Stochastic Hydrologic Analysis of the Upper Rio Grande Surface Water System in New Mexico

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1. Abstract

Climatic trends and statistics from 604 years (1400-2003) of tree ring data from the southwestern United States was used to generate 1000 synthetic hydrologic sequences for analysis with a monthly timestep hydrologic model of the Upper Rio Grande system in New Mexico. Results from the analysis suggest that if future climate is similar to long term historic trends, decreased streamflows and significant reductions in reservoir storage compared to historic records can be expected throughout the system. Results also suggest that although New Mexico should be able to meet downstream delivery obligations to Texas, Article VII of the Rio Grande Compact will severely limit options for storage of native water in reservoirs upstream of Elephant Butte in a majority of future years. In combination, these results suggest that New Mexico's ability to relinquish a given amount of compact credit in exchange for the right to store that amount of native water upstream during Article VII conditions may be an important tool for the State in the future. The analysis does not currently take into account effects of future population growth or temperature rise, but provides the framework for stochastic analysis of hydrologic policy options in the basin.

2. Introduction

Managing water resources in the Upper Rio Grande basin requires an understanding of both the uncertainties associated with the timing and magnitude of renewable water supplies, and the operational flexibilities of infrastructure capable of storing and moving the water. A very complex numerical representation of the operational capabilities of the system has been developed in the form of the Upper Rio Grande Water Operations Model (URGWOM), a daily timestep reservoir operation and river routing model developed in Riverware (USACE et al 2002). State of the art techniques have also been developed to generate suites of synthetic climate sequences based on both long term climate records, and shorter term directly observed stream flow data. This report outlines an approach that brings together the variability of the natural inflow and the mathematical description of flow through the surface water system in order to estimate the range of outputs expected from stressing the physical and management system with the full range of climate inputs suggested by hundreds of years of tree ring data.

3. Methods

3.1. Generation of synthetic sequences:

In developing stochastic analysis capabilities for the Upper Rio Grande Basin, the first step was generation of synthetic sequences of flow years from the observed record whose overall statistics were based on longer term climatic trends from available tree ring records. This analysis was carried out by AMEC Earth and Environmental in Boulder Colorado (AMEC) and included correlation of paleo records to Rio Grande Hydrology, generation of a transient climate state transition probability matrix, and climate sequence generation, and finally hydrologic sequence generation. Each of these steps is explained briefly here.

3.1.1. Correlation of tree ring records to Rio Grande hydrology:

A ½ degree gridded Palmer Drought Severity Index (PDSI) was reconstructed from tree ring data by Clark et al (2004). From this data set, AMEC chose a single grid cell in which the reconstructed PDSI correlated most closely to the OIS for the period 1940-2003 which is the period of overlap for the two data sets. This ½ degree grid cell is centered at latitude 37.5N, and longitude 110.0W, and encompasses area in Utah, Colorado, Arizona, and New Mexico. 604 years (1400-2003) of this reconstructed PDSI timeseries were then classified as either wet or dry, with the definition of wet and dry selected so that approximately half of the years fell in each class.

3.1.2. Transient climate state transition probability matrix:

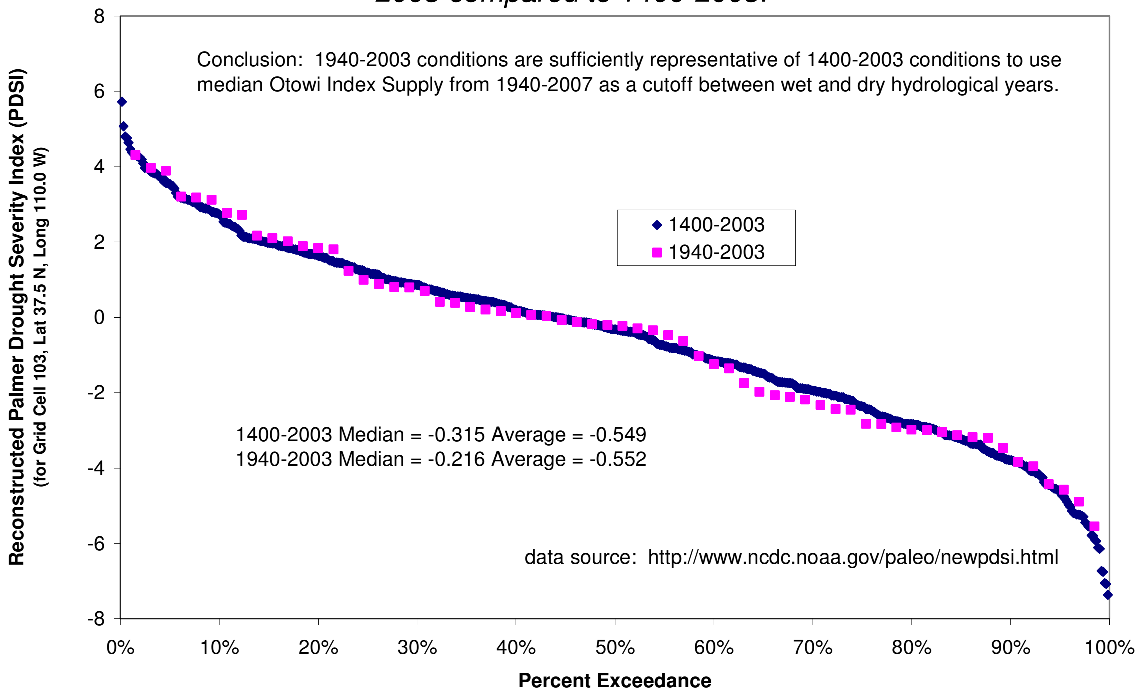
Next, the observed state of the system (wet or dry) through time was used to generate a transient two state transition probability matrix. A two state transition probability matrix gives the likelihood of moving from a wet year to a dry year, a wet year to a wet year, a dry year to a dry year, or a dry year to a wet year from one year to the next. A transient transition probability matrix then changes through time. So, for example, the analysis suggests that a dry year was less likely to be followed by a dry year early in the 19th century than later that same century. This approach is used so that climate cycles may be captured in the synthetic sequences, rather than relying on long term averages alone.

3.1.3. Synthetic climate and hydrology sequences:

Once the transient transition probability matrix was developed, 1000, 100 year long synthetic climate sequences were generated by selecting at random an initial state (wet or dry), and moving through a randomly selected 100 year window of the transient transition probability matrix one year at a time, randomly generating either a wet or a dry climatic state based on the previous year state and the transition probability matrix that year. The final step in the generation of synthetic hydrologic sequences was to replace wet and dry climatic years with wet and dry years from the observed record, effectively going from a synthetic climatic sequence to a synthetic hydrologic sequence. This final step was accomplished by specifying the smallest 50% of the 1940-2007 annual Otowi Index Supply (OIS) values as occurring in “dry” years, and the rest as occurring in “wet” years. The implicit assumption in this step is that 1940-2007 climate was representative of

1400-2003 climate, and thus 1940-2007 hydrology can be used to generate sequences representative of expected 1400-2003 hydrology. This assumption was checked after the fact by comparing the exceedance probability[1] of the 1940-2003 subset of tree ring data to the overall 1400-2003 dataset. This comparison is shown in Figure 3-1 below, and suggests that 1940-2003 climate patterns were representative of 1400-2003 climate patterns.

Figure 3-1: Cumulative Exceedance Distribution for Reconstructed PDSI Data 1940-2003 compared to 1400-2003.



In transitioning from one historic year to another, transitions from similar years in the observed record were favored, again retaining some of the year to year transition properties that have been observed historically. So if the year 1977 ("dry", 297 kAF OIS) was the last year selected, and the climate sequence called for another dry year, than "dry" years that followed a year similar to 1977 would be the most likely selections for the next year in the sequence. This selection process is referred to as a conditional K-nearest neighbor (K-nn) bootstrap selection, and is designed to maintain historically observed transition magnitudes. As a result of the K-nn bootstrap approach, in many of the sequences, historic years appear in sequential order. The combination of a transient transition probability matrix and a K-nn bootstrap approach was introduced by Prairie et al (2008) for stochastic analysis of the Colorado River at Lees Ferry, and is designed to take advantage of the strengths of both long term paleoreconstructed data, and the observed hydrologic records to generate synthetic sequences. Using this approach AMEC Earth and Environmental delivered 1000, 100 year sequences of historic years

[1] Exceedance probability is estimated by calculating the percent of observations greater in magnitude than a given data point.

between 1950 and 2004 as synthetic sequences representative of long term climate variability in New Mexico's Rio Grande Basin. The reader is referred to the technical memo from AMEC to Dr. Nabil Shafike of the New Mexico Interstate Stream Commission dated June 24, 2008 (Gangopadhyay and Harding, 2008) for additional details on the methods used to generate the synthetic sequences.

3.2. Extension of model inputs back to 1950

In order to increase the number of years in the observed record from which to sample, the model inputs for the monthly timestep URGWOM model developed by Sandia National Laboratories in Powersim Studio (monthly model) (Roach 2007), were expanded back in time to include 1950-1974 years in addition to the 1975-2004 historic period already contained in the model. The monthly model is driven by gaged streamflow data and observed climate data, each of which was extended back to 1950.

3.2.1. Extension of streamflow data back to 1950

Input hydrographs for gage locations shown in Table 3-1 were provided by the USGS from 1950 forward, with missing data filled in based on correlations to nearby gages. Refer to Engdahl et al (2008) for details on this process.

Table 3-1. Stream flow gages for which values from 1950-2004 are used to drive inputs to the monthly model. Correlation methods were used to fill in missing data from 1950-2007 to ensure a complete 1950-2007 monthly time series for each gage.

Gage	USGS Gage#	URL: http:// +
Rio Grande near Lobatos	NA	www.dwr.state.co.us/surfacewater/data/detail_graph.aspx?ID=RIOLOBCO
Costilla Creek near Garcia	8261000	waterdata.usgs.gov/nwis/nwisman/?site_no=08261000
Red River below Fish Hatchery	8266820	waterdata.usgs.gov/nwis/nwisman/?site_no=08266820
Rio Pblo de Taos blw Los Cordovas	8276300	waterdata.usgs.gov/nwis/nwisman/?site_no=08276300
Embudo Creek at Dixon	8279000	waterdata.usgs.gov/nwis/nwisman/?site_no=08279000
Rio Chama near La Puente	8284100	waterdata.usgs.gov/nwis/nwisman/?site_no=08284100
Rio Ojo Caliente at La Madera	8289000	waterdata.usgs.gov/nwis/nwisman/?site_no=08289000
Rio Nambe below Nambe Falls Dam	8294210	waterdata.usgs.gov/nwis/nwisman/?site_no=08294210
Santa Fe River above Cochiti	8317200	waterdata.usgs.gov/nwis/nwisman/?site_no=08317200
Galisteo Creek Below Galisteo Dam	8317950	waterdata.usgs.gov/nwis/nwisman/?site_no=08317950
Jemez River near Jemez	8324000	waterdata.usgs.gov/nwis/nwisman/?site_no=08324000
N. Floodway Channel near Alameda	8329900	waterdata.usgs.gov/nwis/nwisman/?site_no=08329900
Tijeras Arroyo near Albuquerque	8330600	waterdata.usgs.gov/nwis/nwisman/?site_no=08330600
S. Div. Channel above Tijeras Arroyo	8330775	waterdata.usgs.gov/nwis/nwisman/?site_no=08330775
Rio Puerco near Bernardo	8353000	waterdata.usgs.gov/nwis/nwisman/?site_no=08353000

Flows in the Rio Blanco, Little Navajo River, and Navajo River above the San Juan-Chama diversion locations were based on published estimates for 1950-1971 and gage and operation information from 1971-2004 (USDoI-BoR 1989 and Boroughs 2009). Following San Juan-Chama project operational rules, the model uses flows at these three locations, minimum bypass requirements, conveyance and storage capacities, and legal diversion limits to calculate San Juan-Chama project diversions at each model timestep.

3.2.2. Extension of climate data back to 1950

The monthly model uses methods from the ET Toolbox (Brower 2004) to estimate reference evapotranspiration (ET) and crop coefficients on a monthly basis from 1975 forward based on average monthly temperature, average monthly minimum temperature, average monthly maximum temperature, average monthly relative humidity, average monthly windspeed, and average monthly solar radiation climate inputs (Roach, 2007). Those inputs were based on a limited number of climate stations, especially from 1975-1985, and as a result, it was decided that attempts to extend all input data fields back to 1950 would not be practical. Long term climate estimates for temperature fields do exist, so the strategy pursued was to extend the temperature fields back to 1950 and use a reference ET model dependent on temperature only. In addition to reference ET and crop coefficients, historic precipitation measurements are used in the monthly model to drive inflows to reservoirs (Roach, 2007).

Spatially gridded monthly average temperature and cumulative precipitation estimates from 1950 or before forward are available from at least two sources: PRISM (http://mole.nacse.org/prism/nn/), and Green Data Oasis (http://www.agu.org/eos_elec/2007/47-504.html). Of these, PRISM was selected for use for three reasons:

1. PRISM data goes back further in time (1895 vs 1950), which may allow a sampling of a larger number of historic years.
2. The Hargreaves equation, which according to Shuttleworth (1993) is the best available temperature (only) dependent estimate of reference evapotranspiration (ET), requires both monthly maximum and minimum temperature fields. PRISM has estimates of monthly average maximum, minimum and mean temperatures, while the Green Data Oasis data set includes only monthly mean temperature estimates.
3. PRISM data is available at a spatial resolution of 1/24 degree grid cells, or about 4km on a side, while the Green Data Oasis data set is available at a spatial resolution of 1/8 degree, or about 12km on a side.

Next, the temperature and precipitation data was sampled at gage locations using the PRISM Data Explorer (http://mole.nacse.org/prism/nn/). Those locations are shown in Table 3-2 below. Next, the temperature, and latitude values at the beginning and end gage locations were averaged for each of the 17 reach's to come up with a representative reach value for each month. The precipitation value for the gage location below each of the seven modeled reservoirs was used as the monthly value for that reservoir.

3.3. Hydrologic Model Setup

Once the needed input data had been processed to allow the monthly timestep hydrologic model of the Upper Rio Grande system (Roach 2007) to sample data from 1950 forward, the model was ready to run hundreds of times to evaluate the range of outputs expected from a range of likely (according to historic patterns) climate scenarios. The model was calibrated from 1975-1999, and validated from 2000-2004 as described in Roach 2007. Scenario runs of 100 years start on January 1, 2005. Initial conditions and baseline scenario options were defined and held constant for each batch of model runs so that the range of outcomes for a given set of runs would be dependent on climate variability only.

Table 3-2: Gage locations that define the beginning and end point of the reaches and the approximate location of the seven modeled reservoirs in the monthly model.

Gage Name	USGS Gage#	Lat	Long	Reach Beginning	Reach End	Reservoir
Rio Grande near Lobatos	CoDWR	37.079	-105.756	Lobatos to Cerro		
Rio Grande near Cerro	8263500	36.740	-105.683	Cerro to Taos Bridge	Lobatos to Cerro	
Rio Grande below Taos Junction Bridge	8276500	36.320	-105.754	Taos Bridge to Embudo	Cerro to Taos Bridge	
Rio Grande at Embudo	8279500	36.206	-105.964	Embudo to Otowi	Taos Bridge to Embudo	
Rio Grande at Otowi	8313000	35.874	-106.142	Otowi to Cochiti	Embudo to Otowi	
Rio Grande below Cochiti	8317400	35.618	-106.324	Cochiti to San Felipe	Otowi to Cochiti	Cochiti
Rio Grande at San Felipe	8319000	35.444	-106.439	San Felipe to Albuquerque	Cochiti to San Felipe	
Rio Grande at Albuquerque	8330000	35.089	-106.680	Albuquerque to Bernardo	San Felipe to Albuquerque	
Rio Grande Floodway near Bernardo	8332010	34.417	-106.800	Bernardo to San Acacia	Albuquerque to Bernardo	
Rio Grande Floodway at San Acacia	8354900	34.256	-106.891	San Acacia to San Marcial	Bernardo to San Acacia	
Rio Grande Floodway at San Marcial	8358400	33.681	-106.992	San Marcial to Elephant Butte	San Acacia to San Marcial	
Rio Grande below Elephant Butte Dam	8361000	33.146	-107.206	Elephant Butte to Caballo	San Marcial to Elephant Butte	Elephant Butte
Rio Grande below Caballo Dam	8362500	32.893	-107.292		Elephant Butte to Caballo	Caballo
Azotea tunnel at outlet near Chama	8284160	36.853	-106.672	Chama: Willow Creek to Heron		
Willow Creek below Heron	8284520	36.666	-106.704	Chama: Heron to El Vado	Chama: Willow Creek to Heron	Heron
Rio Chama below El Vado	8285500	36.580	-106.724	Chama: El Vado to Abiquiu	Chama: Heron to El Vado	El Vado
Rio Chama below Abiquiu Dam	8287000	36.237	-106.416	Chama: Abiquiu to Chamita	Chama: El Vado to Abiquiu	Abiquiu
Rio Chama near Chamita	8290000	36.073	-106.109		Chama: Abiquiu to Chamita	
Jemez River near Jemez	8324000	35.662	-106.743	Jemez: Pueblo to Canyon Dam		
Jemez River below Jemez Canyon Dam	8329000	35.390	-106.534		Jemez: Pueblo to Canyon Dam	Jemez

3.3.1. Initial Conditions:

Initial conditions are necessary for any of the variables whose values at any given timestep is dependent on the value at the previous timestep. Such variables include reservoir volumes, aquifer volumes, and the New Mexico Rio Grande Compact Balance. Initial values for these variables were set to measured values on January 1, 2005 for reservoir volumes and Compact Balance, and best estimated volume on January 1, 2005 for the aquifers of the Espanola, Albuquerque, and Socorro groundwater basins. It is important to note that the overall outcomes of a one hundred year run will be fairly insensitive to the initial conditions chosen for the surface water system (starting reservoir volumes and Compact Balance), and for the groundwater system (starting aquifer volumes) within a reasonable range.

3.3.2. Baseline Scenario Inputs:

The monthly timestep hydrologic model of the Upper Rio Grande system (Roach 2007) is set up to allow user inputs to evaluate human demand and management related variables. A set of baseline scenario inputs was defined for initial stochastic runs of the model. Baseline demands were fixed at 1999 or 2000 levels as follows:

- Municipal and Industrial demand: Based on population and per capita usage fixed at 2000 levels.
- Agricultural demand: Based on fixed 1999 crop area.
- Riparian demand: Based on fixed 1999 vegetation area.

Other important scenario related inputs defined as baseline included 2008 as the year that Albuquerque starts to divert San Juan Chama (SJC) water directly from the Rio Grande for domestic use, and the rules used to govern reservoir operations summarized below.

3.3.3. Baseline Reservoir Operations:

3.3.3.1. <u>Heron Reservoir Release Rules</u>

Heron Reservoir is operated by the United States Bureau of Reclamation to store San Juan Chama (SJC) water diverted from the Colorado river basin into the Rio Grande Basin for use by entities with contracts to the water. There are currently 17 contractors with rights to almost all 96,200 AF of annual allocation of SJC water (USDoI-BoR 2006). For simplicity, the URGWOM planning run and the monthly model consider three of the contractors specifically: the City of Albuquerque, with annual rights to 48,200 AF; the MRGCD, with annual rights to 20,900 AF; and the Cochiti Recreation Pool, with annual rights up to 5,000 AF. All other contractors are lumped into a "combined" contractor account with annual rights to 21,100 AF. The final 1,000 AF is unallocated water reserved for future Native American water rights settlements and not considered in the model. In April of each year, the contractor allocation of SJC water in Heron available for use in that year is set to the annual right. Any amount not used by the end of the next March, reverts to the general pool from which the allocations are reset in April. In the model, the contractors try to move all water out of Heron for which they have a need or storage available downstream by the end of February. In practice, to avoid dramatic releases of unused contractor water from Heron before the allocations are reset, there is some flexibility in release date granted to the contractors to allow releases of the previous year's water in the first few months of the next year. These storage date "waivers" are not currently modeled.

In simple terms then, Heron is modeled to pass through all native water, and release SJC water based on modeled requests from contractors up to their annual allocation. The legal framework of SJC operations mean that evaporative losses are not charged to a given contractor, so the annual allocation of water is available to the contractor at any time in the year. In other reservoirs where the contractors may be allowed to store SJC water, the water is subject to evaporative losses. The result of this is that contractors are assumed to prefer to leave their allocation of water in Heron until they have use for it downstream, only moving it into downstream storage to avoid losing the water to the general pool in April.

In recent years, the Bureau of Reclamation (BoR) has leased water from other contractors for use in meeting minimum downstream flows for the benefit of endangered species. This possibility is covered in the model by allowing up to 8000 AF/yr of "combined" contractor water, if it is still in storage in Heron at the end of February, to be transferred to a Bureau of Reclamation account. This amount is based on what BoR thinks can be obtained in the near future (Marc Sidlow, USACE personal communication 2006), and can be changed by the model user. Abiquiu is the only reservoir in the model which allows storage of water by BoR, so any water obtained by BoR in Heron in February must be moved to Abiquiu for storage in March, or it is lost to BoR when all accounts in Heron are reset in April. BoR water (or native conservation storage water if that option is selected by the model user) is used to meet minimum flow targets as shown in Table 3-3 below. Year type is calculated by the model at the beginning of April, based on January through March flows at La Puente on the Chama, and Embudo on the Rio Grande, and the designation is kept until the next April. Article VI and VII conditions are calculated by the model based on New Mexico's Rio Grande Compact balance, and specific reservoir storage information.

Table 3-3. Target flow information.

Year type	Target Location	Minimum Flow
Dry (or Article VI or VII)	Central Bridge	100 cfs
Average	Below Isleta Diversion	100 cfs
Wet	Below Isleta Diversion	150 cfs

3.3.3.2. El Vado Reservoir Release Rules

El Vado Reservoir is operated by the Middle Rio Grande Conservancy District (MRGCD) primarily to store native spring runoff to augment irrigation supplies later in the season when natural flows are low. The priority of surface water rights in New Mexico, as in most of the west is determined by the date of first beneficial use (e.g. Clark 1987). As a result, the native rights in the Rio Grande are the most senior in the basin, superseding all other rights and claims. The irrigation served by the MRGCD includes almost 9000 acres of native American lands with rights that are prior and paramount to all other irrigation rights[2]. Article VII of the Rio Grande compact prohibits additions to non prior and paramount native storage in El Vado if the total project water[3] stored in Elephant Butte and Caballo is less than 400,000 AF. MRGCD can also store its SJC water in El Vado, and lease space for storage of SJC water to other contractors. For modeling purposes, when irrigation demands below Cochiti are satisfied by Rio Grande flows, El Vado is operated to capture all native inflows that are physically and legally allowed, less a minimum release to irrigate approximately 5000 acres of agricultural lands along the Chama. If Rio Grande flows are not sufficient to cover irrigation demands below Cochiti, native water is released from El Vado if available to satisfy those demands. Irrigation demands below Cochiti are taken from Table 3-4 below as a default, though the user can choose to have the irrigation demands calculated based on crop type, area, and reference evapotranspiration instead. If native water is insufficient, MRGCD-owned SJC water is released, and when that is gone also MRGCD calls for SJC releases directly from Heron Reservoir. Any MRGCD SJC allocation remaining in Heron at the end of the year is moved to El Vado. All releases of SJC water from Heron not intended for storage in El Vado are passed through. Combined SJC contractor storage in El Vado is allowed as a user input to the model.

Table 3-4. Assumed Irrigation Demand (AF/mo) Cochiti to Elephant Butte. From URGWOM daily timestep planning model.

Feb	595	Mar	26380	Apr	41157
May	46215	Jun	49289	Jul	52264
Aug	50380	Sep	42843	Oct	31140

3.3.3.3. <u>Abiquiu Reservoir Release Rules</u>

Abiquiu Reservoir is operated by the United States Army Corps of Engineers (USACE) primarily as a flood control reservoir, though storage of SJC water, primarily by Albuquerque, has become a significant part of operations. Native water is stored in Abiquiu only temporarily to prevent flows downstream from exceeding 1,800 cfs, 3,000 cfs, and 10,000 cfs, below the reservoir, at the confluence with the Ojo Caliente, and at the confluence with the Rio Grande respectively. Stored native flood water is released as quickly as possible within the maximum flows listed above, with one exception called carryover storage. To ensure that flood waters that would have been largely unused had they not been stored are not used to supplement irrigation, if flows in the Rio Grande at Otowi are less than 1,500 cfs at any point after July 1 in an irrigation season, then any flood water stored during that irrigation season is delivered downstream after the irrigation season is over. For modeling purposes, native water is not stored except for

[2] As a rule of thumb, each acre of irrigated agriculture requires 3 feet of water per year, or 3 acre feet per acre.

[3] Project water in Elephant Butte and Caballo is all water in the reservoirs, less any SJC water in Elephant Butte for recreation pool purposes, and less any credit water from New Mexico or Colorado deliveries to Elephant Butte in excess of legal requirements. It is basically required delivery water from New Mexico.

flood control purposes, and released downstream as soon as possible within the constraints of carryover storage. There is some discussion of native water storage at Abiquiu for stream augmentation purposes in the future, and this option is allowed as a user input. As a default, the model allows Albuquerque, MRGCD, the combined contractor, and BoR to store 130,000 AF, 2,000 AF, 11,000 AF, and 50,000 AF respectively in Abiquiu based on URGWOM values (Marc Sidlow, USACE personal communication 2006). This storage space is used by the contractors as available to avoid losses of allocated water in Heron at the beginning of each new year, and vacated first by the contractors when there is need for it downstream. The user can also select an option for more flexible use of that storage space which essentially gives Albuquerque the right to store up to 130,000 AF, but the combined or BoR accounts to use any of the space that Albuquerque is not using.

3.3.3.4. Cochiti Reservoir Release Rules

Cochiti Reservoir, like Abiquiu upstream, is operated by the USACE primarily as a flood control reservoir. The only native storage allowed in Cochiti is native flood control storage to limit Rio Grande flows between Cochiti and Elephant Butte reservoirs to a maximum of 7,000 cfs. This storage is temporary and evacuated as quickly as possible subject to the same carryover storage requirements described for Abiquiu reservoir above. The only SJC storage allowed in Cochiti is that amount necessary to maintain approximately 1,200 acres of reservoir area for recreation purposes. The 5,000 AF/yr SJC allocation to the Cochiti Recreation Pool is used to offset evaporative losses to the recreation pool in Cochiti. Additional storage is disallowed in Cochiti in part because large storage volumes in the reservoir lead to high leakage with adverse consequences to agricultural lands downstream of the dam (e.g., Smith 2001).

3.3.3.5. Jemez Reservoir Release Rules

Jemez Reservoir, like Abiquiu and Cochiti, is operated by the USACE primarily for flood control. The reservoir also acts as a sediment barrier to prevent sediment from discharging to the Rio Grande. For model purposes, the only storage allowed in Jemez is native flood control to aid Cochiti in maintaining Rio Grande flows between Cochiti and Elephant Butte from exceeding 7,000 cfs. Flood storage in Jemez is subject to the same carryover storage requirements described for Abiquiu reservoir above.

3.3.3.6. Elephant Butte Reservoir Release Rules

Elephant Butte Reservoir is operated by the Elephant Butte Irrigation District (EBID) to store water delivered from New Mexico to Texas under the requirements of the Rio Grande compact. The water is released for irrigation in southern New Mexico and western Texas. The water released from Elephant Butte (and then Caballo) is consumed outside of the model boundary according to rules not included in the model. Elephant

Butte reservoir rules are limited to flood control and a target release table. The available water up to the target value is released for each month. Available water includes water in the reservoir less SJC and New Mexico or Colorado credit water. The model release targets from Elephant Butte by month are shown in Table 3-5 below.

Table 3-5. Target releases used for Elephant Butte and Caballo reservoirs during scenario evaluation.

	Elephant Butte [AF]	**Caballo [AF]**
January	23600	7500
February	52100	28100
March	82700	109100
April	102700	89500
May	122800	101800
June	133000	128900
July	117500	135100
August	81000	107400
September	42100	67100
October	14600	15500
November	6600	0
December	18300	0
Total	797000	790000

3.3.3.7. Caballo Reservoir Release Rules

Caballo Reservoir, like the larger Elephant Butte just upstream, is also operated by EBID. Caballo serves largely as additional storage to moderate releases from Elephant Butte and add flexibility to EBID operations. There are no irrigation diversions between Elephant Butte and Caballo, and Caballo serves as an extension of and reregulation dam for the larger Elephant Butte Reservoir. Release targets used in the model for Caballo Reservoir are shown in Table 3-5.

4. Results:

Study results include analysis from the development and processing of climatic data from 1950-1975, analysis of the effects of a Hargreaves based Reference ET estimate for 1950-1974 compared to the use of a modified Penman Monteith based Reference ET calculation for 1975-2004, the development and processing of stream flow data from 1950-1975, and model results.

4.1. Precipitation Input Data Results and Analysis:

In order to gain some confidence in the PRISM derived precipitation value for 1950-1974, 1975-2005 PRISM precipitation values for each reservoir as described above were compared with the values already used in the monthly model for the same time period. Sources of the monthly model data for reservoir precipitation 1975-2005 are shown in Table 4-1 below.

Table 4-1. Historic reservoir precipitation data used in the monthly model.

Reservoir	1975-2005 monthly model primary data source
Heron	URGWOM start up data files
El Vado	El Vado measurements National Weather Service Cooperative (COOP) station http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmelva
Abiquiu	Abiquiu measurements National Weather Service Cooperative (COOP) station http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmabiq
Cochiti	Cochiti measurements National Weather Service Cooperative (COOP) station http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmcoch
Jemez	Cochiti measurements
Elephant Butte	Elephant Butte measurements National Weather Service Cooperative (COOP) station http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmelep
Caballo	Caballo measurements: National Weather Service Cooperative (COOP) station http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmcaba

According to the PRISM documentation, "Point estimates of monthly precipitation originated from the following sources: National Weather Service Cooperative (COOP) stations, 2) Natural Resources Conservation Service (NRCS) SNOTEL, 3) local networks, and 4) statistically in-filled missing monthly data to produce a serially complete station data set, generated by the National Center for Atmospheric Research (NCAR)" (http://prism.oregonstate.edu/docs/meta/ppt_103yr.htm#1). There was excellent agreement (R^2 of best fit line through origin > 0.95) between the data sets at El Vado, Abiquiu, and Cochiti, good agreement ($0.75 < R^2 <0.95$) at Heron and Caballo, and poor agreement ($R^2 < 0.55$) at Jemez and Elephant Butte as shown in Figures 4-1 through 4-7. The poor agreement at Jemez Canyon Dam is probably because the monthly model used Cochiti as a proxy for 1975-2004 precipitation. There is a National Weather

Figure 4-1: Comparison of PRISM and ETToolbox precipitation estimates for Heron Reservoir 1975-2005.

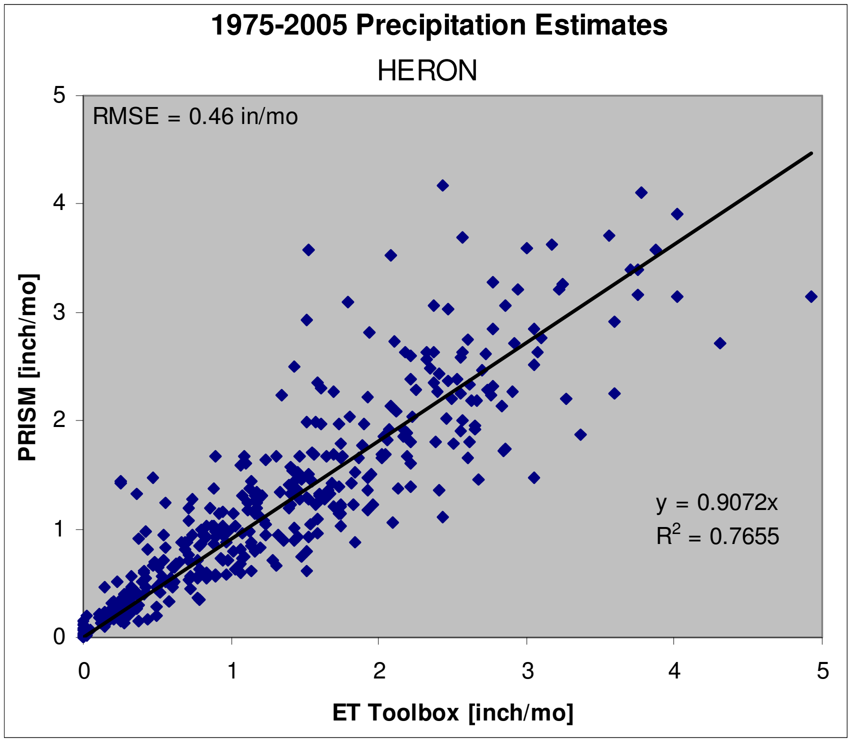


Figure 4-2: Comparison of PRISM and ETToolbox precipitation estimates for El Vado Reservoir 1975-2005.

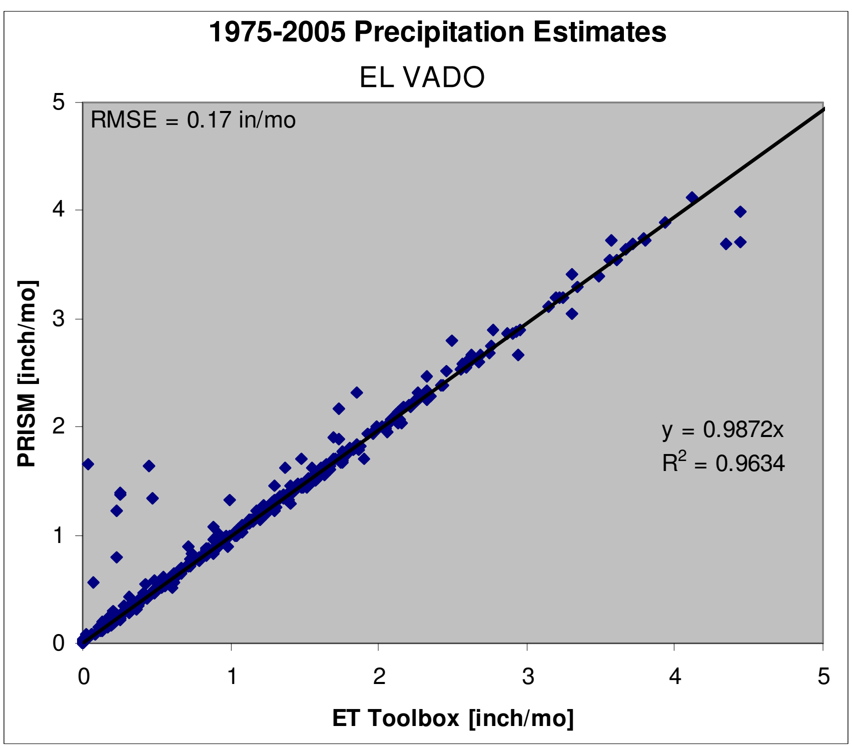


Figure 4-3: Comparison of PRISM and ETToolbox precipitation estimates for Abiquiu Reservoir 1975-2005.

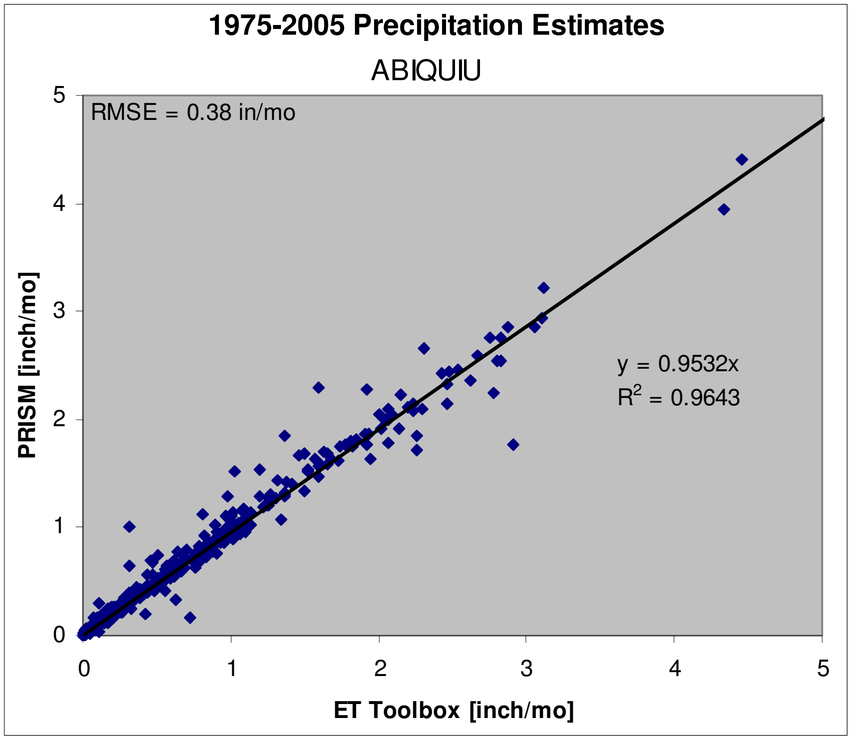


Figure 4-4: Comparison of PRISM and ETToolbox precipitation estimates for Cochiti Reservoir 1975-2005.

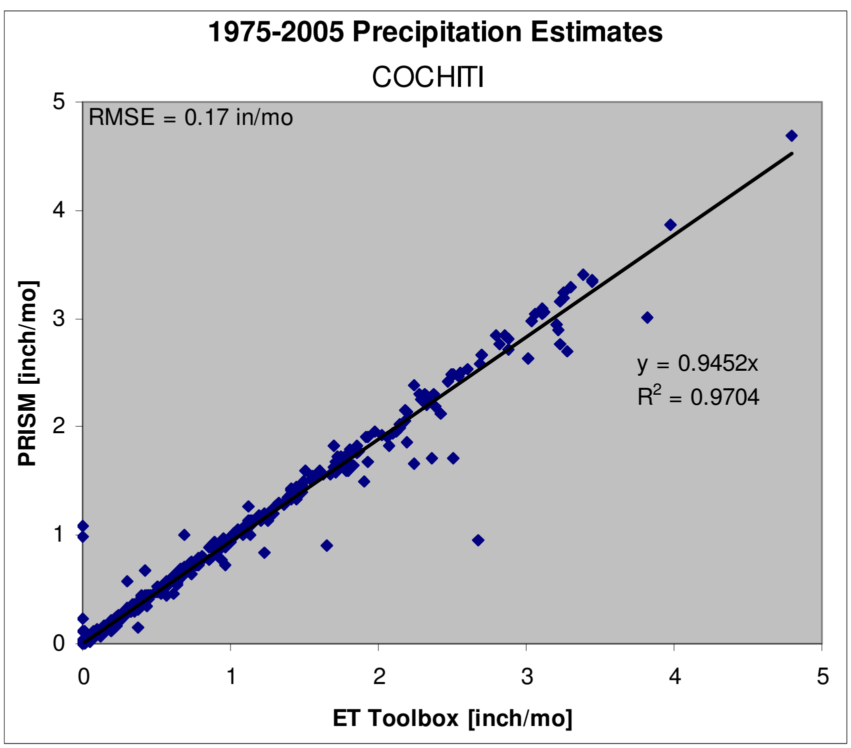


Figure 4-5: Comparison of PRISM and ETToolbox precipitation estimates for Jemez Canyon Dam 1975-2005.

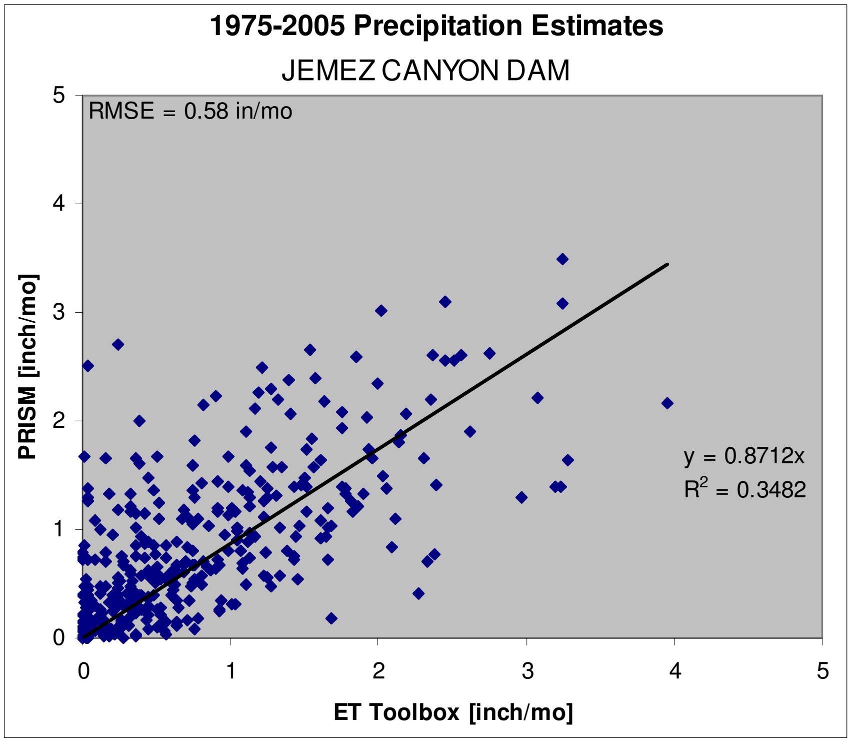


Figure 4-6: Comparison of PRISM and ETToolbox precipitation estimates for Elephant Butte Reservoir 1975-2005.

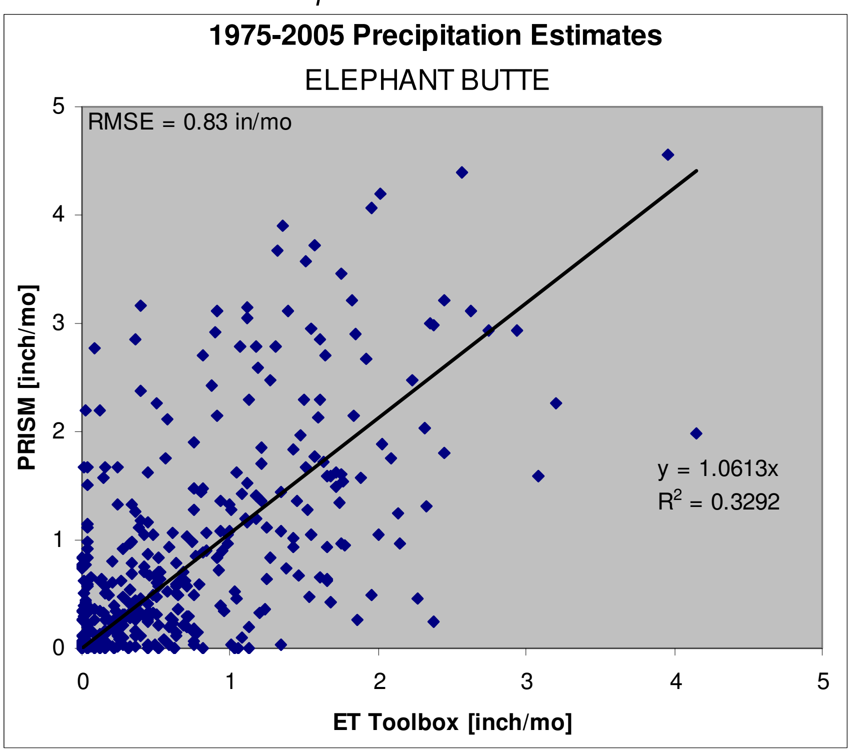
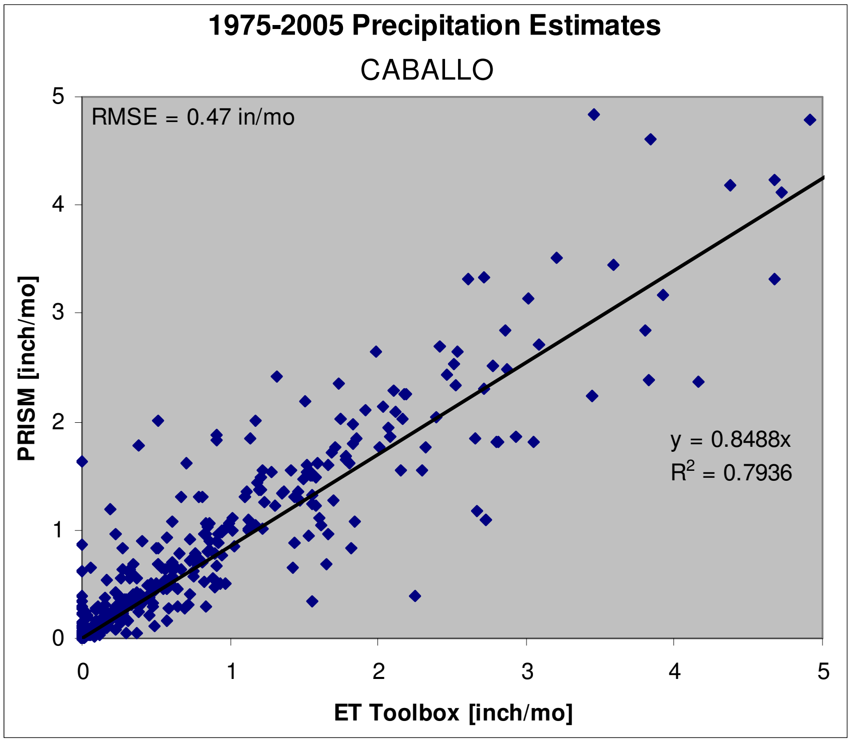


Figure 4-7: Comparison of PRISM and ETToolbox precipitation estimates for Caballo Reservoir 1975-2005.



Service Cooperative (COOP) station at Jemez Dam also (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm4366), so it is unclear why Jemez precipitation was estimated based on Cochiti values in the monthly model, and this is an area for improvement in the future. The discrepancy at Elephant Butte is not understood because there is a National Weather Service Cooperative (COOP) station with a long period of record at that location.

Precipitation rate is multiplied by reservoir surface area to get volumentric inflow to the model. Therefore, depending on timing of precipitation events with respect to reservoir volumes, errors in precipitation rates are not translated directly into errors in volumetric inflow to the model. Not surprisingly, the poor precipitation rate agreement at Jemez and Elephant Butte leads to poor agreement on estimates of precipitation inflows to those reservoirs in the model from 1975-2004. Total inflows to the model from reservoir precipitation average about 40,000 acre feet per year, and thus represent about 4% of the 1 million AF/yr average surface water inflows to the model (Roach 2007). Of this 40,000 AF/yr, almost half comes from Elephant Butte due to its large surface area. Because Jemez is a small reservoir that is often empty or close to empty, differences in the Jemez precipitation data result in negligible inflow differences. As seen in Figures 4-8 and 4-9, inflows to the reservoirs from precipitation were estimated acceptably with the PRISM data for all reservoirs except Elephant Butte. However, due to the poor but relatively unbiased nature of the relationship between PRISM and ETToolbox precipitation data for Elephant Butte shown in Figure 4-6, no adjustment was made to any of the PRISM precipitation data. As a result, the PRISM precipitation data adds an average of about 4000 AF/yr extra water to Elephant Butte, and 3000 AF/yr extra water to the entire model. These volumes are negligible to the overall water budget, but may cause slight differences in model results than would be obtained with the ETToolbox reservoir precipitation data set.

Figure 4-8: Comparison of PRISM and ETToolbox based estimates of 1975-2004 model inflows due to reservoir precipitation on all reservoirs except Elephant Butte.

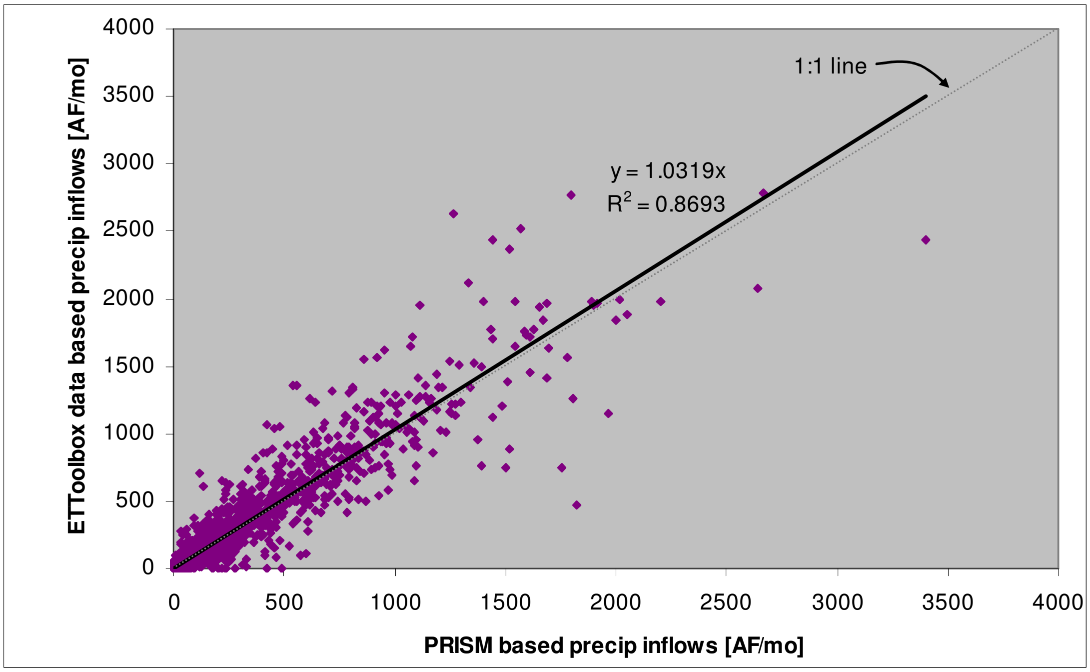
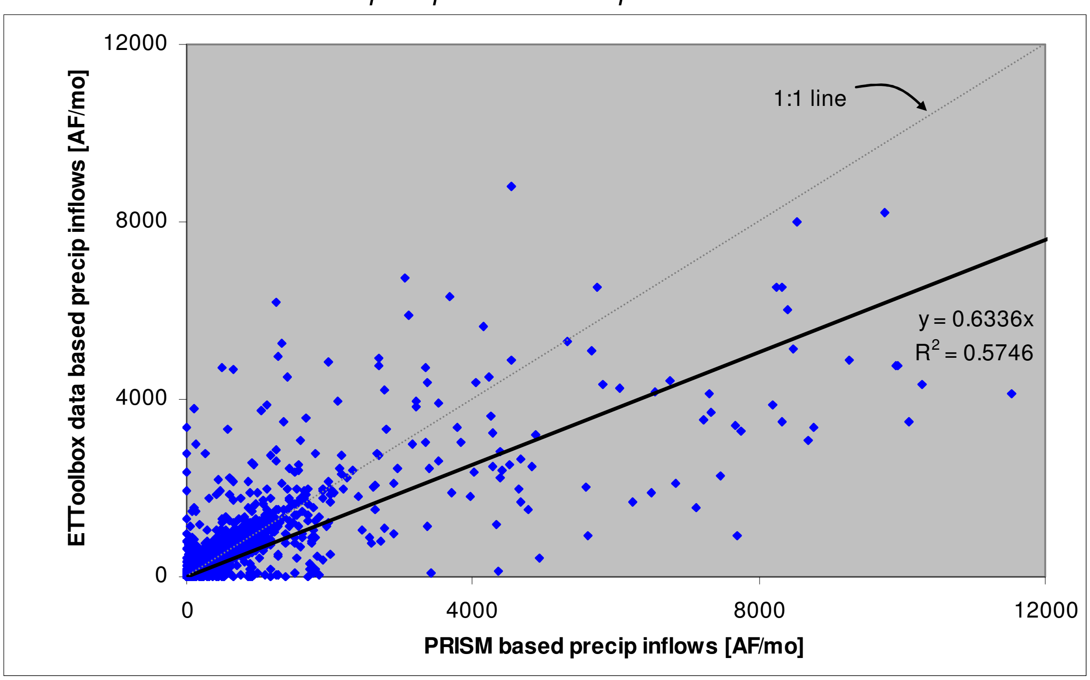


Figure 4-9: Comparison of PRISM and ETToolbox based estimates of 1975-2004 model inflows due to precipitation on Elephant Butte Reservoir.



4.2. Temperature Input Data Results and Analysis:

Analogous to the analysis for reservoir precipitation, 1975-2005 PRISM average monthly minimum and maximum temperature values for each reach, developed as described previously were compared with the values used in the monthly model for the same time period. Monthly model temperature data for 1975-2005 came from the ET Toolbox (Brower 2004) dataset for all reaches below Cochiti Reservoir. Sources of average monthly minimum and maximum temperature values for reaches above Cochiti Reservoir are shown in Table 4-2 below.

Table 4-2. Historic climate data sources used for reaches above Cochiti. The 1st and 2nd replacement stations are stations or methods used when data is not available from original station. Reaches below Cochiti use ET Toolbox data set (Brower 2004).

Reach	Temperature Station	Temperature 1st Replacement	Temperature 2nd Replacement	RH, Wind, and Solar Radiation Station	RH, Wind, and Solar Radiation 1st Replacement
Chama: Willow Creek to Heron	El Vado Dam			Alcalde	Alcalde historic average
Chama: Heron to El Vado	El Vado Dam			Alcalde	Alcalde historic average
Chama: El Vado to Abiquiu	Abiquiu Dam			Alcalde	Alcalde historic average
Chama: Abiquiu to Chamita	Abiquiu Dam			Alcalde	Alcalde historic average
Lobatos to Cerro	Cerro	Cerro historic average		Alcalde	Alcalde historic average
Cerro to Taos Junction Bridge	Cerro	Cerro historic average		Alcalde	Alcalde historic average
Taos Junction Bridge to Embudo	Alcalde	Espanola	Alcalde historic average	Alcalde	Alcalde historic average
Embudo to Otowi	Alcalde	Espanola	Alcalde historic average	Alcalde	Alcalde historic average
Otowi to Cochiti	Cochiti Dam	Cochiti historic average		Alcalde	Alcalde historic average

There was excellent agreement (R^2 of best fit line > 0.95) between data sets for average monthly maximum and minimum temperatures (Tmax and Tmin) for all reaches, with the single exception of Tmin in the San Marcial to Elephant Butte reach (R^2 = 0.92). This exception demonstrates a bimodal pattern, perhaps due to sensor drift or replacement as shown in Figure 4-10. All other reach based comparisons of Tmax and Tmin are shown in Appendices A and B.

Figure 4-10: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for river reach from San Marcial to Elephant Butte.

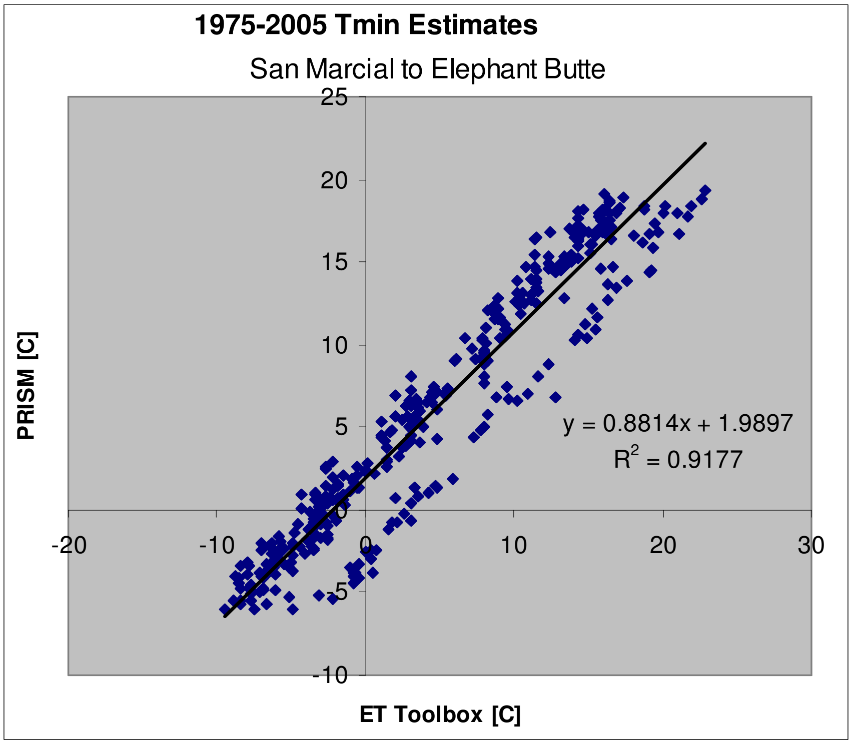


Figure 4-11: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for all reaches and months 1975-2005.

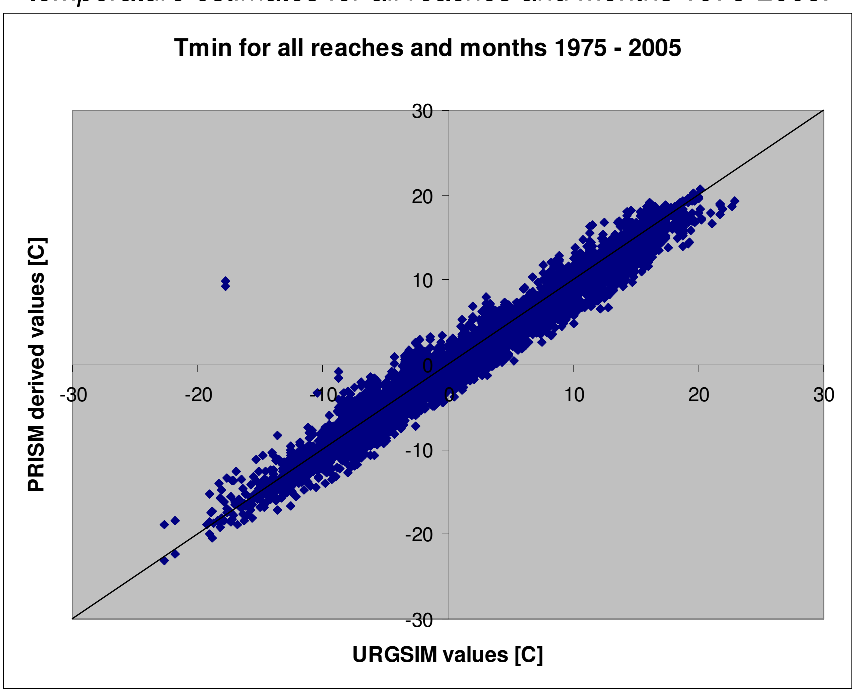
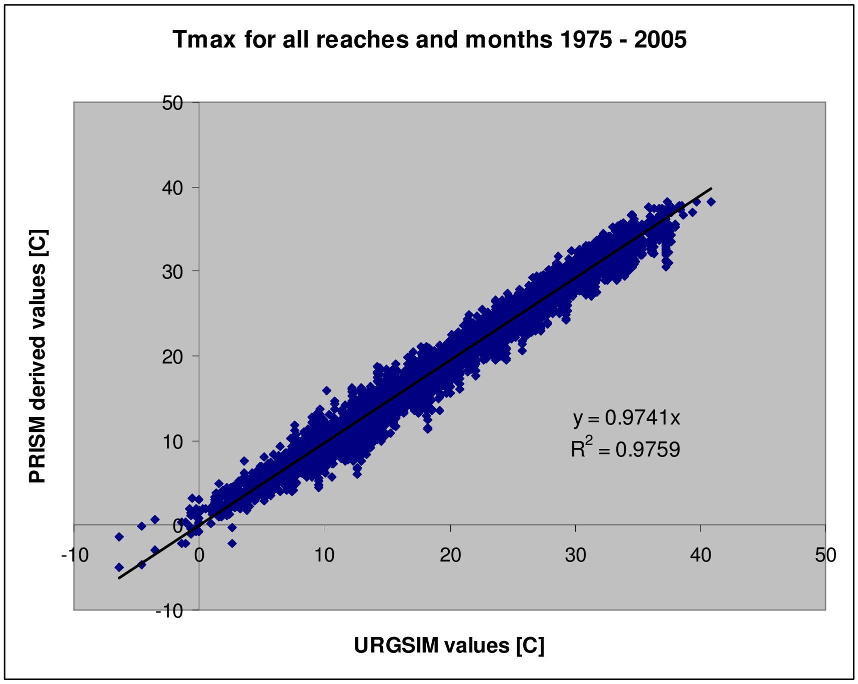


Figure 4-12: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for all reaches and months 1975-2005.



Figures 4-11 and 4-12 compare monthly Tmin and Tmax data in all reaches for all months between 1975-2005. Due to the high level of agreement between the temperature datasets seen in Figures 4-11 and 4-12, no attempt was made to "correct" the PRISM temperature data to the ETToolbox data.

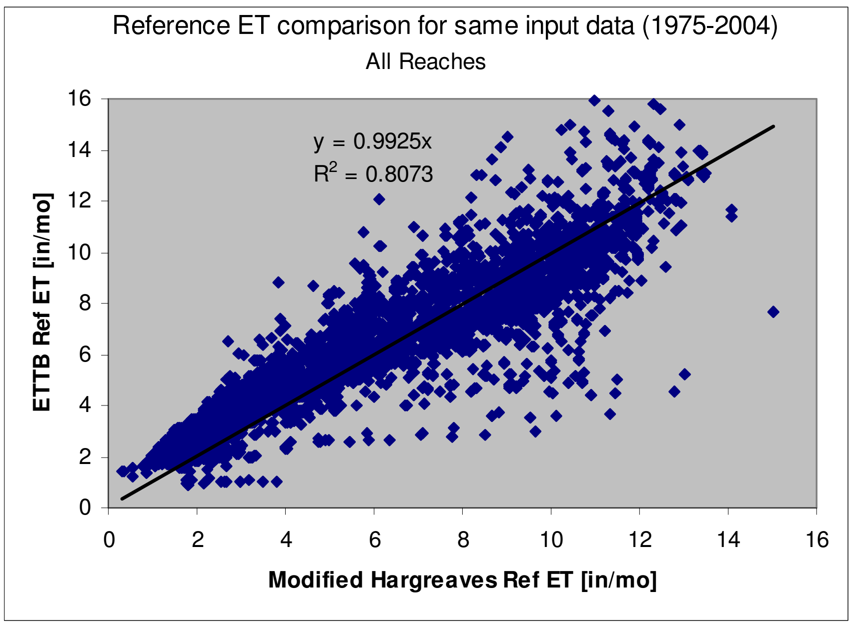
4.3. Reference ET Results and Analysis:

The monthly model uses a modified Penman equation to estimate reference ET following the approach used by the ET Toolbox (Brower 2004). This equation requires windspeed, solar radiation, and humidity data in addition to temperature data. This full suite of data is available by URGWOM river reach from 1975-2004 as documented in Roach 2007. The Hargreaves equation on the other hand,(Hargreaves and Samani 1985) can be used to estimate reference evapotranspiration (ET) using only temperature and latitude data, and according to Shuttleworth (1993), is the most reliable temperature based method in common use. The PRISM temperature data used as an input to the Hargreaves equation thus allows an estimate of reference ET for years prior to 1975. Several comparisons were made in order to evaluate the effect of using the Hargreaves equation and PRISM data instead of the ET Toolbox equation and data.

4.3.1. Hargreaves Equation Analysis:

First, the Hargreaves equation was used to calculate reference ET using the same temperature data used for the ET Toolbox calculations. The results suggest that in this area, the Hargreaves equation underestimates reference ET as estimated by the ET Toolbox method by about 35% on average. Because the model was calibrated from 1975-1999 using the ET Toolbox method, the Hargreaves equation was multiplied by a correction factor of 1.35 for all reaches to get a closer agreement between reference ET estimated by the two methods using the same data. The magnitude of this correction factor warrants additional analysis (Westfall 2009), however such analysis is beyond the scope of current resources. Reach specific correction factors would have varied between 1.24 and 1.48, with 12 of 17 total between 1.3 and 1.4, and all reaches in the evaporation dominated Middle Valley (Cochiti to Elephant Butte) between 1.3 and 1.4. A single correction factor was considered adequate given this distribution and the general uncertainty inherent in estimating reference ET using a semi-empirical equation. A comparison of reference ET values estimated by the two methods using the same data for all reaches and all months between 1957 and 2004 is shown in Figure 4-13 below.

Figure 4-13: Comparison of monthly Reference ET values calculated from the same climate data by modified Hargreaves (x-axis) and modified Penman-Monteith (ETToolbox) (y-axis) equations. Values for all model reaches and all months 1975-2004.



Next, the overall effect of using the PRISM data and Hargreaves equation on potential evaporation *volumes* for crops and riparian vegetation was compared. It should be noted that the vegetation coefficients for certain crops and riparian species are calculated with the growing degree day (GDD) method as documented in Roach 2007, and consistent with the ET Toolbox approach (Brower, 2004). The GDD method requires maximum and minimum temperature data, and for the Hargreaves-PRISM approach, the GDD was also calculated with the PRISM data. Potential crop and riparian evapotranspiration volume by reach was calculated using the ET Toolbox methods and data, and compared to the potential crop and riparian ET volume by reach calculated with the Hargreaves equation using PRISM data. Figures 4-14 and 4-15 show the comparison for 1975-2004.

Figure 4-14: Potential Crop ET calculated by the ETToolbox methods and data, and by the modified Hargreaves equation using PRISM temperature data.

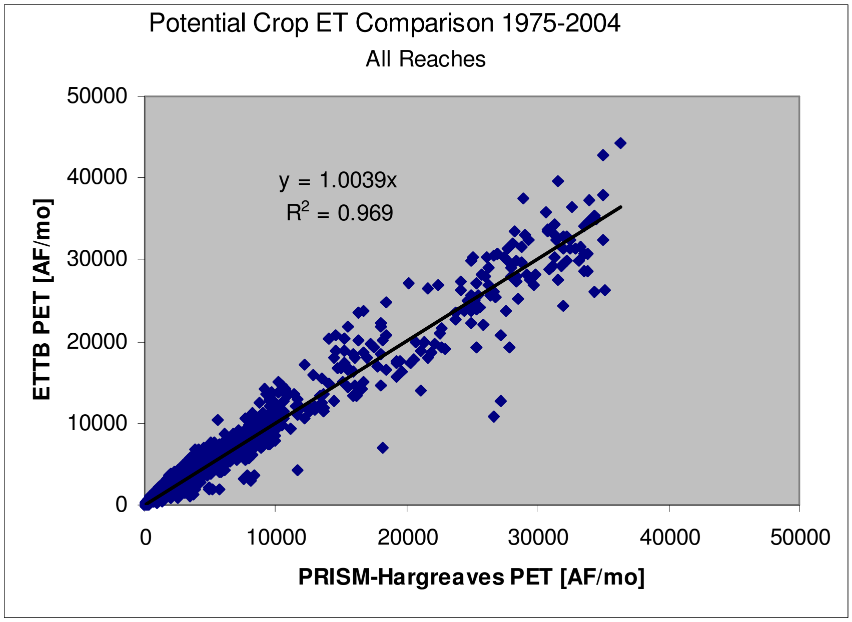
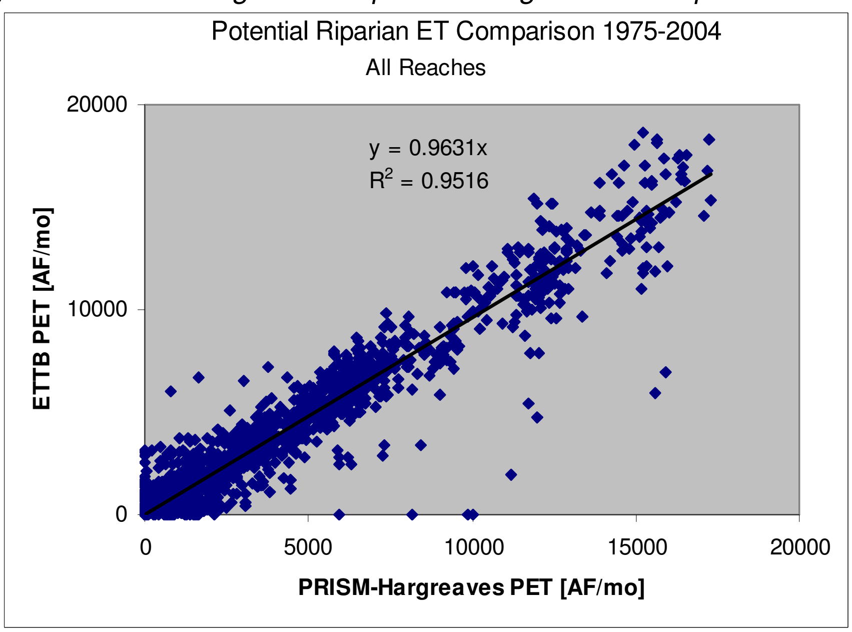


Figure 4-15: Potential Riparian ET calculated by the ETToolbox methods and data, and by the modified Hargreaves equation using PRISM temperature data.



These results suggest that the Hargreaves-PRISM method is able to match the ET Toolbox evaporative demand estimates to a reasonable degree, and stochastic analysis of climate sequences going back as far as 1895 using the Hargreaves-PRISM method is a reasonable endeavor.

4.4. Stream Flow Input Data Results and Analysis:

The reader is referred to Engdahl et al (2008) for analysis of results on stream flow input data extension.

4.5. Baseline Model Run Results and Analysis:

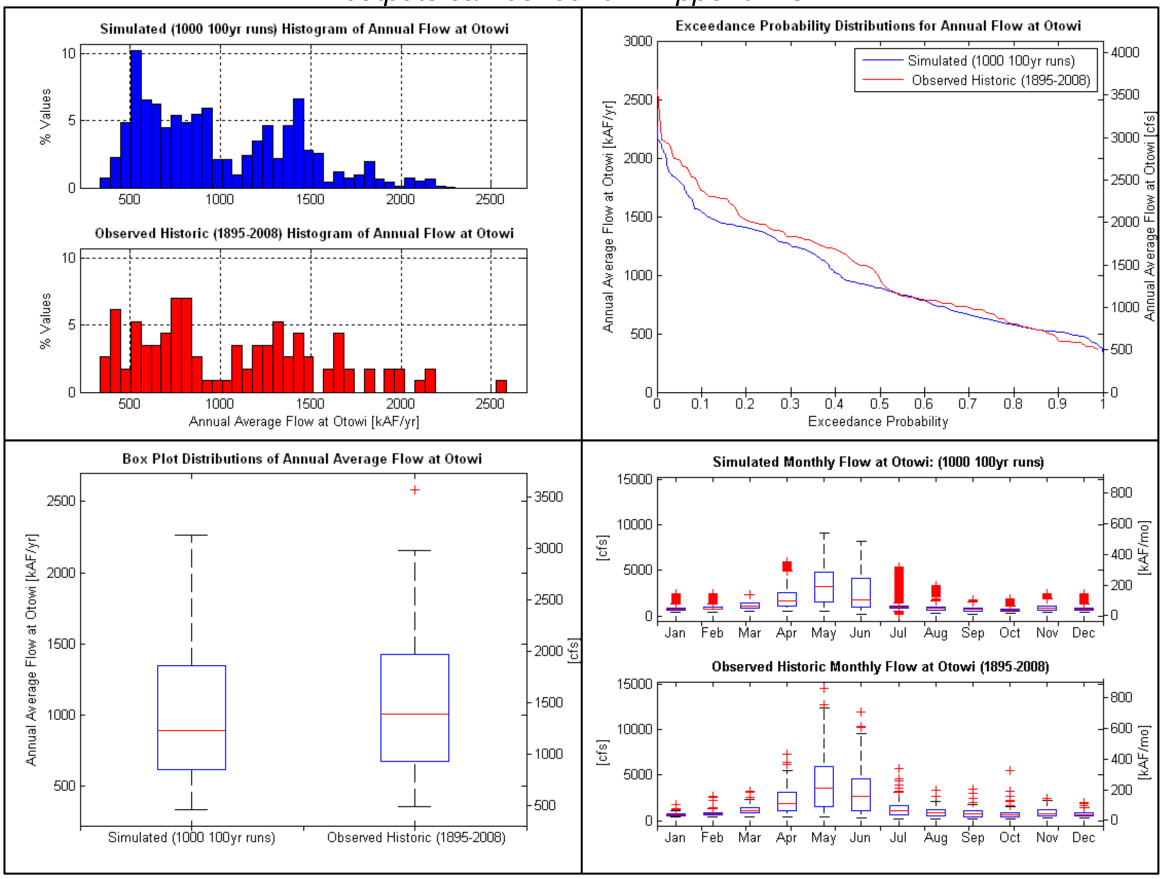
Using the extended historical data set, 1000, 100 year runs of the model were made, with each run varying only in the sequence of historic years used to drive the hydrologic and climatic inputs to the model. The following model outputs were tracked:

- Monthly average flow past the gage locations at Otowi (USGS gage#8313000), Central (USGS gage# 8330000), San Marcial (USGS gage#8358400), and below Caballo (USGS gage# 8362500).
- Beginning of month reservoir storage in Heron, El Vado, Abiquiu, Cochiti, Jemez, Elephant Butte, Caballo, reservoirs, as well as the sum of these.
- Monthly Otowi Index Supply values.
- Annual values for New Mexico's Rio Grande Compact Balance.
- Months in Article VII conditions of the Rio Grande Compact.
- Potential agricultural ET shortages defined as potential ET less actual ET.
- Approximate City of Albuquerque San Juan Chama drinking water project shortages defined as annual available less annual used.
- Months in which flow targets are missed, and the magnitude of the shortages.
- ET in the Middle Rio Grande for riparian vegetation, crop vegetation, municipal-industrial outdoor use, and the sum of these.

Individual model outputs are compared visually to historic data with four charts as shown for flow at Otowi in Figure 4-16. Annual average values are compared in two histograms with the same axis ranges and bins (upper left chart in Figure 4-16), as well as based on exceedance probability distributions (upper right chart in Figure 4-16). Box plots are used to compare both annual (lower left chart in Figure 4-16) and monthly (lower right chart in Figure 4-16) values of stochastic results to corresponding historic data. The red line in the box plots represents the median value, while the blue box contains the middle 50% of the data (from the 25% value to the 75% value). The height of the blue box, which is the distance between the 25% and 75% values is known as the interquartile distance. The whiskers that extend beyond the blue box contain the remaining data within 1.5 interquartile distances of the blue box. Any values beyond the whiskers are considered outliers and are marked with a red cross. The historic values used for comparison depend on the range of historic data available for a given model output. Figures C-1 through C-23 in appendix C show the four comparison charts for each of the model outputs.

Model outputs are discussed in more detail here in categories related to river flow, reservoir storage, Rio Grande Compact credit, evapotranspiration, and shortages. In general, when compared to historic observations, the stochastic output suggests decreased river flows and reservoir storages, increased average Rio Grande Compact credit, decreased evapotranspiration, and increased shortages.

Figure 4-16: Stochastic model output compared to observed record (1895-2008) for Rio Grande flow at Otowi (USGS Gage# 8313000). Similar figures for all tracked model outputs can be found in Appendix C.



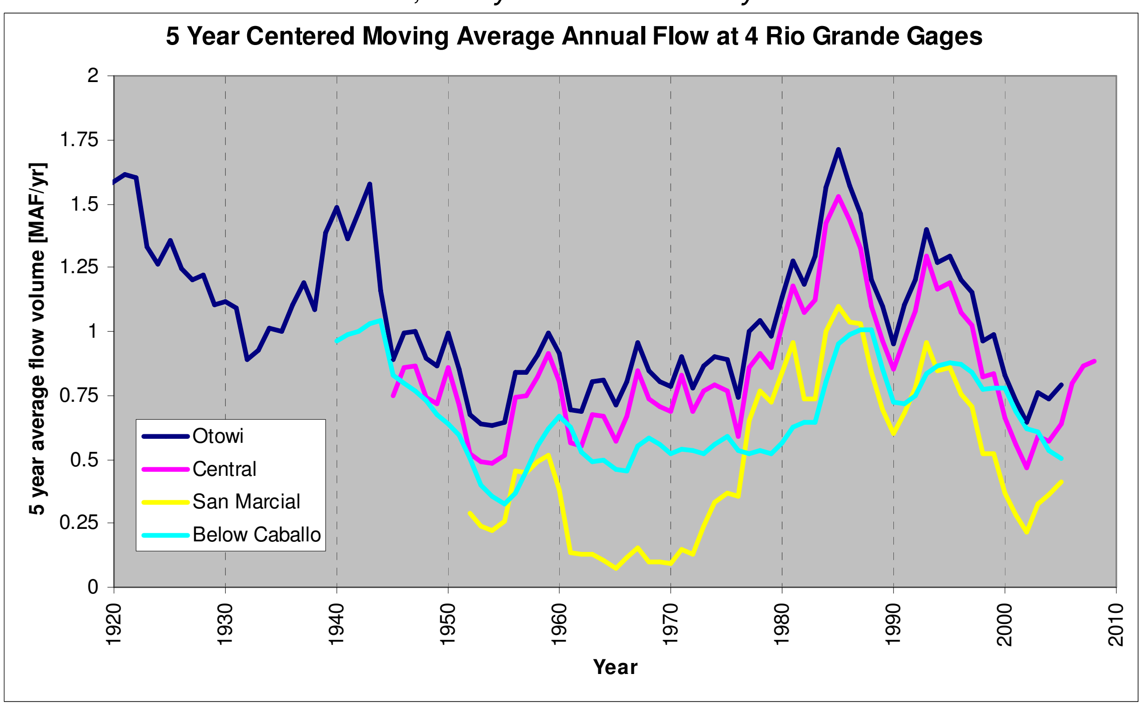
4.5.1. River Flow:

In general, river flows are reduced, both when compared to the entire period of record at each gage, and even more significantly when compared to the 1975-2000 period that has been used extensively for model development and calibration by both the monthly and daily timestep models. This comparison is shown for average annual flows in Table 4-3. Due to agricultural conveyance structures, the Central and San Marcial gages do not measure all surface water moving through the system at those locations. This explains the increase in flows below Caballo as compared to San Marcial in all rows of Table 4-3, and also explains why the stochastic results show larger flow than the historic record in the river channel at San Marcial. The Low Flow Conveyance Channel (LFCC), which bypasses the river gage at San Marcial was used extensively from the 1950's into the 1980's (Shafike, 2005). Use of the LFCC has fallen since the late 1980's due to siltation and the onset of endangered species management of the river channel, and the model does not divert water from the river into the LFCC during the simulation period (Modeled fow in the LFCC is a result of agricultural returns and drain capture.). Future stochastic runs should track the conveyance system flows at Central and San Marcial to get a sense of the total mass balance of surface water moving through the system at these cross sections. The trend of reduced flows, especially compared to 1975-2000 records is not surprising as 1975-2000 was relatively wet in the Rio Grande basin as seen in Figure 4-17. Figure 4-17 shows the five year running average Rio Grande flow measured at Otowi, Albuquerque, San Marcial, and below Caballo.

Table 4-3: Annual average Rio Grande flow (Millions of Acre Feet per Year) at Otowi, Albuquerque (Central Avenue), San Marcial, and below Caballo gages for the historic period of record and the stochastic simulations.

Gage location:	**Otowi**	**Albuquerque**	**San Marcial**	**Below Caballo**
Period of Complete Record for Annual Flow:	1896-1905, 1910-1913, 1919-2007	1943-2008	1950-2007	1938-2007
Period of Record average:	1.07	0.84	0.48	0.67
1975-2000 average:	1.18	1.05	0.76	0.75
Stochastic average:	0.99	0.77	0.55	0.64

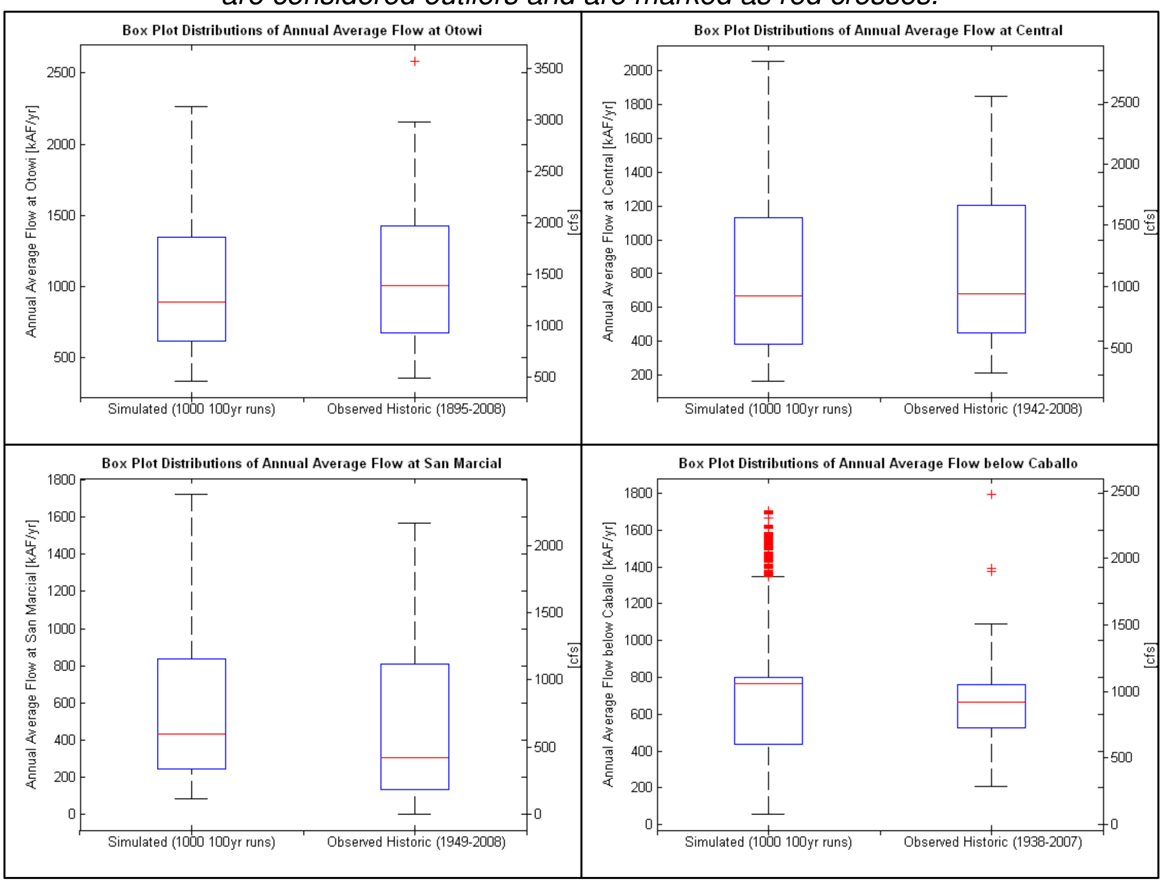
Figure 4-17: Five year average Rio Grande flow values at Otowi, Albuquerque (Central Avenue), San Marcial, and below Caballo gages. A dry period is evident beginning in the late 1940s and extending into the early 1970s. From the late 1970's through the late 1990's, the system was relatively wet.



Figures 4-18 and 4-19 compare the stochastic distributions of annual average river flow at each of the gage locations considered here. While annual average flows decreased in the stochastic analysis for all locations except San Marcial as shown in Table 4-3 and described above, Figure 4-18 shows smaller median flows compared to the observed record only at Otowi. At Central the medians are similar, and at San Marcial and below Caballo, the stochastic medians are above the observed historic. The agreement at

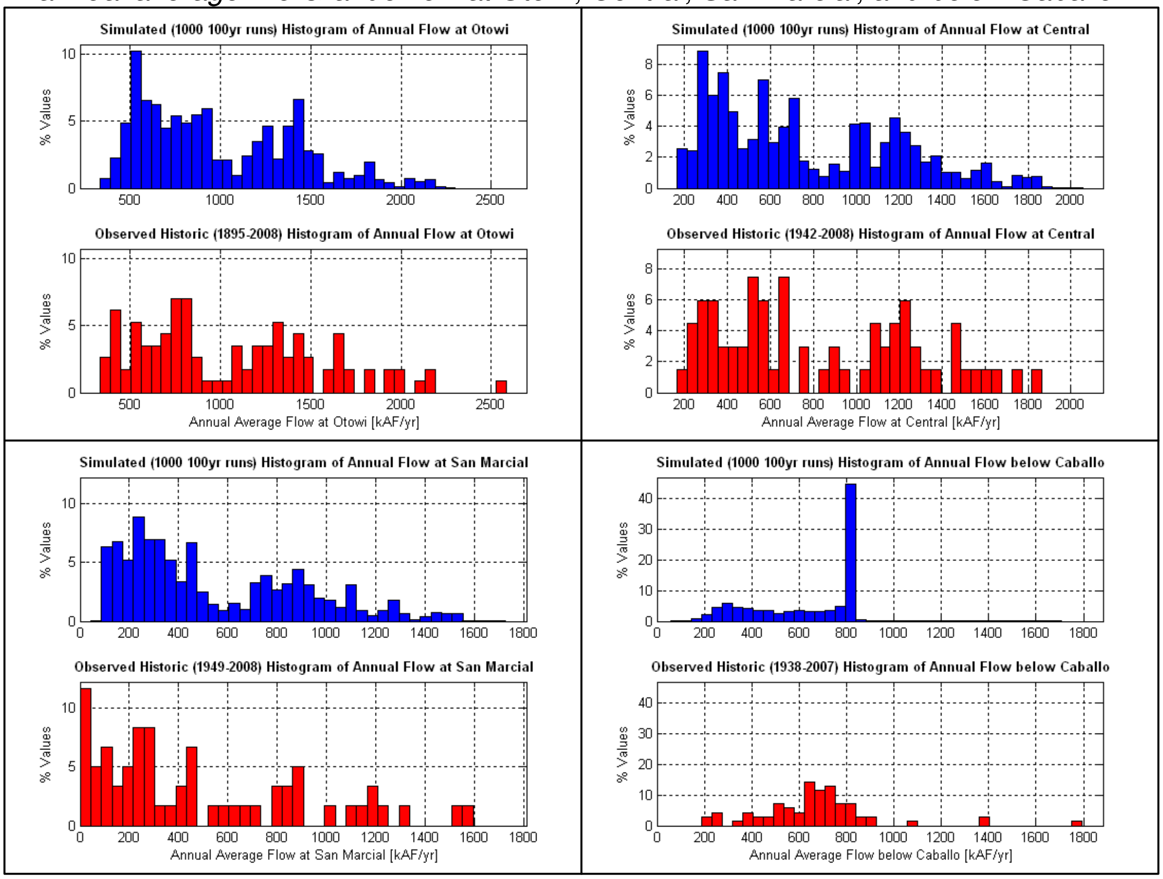
Central may be a result of the fact that the historic record at Central (1942-2008) happens to capture a period that according to the paleohydrology was fairly representative of the past 500 years of climate in New Mexico (see Figure 3-1). The increased San Marcial median flow is a result of differences in LFCC operations as described above. The Caballo median is skewed up by high outlier values associated with flood control releases associated with wet climate sequences. The box plots also show that the range of non-outlier values is greater for the stochastic analysis than the period of record at all four gage locations considered.

Figure 4-18: Box plot comparisons of stochastic and period of record distributions of annual average Rio Grande flow at Otowi, Central, San Marcial, and below Caballo. The blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and are marked as red crosses.



The histograms shown in Figure 4-19 show a distinct bimodal pattern in both the stochastic distributions and the historic record at Otowi, Central, and San Marcial. The reason for this bimodal distribution is worthy of further study. This pattern is lost below San Marcial due to storage and regulation in Elephant Butte and Caballo reservoirs. The majority of Caballo releases are 790,000 acre feet per year, the target release for agricultural use. Releases below this indicate a shortage situation, while releases above this indicate releases from high storage to maintain flood control capacity.

Figure 4-19: Histogram comparisons of stochastic and period of record distributions of annual average Rio Grande flow at Otowi, Central, San Marcial, and below Caballo.



4.5.2. Reservoir Storage:

Perhaps the most striking result from the stochastic analysis described here is the dramatic change predicted for reservoir storage levels compared to historic. The difference is most noticeable for Heron, El Vado, Abiquiu, Elephant Butte, and Caballo, the storage reservoirs, as compared to Cochiti and Jemez, which are almost exclusively operated for flood control as discussed in Section 3.3.3. Figures 4-20 and 4-21 compare the stochastic distribution of reservoir storage at the storage reservoirs to historic distributions. The reduced reservoir storage for the stochastic analysis as compared to the historic period makes sense when we consider that the period of record for the reservoir storage values is 1975-2008 for all reservoirs except El Vado, where it goes back to 1965. As discussed above (Section 4.5.1), and seen in figure 4-17, this period was extremely wet when compared to the longer climate record. In addition to reduced surface water supply, the system demands have also increased compared to the 1965-2008 historic period. This is due to an increased municipal population, and the direct municipal use of surface water in the scenario period. For both of these reasons, reservoir storage is dramatically reduced in the stochastic analysis as compared to the historic record. The magnitude of this decrease is tremendous however, and somewhat unexpected.

Figure 4-20: Box plot comparisons of stochastic and historic annual average reservoir storage in Heron, El Vado, Abiquiu, Elephant Butte, Caballo, and all modeled reservoirs (Cochiti and Jemez in addition to the five above). The blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and marked as red crosses.

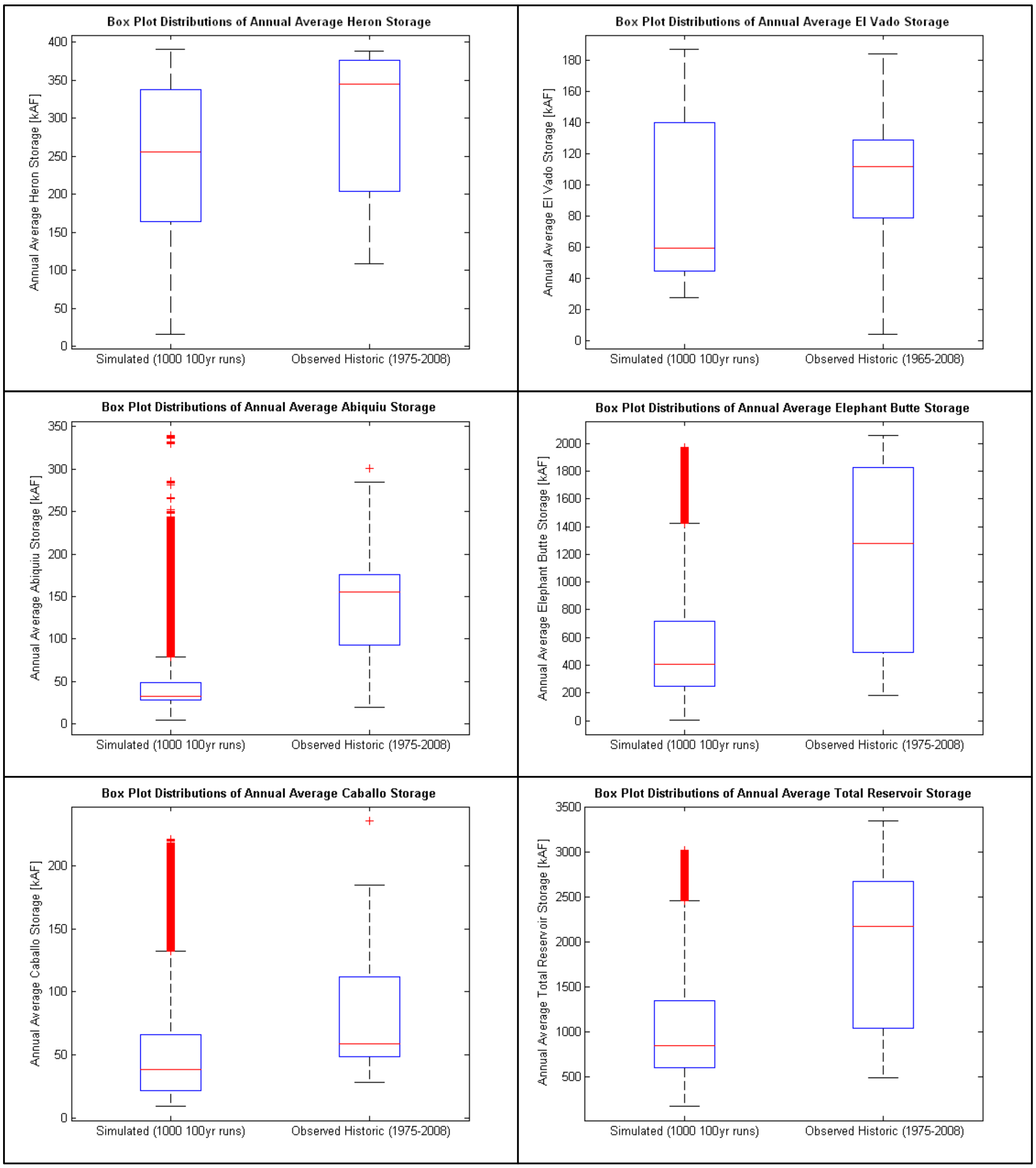
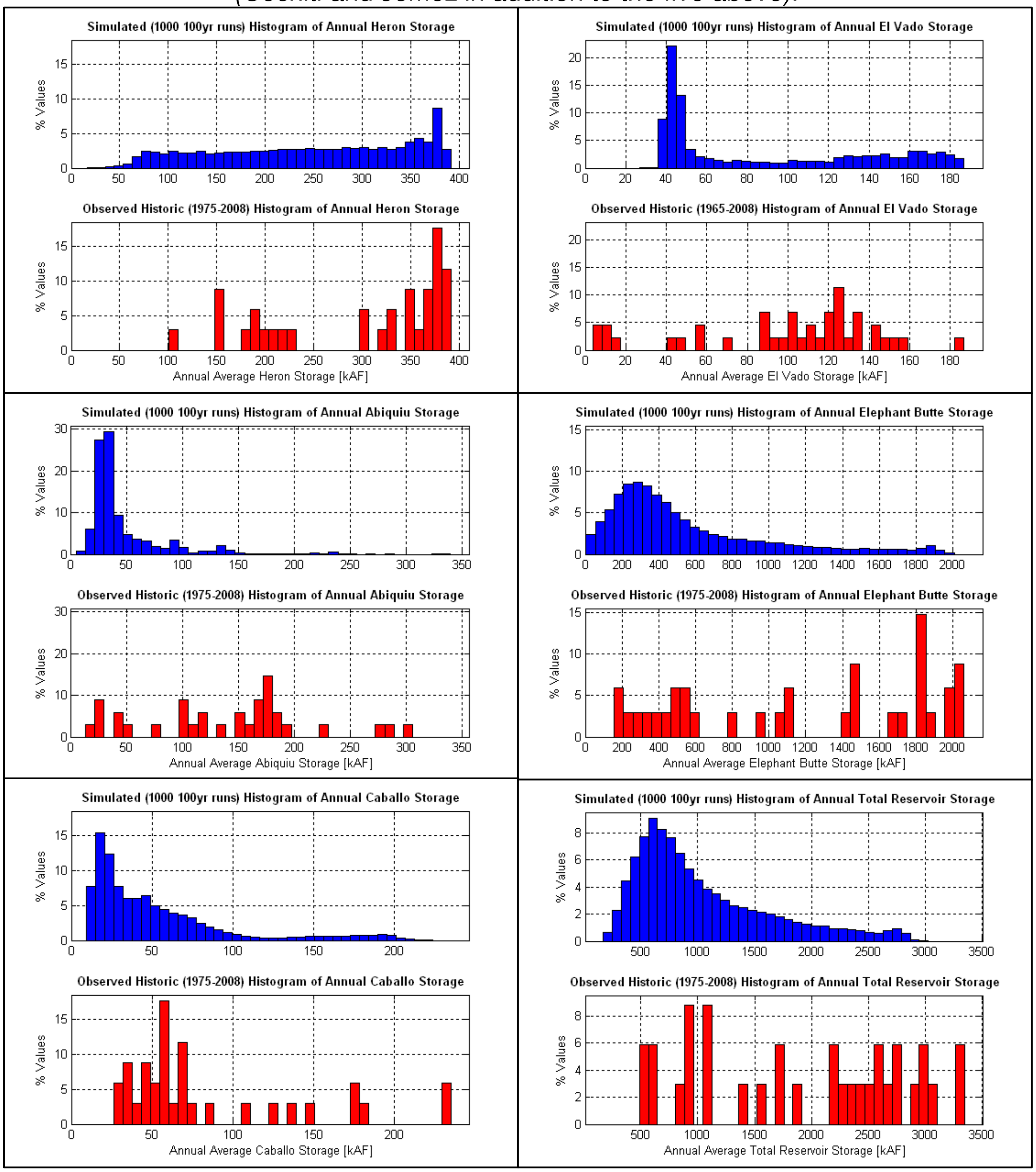


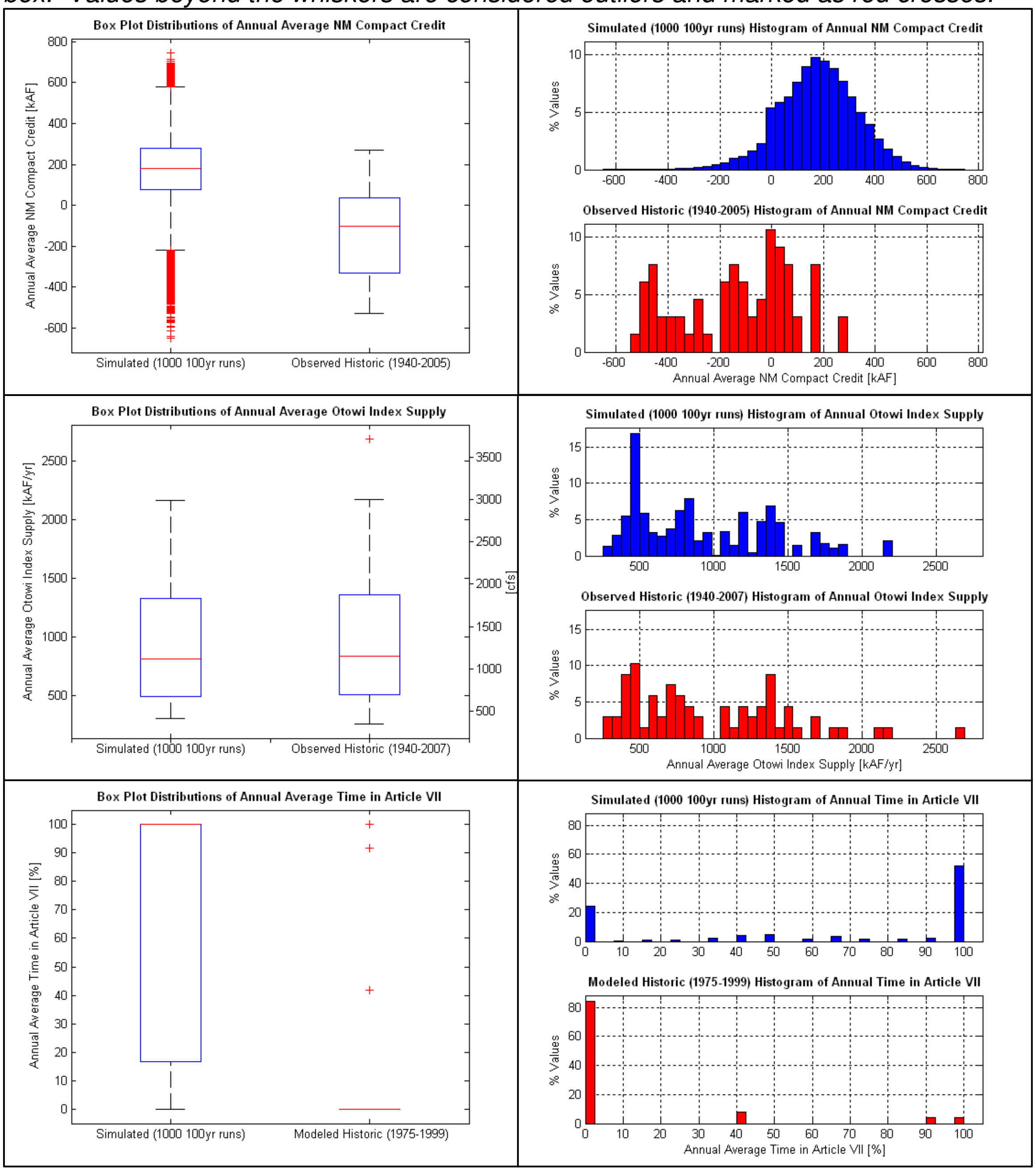
Figure 4-21: Histogram comparisons of stochastic and historic annual average reservoir storage in Heron, El Vado, Abiquiu, Elephant Butte, Caballo, and all modeled reservoirs (Cochiti and Jemez in addition to the five above).



4.5.3. Rio Grande Compact

In addition to tracking New Mexico's Rio Grande Compact credit through time, the Otowi Index Supply (OIS) and the amount of time in Article VII conditions were also tracked during the stochastic analysis. (The OIS can be thought of as a naturalized flow at Otowi, the flow that would have been expected without dams or transboundary water imports, while Article VII conditions are based on storage in Elephant Butte, and impose restrictions to native water storage upstream. The stochastic and historic distributions of these three parameters are shown in box plot and histogram form in Figure 4-22.

Figure 4-22: Box plot and histogram comparisons of stochastic and historic annual Otowi Index Supply, New Mexico's Rio Grande Compact credit, and % time in Article VII conditions. In the box plots, the blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and marked as red crosses.



The distribution of OIS values (middle two charts in Figure 4-22) calculated in the stochastic analysis is effectively the same as the 1940-2007 observed values, which is a direct result of the creation of the synthetic sequences based on 1940-2007 OIS values (see Section 3.1.3). The New Mexico Compact credit is the cumulative value at the end of each year in the stochastic sequence, and is generally more positive in stochastic simulations than it was from 1940-2007 (top two charts in Figure 4-22). There are three main factors that may help explain the more positive Compact credit during the stochastic analysis, namely the San Juan Chama project, municipal wastewater returns, and possibly an increased ability by New Mexico to meet the compact balance during dry years (due to reduced downstream delivery requirements). First, imported water from the San Juan Chama project which began in the early 1970's does not increase New Mexico's downstream obligation, but adds additional water to the system which increase downstream deliveries. Second, water transfer from the groundwater system to the surface water system as municipal areas near the river pump groundwater as part of their supply, and return some portion of that groundwater as effluent to the river. Finally, select model analysis of New Mexico's Rio Grande Compact credit sensitivity to climate sequence predicts that New Mexico would maintain a higher compact credit with a relatively dry climate sequence (the URGWOPS sequence(USACE et. Al. 2006)) than with the relatively wet 1975-1999 climate sequence loop (Roach, 2007, Figure 4-18).

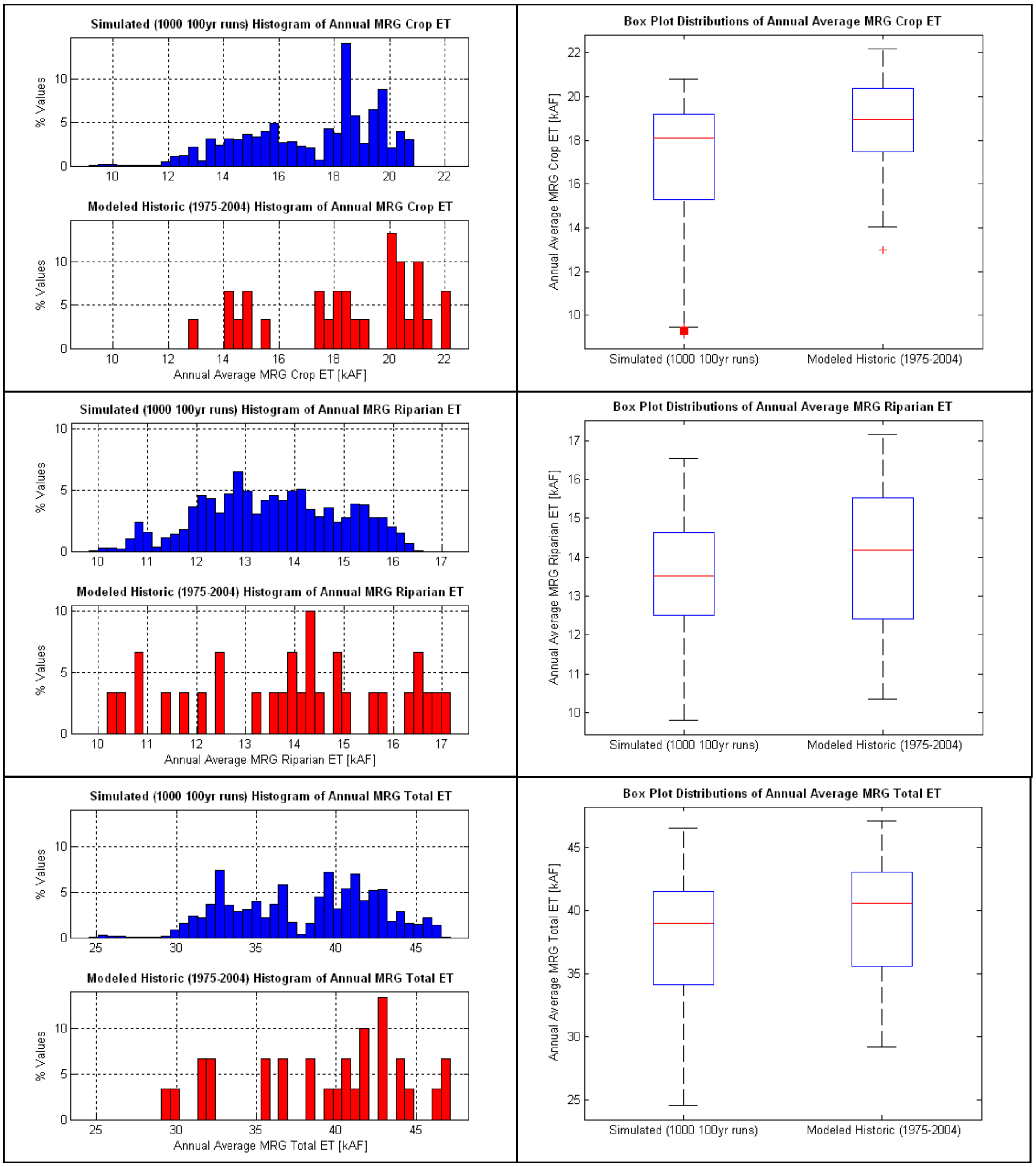
As seen in the bottom charts in Figure 4-22, the stochastic runs suggest that due to low storage in Elephant Butte Reservoir (see Figures 4-20 and 4-21), Article VII conditions would be the norm under the climate conditions of the past 600 years. In fully half of the simulated years, Article VII conditions exist for the entire year. In combination with the compact balance results, this suggests that New Mexico's ability to relinquish a given amount of compact credit in exchange for the right to store that amount of native water upstream during Article VII conditions may be an important tool for the State in the future. These credit relinquishments, which do happen in practice, are not currently simulated in the monthly timestep model, but will be included in future model enhancements.

4.5.4. Evapotranspiration

While stochastic results of decreased stream flows and reservoir storages would lead to increased water scarcity, evaporative water loss between Cochiti and Elephant Butte (the dominant consumptive use of water in the basin) tends to decrease slightly in stochastic runs as compared to the historic period. This is seen clearly in Figure 4-24, and is partly a result of slight increases in 1975-2004 Reference ET as compared to 1950 - 1974 reference ET shown in Figure 4-25. The difference in Reference ET is in turn partly the result of slight increases to average temperature for 1975-2004 as compared to 1950-1974 as seen in Figure 4-26. Because the stochastic model is using data from as far back as 1950 to drive climatic inputs, lower average temperatures before 1975 result in lower values for Reference ET in model runs as compared to the 1975-2004 historic period.

Decreases to Reference ET explain the drop in evapotranspiration seen in the riparian sector (middle charts in Figure 4-24), but do not explain the negative spread to the distribution of crop evapotranspiration values seen in the upper charts in Figure 4-24.

Figure 4-24: Box plot and histogram comparisons of stochastic and historic estimated evapotranspiration by crops, riparian ET, and total, including municipal and industrial outdoor use. ET drops about 5% on average. In the box plots, the blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and marked as red crosses.



The low end of crop evapotranspiration values are a result of very dry years in the stochastic analysis and thus of water scarcity which spreads the distribution of evapotranspiration values to the left, and also brings down the median value. Thus the combination of reduced availability in some years and decreased Reference ET explains the overall drop in evapotranspiration predicted by stochastic analysis. It is important to note that temperatures will most likely rise in the future rather than falling to average 1950-2004 levels, which draws out a weakness in the current stochastic approach. Basing climate predictions on the past 600 years of climate data may not be a strong approach in the context of global warming and climate change, especially given the strong relationship between temperature and evapotranspiration.

Figure 4-25: Average reference ET calculated for 1975-2004 (historic period) is greater than that calculated from 1950-1974, regardless of calculation method. Before 1975, data limitations mean reference ET can only be calculated by the Hargreaves method.

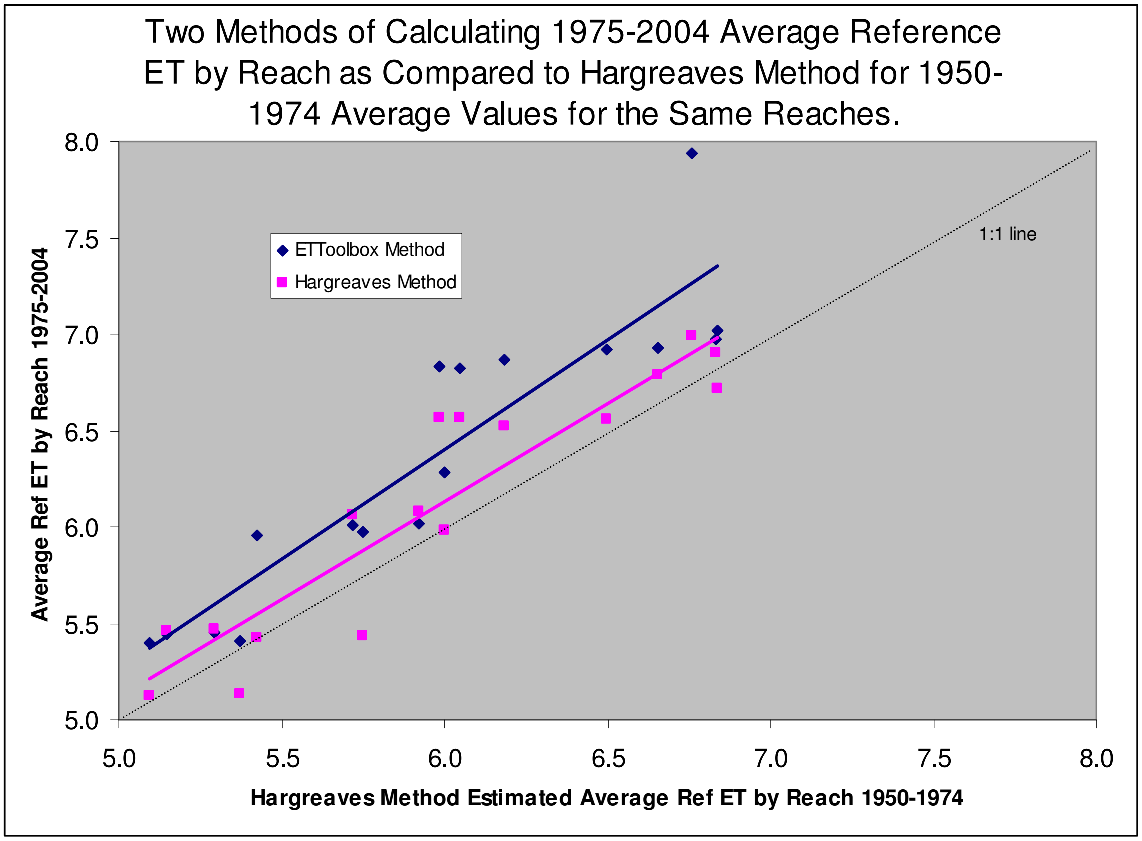
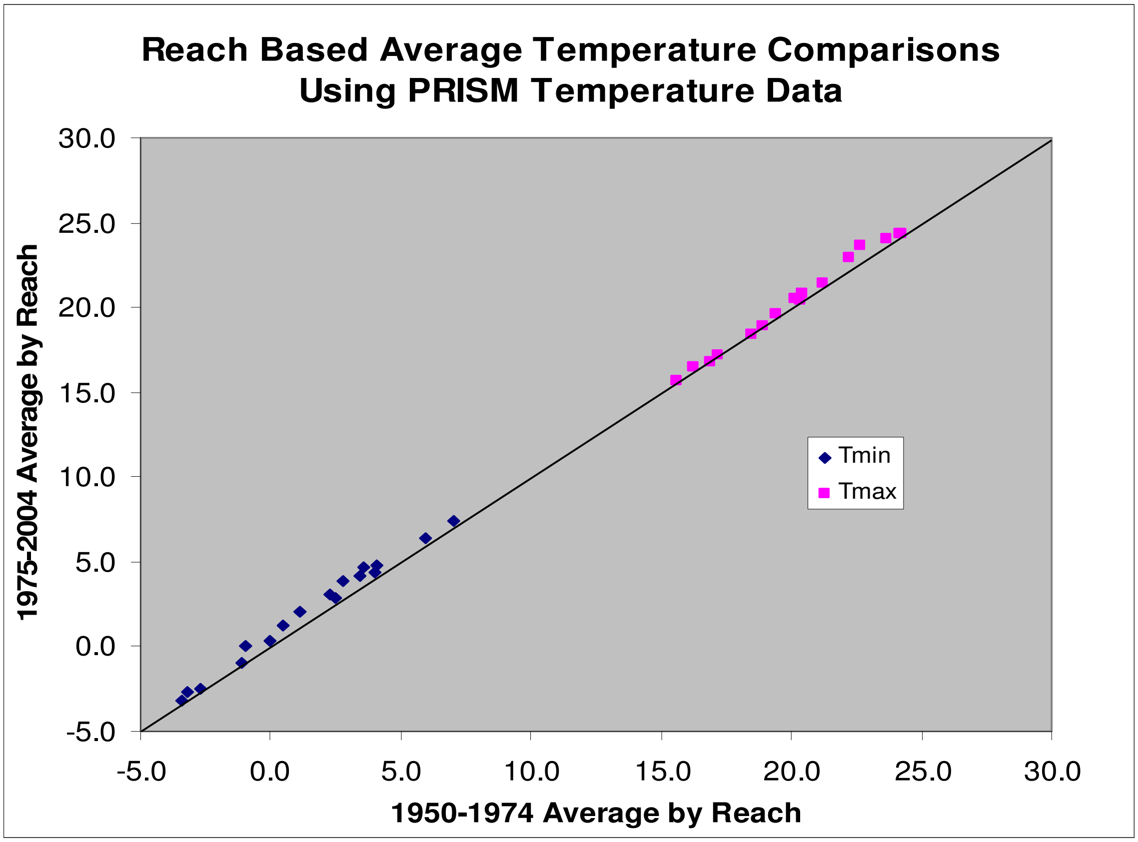


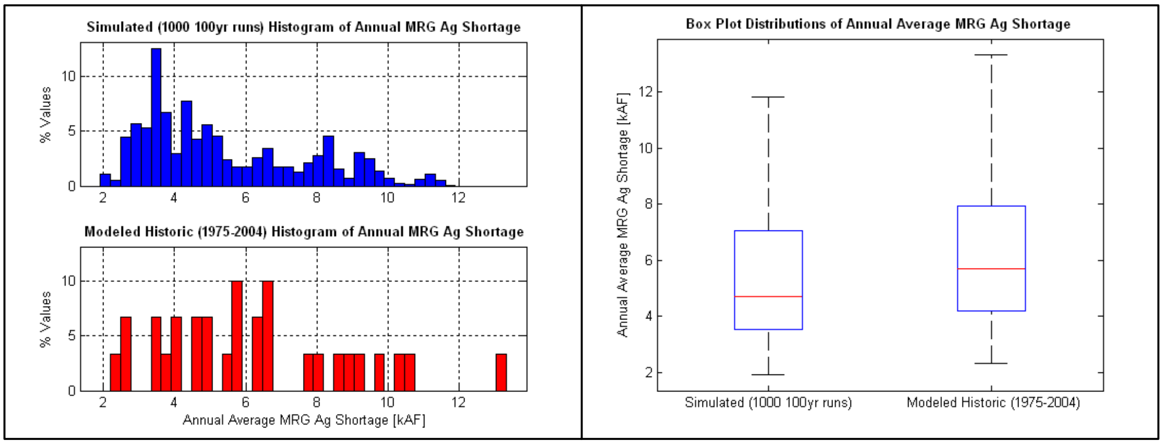
Figure 4-26: PRISM data based averages of 1975-2004 Tmin and Tmax for each reach as compared to 1950-1974 averages. All averages are larger for the period from 1975-2004, than for the period from 1950-1974, and thus using temperature data from 1950-2004 to drive Reference ET calculations results in smaller Reference ET on average for the stochastic runs than for the 1975-2004 historic period.



4.5.5. Shortages

Agricultural shortages are defined as the difference between crop potential ET and actual crop ET. Interestingly, despite decreased river flows (Section 4.5.1) and reduced reservoir storage volumes (Section 4.5.2), agricultural shortages drop on average in the stochastic simulations as compared to historic. This decrease can be seen in Figure 4-27. There are several possible reasons for the small decrease. The first is the reduced agricultural ET demand discussed in Section 4.5.4. The second reason has to do with modeling of the conveyance system between Cochiti and Elephant Butte. During the historic period, the monthly model specifies diversions from the river into the conveyance system based on historic data, and independent of calculated crop demand. This creates the potential for shortages that are a result of poor historical supply or demand data. During the scenario period, the diversions are based on historic averages, and as a result, anomalous data points are averaged out leading to a more stable supply system. Finally, the model tries to supply each diversion a historic average value, independent of the flow in the river, or the reduced ET demand. Thus, even with less water in the system, and reduced agricultural demand, the model tries to divert as much water for agricultural use as it did on average between 1975 and 2004. All of these factors result in slightly reduced calculated agricultural shortages in the scenario period as compared to 1975-2004.

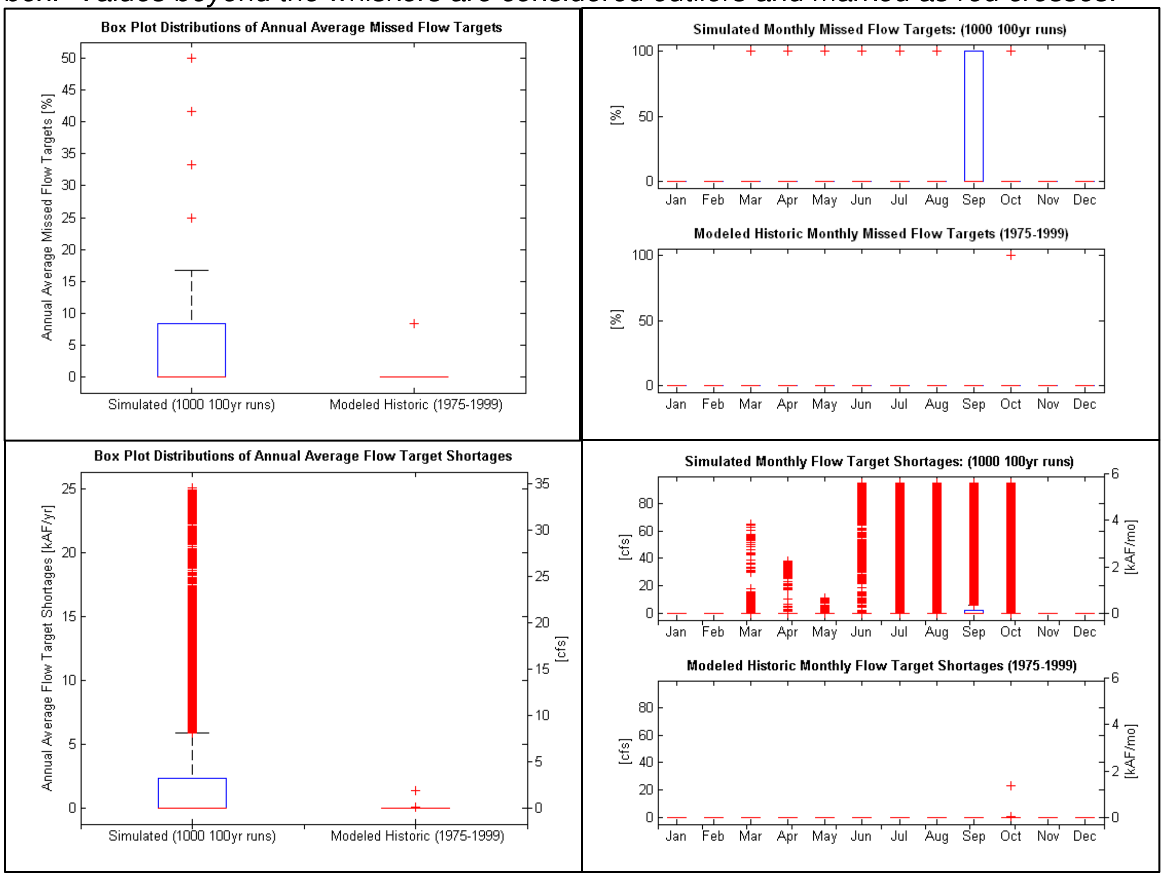
Figure 4-27: Box plot and histogram comparisons of stochastic and historic estimated agricultural shortages. Agricultural shortages drop slightly in the stochastic runs as compared to historic simulations. In the box plots, the blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and marked as red crosses.



In-stream flow targets are described in Section 3.3.3.1. As seen in Figure 4-28, on a monthly average basis, flow targets are missed in one month of the year or less in 75% of the modeled scenario years, and the month presenting the most difficulty is September. The shortages in a given year are less than 2000 AF/yr 75% of the time. Current modeling efforts focused on improving the model's ability to meet downstream flow targets with stored water should reduce these shortages in future model runs.

Shortages at the Albuquerque drinking water project are calculated for this analysis as the difference between the annual allocation of San Juan Chama project to Albuquerque, and the amount that is actually diverted. This metric ends up counting reservoir evaporation of Albuquerque's stored San Juan Chama water as a shortage, and should be redefined for future analysis. In addition, the model is currently being reworked to include minimum bypass flow and maximum diversion restrictions that will likely alter modeled diversion behavior in future runs. There is not any historic data related to these shortages. Output can be seen in Appendix C, Figure C-23.

Figure 4-28: Annual and monthly box plot comparisons of stochastic and historic estimated in-stream flow target shortages. Annual average values (upper left chart) are discrete at 1/12 (8%), 2/12(17%), 3/12(25%), etc due to a monthly timestep model resolution. In the box plots, the blue box contains the middle half of the data (from 25% to 75%) with a red line at the median. The whiskers that extend beyond the blue box contain the remaining data with a maximum length of 1.5 times the height of the blue box. Values beyond the whiskers are considered outliers and marked as red crosses.



5. Conclusions:

This paper has outlined the methods and results associated with a stochastic analysis of water operations in the Upper Rio Grande basin in New Mexico. Synthetic hydrologic sequences were derived from a combination of over 600 years of tree ring data and 54 years of direct hydrologic observations. These sequences were run through a rapid, monthly timestep hydrologic model, and major outputs were analyzed.

In terms of major outputs, the reduction in stream flows may not be surprising to local water professionals, however the reduction in reservoir storages predicted by the stochastic analysis are staggering. Future analysis should track a few more important output as outlined in the text.

The weaknesses of this analysis occur on both the supply and demand sides. On the supply side, the analysis is somewhat limited by the assumption that future climate conditions will be described by the past 600 years of climate in the region. This assumption may be weak in the face of current scientific predictions of global climate change and temperature rise. Future work could look at estimating the impacts of global climate change by adjusting input temperature data by a given amount, and by altering runoff timing. On the demand side, the analysis does not consider the impacts of population growth, which is likely to be significant over the 100 year timescale of the stochastic analysis.

Finally, current efforts to compare URGWOM to the monthly timestep model will give an idea of the reliability of these stochastic results and the usefulness of the monthly model as a screening tool for the higher temporal resolution URGWOM model.

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Appendix A:

Reach based maximum temperature data comparison figures.

Figure A-1: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Willow Creek to Heron.

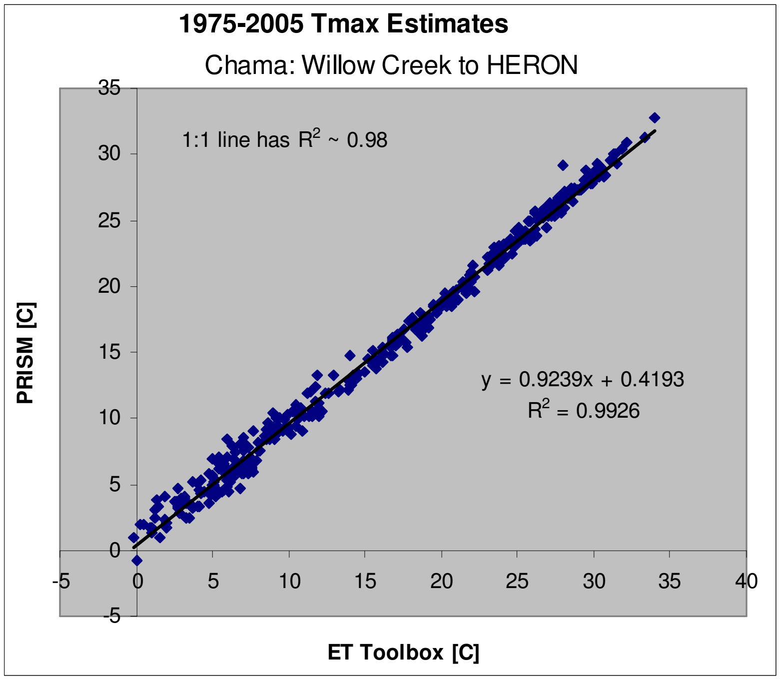


Figure A-2: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Heron to El Vado.

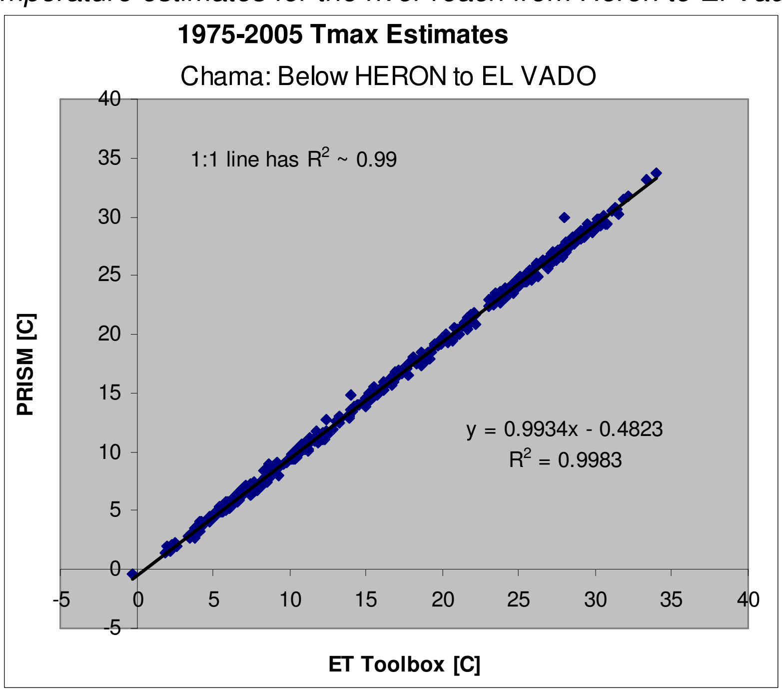


Figure A-3: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from El Vado to Abiquiu.

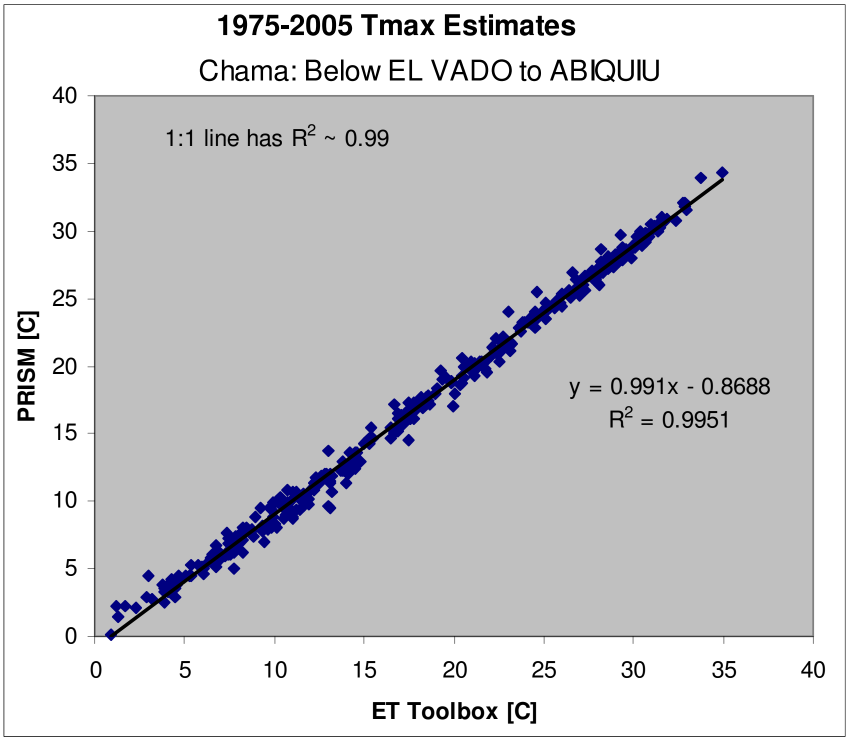


Figure A-4: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Abiquiu to Chamita.

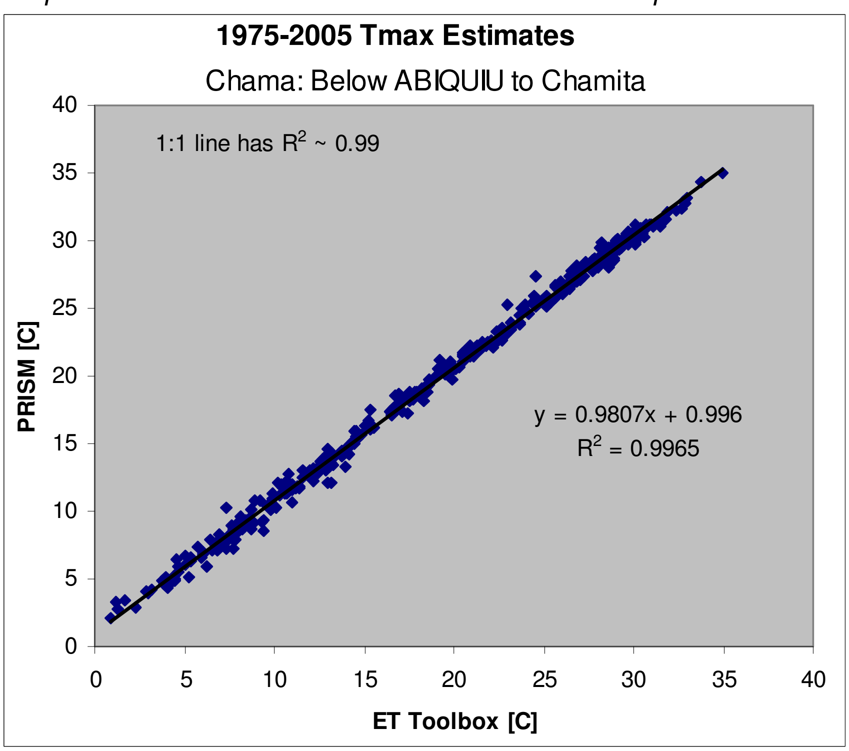


Figure A-5: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Lobatos to Cerro.

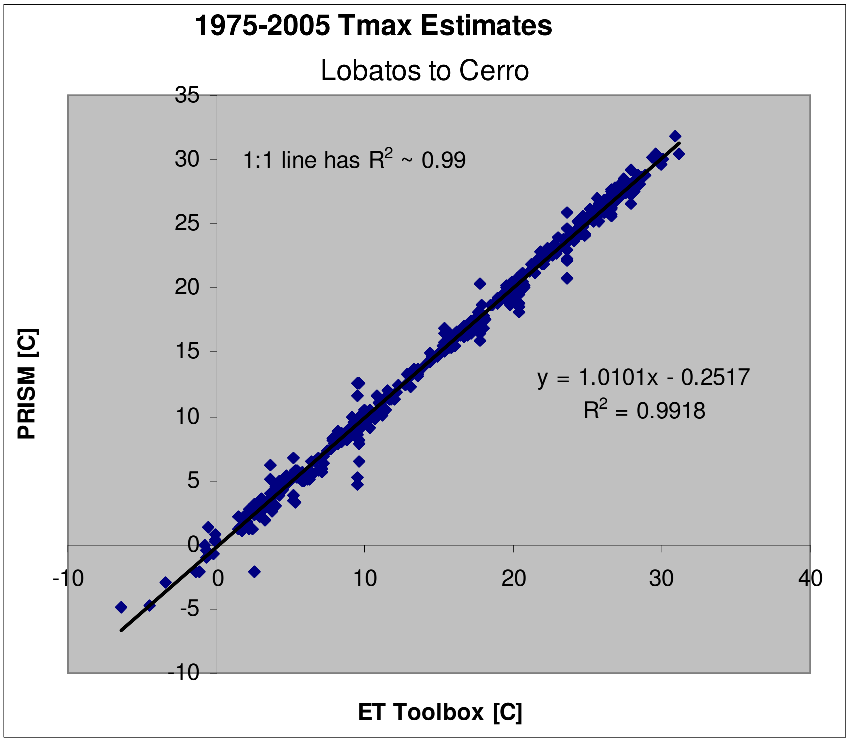


Figure A-6: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Cerro to Taos Junction Bridge.

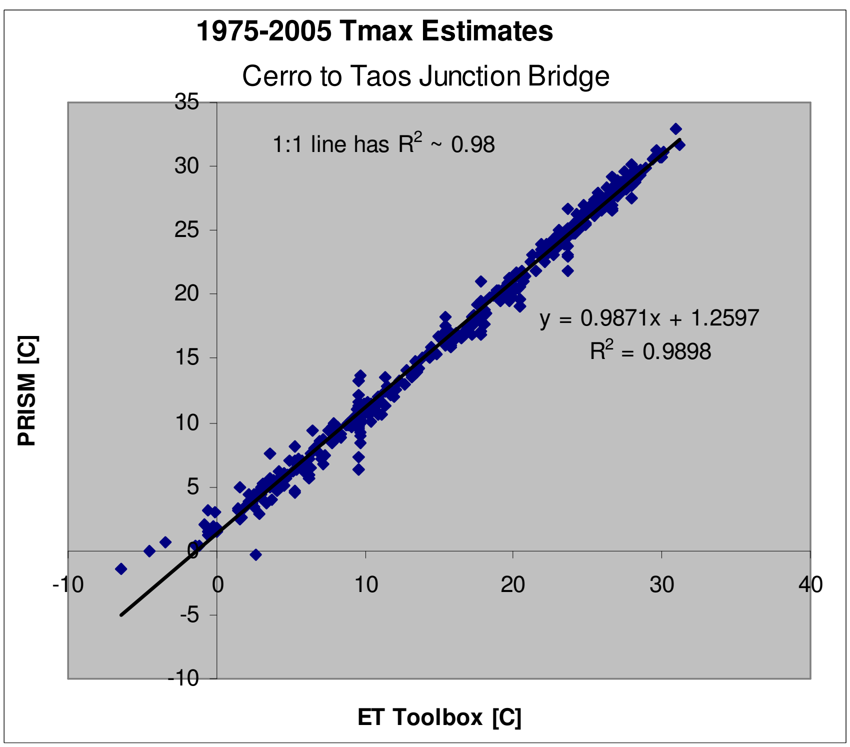


Figure A-7: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Taos Junction Bridge to Embudo.

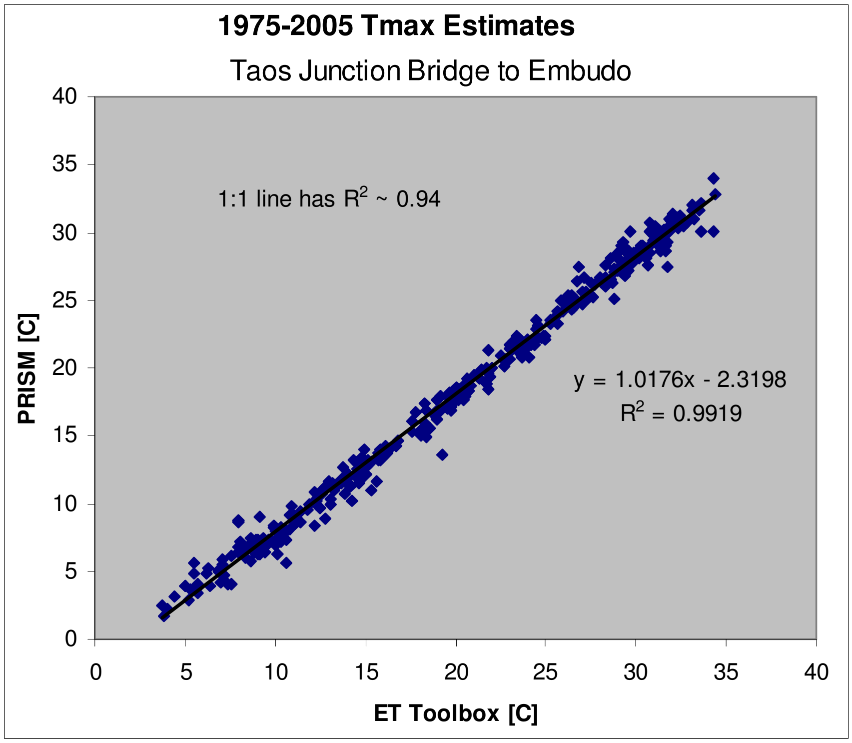


Figure A-8: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Embudo to Otowi.

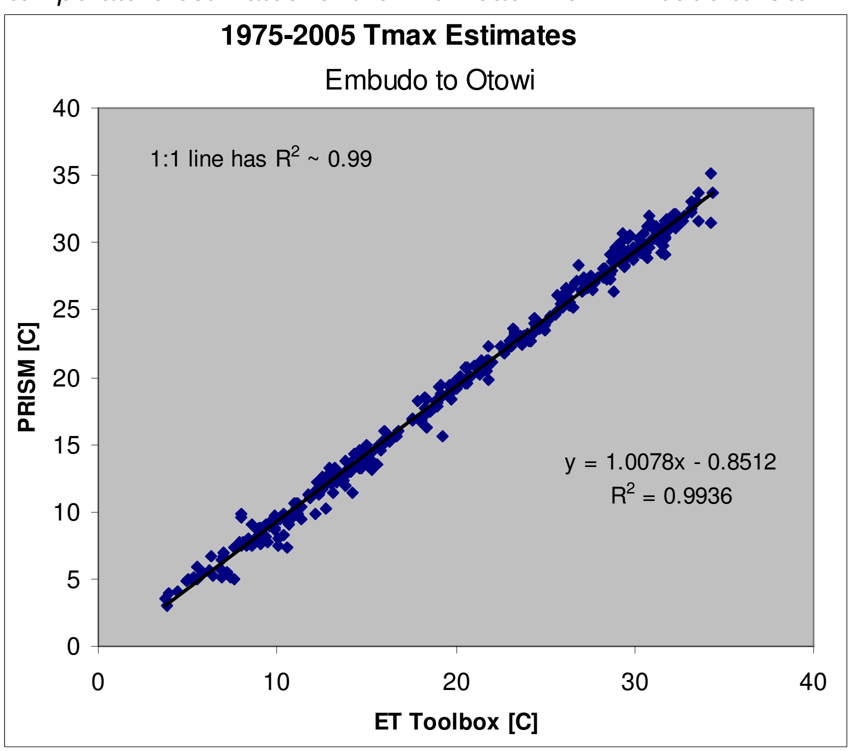


Figure A-9: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Otowi to Cochiti.

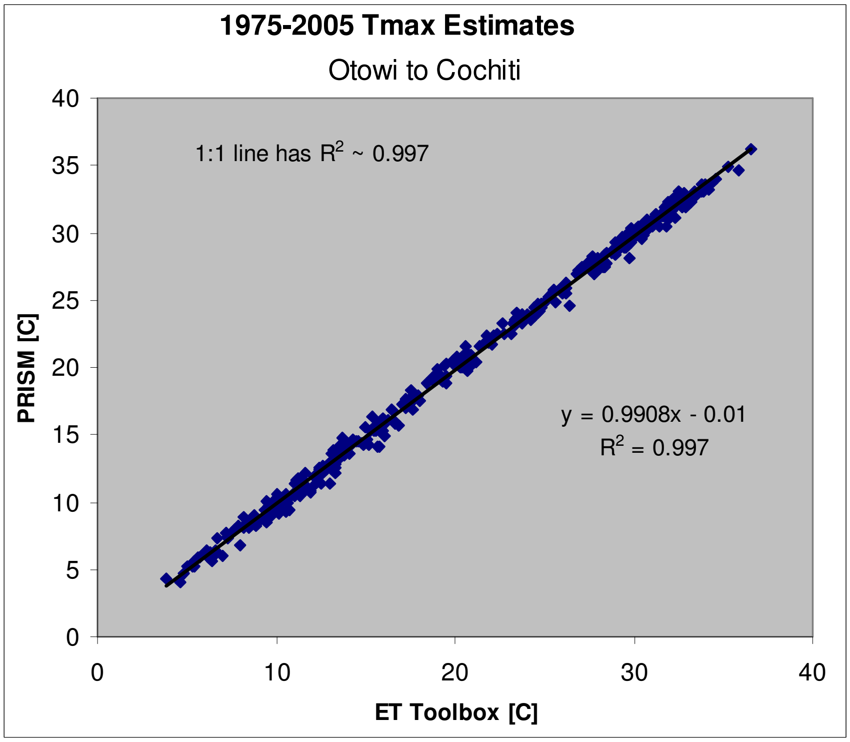


Figure A-10: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Cochiti to San Felipe.

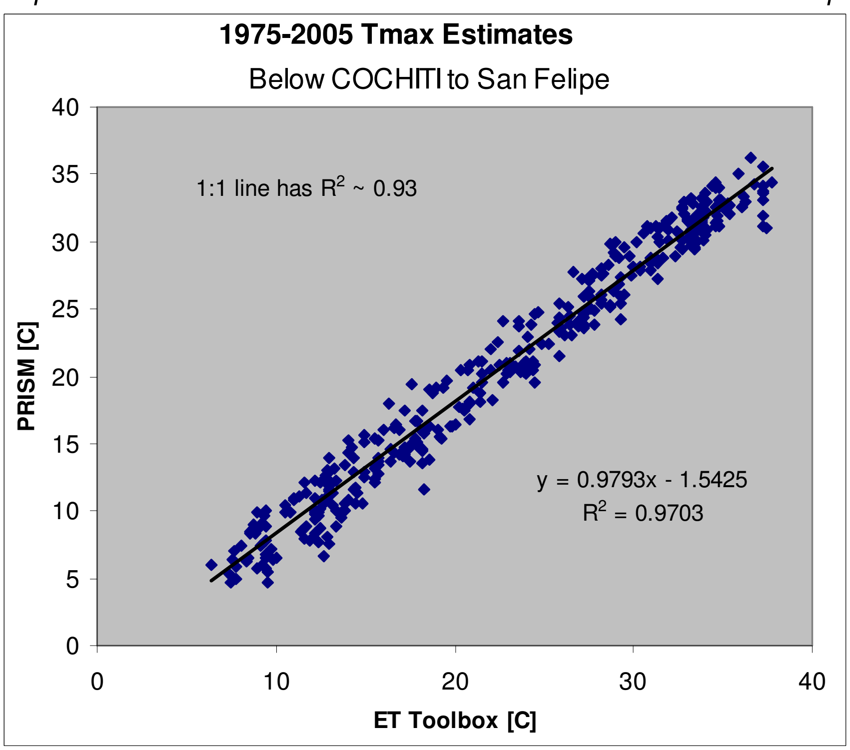


Figure A-11: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Jemez Pueblo to Jemez Canyon Dam.

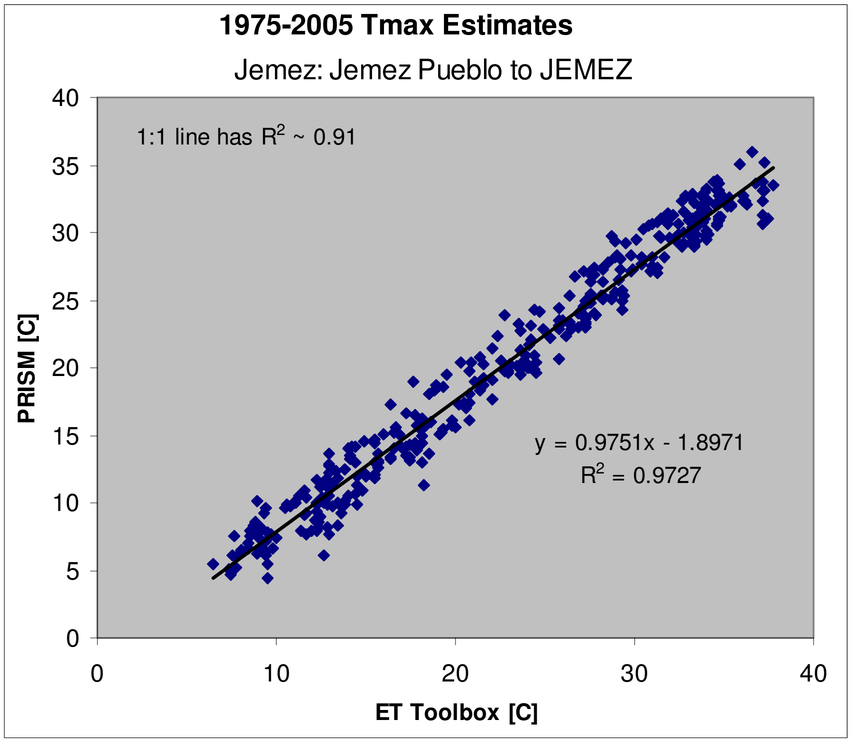


Figure A-12: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from San Felipe to Albuquerque.

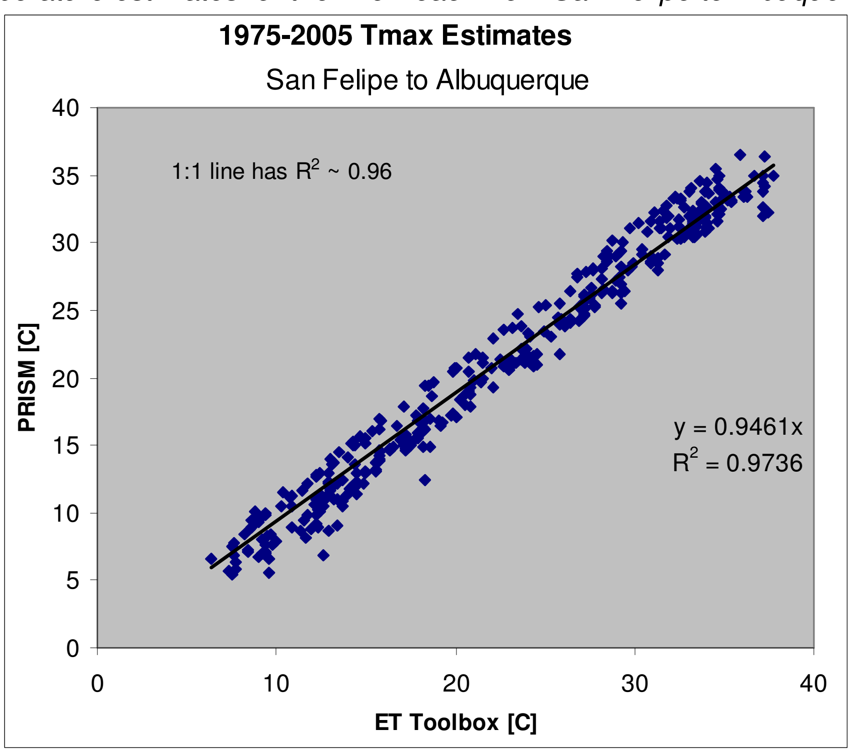


Figure A-13: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Albuquerque to Bernardo.

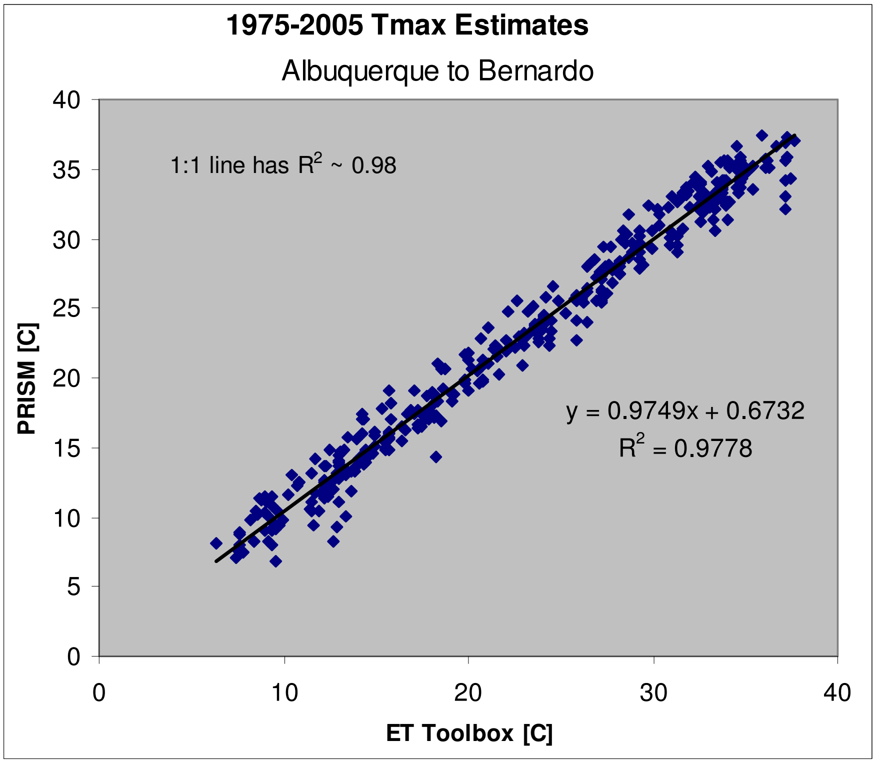


Figure A-14: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Bernardo to San Acacia.

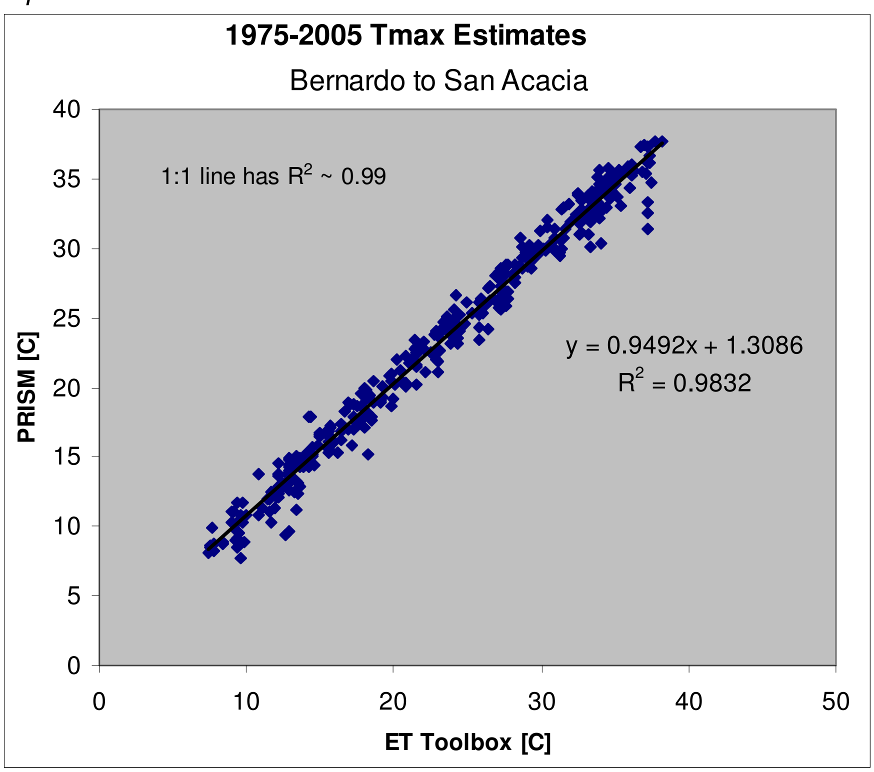


Figure A-15: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from San Acacia to San Marcial.

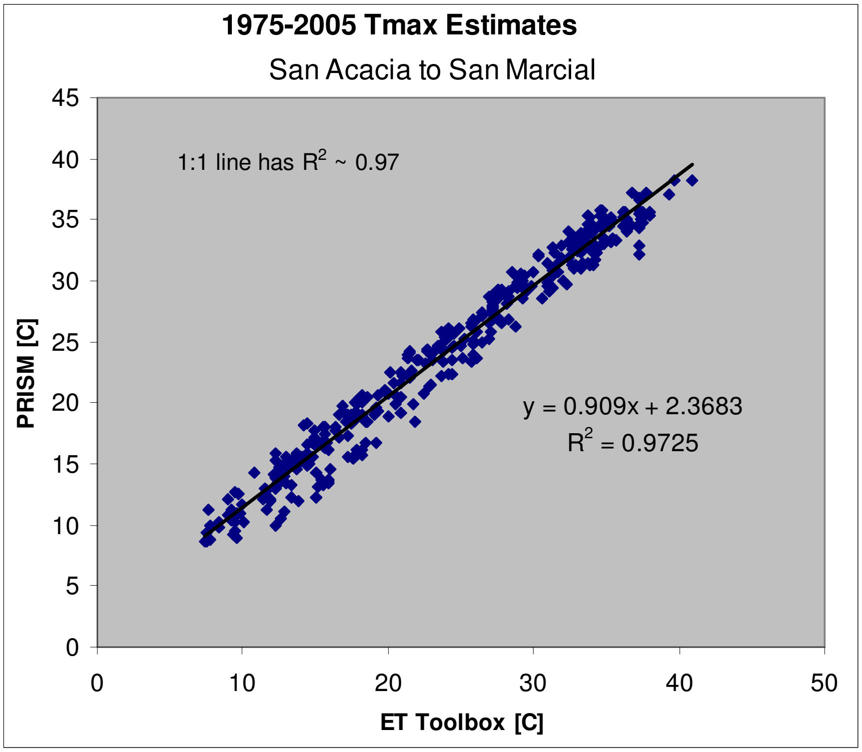


Figure A-16: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from San Marcial to Elephant Butte.

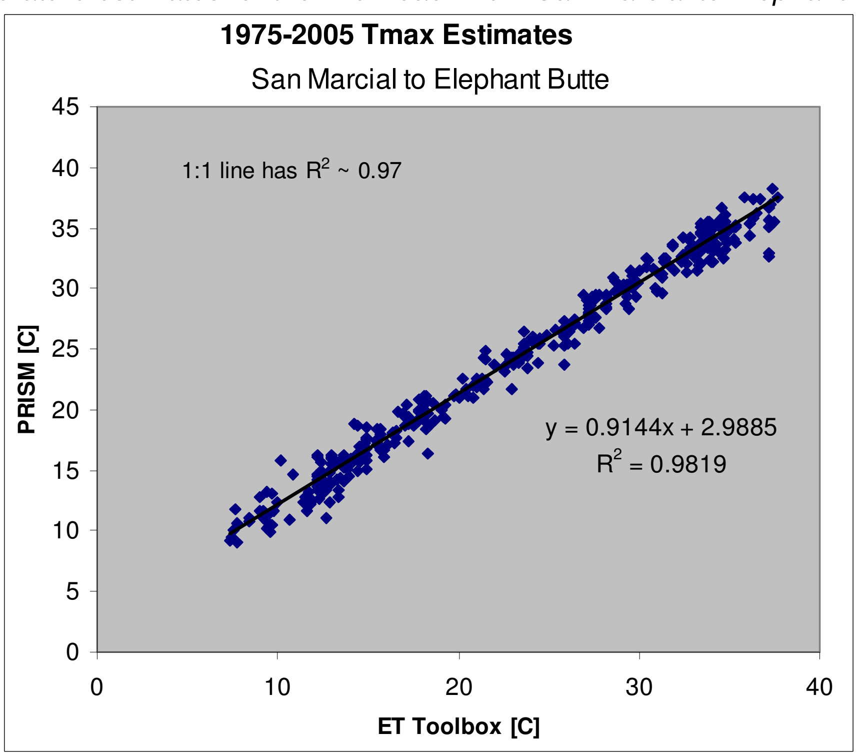
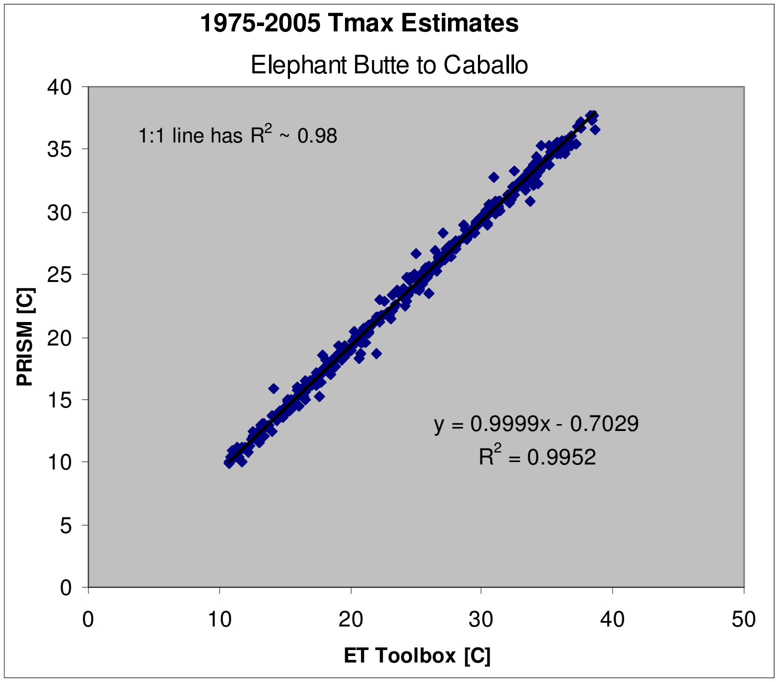


Figure A-17: Comparison of PRISM and ETToolbox monthly average maximum temperature estimates for the river reach from Elephant Butte to Caballo.



Appendix B:

Reach based minimum temperature data comparison figures.

Figure B-1: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Willow Creek to Heron.

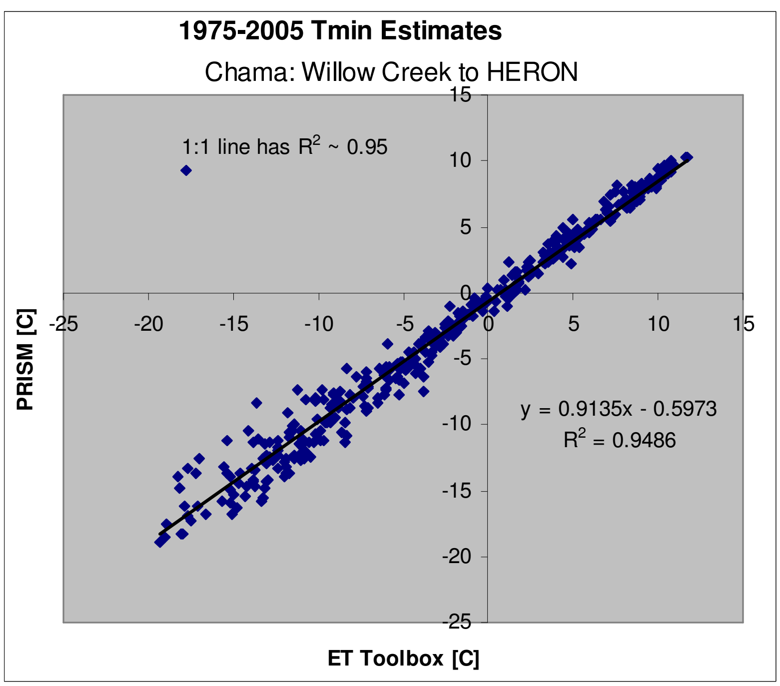


Figure B-2: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Heron to El Vado.

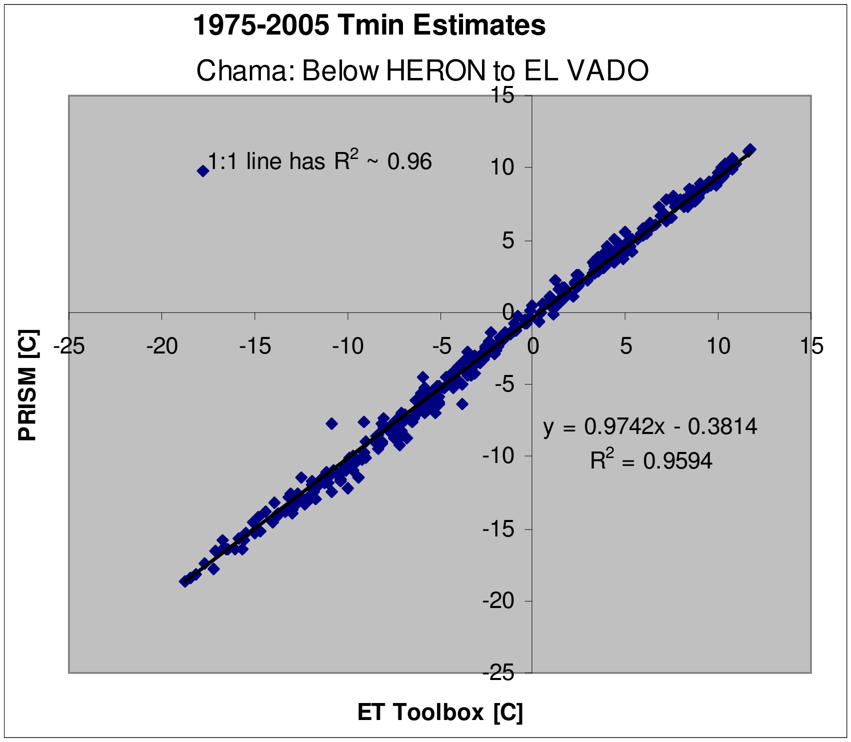


Figure B-3: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from El Vado to Abiquiu.

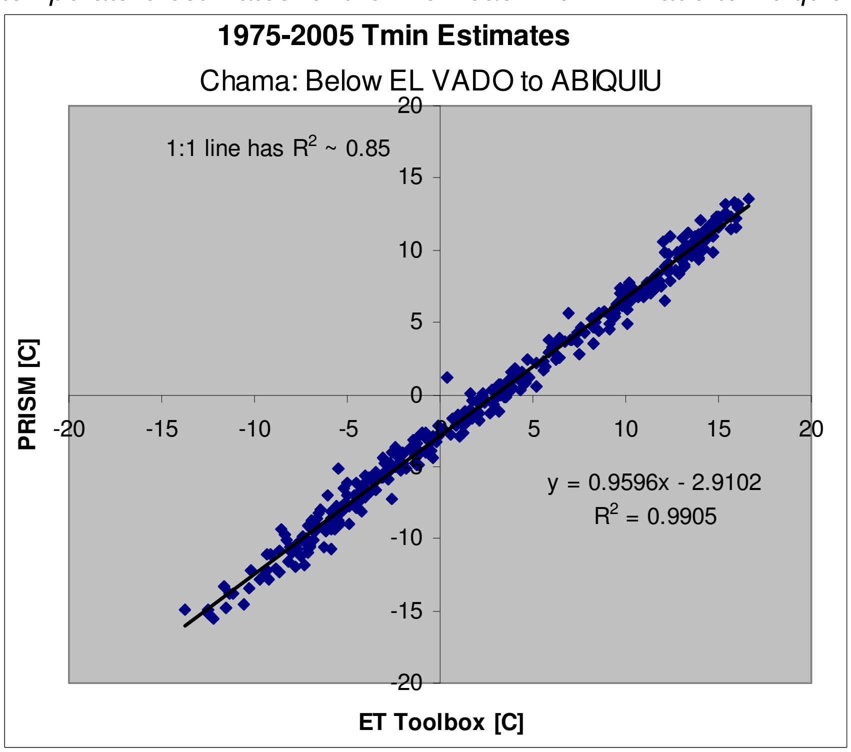


Figure B-4: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Abiquiu to Chamita.

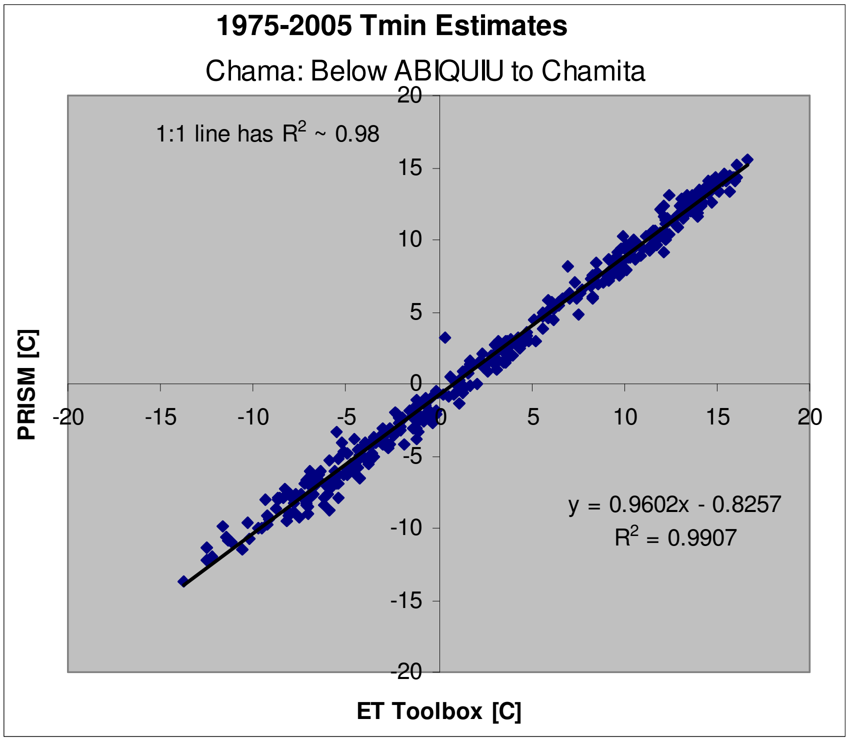


Figure B-5: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Lobatos to Cerro.

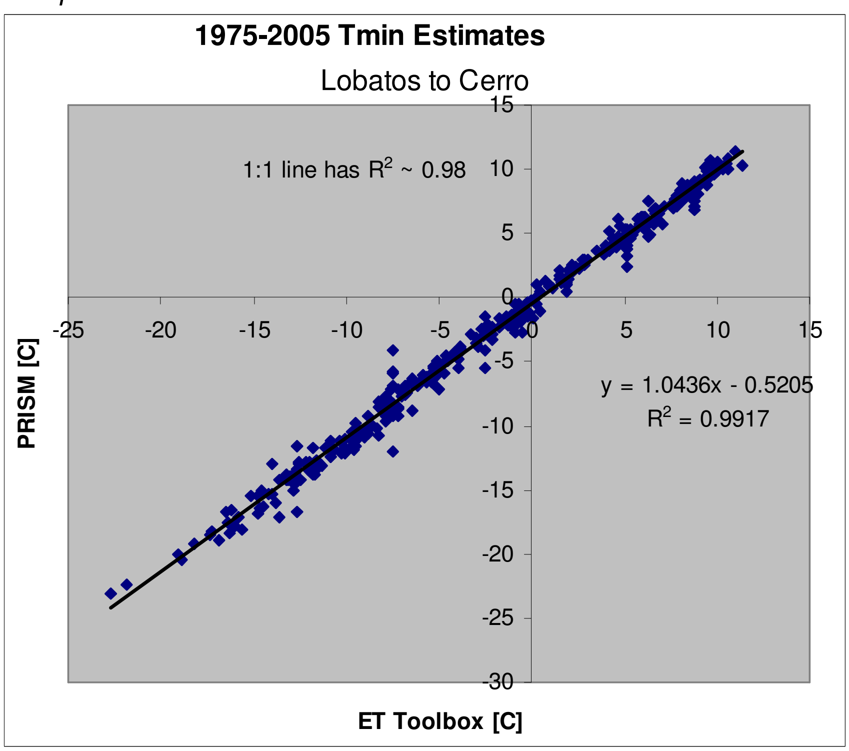


Figure B-6: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Cerro to Taos Junction Bridge.

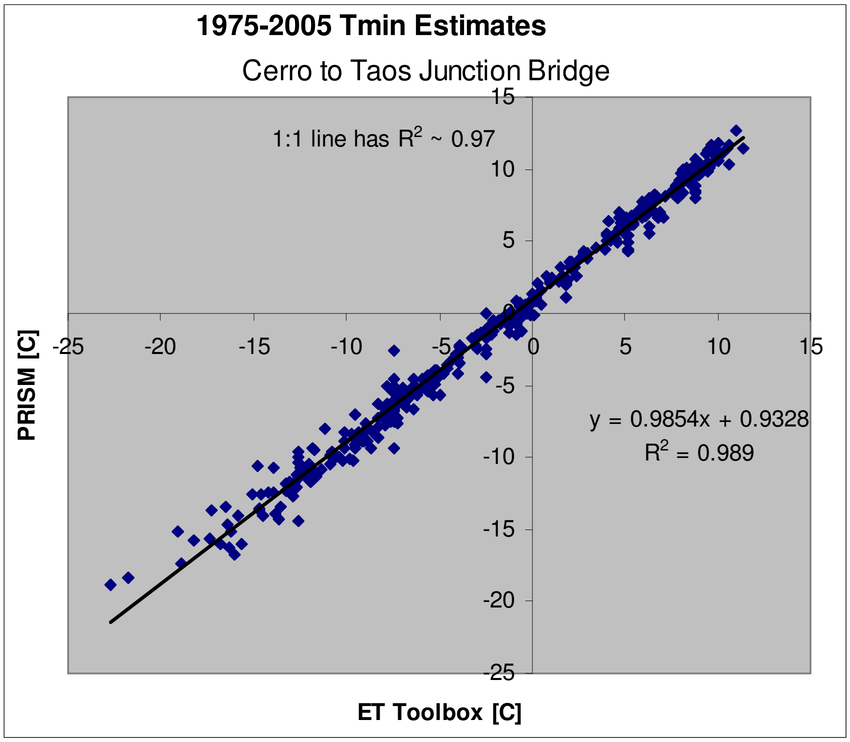


Figure B-7: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Taos Junction Bridge to Embudo.

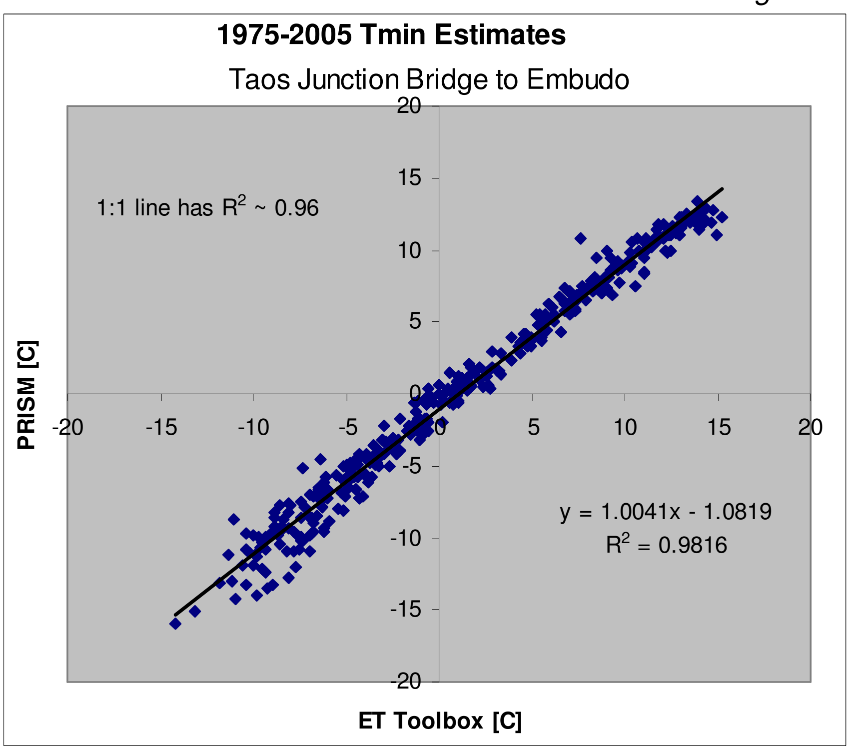


Figure B-8: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Embudo to Otowi.

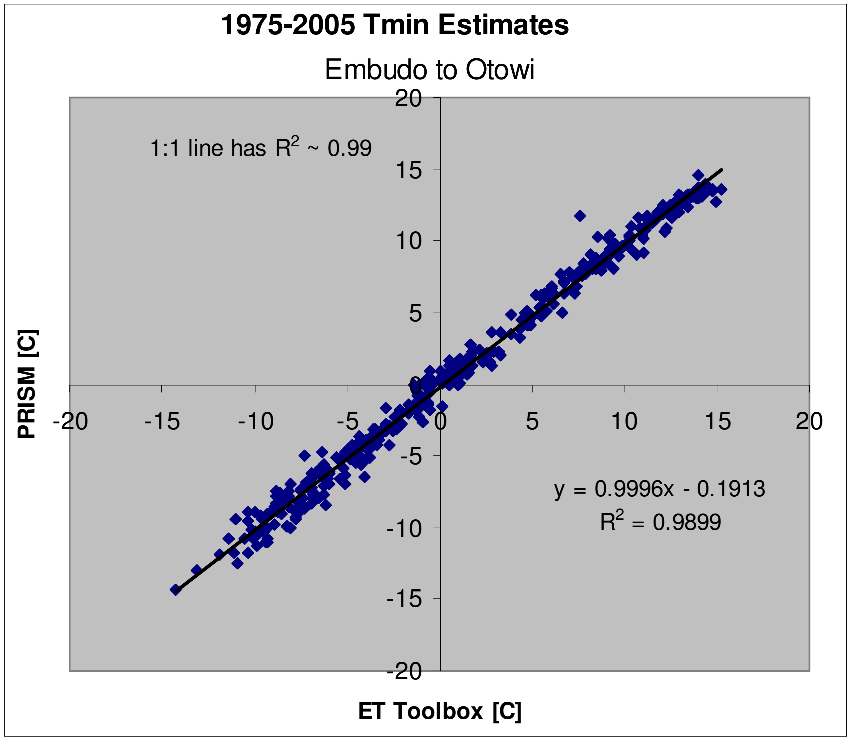


Figure B-9: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Otowi to Cochiti.

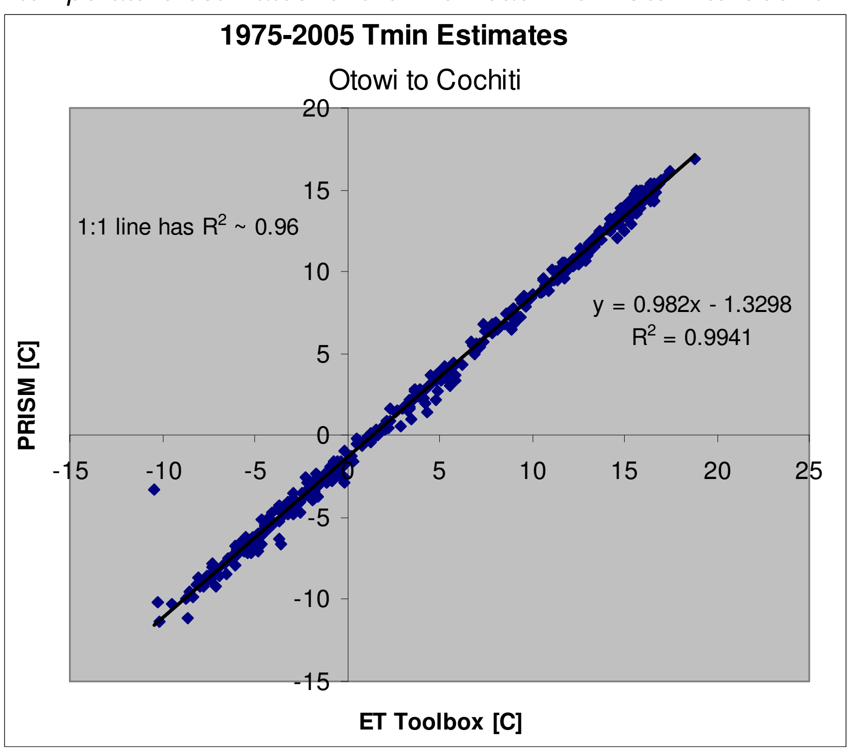


Figure B-10: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Cochiti to San Felipe.

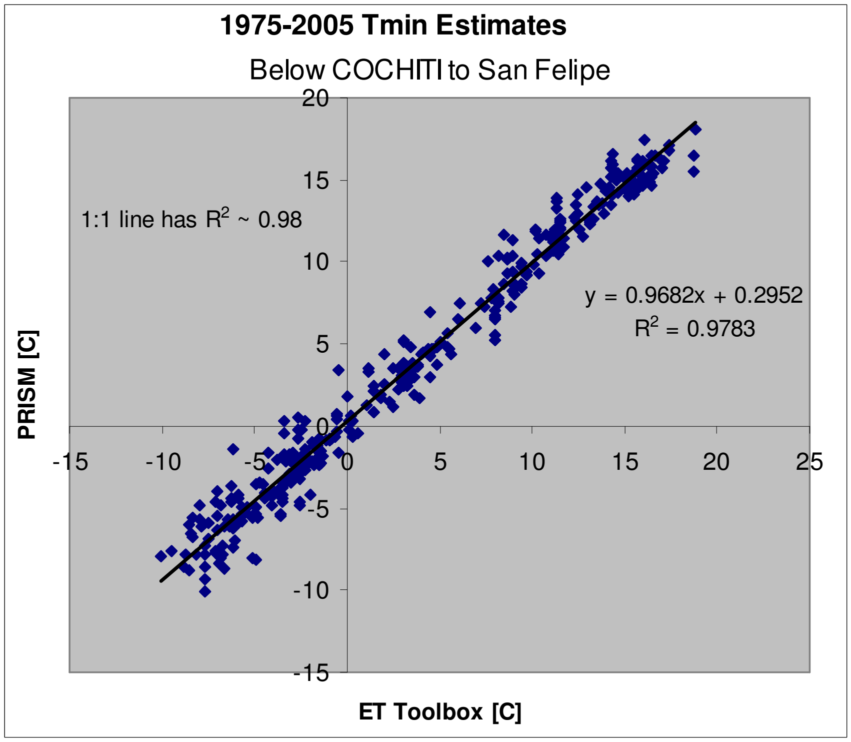


Figure B-11: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Jemez Pueblo to Jemez Canyon Dam.

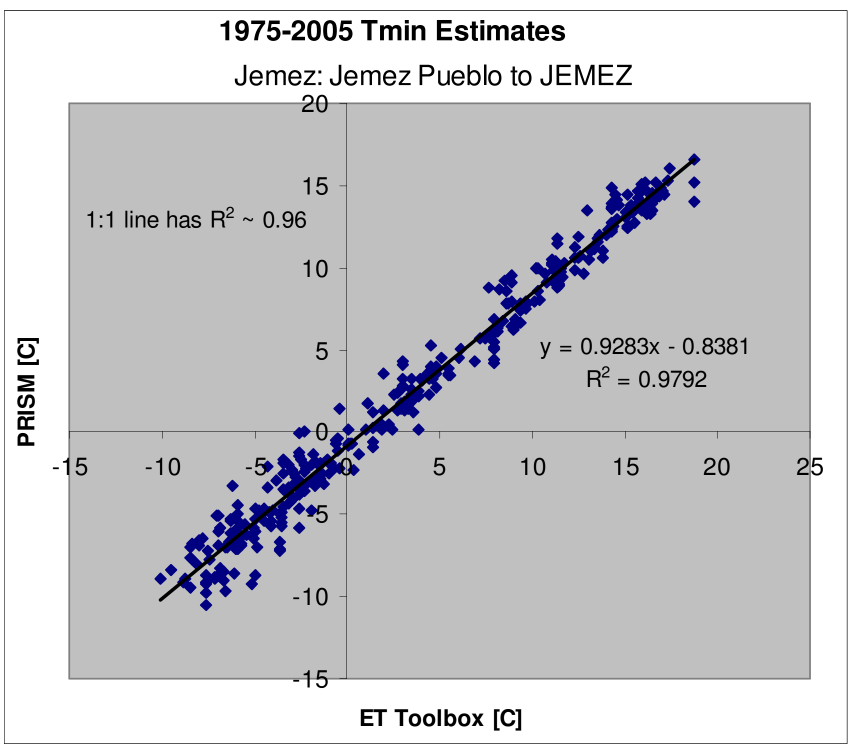


Figure B-12: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from San Felipe to Albuquerque.

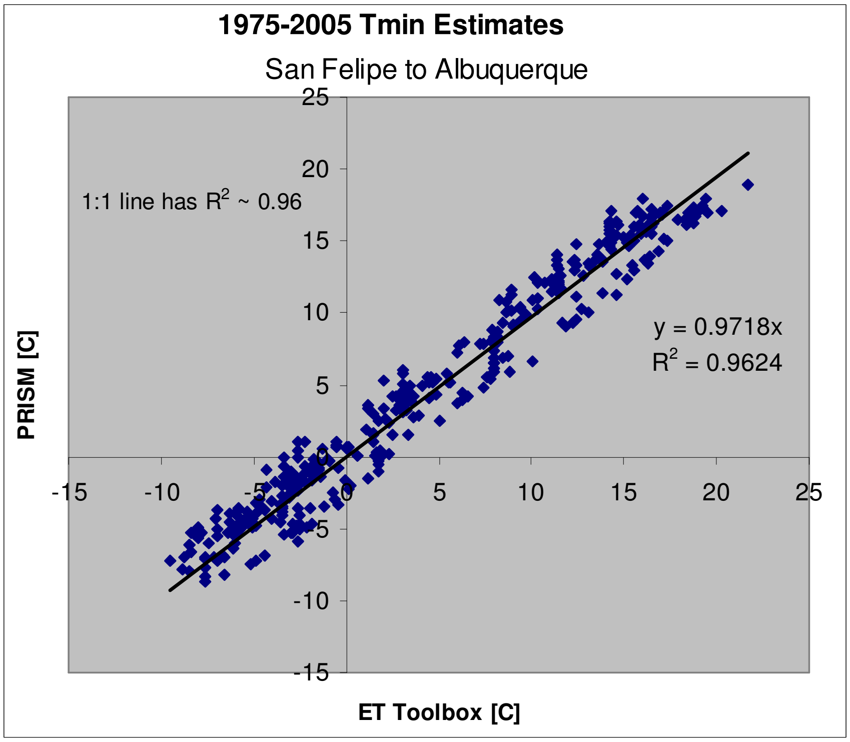


Figure B-13: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Albuquerque to Bernardo.

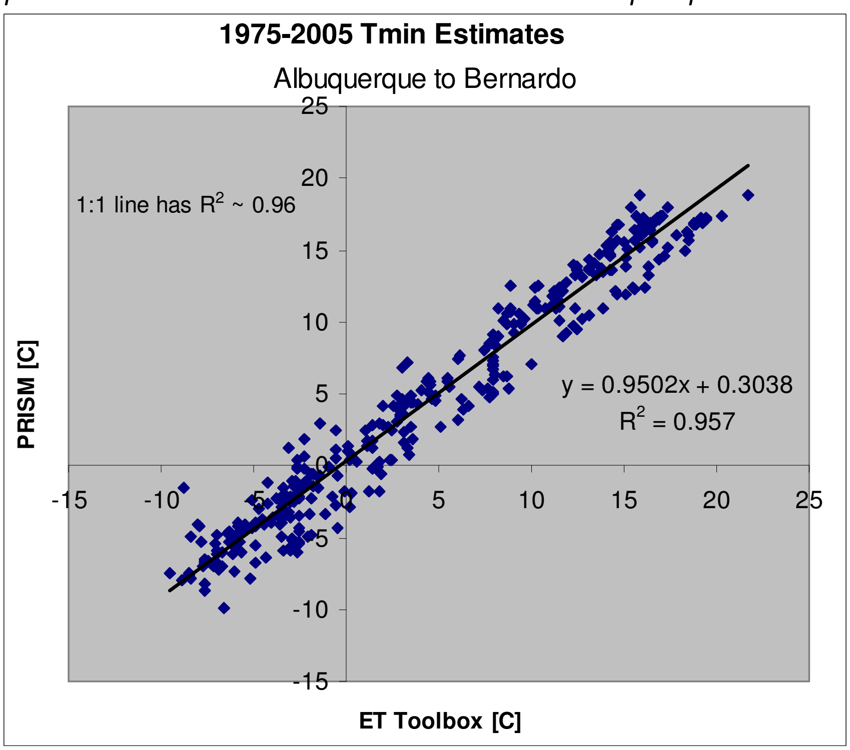


Figure B-14: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Bernardo to San Acacia.

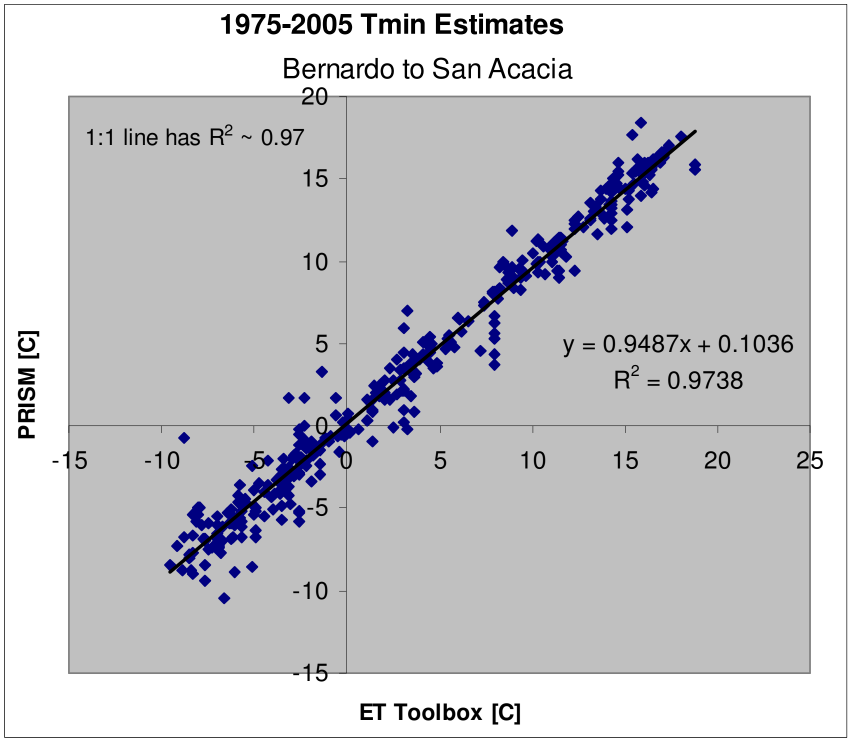


Figure B-15: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from San Acacia to San Marcial.

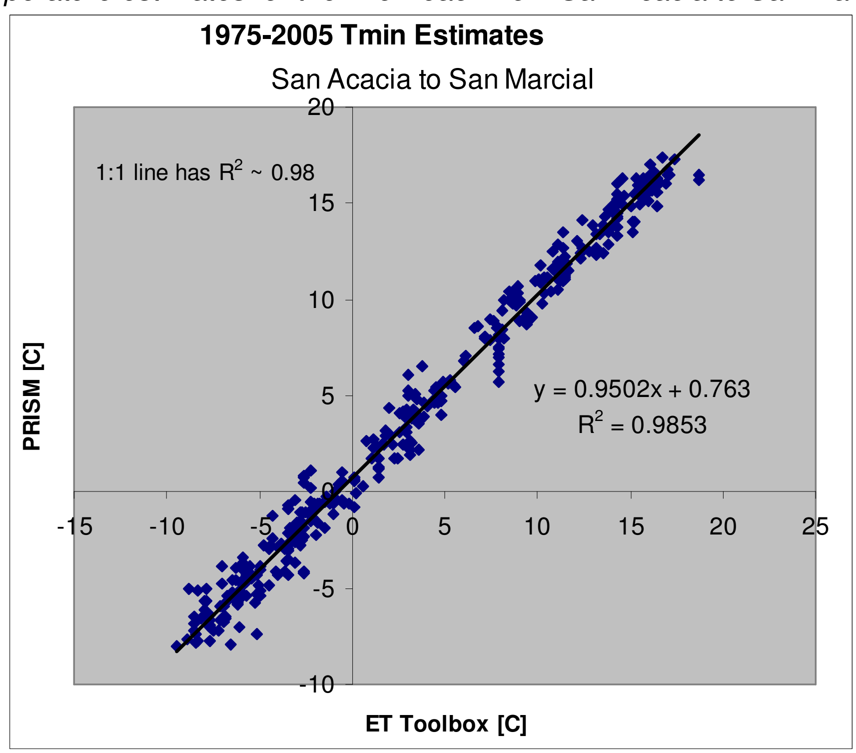


Figure B-16: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from San Marcial to Elephant Butte.

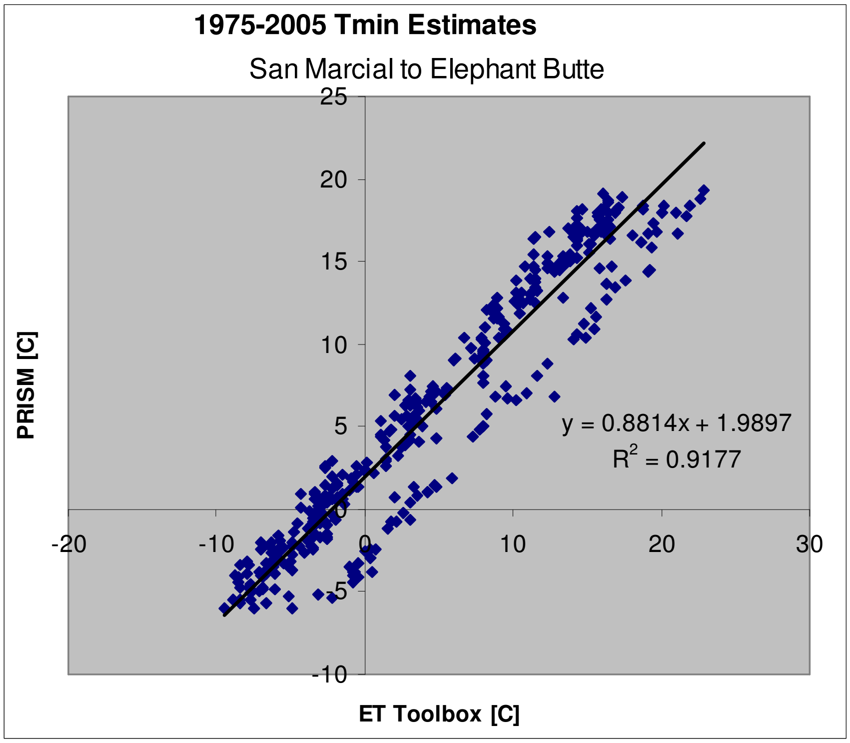
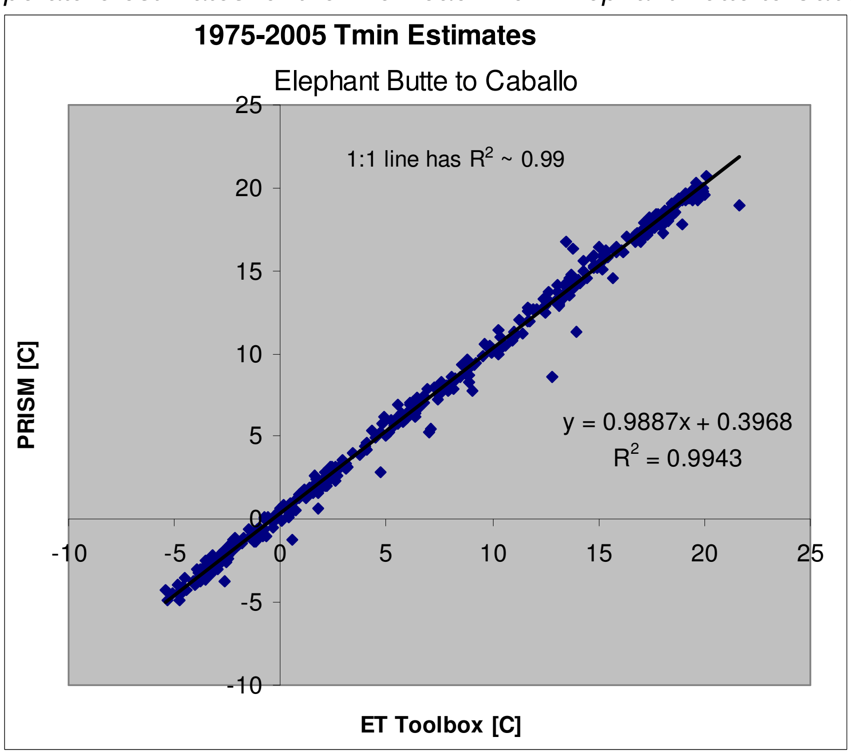


Figure B-17: Comparison of PRISM and ETToolbox monthly average minimum temperature estimates for the river reach from Elephant Butte to Caballo.



Appendix C:

Output for baseline run:

Figure C-1: Stochastic model output compared to observed record (1895-2008) for Rio Grande flow at Otowi (USGS Gage# [8313000](8313000)).

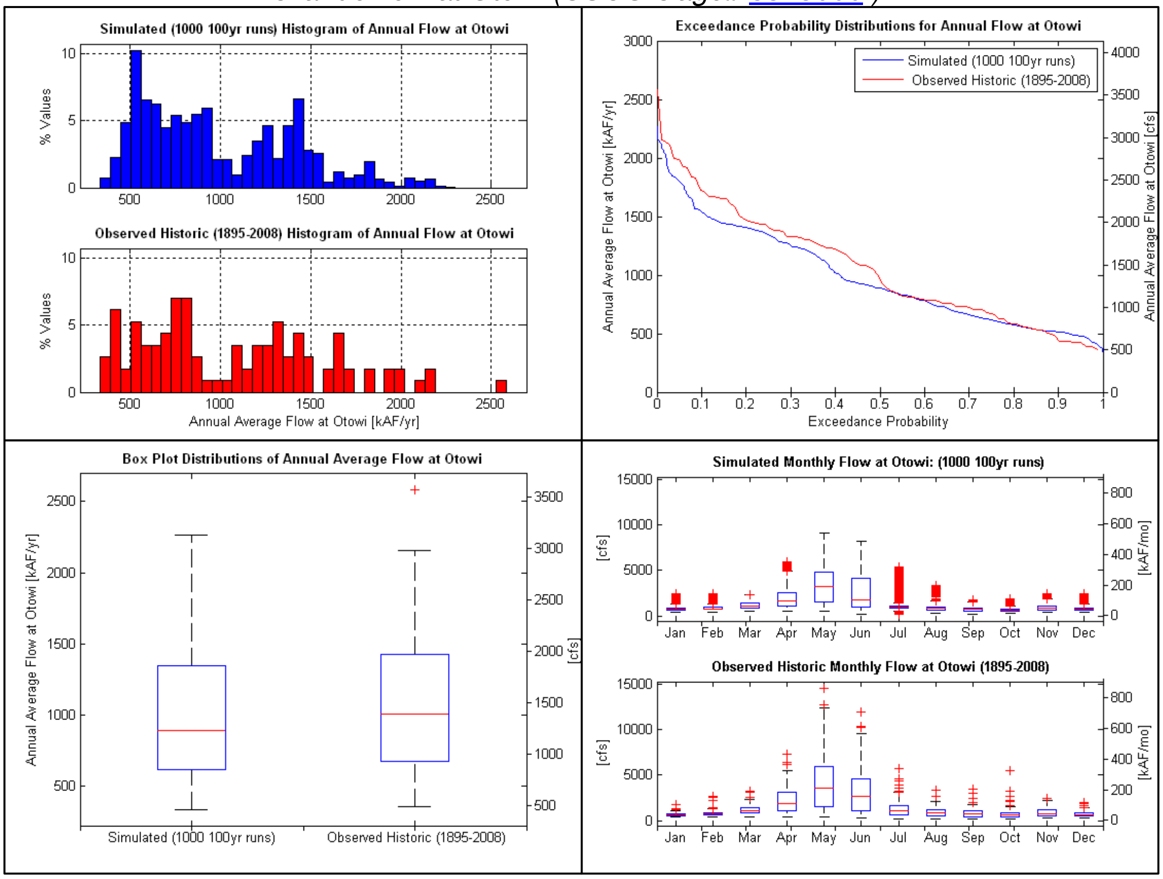


Figure C-2: Stochastic model output compared to observed record (1942-2008) for Rio Grande flow at Central Bridge in Albuquerque (USGS Gage# [8330000](8330000)).

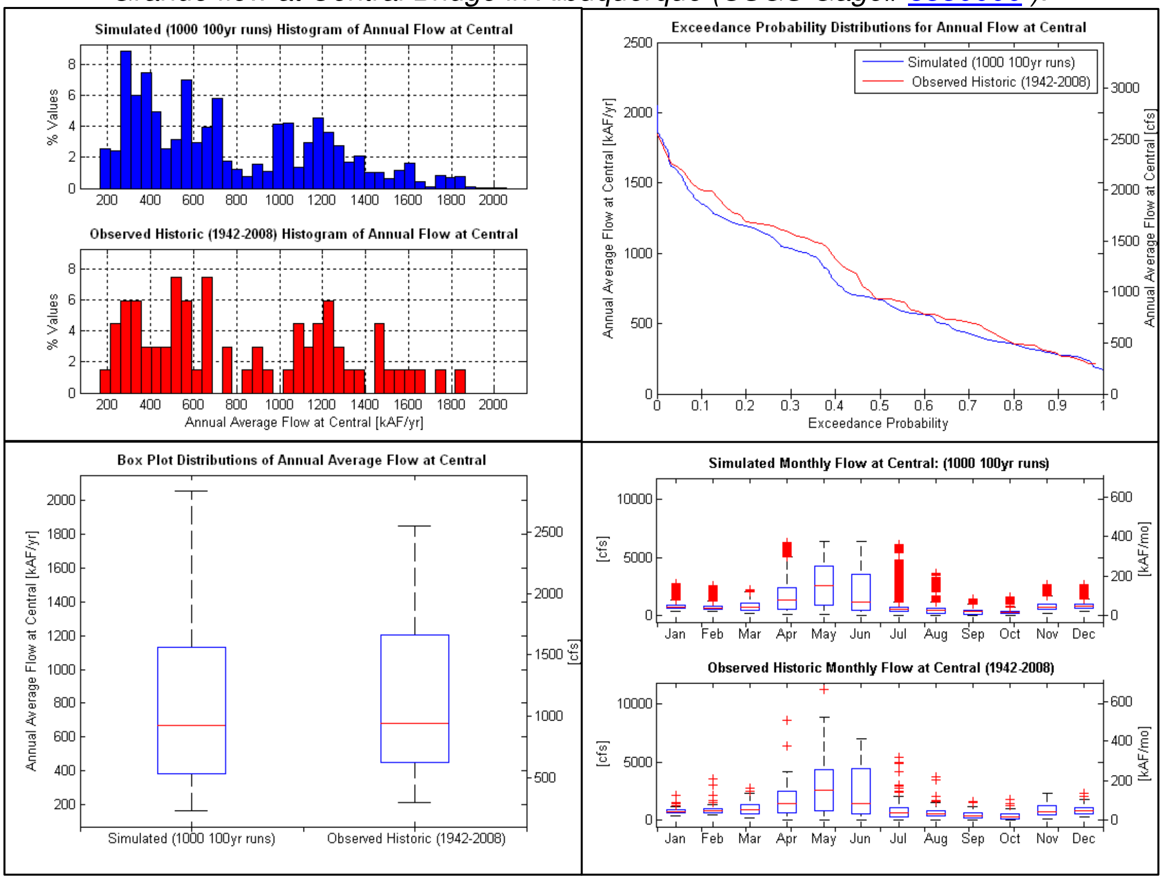


Figure C-3: Stochastic model output compared to observed record (1949-2008) for Rio Grande flow at San Marcial (USGS Gage# 8358400).

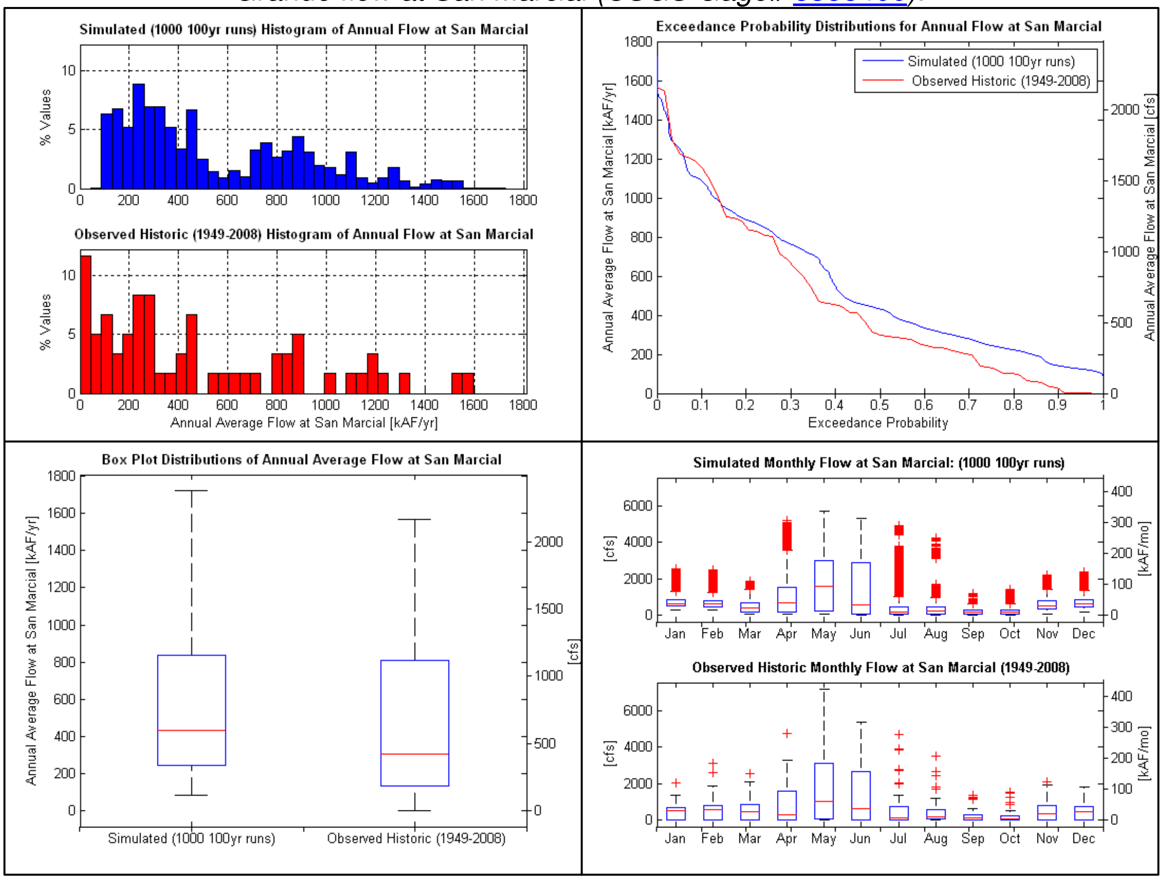


Figure C-4: Stochastic model output compared to observed record (1938-2008) for Rio Grande flow below Caballo (USGS Gage# [8362500](8362500)).

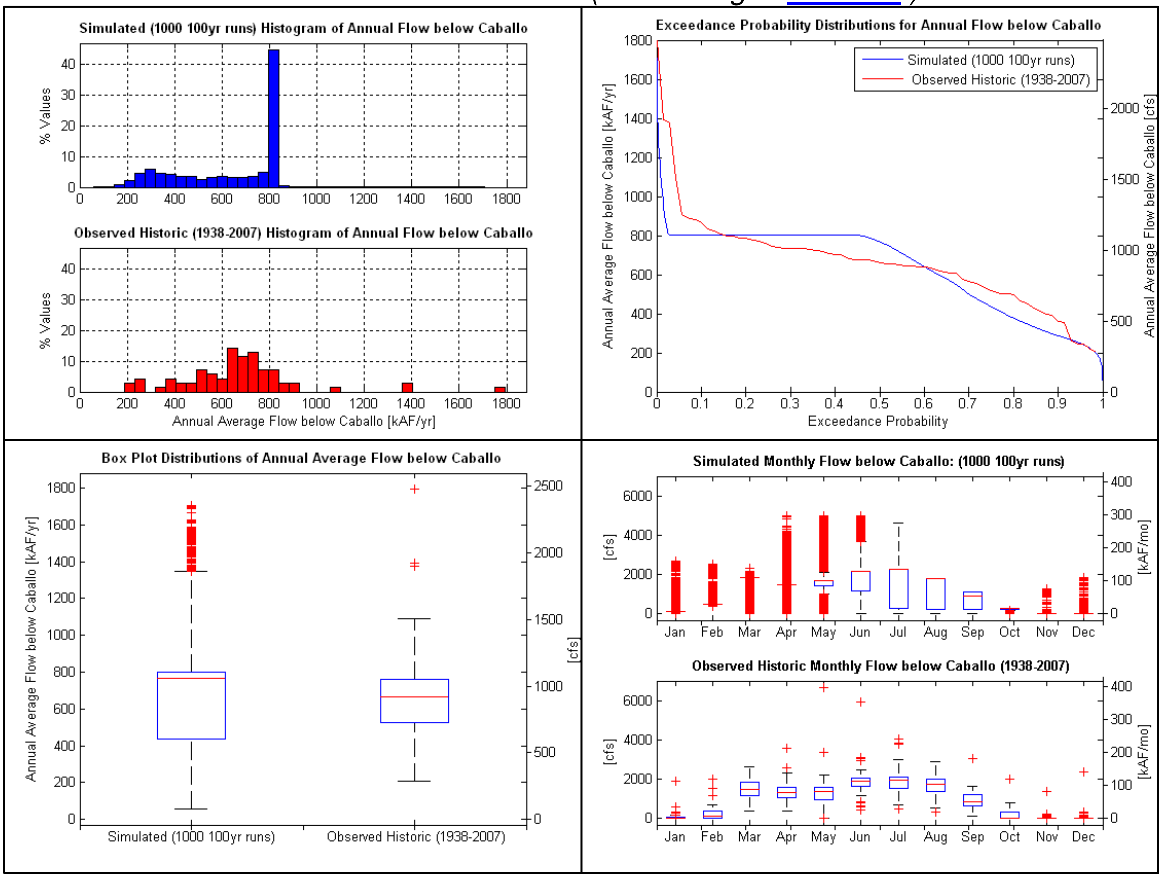


Figure C-5: Stochastic model output compared to observed record (1975-2008) for storage in Heron Reservoir.

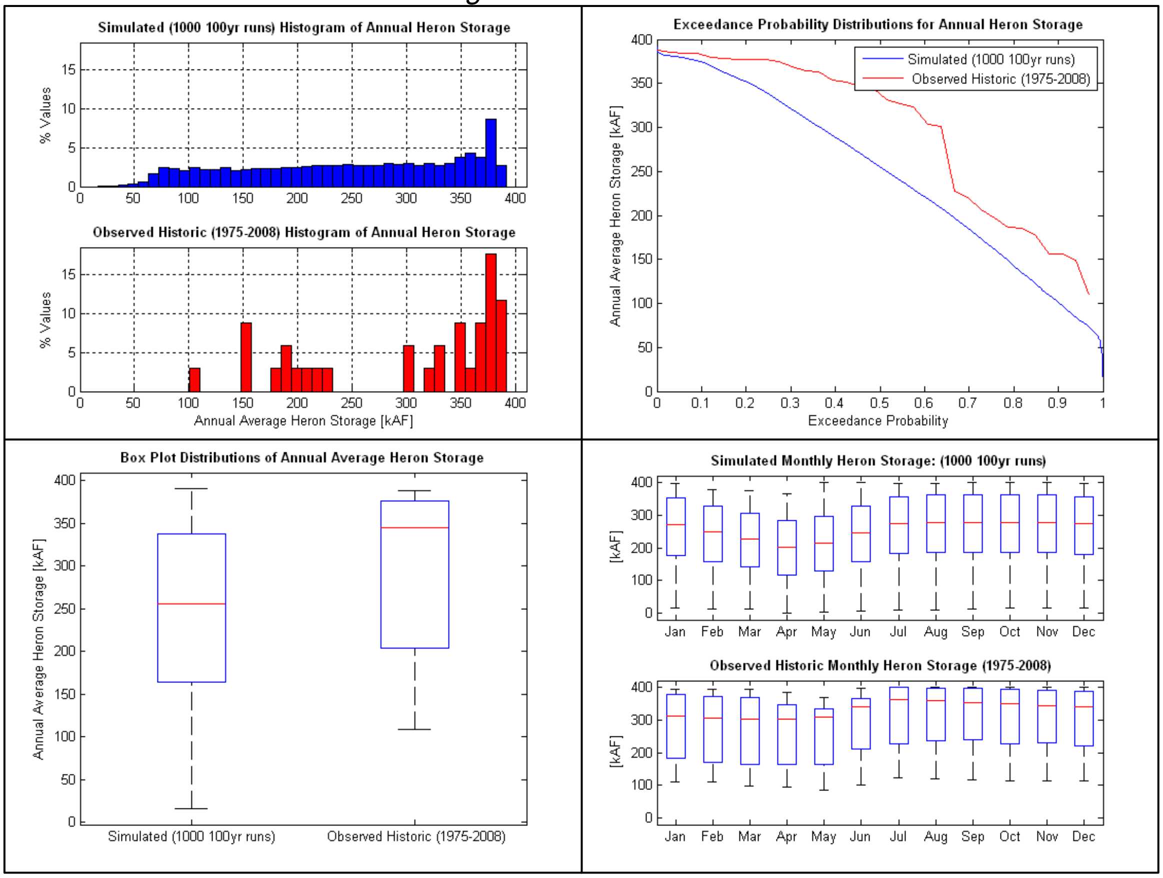


Figure C-6: Stochastic model output compared to observed record (1965-2008) for storage in El Vado Reservoir.

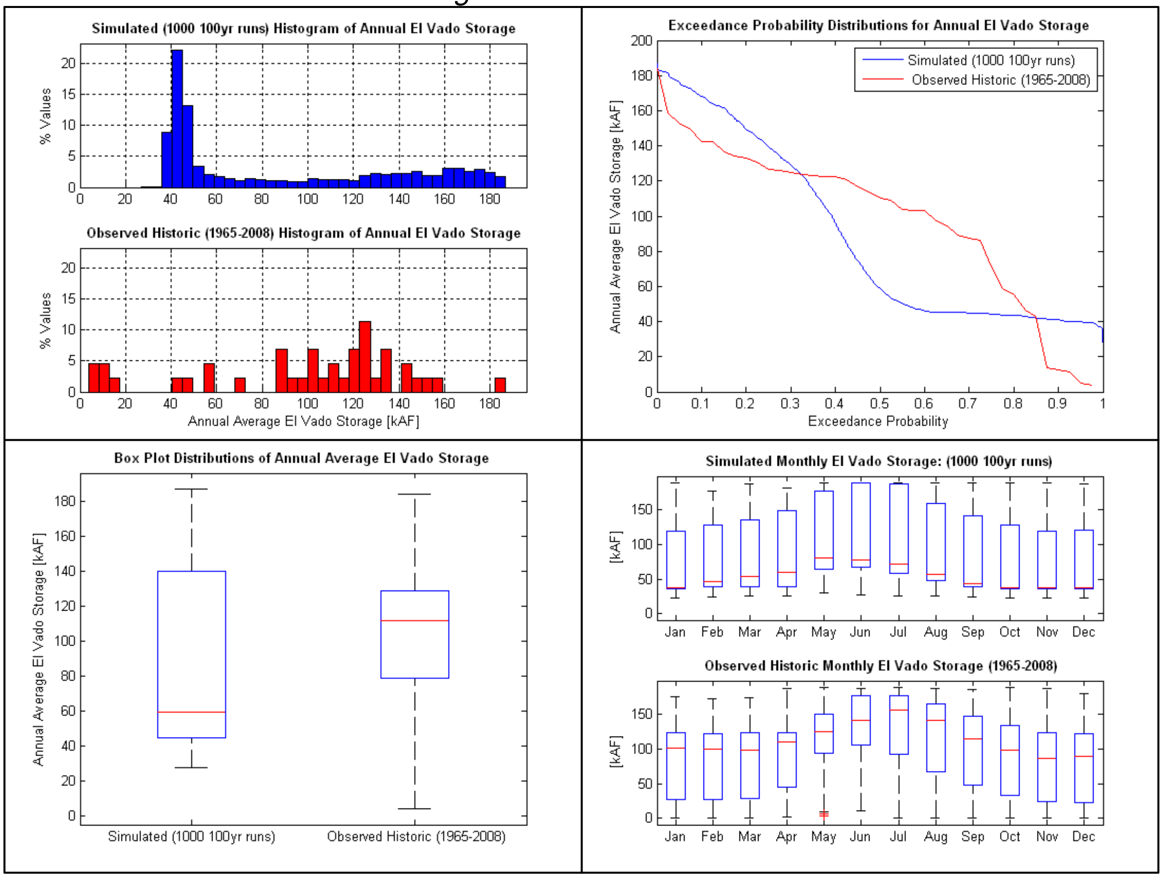


Figure C-7: Stochastic model output compared to observed record (1975-2008) for storage in Abiquiu Reservoir.

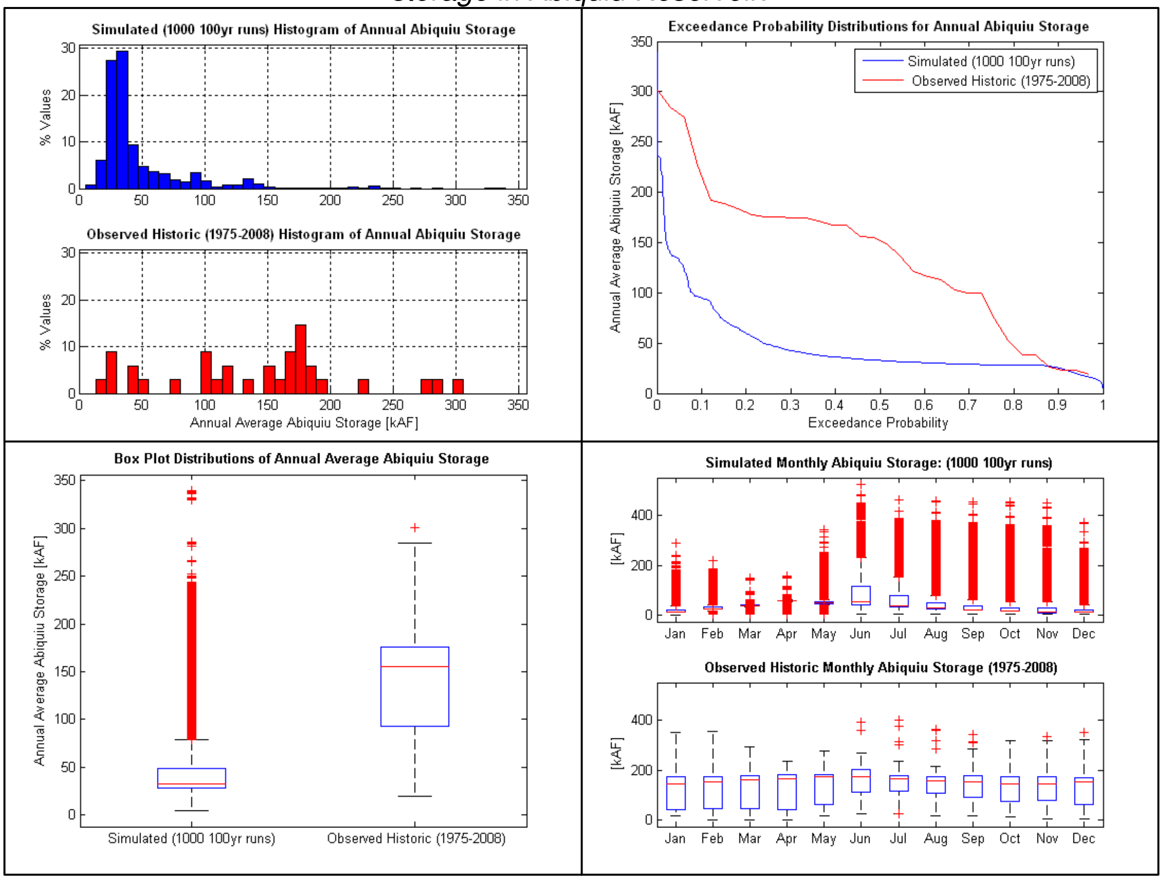


Figure C-8: Stochastic model output compared to observed record (1975-2008) for storage in Cochiti Reservoir.

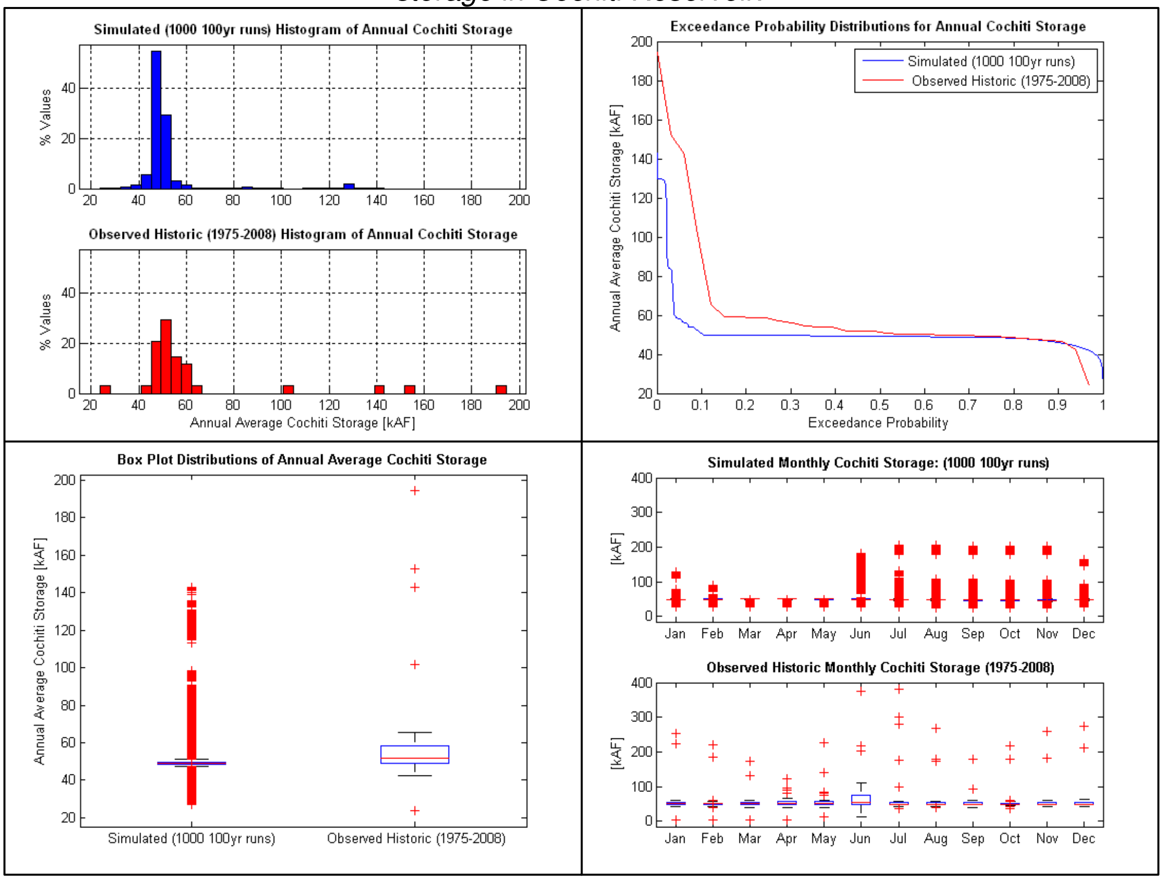


Figure C-9: Stochastic model output compared to observed record (1975-2008) for storage in Jemez Reservoir.

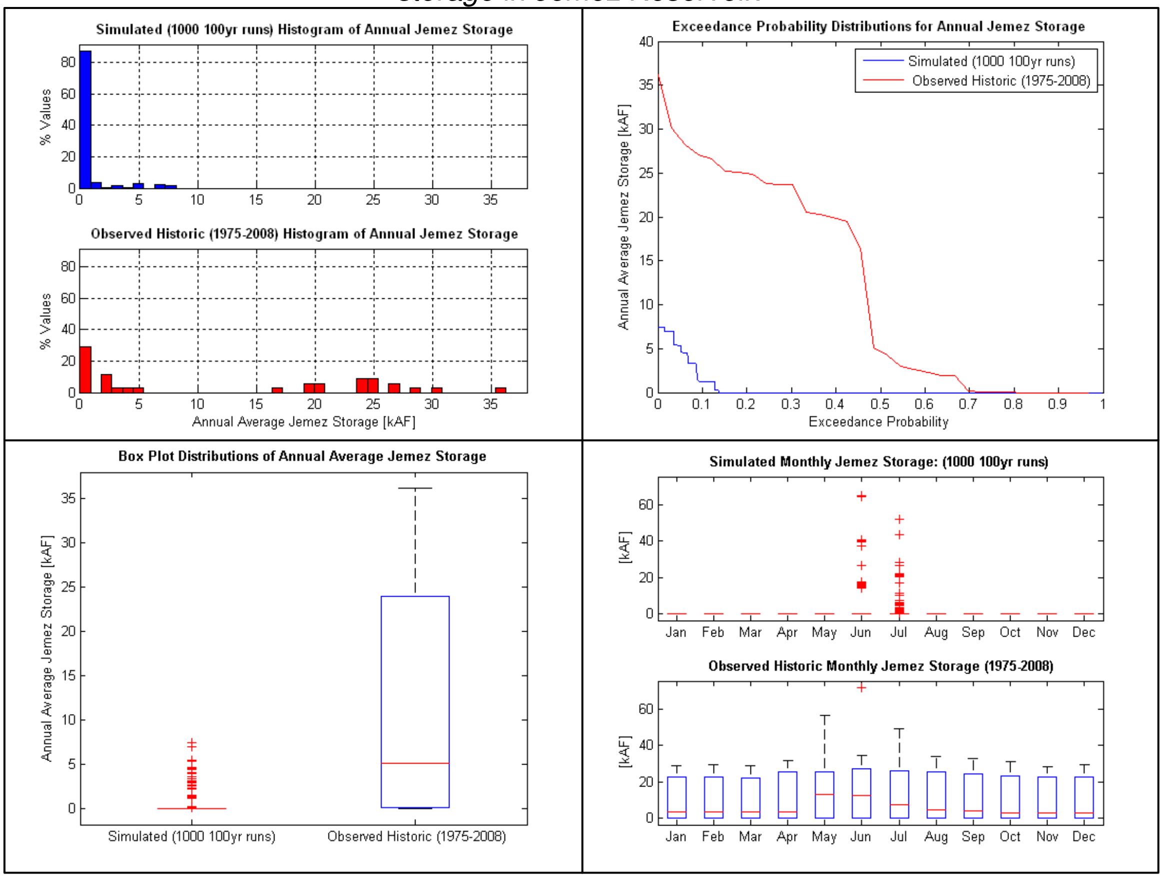


Figure C-10: Stochastic model output compared to observed record (1975-2008) for storage in Elephant Butte Reservoir.

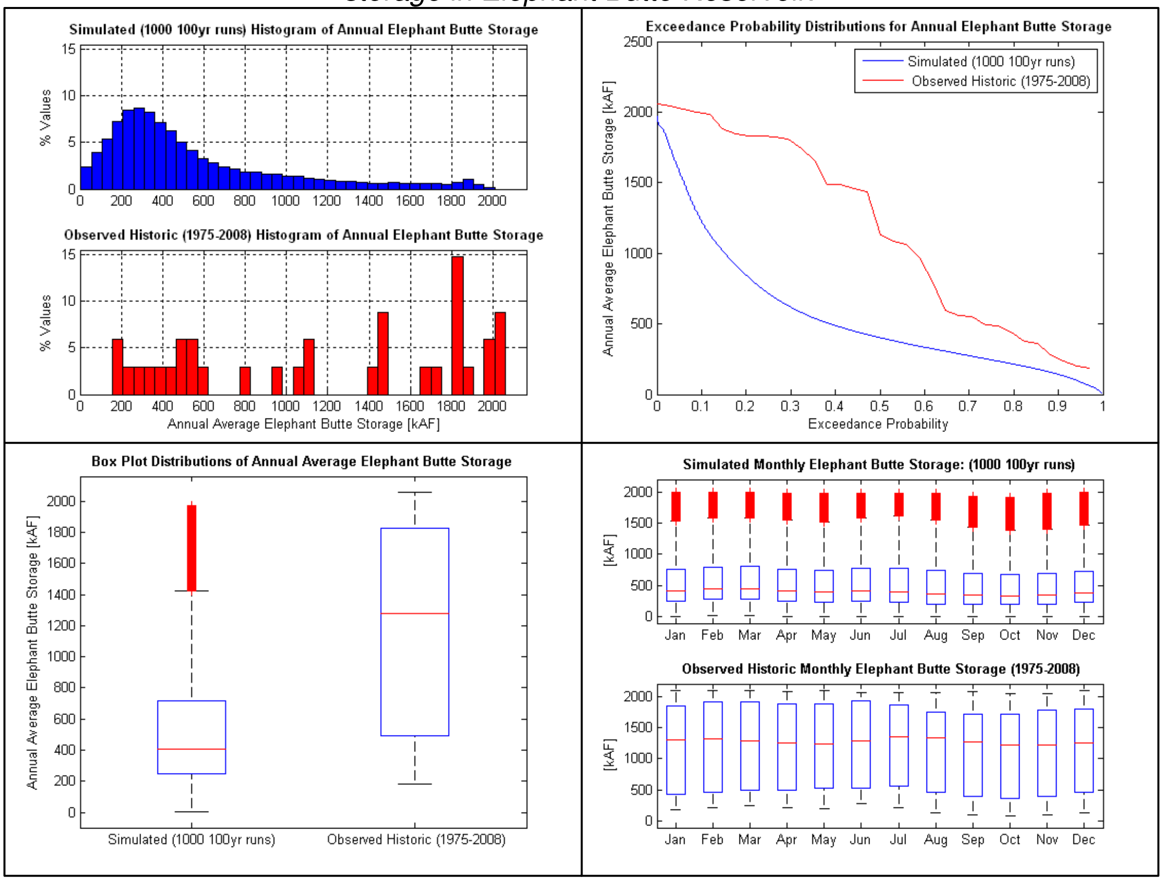


Figure C-11: Stochastic model output compared to observed record (1975-2008) for storage in Caballo Reservoir.

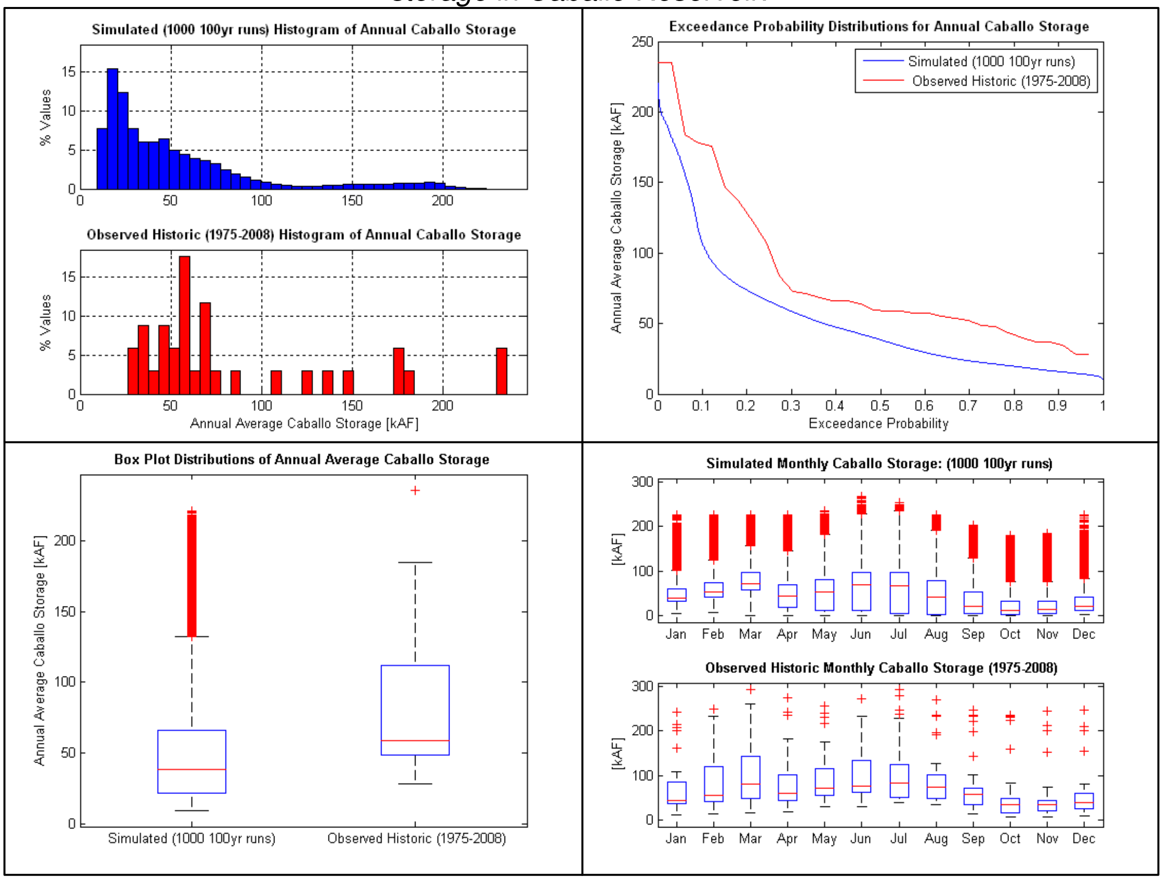


Figure C-12: Stochastic model output compared to observed record (1975-2008) for total storage in Heron, El Vado, Abiquiu, Cochiti, Jemez, Elephant Butte, and Caballo Reservoirs.

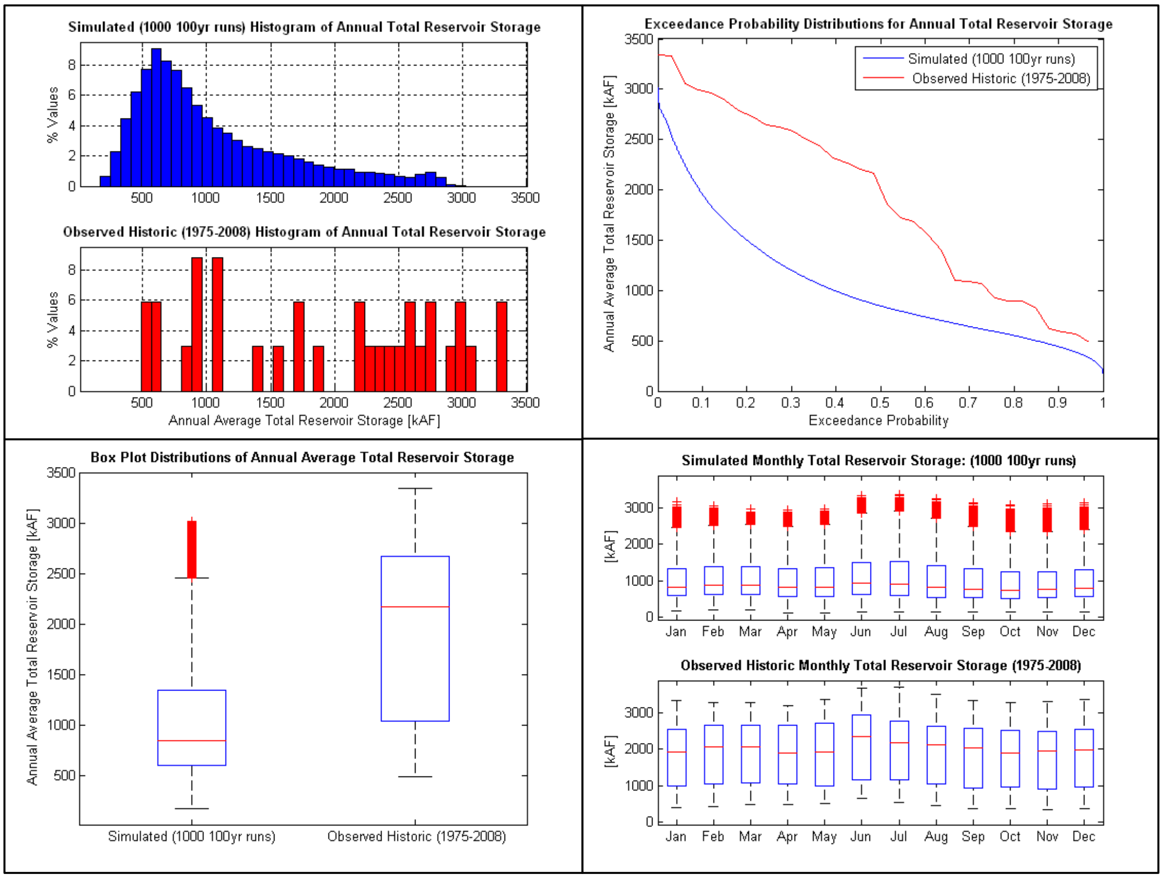
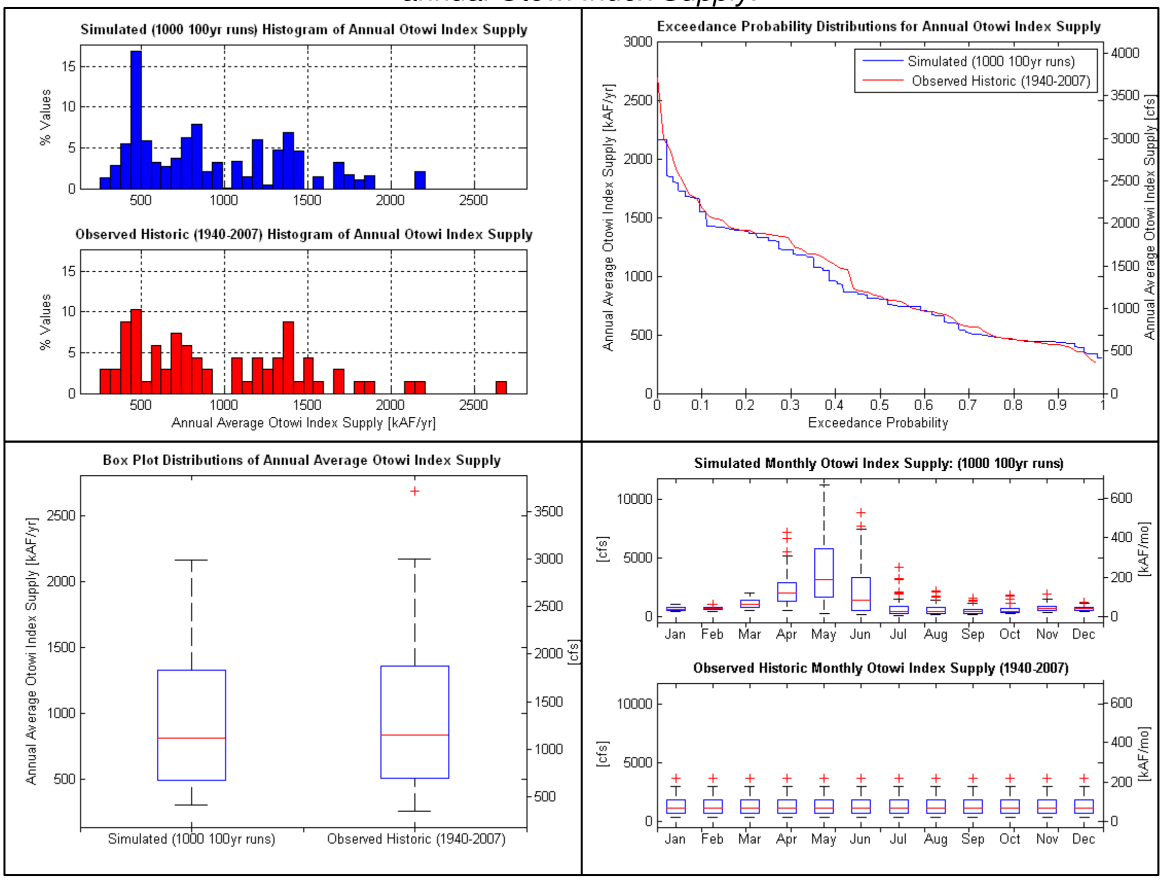


Figure C-13: Stochastic model output compared to historic record (1940-2007) for annual Otowi Index Supply.



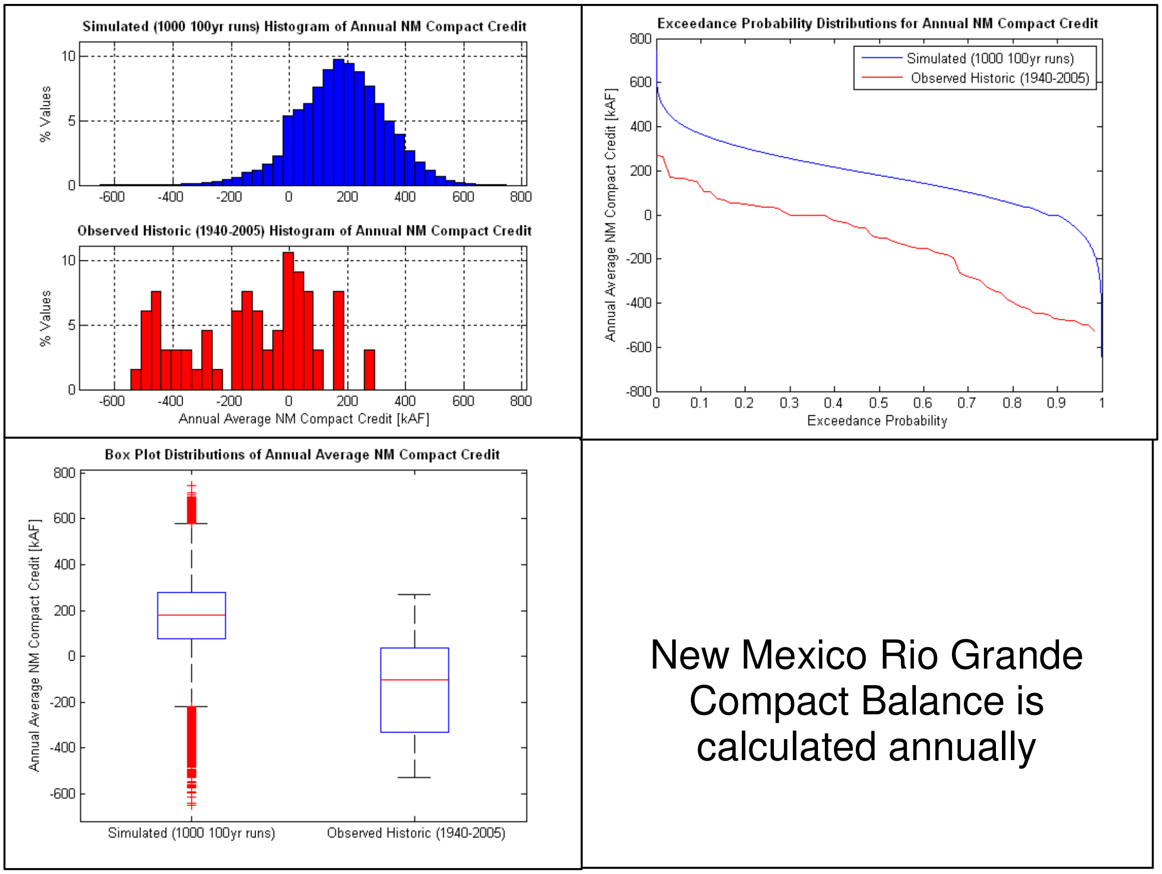


Figure C-14: Stochastic model output compared to historic record (1940-2005) for New Mexico Compact Balance.

Figure C-15: Stochastic model output compared to historic simulation values (1975-1999) for Percent of the year New Mexico is in Article VII conditions.

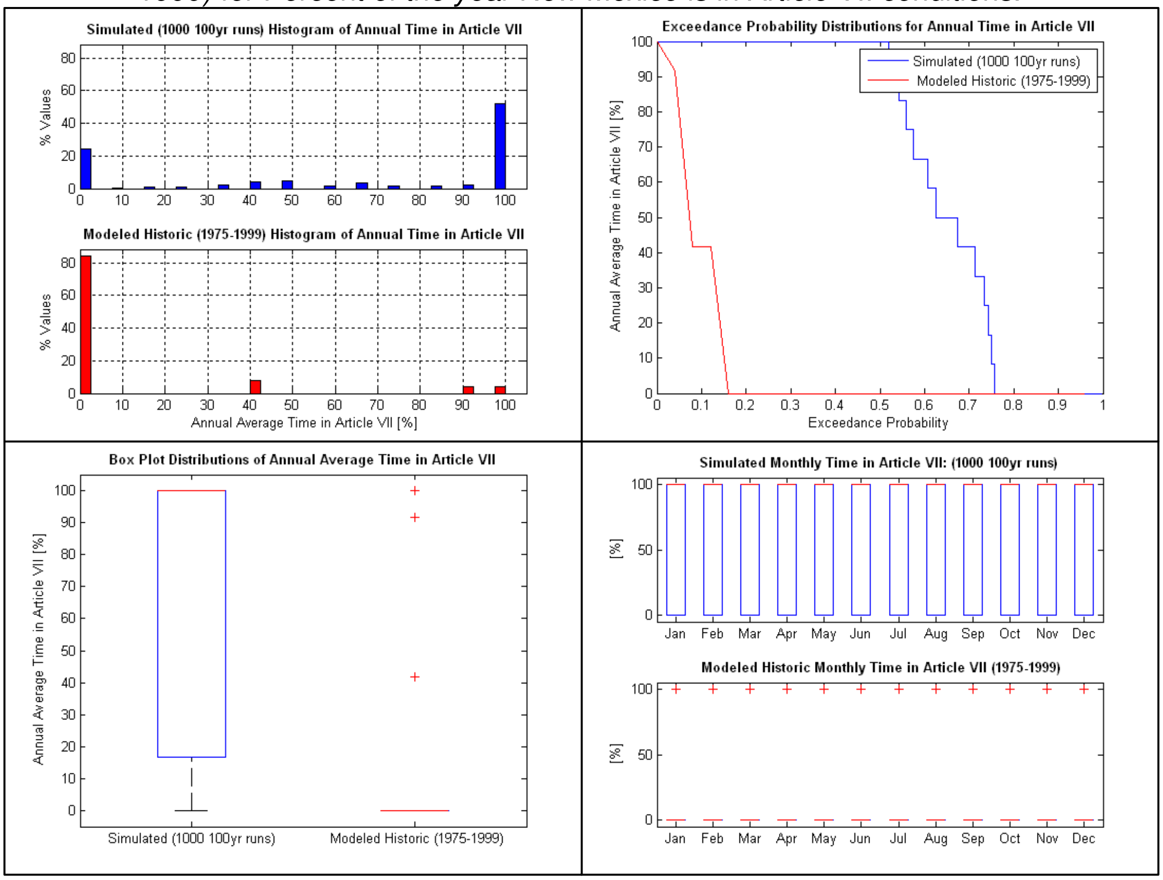


Figure C-16: Stochastic model output compared to historic simulation values (1975-1999) for Middle Rio Grande (Cochiti to Elephant Butte) crop evapotranspiration.

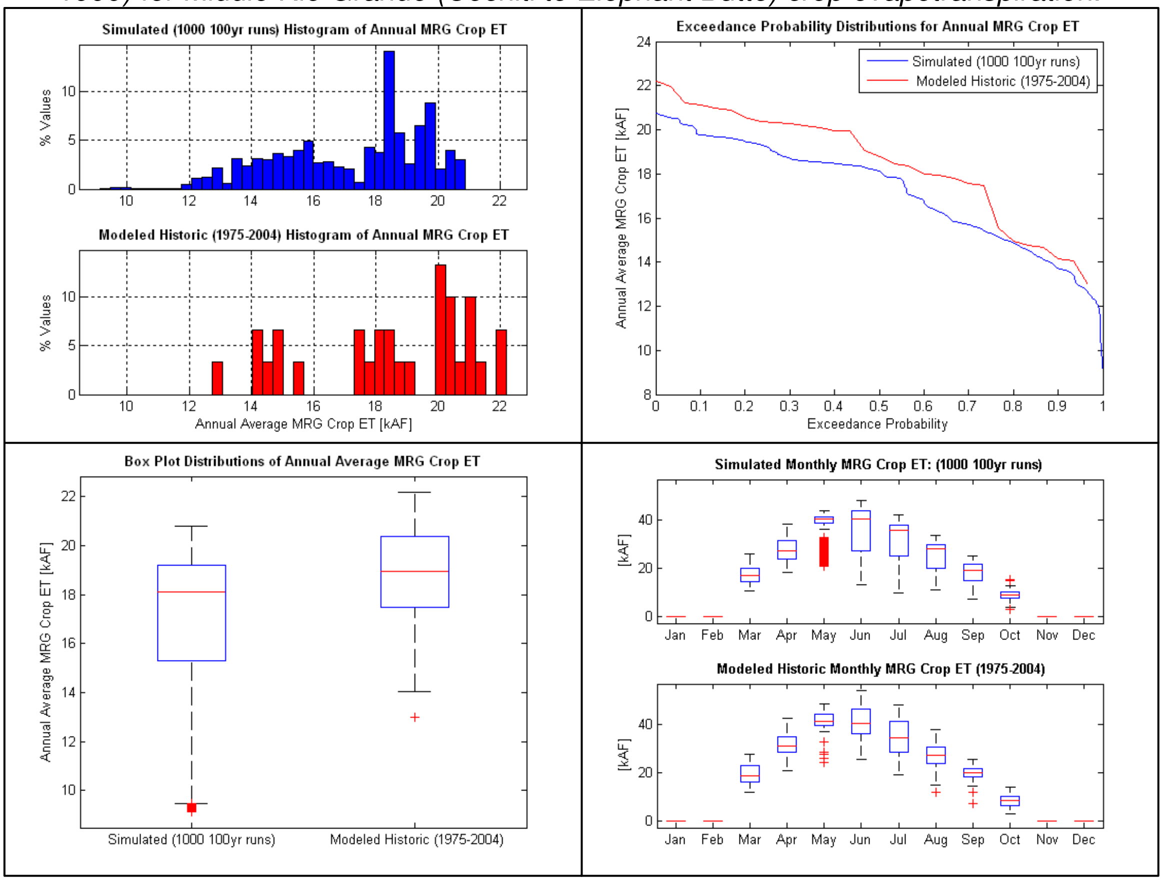


Figure C-17: Stochastic model output compared to historic simulation values (1975-1999) for Middle Rio Grande (Cochiti to Elephant Butte) riparian evapotranspiration.

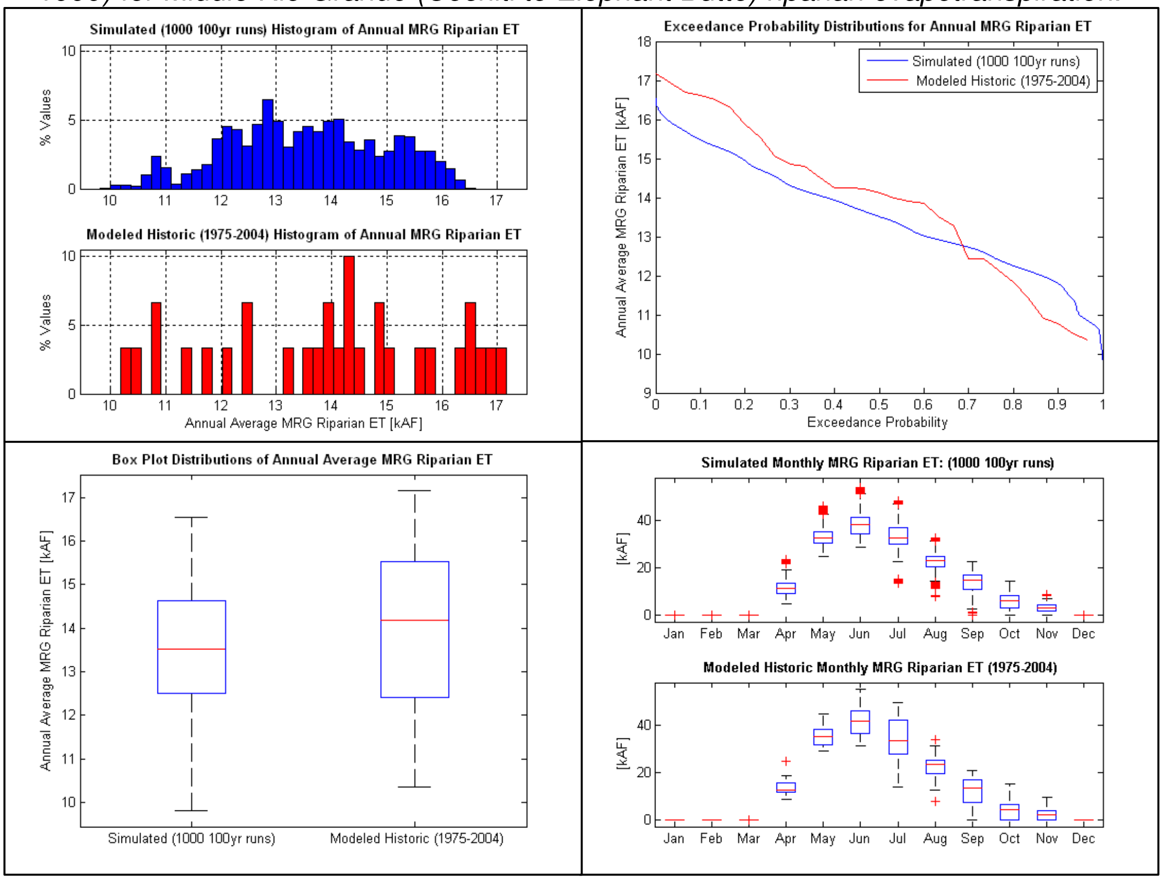


Figure C-18: Stochastic model output compared to historic simulation values (1975-1999) for Middle Rio Grande (Cochiti to Elephant Butte) outdoor use by the municipal and industrial sector.

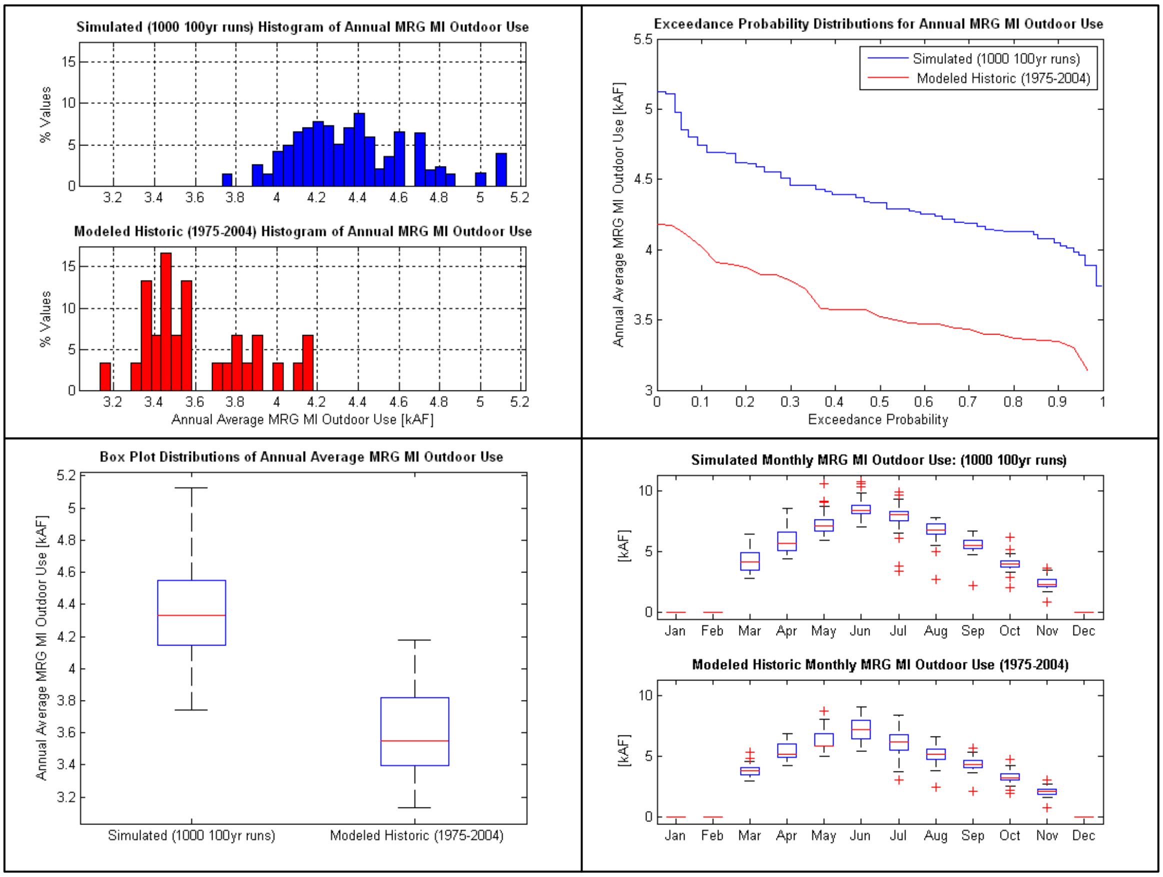


Figure C-19: Stochastic model output compared to historic simulation values (1975-1999) for Middle Rio Grande (Cochiti to Elephant Butte) total evapotranspiration (crop, riparian, and municipal-industrial).

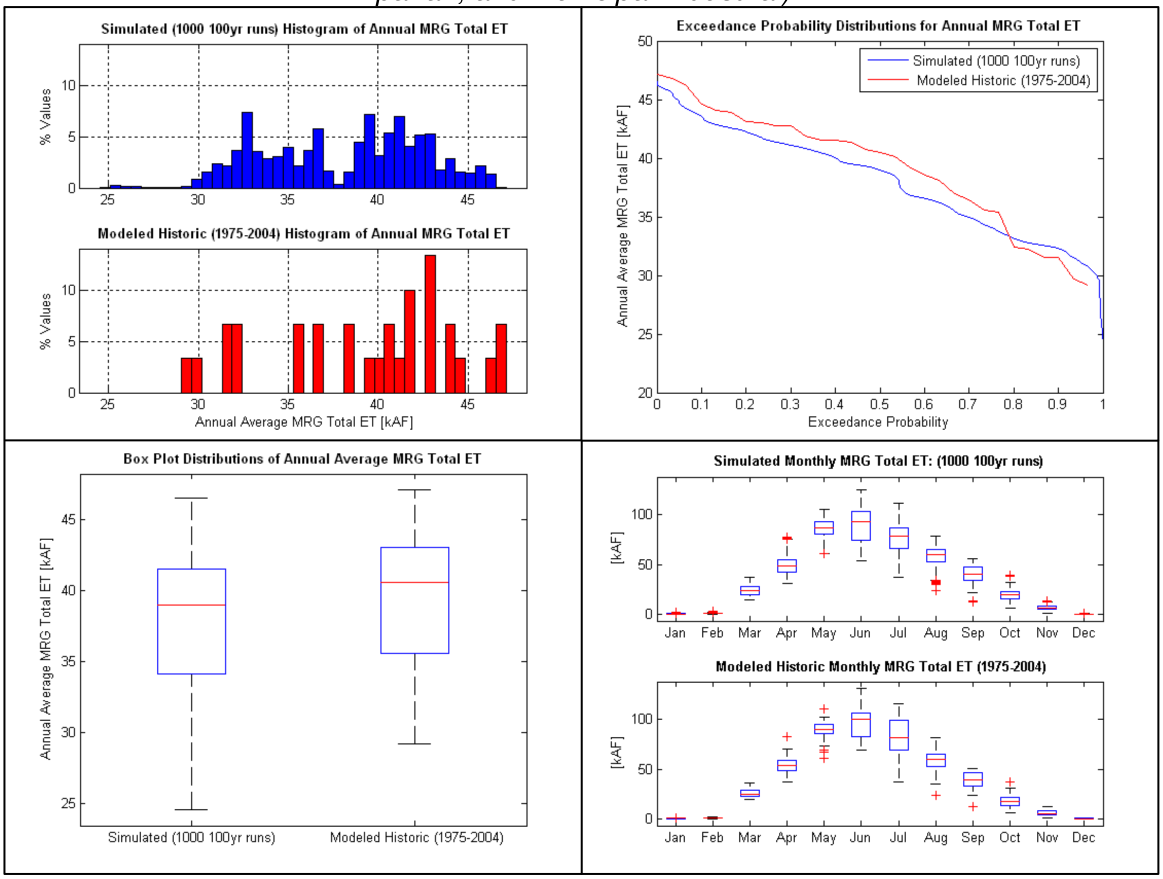


Figure C-20: Stochastic model output compared to historic simulation values (1975-1999) for Middle Rio Grande (Cochiti to Elephant Butte) agricultural shortages.

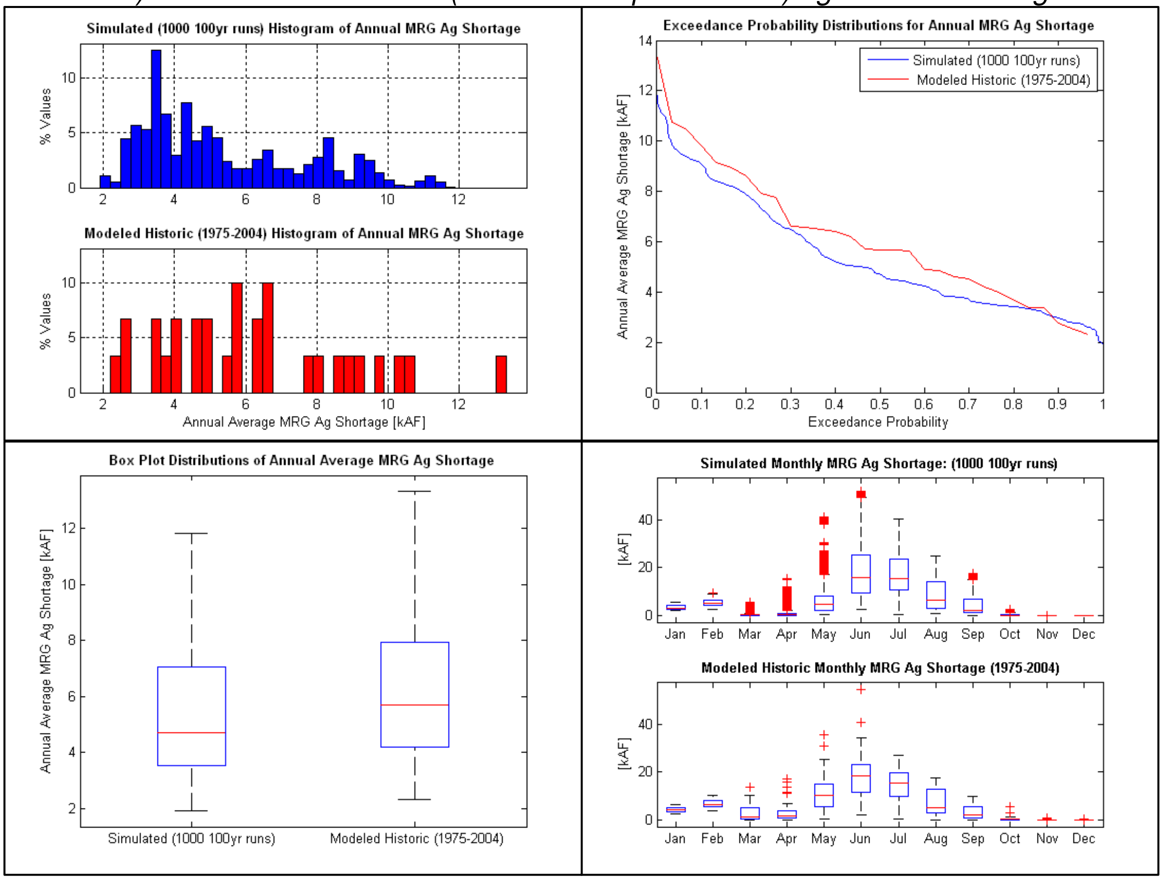


Figure C-21: Stochastic model output compared to historic simulation values (1975-1999) for percent of year flow targets are missed.

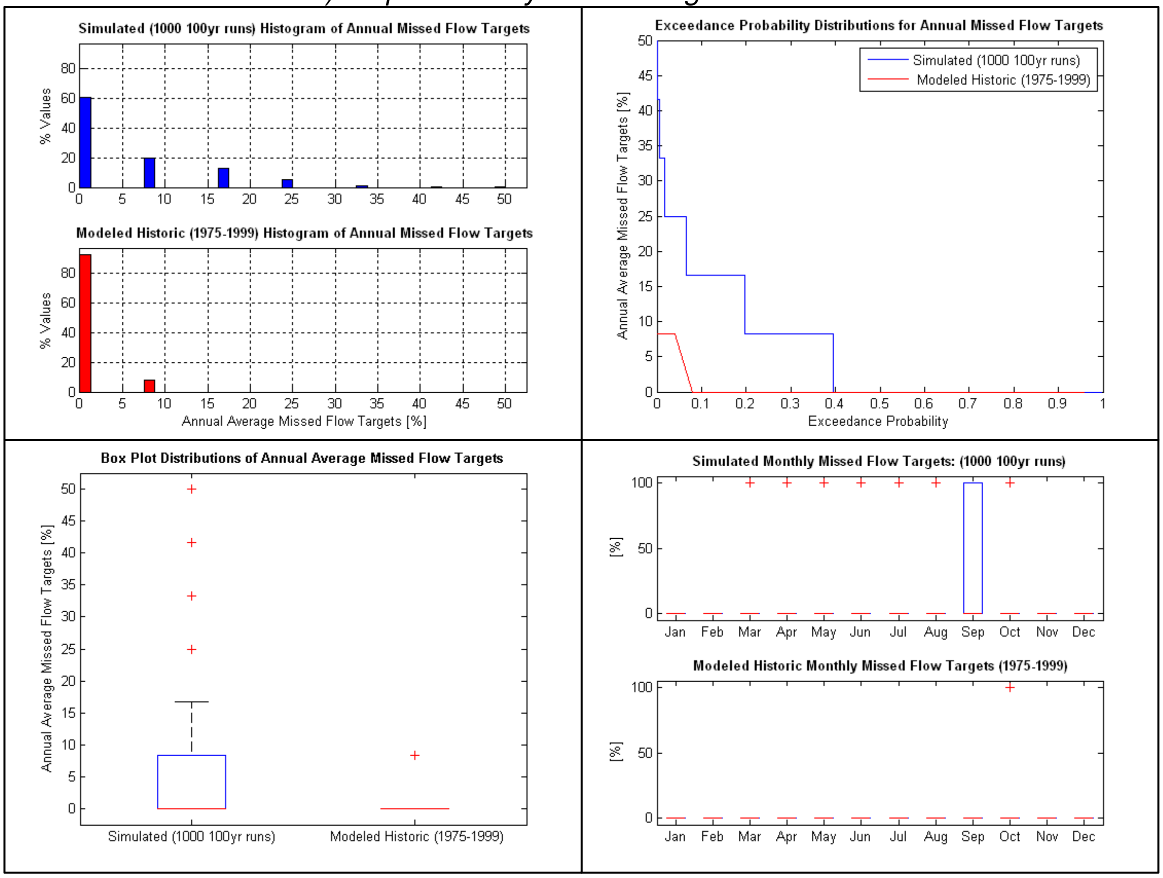


Figure C-22: Stochastic model output compared to historic simulation values (1975-1999) for flow target shortages.

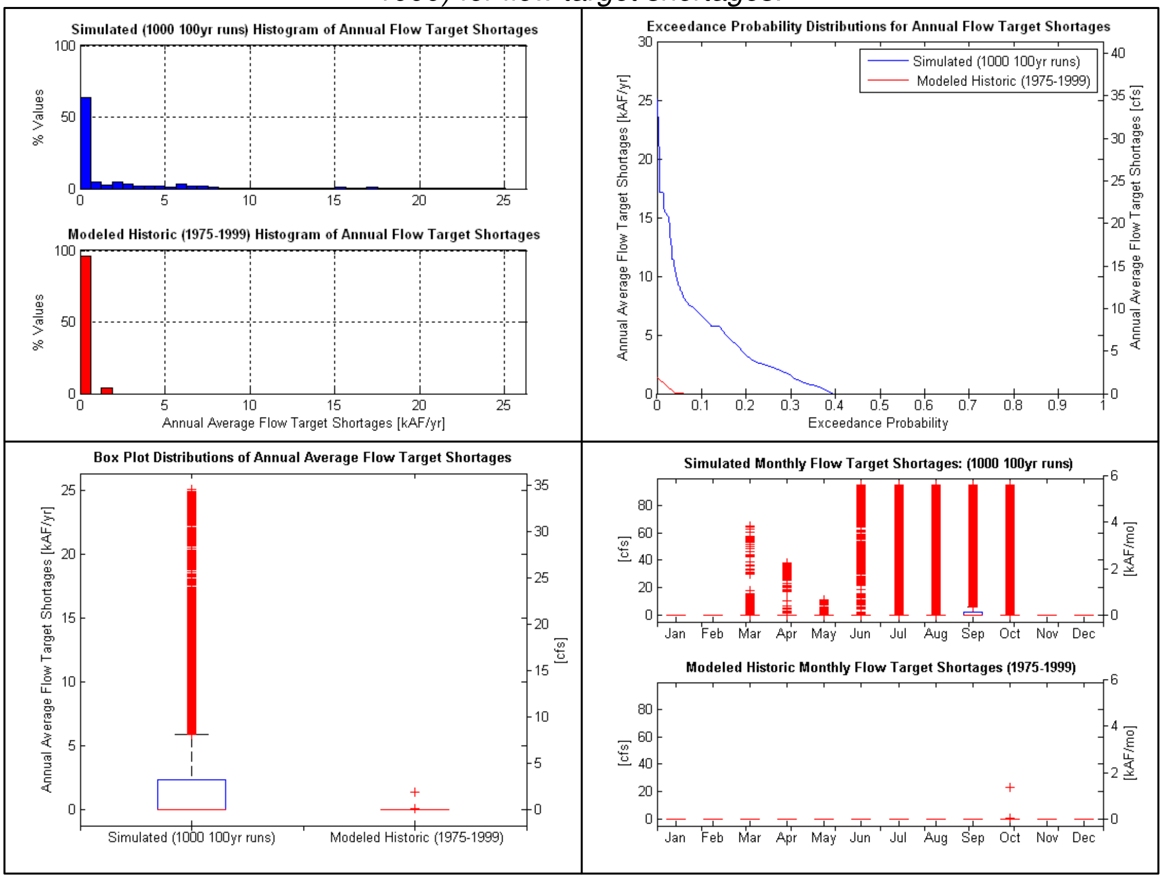


Figure C-23: Stochastic model output for City of Albuquerque San Juan Chama Drinking Water Project shortages (no historic data). These shortages are calculated as the difference between the available allocation as a monthly average,, and the amount that is actually diverted. This metric can thus be negative in a given timestep, and ends up counting reservoir evaporation of stored San Juan Chama water as a shortage.