|---|---|
| Very dry | 23,904 | 37,181 | 25,963 | 57,719 | 14,277 | 72,466 |
| Dry & Consistent | 23,726 | 38,818 | 30,421 | 60,974 | 17,012 | 85,708 |
| Dry & Variable | 27,707 | 41,909 | 27,895 | 64,961 | 15,447 | 78,152 |
| Moderately dry & consistent | 24,113 | 39,706 | 31,143 | 60,889 | 17,388 | 87,634 |
| Moderately dry & variable | 27,121 | 43,001 | 31,405 | 67,880 | 17,640 | 88,714 |
| Average & consistent | 24,240 | 40,547 | 34,003 | 64,728 | 19,236 | 96,437 |
| Average & variable | 24,466 | 41,355 | 33,859 | 65,907 | 19,099 | 95,851 |
| Moderately wet & consistent | 30,658 | 48,651 | 37,157 | 75,684 | 21,122 | 105,537 |
| Moderately wet & variable | 26,822 | 44,352 | 36,939 | 72,188 | 21,028 | 104,906 |
| Very wet | 27,750 | 46,821 | 40,919 | 76,141 | 23,521 | 116,898 |
| Minimum | 23,726 | 37,181 | 25,963 | 57,719 | 14,277 | 72,466 |
| Maximum | 30,658 | 48,651 | 40,919 | 76,141 | 23,521 | 116,898 |
| Average | 26,051 | 42,234 | 32,970 | 66,707 | 18,577 | 93,230 |
| Standard deviation | 2,194 | 3,386 | 4,307 | 5,968 | 2,658 | 12,775 |

Table 21 shows the average flow for each gage and each climate scenario. The range in average flows for each gage across the climate scenarios is between 300 and 400 cfs. Expressed as a percentage of the average flow across the climates, the range runs from a low of 23 percent of the gage-climate average for Cochiti Dam to a high of 45% for San Marcial (not including the LFCC). Thus, variability is once again higher in lower reaches. Table 22 shows the minimum and maximum occurring flows for each gage and climate.

Graphical representation of the simulation results is interesting also. Figures 18 – 25 show histograms for the values of each gage across all climates, while Figures 26 – 33 show that information in the form of cumulative probability curves. The histograms and cumulative probability charts provide a probabilistic description of each gage’s flow values for a wide variety of climates and corresponding precipitation profiles. The bin values for the histograms were structured around the mean values for historical gage data. Also, the years 2000 to 2004 were not included in the data set because these years utilized controlled inputs for runoff and Cochiti inflow and did not vary across climates.

**Table 20.** Minimum and maximum occurring runoff for each reach and climate

| Climate scenario | | Reach 1<br>AF/yr | Reach 2<br>AF/yr | Reach 3<br>AF/yr | Reach 4<br>AF/yr | Reach 5<br>AF/yr | Reach 6<br>AF/yr |
|---|---|---|---|---|---|---|---|
| Very dry | Min | 5599 | 9652 | 6458 | 12748 | 2875 | 16070 |
| | Max | 42479 | 68118 | 61790 | 125061 | 36344 | 178996 |
| Dry & Consistent | Min | 8439 | 14263 | 3255 | 12748 | 1323 | 7937 |
| | Max | 39324 | 63158 | 61790 | 116736 | 36344 | 178996 |
| Dry & Variable | Min | 11388 | 9652 | 755 | 19851 | 308 | 2228 |
| | Max | 39324 | 63158 | 49543 | 108425 | 28591 | 141822 |
| Moderately dry & consistent | Min | 8439 | 14263 | 9989 | 19851 | 4693 | 25549 |
| | Max | 39324 | 68118 | 57701 | 108425 | 33748 | 166561 |
| Moderately dry & variable | Min | 12331 | 19000 | 3255 | 19851 | 1323 | 7937 |
| | Max | 42479 | 78048 | 90521 | 141743 | 54721 | 266817 |
| Average & consistent | Min | 8439 | 14263 | 3255 | 19851 | 1323 | 7937 |
| | Max | 48801 | 87990 | 90521 | 141743 | 54721 | 266817 |
| Average & variable | Min | 11388 | 19000 | 6458 | 19851 | 2875 | 16070 |
| | Max | 42479 | 73081 | 86408 | 125061 | 52079 | 254211 |
| Moderately wet & consistent | Min | 12331 | 25365 | 13700 | 27344 | 6757 | 35859 |
| | Max | 48801 | 87990 | 78189 | 141743 | 46809 | 229048 |
| Moderately wet & variable | Min | 12331 | 25365 | 17096 | 35075 | 8387 | 42910 |
| | Max | 42479 | 73081 | 69982 | 116736 | 43415 | 203969 |
| Very wet | Min | 12331 | 25365 | 17096 | 35075 | 8387 | 42910 |
| | Max | 48801 | 87990 | 90521 | 141743 | 54721 | 266817 |

**Table 21.** Average gage flows for climate scenarios and reaches

| Climate scenario | Cochiti | San Felipe | Albu-querque | Ber-nardo | San Acacia | San Acacia LFCC | San Marcial | San Marcial LFCC | EB Dam gage | EB Volume |
|---|---|---|---|---|---|---|---|---|---|---|
| | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | AF |
| Very dry | 1248 | 1271 | 993 | 790 | 778 | 4 | 691 | 113 | 825 | 944,265 |
| Dry & Consistent | 1240 | 1263 | 987 | 789 | 782 | 4 | 694 | 114 | 846 | 950,973 |
| Dry & Variable | 1420 | 1448 | 1177 | 971 | 968 | 4 | 878 | 115 | 1018 | 1,077,780 |
| Moderately dry & consistent | 1259 | 1282 | 1007 | 809 | 799 | 4 | 711 | 117 | 878 | 998,124 |
| Moderately dry & variable | 1394 | 1421 | 1151 | 950 | 949 | 4 | 860 | 118 | 1015 | 1,125,693 |
| Average & consistent | 1264 | 1287 | 1014 | 820 | 816 | 4 | 729 | 118 | 896 | 1,003,334 |
| Average & variable | 1274 | 1298 | 1026 | 831 | 829 | 4 | 741 | 118 | 886 | 1,033,927 |
| Moderately wet & consistent | 1553 | 1585 | 1323 | 1131 | 1141 | 5 | 1053 | 120 | 1204 | 1,371,888 |
| Moderately wet & variable | 1381 | 1408 | 1140 | 949 | 954 | 5 | 867 | 120 | 1047 | 1,161,194 |
| Very wet | 1423 | 1451 | 1187 | 1002 | 1013 | 5 | 927 | 121 | 1111 | 1,216,194 |
| Minimum | 1240 | 1263 | 987 | 789 | 778 | 4 | 691 | 113 | 825 | 944265 |
| Maximum | 1553 | 1585 | 1323 | 1131 | 1141 | 5 | 1053 | 121 | 1204 | 1371888 |
| Average | 1345 | 1371 | 1101 | 904 | 903 | 4 | 815 | 117 | 973 | 1,088,337 |
| Standard deviation | 99 | 102 | 106 | 108 | 115 | 0 | 115 | 2 | 119 | 127088 |
| Historical average | 1357 | 1402 | 1164 | 854 | 773 | | 664 | | 999 | |

**Table 22.** Minimum and maximum occurring annual flows for each gage and climate

| | | Co-chiti | San Felipe | Albu-querque | Ber-nardo | San Acacia | San Acacia LFCC | San Marcial | San Marcial LFCC | EB Dam gage | EB Volume |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | cfs | AF |
| Very dry | Min | 398 | 393 | 60 | 4 | 8 | 0 | 0 | 33 | 9 | 293,789 |
| | Max | 2097 | 2145 | 1884 | 1691 | 1753 | 5 | 1666 | 131 | 1876 | 1,654,341 |
| Dry & Consistent | Min | 539 | 538 | 212 | 67 | 67 | 2 | 0 | 33 | 17 | 287,612 |
| | Max | 1945 | 1990 | 1731 | 1573 | 1637 | 5 | 1553 | 133 | 1786 | 1,589,208 |
| Dry & Variable | Min | 566 | 571 | 371 | 155 | 181 | 3 | 85 | 28 | 46 | 333,271 |
| | Max | 1968 | 2013 | 1737 | 1575 | 1630 | 5 | 1545 | 133 | 1763 | 1,572,779 |
| Mod dry & consistent | Min | 539 | 538 | 214 | 70 | 60 | 2 | 0 | 37 | 189 | 436,435 |
| | Max | 1956 | 2000 | 1749 | 1584 | 1638 | 5 | 1555 | 135 | 1818 | 1,932,648 |
| Mod dry & variable | Min | 566 | 571 | 394 | 193 | 211 | 3 | 116 | 53 | 189 | 436,435 |
| | Max | 2086 | 2134 | 1871 | 1699 | 1727 | 5 | 1641 | 133 | 1904 | 1,934,874 |
| Ave & consistent | Min | 550 | 550 | 220 | 64 | 62 | 2 | 0 | 35 | -19 | 286,026 |
| | Max | 2367 | 2425 | 2203 | 2110 | 2211 | 5 | 2142 | 134 | 1982 | 2,137,337 |
| Average & variable | Min | 566 | 571 | 377 | 174 | 176 | 3 | 87 | 53 | 156 | 412,341 |
| | Max | 2086 | 2134 | 1886 | 1753 | 1827 | 5 | 1746 | 135 | 2008 | 1,933,724 |
| Mod wet & consistent | Min | 566 | 571 | 394 | 193 | 211 | 3 | 116 | 53 | 189 | 436,435 |
| | Max | 2378 | 2436 | 2219 | 2101 | 2207 | 5 | 2132 | 136 | 2247 | 2,086,453 |
| Mod wet & variable | Min | 566 | 571 | 394 | 193 | 211 | 3 | 116 | 53 | 189 | 436,435 |
| | Max | 2097 | 2145 | 1891 | 1732 | 1795 | 5 | 1717 | 134 | 2026 | 1,941,590 |
| Very wet | Min | 566 | 571 | 394 | 193 | 211 | 3 | 116 | 53 | 189 | 436,435 |
| | Max | 2378 | 2435 | 2205 | 2081 | 2180 | 5 | 2108 | 134 | 2269 | 2,099,491 |

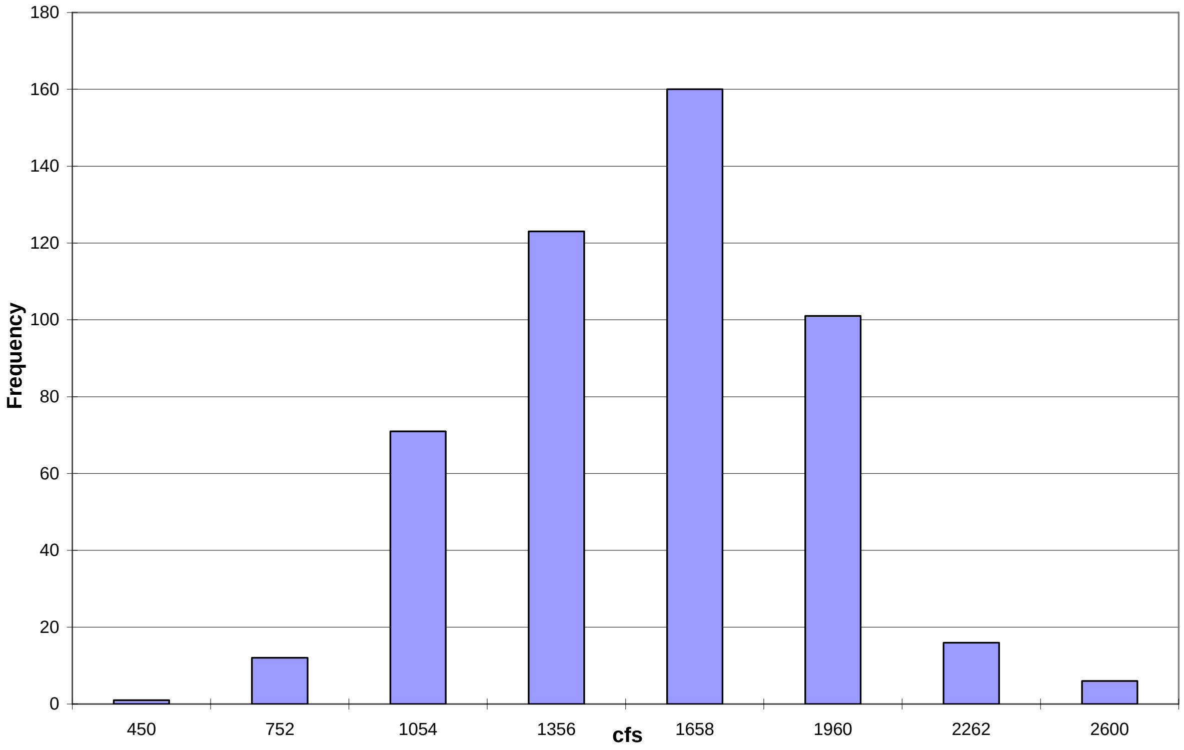


Figure 18.  Histogram:  Cochiti Dam gage,  all climates

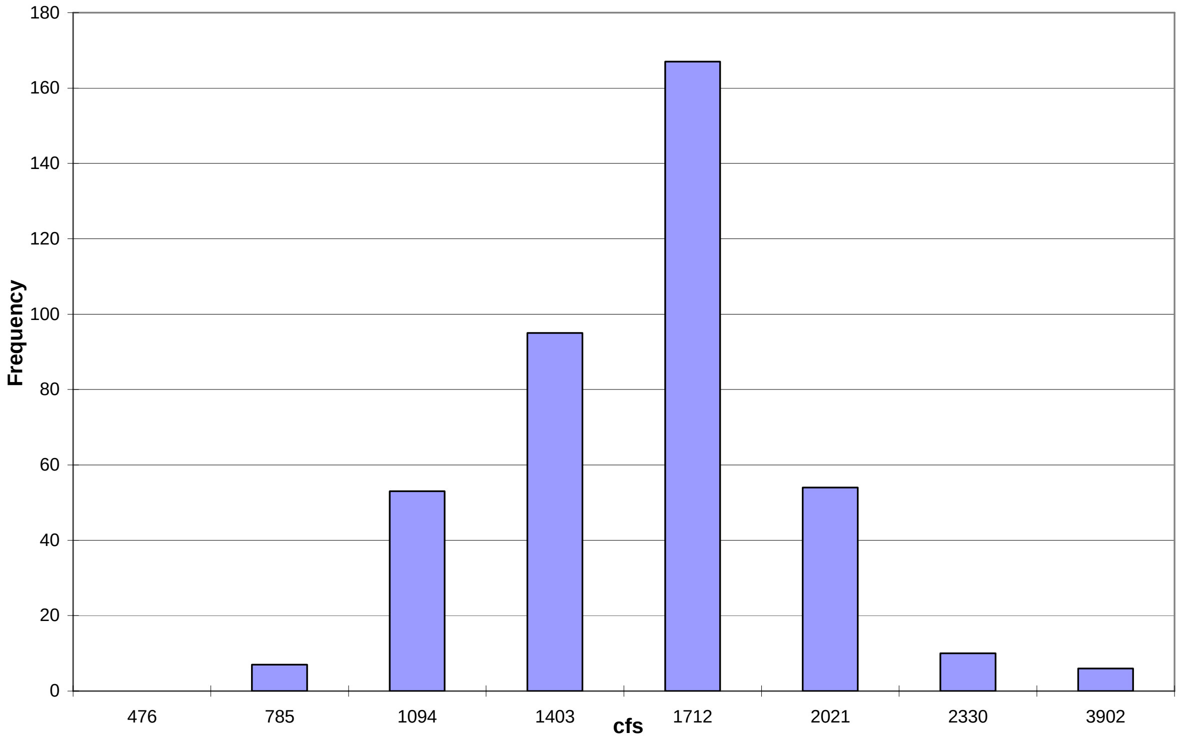


Figure 19.  Histogram:  San Felipe gage:  all climates

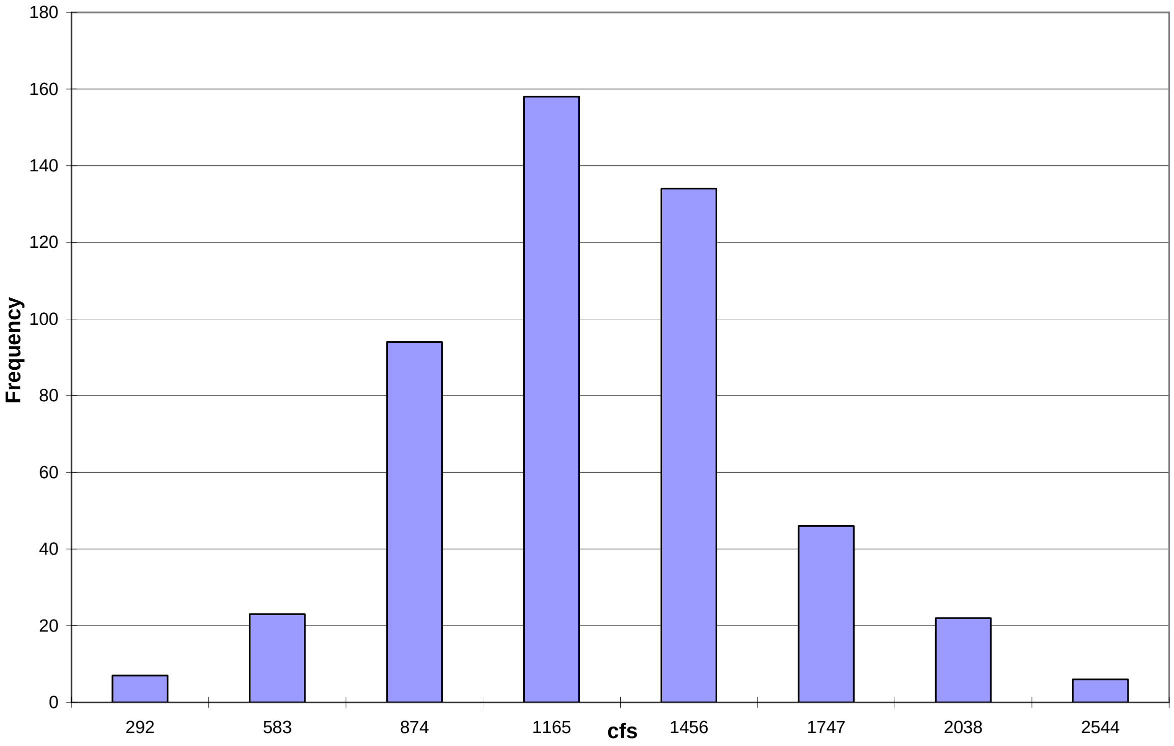


Figure 20. Histogram: Albuquerque gage: all climates

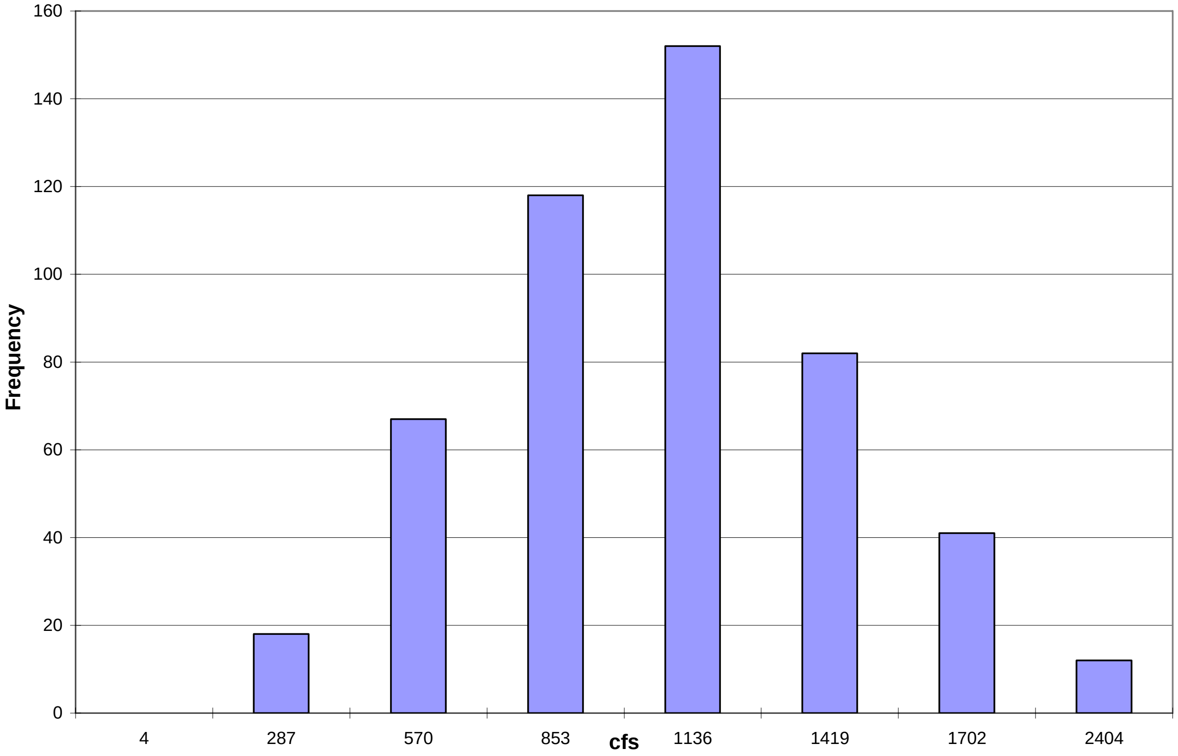


Figure 21. Histogram: Bernardo gage: all climates

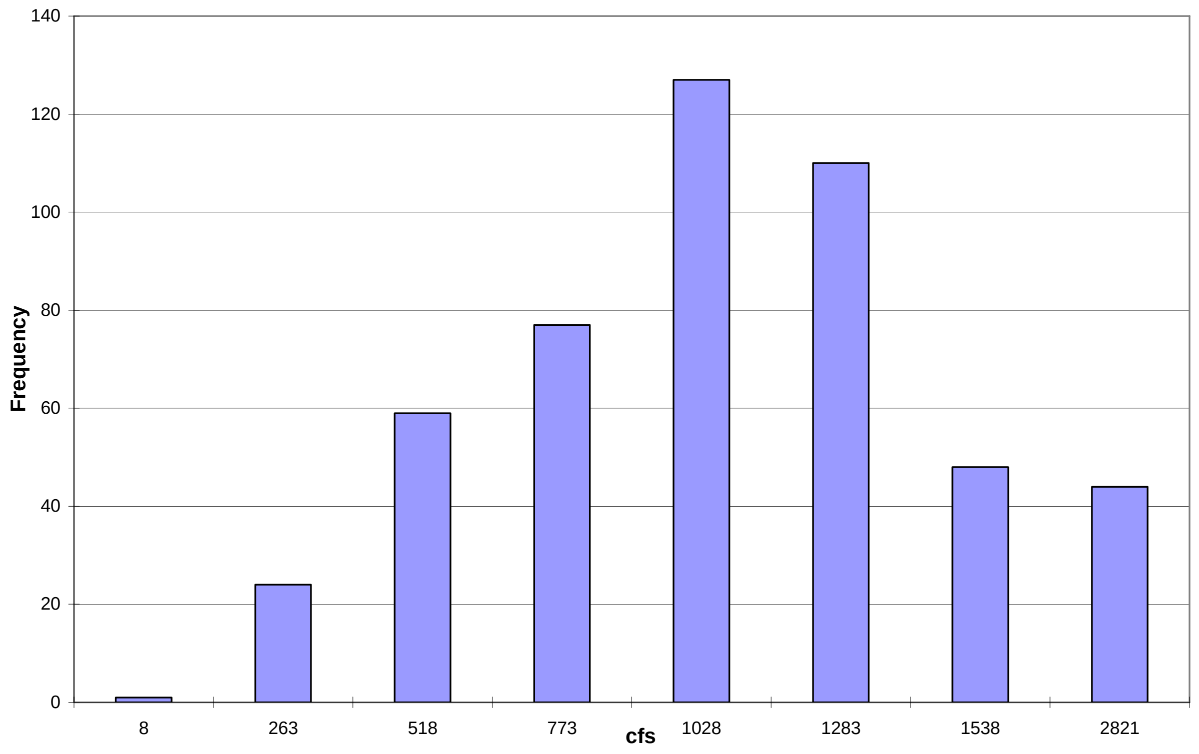


Figure 22. Histogram: San Acacia gage: all climates

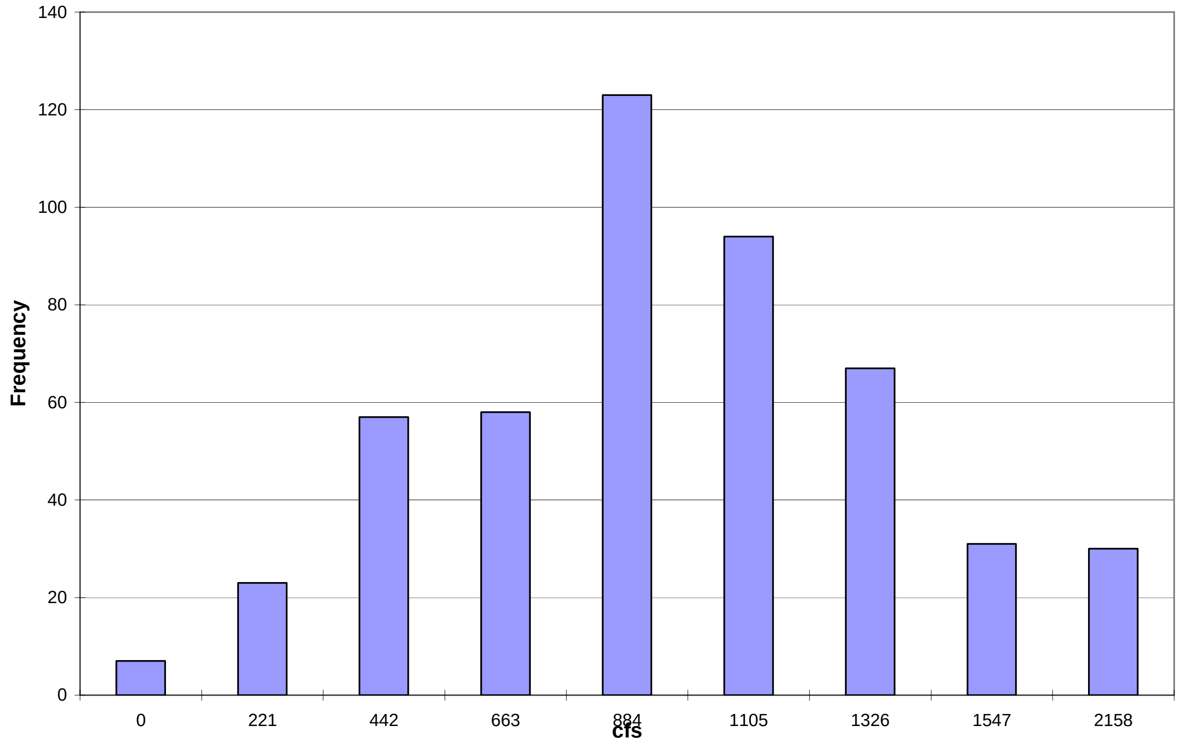


Figure 23. Histogram: San Marcial gage: all climates

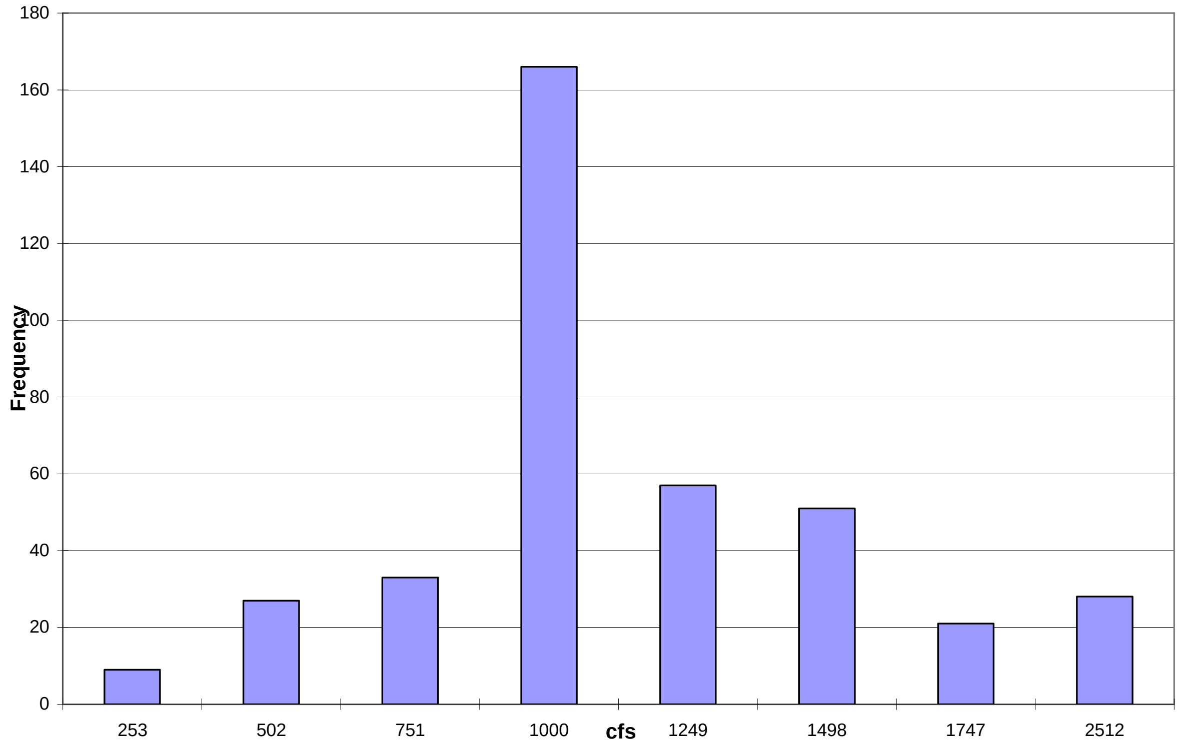


Figure 24. Histogram: Elephant Butte Dam gage: all climates

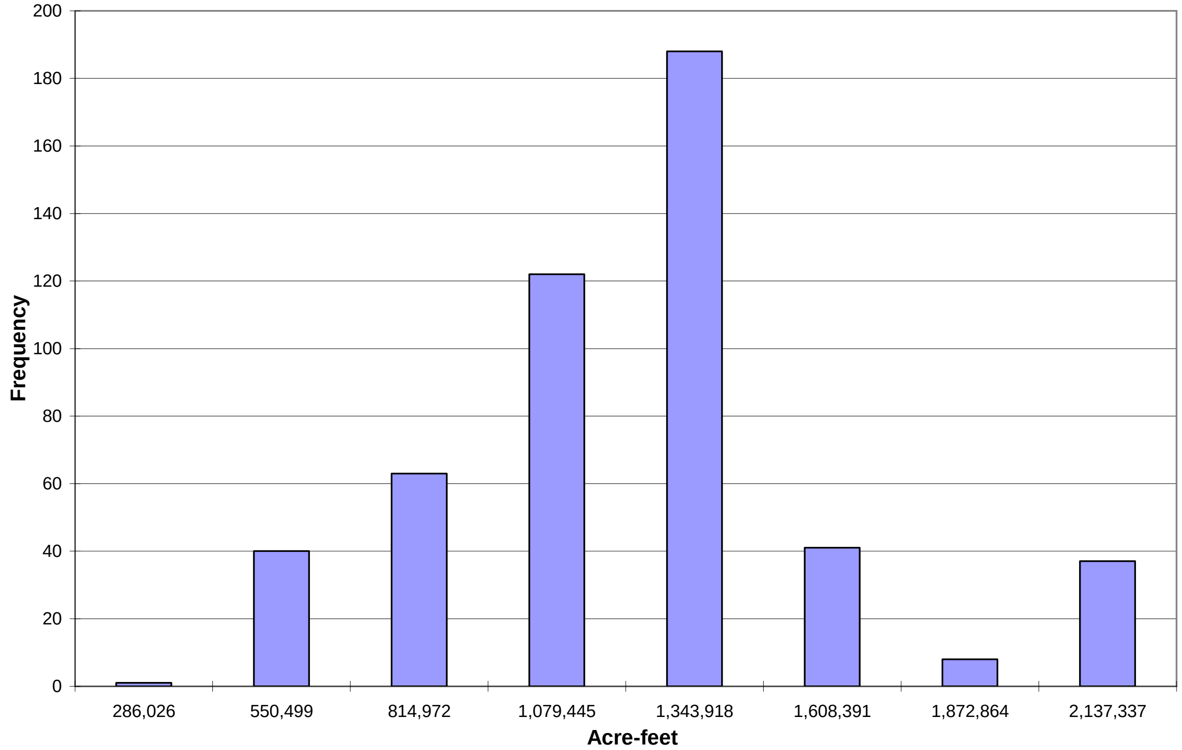


Figure 25. Histogram: Elephant Butte volume: all climates

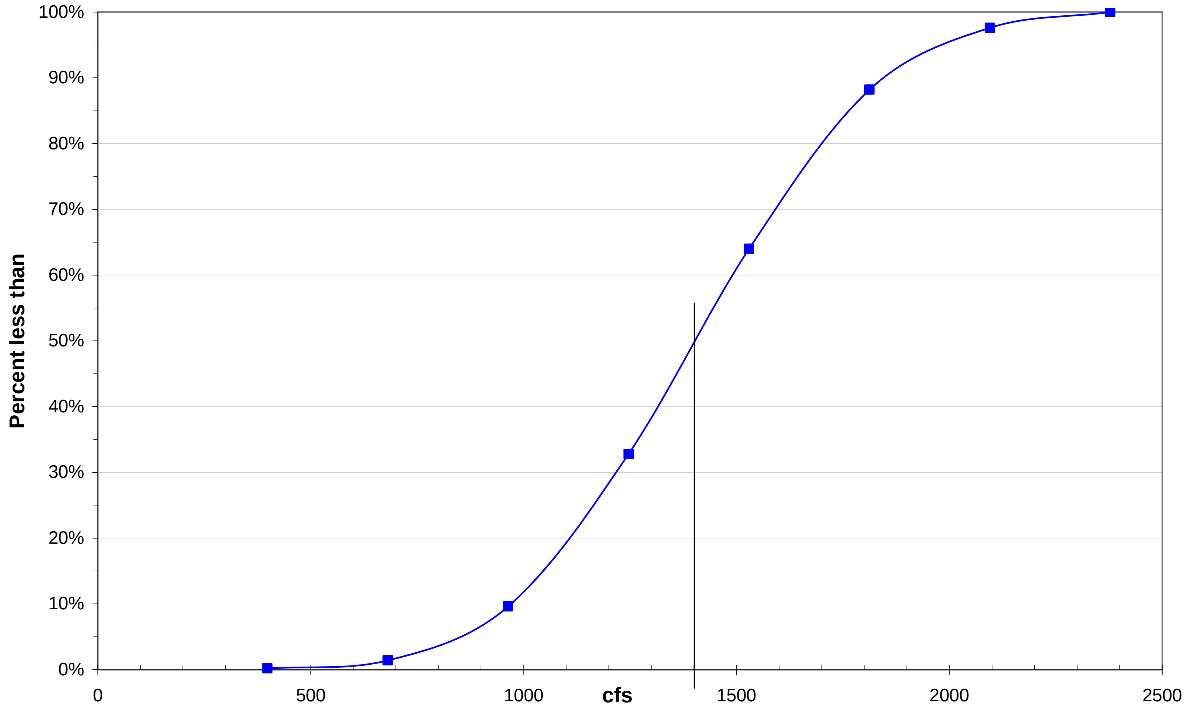


Figure 26. Cumulative probability: Cochit Dam gage: all climates

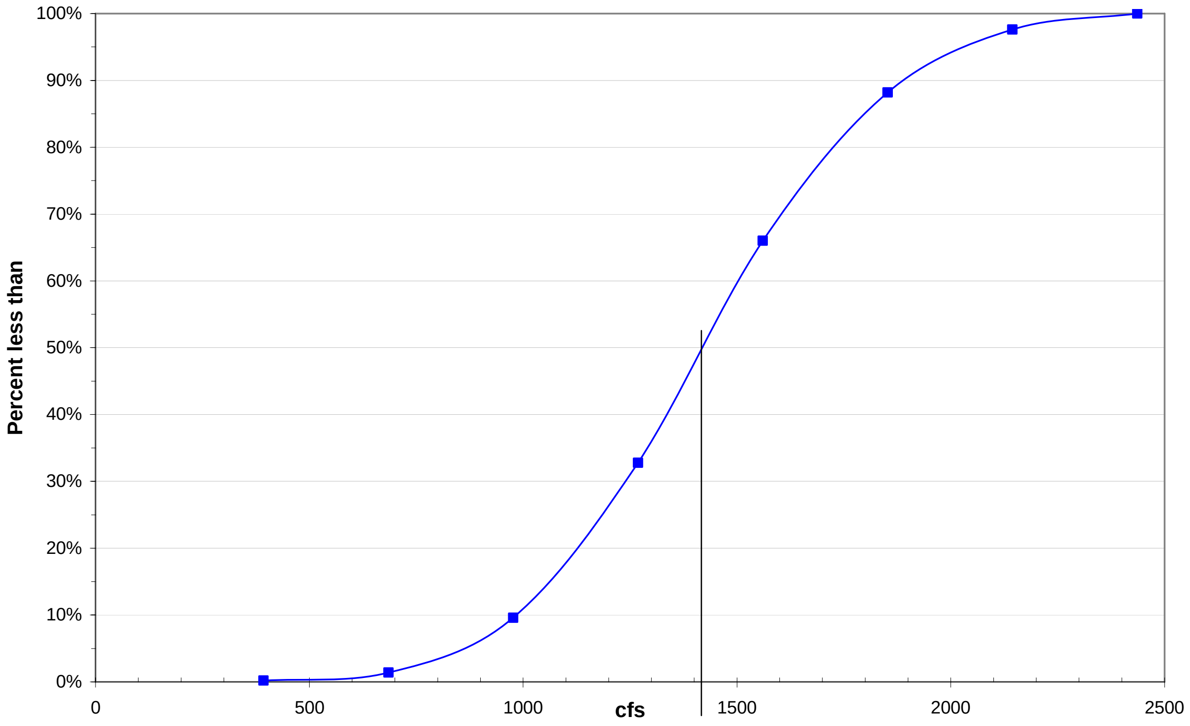


Figure 27. Cumulative probability: San Felipe gage: all climates

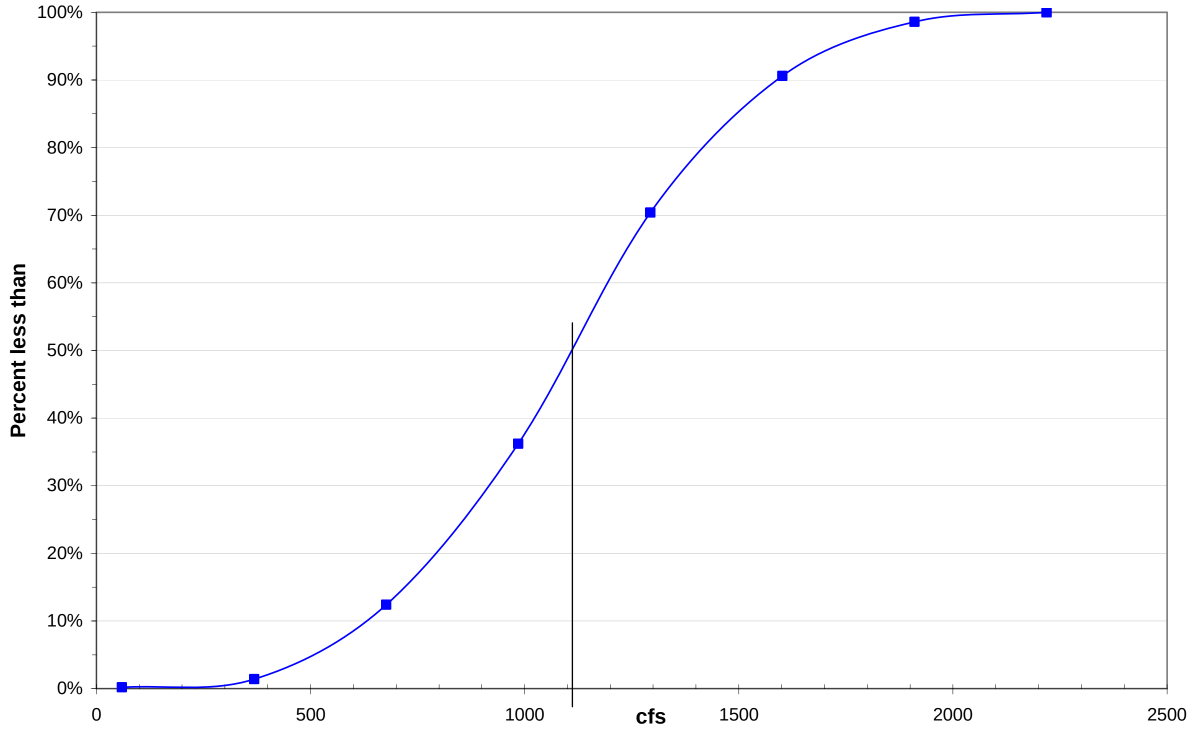


Figure 28. Cumulative probability: Albuquerque gage: all climates

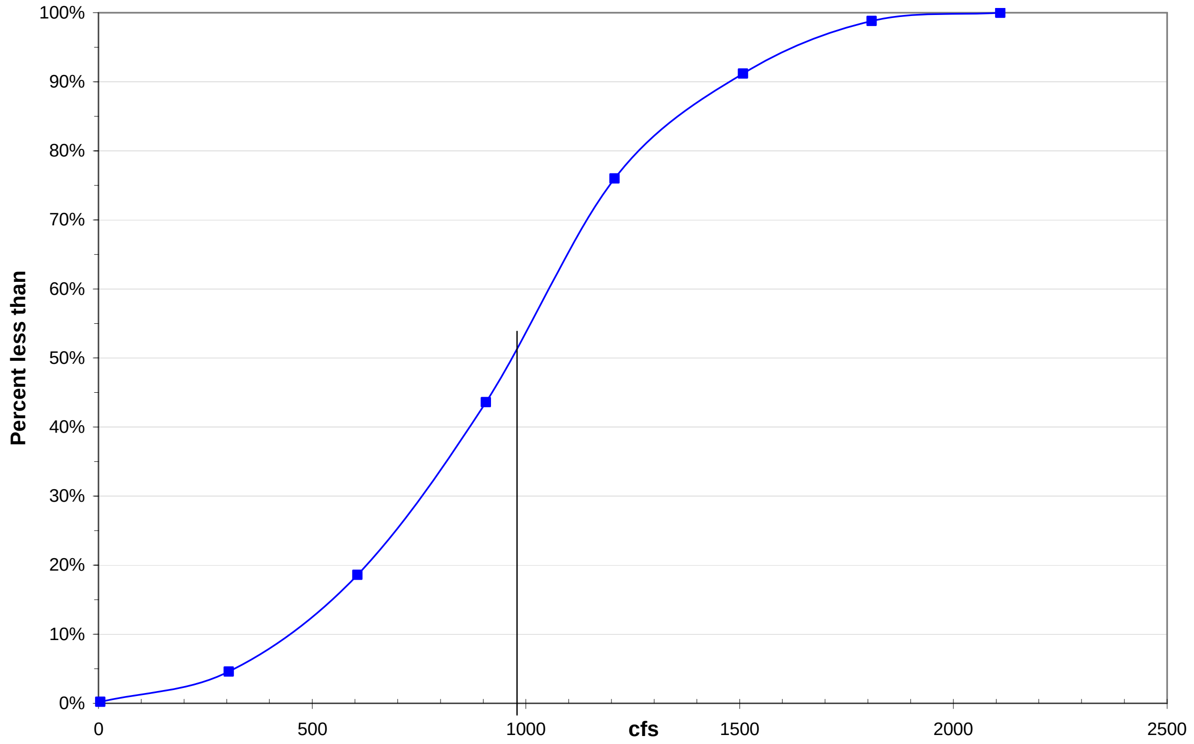


Figure 29. Cumulative probability: Bernardo gage: all climates

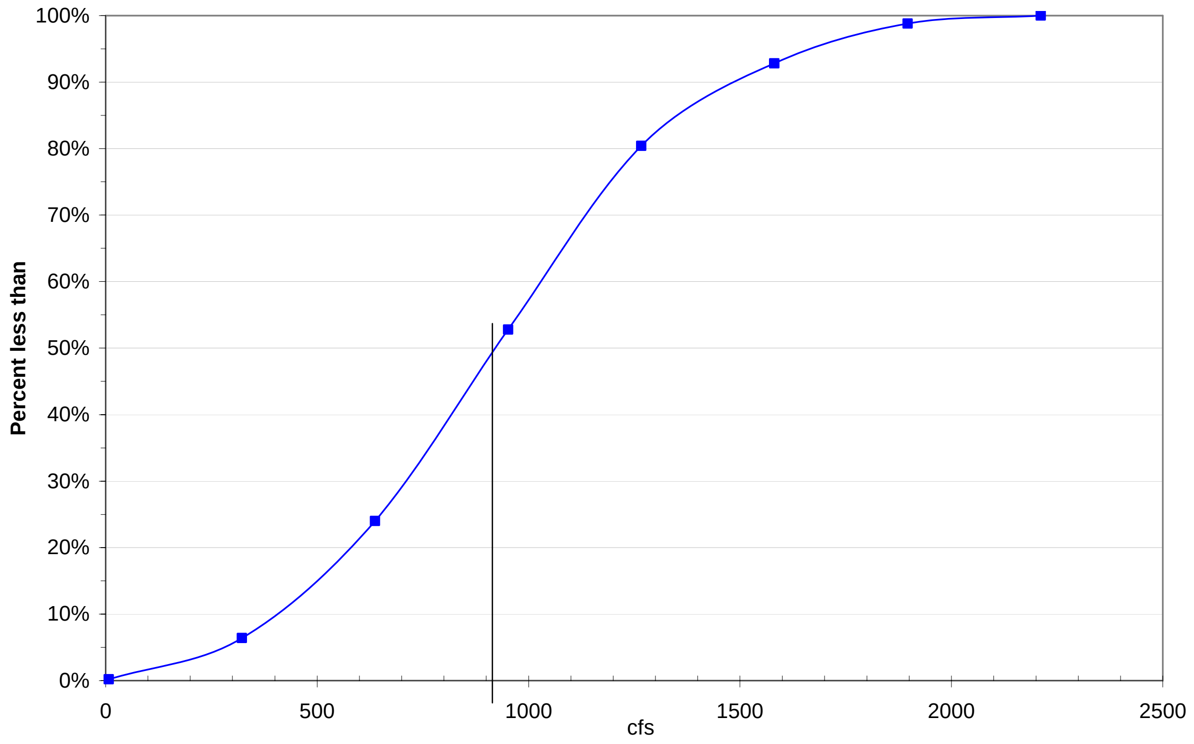


Figure 30. Cumulative probability: San Acacia gage: all climates

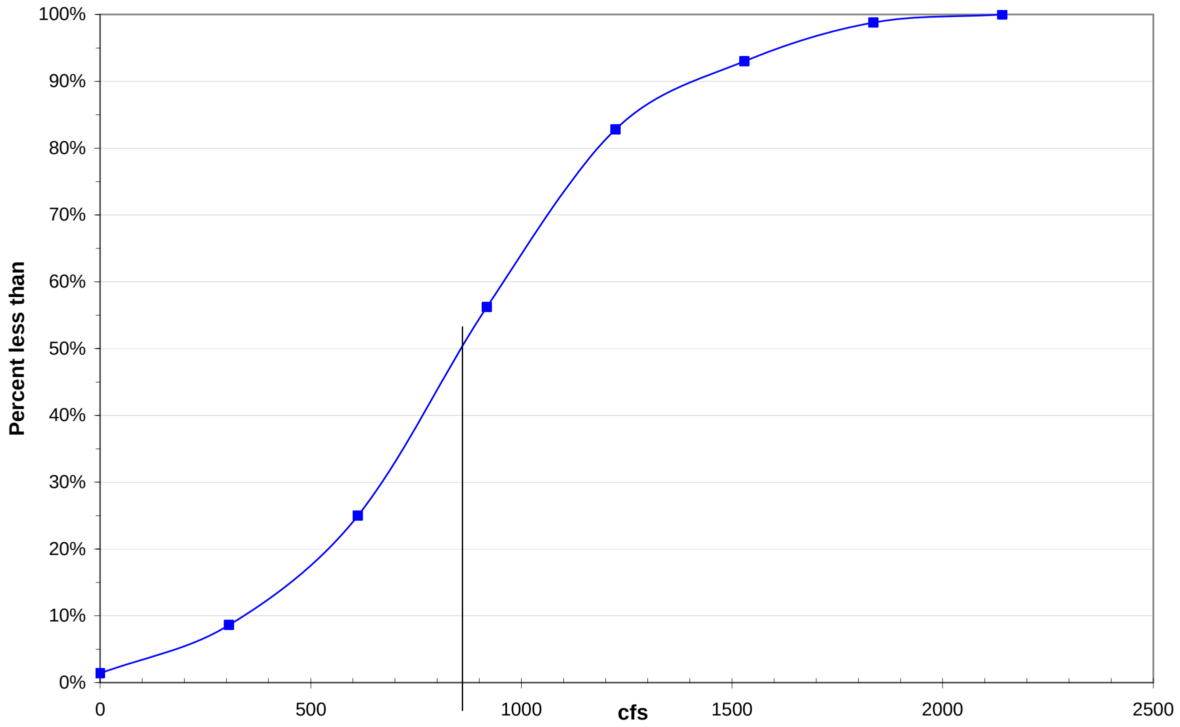


Figure 31. Cumulative probability: San Marcial gage: all climates

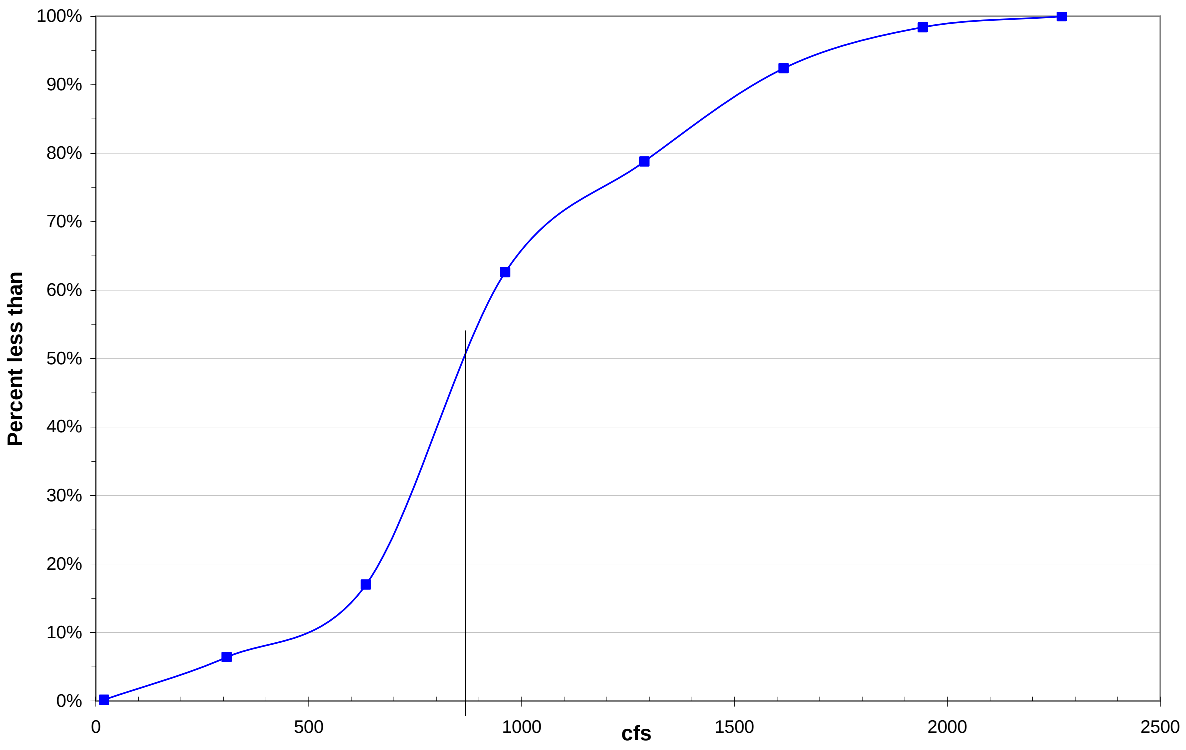


Figure 32. Cumulative probability: Elephant Butte Dam gage: all climates

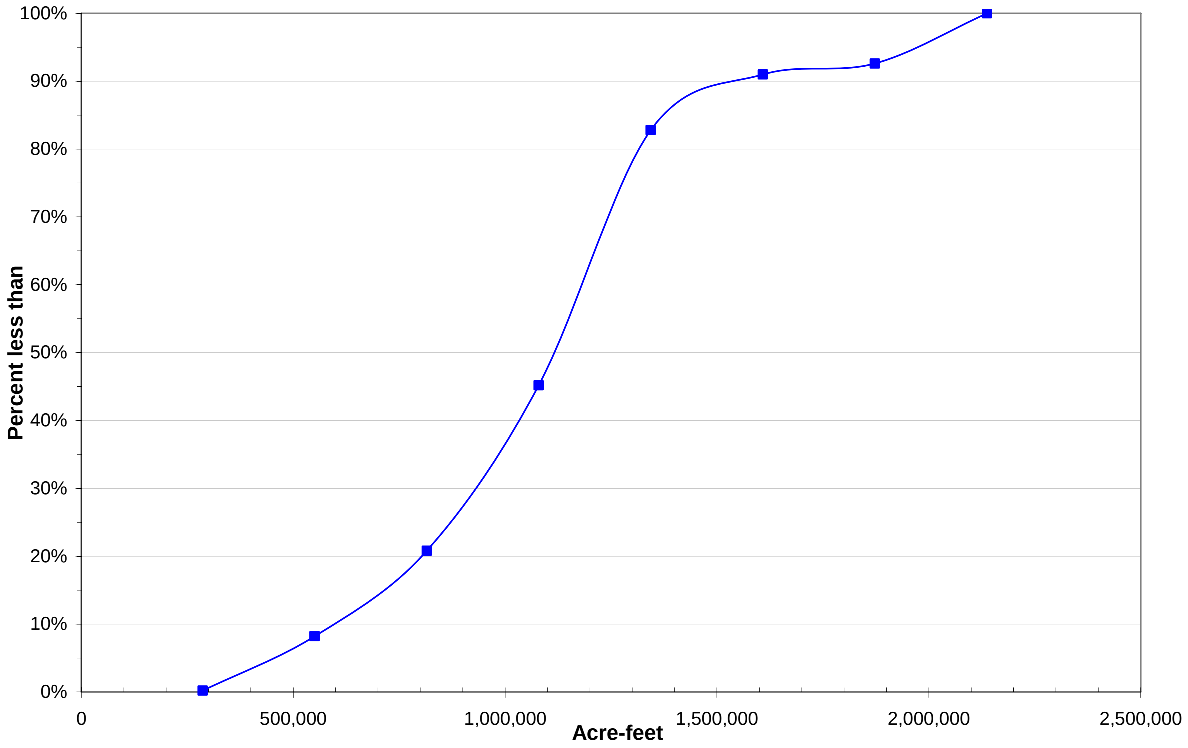


Figure 33. Cumulative probability: Elephant Butte volume: all climates

Cochiti Dam through Bernardo show a relatively normal distribution, with the two upstream gages showing a slightly more frequent occurrence of lower values than higher values. Albuquerque shows the converse, while Bernardo is more similar to Cochiti Dam and San Felipe in its distribution. San Acacia has a wide spread of values in its distribution and a perhaps a very slight tendency to wetter values. San Marcial also has a wider distribution that is only roughly normal and an even slighter tendency to wetter values.

Figure 34 shows the difference in sub-basin runoff between some consistent and variable climates for Reach 1, while Figure 35 shows the same for Reach 5. Likewise, Figures 36 and 37 show the difference in the corresponding gage flow for the same climates.

The next group of figures (Figures 38, 39, and 40) compares the effect of variable climates at three crucial points, the Cochiti Dam, Bernardo, and San Marcial gages. Cochiti Dam is the inflow to the Middle Rio Grande, while Bernardo and San Marcial are known for dry conditions and these areas are important to the silvery minnow. Figures 41 through 44 offer a less complicated look at the effects of climate on gage flow for Bernardo, while Figures 45 through 48 do the same for San Marcial.

The model also analyzes the available irrigation water to determine crop failure. Crop failure is defined as occurring when there is inadequate water to supply crop ET after irrigation losses. Table 23 shows the incidence of crop failure during the climate simulation runs. Crop failure occurred almost exclusively in Reach 5.

**Table 23.** Incidence of crop failure during climate simulation runs

| Year | Climate | Reach | % |
|---|---|---|---|
| 2038 | Very dry | 5 | 86 |
| 2043 | | 3 | 59 |
| | | 5 | 48 |
| 2044 | | 5 | 82 |
| 2026 | Dry consistent | 5 | 28 |
| 2039 | | 5 | 81 |
| 2046 | Moderately dry consistent | 5 | 74 |
| 2014 | Average consistent | 5 | 79 |

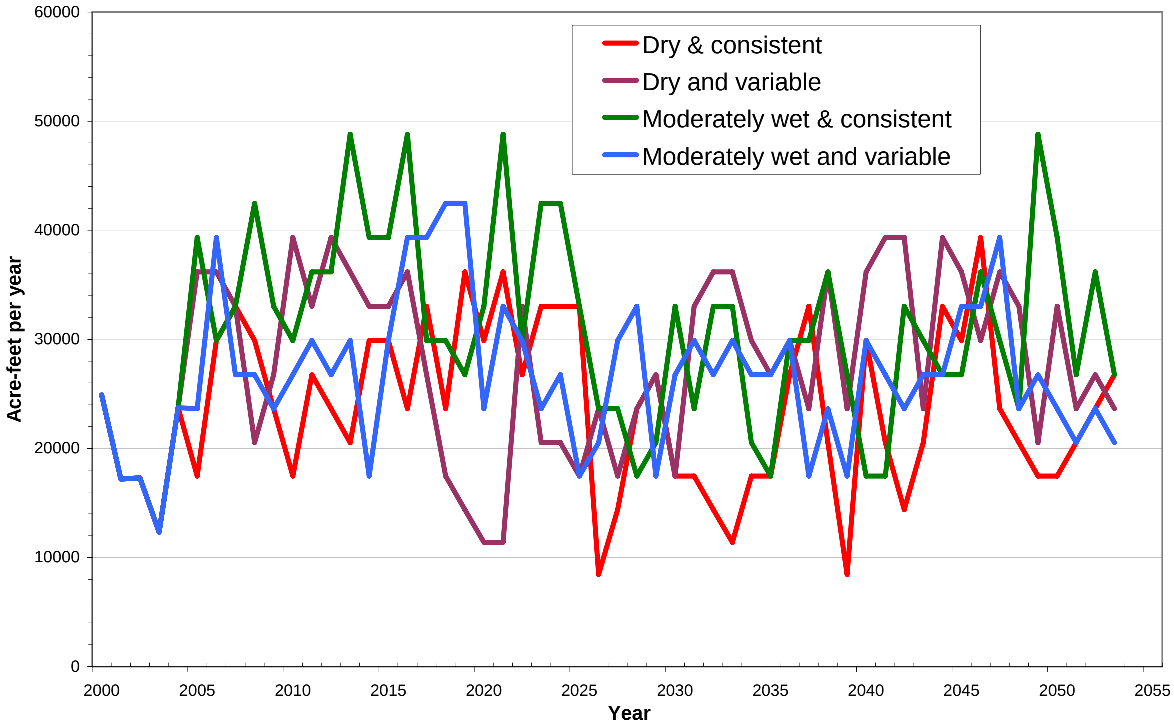


Figure 34. Consistent and variable climate scenarios: sub-basin runoff for Reach 1

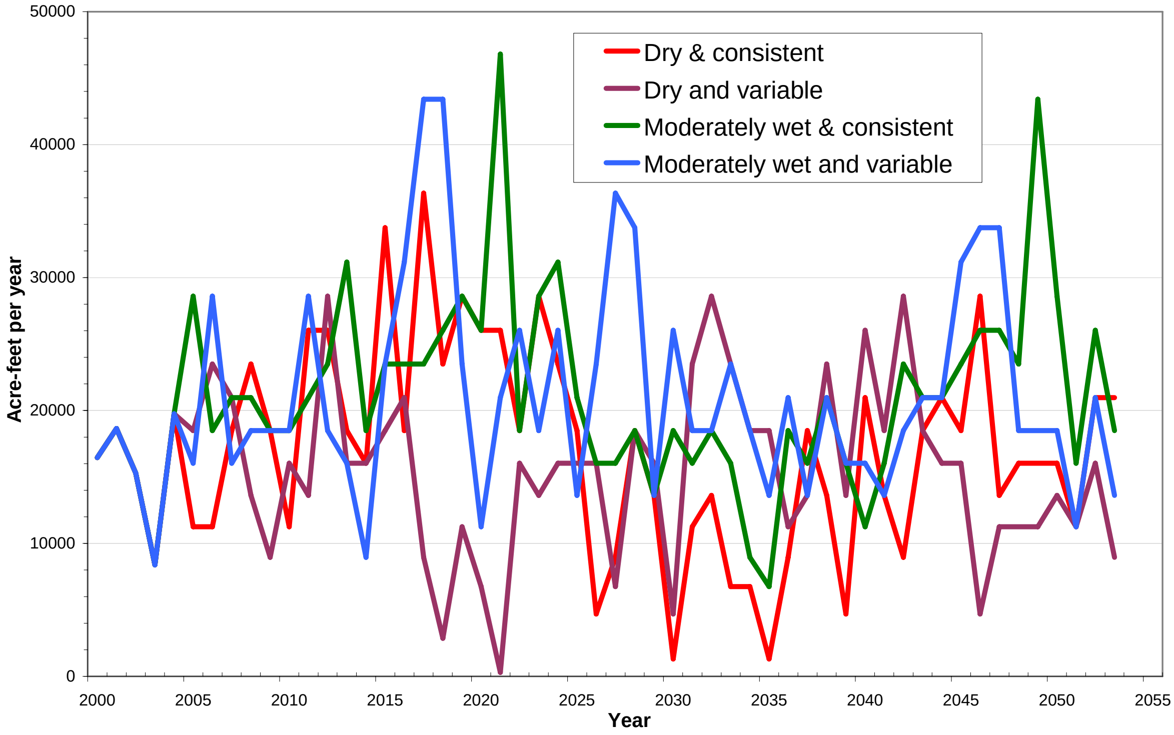


Figure 35. Consistent and variable climate scenarios: sub-basin runoff for Reach 5

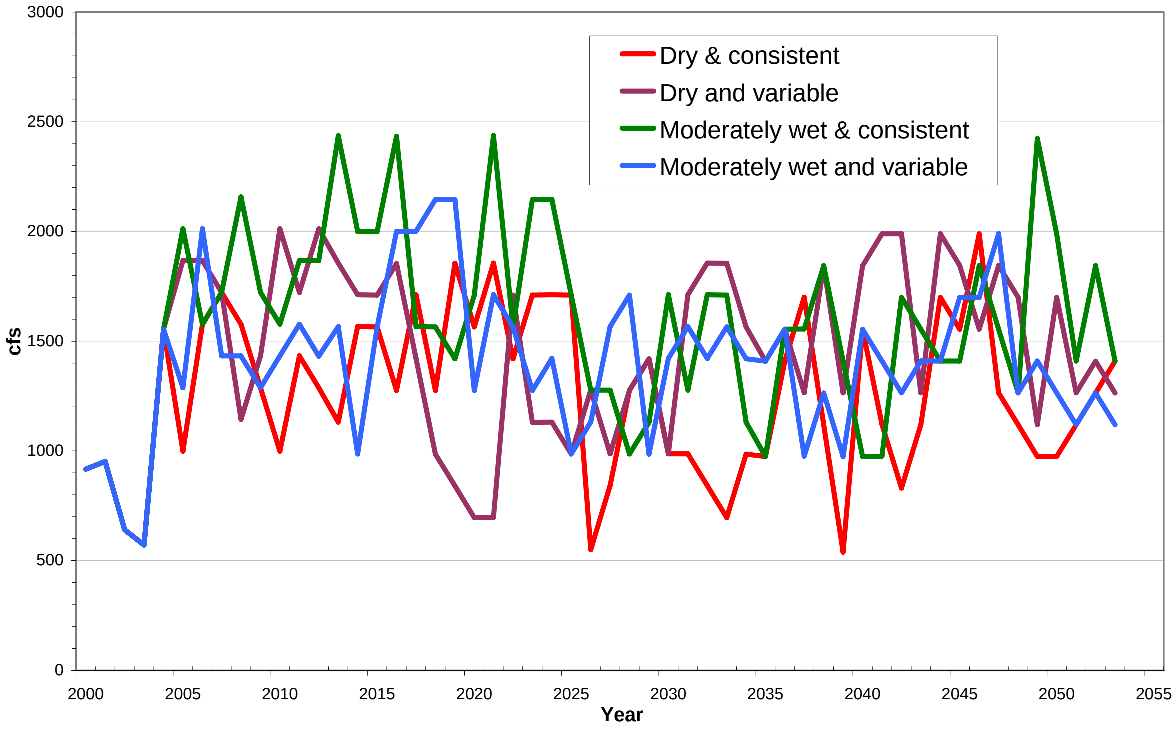


**Figure 36. Consistent and variable climate scenarios: San Felipe gage**

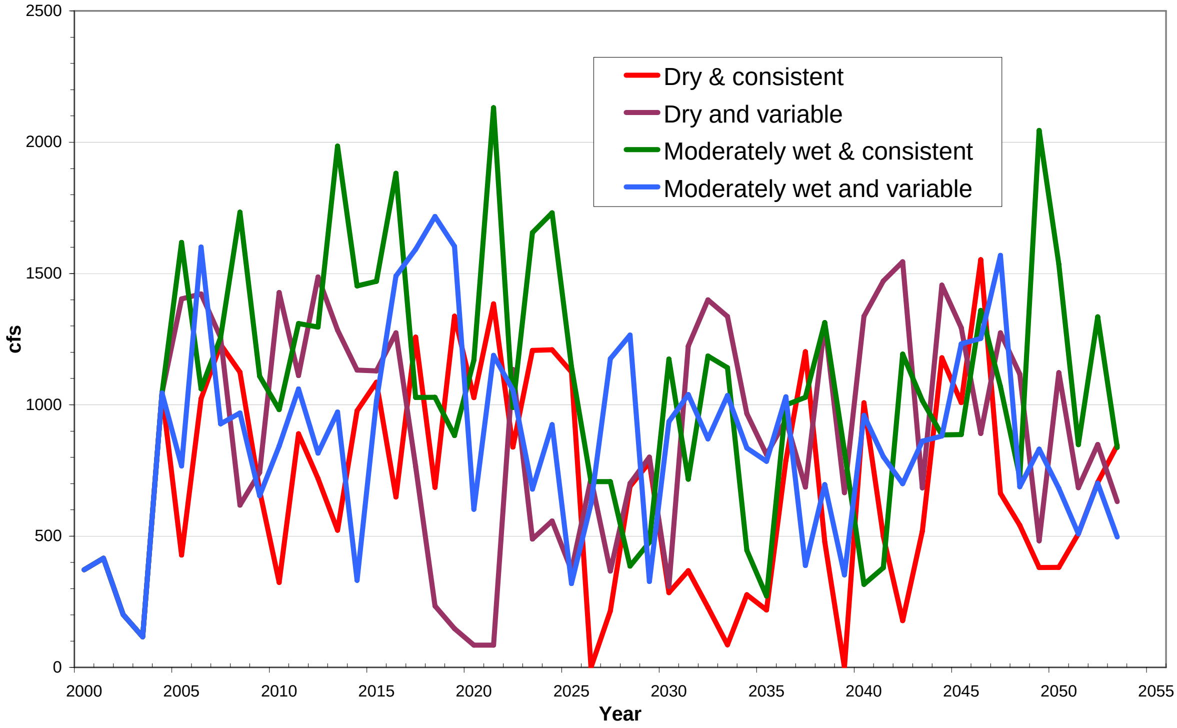


**Figure 37. Consistent and variable climate scenarios: San Marcial gage**

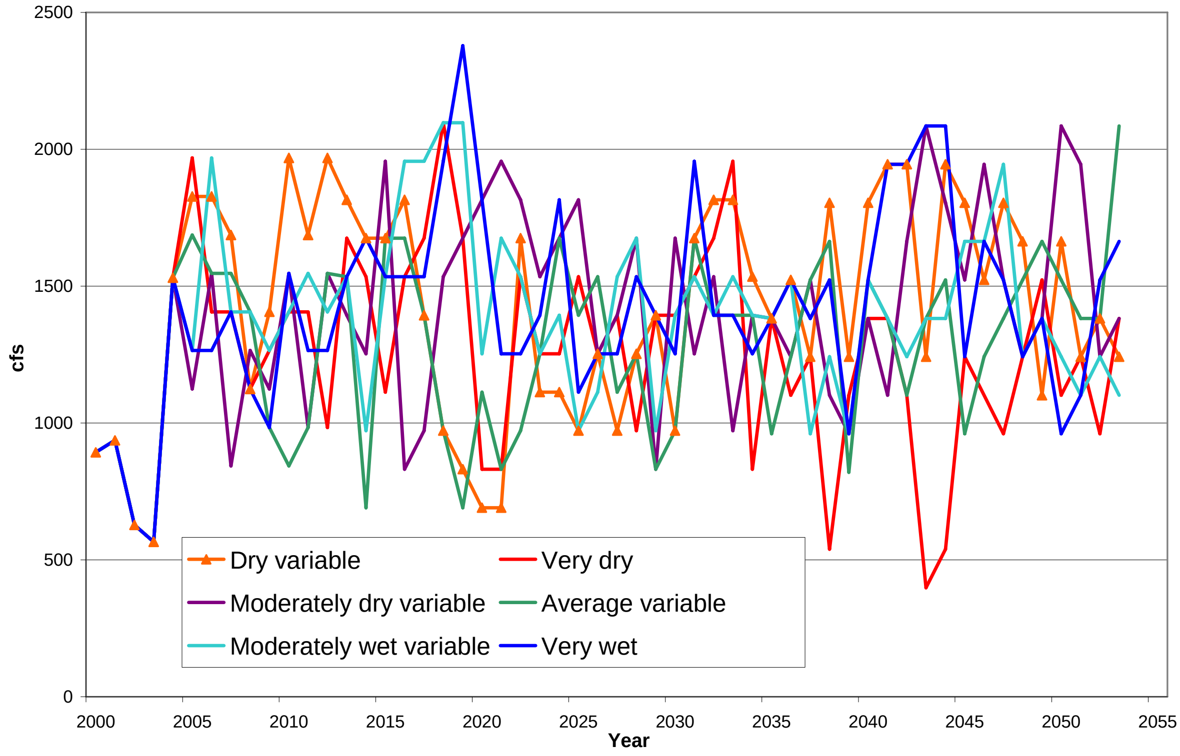


Figure 38. Cochiti gage: variable climates

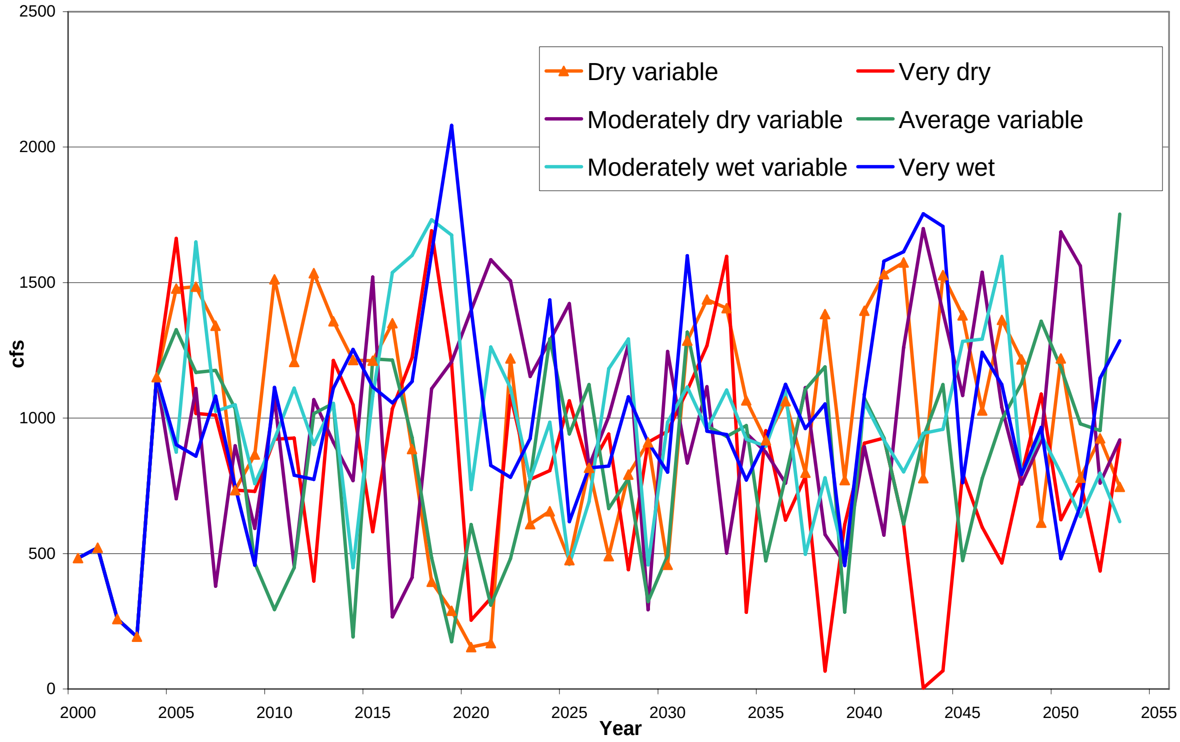


Figure 39. Bernardo gage: variable climates

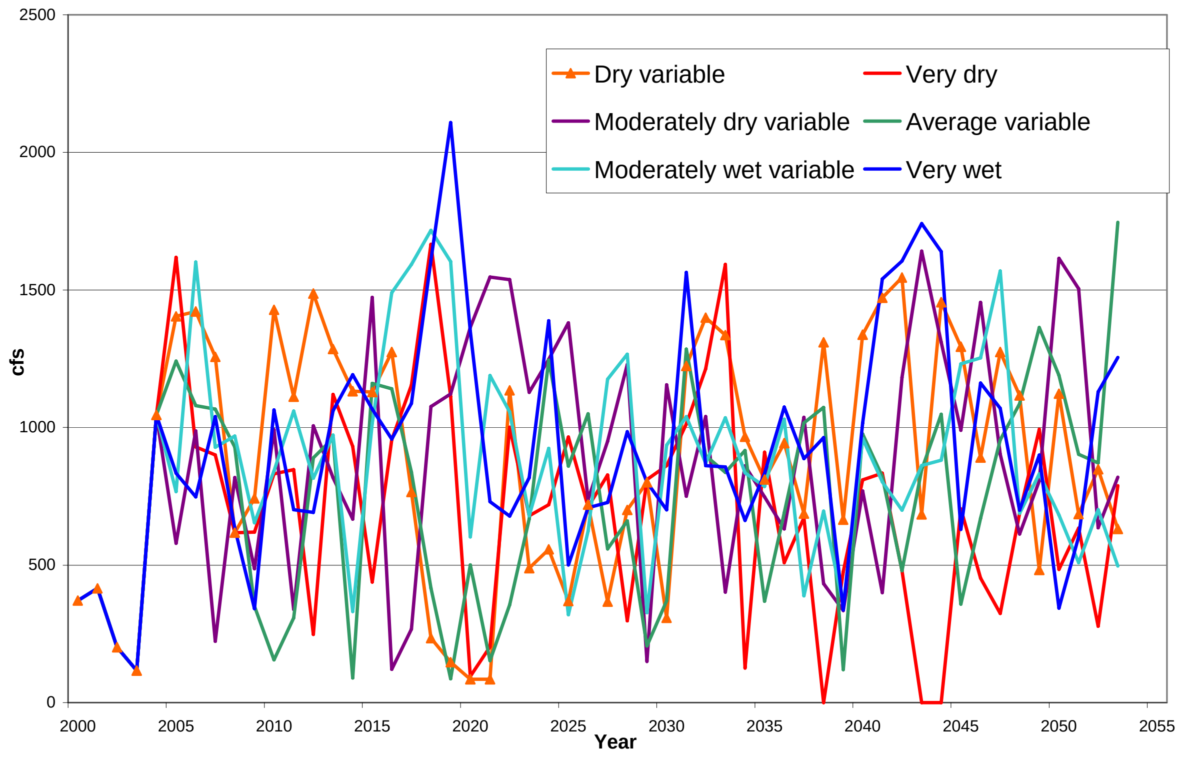


**Figure 40. San Marcial gage: variable climates**

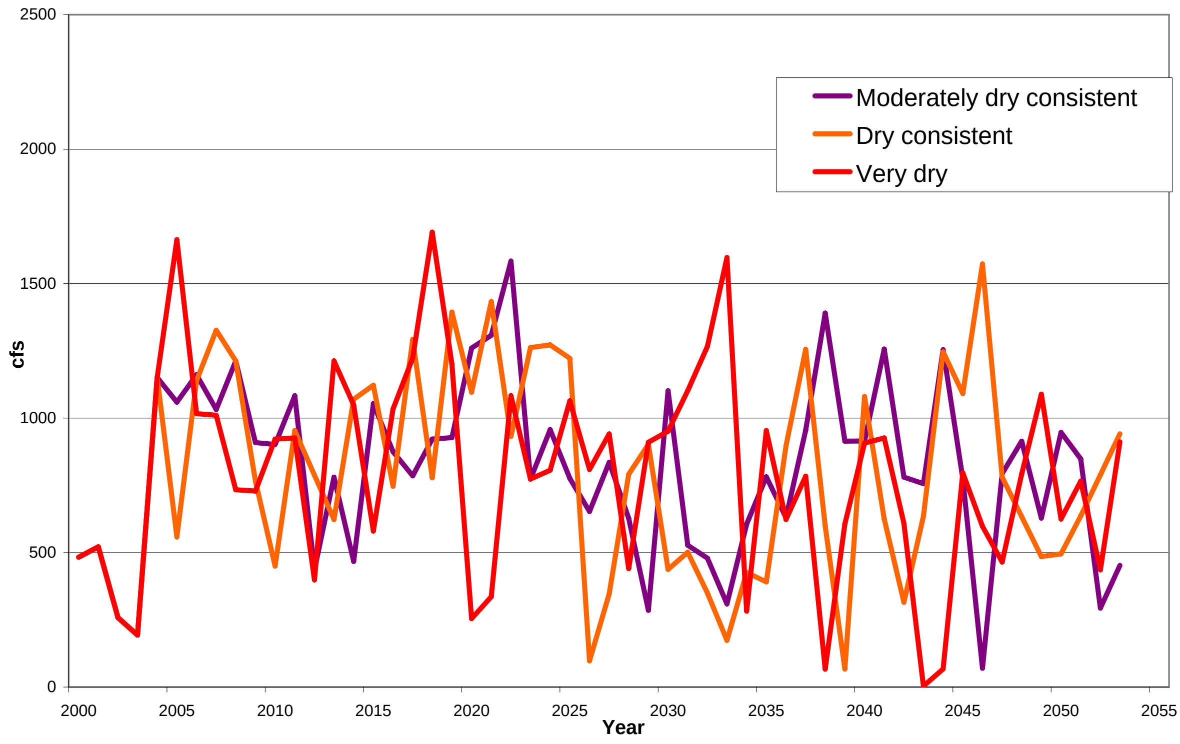


**Figure 41. Bernardo gage: consistent dry climates**

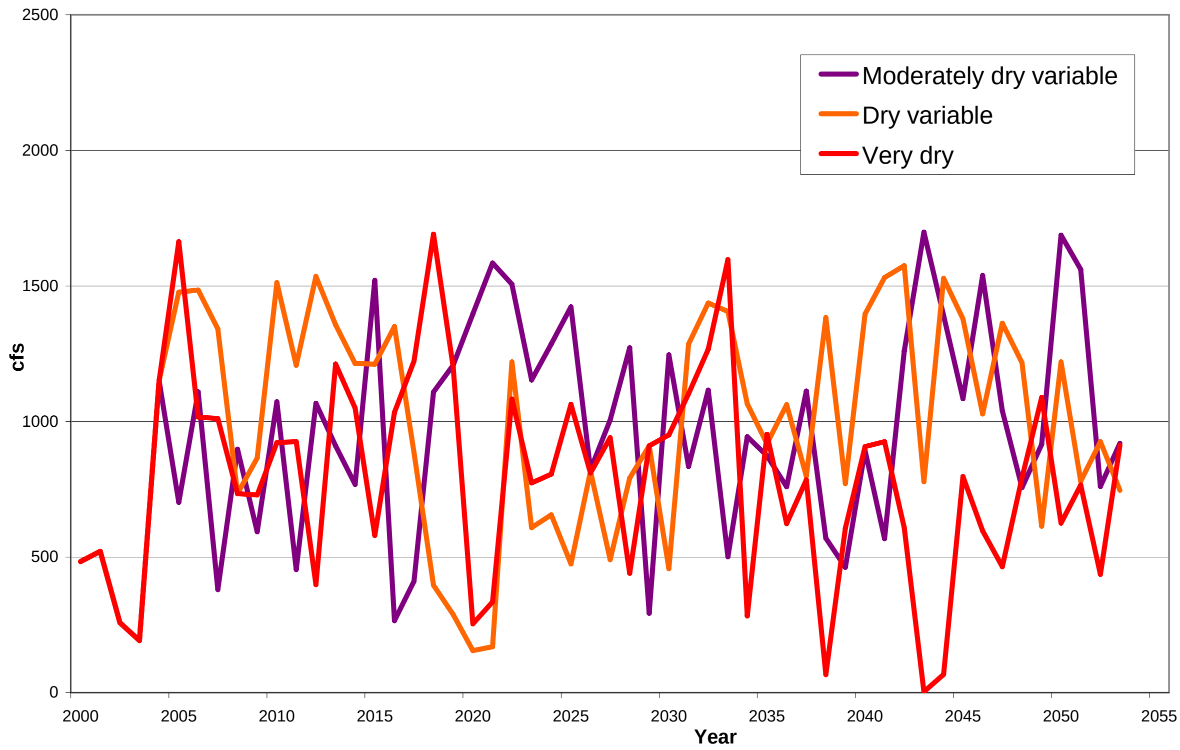


Figure 42. Bernardo gage: variable dry climates

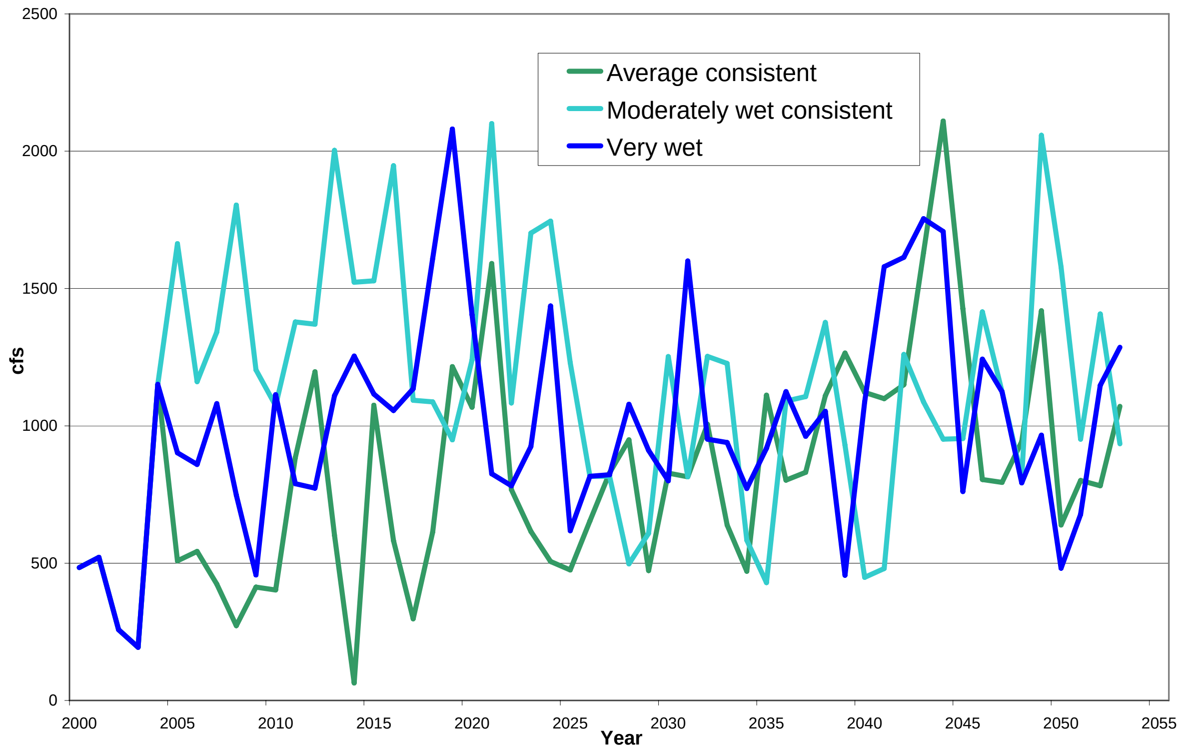


Figure 43. Bernardo gage: consistent wet climates

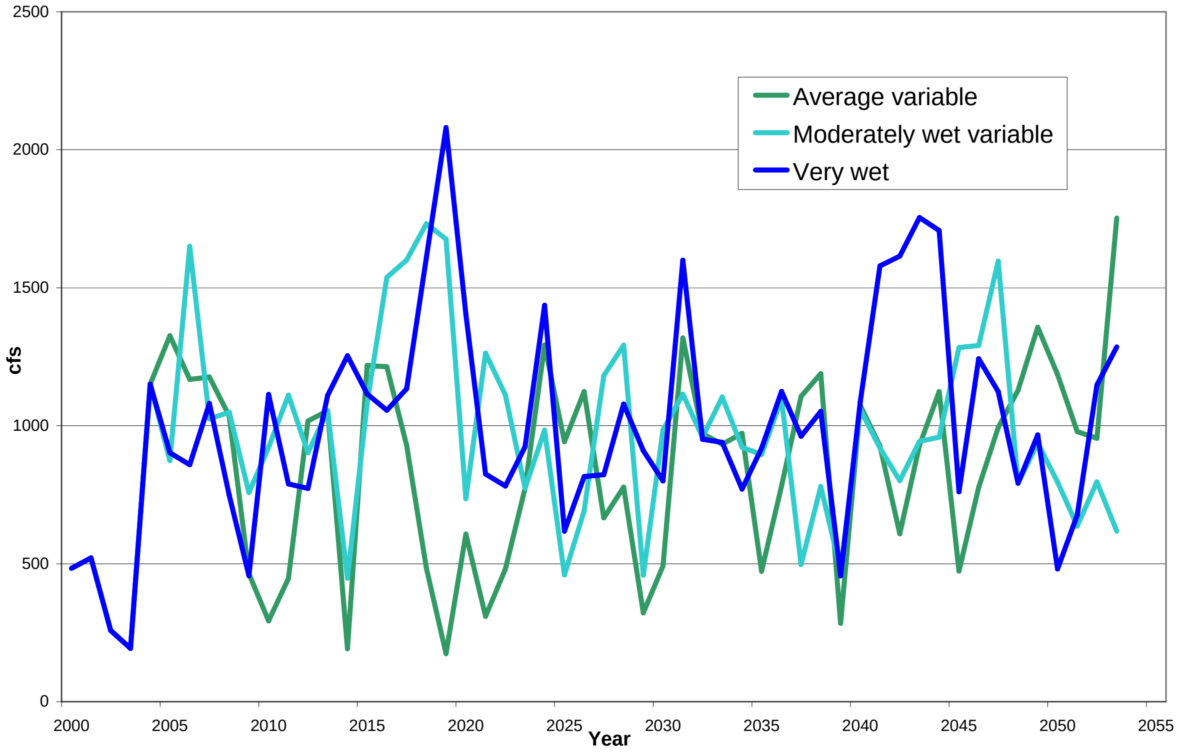


Figure 44. Bernardo gage: variable wet climates

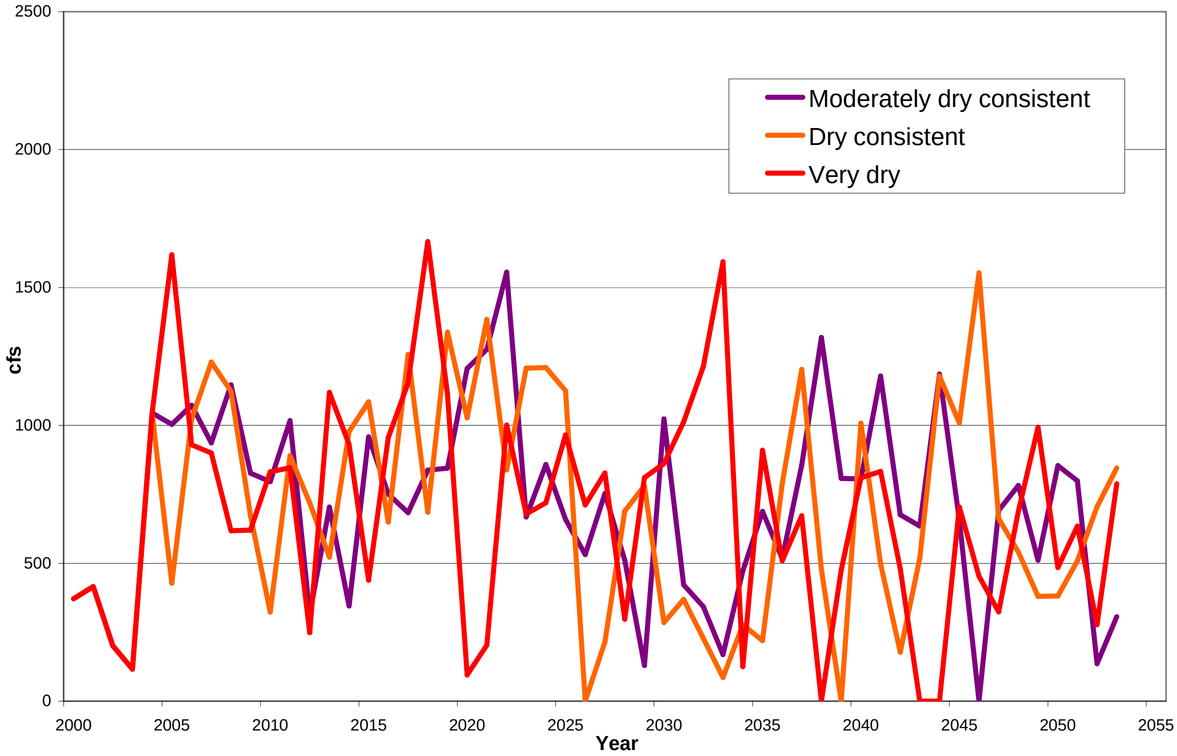


Figure 45. San Marcial gage: consistent dry climates

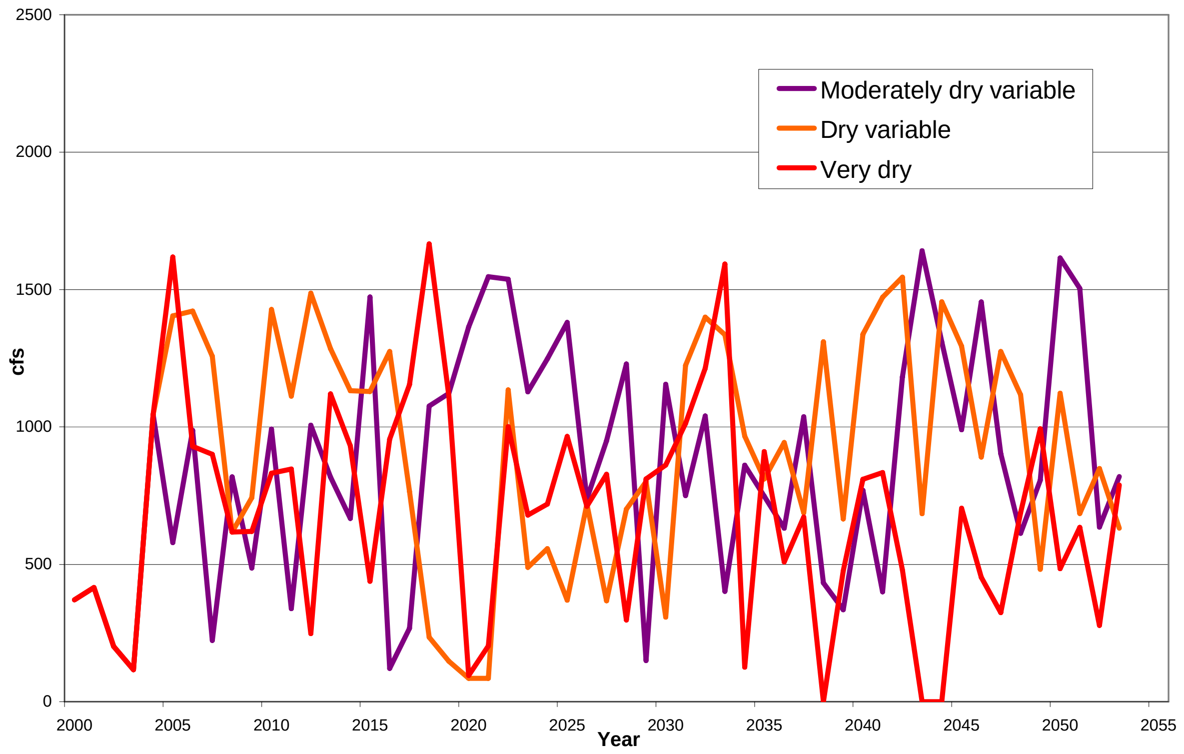


Figure 46. San Marcial gage: variable dry climates

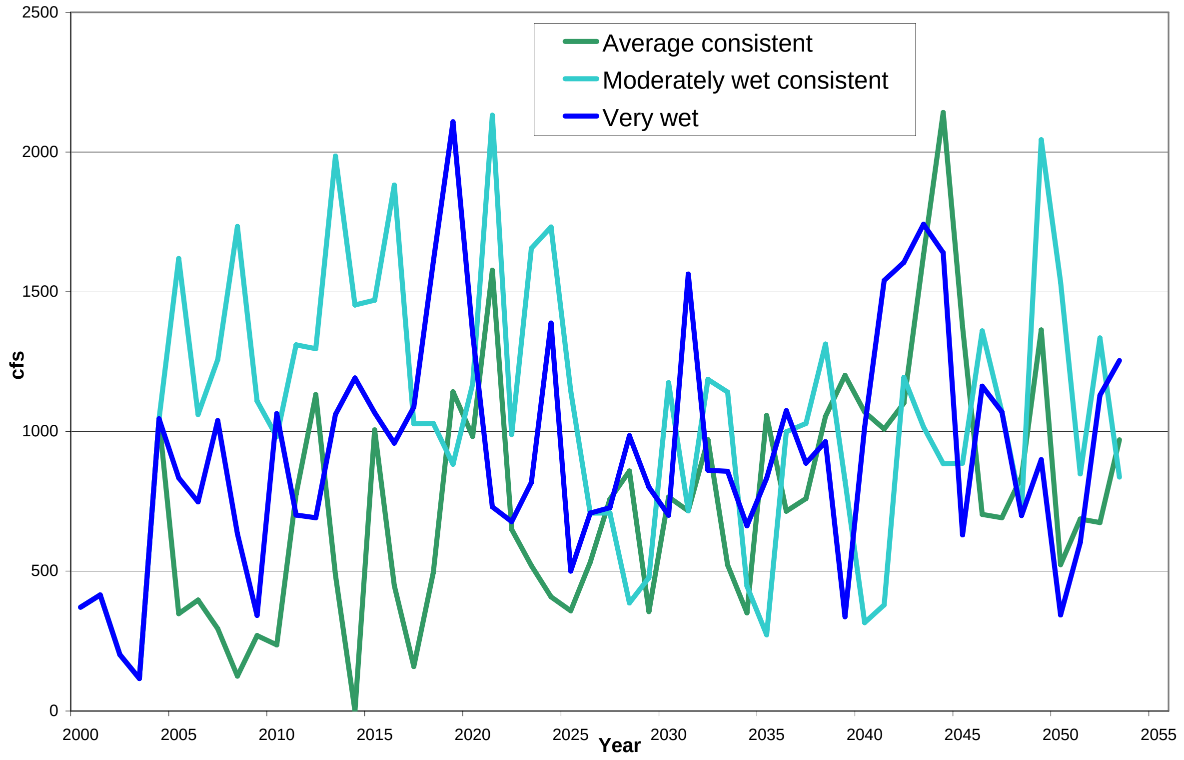


Figure 47. San Marcial gage: consistent wet climates

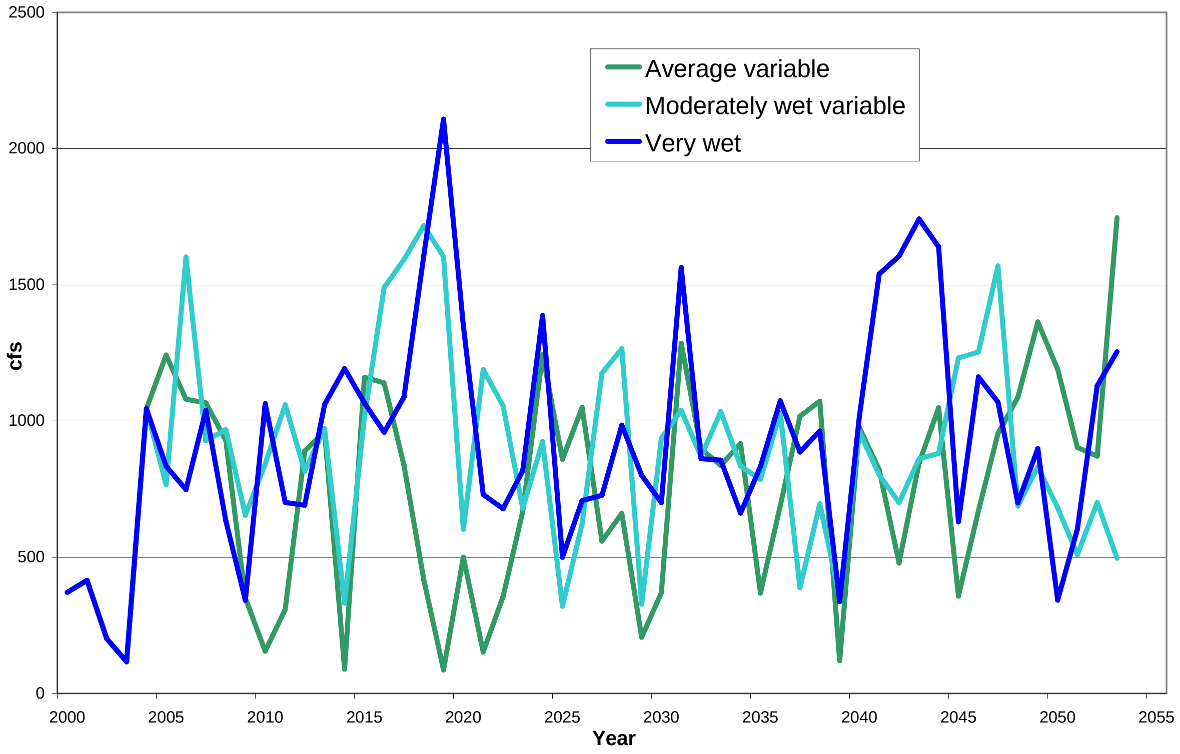


**Figure 48. San Marcial gage: variable wet climates**

The model also reported results on compliance with the Rio Grande Compact across all climates. Table 24 contains descriptive statistics for accrued credits/debits for all climates as well as the number of years during which New Mexico had accrued debits. Annual credits and debits for the climate with the fewest years of accrued debit status are shown in Figure 49. The same information for climates with an average number of years spent in accrued debit status and the most years are shown in Figures 50 and 51. Even though the moderately dry climate never entered accrued debit status, in 18 years of the simulation releases were below scheduled delivery. Conversely, the average consistent climate showed the most years spent in accrued debit status, but it only had 18 years of annual debits. Figures 52 – 55 compare the credit/debit accrual status across a variety of climates. A red line indicates zero accrual of either credits or debits.

**Table 24.** Descriptive statistics for accrued credits/debits for all climates

| Climate scenario | Minimum | Maximum | Average | # of years below zero |
|---|---|---|---|---|
| Very dry | -269,574 | 388,553 | 50,140 | 19 |
| Dry & Consistent | -857,119 | 588,607 | -30,305 | 21 |
| Dry & Variable | -76,890 | 512,660 | 188,060 | 4 |
| Moderately dry & consistent | 37,582 | 857,150 | 449,540 | 0 |
| Moderately dry & variable | -188,532 | 450,449 | 113,561 | 14 |
| Average & consistent | -833,114 | 371,212 | -287,278 | 38 |
| Average & variable | -296,501 | 555,868 | 61,497 | 24 |
| Moderately wet & consistent | -187,428 | 538,510 | 122,330 | 23 |
| Moderately wet & variable | -55,938 | 1,199,443 | 525,684 | 5 |
| Very wet | -69,999 | 1,058,393 | 313,715 | 7 |
| Average | | | 150,694 | |
| Standard deviation | | | 224,216 | |

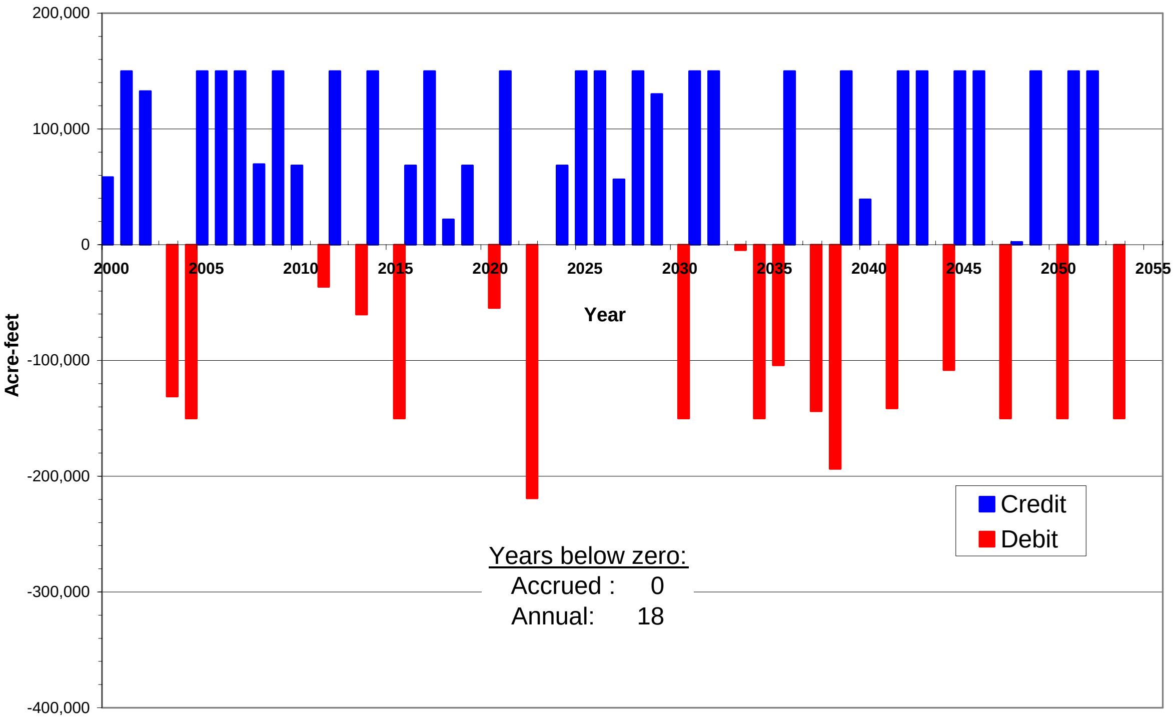


**Figure 49. Rio Grande Compact: annual credits and debits for moderately dry and consistent climate**

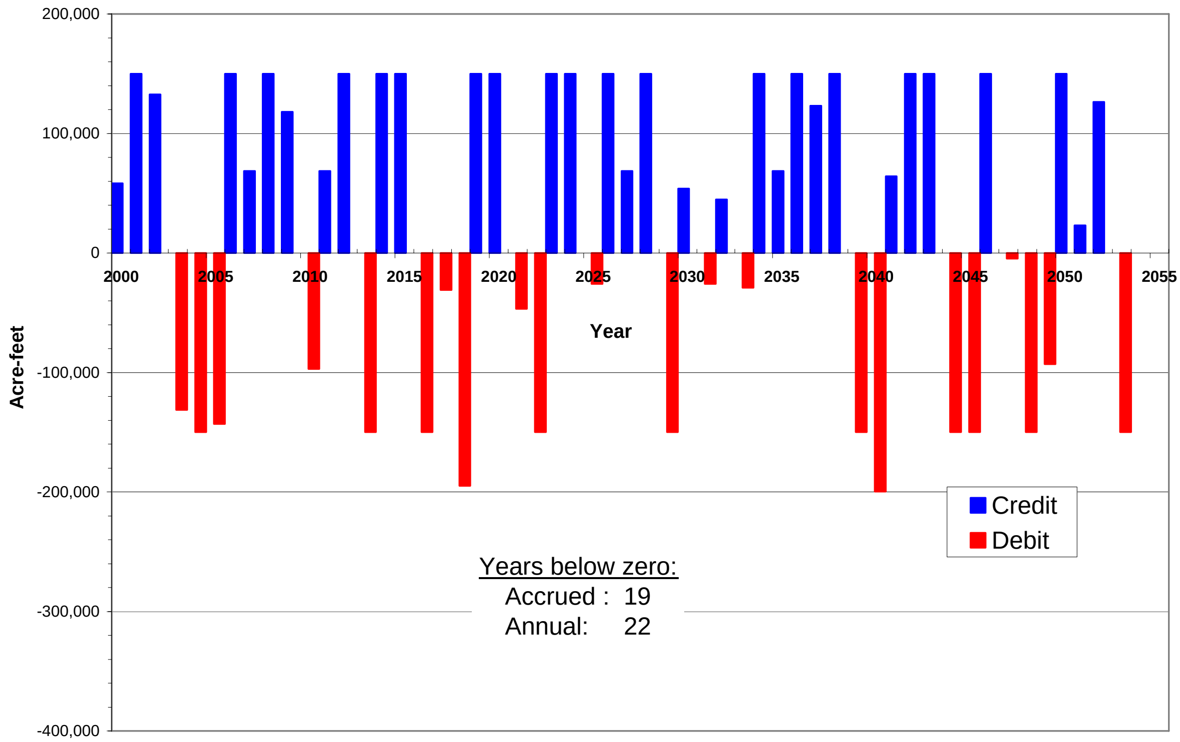


Figure 50. Rio Grande Compact: annual credits and debits for very dry climate

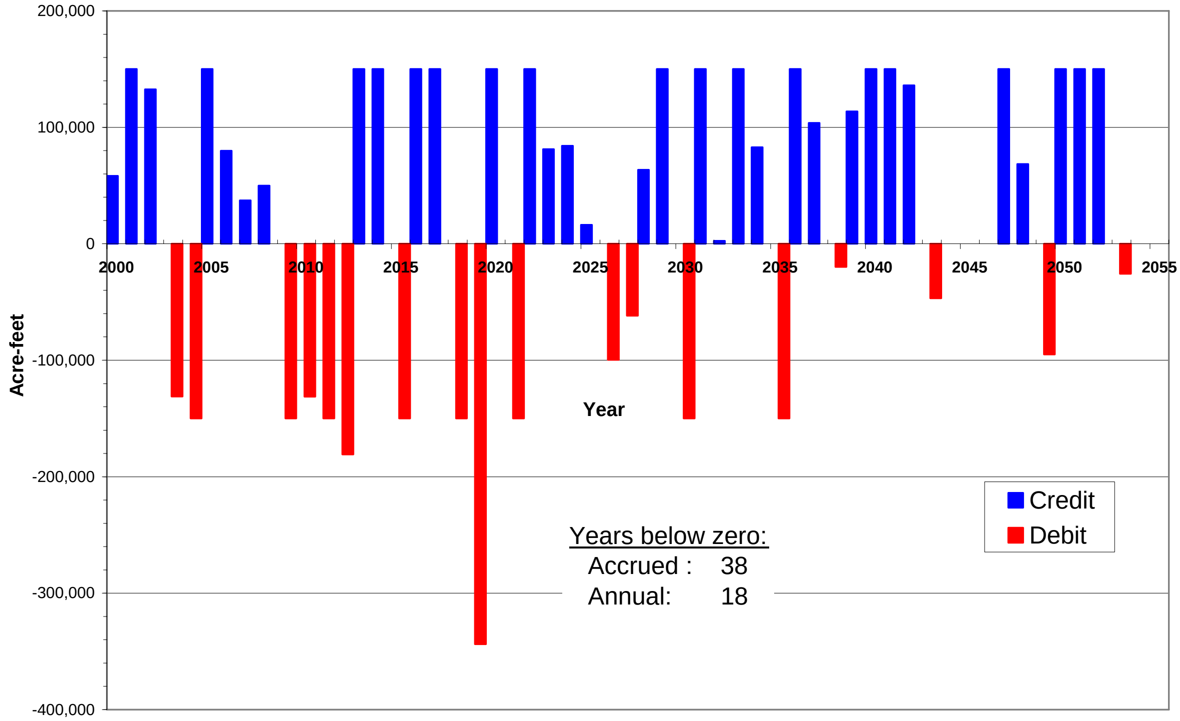


Figure 51. Rio Grande Compact: annual credits and debits for average consistent climate

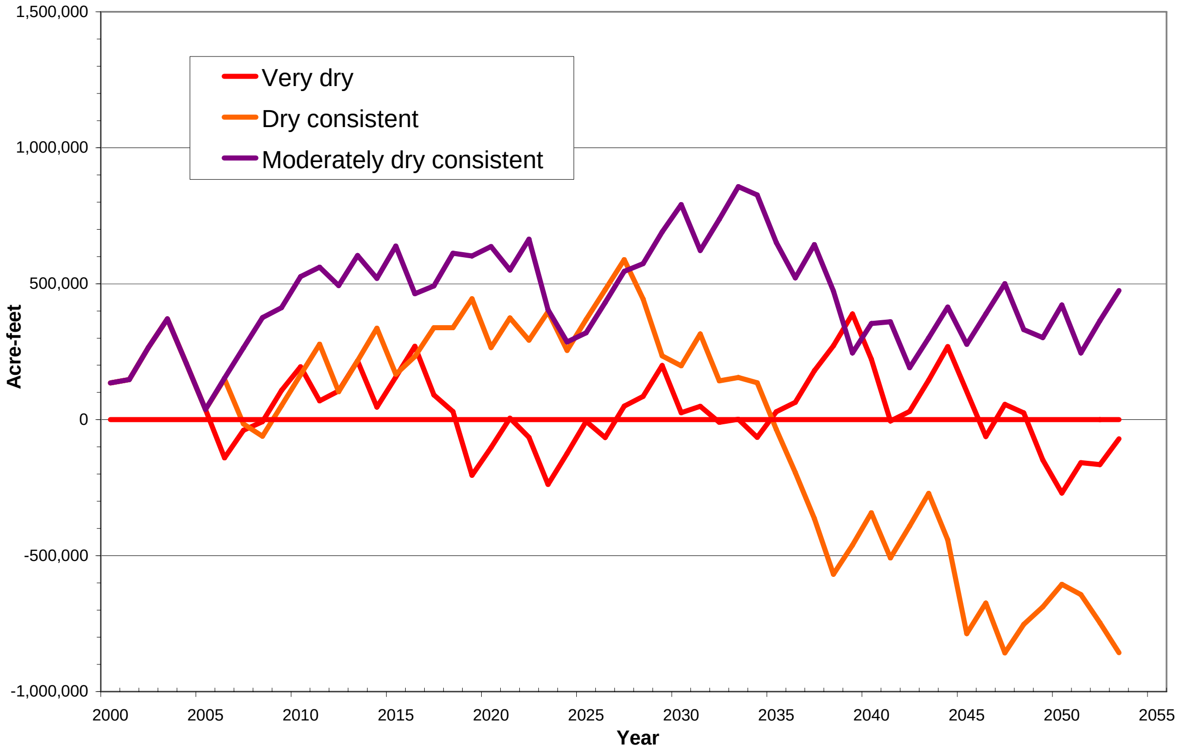


**Figure 52. Rio Grande Compact: accrual status for consistent dry climates**

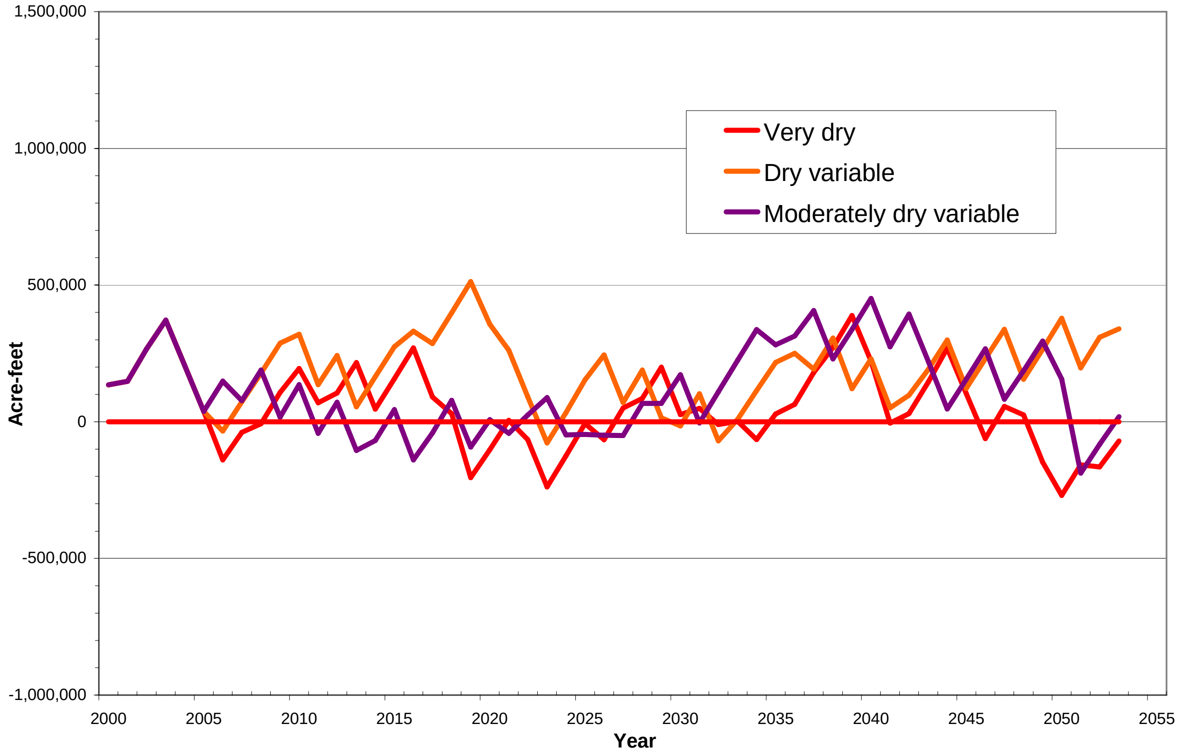


**Figure 53. Rio Grande Compact: accrual status for variable dry climates**

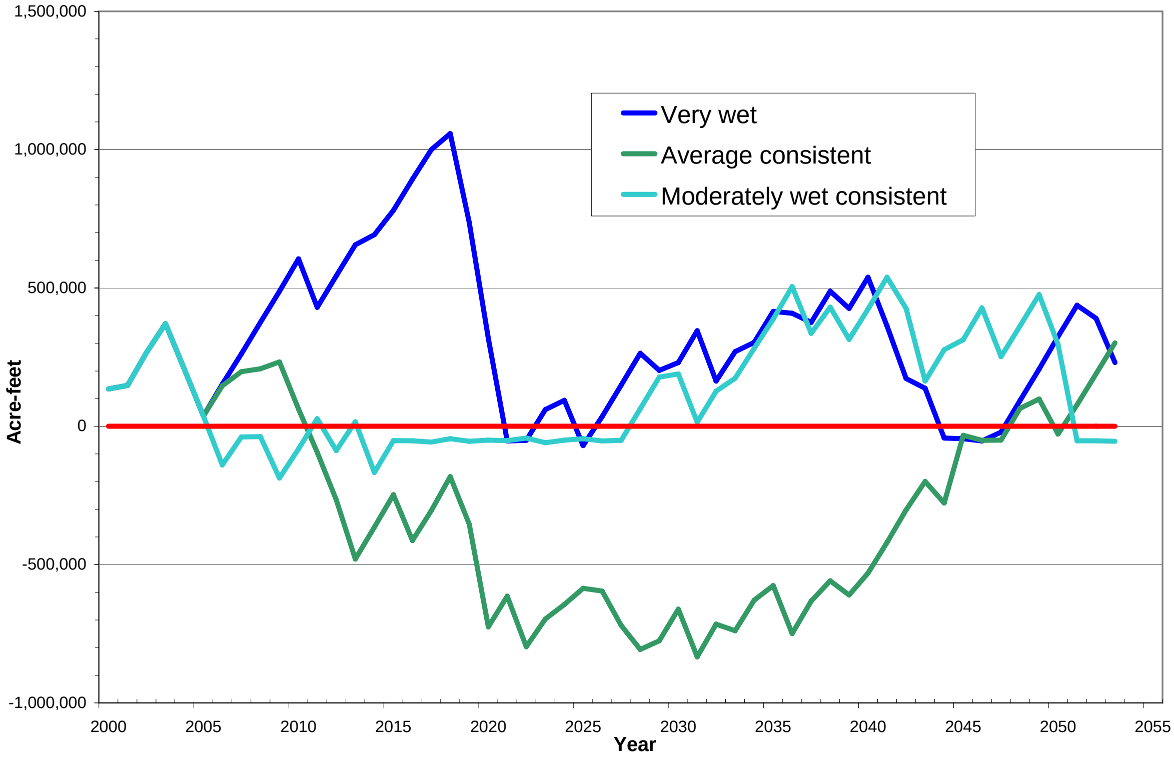


Figure 54. Rio Grande Compact: accrual status for consistent wet climates

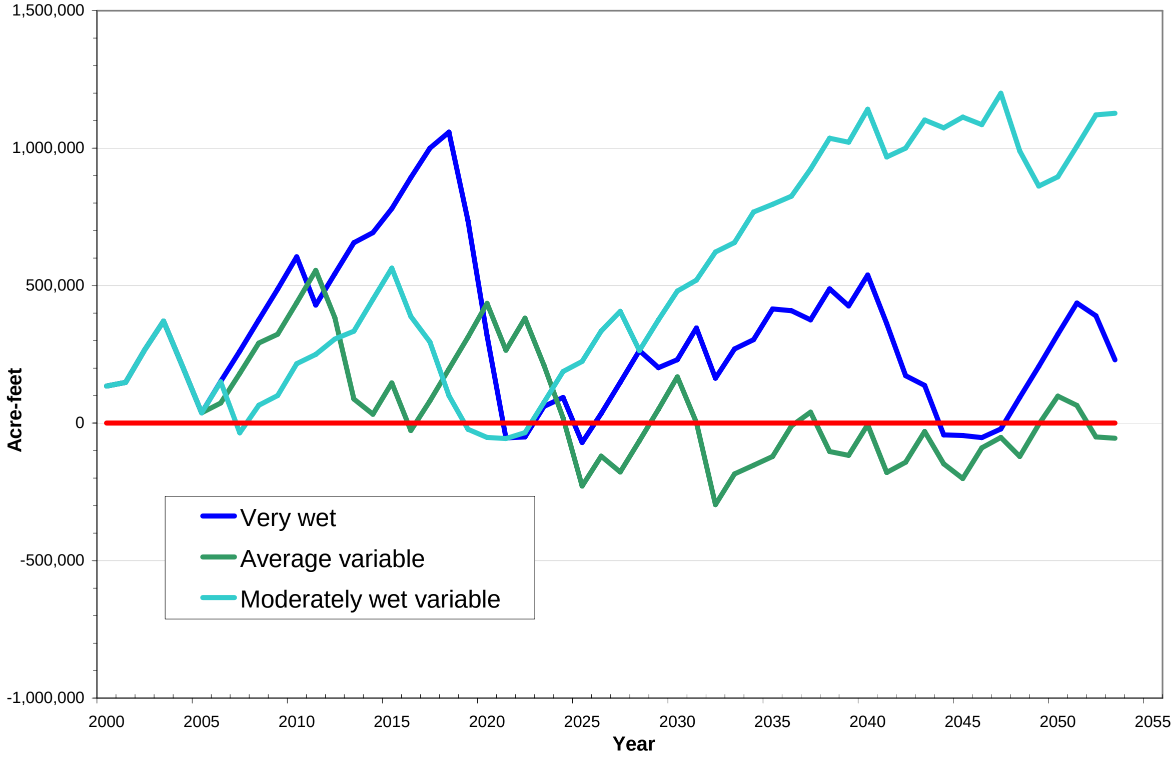


Figure 55. Rio Grande Compact: accrual status for variable wet climates

A correlation analysis was also performed using a very dry climate scenario, with some of the results shown in Table 25. The table shows correlation coefficients for groups of two parameters. For instance, the Reach 1 irrigation diversion and the San Felipe gage flow had a correlation coefficient of 0.63, meaning 63 percent of the variability in the San Felipe gage flow can also be seen in the R1 irrigation diversion. It also displays the results for correlation of some Reach 1 parameters and the San Marcial gage. For instance, the Reach 1 evaporation and the San Marcial gage had a correlation coefficient of 0.60. Not included in the table is the correlation of sub-basin runoff with gage flows, because each reach's runoff was completely correlated (r = 1) with its outflow gage.

**Table 25.** Correlation coefficients for various parameters for a very dry climate simulation

| Gage flows | | Irrigation diversions | Agricultural Uses & Losses | Irrigated acreage | Total Albuq use (R2 & R3) | R2 diversion | R3 diversion | Total river leakage | Evaporation |
|---|---|---|---|---|---|---|---|---|---|
| San Felipe | R1 | 0.63 | -0.29 | -0.20 | -- | -- | -- | 0.00 | 0.66 |
| Albuquerque | R2 | 0.57 | -0.37 | -0.09 | -0.20 | -0.02 | -- | -0.10 | 0.83 |
| Bernardo | R3 | 0.54 | -0.15 | -0.12 | -0.16 | 0.01 | 0.06 | -0.12 | 0.87 |
| San Acacia | R4 | -- | -0.32 | -0.11 | -0.17 | 0.00 | 0.05 | -0.11 | 0.92 |
| San Marcial | R5 | 0.51 | 0.14 | -0.11 | -0.17 | 0.00 | 0.05 | 0.00 | 0.86 |
| EB Dam | R6 | -- | -- | -- | -- | -- | -- | 0.00 | 0.32 |
| San Marcial | R1 | 0.51 | -0.33 | -0.11 | -- | -- | -- | -- | 0.60 |
| San Marcial | R2 | 0.45 | -0.40 | -0.11 | -- | -- | -- | -- | 0.79 |
| San Marcial | R3 | 0.48 | -0.18 | -0.11 | -- | -- | -- | -- | 0.85 |
| San Marcial | R4 | -- | -0.32 | -0.11 | -- | -- | -- | -- | 0.91 |

### *7.3 Effect of price and urban use on gage flows*

Five simulation runs were made to explore the effect of price on total water use, surface water diversion (San Juan-Chama water), and gage flows. Four of the price paths had annual price increases of 0%, 1.25%, 1.50%, and 2.5% while the fifth simulation used the price path established by conservation goals, as described in the Model Data section. All five price paths can be seen in Figure 56. The effect of price on Albuquerque's total urban use (ground water and surface water) is illustrated in Figure 57. The red line shows the increase in use if the current price is maintained and population growth continues. The surface water portion of the total urban use is Albuquerque's San Juan-Chama water. It is diverted in Reach 2, as is Bernalillo's. The effect of price on this diversion is shown in Figure 58.

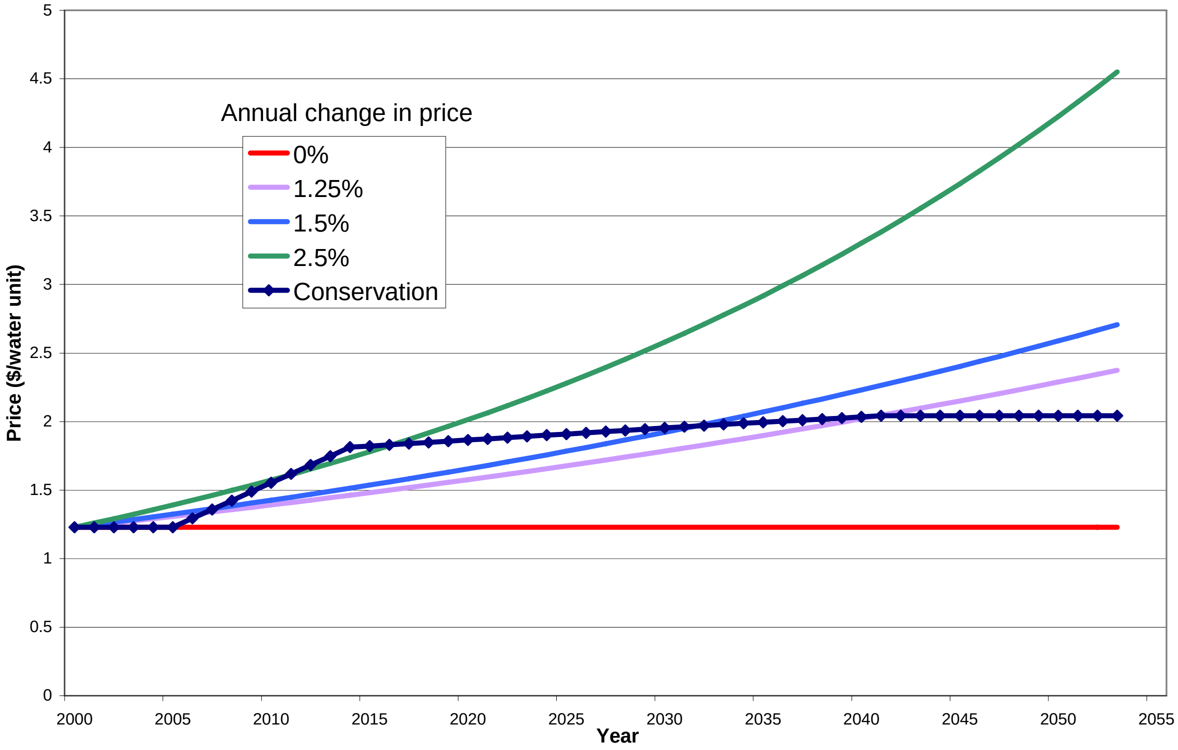


Figure 56. Price paths

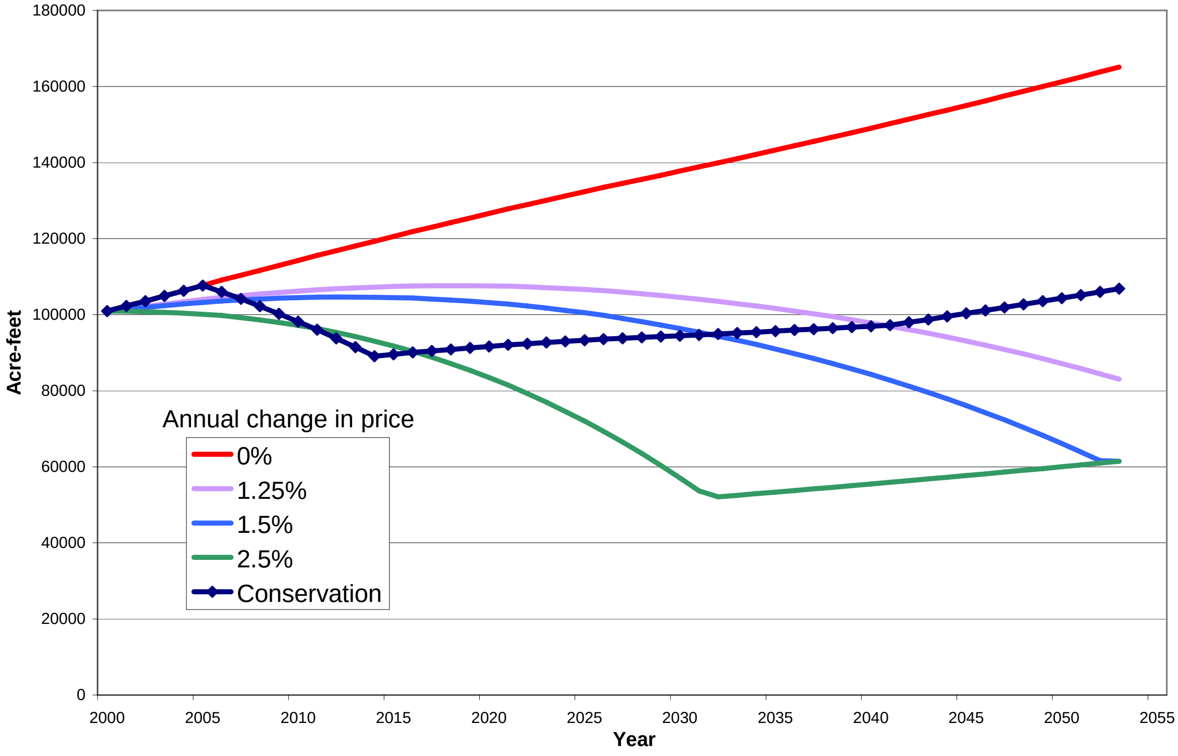


Figure 57. Price increases: Total Albuquerque urban use

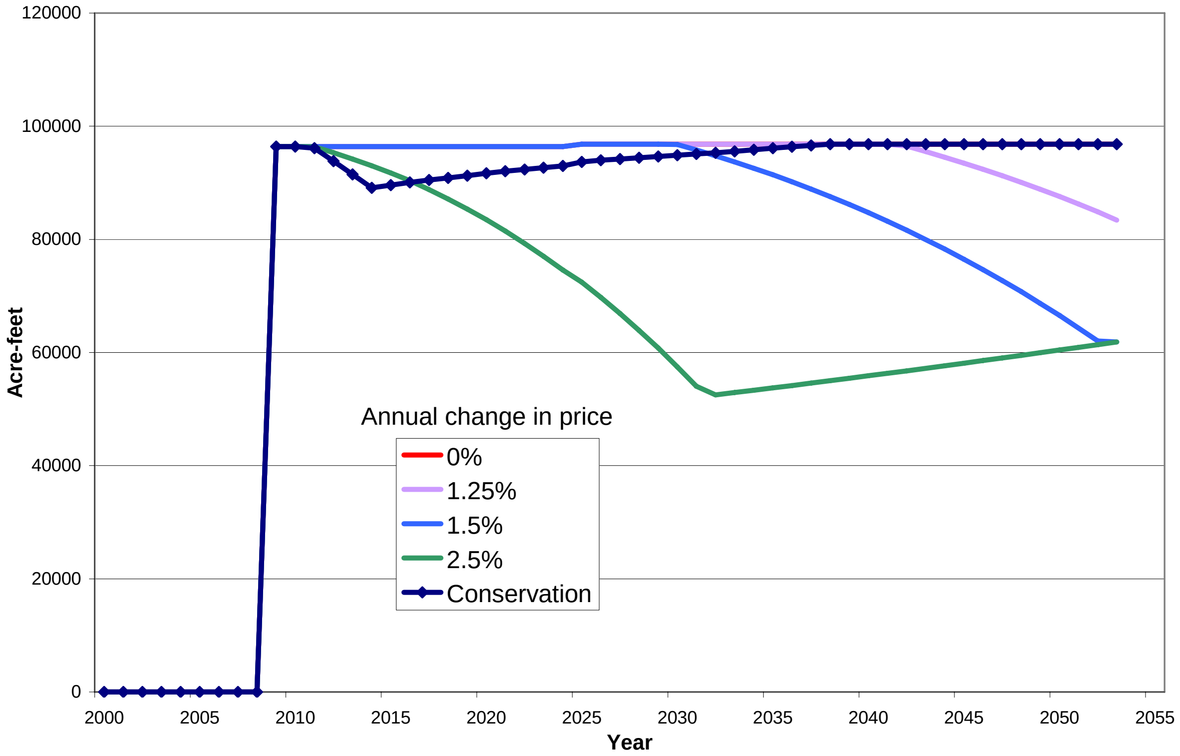


**Figure 58. Price increases: Reach 2 urban diversion of San Juan-Chama water**

Figures 59 – 62 show the influence of different prices on gage flows for the Albuquerque, Bernardo, San Acacia, and San Marcial gages. Price decreases caused an increase in the Albuquerque gage flow, relative to the no-price-increase simulation. In contrast, the Bernardo gage shows a decrease in gage flow, relative to the no-price-increase simulation. The San Acacia and San Marcial gages show the exact same decrease.

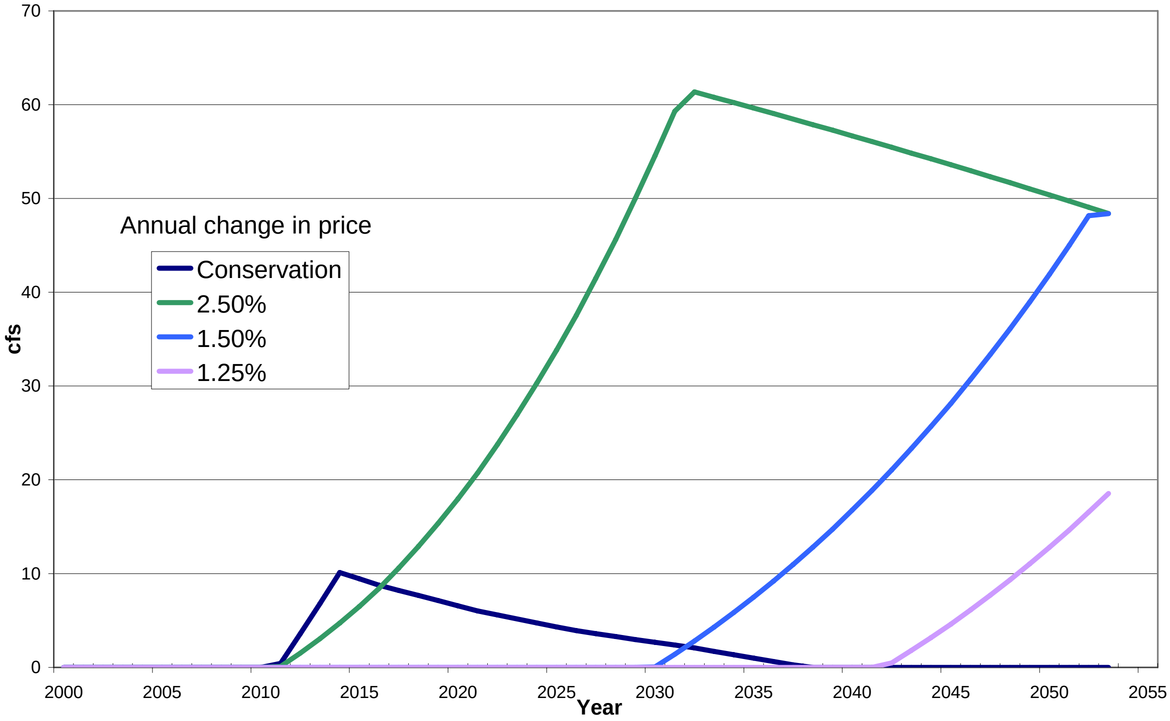


**Figure 59. Rise in Albuquerque gage due to price increases (relative to flows with today's price held constant)**

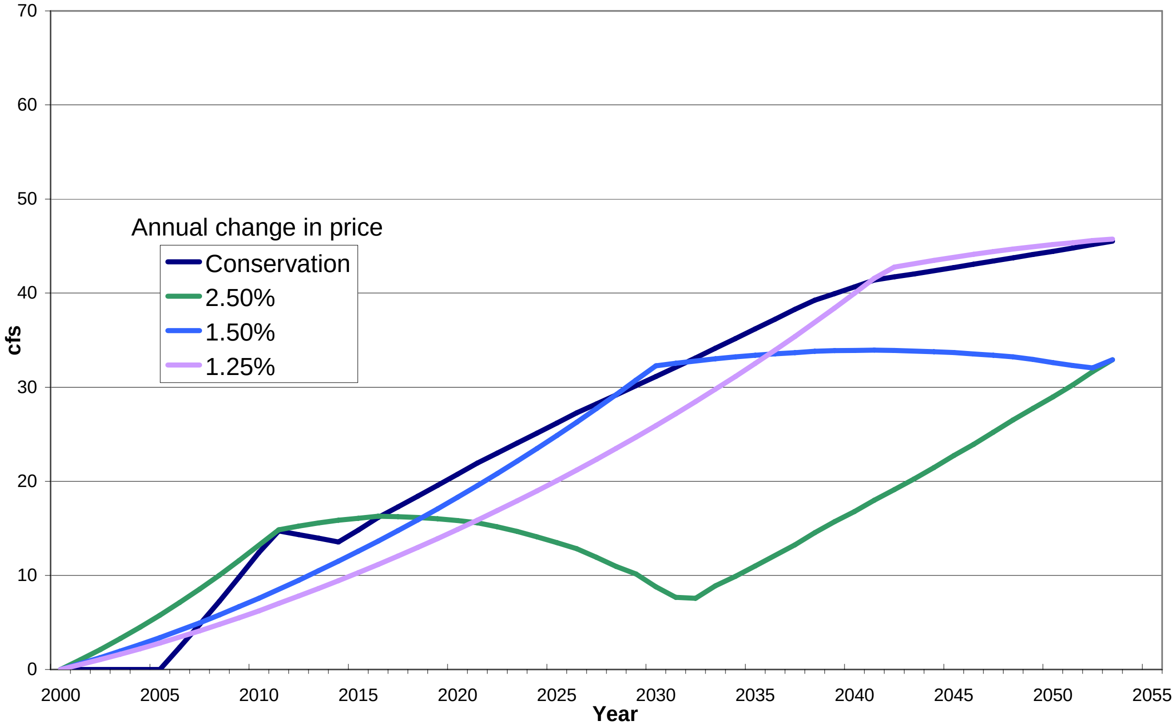


**Figure 60. Drop in Bernardo's gage due to price increases (relative to flows with today's price held constant)**

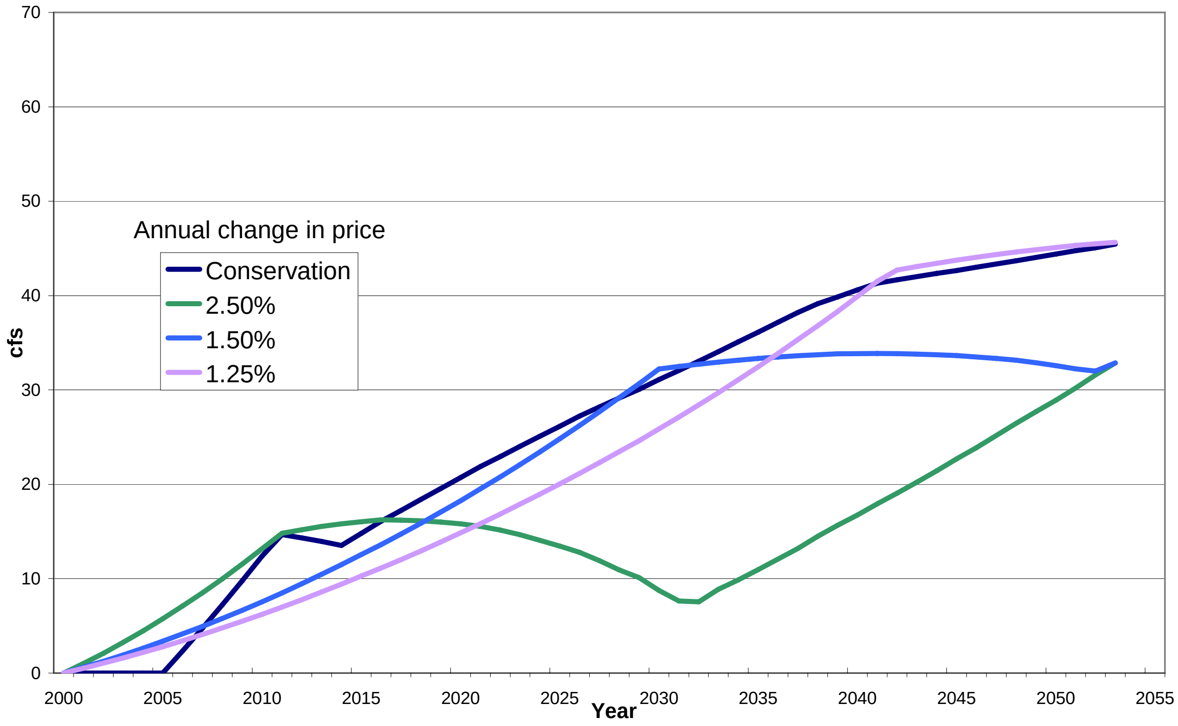


**Figure 61. Drop in San Acacia gage due to price increases (relative to flows with today's price held constant)**

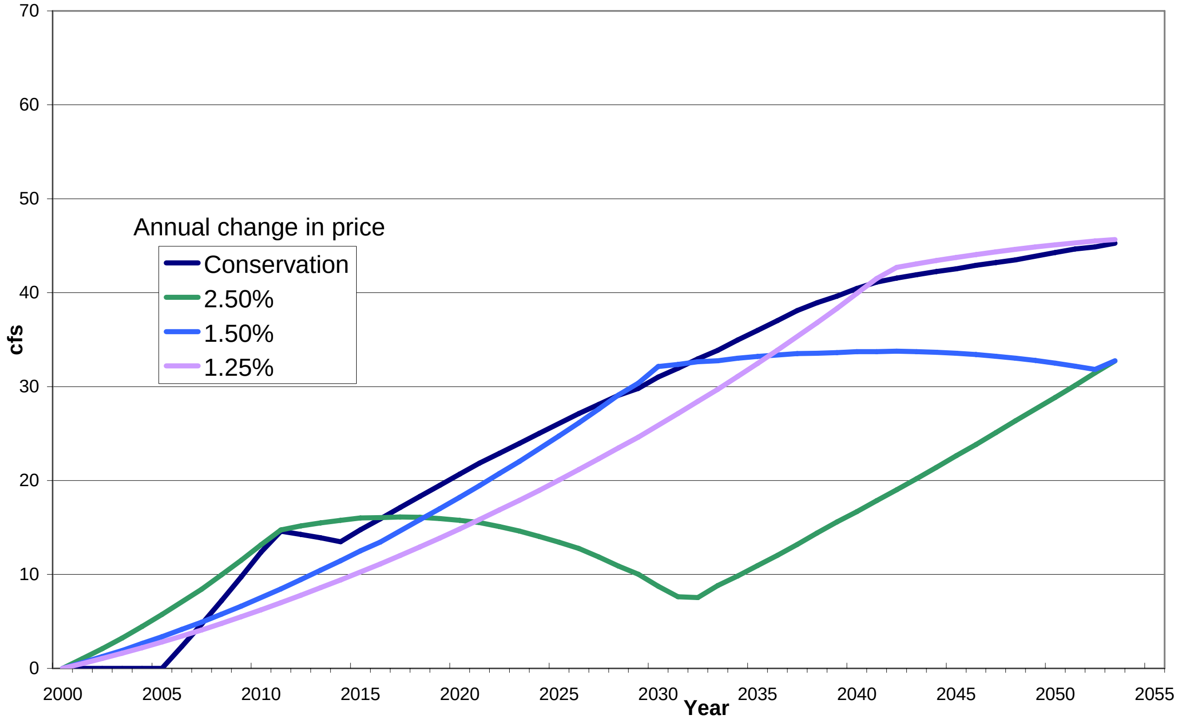


**Figure 62. Drop in San Marcial gage due to price increases (relative to flows with today's price held constant)**

# 8. DISCUSSION

## *8.1 Calibration*

The changes needed to calibrate the model to historical gaged flows for 2000 to 2003 were illuminating. First and foremost were the changes to the base leakage variable, 2001 leakage. The model combines this variable with annual increases and decreases (due to changes in pumping impact) to produce the total amount of leakage available each year for riparian ET, capture by drains, and loss to ground water. As seen in Table 10, the 2001 Leakage variable had to be reduced in Reaches 1 – 4 and increased in Reach 5. The reduction would seem to indicate a lesser effect for ground water pumping in these reaches than previously thought. Nevertheless, the leakage is still substantial, as seen in Table 26.

**Table 26.** Average model estimates for total river leakage

| Reach | Total river leakage AF/yr |
|---|---|
| 1 | 7,622 |
| 2 | 224,810 |
| 3 | 145,009 |
| 4 | 43,312 |
| 5 | 62,798 |
| 6 | 38,256 |

Riparian ET values needed to be changed, also, most drastically in Reach 5. This may be a reflection of the limited data points and their applicability to a Middle Rio Grande-wide average. Also, density of the vegetation most likely plays a role in the per acre rate and was not accounted for in the analysis of riparian vegetation acreage. Further, it is assumed the water table used by riparian plants is solely supplied by leakage from the river. If leakage is only a partial source of water for riparian plants, then the model's ET rates are over-stated relative to their impact on the surface water flows. It is interesting to note Papadopulos (2004) treats riparian ET as a static term because of the complexity of the causative factors.

The increase needed in the Reach 4 sub-basin runoff can not be directly explained. Perhaps the soils and land use data is not completely accurate across this sub-basin, which is the largest of the 6. The occurrence of both positive and negative disparities plus the changes needed in Reach 5 make it clear that our understanding of this reach needs to be improved. Other changes may simply reflect a correction of faulty assumptions; for instance, the partition of Reach 5 irrigation return flow between the river and the LFCC was assumed to mirror the number of connections between the irrigation canals and the river (two of nine) and the LFCC (seven and nine). The calibration changed this to 5% and 95%, respectively.

Finally, although irrigated or riparian acreage was not varied during the calibration, there is a good deal of uncertainty in the values for these variables. Total riparian acreage may be more reliable as it is derived from satellite and photographic interpretation; however, composition is more difficult to properly estimate. Also, Papadopulos (2004) found some information sources that indicated irrigated acreages were over-stated.

### *8.2 Sensitivity*

The sensitivity results were not as high as expected (Table 14). While the computation of open water evaporation volumes for each reach showed a complete sensitivity to the changes in the pan evaporation values, the river reaches showed little reaction to the changes. Most likely, this is due to the relatively small volume of evaporation (Table 27) as compared to sub-basin runoff (Table 19) and leakage (Table 26). The exception to this is evaporation from Elephant Butte, which is a quite large volume.

**Table 27.** Average model estimates for open water evaporation, very dry climate scenario

| Reach | Open water evaporation AF/yr |
|---|---|
| 1 | 3,804 |
| 2 | 15,316 |
| 3 | 19,510 |
| 4 | 3,410 |
| 5 | 11,392 |
| 6 | 1,175 |
| Elephant Butte North | 35,590 |

The river showed little sensitivity to changes in the riparian ET rates (Table 15), although the riparian ET volumes showed changes corresponding to the variation in the rates. As confirmation, Papadopulos (2004) found a 15% change in riparian ET volumes resulting from a 16% reduction in the ET rate across the entire Middle Rio Grande. However, Papadopulos (2004) does not estimate the river flows at any particular point and instead focuses on annual Compact debits. Compact compliance sensitivity was not assessed in this model because the Elephant Butte Dam gage was not calibrated. The only other sensitivity analysis conducted by Papadopulos (2004) was on agricultural consumption rates.

The river's lack of sensitivity may occur because the model structures riparian ET as a subset of total leakage, but ET does not drive leakage. Instead, leakage is assumed to be relatively static and influenced only by changes to anthropogenic ground water pumping.

Sensitivity of the river to variation in leakage was more noticeable (Table 17). This increase over the sensitivity to evaporation and riparian ET could partly be caused by the fact that volumes were modified for leakage, while rates were modified for evaporation and riparian ET. Therefore, the degree of change is greater. Only the Reach 1 riparian ET only showed sensitivity to leakage variation, because it consumes all the leakage (as modeled). Leakage to drains and ground water showed great sensitivity to leakage variation, with sensitivity increasing downstream.

Once again, this is due to the model structure that computes leakage to drains and ground water as a subset of total leakage. The changes in leakage to drains and ground water were a good deal greater than the changes to the total leakage in the lowest reaches. This is because leakage is much less in these reaches; consequently, riparian ET consumes a greater proportion of the leakage in these reaches. Since the ET volume did not change, the effect of changes to the total leakage is magnified in the amount available for capture by drains or loss to ground water

### *8.3 Effects of climate on gage flows*

As with all models, the simulation results for this model should not be used to predict river flows for any specific year or time period in the future. Also, directly comparing the results to the past 50 years in New Mexico conditions is inappropriate, especially without trying to match the historical precipitation profile across the sub-basins. However, a probabilistic analysis can compare the distribution of simulation results to historical data to see if the model produces the same range of flows as history. This is valid if both the historical period and the model scenarios cover a wide variety of underlying conditions.

According to Papadopulos (2004), the past 50 years represent the variability of the climate of the last 1000 years as well as the extremes and the average. The model encompasses ten difference climate scenarios, drawn from paleoprecipitation reconstructions over the last 1000 years. Like the last 50 years, the model scenarios well represent climate variability, extremes, and average values. This is shown in Figures 63 and 64, which show histograms for the normalized paleoprecipitation reconstruction for climate division five and the normalized precipitation for all ten climate scenarios.

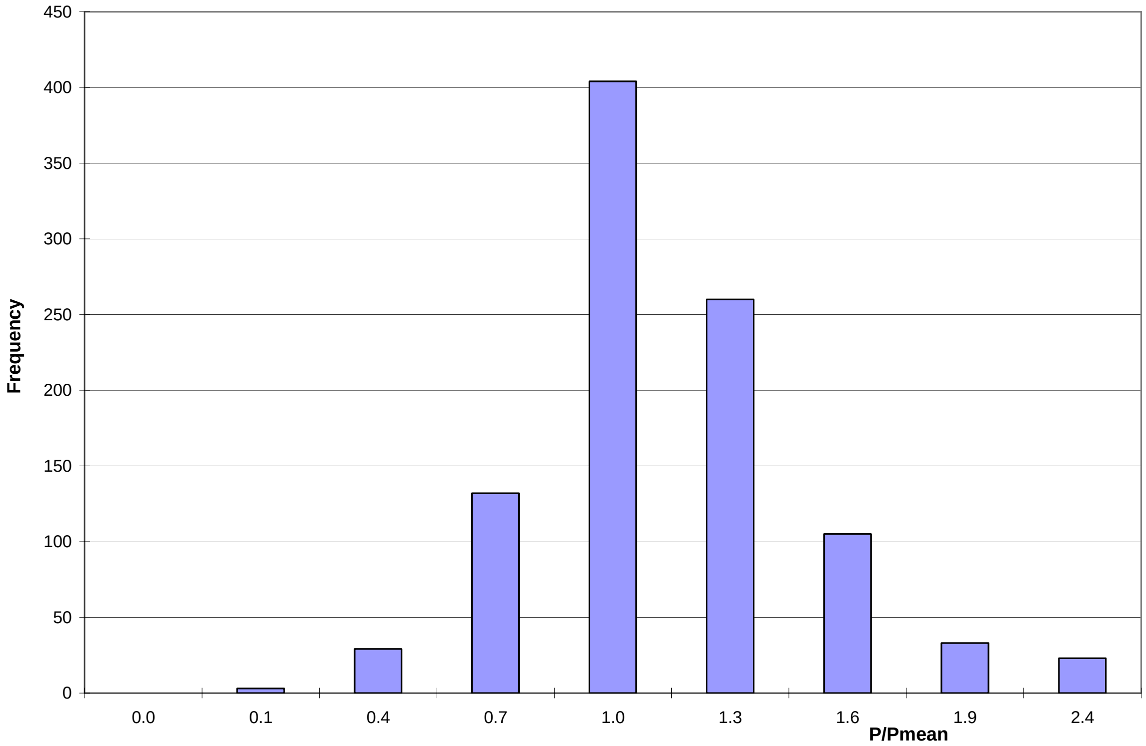


**Figure 63. Histogram: cool season precipitation reconstruction for climate division 5**

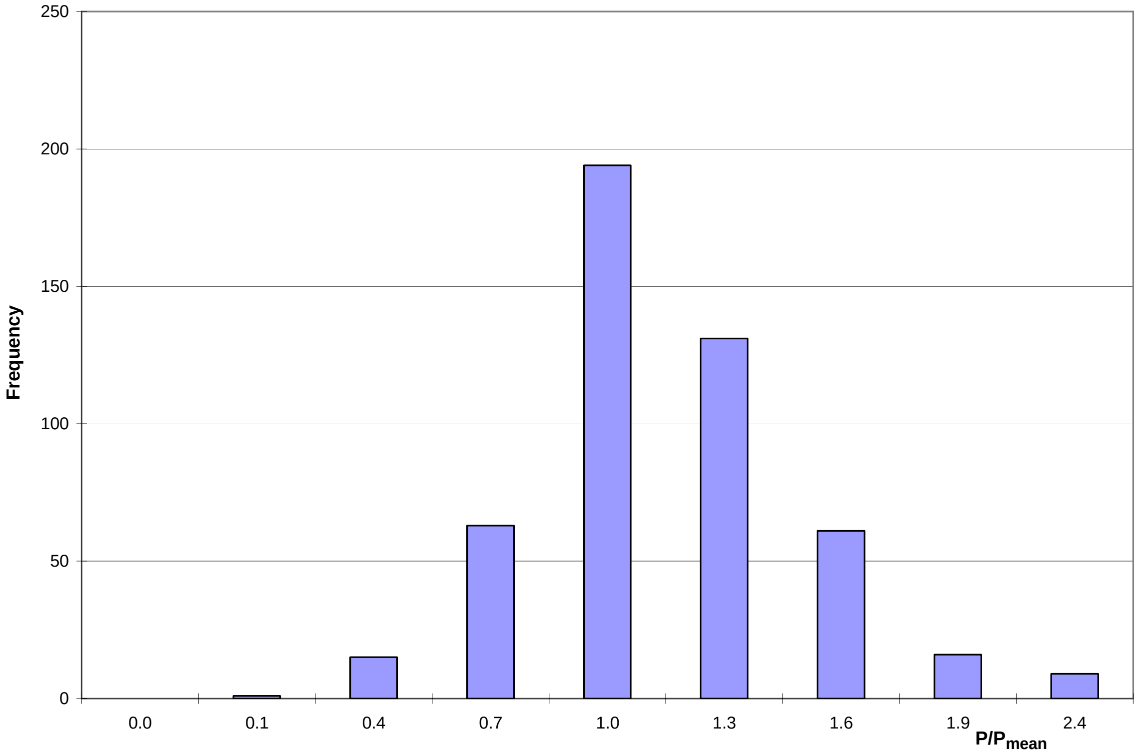


**Figure 64. Histogram: Reach 5 precipitation (climate divison 5)**

The histograms and cumulative probability charts (Figures 18 – 33) provide a probabilistic description of each gage's flow values for a wide variety of climates and corresponding precipitation profiles. Table 28 summarizes the information in the figures, showing the first and second most frequently occurring ranges of flow values across all climates. That information can be compared to historical gage data in Table 29.

**Table 28.** Most frequently occurring simulated gage flows across all climates

| Gage | Most frequently occurring flow volume (cfs) | Cumulative percentage (%) | Second most frequently occurring (cfs) | Cumulative percentage (%) |
|---|---|---|---|---|
| Cochiti | 1658 - 1356 | 75 | 1356 - 1054 | 42 |
| San Felipe | 1712 - 1403 | 82 | 1403 - 1094 | 40 |
| Albuquerque | 1165 - 874 | 58 | 1456 - 1165 | 85 |
| Bernardo | 1136 - 853 | 73 | 853 - 570 | 41 |
| San Acacia | 1028 - 773 | 59 | 1283 - 1028 | 81 |
| San Marcial | 884 - 663 | 55 | 1105 - 884 | 74 |
| Elephant Butte Dam | 1000 - 751 | 60 | 1249 - 1000 | 75 |

**Table 29.** Most frequently occurring historical gage flows (using Table 28 bin values)

| Gage | Most frequently occurring flow volume (cfs) | Cumulative percentage (%) | Second most frequently occurring (cfs) | Cumulative percentage (%) |
|---|---|---|---|---|
| Cochiti | 1054 - 752 | 42 | 752 - 450<br>1960 - 1658 | 21<br>82 |
| San Felipe | 1094 - 785 | 44 | 785 - 476 | 21 |
| Albuquerque | 583 - 292 | 25 | 874 - 583<br>1747 - 1456 | 43<br>79 |
| Bernardo | 287 - 4 | 28 | 570 - 287 | 48 |
| San Acacia | 264 - 8 | 29 | 773 - 518 | 60 |
| San Marcial | 221 - 0 | 30 | 442 - 221 | 54 |
| Elephant Butte Dam | 1000 - 751 | 54 | 1249 - 1000 | 89 |

Interestingly, the histograms for the historical data (Appendix E) show a very strong tendency to lower values and the distribution is almost always bi-modal, except for Elephant Butte. Cochiti has a widely spread distribution, with almost equal frequency of occurrences of the top three values. Elephant Butte Dam, on the other hand, is extremely tightly grouped with the vast majority of occurrences between 1000 cfs and 751 cfs. This confirms the model assumption that Elephant Butte releases are managed to achieve consistent flow values.

The simulation results only show a very slight tendency to lower values in the upper reaches and possibly a slight tendency to higher values at San Acacia and San Marcial. Also, the most frequently occurring values are significantly higher for the simulated data than the historical data. Cochiti is an exception, with historical data showing a second most frequently occurring range higher than the simulated data.

This comparison could indicate that the simulations were run over a wider variety of climates than encompassed in the historical record, with most of the historical gage data beginning in the 1940's and 1950's. The Elephant Butte Dam gage period of record extends back to 1917. Furthermore, the period 1950 – 2002 includes both one (1945 – 1963) of the five driest and one (1978 – 1992) of the five wettest periods and "when averaged over the 52 years, represents long-term average conditions well" (Papadopulos 2004). Likewise, the model climate scenarios include one (1272 – 1297) of the driest and one of the wettest (1627 – 1653) periods. However, when comparing the histograms for the paleoprecipitation reconstruction and the simulated gage data, the same slight tendency to wetter values is seen. Thus, the climate scenarios in the model may represent the past 1000 years, but are most likely different from the past 50 years. Indeed, the bi-modal distribution of the historical gage data could be interpreted as a result of 2 time periods with very disparate climates.

On the other hand, perhaps the probability distribution analysis indicates the model was "over-calibrated" with too much reduction in various outflows. However, simulation results are closer to the historical distribution in the upper reaches, implying the model's balance of inflows and outflows is acceptable there. Many calibration changes were focused in Reaches 4 and 5. For instance, during the very low flows of 2002 and 2003, enlightened management and legal implications caused the reduction of irrigation diversions, so calibration changes incorporated this into the model, with emphasis in the lower reaches. However, over the past 50 years, diversion reductions were not so responsive to low flow conditions and more water was kept in the agricultural sub-system and the LFCC. Thus, the calibration to 2002 and 2003 may have helped to cause the probabilistic disparity between the model and the past 50 years, but still reflects future management.

Turning to the cumulative probability curves, comparison of the 50 percent values between historical and simulation values is shown in Table 30. There is a 50 percent chance a gage flow will be equal to or less than the values listed in Table 30. The upstream reaches have fairly good agreement and the historical 50% value is higher than the simulation value. But moving downstream, the divergence increases.

**Table 30.** Cumulative probability results: 50 percent occurrence values (approximate)

| Gages | Simulation results (cfs) | Historical data (cfs) |
|---|---|---|
| Cochiti | 1400 | 1450 |
| San Felipe | 1425 | 1300 |
| Albuquerque | 1100 | 1000 |
| Bernardo | 975 | 650 |
| San Acacia | 900 | 600 |
| San Marcial | 850 | 475 |
| Elephant Butte Dam | 875 | 975 |

Looking at average gage flows seems to bring the simulations and historical data closer. As seen in Table 21, the upper reaches have good agreement with slight divergence once again beginning at Bernardo and increasing downstream. Again, the simulated values are higher than historical. Yet, the averages are closer together than the 50 percent cumulative probability values. For instance, the simulated average San Marcial gage flow is 81% of the historical value, but the 50 percent cumulative probability value for San Marcial is only 56% of the historical value.

This would imply the model actually represents the last 50 years fairly well in the upper reaches, but has difficulty in the lower reaches. This is confirmed by the calibration results, comparing Table 11 to Table 8. Taking into account both the histograms and the cumulative probability curves, the results indicate that the majority of the climate scenarios are wetter than the previous 50 years. This would especially be true in the lower reaches. On the other hand, it could also indicate that our knowledge of conditions in lower reaches may need further refinement.

Furthermore, the simulated sub-basin runoff values had a one to one correlation with simulated gage flows in every reach. So the probability distribution analysis indicates a need for improvement in knowledge of soils and land use conditions across the sub-basins for the lower reaches. The calibration results would seem to reinforce the need for more accurate data for the river and contributing sub-basins, especially in very dry years like 2002 and 2003 and in the lower reaches.

Interestingly, although the Elephant Butte Dam gage was not calibrated, the probability distribution is relatively close between simulation results and historical data. The first and second most frequently occurring values are exactly the same for historical and simulated data, although the cumulative percentages are different. Figure 65 shows the cumulative probability curve for historical Elephant Butte Dam gage flows. It shows a strong similarity in shape and values to the simulation results (Figure 32). The two begin to diverge at about the 70 percent point. Therefore, the modeling of the release rules for Elephant Butte may be a fairly good representation of reality.

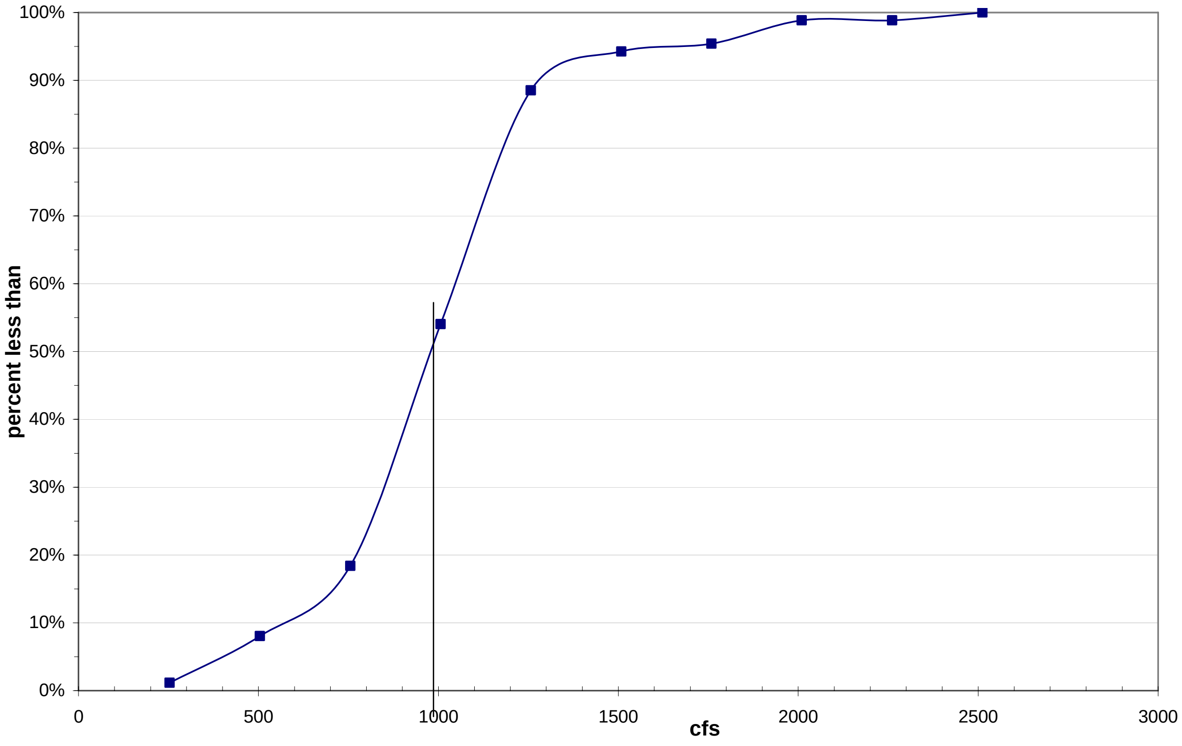


**Figure 65. Cumulative probability: Elephant Butte Dam gage (historical)**

However, the caveat mentioned in the Results section must be reiterated. The simulation results are not really comparable to conditions experienced in New Mexico over the past decade or 50 years, especially without trying to match the historical precipitation profile across the sub-basins. That information is not available. Also, simulation results cannot be used to predict conditions for any given year or span of years in the future. A more appropriate use of the simulation results is to describe a possible range of gage flows under the specified conditions. In this model, the climate scenarios represent a wider and possibly wetter range of underlying conditions than does the past 50 years.

Next the focus turns to analysis of the interaction between parameters of the model and their effect on gage flows. Figures 34 and 35 show simulated runoff over time for 4 climates for Reach 1 and Reach 5. These can be compared to Figures 36 and 37, which show simulated gage flows for the same climates and reaches. Visually comparing the Reach 1 runoff (Figure 34) and San Felipe gage flow (Figure 36), one can see a striking similarity in the patterns although the gage flows are roughly half the magnitude of the runoff volumes. In Reach 5, there is some similarity in pattern between Reach 5 runoff and San Marcial gage flow, but nowhere as striking as in Reach 1. This is probably because San Felipe is influenced by Reach 1 runoff and other parameters, while San Marcial is affected by runoff for Reaches 1 to 5 and all the parameters for those reaches. As mentioned previously, there is a one to one correlation between each reach's runoff and exit gage flow.

The next comparison is made between gage flows. Figures 38, 39 and 40 show gage flows for several climates. The year to year pattern is clearly maintained in each gage, showing a correlation between the gages. Also of interest, the drop between Cochiti Dam and Bernardo is large while there is minimal drop between Bernardo and San Marcial. Therefore, the model indicates that the majority of loss is occurring above Bernardo. These losses are primarily leakage and agricultural uses and losses.

The next set of figures show the impact of climate on the availability of water at Bernardo (Figures 41 – 44) and San Marcial (Figures 45 – 48). The Bernardo patterns for each climate grouping are nearly identical to the San Marcial patterns. Clearly, the same factors equally affect both gages although they are slightly magnified at San Marcial. Again, this downstream magnification is a result of accumulation of effects.

For both Bernardo and San Marcial, the gage flows for the variable dry climates (Figures 42 and 46) exhibits more year to year variability in gage flows than the consistent dry climates (Figures 41 and 45), as expected. Of course, variable is a relative term; all these flows are quite variable. However, as anticipated, consistent dry climates tend to produce lower gage flows over a longer period of time. Both variable and consistent dry climates have several periods have very low flow, but visually the consistent dry climates seem to present a worse scenario than the variable dry climates. It should be noted the gage flows for the very dry scenario are included on both consistent and variable charts as a reference. The very dry climate is the worst scenario of all.

In contrast, the variable and consistent wet climates' impact do not show the same difference between consistent and variable climates. They seem similarly variable. Comparing amplitudes, the wet consistent climates have some sharply dry extended periods early on. But the wet variable climates have more dry periods of the same magnitude although they tend to be briefer in duration. Comparing wet to dry, the dry consistent climates seem to present the worse case while the consistent wet climates are markedly higher in flow.

While these comparisons analyze the very important in-stream flow, there are other users in the Middle Rio Grande. The impact of climate on agriculture is expressed as an incidence of crop failure, shown in Table 23. Crop failure was not extensive and did not occur in many years. However, when it did occur, it occurred almost exclusively in Reach 5. This seems realistic in that downstream irrigators are more likely to get shorted on their water supply as upstream irrigators continue to maintain their full water use.

The rarity of crop failure may indicate that the model is reducing diversions more often than occurs in reality. Also, the model default is for a diversion of 7.2 AF per acre per year. Estimates of previous diversions have ranged from eight to 12 AF per acre (Papadopulos 2002). During calibration simulated flows were generally lower than historical, so an increase in the diversion rate did not appear to be needed.

These in-stream flows and agricultural uses are important, but there is another important user of water from the Middle Rio Grande: Texas. So the model attempts to simulate compliance with the Rio Grande Compact, which is legalistic and elaborate. Compliance begins with releases from Elephant Butte, as measured by Elephant Butte Dam gage and controlled by several "rules." The probability distribution analysis of the simulation results for Elephant Butte Dam gage suggests the rules and resulting releases may be fairly close to actual practices.

The releases from Elephant Butte are compared to the Compact scheduled deliveries to calculate annual credits and debits. These are shown in figures 49, 50 and 51 for the three climates that resulted in the best, average, and worst patterns of accrued credits/debits. The simulation of the average consistent climate created 38 years of accrued debit status and 18 years of annual debits. The best case, a simulation of the moderately dry and consistent climate, also had 18 years of annual debits. But they were interspersed with years of annual debits, balancing the accrual status. The average consistent climate simulation had sequential years of annual debits plus one year with a very large annual debit. The model caps annual debits at -200,000 plus changes in storage in Elephant Butte.

The model accumulates annual credits and debits in a level called accrual status in accordance with the Rio Grande Compact. However, Cochiti Reservoir is not included in the model so the accrual status may not be entirely accurate. Nonetheless, the accrual status is shown for all the climates (Figures 52 – 55) in the same climate groupings used earlier for the Bernardo and San Marcial figures. In contrast to the correlation of climate variability/consistency to the year to year variability of the Bernardo and San Marcial gage flows, the variable dry climates show much less year to year variability than the consistent dry climates. Also, the variable dry climates show much fewer years in accrued debit status, although the accrued credits are not as high as the consistent dry climates (when they exist).

Again the wet climates show little difference between variable and consistent scenarios. As with the variable dry climates, the variable wet climates show more years in accrued credit status, with higher credits. However, the average consistent scenario is abysmal in its accrual status, with 38 sequential years in accrued debit status and a maximum accrued debit of -833,144 AF. Historically, the greatest accrued debit since 1940 was -529,000 AF in 1956.

Comparing wet to dry, the model seems to manage compliance with the Compact quite optimistically across both wet and dry. However, with the exception of the average consistent climate, the wet climates clearly generate more years of accrual credit status and a greater magnitude of accrued credits.

Clearly, the optimistic compliance record of all these climates may not be realistic. The model computes releases in hindsight, in a sense, based on the year's total flow. It is as if releases were made once a year after all the inflows and outflows had been accounted for. Reality is far different with continual inflows, losses, and releases. Those who manage the releases must anticipate future conditions month to month and day to day. When flows are ample, this isn't a problem but dry years are challenging.

Also, there are the pressures to maintain volume in Elephant Butte for recreation, which is an economic mainstay for the surrounding region. The model uses a minimum capacity of only 300,000 AF, but the volume on 6 October 2005 was only 336,350 AF. Furthermore, the average December volume was only 193, 239 AF and the reservoir had dropped as low as 96,000 AF in September 2004 (USBR 2005).

Turning to the correlation results, the very dry climate simulation was used for the correlation analysis. The results were not surprising. Gage flows for each reach showed a positive 1 to 1 correlation with that reach's sub-basin runoff. The variability in runoff is completely mirrored in the gages. Table 25 shows correlation coefficients (r values) for other parameters. Total leakage showed virtually no correlation because it is modeled as a static value except for the limited changes from ground water pumping impacts.

Gage flows had no correlation with urban diversions, either, because the simulation was run with constant full use of San Juan-Chama water rights. Interestingly, total Albuquerque water use showed a faint negative correlation with gage flows (r = -0.20 with Albuquerque gage and r = -0.17 for San Marcial), even though there is no relationship between the two. A relationship only exists if total Albuquerque use drops below the San Juan-Chama water right. So this is simply a random effect.

Gage flows were moderately positively correlated with open water evaporation volumes, with r-values ranging from 0.66 (Reach 1 and San Felipe) to 0.92 (Reach 4 and San Acacia). The correlation in Reach 1 may have been lower because of the higher elevation and lower temperatures. The correlation of Reach 6 open water evaporation and Elephant Butte Dam gage is only 0.32. This low correlation results from the short stretch of river in Reach 6 compared to the surface area of the reservoir. Evaporation from the north reservoir was very highly correlated with the volume of Elephant Butte, with an r value of 0.97. The correlation between reservoir evaporation and Elephant Butte Dam gage dropped to 0.89, reflecting the anthropogenic controls on releases. The correlations are positive although the exit reach was used in the analysis, but this is not unexpected because the exit flows are partially based on the inflows which drive the evaporation equations. Although evaporation reduces flows and reservoir volumes, high flows and high volumes mean more surface area and more evaporation. Furthermore, this provides a partial picture of the correlation between river inflows and river outflows within a reach.

Irrigation diversions and gage flows showed some positive correlation, with r values ranging from 0.63 to 0.51. In this simulation, the diversion rate and acreage were held constant, so this correlation reflects changes to diversions based on low flow conditions. Agricultural uses and losses showed a further reduced but negative correlation. This reveals their impact on return flows to the river. Using a simulation where alfalfa acreage was gradually reduced to 75 percent of its original value (without replacement by another crop), irrigated acreage and gage flows show an r value of -0.10 to -0.20, again reflecting the impact of agricultural uses and losses on return flows.

Interestingly, the upper reaches' agricultural uses and losses show a very close negative correlation with the San Marcial gage flows in comparison to their correlation with their own exit gages. This means upstream uses and losses are propagating equally downstream and are not being mitigated by any inflows.

### *8.4 Effect of price and urban use on gage flows*

The model limits the use of San Juan-Chama water to residents of the city of Albuquerque in order to evaluate the possible effect of the price of water on diversions if Albuquerque and the surrounding area restricted its growth. Albuquerque already extends water to non-residents and intends to continue this. Since severe growth restriction is unlikely, Albuquerque will probably always divert the full 96,400 AF per year except in years of extended low flow conditions.

Nevertheless, the analysis is interesting. The price paths are shown in Figure 56. The conservation price path shows the changes to the annual increase in price that is necessary to achieve stated conservation goals. The first goal is 150 gallons per person per day by 2014 and the second is 130 gallons per person per day by 2040.

It should be noted that the effect of price is limited to the point where it drives per capita use lower than 75 gallons per day. As discussed previously, this is an achievable result in a city with a high degree of conservation measures in its homes and businesses. Lower per capita use than this may start to deeply affect quality of life.

As seen in Figure 57, by 2005, the effect of the conservation price path on total water use is steep at first, but the effect of the price increases is moderated by population pressures. This is because it was assumed Albuquerque could grow indefinitely. In a way, this approximates use of San Juan-Chama water by non-Albuquerque residents. In Figure 58, it can be seen that full use of the San Juan-Chama water is reduced almost immediately, in 2011, with a per capita use of 167 gallons. Population pressures intervene very quickly, though. The diversion reaches a low in 2014, when per capita use is 150 gallons. Full use of the San Juan-Chama water once again occurs in 2038 even though the per capita use is only 132 gallons at that point. And total use once again attains present day volumes in 2045.

The annual price increases were designed to reach different levels of per capita use by certain dates. The 2.5 percent annual increase is the most severe, affecting the San Juan Chama diversion as soon as 2011 with a per capita use of 168 gallons. The steep decline in total use continues until 2032, when per capita use reaches the lower limit of 75 gallons. After this, population pressure is no longer balanced by reductions in per capita usage.

Even this price increase may be too high to be accepted by residents although it offers a good reduction in use that is close to the conservation goals. The drop to 168 gallons per day by 2011 is a 16% decrease over the 2000 per capita use of 200 gallons per person per day but doesn’t meet the per capita use goal of 150 gallons by 2014. A combination of price increases and positive inducements may help residents achieve lower use goals.

If Albuquerque follows a path of combined price increases and positive rewards, the 1.5 percent annual increase could be an option. It causes per capita usage to reach the 75 gallon lower limit by the end of the model period, 2053. By itself, it does not immediately reduce use; instead there is a slight annual increase in the volume of total use, even though per capita use is declining. This is because the population is growing faster than the per capita use is dropping. Diversion of San Juan-Chama water is reduced beginning in 2030 (140 gallons per person per day) and does not rebound to full use within the model period.

Lastly, the 1.25 percent increase may be an easier option for citizens to accept. It allows total use to increase for a longer period of time if not balanced by other conservation measures. Total use is not reduced below the diversion volume until 2042, when per capita use drops to 127 gallons per person per day. There is no rebound and total per capita use reaches a low of 101 gallons.

The effect of these price changes can be seen on the downstream gages in Figures 59 – 62. The changes to the simulated flows were low, less than 70 cfs per year. As a result, the graphs show differences between flows at the different prices, instead of the actual flows themselves. As expected, the flows at Albuquerque rise in accordance with the price changes' effects on the San Juan-Chama diversion. For instance, the conservation price path shows an increase in the Albuquerque gage beginning in 2011. It reaches a peak increase of 10 cfs and then declines as the urban diversion increases.

However, flows at Bernardo decrease immediately in accordance with the drops in per capita use. For instance, by 2011, the conservation price path caused a decrease of 15 cfs in the annual Bernardo flow. This is due to the drop in per capita use, which determines the amount of sewered flow use, 50 percent of which typically becomes return flow. The Albuquerque wastewater return flow enters the river in Reach 3.

The drop at Bernardo is slightly moderated by the increase in the Albuquerque gage until 2014, the low point in San Juan Chama use under the conservation price path. Then once again, the Bernardo flow decreases, reaching a decline of 45 cfs by 2053. This is due to the declining per capita use. So the price doesn't affect the San Juan Chama diversion enough to offset the decrease in wastewater returns. Consequently, the conservation price path offers minimal benefit to Albuquerque and provides a slight detriment to downstream river flows. The decrease in Bernardo is passed straight through to San Acacia and San Marcial as seen in Figures 61 and 62, respectively.

The best option from the perspective of the river at Bernardo is the 2.5 percent annual price increase. Since it strongly affects total urban use and consequently the San Juan-Chama diversion, the Albuquerque gage sees a rise in flow that increases to 60 cfs. Bernardo and other downstream gages benefit from that increase, with the decline dropping to just under 8 cfs in 2032. However, per capita use reaches its limit in 2032 and thereafter population pressures drive up the San Juan-Chama diversion. Nevertheless, in 2053, the decline at Bernardo is only 32 cfs compared to a decline of 45 cfs under the conservation and 1.25 percent price paths.

Of course, these are actually very small drops in flow when compared to average flows at Bernardo of 904 cfs. On the other hand, the minimum annual flow that occurred at Bernardo was only 4 cfs for the very dry climate scenario and 64 cfs for the average consistent scenario (Table 22). These correspond to 60 cfs and 220 cfs for the Albuquerque gage, which can be used to approximate the flow levels at the diversion point. Given such low flows, it is highly probable the city will have curtailed or eliminated diversions and the impact at Bernardo will be ameliorated. However, this analysis highlights Albuquerque's reliance on wastewater return flows to offset its diversion of twice its San Juan-Chama right (48,200 AF per year or 65 cfs).

The diversion of 96,400 AF per year is based on a “credit” for return flows which typically have been 55,000 AF per year or 74 cfs. Fortunately for Albuquerque, increased demand due to population growth can offset the wastewater reduction. For instance, in 2008, when a 10 cfs reduction first occurs, wastewater flows are still approximately 60,000 AF. And the maximum Bernardo drop of 45 cfs, occurring in 2053, results from a wastewater flow of 69,355 AF per year. Thus, Albuquerque maintains its needed return flow credit (although pumping-induced leakage continues).

However, drops in per capita use may not be the only result of conservation measures, whether they are price driven or positive inducements. Decreases in the return flow rate will probably also occur, compounding the reduction in wastewater volumes. The simulations run for the 10 climate scenarios did not take this into account and instead incorporated full wastewater returns for the full period.

If greater decreases in wastewater return flows do occur, then legal implications may occur for Albuquerque. Albuquerque has not stated any plans to reduce diversions in accordance with reduced wastewater flows and this possibility is not mentioned in the environmental impact statement for the Albuquerque San Juan-Chama diversion.

## 9. CONCLUSION

Directly comparing the results to the past 50 years in New Mexico conditions is inappropriate, especially without trying to match the historical precipitation profile across the sub-basins. However, a probabilistic analysis can compare the distribution of simulation results to historical data to see if the model produces the same range of flows as history. This is valid if both the historical period and the model scenarios cover a wide variety of underlying conditions.

Generally, probabilistic analysis indicates the model may be optimistic in its estimation of river flows, although not in the year to year variability of those flows. Furthermore, although the model distribution did exhibit a slight skew towards lower flow values for most gages, the skew was nowhere as strong as the historical data. Thus, either the inflows are overestimated by the model, or the outflows are underestimated, or a combination of both. On the other hand, the model seems to represents the last 50 years fairly well in the upper reaches, but has difficulty in the lower reaches.

The disparity in flow values for the lower reaches was also seen during calibration, although the uncalibrated simulation results had the opposite disparity, underestimating flows for the 2000 to 2003 time period. This all suggests that perhaps the model was “over-calibrated” with too much reduction in various outflows, especially in the lower reaches. Also, diversion rates and irrigated acreage values might need adjustment. Interestingly, although the Elephant Butte Dam gage was not calibrated, the probability distribution was relatively close between simulation results and historical data.

Another issue is that most of the underlying system parameters are not definitively quantified. The model uses the current estimates, as modified by the calibration. So the overestimation of flow values may be a combined result of over-calibration, impaired understanding of the underlying parameters and processes in the lower reaches, and the use of climate scenarios that were too wet for the lower reaches in comparison to the last 50 years. Certainly, the model would benefit from refinement of our knowledge of conditions across the entire Middle Rio Grande and its contributing sub-basins.

Nevertheless, the model can provide useful information when comparing simulation results to each other. For instance, the year to year variability is very high and is clearly maintained from gage to gage. Also of interest, the decline in flow levels between Cochiti Dam and Bernardo is large while there is minimal drop between Bernardo and San Marcial. Therefore, the model indicates the majority of loss is occurring above Bernardo (not including evaporation at Elephant Butte) and there are little to no mitigating inflows below that point.

Not surprisingly, the very dry climate is the worst climate scenario, with a lowest average flow at San Marcial of 691 cfs. The scenario with the highest flows at San Marcial was the moderately wet and consistent climate with an average flow of 1053 cfs. However, when considering compliance with the Rio Grande Compact, the simulation results point toward the average consistent climate as the worst. The simulation of the average consistent climate created 38 years of accrued debit status and 18 years of annual debits. However, the other climates had an optimistic record of accrued credits and debits, although the wetter climates generated more years in accrued credit status than did the drier climates.

This can probably be partially attributed to the difficulty of modeling the intricate Compact accrual rules. Additionally, the model computes releases in hindsight, in a sense, based on the year's total flow. Reality is far different with continual inflows, losses, and releases.

Turning inward to the relationship between system components, the results of the correlation analysis seemed logical. Gage flows for each reach showed a positive 1 to 1 correlation with that reach's sub-basin runoff, meaning the variability in runoff is mirrored in the gages. Total leakage showed virtually no correlation because it is modeled as a static value except for the limited changes from ground water pumping impacts.

Open water evaporation was positively correlated to a moderate extent with gage flows, reflecting the influence of surface area on evaporation. For instance, evaporation from the north reservoir had almost a one to one correlation with the volume of Elephant Butte. A weaker and negative correlation was seen between gage flows and agricultural uses and losses. Also, the upper reaches' agricultural uses and losses showed a very similar negative correlation with the San Marcial gage flows, compared to their own exit gages. This means upstream agricultural uses and losses are propagating equally downstream and are not being mitigated by any inflows.

In addition to these analyses, the simulation results revealed the effects of the price of water by using an economic demand equation. Two assumptions are key; first, the city will reduce its diversion in accordance with the reduction in total demand and second, price alone will be used to meet conservation goals. Price paths were then created to achieve various per capita use values by different time frames.

The "conservation" price path was designed to meet Albuquerque's stated goals of 150 gallons per person per day by 2014 and 130 by 2040. This path and the 2.5 percent annual increase caused immediate reductions in the total demand volume and reductions in the San Juan-Chama diversion reduction by 2014.

However, the conservation price path leads to a rebound in the diversion, with full diversion once again occurring by 2038 even though per capita use was only 132 gallons per person per day. The 2.5 percent price path begins to rebound in 2032 when per capita use reaches the lower limit of 75 gallons per person per day.

More moderate price increases of 1.25 percent and 1.5 percent did not immediately reduce total demand volume because population-driven increases in demand outweighed the per-capita use-driven decreases. Eventually, the reduction in demand was able to reduce the San Juan-Chama diversion, occurring in 2042 and 2030, respectively. No rebound occurred and per capita use reached a low of 75 and 101 gallons per person per day by 2053.

If maximum reduction of the San Juan-Chama diversion by 2053 was a goal, the best price choice is either the 1.5 percent or 2.5 percent annual price. These two converge in 2053 with the San Juan-Chama diversion at almost 62,000 AF per year, with per capita use of 75 gallons per person per day.

While reduction of the San Juan-Chama diversion leads to rises in the surface water flow at the Albuquerque gage, declines in per capita use result in a decrease in the flow at the Bernardo gage. The drop is caused by declines in wastewater return flows which enter the river before Bernardo. The simulated drop in the Bernardo gage flow is small, less than an annual average of 45 cfs at its maximum. This is within the two lowest occurring annual Bernardo flows of 4 and 64 cfs. While the conservation-induced Bernardo drop is within the minimum occurring flows, Albuquerque has agreed to reduce or eliminate the San Juan-Chama diversion when flows become very low. So reducing the diversion would ameliorate the reduction in wastewater returns in these low flow circumstances.

Is it possible that reductions in wastewater returns could conceivably pose a legal problem for Albuquerque sometime in the future? Albuquerque’s diversion of twice its water right (48,200 AF per year) is based on a “credit” for return flows which typically are 55,000 AF per year. Thus, wastewater flows should not fall below 48,200 AF or roughly 67 cfs. This is unlikely, given the pressures of population growth, which will offset the decrease caused by a fall in per capita use. However, non-price conservation measures may drop the return flow rate, even further reducing the wastewater return flows.

In conclusion, although the model does not produce simulation results with a distribution similar to the past 50 years, it provides an interesting platform for exploring the relative impact of management alternatives. So the model should not be used to predict conditions for any particular year or time frame. Instead, a more appropriate use of the simulation results is to describe a possible range of gage flows under the specified conditions. In this model, the climate scenarios represent a wider and possibly wetter range of underlying conditions than the past 50 years.

Furthermore, although the distribution of simulation results is different from the recent record, the averages are not as far apart.  This makes it clear that “average” is a dangerous word for the Middle Rio Grande and may misrepresent future climates and river flows.

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