

WATER AVAILABILITY MODELING TO SUPPORT WATER MANAGEMENT IN THE
LOWER RIO GRANDE VALLEY OF TEXAS

A Dissertation

by

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ABSTRACT

The Rio Grande River is considered as an over-appropriated river basin in Texas, where the number of permits to use surface waters exceed the amount of available water. Agricultural and municipal water supply and use in the Lower Rio Grande Valley (LRGV) are essentially dependent upon storage of the International Amistad and Falcon Reservoirs, which are owned and operated by the International Boundary and Water Commission (IBCW) based on provisions of the 1944 treaty between Mexico and the United States. The Texas share of the waters of the Rio Grande is allocated among numerous farmers, irrigation districts, and cities by a unique water rights permit system administered by the Rio Grande watermaster of the Texas Commission on Environmental Quality (TCEQ). The Rio Grande Water Availability Model (WAM) obtained from the TCEQ WAM System has a hydrologic period-of-analysis of 1940-2000. However, hydrology since 2000 includes the severe 2008-2014 drought and is important to the simulation study. The hydrologic period of analysis for the Rio Grande WAM was extended from 2001 to 2015 using Water Rights Analyses Package (WRAP) programs and methodologies. Extending the hydrologic period-of-analysis of the Rio Grande WAM to cover 1940-2015 was an initial major task in the research.

A WRAP/WAM simulation combines natural hydrology represented by sequences of monthly naturalized streamflows and reservoir evaporation-precipitation rates for a specified hydrologic period-of-analysis, 1940-2015 in this study, with specified scenarios of water resources development, allocation, management, and use. Water availability is assessed based on supply reliability metrics and storage and flow frequency metrics computed from simulation results.

Additionally, the Rio Grande WAM original 1940-2000 hydrologic period of analysis is extended to cover 1940-2015 and long-term simulations were performed to develop water supply reliability and storage frequency metrics for major water right groups, reallocation of municipal water rights in the Amistad-Falcon Reservoir system, and water planning scenarios including drought management. The Conditional Reliability Modeling (CRM) methods were applied to assess short-term water planning and management strategies for the LRGV along with the drought management scenarios were simulated to predict the likelihood of extended

drought conditions based on beginning storage in the Amistad-Falcon Reservoir system. The reliability and exceedance frequencies of maximum end-of-month storage at Amistad and Falcon reservoirs were developed using CRM.

DEDICATION

To the memory of my beloved father—Khurram Karimov.

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NOMENCLATURE

AAR	Area-Average Runoff
CFDC	Conditional Frequency Duration Curve
CRM	Conditional Reliability Modeling
DAT	Input File Consisting of Water Rights Data
DIS	Input File Consisting Control Point Selections and Watershed Parameters
DMI	Domestic-Municipal-Industrial
DEAD	Dead Zone of the Reservoir Where Sediments Accumulate
ENSO	El Nino Sothern Oscillation
EVA	Hydrology Input File Consisting of Monthly Net Evaporation Minus Precipitation Depths
FAD	Input File Consisting of Springflow Adjustments
FLO	Hydrology Input File Consisting of Monthly Naturalized Flow Volumes
FF	Flow Frequency Option
HYD	WRAP Hydrology Program
LOW-A-IRR	Lower Rio Grande Class A Irrigation Water Rights
LOW-B-IRR	Lower Rio Grande Class B Irrigation Water Rights
LRGV	Lower Rio Grande Valley
LSM	Land Surface Model
MID-A-IRR	Middle Rio Grande Class A Irrigation Water Rights
MID-B-IRR	Middle Rio Grande Class B Irrigation Water Rights
MUNIMID	Middle Rio Grande Municipal Rights
MUNILWR	Lower Rio Grande Municipal Rights

PDO	Pacific Decadal Oscillation
SFF	Storage Flow Frequency Option
SIM	WRAP Simulation Program
SSTA	Surface-Temperature Anomalies
SWAT	Soil Water Assessment Tool
TABLES	WRAP Program to Develop Flow Frequency and Statistics Tables
TCEQ	Texas Committee on Environmental Quality
TEXAMI	Texas Portion of Amistad Reservoir
TEXFAL	Texas Portion of Falcon Reservoir
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WAM	Texas Water Availability Model
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

The proposed research applies the Texas Water Availability Modeling (WAM) System to formulate and assess strategies for improving capabilities for water management during a drought in the Lower Rio Grande Valley. The WAM System maintained by the Texas Commission on Environmental Quality (TCEQ) consists of the Water Rights Analysis Package (WRAP) Modeling system developed at Texas A&M University and WRAP input datasets for all of the river basins of Texas. WRAP is generalized for application to river/reservoir systems located anywhere. WRAP combined with variations of one of the basin-specific datasets from the TCEQ WAM System is called a water availability model (WAM). The Rio Grande WAM is applied in the dissertation research to develop an enhanced understanding of water management in the Lower Rio Grande and modeling thereof, with a particular focus on the following issues:

- Assessing impacts on water availability for all affected water rights, resulting from transfers of water rights from agricultural irrigation to municipal use.
- Assessing impacts on water availability for all affected water rights resulting from modifications of storage allocations and operating rules of Amistad and Falcon Reservoirs.
- Application of short-term conditional reliability modeling to forecast water availability for future periods ranging from several months to several years for given initial storage levels in Amistad and Falcon Reservoirs.

The Rio Grande WAM obtained from the TCEQ WAM System has a hydrologic period-of-analysis of 1940–2000. However, hydrology since 2000 includes the severe 2012–2014 drought and is important to the simulation study. Extending the hydrologic period-of-analysis of the Rio Grande WAM to cover 1940–2015 is an initial major task in the research.

A WRAP/WAM simulation combines natural hydrology represented by sequences of monthly naturalized streamflows and reservoir evaporation-precipitation rates for a specified hydrologic period-of-analysis, 1940–2015 in this study, with specified scenarios of water resources development, allocation, management, and use. Water availability is assessed based

on supply reliability metrics and storage and flow frequency metrics computed from simulation results.

WAMs from the TCEQ WAM System for many of the other river basins of Texas have been applied extensively over the past decade to support water right permit applications and planning studies. However, similar applications of the Rio Grande WAM have been limited. The Rio Grande is over-appropriated, and the TCEQ approves no applications for additional water right appropriations. Water right permit applications in the Rio Grande have been limited essentially to market transfers, typically municipalities purchasing water rights from agricultural irrigators.

Hydrology and water resources allocation and management in the Lower Rio Grande Valley are very different than throughout the rest of Texas. The Rio Grande WAM is more complex than other WAMs in many respects. Several major differences in both water management and modeling thereof are noted in the following paragraphs.

The Rio Grande Basin is much larger and more arid than the other river basins of Texas. Developing and updating hydrology datasets for the Rio Grande WAM are significantly more difficult than for the other WAMs.

The water resources of the Rio Grande are shared by Mexico and the United States. The Rio Grande flows above and below Fort Quitman are allocated between the two countries by 1906 and 1944 treaties, respectively. Fort Quitman is located several kilometers downstream of the City of El Paso. All of the WAMs including the Rio Grande WAM are designed for assessing water availability in Texas, but the effects of water use in Mexico and neighboring states are considered. The Rio Grande WAM incorporates the provisions of the 1906 and 1944 international treaties as well as the Pecos River and Rio Grande interstate compacts between Texas and New Mexico.

The water rights system administered by the TCEQ in allocating the Texas share of the waters of the Rio Grande below Fort Quitman is very different from the water rights system applied for the remainder of Texas. Water rights for the Rio Grande below Fort Quitman were adjudicated by court action during the 1950s–1970 in conjunction with a massive lawsuit motivated by the 1950–1957 drought. Water rights for the remainder of Texas have administratively adjudicated pursuant the Water Rights Adjudication Act of 1967. Unlike the conventional prior appropriation system implemented throughout the rest of Texas, water

rights in the Lower Rio Grande Valley are categorized as being either municipal or falling within two categories of agricultural rights. A detailed accounting of both diversions from the river system and storage in Amistad and Falcon Reservoirs is maintained for each water right permit.

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Texas Water Availability Modeling (WAM) System

The 1997 Senate Bill 1 authorized the Water Availability Modeling (WAM) system and directed the TCEQ to develop a consistent set of databases and modeling tools for use both in conducting planning studies and in preparing and evaluating water rights permit applications (Sokulsky 1998). The WAM system consists of the WRAP model along with 20 sets of input files covering the 23 river basins of the state, geographic information system (GIS), and other supporting data (Wurbs, 2005). The TCEQ, in contract with several engineering firms, universities, and research institutes, developed complete WAM datasets for each river basin of Texas, including the Rio Grande (TCEQ, 2015). The WAM system facilitates the assessment of hydrologic and institutional water availability and reliability through the use of a WRAP model.

Water Rights Analysis Package Modeling System

WRAP, developed at Texas A&M University, was sponsored by the Texas Water Resources Institute (TWRI), Texas Commission on Environmental Quality (TCEQ), USACE Fort Worth District, and other agencies in Texas and greatly expanded during 1997–2002. Water rights in WRAP are defined as a set of water use requirements, reservoir storage, and conveyance facilities' operating rules and institutional arrangements for managing water resources (Wurbs, 2005). WRAP is comprised of *SIM*, *HYD* and *TABLE S* programs that simulate river and reservoir water allocations using monthly time-step, converting gauged flows to naturalized flows by removing used water diversions and return flows and net evaporation rates for reservoirs, and organizing simulation results by developing frequency relationships, reliability indices, and summary statistics, respectively.

WRAP input files covering 23 river basins of Texas, a GIS, and another supporting system to the WRAP model were developed by TCEQ under the 1997 Senate Bill1 as the WAM system. It is available to users in monthly or sub-monthly time-steps in order to simulate river basin hydrology that is represented by sequences of naturalized streamflows.

WRAP is a generalized model designed to simulate a river basin under a priority-based water allocation system (Wurbs, 2005). WRAP evaluates the ability of the river/reservoir system to meet demand during hypothetical repetitions of historical hydrology. The spatial connectivity of the system is modeled as a set of control points. The computational algorithms are based on the location of each control point related to others as defined in the input data. Simulation results include regulated flows (physical flows at a location), reservoir storage contents, diversions, water rights shortages, unappropriated flows (flows left in the stream after all diversions are met), reliability indices, and other variables (Wurbs, 2003).

WAM datasets include FLO, EVA, DIS, and DAT files for simulations of water allocations. The monthly naturalized flow volumes and net evaporation less precipitation depth at pertinent control points are stored in FLO and EVA files, respectively. Naturalized flows are distributed from primary (gaged) control points to secondary (ungaged) control points by using watershed parameters that are stored in DIS files. Water use requirements, water right permits, and river/reservoir system operating rules and practices are stored in DAT files

(Wurbs, 2009a). Also, the spring flows are also naturalized and included in WAM datasets as FAD files for some river basins, including the Rio Grande.

WRAP is divided into three main modeling programs: (1) WRAP-SIM—the river/reservoir water allocation/management program for input sequences of monthly naturalized flows and net evaporation rates; (2) WRAP-HYD—the program that assists in developing monthly naturalized streamflow and reservoir net evaporation less precipitation depth data for the WRAP-SIM hydrology input files; and (3) WRAP-TABLES—the program that is used to develop frequency relationships, reliability indices, and various user-specified tables for organizing, summarizing, and displaying simulation results (Wurbs and Kim 2011). Naturalized flows represent natural conditions without water resources development and use.

Permit application and planning processes with WRAP include two water-use scenarios: (1) authorized use (Run 3), which includes full use of authorized water targets while excluding return flows, sediment accumulations in reservoirs, and term permits; and (2) current use (Run 8), which includes best estimates of return flows, sediment accumulation reflecting the year 2000 conditions, and water use targets and settings for each water right based on the maximum annual amount actually used in any year during a recent 10-year period (Wurbs, 2005). The authorized use (RG3) of the Rio Grande WAM datasets was used for this research.

Rio Grande Water Availability Model

The Rio Grande WAM datasets covering the 1940–2000 hydrologic period of record were developed by the R.J. Brandes Company in 2004 in contractual agreement with TCEQ in order to meet the requirements of Senate Bill 1 of the 76th Texas Legislature regarding the development of a new Rio Grande Basin water-availability simulation modeling. It consists of 963 control points with 55 primary (gaged) control points for which monthly naturalized flows were developed and distributed to the rest of the 908 secondary (ungaged) control points. This model is capable of determining water availability in the basin under a range of policy and planning scenarios by the prior appropriation doctrine and the TCEQ Rio Grande operating rules (Brandes, 2004). A 2014 version of the program with fully authorized Rio Grande WAM input datasets was used in this research.

Literature Review

River/reservoir simulation models are developed based on various linear and nonlinear programming methods and ad hoc simulation algorithms. This section provides a summary of optimization and simulation modeling methods, their goals and uses, and applications in generalized models.

Optimization and Simulation Models

Over the past several decades, optimization of reservoir system operation has been a major field of water resources studies. Progress has been achieved due to the improvements in mathematical models and optimization methods and advancements in computer technology and calculating tools. Despite these achievements, optimization of integrated systems of reservoirs remains challenging. Mathematical modeling of reservoir system optimization and simulations gained traction in the last decades in order to improve operation efficiencies of water diversions and allocations.

Optimization models are formulated in terms of determining values for a set of decision variables that will maximize or minimize an objective function subject to constraints. The objective function and constraints are represented by mathematical expressions as a function of the decision variables. For a reservoir operation problem, the decision variables are typically released rates and end-of-period storage volumes (Wurbs, 1993).

Yeh (1985) conducted a state-of-the-art review of optimization methods on all existing reservoir management and operations models and categorized them into four major groups: (1) Linear programming (LP); (2) Dynamic programming (DP); (3) Nonlinear programming (NLP); and (4) simulation. Selection of a particular model depends on the availability of data, reservoir operation characteristics, specified objectives, and constraints. LP is widely used in reservoir operations as an optimization technique and formulated to either minimize or maximize objective function subject to a pre-defined set of constraints. DP is used as a procedure for optimizing a multistage decision process and translates nonlinear and stochastic characteristics of water resources systems. NLP is an underutilized technique because it does not easily accommodate the stochastic nature of flows, but as computing technology improves,

it might be effective in the development of multiobjective optimization methods. The simulation model provides the response of the system for certain inputs such as decision rules and allows the decision maker to examine impacts of existing or anticipated system operations.

Labadie (2004) also provided an extensive review of developments and applications of heuristic programming methods using evolutionary and genetic algorithms and application of neural networks and fuzzy rule-based systems in reservoir system operating rules. Also, mathematical programming of LP, DP, NLP optimization models along with applications in generalized and site-specific models were described in detail.

Loganathan and Bhattacharya (1990) described goal-programming techniques for optimal reservoir operations. Preemptive and fuzzy goal programming have been widely used as part of reservoir simulation models. Preemptive modeling is based on priorities, where higher-order priorities must be optimized before lower-order goals can even be considered, and trading a small decrease in a high-priority objective for a large improvement in a low-priority objective is not allowed. This drawback can be solved by using weighted goal programming. In a fuzzy goal programming approach, the objective function values are forced to be as close to the particular values as possible.

Srivastave and Awchi (2009) applied combinations of LP, DP, artificial neural networks (ANN), hedge rules (HR), and simulation programs to optimize water yield and operational performance of the multipurpose Mula Reservoir in India. The objective of the study was to test and reevaluate current operational parameters of the reservoir under water stress periods and determine annual yields for water supply and irrigation. Dariane and Mumtahen (2009) presented a direct search method using generic algorithms, which seeks to find directly optimal parameters for prescribed operating policies that are utilized for optimization of multireservoir operational problems and several modifications for the Greater Karoon system in Iran.

Deka and Chandramouli (2009) applied a hybrid model that combines the learning ability of ANN and transplant nature of fuzzy logic to study the behavior of optimal release operating policy for a reservoir on the Pagladiya River in the Assam State of India. Reservoir operating policies were formulated through DP, and optimal release was related to storage, inflow, and demand. The study found the model to be highly adaptive and efficient in investigating nonlinear relationships among different variables. Zagona et al. (1998) and

Biddle (2001) reported the use of preemptive goal programming to provide optimization capabilities and applications of the model to the Tennessee Valley Authority (TVA) system for operational planning.

Wurbs (1993) defined simulation models as representations of a system used to predict the behavior of the system under a given set of conditions. A network flow programming defined as nodes connected by arcs to represent flow directions has also been used in various simulation models. Diversion and storage points are represented as nodes, while reservoir releases, channel or pipe flows, evaporation, and other losses are represented as arcs. Prescriptive optimization models offer an expanded capability to select systematically optimal solutions, or families of solutions, under agreed-upon objectives and constraints. Optimization models are more mathematically complex than simulation models and, therefore, harder to comprehend (Labadie, 2004).

Wurbs and Yerramreddy (1994) categorized computer models that are being developed to evaluate river basin systems as simulation, optimization, and combinations of simulation and optimization. Their study also presented advantages of network flow modeling based on mathematical optimization techniques and suggested grouping all simulation and optimization models as descriptive and prescriptive models. Descriptive models demonstrate what will happen if a specific plan is adopted. Prescriptive models automatically determine the plan that should be adopted to best satisfy the decision criteria. Simulation models are generally descriptive, but optimization techniques greatly enhance capabilities to develop models that are more prescriptive. Descriptive models do not automatically find an optimal set of reservoir release and storage values, but do show the releases and storage that would result from a particular operating plan. Prescriptive models provide the advantages of determining the sequences of operating decisions that optimize a specific criterion function. Applications of generalized simulation models in reservoir/river systems are given for the illustrative case study on the Brazos River Basin and development of these models in Wurbs and Saleh (1995) and Wurbs (1998).

Stevens (1986) described a computer model called the “24-month study” that is used for planning the monthly and seasonal operation of the reservoir and power plant system of the Lower Colorado River Basin. It is a water-accounting computer model and is derived from the Colorado River Simulation System model developed by the United States Bureau of

Reclamation (USBR) in the 1970s. The model output includes the previous 12-month historical reservoir operations and future 24-month projected operations.

Draper et al. (2004) presented CalSim, a general-purpose, river/reservoir simulation model that is being developed by the California State Department of Water Resources and the USBR Mid-Pacific Region for the planning and management of the State Water Project and the Central Valley Project. It is a prescriptive type simulation model in which the user specifies a series of objectives in the form of relative priorities for water allocation and storage based on a single time-step optimization technique.

Shluter et al. (2005) applied an EPIC simulation modeling system in the semi-arid Amudarya delta region of the Aral Sea Basin in Central Asia. The model determines optimal water allocation in the irrigation network by using a multiobjective optimization technique based on monthly time steps. Water management alternatives can be developed for a time-period of up to 15 years based on changing requirements of the water users, streamflows, and priorities of the optimization criteria.

Generalized Models

Wurbs (2005) provided a detailed inventory of various optimization techniques along with site-specific and generalized simulation models on reservoir operations and management. In addition, Texas A&M University, in collaboration with USBR, provided an inventory of hydrologic, hydraulic, environmental, and other types of models that can be found at <http://hydrologicmodels.tamu.edu>. The models can also be generalized or site-specific subject to the specific purpose of its use and are grouped as descriptive or prescriptive. In generalized models, the simulation data files input directly to the program interface, thereby eliminating the need for writing or modifying computer code every time a different system needs to be modeled. Most of the generalized models are considered descriptive, except the RIVERWARE model, which has a prescriptive element. Various optimization techniques, such as LP, are designed for prescriptive modeling. Simulation models are used to replicate the behavior or pattern of a historical hydrologic period of record and belong to a descriptive category.

MIKE-BASIN simulates multipurpose, multireservoir systems based on a network formulation of nodes and branches while integrating GIS and using monthly streamflow data

as input. It was developed and maintained by the Danish Hydraulic Institute (<http://www.dhi.dk>) and has various options for specifying reservoir operating rules and allocating water between competing users. It can either be operated for local or global priorities of water allocation. The distribution of water from a node on the river to users immediately connected to it can be modeled with local priority rules, which is useful for modeling. The prior appropriation rights can be modeled using the global priorities' mode since it allows water to be allocated according to rules that can affect any node in the system. It was applied by Jha and Gupta (2003) to model the Mun River in Thailand and evaluate its basin performance in order to recommend optimal allocation practices.

Water Evaluation and Planning (WEAP) is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analysis. It was developed by the Stockholm Environmental Institute (<http://www.weap21.org>) and allocates surface and groundwater sources to different demands. WEAP operates on a monthly time step and uses a linear optimization algorithm to optimize the supply of demands and instream flow requirements subject to supply priorities, mass balance, and other constraints. It can also be used to address water resources management issues, including reservoir operations, water rights and allocation priorities, pollution tracking, and cost-benefit analysis. The model was applied by Levite et al. (2003) to assess alternative water allocation scenarios in the Olifants River Basin in South Africa. Blanco and McKinney (2013) applied the model to simulate stream flows in the Conchos River watershed, which contributes about 55 percent of flows into the Rio Grande based on the 1944 Treaty.

RIVERWARE is an object-oriented river/reservoir simulation model with multiobjective modeling capabilities (Zagona et al., 2002) that was developed at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado; it was jointly funded by USBR and TVA. RiverWare consists of tools based on the point-and-click graphical user interface that allows the user to construct a model for a particular river/reservoir system. It is used to both simulate and optimize the management of multipurpose reservoir systems for daily operations (Eschenbach et al., 2001). Wurbs (2005) described the RiverWare model as suitable for formulating a broad range of operating policies at a variety of large, multipurpose river basins. The policy can be changed easily, and RiverWare automatically generates an efficient and robust preemptive goal program to

optimize the policy. The solution to the goal program automatically defines a simulation run, which can predict the exact consequences of the optimization solution. Higgins and Brock (1999) described the facilities, operating procedures, and performance of the reservoir release improvements on water quantity and quality in 20 reservoir systems of the TVA.

RESSIM was developed by the United States Army Corps of Engineers' (USACE) Hydrologic Engineering Center (HEC) and consists of a graphical user interface, a computational program to simulate reservoir operation, data management capabilities, and graphics and reporting features. It can also be set up in three different modules: (1) a watershed module to provide a common framework for watershed creation and definition among different modeling applications; (2) a reservoir network module that allows the user to construct a river schematic in order to describe the physical and operational elements of the reservoir system; and (3) a simulation module to configure and perform a simulation (Wurbs, 2005). USACE HEC applied the ResSim to the Sacramento and San Joaquin rivers (Rosenberg, 2003). It was also applied to the Tigris and Euphrates rivers in Iraq by HEC in partnership with Development Alternatives, Inc., with sponsorship by the U.S. Agency for International Development (USAID), in order to provide decision support for the Iraqi Ministry of Water Resources in its operation of complex reservoir systems (Hanbali, 2004).

MODSIM was developed at Colorado State University with support from the USBR and is based on user-specified priorities and network flow programming that are designed for analyzing physical, hydrologic, and institutional aspects of river basin management (Wurbs, 2005). Reservoir evaporation rates and sequences of stream inflows are used as inputs and simulated in monthly, weekly, or daily time steps. MODSIM also has been linked and integrated with MODFLOW, a groundwater simulation model, and QUAL2E, a streamflow water-quality model (Fredericks et al., 1998; Dai & Labadie, 2001). The model's object-oriented graphic user interface allows creation of a node-link network representing the spatial relationships between the physical entities in the basin. It solves a minimum-cost network flow problem to find the required water and storage allocation for competing demands based on specific priorities and operating rules (Wurbs, 1993; Labadie, 2001). It can be used in monthly, weekly, or daily computation modes and considers reservoir operation targets, consumptive and instream flow demands, evaporation and channel losses, reservoir storage rights, and exchanges.

Texas Water Development Board's *SIMYLD-II* (Brandes, 1998) model is applied to simulate flows in Amistad and Falcon reservoir system and is based on network flow programming. It is a monthly simulation model designed to meet a set of specific demands in a given order of priority. Simulation models are considered descriptive models that demonstrate what will happen if a specified plan is adopted, while optimization models are considered more prescriptive models that automatically determine the plan that should be adopted to best satisfy the decision criteria (Wurbs, 2005).

Generalized models serve specific purposes in their simulations of stream river/reservoir systems around the world. The development of input datasets for each model may vary depending on the outcome of the results. The advantage of the WRAP model is that it is integrated with Texas water rights systems and built for developing input data sets while providing special programming tools on the simulation of water rights. In addition, it has a conditional reliability model that simulates different water shortage or drought scenarios while developing firm-yield and reliability analysis.

WRAP has evolved and is continuously being upgraded, and the latest versions of the program, along with manuals and instructions, can be downloaded at <https://ceprofs.tamu.edu/rwurbs/wrap.htm>. It was chosen for this research to (1) extend existing Rio Grande WAM, (2) develop short-term and long-term reliability analysis for water management and planning using conventional and conditional reliability modeling, and (3) simulate drought conditions using prescribed initial storage levels.

Conditional Reliability Modeling

The probability distribution of storage with initial storage conditions at the end of each simulation period was presented by Moran (1954) and was based on the Markov chain and transition matrix. Gould (1961) modified Moran's model for a monthly time step that considered reservoir evaporation and precipitation, surface area and storage capacity relationships, and monthly operating policies. The transient analysis was used to predict future storage distributions based on initial storage conditions in PROCTOR, a computer program developed by Vaughn and Maidment (1987). It assumes that all sequences of historical hydrology are equally likely to occur.

The transient analysis method was further modified by Salazar and Wurbs (2004) by assigning weights to each of the sequences of historical hydrology using conditional frequency duration curves (CFDC). A CFDC is an exceedance frequency table for streamflows following a specified initial storage content that is determined using the Weibull formula. The results of a long-term simulation for specific storage intervals are used to develop CFDC.

Brandes and Sullivan (1998) developed a Conditional Probability Modeling (CPM) based on CFDC method and applied it to the Amistad and Falcon reservoir system on the Rio Grande River in order to develop firm-yield relationships conditioned upon beginning of the year storage condition. The storage capacity of each reservoir was divided into 40 horizontal layers of equal volumes. The probability of starting a forecast period at or below one of the 40 predefined storage levels and long-term simulation relationship in addition to the reliability of meeting water demand downstream of the reservoirs were developed.

Wurbs (2003) described development and implementation of WRAP, a generalized modeling system of the Brazos River Basin and short and long-term water availabilities using conditional reliability modeling techniques. According to his study, the Texas WAM studies indicate that reliabilities are not very sensitive to changes in demand targets. Conversely, the amounts that may be supplied vary widely with relatively small changes in reliability requirements. The quantity of water supplied from Texas river systems can be increased significantly by accepting higher risks of shortages or emergency-demand reductions (Wurbs, 2003).

Olmos (2004) proposed a new Storage Flow Frequency (SFF) method while analyzing equal weight, CDFC curve methods in a comparative study for Lake Waco in the Brazos River System. The SFF method works by assigning a probability of occurrence to each sequence in the simulation based on the relationship between storage volume and naturalized flow volume. The study found the SFF model to be more conservative for low initial storage conditions and to produce higher reliability for high storage conditions. The CDFC method now has been abandoned for the SFF method due to the CDFC's inconvenience in practical applications. The equal weight and probability array options to assign probabilities to the simulation sequences in CRM were added by Wurbs et al. (2007).

Schnier (2010) presented a sensitivity analysis for different options available for CRM in the WRAP and recommended the use of SFF for simulation length of fewer than six months

in general. The initial storage content value was found to be dependent upon the storage reservoir frequency curve for individual reservoirs. Wurbs et al. (2012) performed a comparative study of equal weight and probability array method for a condensed version of the Brazos WAM system with a 108-year hydrologic period of analysis. The storage frequency relationship for Lake Proctor and a Four Reservoir System was computed for the end of September and June using both equal weight and probability array methods. The study found approximately the same values for equal weight and probability array methods at preceding storage levels of 100% and 75% capacity, but for preceding storage contents of 50% and 25%, the difference was significant.

Bista (2015) demonstrated equal weight and probability array options of WRAP reliability simulations by applying the modeling to Highland Lakes in the Colorado River Basin of Texas . The CRM and long-term reliability simulations were compared, and drought management plans and impacts of global climate model results on future water availability in the basin were analyzed. Sechi and Sulis (2009) used simulation and optimization models to generate period and volume reliabilities for multipurpose and multireservoir systems. Modeling tools and results of simulation analysis are provided in the illustrative case study from the reservoir water systems in Sardinia, Italy. The case study presents the description of the water resources system optimization aided by the graphical interface decision support system to achieve interactions between the optimization and simulation models in order to implement a proactive approach, particularly to address drought.

Drought Management

Wilhite and Glantz (1985, page 24) defined drought as “a condition about some long-term average condition of balance between rainfall and evapotranspiration in a particular area, a condition often perceived as normal.” The authors divided drought into meteorological, agricultural, hydrological, and socioeconomic categories based on drought characteristics. Importantly, there is an absence of concrete drought management plans on both sides of the border to reallocate water shortage during a recurrence of events in the Rio Grande Basin. Technically, there is no need for specific drought management plans for the Amistad-Falcon Reservoir system because of the special Rio Grande water rights that favors domestic,

municipal, and industrial (DMI) allocations over Class A and Class B rights. In times of drought, Class A and Class B rights are curtailed accordingly and based on previous estimates, such as when the municipal pool at Amistad-Falcon system exceeds original reserves of 225,000 acre-feet per month (Mumme, 1999). Schmandt (2002) also presented in a case study a comparison analysis of the drought in the 1990s in the Lower Rio Grande to the one in the 1950s. Droughts, which result from variability in supply and from increased demand due to urbanization, have severe implications on local and regional water supply systems. In the context of short-term (monthly or seasonal) water management, predicting these supply variations well in advance are essential to advocating appropriate conservation measures before the onset of drought (Golembesky et al., 2009). Characklis et al. (1998) proposed allowing water rights' leasing options between agricultural and municipal users in the Lower Rio Grande to alleviate water shortages during drought while ensuring balanced water supply. Draper and Kundell (2007) proposed integrating climate change effects on transboundary water sharing agreements and policies. Their study evaluated the Intergovernmental Panel on Climate Change (IPCC) report and impacts of its findings in an illustrative case study of the Rio Grande. Hadjigeorgalis (2008) proposed alternatives for agricultural water resource management in areas of recurrent drought by allocations of market mechanisms. That research proceeded to evaluate farmer preferences for a variety of market mechanisms in the lower portion of the Rio Grande Basin in New Mexico, an area where formal water markets currently do not exist. While previous research aimed to explain why farmers are reluctant to participate in already established water markets, it also sought to identify the appropriate market mechanism given farmers' preexisting attitudes toward water markets.

Brekke et al. (2009) presented a flexible methodology for conducting climate-change risk assessments involving reservoir operations and applied it to California's Central Valley Project and State Water Project Systems. Multiple scenarios were conducted in order to show how choices made in conducting the risk assessment, choices known as analytical design decisions, could affect assessed risk. Decision makers can apply this methodology to their systems by selecting future periods and risk metrics relevant to their planning questions and by collectively evaluating system impacts relative to an ensemble of climate-change projection scenarios.

Wurbs et al. (2005) presented a case study investigation of the potential effects of climate change on assessments of water-supply capabilities and focused on whether and how climate-change considerations should be incorporated in the WAM system. The modeling approach was adopted to explore the impacts of climate change on hydrologic and institutional water availability for the numerous water users who depend on supplies provided by the Brazos River Basin. The study highlighted the greatest uncertainties associated with the use of global circulation models and challenges to obtain better predictions of future climate change at the river basin and sub-basin scale. However, the generalized modeling strategy presented in that research allows a predicted climate-change scenario to be translated to impacts on streamflows and water supply reliabilities.

Santos (2005) simulated several drought scenarios in the Rio Grande using equal-weight probability option within WRAP and provided mitigation options to manage future water allocations. The simulations were based on five drought categories recommended by the TWDB: (1) Abnormally Dry; (2) First-Stage Drought; (3) Severe Drought; (4) Extreme Drought; and (5) Exceptional Drought. The agency is responsible for compiling information, determining the trigger values, and developing an overall level of concern regarding water availability during drought. Muttiah et al. (2002) used WRAP simulation reliabilities from the Brazos and San Jacinto rivers, Soil and Water Assessment Tool (SWAT) modeling results, and general circulation model outputs to assess the impacts of potential future climate change on water supply capabilities. Khedun (2012) studied impacts of drought in the Rio Grande Basin using the climatic influence of the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in short-term and long-term water resources planning and management. A land surface model (LSM) and area-averaged runoff (AAR) were used to generate flows while dividing the basin into six sub-regions to analyze the influence of recent major ENSO events. The study found that not all ENSO events are created equal; some events have a short duration but high intensity while others linger for several years with lower sea surface-temperature anomalies (SSTA).

Gastelum and Cullom (2013) presented the application of the Colorado River Simulation System (CRSS) model in the Central Arizona Project to simulate multireservoir reliabilities during drought periods. CRSS is a sophisticated, object-oriented, surface-water simulation model developed under the RiverWare modeling environment and maintained by

the USBR. It incorporates important aspects of the Colorado River Basin: main stem, reservoirs along the river, water inflows to the river, and points of water deliveries.

Wurbs and Ayala (2014) studied impacts of evaporation from reservoirs in Texas and found that evaporation lowers storage levels severely during extended drought periods. Schnier (2010) and Bista (2015) found that using up to a six-month cycling option in short-term mode would produce better reliability. However, the simulations exceeding a six-month cycling option would be closer to long-term simulation using an equal-weight option.

Objective and Scope of the Research

This dissertation research included simultaneous investigations of both water management strategies and modeling capabilities for evaluating water management strategies. A comprehensive review of the literature has been performed. Published and unpublished studies of the Rio Grande have been explored. River/reservoir system modeling capabilities that have been developed throughout the world and reported in the literature have also been reviewed. The objectives of the research were to accomplish the following:

- Test, evaluate, and improve WRAP/WAM modeling capabilities.
- Develop a better understanding of the effects on water supply capabilities of transfers of diversion and storage rights between agricultural irrigation and municipal use and associated modifications of reservoir storage allocations and operating rules.
- Investigate the potential for short-term (several months to several years) forecasts of future storage levels and water availability based on WRAP conditional reliability modeling (CRM) in order to improve water management capabilities in the Lower Rio Grande Valley.

The simulation study of the Rio Grande Basin consisted of the following major tasks:

- Updating the 1940–2000 hydrologic period-of-analyses to cover 1940–2014.
- Performing a water availability modeling study in WRAP long-term simulation mode to investigate the effects on reliabilities of all water rights when (1) transferring water rights between agricultural and municipal use, and (2) increasing

or decreasing the municipal pool or changing other operating rules for Amistad and Falcon Reservoirs.

- Developing supply reliability and storage frequency metrics from future short-term forecasts based on using WRAP conditional reliability modeling (CRM) capabilities.

Research Methods

WRAP/WAM modeling system capabilities were explored and applied in the simulation study of the Rio Grande performed in this dissertation research. WRAP modeling capabilities were tested and expanded as appropriate. The modeling system was adapted as necessary to address the hydrologic conditions and unique water management strategies/practices of the Lower Rio Grande Valley. The remainder of this chapter describes the methodologies that were implemented.

Extension of the Hydrologic Period-of-Analysis

The goal of the flow extension process is to reproduce the statistical characteristics of the naturalized flows and seasonal patterns of flow sequences. The extension methodology is described in *Hydrology Manual* (Wurbs, 2013). The HYD extension model combines base flow and precipitation-runoff components to convert input precipitation and evaporation sequences into computed naturalized flows. The flow extension procedures are performed in the following steps (Pauls et al., 2013):

- Calibration of the flow extension model for each control point:
 - Level 1—initial calibration process to obtain values for basic parameters.
 - Level 2—final calibration process that incorporates additional parameters.
- Extension of flows with the calibrated flow extension model for each control point.

Level 1 calibration procedures are based on a complex set of optimization algorithms incorporated into HYD and designed to replicate known flows. Level 2 calibration deals with additional parameters designed to improve model capabilities for reproducing relevant statistical characteristics.

This procedure has continuously been implemented to develop extended, naturalized flows and net evaporation files for numerous river basins in Texas, including the Colorado, Guadalupe, Neches, Trinity, Brazos, and Sabine (Wurbs, 2012; Pauls, 2013). Also, *Hydrology* (Wurbs, 2013), *Reference* (Wurbs, 2012), and *Users* (Wurbs, 2012) *Manuals* provide documentation of WRAP datasets development and use (Wurbs, 2012). Applications and expansion of WRAP include daily simulations, salt simulations, condensing of the comprehensive datasets and performance simulations using SWAT modeling, climate change models, reservoir evaporations, and other applications.

Extending the Hydrologic Period-of-Analysis for the Rio Grande

WRAP allocates naturalized streamflows to meet water right requirements subject to net reservoir evaporation and channel losses. Naturalized flows represent natural conditions without water resources development and use. Regulated and unappropriated flows computed by WRAP reflect the effects of reservoir storage and water use associated with the water rights' requirements. Unappropriated flows are the amounts of stream flows still uncommitted after all water users have received their allocated share of water (Wurbs et al., 2005).

The Rio Grande WAM contains reservoir net evaporation depths for 55 control points for the 1940–2000 period of record. However, these datasets have not been developed to the present day due to the complexities of the process and significant cost and time associated with it. An alternative methodology for the development of input datasets using flow extension for WRAP simulations was developed to make current hydrological datasets available. The extension process involves all WRAP programs—SIM, HYD, and TABLES—as well as auxiliary programs such as ArcMap (ESRI, 2015), Microsoft Excel (2015), Notepad⁺⁺ (2015), and HEC-DSSVue (2015) for data manipulation, display, and analysis. It includes an extension of naturalized flow and net evaporation records for primary control points using a two-step calibration method.

TWDB (2015) maintains monthly evaporation and precipitation datasets from 1940 to 2014 based on the 168 one-degree quadrangles covering an area extending from 12° longitude and 14° latitude to with about 4,000 square miles of the area covering Texas. The datasets include an additional 76 quadrangles located outside of Texas, especially in the Mexico part

of the Rio Grande Basin, but there are periods of missing data for these quadrangles. The files *Evaporation.EEE* and *Precipitation.PPP* were created containing monthly evaporation and precipitation depths for each quadrangle covering both the Mexico and Texas parts of the Rio Grande. The quadrangles covering the Mexico side of the Rio Grande were created using ArcMap software. Watersheds were delineated to each main control point based on contributing upstream tributaries, and appropriate drainage areas were calculated using ArcGIS software. The numbers and areas of each of these quadrangles were entered to the HIN input file created for HYD program simulations in the Level 1 calibration step.

The Rio Grande WAM was simulated using an SIM program, which computed output file containing regulated flows for each control point after simulations of the water rights, reservoir storage and diversion contents, and river management based on the DAT file. The naturalized flows were computed by adding adjustments to actual gaged flows using an HYD program. The HYD read naturalized flows, regulated flows, reservoir storage volumes, and storage capacities from an output file produced by SIM and computed flow adjustments as follows:

$$\begin{aligned}\text{Flow adjustment} = & \text{ naturalized flow} - \text{regulated flow} \\ & + \text{storage shortage} + \text{diversion shortage}\end{aligned}$$

The purpose of the flow calibration process is to reproduce known naturalized flows as close as possible using SIM, HYD, and TABLES programs. The HYD naturalized flow extension for the Rio Grande was performed in two levels. In Level 1, the initial values were determined for hydrology-based models and optimization algorithms used to minimize differences between computed and known flows. In Level 2, parameters of the model were adjusted to reproduce the statistical characteristics of known flows. The final calibrated model was used to extend flows.

Wurbs and Kim (2011) extended sequences of the hydrologic period of record for the Brazos River Basin forward to the future and backward to the past and analyzed reliability results and developed various forms of a streamflow by modeling system, including naturalized flows, flows available to a system of interest considering the effects of other water managers or users, and regulated and unappropriated flows for a specified development or use scenario. In addition, the study developed condensed data sets and examined limitations of the model.

Operational parameters and management strategies of water diversions in Amistad-Falcon reservoir system were developed using CRM with extended WAM datasets that cover the 1940–2014 period. Application and analysis of the results from previous tasks were utilized to examine increased municipal pool reliabilities in the Amistad-Falcon system and their impacts on future irrigation-water allocations in the Lower Rio Grande Valley.

Conditional Reliability Modeling

Conditional reliability modeling (CRM) is used to assess the likelihood of meeting targets for streamflow, reservoir storage, water supply diversion, and hydroelectric power generation in the near future, conditional upon preceding storage. Rio Grande River Basin was chosen for this research as a case study. The equal weight option (conventional) of reliability analysis within WRAP is based on assigning probabilities equally likely to occur in each hydrologic period while initial reservoir storage levels sit full at the beginning of month simulations. With this method, reliabilities of meeting water demand for long-term planning would be higher than the CRM method. In the CRM method, the initial reservoir storage level is considered with settings of various values, and the end of the month storage is used as the beginning of storage in the following month. However, the conventional method covers seasonality in the simulations, unlike the CRM method, which does not. The conventional method is useful for long-term planning, whereas CRM is advantageous for developing short-term reliability analysis using different approaches (Schnier, 2010).

WRAP *SIM* may be applied in three alternative modes: (1) a single long-term simulation, (2) a yield-reliability analysis option, and (3) a conditional reliability modeling option (Wurbs 2009a). Within WRAP, there are two options for dividing a long period of hydrology into several shorter sequences: the annual cycle or a monthly cycle. The annual cycle simulates one sequence per year, and each sequence always begins in the same month. The maximum sequence length is equal to the number of months in the period-of-analysis.

In this research, the October 2014 full appropriation (TCEQ Run 3) of the Rio Grande (RG3) WAM datasets was used as the base model for extension of the hydrologic period of records as well as for the simulation analysis. TCEQ uses the full authorization option of the WRAP applications, assuming that the reservoirs are full at the beginning of simulation for

evaluations of permit applications. It is based on the rationale that the results for a long period of analysis are not significantly affected by the initial storage conditions. However, this may not be a realistic assumption for arid areas like the Rio Grande Basin. Wurbs (2005) concluded that the initial storage content less the storage content at the end of the simulation represents extra water that could result in estimated reliabilities being higher than they should. Thus, the Beginning-Ending Storage (BES) feature in WRAP was used to determine initial storage conditions for the Amistad-Falcon reservoirs system. The BES feature is based on setting the beginning and ending storage equal, which reflects the concept of a cycling hydrologic simulation period.

The yield-reliability simulation is based on repeating the long-term simulation to develop a diversion target (yield) versus reliability table that includes the firm yield if a firm (100% reliability) yield is possible. CRM is based on many short-term simulations starting with the same initial storage condition. Firm yield is the maximum water supply diversion that can be achieved with a volume and period reliability of 100 percent based on the premises reflected in the model (Wurbs, 2009a).

In a conventional, long-term simulation, WRAP allocates water for each month of a single hydrologic sequence starting with the first month of the period-of-analysis. For example, for a hydrologic period-of-analysis covering 1940 to 2014 (864 months) of the Rio Grande WAM, water is allocated during each sequential month of a single 864-month hydrological sequence beginning in January 1940. The conventional approach is commonly used to support long-term planning studies and evaluate water right permits. Santos (2005) applied conventional simulation on the Rio Grande to develop long-term water allocation reliabilities among DMI and irrigation water right holders and to develop drought management plans based on storage trigger percentages. For this study, the extended Rio Grande WAM datasets were used with both annual and monthly cycling options to develop water allocation and drought management scenarios that could be useful for irrigation districts, the TCEQ watermaster, and regional water planning groups.

CRM uses preceding reservoir storage to develop short-term reliabilities and frequency estimates. The input hydrology is divided into several short hydrologic sequences (months or a few years). The program SIM repeats the simulation for each hydrologic sequence, always beginning with the same initial storage condition. The program TABLES uses the simulation

results to develop flow and storage frequency relationships and water supply and hydropower reliabilities.

The choices involved in assigning probabilities to streamflow sequences are outlined below (Wurbs et al., 2009):

- Equal-Weight Option:
 - Choice of annual or monthly cycle options (CR record).
- Flow Frequency (FF) Relationship Option:
 - Choice of annual or monthly cycle options.
 - Selection of control points for naturalized flow.
 - Upper and lower limits defining reservoir storage range.
 - Choice of log-normal or Weibull.
- Storage-Flow-Frequency (SFF) Relationship Option:
 - Choice of annual or monthly cycle options.
 - Selection of control points for naturalized flow.
 - Upper and lower limits defining reservoir storage range.
 - Choice of regression equation.
 - Choice of log-normal or Weibull.

Applications of CRM include development of reservoir system operating rules and drought management plans, operational planning studies, administration of water right permits and water supply contracts, and decision support during drought (Wurbs et al., 2012).

Period reliability (R_P) is based on counting the number of periods of the simulation during which the specified demand target is either fully supplied or a specified percentage of the target is equaled or exceeded and is defined as follows:

$$R_P = \frac{n}{N} \times (100\%) \quad (\text{Eq. 1.1})$$

where n is the number of periods during the simulation for which the specified percentage of the demand is met, and N is the total number of periods considered.

Volume reliability is the percentage of the total demand that is actually being supplied. Volume reliability (R_V) is the ratio of the total diversion volume supplied or energy produced (v) to the total volume or energy target demanded (V) during a specified period of time. R_V

may also be viewed as the ratio of the mean actual water supply diversion rate to the mean target diversion rate.

$$R_V = \frac{v}{V} \times (100\%) \quad (\text{Eq. 1.2})$$

The exceedance frequency (F) is defined as the percentage ratio of the number of periods that a specified amount is equaled or exceeded (n) to the total number of time periods considered (N).

$$F = \frac{n}{N} \times (100\%) \quad (\text{Eq. 1.3})$$

WRAP also provides options to apply the normal or log-normal probability distributions to the series of monthly flow and storage volumes generated by SIM program. The random variable X in Eq.4 may be naturalized flows, regulated flows, unappropriated flows, instream flow shortages, reservoir storage volumes, or elevations.

$$X = \bar{X} + z \times S \quad (\text{Eq. 1.4})$$

The frequency factor (z) is derived from a normal probability distribution table, and \bar{X} and S are defined as the sample mean and standard deviation of the data read from the SIM output file.

The log-normal distribution consists of the normal distribution applied to the logarithms of X , with the mean $\log \bar{X}$ and standard deviation $S_{\log X}$ of the logarithms of the data computed from the SIM output file.

$$\log X = \log \bar{X} + z S_{\log X} \quad (\text{Eq. 1.5})$$

The *equal-weight option* is based on weighing each of the hydrologic sequences the same in applying the basic relative frequency concepts expressed in (1), (2), and (3) above with selected annual or monthly cycle options. Also, frequencies and reliabilities are estimated based on simply treating each simulation sequence as one possibility out of the total number of simulation sequences. Preceding storage is not explicitly considered in assigning probabilities to sequences. The annual cycle option starts each simulation sequence with the same specified month. In the monthly cycle option, the multiple simulations with the same starting storage condition begin in a different month, with approximately the same number of simulations beginning in each of the 12 months of the year (Wurbs, 2012).

The *probability array option* allows probabilities to be assigned to each hydrologic sequence with alternative sets of methods designed to consider preceding storage contents. In

addition to annual or monthly cycles, it includes a selection of a particular control point, a number of months for flows, and a choice of either a lognormal distribution or the Weibull formula. The probability array option can further be divided into the *flow-frequency relationship* (FF) and *storage-flow-frequency* (SFF) options. The FF option is based on assigning exceedance probabilities directly to naturalized flow volumes using either the log-normal probability distribution (5) or the Weibull formula (6), and preceding storage may simply be ignored.

$$P = \frac{m}{N + 1} \quad (\text{Eq. 1.6})$$

Where,

P exceedance probability

m rank of the values ($m = 1, 2, 3, \dots, N$)

N total number of sample values of the random variable

The SFF option is based on probabilistically representing deviations in naturalized flow volumes from the amounts indicated by a regression relationship between preceding reservoir storage volume and naturalized streamflow volume.

The equal-weight option, as the name implies, weighs each sequence as equally likely. An FF relationship assigns probability directly to naturalized flows using either a log-normal probability distribution or the Weibull formula. The SSF relationship uses log-normal or Weibull to relate exceedance probabilities to the random variable known as the flow ratio R .

$$R = \frac{Q}{Q_s} \quad (\text{Eq. 1.7})$$

where R is the ratio of observed flows (Q) over expected flows (Q_s). The expected flows are developed using regression relationship between preceding storage and naturalized flows (Wurbs, 2012).

Reliability Analysis

Short-term reliability scenarios for irrigation water rights were developed using preceding storage change intervals for the Amistad-Falcon reservoir system using WRAP CRM. The reliabilities of the municipal water rights were increased incrementally,

hypothetical reliability scenarios were simulated, and impacts on irrigation rights were examined.

Unlike the water rights in the rest of the river basins in Texas, water rights in the Rio Grande are based on the purpose of use where DMI have priority over irrigation and mining rights. In addition, two types of irrigation rights exist—Class A and Class B—wherein class A has seniority over Class B water rights. Also, irrigation water rights can be sold and converted into municipal rights, which seems to be an increasing case in the basin. Class A irrigation rights have 85% of the available water rights holdings in the basin, and there is no seniority among them (Characklis, 1999). However, these rights have the same proportions of storages in the Amistad-Falcon system, but implications of increased water right conversions may decrease reliabilities. As water rights transactions increase, actions of several users have impacts on the entire group of users. These effects have not been studied, and this research aimed to examine those changes quantitatively using hypothetical simulation scenarios. The overall objective of this research is to improve water management in the Lower Rio Grande by utilizing the extended hydrologic input data sets using WRAP.

An analysis using short-term and long-term simulations with initial reservoir storage levels of 75%, 50%, 30%, and 15% using monthly and annual cycling options was performed. In addition, through hypothetically increasing the municipal pool by 5%, 15%, 25%, and 40% incrementally, the impacts on irrigation reliabilities were analyzed. In addition, diversions for irrigation water rights were decreased incrementally, changes in period and volume reliabilities were recorded, and the effects on the rest of the users were studied.

Drought Management

Water availability issues in Texas include a rapidly growing population, declining groundwater supplies, intensifying demands on limited surface water resources, extreme hydrologic variability (including severe droughts), and very diverse climate (Wurbs, 2015). These issues are evident in the Rio Grande Basin, where evaporation exceeds precipitation, leaving the region susceptible to prolonged and severe drought and limiting surface water availability. The aim of this research was to quantify reliabilities of water allocations in the

Rio Grande during drought conditions and investigate water management plans during drought.

Drought management in the research was developed based on the trigger of the percentage of storage volume availability at the Amistad-Falcon Reservoir system versus the reliability or probability of having water allocation amounts for irrigation rights. The trigger levels currently recommended by the TWDB and the IBWC were also studied and integrated into the simulation analysis. In the short-term simulation mode, the SSF method with incremental initial storage levels of 15%, 25%, 40%, and 55% was used, followed by the same scenarios for the equal-weight option in order to determine long-term impacts of drought. Six-month cycles, from March through September, and alternatively, three-month cycles from May through July with SSF short-term simulations were conducted.

An increasing amount of literature (Santos, 2015; Griffin, 1998; Leidner, 2010) suggests that the municipal pool in the Amistad and Falcon Reservoir system is overly protected by excess storage. Although there is a water trade that exists from municipality to municipality and irrigation to irrigation, water marketing and trading from municipality and industry to irrigation are prohibited. WRAP simulation accompanying this issue was also performed in order to alleviate drought by reallocating some of the municipal water to irrigation based on hypothetical initial storage trigger levels.

Water allocations' databases for the 1990–2014 period of record from the TCEQ watermaster were compared to the WRAP simulation results to investigate similar patterns and changes in supply/demand covering the recent drought in the Lower Rio Grande region. The results of the study will help local irrigation districts manage water allocations more efficiently by letting them know the likelihood of meeting targeted demand during water shortages and peak irrigation seasons.

Organization of the Dissertation

This dissertation is divided into seven chapters. Chapter I introduced the research objectives, scope, and literature review related to the topics pursued and describes the methodologies of carrying out the hydrologic period of extension process along with examples of applied modeling. The Rio Grande River Basin is used as a case study in this research and

details are provided in Chapter II. The extension of the hydrologic period of records for the Rio Grande covering 1940–2015 is presented in Chapter III. Long-term reliability simulations are provided in Chapter IV that are based on the 76-year extended hydrologic period of analysis covering 1940–2015. In Chapter V, conditional reliability modeling applied to the Rio Grande to simulate short-term water availability is presented, and results are provided. The management of available water resources during the drought in the Lower Rio Grande by reallocating the municipal pool in the Amistad-Falcon reservoir system to irrigation use and is discussed in Chapter VI. Summary and conclusions of the research are given in Chapter VII.

CHAPTER II
CASE STUDY: RIO GRANDE BASIN
Basin Description

The Rio Grande is a transboundary water source shared by the United States and Mexico. The river originates in the San Juan Mountains of southern Colorado, flows 666 miles from its headwaters through the state of New Mexico, enters Texas about 7 miles northwest of El Paso, and continues for 1,263 miles to the Gulf of Mexico (Figure 2.1). It is the fifth longest river in North America (1,930 miles), and among the 20 longest rivers in the world. Through Texas, the river forms the border between the United States and Mexico from El Paso to the river's mouth at the Gulf of Mexico near Brownsville. It carries little water compared to other rivers of its length, and it tends to shrink in size as it flows downstream, which is typical of rivers passing through arid regions (Gomez-Patino et al., 2007). The Rio Grande Basin covers 335,000 square miles and includes portions of southern Colorado, New Mexico, west and south Texas, and parts of the Mexican states of Chihuahua, Durango, Coahuila, Nuevo Leon, and Tamaulipas.

Much of the area is non-contributing, and the contributing drainage area is approximately 176,000 square miles, which is roughly split between the United States and Mexico. This research focuses on the portions of the basin in Texas and Mexico. The contributing drainage area within Texas is about 40,000 square miles, and within Mexico is about 87,000 square miles.



Figure 2.1. Rio Grande Basin (Brandes, 2004)

The Rio Grande system through Texas and Mexico consists principally of the mainstem of the Rio Grande and nine major tributaries. The Pecos and Devils Rivers are the primary

tributaries in Texas. The Conchos, San Diego, San Rodrigo, Escondido, Salado, Alamo, and San Juan Rivers are the primary tributaries in Mexico (Figure 2.2).

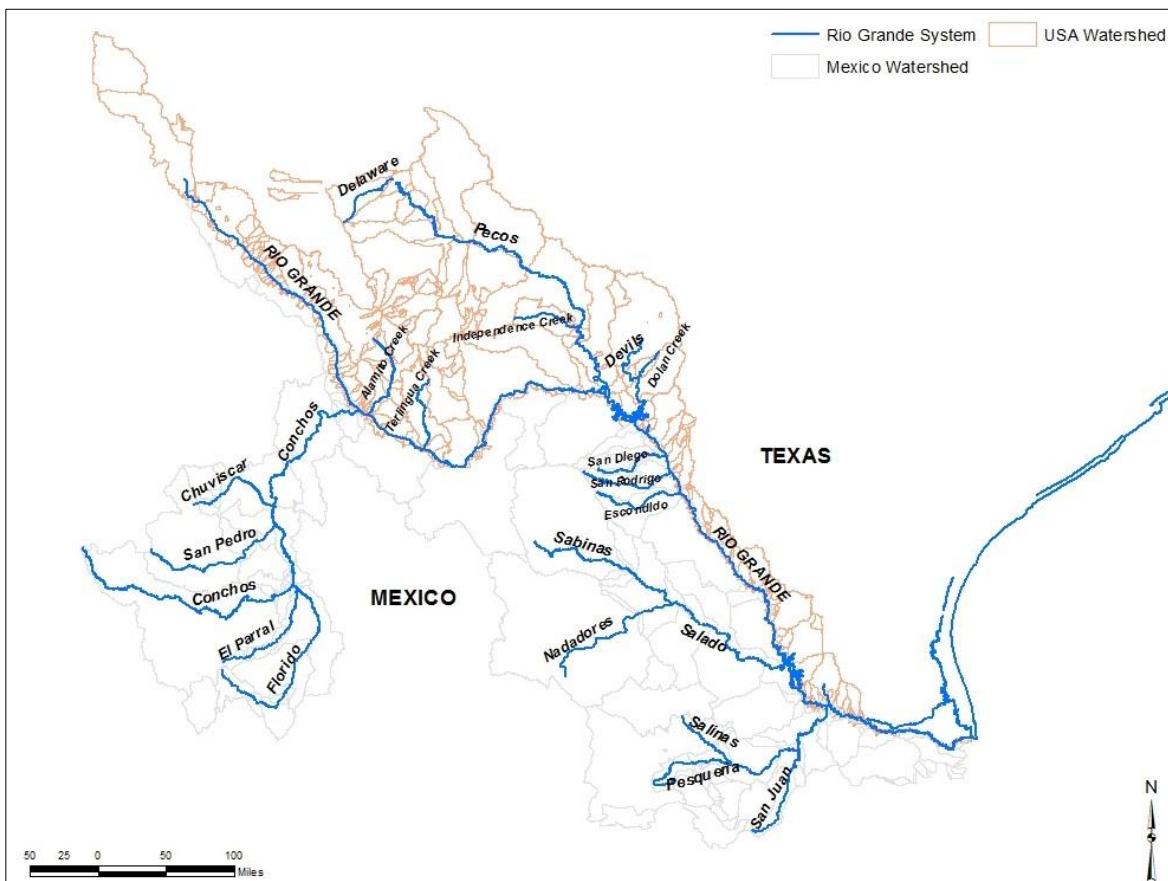


Figure 2.2. Primary tributaries of the Rio Grande

There are 26 major reservoirs in the basin, eight in Texas and 18 in Mexico, including associated off-channel reservoirs. Of the eight in Texas, three are on the main stem, four are on major tributaries, and one is off-channel (Figure 2.3). Major reservoirs are defined as those having a conservation storage capacity of 5,000 acre-feet or greater (Brandes, 2004).

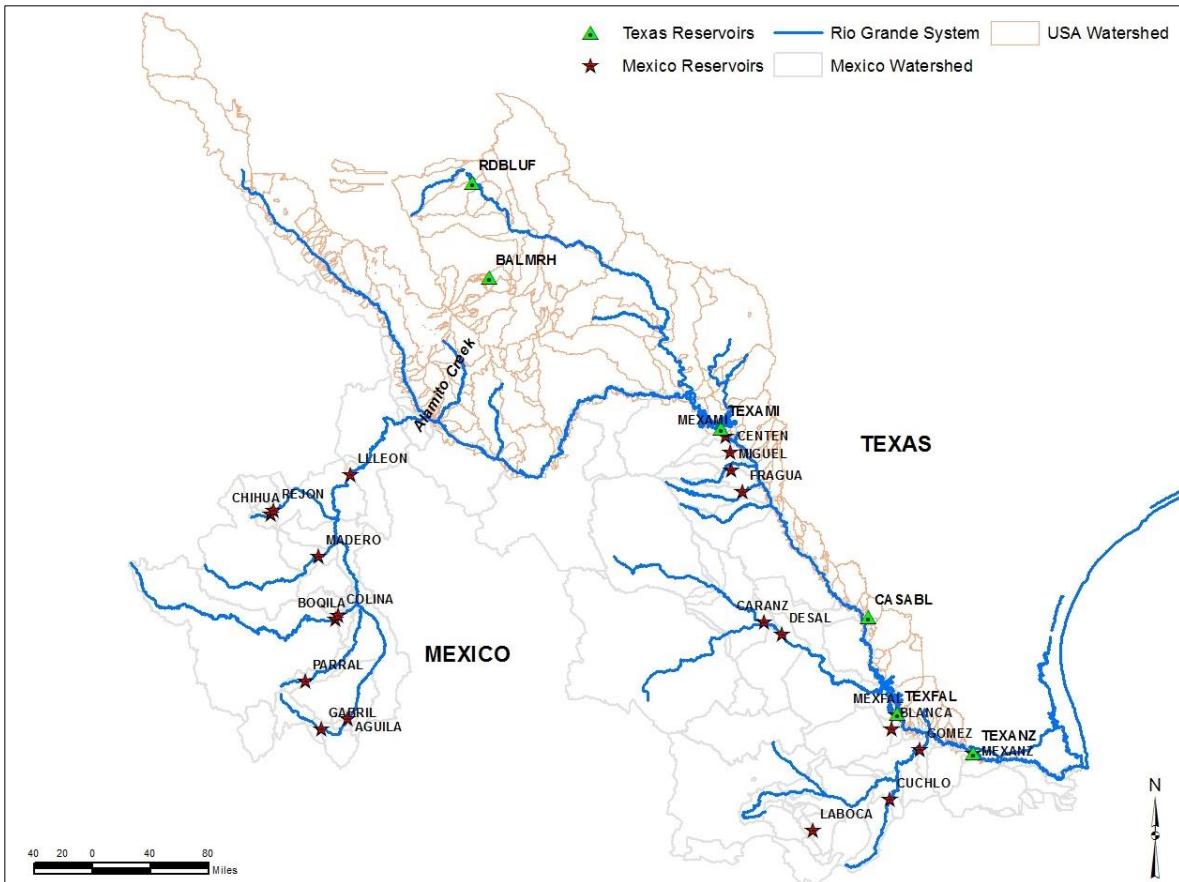


Figure 2.3. Major reservoirs and tributaries of the Rio Grande

The climate varies widely throughout the Rio Grande Basin. The western portion of the basin in Texas is desert, with an annual precipitation of approximately 8 to 16 inches. Precipitation increases toward the east and southeast; the southeastern portion of the basin is humid subtropical, with a maximum annual precipitation of approximately 24 inches near the coast. Average annual lake surface evaporation ranges from about 72 to 80 inches along the upper and middle Rio Grande to 56 inches near the coast. Elevations range from about 4,000 feet at El Paso, to over 8,000 feet in the mountains of west Texas, and to sea level at the coast. The climactic variation in northern Mexico is even more extreme than in Texas. Because of the extreme topographical variation in Mexico and the moisture arriving from the Gulf of Mexico, annual precipitation exceeds 40 inches in the 10,000-foot Sierra Madre Oriental mountain range near Monterrey in the southern portion of the basin. The upper watershed of

the Rio Conchos in the northwestern portion of the basin has a mean elevation that exceeds 5,000 feet and an annual precipitation ranging between 20 to 32 inches. However, lower elevations are desert, with an annual precipitation of 8 to 12 inches (Brandes, 2004).

Water Rights

Water rights in Texas evolved over the past 350 years from Spanish land laws and British common laws, both of which were based on a riparian doctrine that dictated that the property owner adjacent to a watercourse has the right to use its water (Table 2.1). Neither the amount of water nor purpose of use was specifically limited as long as it was reasonable (Caroom & Elliott, 1981). However, because of agricultural development in the West, prior appropriations doctrine was adopted. Under the prior appropriation system, an appropriator must obtain a license to divert a specified quantity of water to be applied to a specific beneficial use. The “first in time, first in right” rule applied to the system, with senior rights being satisfied to the exclusion of junior rights in time of shortage (Jarvis, 1991).

In 1967, the state of Texas passed legislation to integrate all pre-existing water rights into one unique permitting system based on prior appropriation doctrine in which priorities were given to the permits with older dates. However, the Rio Grande water rights were formed based on a special prior appropriations doctrine in which DMI water rights have priority over irrigation and mining rights. Irrigation and mining rights are also grouped into Class A and Class B rights, in which Class A users have 1.7 times more allocation than Class B users and have advantage during water shortages or droughts over Class B, which is subject to curtailment during such periods. Historical cropped acreages were used to assign those rights, and of the 742,809 acres of agricultural land in the Lower Rio Grande Valley deemed eligible, 641,221 acres were assigned to Class A irrigation rights. The remaining 101,588 acres were assigned Class B irrigation rights. About 85% of the water rights in the Lower Rio Grande are based on Class A rights. Priorities among each class of water rights do not exist.

Water Right Permitting

Water rights are granted by a state license, or permit, that allows the holder to divert a specified amount of water annually at a specific location, for a specific purpose, and to store water in reservoirs of specified capacity. Anyone may submit an application to the TCEQ to procure a new water right or to change an existing water right at any time. The TCEQ will approve the application if unappropriated water is available, a beneficial use of the water is contemplated, water conservation will be practiced, existing water rights are not impaired, and the water use is not detrimental to the public welfare.

After approval of an application, the TCEQ issues a permit giving the applicant the right to use a stated amount of water in a prescribed manner. Once the right to the use of water and the subsequent beneficial use of the water by the permit holder has been established, the user is issued a permit by the TCEQ, and the water is authorized to be appropriated unless the permit is cancelled. A permit may be cancelled if water is not used during a 10-year period. Special term permits may also be issued allowing water use for specified periods of time. The Rio Grande and segments of other rivers are currently over-appropriated, with no new rights for additional water being granted. A watermaster office has administered water rights and accounted for water use in the Rio Grande Basin since the 1960s (Wurbs, 1999).

Water Allocations and Management

The International Boundary and Water Committee (IBWC) owns and manages several reservoirs in the Rio Grande, including Amistad and Falcon Reservoirs on the main stem of the Rio Grande River. These two reservoirs are operated as a system and shared by United States and Mexico, as specified in the 1944 treaty. More than 50% of the storage of the system belongs to the United States portion, while the rest belongs to Mexico. IBWC executes the 1944 treaty and 1906 convention principles and guidelines as it allocates stored water to Mexico and the United States. The 1906 Convention obligates the United States to deliver 60,000 acre-feet of water each month to Mexico via the Aceque Madre at El Paso from Elephant Butte reservoir in New Mexico. Under drought conditions, the treaty calls for a proportional reduction in water for U.S. and Mexican irrigators. The 1944 treaty governs

allocations of Rio Grande waters between Mexico and United States from the gaging station at Fort Quitman to the Gulf of Mexico and obligates the United States to deliver 1.5 million acre-feet annually to Mexico through the Colorado River. The 1944 treaty apportions the flow of the Rio Grande equally between the signatories while the United States is allocated either one-third or 350,000 acre-feet of the flow from certain Mexican tributaries. These tributaries must deliver 1.75 million acre-feet to the Rio Grande main stem over a five-year accounting cycle. Shortfalls must be made up over the ensuing cycle. The treaty also allocates Amistad and Falcon Reservoir storage between the United States and Mexico.

The TCEQ watermaster is responsible for water allocations and permitting on the Texas part of the Rio Grande. Weekly water demands are collected by the watermaster office and submitted to the IBWC for diversions. A 6-day travel time for water to reach the lower part of the region must be considered during such request (Douglas, 2009).

The International Amistad and Falcon Reservoirs are operated by the IBWC primarily for flood control and water supply for the Lower Rio Grande Valley. They also provide hydroelectric power and recreation. Amistad contains 4.17 billion m³ of conservation storage and 2.15 m³ of flood control storage. Falcon Reservoir contains 3.29 billion m³ of conservation storage and 0.63 billion m³ of flood control storage. In accordance with the 1944 treaty, the United States has 56.2 percent and 58.6 percent of the conservation storage capacity of Amistad and Falcon, respectively, with Mexico owning the remainder. The IBWC operates Anzalduas and Retemal Dams on the lower reach of the Rio Grande to facilitate diversions. The travel time for releases from Falcon Reservoir to reach the furthermost downstream diversion locations is about one week (Wurbs, 1999).

Streamflows into Falcon and Amistad Reservoirs are allocated between the two countries. Flows on a number of major tributaries named in the treaty are gaged and allocated as specified by the treaty. All other flows not otherwise allocated are divided equally between the two countries. Computations are performed weekly to allocate the reservoir inflow and evaporation volumes that are combined with recorded releases to determine the amount of water that each country has in storage.

The IBWC is responsible for flood control operations. Hydroelectric power generation is essentially limited to using water already being released for other purposes. The U.S. share of the water supply storage in Amistad and Falcon Reservoirs is used to meet demands in the

lower basin and administered by the TCEQ in accordance with the state water rights system. Irrigation districts, individual farmers, and cities communicate their water needs directly to the TCEQ watermaster office, which in turn schedules releases from Falcon and Amistad Reservoirs with the IBWC.

Any water right holder who wants to exercise a water right must obtain written certification from the watermaster prior to diverting water and must post the certification at his/her diversion facility. The certification identifies the specific water right to be used and the number of the pump to be operated. Meters must be installed at the authorized point of diversion by each diverter. Deputies of the watermaster's office regularly check measuring devices to verify accurate measurement and accounting of the quantities of water diverted.

All rights holders reimburse the watermaster for expenses involved in the administration of the watermaster program. An assessment account is established and maintained for each right. The total assessment is the sum of a uniform base charge, a use fee, and a storage fee. The annual flat base charge must be paid regardless of the size of the right or use of the right. A use fee is calculated as the multiple of the account of water authorized for use, and an assessment fee is similarly calculated based on storage authorization and a purpose-dependent fee [Texas Water Commission, 1986].

Amistad-Falcon Reservoir System

The United States and Mexico built the Amistad Dam at the joining of the Rio Grande and the Devils Rivers, which holds 3,505,400 acre-feet of water, of which Texas' share is 56.2%. Below Amistad, there is the Falcon Reservoir, which holds 2,767,400 acre-feet of water, of which Texas' share is 58.6%. Falcon and Amistad Reservoirs were formalized in the treaty of 1944 by the IBWC, which authorized construction of the international reservoirs and provided for the division of stored waters between the two countries. Combined, these two reservoirs provide 95% of the Lower Rio Grande segment of the river with water. Reservoir management is complex in all cases and involves hydrological status, water demands, and issues of risk related to drought and/or flooding. Approximately 80% of withdrawals from the Rio Grande are for irrigation. Water rights in the Rio Grande Basin above Amistad Reservoir are managed based on the prior appropriation doctrine, or "first in time, first in right," as in the

rest of Texas. Water rights in the Middle and Lower Rio Grande that are served by the Falcon-Amistad Reservoir system are based on “purpose of use,” where priority is given to DMI uses.

Water below Amistad is allocated on an account basis, much like having a bank account with a constantly changing balance. Priority is given to all municipal accounts, which means that the storage balance for each municipal account resets to its full authorized water-right amount at the beginning of each year. The municipal priority is guaranteed by the monthly reestablishment of a municipal reserve in the system of 225,000 acre-feet, which is equivalent to one year of average diversions for all municipal demands below Amistad for Texas users (Brandes, 2004).

IBWC manages water appropriations based on the accounting system specified in the treaty. First, 4,600 acre-feet per month is allocated for the dead pool, 75,000 acre-feet per month is left for operation, seepage, and evaporation losses, and 225,000 acre-feet per month is deducted for municipal demands in case of drought or water shortage periods. Second, all municipal water demands for the middle and lower Rio Grande that are requested by the TCEQ watermaster are allocated. Then, demands for Class A water rights are supplied per request. Finally, if any surplus is left in storage, the Class B water demands are supplied. If a drought occurs, all Class B rights are curtailed, then Class A rights, if necessary. Any water shortage or prolonged drought is absorbed by irrigation rights that must endure all water-associated losses (Medellin-Azuara et al., 2007).

According to the Rio Grande watermaster program, irrigation accounts, on the other hand, must rely on balances that are carried forward because irrigation accounts are not reset at the beginning of the year. Each month the watermaster determines how much-unallocated water assigned to the United States is contained in the Falcon-Amistad system. If surplus water is identified in a given month, it is allocated to the irrigation accounts. When water is used, it is subtracted from the respective account by type of use from the account’s unused balance. This system of accounting for water usage was put in place after an international treaty with Mexico was established and by a 1969 district court ruling (TCEQ, 2016).

The allocation procedure followed by the watermaster is based on the following steps (TCEQ, 2000):

1. From the total amount of usable U.S. water stored in the Amistad and Falcon conservation pools, the first step consists of reserving 225,000 ac-ft for domestic, municipal, and industrial (DMI) uses.
2. From the remaining water in storage, the total end-of-month account balances for all irrigation and mining rights are deducted.
3. Next, available water is allocated to an *operational reserve* of 75,000 ac-ft to provide for loss of water by seepage, evaporation, and emergency requirements.
4. The storage is basically allocated in proportion to annual diversion rights, except the Class A rights are multiplied by a factor of 1.7 to allow them a greater storage allocation than Class B rights. Other provisions include limiting each storage allotment to not exceed more than 1.41 times its authorized diversion right; any remaining unallocated water is retained by the watermaster.

Total annual use cannot exceed the permitted amount except in the case of so-called “no-charge” pumping, which is allowed during periods of excess flow.

Water Marketing

Texas’s Lower Rio Grande Valley (LRGV) contains the most active water market in the state. The region’s steady increases in urban population and economic development motivate greater allocation of scarce water for these purposes. It was expected, and the data clearly indicate, that significant volumes of agricultural water have been sold for municipal and industrial purposes in the Valley (Griffin & Chang, 1992). Water rights can be loaned, traded, or sold in the Lower Rio Grande, acts which have widely been applauded as the primary mechanism for self-regulation of water shortages frequently occurring in the region. Class A and Class B rights can be converted to municipal right at 0.5 and 0.4 times of original allocated rights, respectively. However, leasing the rights to municipal purposes and trading from municipal to irrigation rights are prohibited.

The LRGV is somewhat unique in several ways: (1) there is virtually no groundwater option; (2) all rights are correlative (no seniority); (3) surface water diversions are closely monitored; (4) there are many players (no monopolistic power); (5) urban growth has been substantial; and (6) there are no return flow complexities (Griffin & Boadu, 1992).

Class A rights have the privilege to have more diversions. Surface water rights in the LRGV are correlative so that all Class A and Class B rights holders equally share periodic shortage or abundance. Leasing of water rights is possible in the Valley and is referred to as “water contracts.” Further, it is easy to satisfy the administrative requirements for leasing. The lessor need only call the watermaster’s office to inform them of the temporarily changed ownership. On the other hand, the lessee must be a current water right holder, and no change in purpose is permitted for water contracts.

Based upon both formal and informal observations, it appears that Texas has had a positive experience with surface water marketing. Purchase and lease prices of the LRGV water rights can be obtained and contrasted to use values. During the 20 years since the final determination of water rights in the LRGV, some 150+ transfers have occurred. Ninety-nine percent of these transfers are from agricultural to non-agricultural use. Transfers from agriculture to municipalities have amounted to nearly 75,000 acre-feet. Forty percent of current urban holdings of water rights were possessed by agriculture twenty years ago. There are no river authorities operating in the LRGV except the watermaster office of the TCEQ. Many water districts in the LRGV participate in rental markets as both lessors and lessees, but they do not sell water rights. Sales have been from private individuals and firms.

Drought Management

Drought is a persistent problem in the Rio Grande Basin. However, a recent drought event from 1992 to 2003 lasted longer than was ever anticipated in the negotiations of the 1944 treaty between the United States and Mexico. This drought lasted more than 10 years and created numerous difficulties in the Lower Rio Grande below Fort Quitman, Texas. As a result of the drought, Mexico was unable to deliver the quantities of water required under the 1944 treaty and accumulated a “water debt” at the end of two consecutive 5-year treaty accounting cycles. Meeting the treaty obligation became extremely difficult for Mexico during the recent drought. This drought drove the IBWC to develop and implement IBWC Minutes 307 and 308, which called for joint data sharing, joint drought management, and the convening of a binational mechanism toward sustainable management of the Rio Grande Basin.

The Rio Grande Basin is subject to frequent and prolonged drought periods, and since the Amistad-Falcon system is the only water supply buffer for the region, there is a need for the development of alternative water sources, such as treatment of brackish groundwater. There are no known drought management plans in the Lower Rio Grande because of its unique water rights priority system. The TCEQ watermaster requests IBWC to release weekly water demand from the Amistad-Falcon system, but Class B and Class A water rights will be curtailed during droughts after the water accounting process. Water marketing in the region is another reason for the absence of drought management plans. Mexico failed to meet its Rio Conchos obligations in the 1992–97 and 1997–2002 cycles. At the end of the 1992–1997 cycle, Mexico had a delivery shortfall of 1,024 ac-ft. Mexico contended that it is impossible to meet this schedule if the region suffers from an “extraordinary drought.” The drought continued through 1997–2002, and Mexico argued that the only available course of action would be to make up the deficit in the 2002–07 cycle.

Mexican tributary flows (i.e., from north-south; the Rio Conchos, Salado, and San Juan) prevent the City of El Paso and the El Paso and Hudspeth County Irrigation District’s diversions office from dewatering the Rio Grande below Fort Quitman. The Rio Conchos (Rio Salado) enters the Rio Grande above the Presidio-Ojinaga urban corridor (above Falcon Reservoir) and contributes 35–40% of the flow.

Moderate spring rains in 2004 allowed Mexico to lower the debt to 733,000 acre-feet; the debt had reached 1.5 million acre-feet. Mexico delivered the quantities stipulated in the 1944 treaty in the first 24 months of the 2002–2007 cycle and 126,000 acre-feet in the first 10 weeks of 2005. Furthermore, 210,785 acre-feet of Mexican water stored at the international reservoir at Amistad and 56,750 acre-feet at Falcon were transferred to Texas as payment on the international debt (Douglas, 2009). For the case of the RGRB, Mexico is required to deliver on average not less than 349,148 acre-feet/year in cycles of five consecutive years. The treaty allows Mexico to deliver less than 349,148 acre-feet/year in the event of “extraordinary drought,” although what constitutes “extraordinary drought” is not defined. Since 1944, Mexico has breached the Treaty for three cycles 1953–58, 1982–87, and 1992–97. For the first two periods, deficits were paid back during the next cycle. For the last cycle, Mexico accumulated a water delivery deficit of 1,400,914 acre-feet between 1992 and 2004. According

to Mexican government, the country experienced extraordinary drought, hence was not able to pay back on time.

Irrigation Districts

South Texas irrigation districts have an extensive system of engineered networks, including 24 major pumping stations and lifts, 800 miles of large water mains and canals, and 1,700 miles of laterals that deliver water to agricultural fields and urban areas (Figure 2.4).

Though similar in nature and operating under the same state mandates, each of the 28 Rio Grande Valley Irrigation Districts are distinct. Their distinctiveness is apparent in the varying topography, physical location, cropping patterns, and urbanization, as well as in their past and present decisions relating to financing and technological acceptance (Stubbs, 2003).

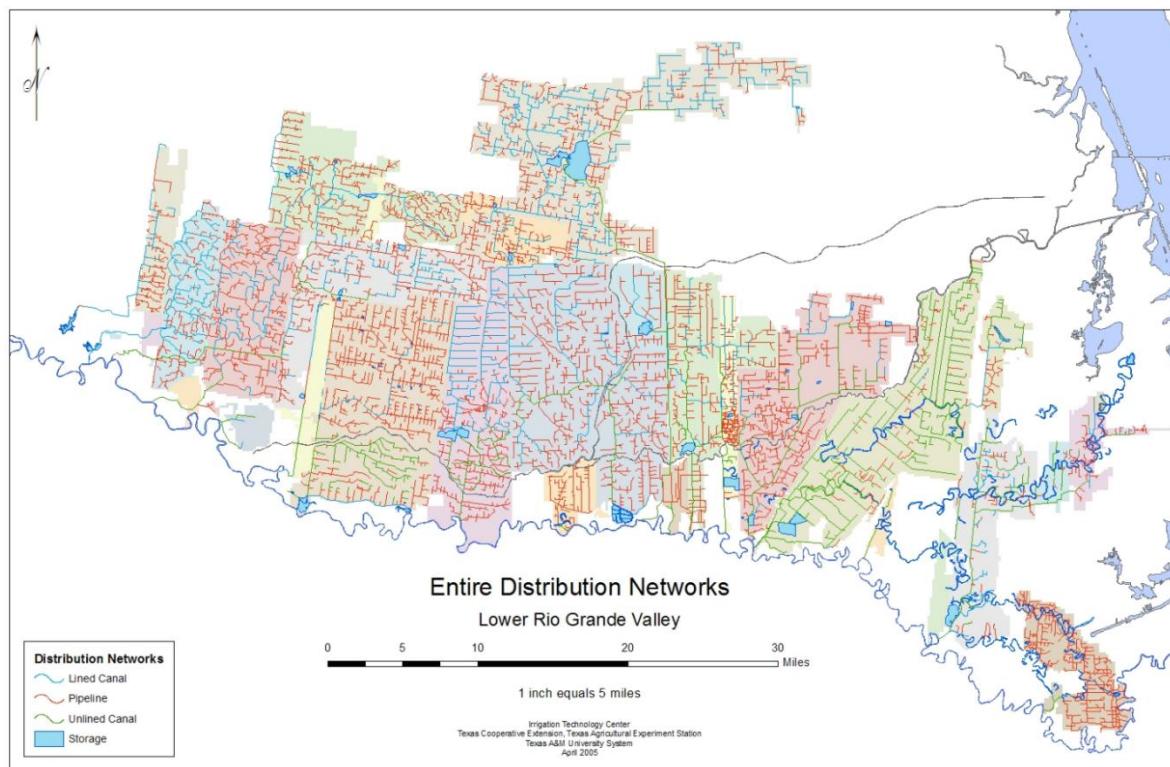


Figure 2.4. Lower Rio Grande irrigation districts (<http://idea.tamu.edu>, 2016)

Twenty-eight irrigation districts (Table 2.1) own about 85% of water rights in the Lower Rio Grande along with 1,207 miles of canals, 234 miles of pipelines, and numerous small reservoirs to convey and store Rio Grande waters. The majority of the districts own main pumping stations on the river along with conveyance infrastructure. Each district delivers waters to DMI, Class A, and Class B water right holders within the designated district boundaries. For instance, Harlingen Irrigation District delvers waters to the city of Harlingen and other small municipal users within its boundaries.

Table 2.1. Lower Rio Grande Irrigation District Annual Allocations

Official Irrigation District Name	Common District Name	Authorized Annual Water Rights (ac-ft)	Percent of Total (%)
Adams Garden Irrigation District No.19	Adams Garden	18,738	1.34
Bayview Irrigation District No.11	Bayview	17,478	1.25
Brownsville Irrigation District	Brownsville	33,949	2.42
Delta Lake Irrigation District	Delta Lake	174,776	12.47
Donna Irrigation District – Hidalgo County No.1	Donna	94,064	6.71
Hidalgo County Irrigation District No.1	Edinburg	85,615	6.11
Engleman Irrigation District	Engleman	20,031	1.43
Harlingen Irrigation District – Cameron County No.1	Harlingen	97,514	6.96
Hidalgo County Irrigation District No.13	HCID No.13	4,857	0.35
Hidalgo County Irrigation District No.5	Progresso	14,235	1.02
Hidalgo County Irrigation District No.6	Mission No.6	34,913	2.49
Hidalgo County Water Control and Improvement District No.18	HCWC&ID No.18	5,505	0.39
La Feria Irrigation District – Cameron County No.3	La Feria No.3	75,625	5.40
Cameron County Irrigation District No.6	Los Fresnos	52,142	3.72
Hidalgo County Water District	McAllen No.3	9,753	0.70
Hidalgo & Cameron Counties Irrigation District No.9	Mercedes No.9	177,152	12.64
Hidalgo County Irrigation District No.16	Mission No.16	20,000	1.43
Hidalgo County Water Control and Improvement District No.19	Mission No.19	11,777	0.84
Cameron County Irrigation No.2	San Benito	147,824	10.55
Hidalgo County Irrigation District No.2	San Juan No.2	137,675	9.82
Santa Cruz Irrigation District No.15	Santa Cruz No.15	77,180	5.51
Santa Maria Irrigation District – Cameron County No.4	Santa Maria No.4	10,183	0.73
United Irrigation District of Hidalgo County	United	64,464	4.60
Valley Acres Water District	Valley Acres	16,124	1.15
Total		1,401,573	100

Source: Rio Grande Water Master 2003

Rio Grande WAM

The Rio Grande is one of the world's most extensively studied rivers, and a myriad of modeling techniques and mathematical algorithms have been developed and applied to the

river basin over the course of the last three decades. The Rio Grande WAM datasets covering the 1940–2000 hydrologic period of record were developed by the R.J. Brandes Company in 2004 in contractual agreement with TCEQ in order to meet the requirements of Senate Bill 1 of the 76th Texas Legislature regarding the development of a new Rio Grande Basin water-availability simulation modeling. It consists of 962 control points with 55 primary (gaged) control points for which monthly naturalized flows were developed and distributed to the rest of the 908 secondary (ungaged) control points (Figure 2.5).

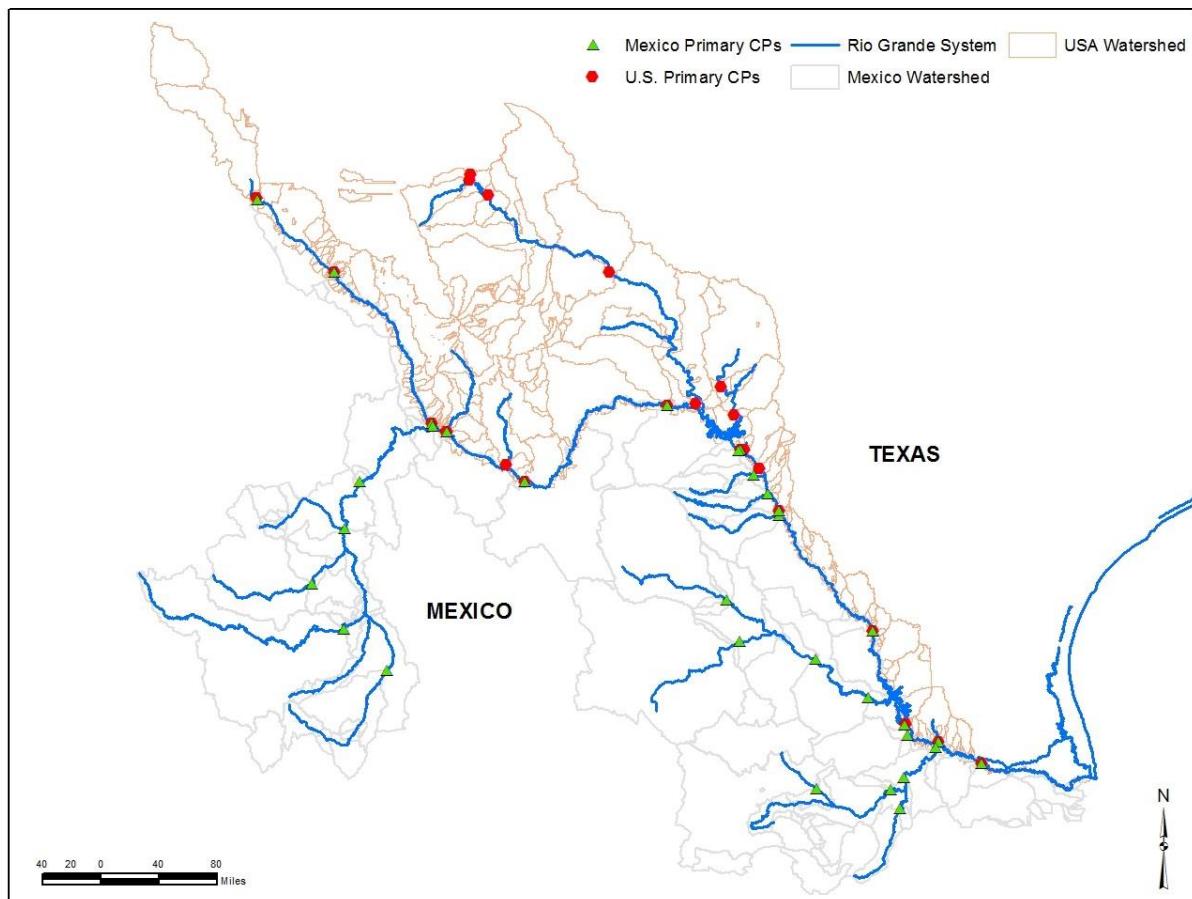


Figure 2.5. Primary control points and main tributaries of the Rio Grande

The most junior water right included in the WAM had a priority date of June 9, 2000. The total amount of authorized diversions for these water rights is approximately five million acre-feet per year. As indicated in Table 2.2, approximately 12 percent of the total authorized diversion

amount is for municipal supplies, 87 percent is for irrigation, and less than one percent is for mining, recreation, and other uses.

Table 2.2. Water Rights for Rio Grande by Category of Use

USE CATEGORY	NUMBER OF RIGHTS BY USE TYPE	AUTHORIZED DIVERSION acre-feet/yr	PERCENT OF TOTAL*
TEXAS			
Municipal	142	366,414	12.4%
Irrigation	1,241	2,574,781	87.3%
Mining	36	7,598	0.3%
Hydroelectric	2	2,100,000	--
Recreation	8	72	0.0%
Other	20	50	0.0%
Texas Total	1,449**	2,984,915*	100.0%
MEXICO			
Municipal	12	378,480	12.3%
Irrigation	20	2,707,606	87.7%
Mexico Total	34	3,086,086	100.0%
GRAND TOTAL	1,483	6,071,001*	--

* Does not include hydroelectric. Hydropower may only be generated from spills or releases made for other uses.

** Many rights have multiple use categories. Total number of individual water rights is 962.

Source: Brandes 2004

There are 32 water commitments, or “concessions” (as they have been referred to by Mexican officials), in the Mexico portion of the Rio Grande Basin that have been included in the WAM. The total amount of diversions for these concessions is approximately 3.1 million acre-feet per year. The distribution between municipal and irrigation uses in Mexico is similar to the uses in Texas.

Table 2.3 and Table 2.4 show 23 primary control points on the Texas portion of the Rio Grande and 32 on the Mexico portions of the Rio Grande. The Rio Grande WAM has essentially developed as two parallel modeling systems to capture streamflow for each country separately. Although the hydrologic period of extension, firm yield, and conditional reliability

modeling simulation involved all control points, this research will mainly focus on the Texas portion of the basin.

Table 2.3. United States Primary Control Points and Mainstream Gages Used in WAM

PRIMARY CONTROL POINT NO.	I.D.	CONTROL POINT LOCATION	IBWC/USG	DRAINAG
			S GAGE NUMBER	E AREA Sq. Mi.
AT/AM200				
0	RG-EP	R Grande at El Paso, TX	08364000	29,270
AT/AM100				
0	RG-FQ	R Grande at Fort Quitman, TX	08370500	31,944
BT/BM1000	RG-AC	R Grande abv R Conchos, TX	08371500	35,000
CT7000	AC-PR	Alamito Ck nr Presidio, TX	08374000	1,504
CT/CM6000	RG-BC	R Grande blw R Conchos, TX	08374200	63,339
CT5000	TC-TE	Terlingua Ck nr Terlingua, TX	08374500	1,070
		R Grande at Johnson Ranch nr Castolon,		
CT/CM4000	RG-JR	TX	08375000	67,760
CT/CM3000	RG-FR	R Grande at Foster Ranch nr Langtry, TX	08377200	80,742
GT5000	PR-RB	Pecos R at Red Bluff, NM	08407500	19,540
GT4000	DR-RB	Delaware R nr Red Bluff, NM	08408500	689
GT3000	PR-OR	Pecos R nr Orla, TX	08412500	21,210
GT2000	PR-GI	Pecos R nr Girvin, TX	08446500	29,562
GT1000	PR-LA	Pecos R nr Langtry, TX	08447410	35,179
CT2100	DR-JU	Devils R nr Juno, TX	08449000	2,730
		Devils R at Pafford Crossing nr Comstock,		
CT2000	DR-PC	TX	08449400	3,960
CT/CM1000	RG-DR	R Grande at Del Rio, TX	08451800	123,302
DT9000	SF-DR	San Felipe Ck nr Del Rio, TX	08453000	46
DT8000	PC-DR	Pinto Ck nr Del Rio, TX	08455000	249
DT/DM500				
0	RG-PN	R Grande at Piedras Negras, COAH	08458000	127,311
DT/DM300				
0	RG-LA	R Grande at Laredo, TX	08459000	132,577
DT/DM100				
0	RG-BF	R Grande blw Falcon Dam	08461300	159,269
ET/EM2000	RG-RG	R Grande at Rio Grande City, TX	08464700	174,362
ET/EM1000	RG-AN	R Grande blw Anzalduas Dam, TX	08469200	176,112

Source: Brandes 2004

Table 2.4. Mexico Primary Control Points and Mainstream Gages Used in WAM

PRIMARY CONTROL POINT NO.	CONTROL POINT I.D.	CONTROL POINT LOCATION	IBWC/CNA GAGE NUMBER	DRAINAGE AREA Sq. Mi.
R Conchos at La Boquilla Reservoir,				
FM6000	RC-BO	CHIH	24077	8,109
FM5000	RF-CJ	R Florida at Cd. Jimenez, CHIH	24225	2,857
FM4000	SP-VI	R San Pedro at Villalba, CHIH	24181	3,633
FM3000	RC-LB	R Conchos at Las Burras, CHIH	24226	19,815
FM2000	RC-EG	R Conchos at El Granero, CHIH	24339	22,526
FM1000	RC-OJ	R Conchos nr Ojinaga, CHIH	08373000	26,404
Arroyo de las Vacas at Cd. Acuna,				
DM9500	AV-CA	COAH	08452000	350
DM7000	SD-JI	R San Diego nr Jimenez, COAH	08455500	853
DM6000	SR-EM	R San Rodrigo at El Moral, COAH	08457100	1,049
DM4000	RE-VF	R Escondido at Villa de Fuente, COAH	08458150	1,459
DM2300	RS-SA	R Sabinas at Sabinas, COAH	24026	4,887
DM2200	RN-PR	R Nadadores at Progreso, COAH	24150	8,918
DM2100	RS-RO	R Salado at Rodriguez, NL	24038	18,329
DM2000	RS-LT	R Salado nr Las Tortillas, TAMPS	08459700	23,154
EM4000	RA-CM	R Alamo at Cd. Mier, TAMPS	08462000	1,675
EM3400	SJ-EC	R San Juan at El Cuchillo, NL	24088	3,397
EM3300	RS-CF	R Salinas at Cienega de Flores, NL	24087	5,660
EM3200	RP-LH	R Pesqueria at Los Herrera, NL	24196	7,734
EM3100	SJ-LA	R San Juan at Los Aldamas, NL	24351	11,627
EM3000	SJ-CA	R San Juan at Camargo, TAMPS	08464200	12,940

Source: Brandes 2004

CHAPTER III

EXTENSION OF HYDROLOGIC PERIOD OF RECORD

Introduction

Although the hydrologic period of extension methodology has been tested, calibrated, and applied to several river basins of Texas, in this study, it was applied to the Rio Grande WAM for the first time. The Rio Grande is a very complex river basin to model because it directly depends on reliable data from the Mexico portion of the watershed. Since the methodology uses monthly precipitation and evaporation depths, there was no need for additional data, which is one of the advantages of this process. The TCEQ uses updated WAM datasets for evaluations of water right permits or applications for such permits that are submitted by new water users. However, the TCEQ simulates the WAM WRAP system for a particular river basin of interest in order to determine if there is any unappropriated water left for the new users after full authorization of all water right permit holders' supplies has been met. Additionally, TWDB also uses the WAM WRAP to determine future water availability conditions for state water planning purposes. As mentioned in previous chapters, the Rio Grande is considered an over-appropriated river basin; new water permits will not be issued in the foreseeable future.

The extension of the Rio Grande WAM hydrology from 2001 to 2015 using recently developed methodologies is described in this chapter. Results of the updated Rio Grande WAM covering the 1940–2015 hydrologic period were used to evaluate reservoir firm yield and reliability analysis, and the results are presented in later chapters.

The objective of this section is to summarize how the TCEQ WAM System WRAP hydrology input dataset for the Rio Grande Basin, which for brevity is called the Rio Grande WAM, was updated. The methodology for extending naturalized flows applied in this research is very different from conventional methods used in the past when the original datasets were developed. The Rio Grande WAM has a hydrologic period-of-analysis extending from January 1940 through December 2000. The new hydrologic period of analysis has been extended to cover January 1940 through December 2015. The original 1940–2000 hydrologic data sequences were combined with the 2001–2015 data sequences described in this chapter. The

Rio Grande WAM hydrology data consist of monthly naturalized flows at 55 control points, monthly net reservoir surface evaporation less precipitation depths assigned to 25 control points, and spring flows at a single control point. The set of procedures for extending flows and evaporation-precipitation rates applied here are described in Chapters 4, 5, and 7 of the *Hydrology Manual*, which supplements the WRAP *Reference* and *Users Manuals* (Wurbs 2015).

The WRAP input datasets in the TCEQ WAM System include both water right files and hydrology files. The hydrology files for all of the WAMs include naturalized flows and reservoir net evaporation-precipitation depths in FLO and EVA files. Several of the WAMs, including the Rio Grande WAM, include a flow adjustment FAD file containing adjustments for spring flows from groundwater.

The original sequences of naturalized flows developed during 1997–2001 for the statewide WAM system are based on adjusting observed flows at about 500 gaging stations in order to remove the effects of reservoirs, water supply diversions, return flows from surface and groundwater sources, and other aspects of water resources development and use. WRAP-HYD provides several sets of routines to facilitate the development of naturalized flows based on adjustments to gaged flows. Regardless of whether HYD, Excel, or another software is used, complexities of the flow adjustment approach include difficulties in compiling the water management data upon which the flow adjustments are based and the discontinuation of a significant number of stream gaging stations. The process of transforming actual measured flows to naturalized flows is further complicated by channel losses (seepage, evapotranspiration, unaccounted diversions) and travel times between the stream sites of the flows and the locations of the dam, diversion, and return flow sites, which may be many miles upstream. Changes in land use, groundwater, and climate further complicate the development of homogeneous flow sequences.

TWDB Precipitation and Evaporation Datasets

The naturalized flow extension strategy adopted for this research was based on using the database of precipitation and evaporation compiled by the Texas Water Development Board (TWDB) combined with TCEQ WAM datasets of naturalized flows to extend

naturalized flows and on using the precipitation and evaporation rate data to extend WAM net evaporation-precipitation rate sequences. The TWDB datasets of monthly precipitation depths and reservoir surface evaporation depths in inches, the map reproduced in Figure 3.1, and an explanation of methods employed in compiling the data are available at the following website: <http://www.twdb.state.tx.us/surfacewater/conditions/evaporation/index.asp>.

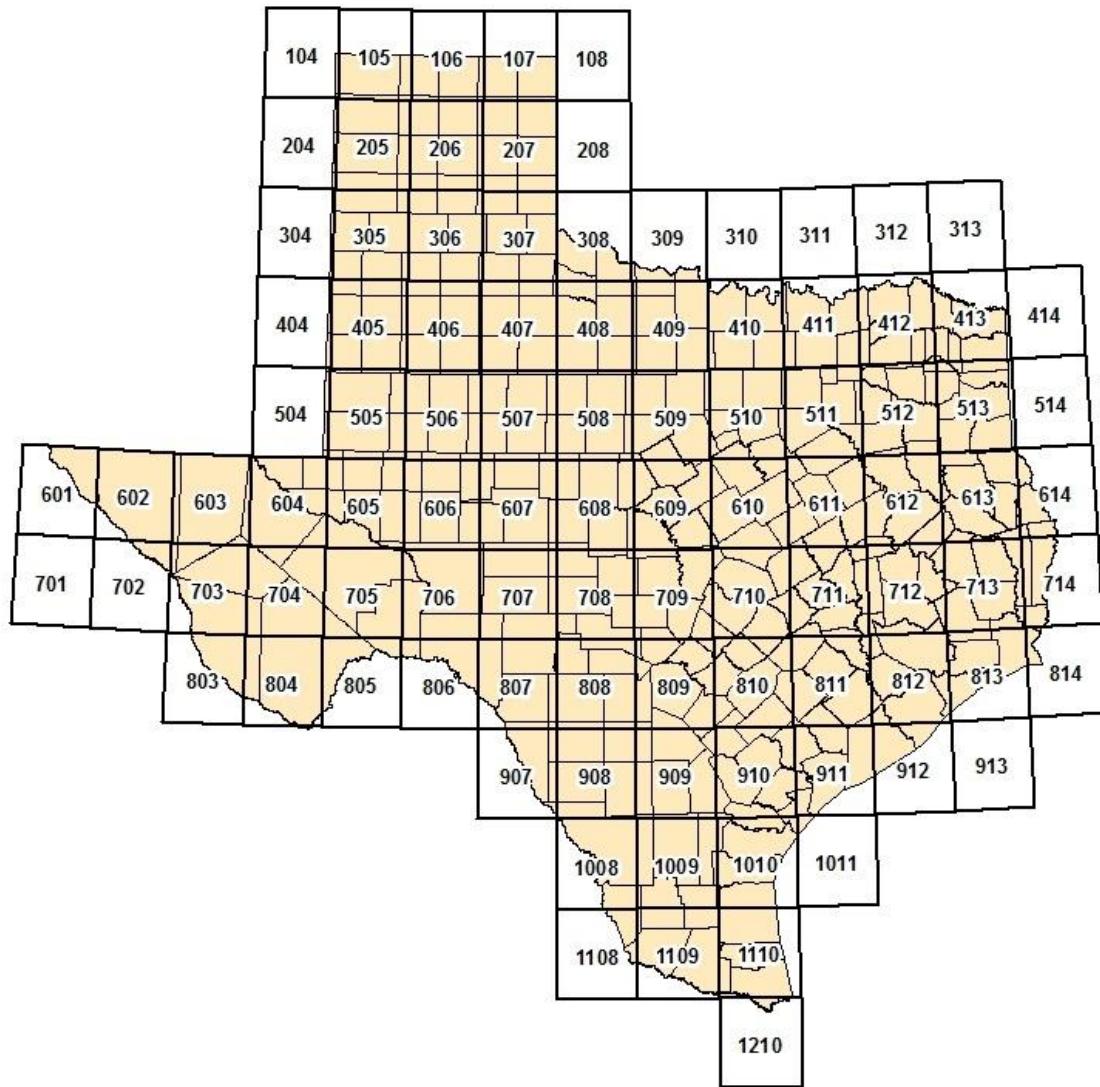


Figure 3.1. Quadrangle map for TWDB precipitation and evaporation datasets

A total of 168 one-degree quadrangles extending 12 degrees longitude and 14 degrees latitude encompass Texas and adjacent, surrounding areas. Complete monthly precipitation and evaporation data for 1940 up to near-present day are available for the 92 quadrangles shown in Figure 3.1 that cover Texas. The datasets include an additional 76 quadrangles located outside of Texas, but there are periods of missing data for these quadrangles. The 168 one-degree quadrangles define a grid with 12 rows and 14 columns. The three or four-digit quadrangle identifiers consist of the row and column numbers. The areas of each quadrangle are about 4,000 square miles. The monthly precipitation and evaporation depths date back to 1940 and are updated each year around May by adding data for January through December of the preceding year. However, the methodology for compiling evaporation data for 1940–1953 was different than for 1954 to the present. The differences are described at the previously cited TWDB website. The TWDB maintains the 1940–1953 evaporation data as a separate dataset. When the new hydrologic period-of-analysis extension capabilities were developed, the statewide precipitation and evaporation datasets for 1940–2015 were obtained from the TWDB in 2016 as text files. Microsoft Excel was used to convert the two files to a consistent format. These two files were updated in 2016 to include 2015 data and can be easily updated each year in the future. The filenames *Precipitation.PPP* and *Evaporation.EEE* were adopted for the two text files of statewide precipitation and evaporation that are read by the WRAP program *HYD* as input files.

Alternative Approaches for Extending Hydrologic Periods-of-Analysis

The WRAP program *HYD* is a set of routines designed to facilitate developing and updating the hydrology input data for the WRAP simulation model *SIM*. Program *HYD* is explained in the previously noted *Hydrology Manual*. The original *HYD* was created during 1999–2001. Major new and expanded capabilities were added to *HYD* during 2007–2008 and 2011–2012. The TCEQ WAM System hydrology datasets were developed during 1997–2001 by consulting firms working for the TCEQ. With the exception of case study investigations performed at Texas A&M University, *HYD* had not been applied previously because the hydrology datasets of naturalized flows and net evaporation–precipitation depths incorporated in the WAM System were completed before *HYD* became available. Most computations

previously performed with Microsoft Excel in developing the original hydrology datasets can also be carried out with *HYD*. Observed flows at stream-gaging stations with watersheds that have experienced little or no development may be adapted for direct use in the WAM System as naturalized flows representing natural conditions of river basin hydrology without human water consumption. However, population growth, economic development, and accompanying water resources development and use significantly affect the flows of most major rivers in Texas. Differences between computed naturalized flows and actual gaged flows are often very significant (Wurbs et al., 2013).

Proposed New Hydrologic Period-of-Analysis Extension Methodology

The alternative strategy developed during 2011–2012 and applied in 2011–2012 Brazos and Colorado River WAM case studies and the existing Rio Grande WAM project relate the original naturalized flows to concurrent precipitation and evaporation. The same TWDB datasets used to compile the evaporation-precipitation rates in an EVA file are used to synthesize naturalized flows for the FLO file. This flow synthesis approach is much easier to apply and is particularly advantageous in situations where accurate data required to adjust observed flows are unavailable or difficult to compile or stream gaging stations have been discontinued. The set of procedures implemented in the WRAP program *HYD* is covered in Chapters 4, 5, and 7 of the *Hydrology Manual*.

Most of the effort and expertise required to apply this new approach is devoted to developing a calibrated hydrologic model for the river basin, which is in the form of an *HYD* input HIN file, for synthesizing naturalized streamflows. Upon completion of the calibration of the hydrologic model, the hydrologic period-of-analysis can be easily extended. This means that the period-of-analysis can be easily updated annually. As the TWDB updates their precipitation and evaporation databases each year, another year can be added to the WAM periods-of-analysis.

Monthly net evaporation-precipitation rates in feet/month are computed with the new *HYD* features using the TWDB datasets by subtracting precipitation depths from evaporation depths. *HYD* reads the TWDB precipitation and evaporation datasets and produces a set of *EV* records. The evaporation-precipitation depths may be associated with a single quadrangle or

may be weighted averages of quantities associated with from two to four quadrangles. Program *HYD* allows evaporation and precipitation rates to be read directly from the TWDB-compiled statewide datasets and to be easily manipulated to produce *EV* records stored in an *EVA* file. Calibration of the flow extension model for each primary control point is the most complex aspect of this process of extending a hydrologic period-of-analysis. *HYD* employs a complex set of mathematical optimization algorithms to calibrate values for the numerous model parameters. For a Rio Grande WAM period-of-analysis of 1940–2000, calibration consisted of determining values for a set of model parameters for a particular control point that resulted in a series of 1940–2000 monthly, computed naturalized flows that reproduced 1940–2000 known naturalized flows as closely as possible. Since the method for compiling evaporation data changed significantly after 1953, alternative hydrologic models were developed using a calibration period that included and excluded 1940–1953.

The update of the WRAP hydrology input files for the Rio Grande WAM for the period of 2001–2015 consisted of developing monthly sequences of the following:

- reservoir surface net evaporation less precipitation rates in units of feet/month recorded on *EV* records in an *EVA* file;
- naturalized flows in units of acre-feet/month assigned to 55 control points recorded on *IN* records in an *FLO* file; and
- spring flows in units of acre-feet/month for a single control point recorded on *FA* records in a *FAD* file.

The program *HYD*-based methods described in Chapters 4, 5, and 7 of the *Hydrology Manual* were applied to update the naturalized flows and evaporation-precipitation depths. The spring flows for the Rio Grande were extended using average flows for the original WAM datasets covering 1940–2000 because the control point to record flows for which the original datasets were developed has been discontinued. These spring flows are treated as separate components of naturalized streamflows in the naturalization process and added back to the flows within the *SIM* simulation as flow adjustments in a *FAD* file.

Extension of Net Evaporation-Precipitation Rates

The WAM hydrology datasets were developed during 1997–2001 by consulting firms working for TCEQ. Microsoft Excel spreadsheets were used extensively in this work. The net reservoir surface evaporation less precipitation rates on the *EV* records in the EVA files were compiled largely from the TWDB evaporation and precipitation datasets noted above. These same TWDB datasets continued to be used in the Rio Grande WAM project reported on here in order to update the EVA files. However, new *HYD* capabilities were adopted that facilitate developing the *SIM* evaporation-precipitation input files directly from statewide TWDB datasets.

Rio Grande WAM Evaporation-Precipitation Quadrangles and Control Points

The TWDB maintains datasets of monthly precipitation and evaporation depths for the 92 quadrangles shown in Figure 3.2 that cover the state of Texas. The Rio Grande Basin is delineated in Figure 3.2. The statewide TWDB monthly precipitation and evaporation depth datasets are stored in files with filenames *Precipitation.PPP* and *Evaporation.EEE*.

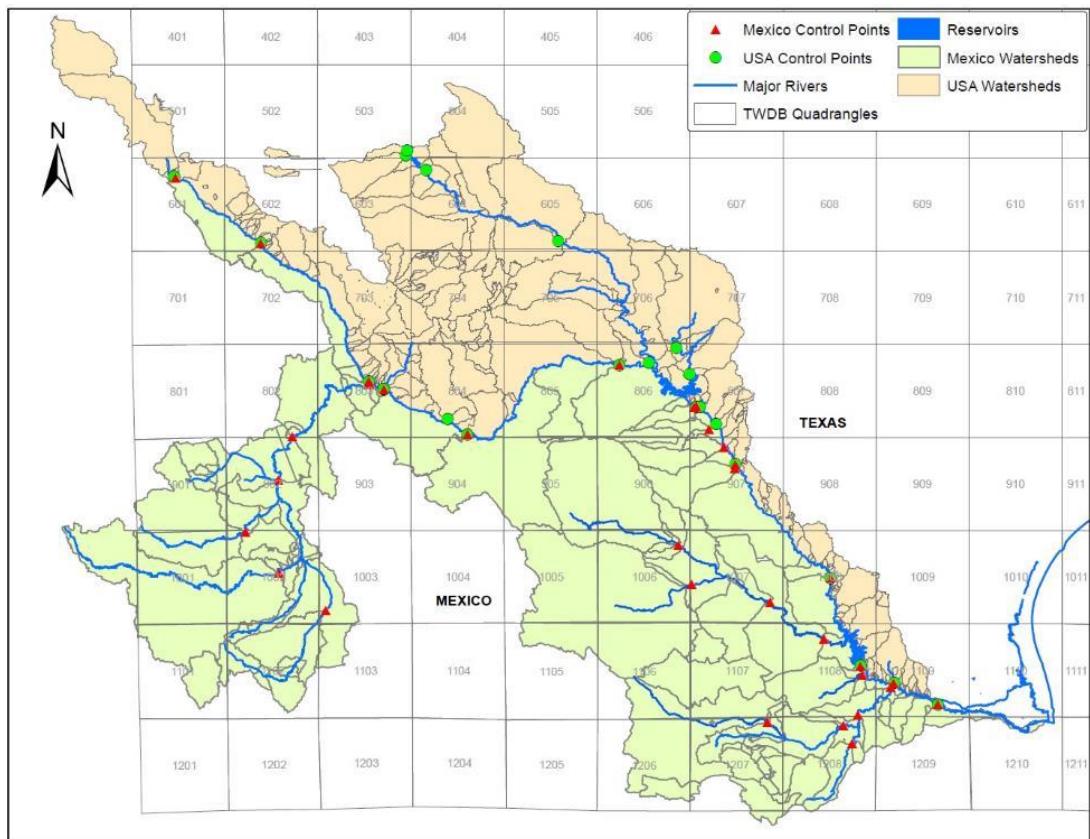


Figure 3.2. Rio Grande primary control points and TWDB quadrangles

The 25 control points that measure reservoir surface net evaporation-precipitation rates are shown in Figure 3.3. Eighteen of these control points are located in the Mexico portion of the Rio Grande Basin, and seven are located in the U.S. portion of the Rio Grande watershed.

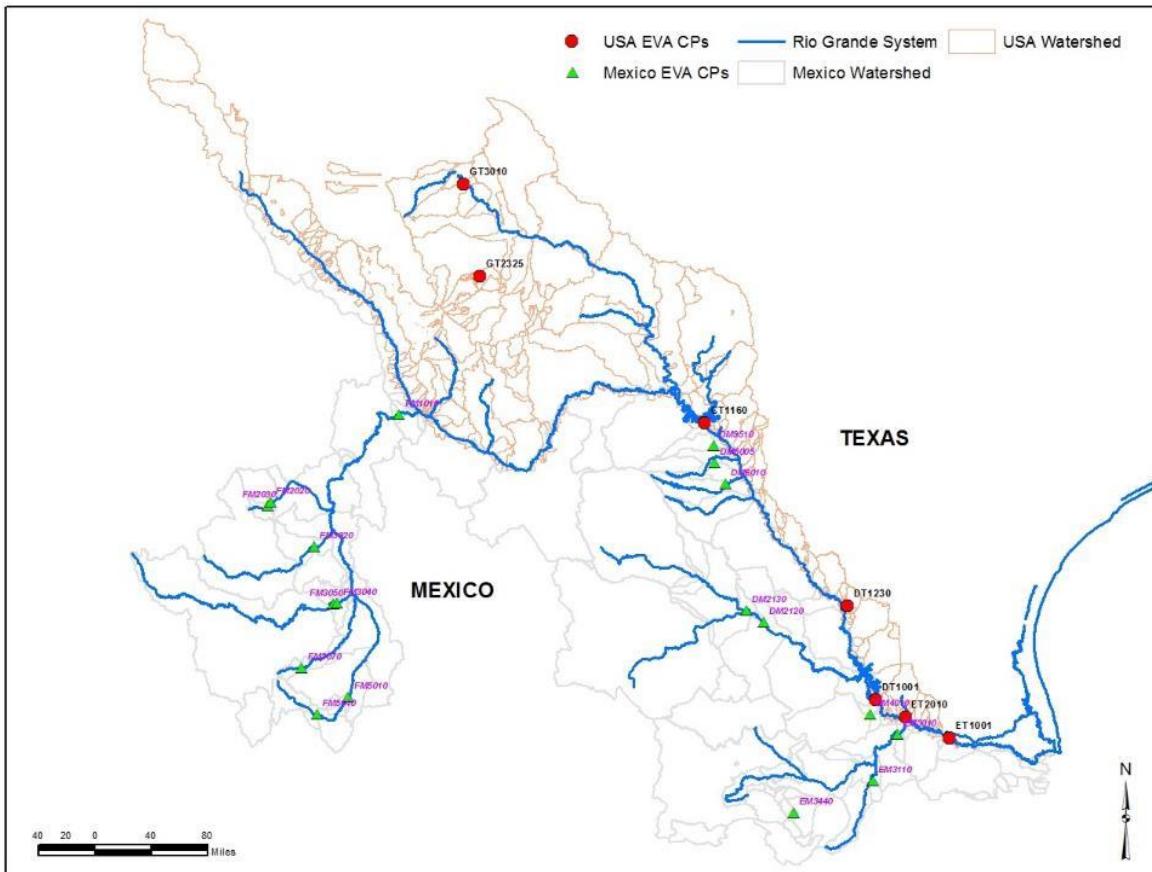


Figure 3.3. Locations of the EVA control points for the Rio Grande Basin

Adjustments for Precipitation Runoff at Reservoir Sites

Evaporation from a reservoir and precipitation falling directly on the reservoir water surface are combined as a net evaporation minus precipitation. Net evaporation less precipitation volumes are computed within the *SIM* simulation by multiplying the reservoir water surface area by net evaporation-precipitation rates provided on *EV* records in dimensions of depth/month.

Precipitation depths are commonly adjusted for reservoir site runoff that is reflected in the naturalized streamflows. Without a reservoir, the runoff from the land area of the non-existent reservoir contributes to streamflow. However, only a portion of the precipitation falling at the reservoir site contributes to streamflow. The remainder is lost through infiltration

and other hydrologic abstractions. With the reservoir in place, all of the precipitation falling on the water surface is inflow to the reservoir.

SIM includes an option activated by parameter EPADJ in *JD* Record Field 10 and EWA(cp) in CP Record Field 9 that is designed to account for the fact that a portion of the precipitation falling on the reservoir water surface is also reflected in the naturalized streamflows. The adjustment computations are performed during the *SIM* simulation based on the simulated reservoir-water surface areas. However, this *SIM* option was not employed in the Rio Grande WAM. Rather, the net evaporation-precipitation rates on the *EV* records were adjusted during the preparation of the *SIM* input EVA file. Equation 3.1 describes the strategy used to compute adjusted net evaporation-precipitation in the original EVA file. Equation 3.2 is an alternate form of the first equation used to compute adjusted net evaporation-precipitation for the *HYD* extension. The regional monthly multiplier factor in the second equation is equivalent to one minus the regional monthly runoff coefficient from the first equation.

$$\begin{aligned} \text{Adjusted Net Evaporation-Precipitation} &= \text{Evaporation} - \text{Precipitation} \\ &+ \text{Precipitation} \times (\text{Regional Monthly Runoff Coefficient}) \end{aligned} \quad (\text{Eq. 3.1})$$

$$\begin{aligned} \text{Adjusted Net Evaporation-Precipitation} &= \text{Evaporation} \\ &- \text{Precipitation} \times (\text{Regional Monthly Multiplier Factor}) \end{aligned} \quad (\text{Eq. 3.2})$$

Extension of the EVA File

An EVA file with 1940–2012 net evaporation-precipitation rates was created by executing *HYD* with the following input files:

- An HIN file controlling the 2001–2015 evaporation-precipitation update.
- An EVA file from Rio Grande WAM with 1940–2000 evaporation-precipitation rates.
- An *Evaporation.EEE* file with TWDB statewide 1940–2015 evaporation data.
- A *Precipitation.PPP* file with TWDB statewide 1940–2015 precipitation data.

The original 1940–2000 net evaporation-precipitation rates were read by *HYD* from an input file with the filename extension EVA. Net evaporation-precipitation rates were computed

by *HYD* for the 2001–2015 extension period based on HIN file input records and values of evaporation and precipitation read from the *Evaporation.EEE* and *Precipitation.PPP* files. *HYD* created an output file with filename extension EVA with original 1940–2000 net evaporation-precipitation rates and extended 2001–2015 net evaporation-precipitation rates that are designed to be read by *SIM* as an input file. *HYD* also includes options for recording the evaporation rates, precipitation rates, and/or net evaporation-precipitations rates in a DSS file to be read with HEC-DSSVue. The time series’ plots presented in this report were prepared with HEC-DSSVue. *HYD* also includes options for creating summary tables showing means and ranges.

The adjusted net evaporation-precipitation rates were extended to include 2001–2015 in a single execution of program *HYD* using input entered on *JC*, *CP*, *EE*, *EX*, *QD*, and *QA* records. Sample HIN file records for control points EM3440, EM4010, ET1001, and FM101 are shown in Table 3.1 for illustration.

Table 3.1. Sample HYD Input HIN File: Adjusted Evaporation-Precipitation Extension

**	1	2	3	4	5	6	7	8	9
**3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123									
** ! ! ! ! ! ! ! ! ! !									
JC 1940 76 1 0 1							1		
EEEM3440 1207 2001 2012 1 7.0833333									
EX0.9854 0.9880 0.9934 0.9804 0.9619 0.9503 0.9763 0.9591 0.9394 0.9611 0.9806 0.9888									
EEEM4010 1108 2001 2012 1 7.0833333									
EX0.9854 0.9880 0.9934 0.9804 0.9619 0.9503 0.9763 0.9591 0.9394 0.9611 0.9806 0.9888									
EEET1001 2001 2012 1 7.0833333									
EX0.9854 0.9880 0.9934 0.9804 0.9619 0.9503 0.9763 0.9591 0.9394 0.9611 0.9806 0.9888									
QD 2 1109 1110									
QA 3 0.863 0.137									
EEFM1010 2001 2012 1 7.0833333									
EX0.9901 0.9862 0.9836 0.9734 0.9763 0.9712 0.9693 0.9731 0.9644 0.9704 0.9880 0.9891									
QD 4 703 704 803 804									
QA 3 0.377 0.333 0.161 0.129									
ED									

The extended EVA datasets of monthly and annual net reservoir evaporation minus precipitation depths covering the 1940–2015 hydrologic period for eight control points in the U.S portion of the Rio Grande Basin are shown in Figure 3.4 through Figure 3.17. Red solid lines (monthly time-series) and area (annual time-series) represent known net evaporation depth covering the 1940–2000 hydrologic period, and blue lines on the same figures represent extended net evaporation depths covering the 2001–2015 period.

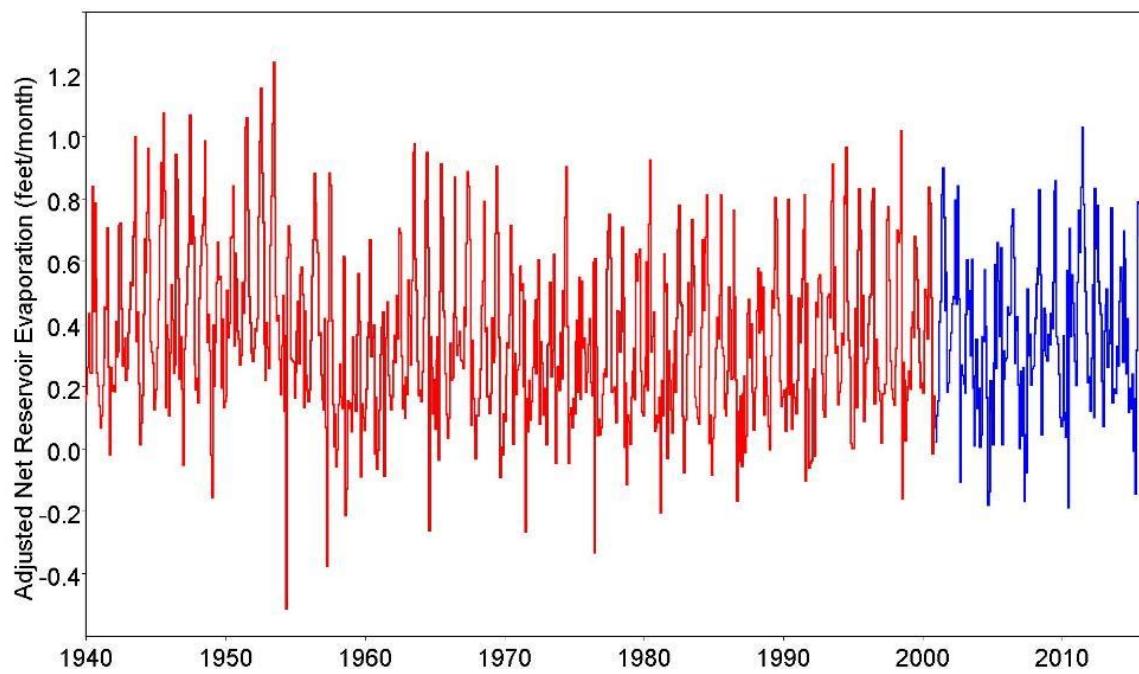


Figure 3.4. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for TEXAMI Reservoir at CT1160

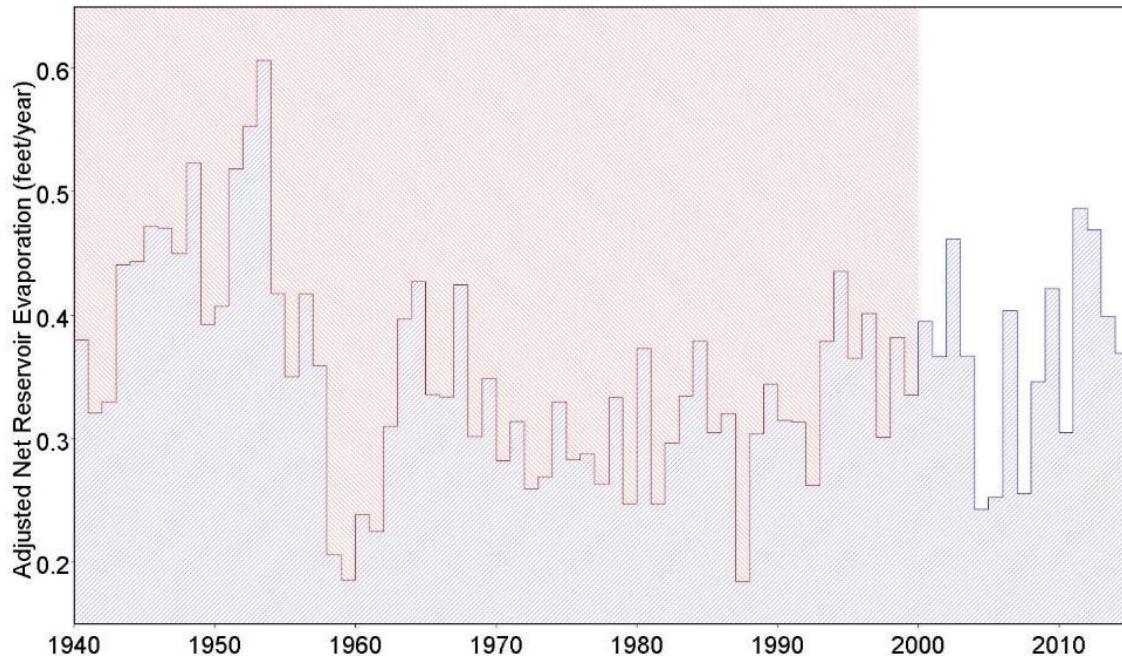


Figure 3.5. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for TEXAMI Reservoir at CT1160

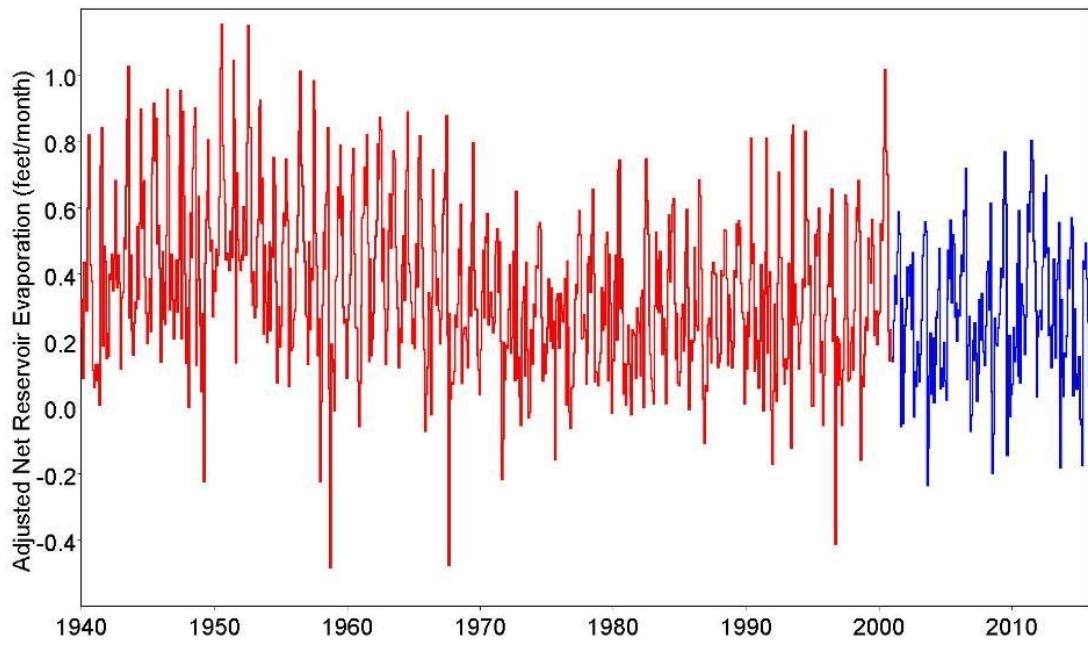


Figure 3.6. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for TEXFAL Reservoir at DT1001

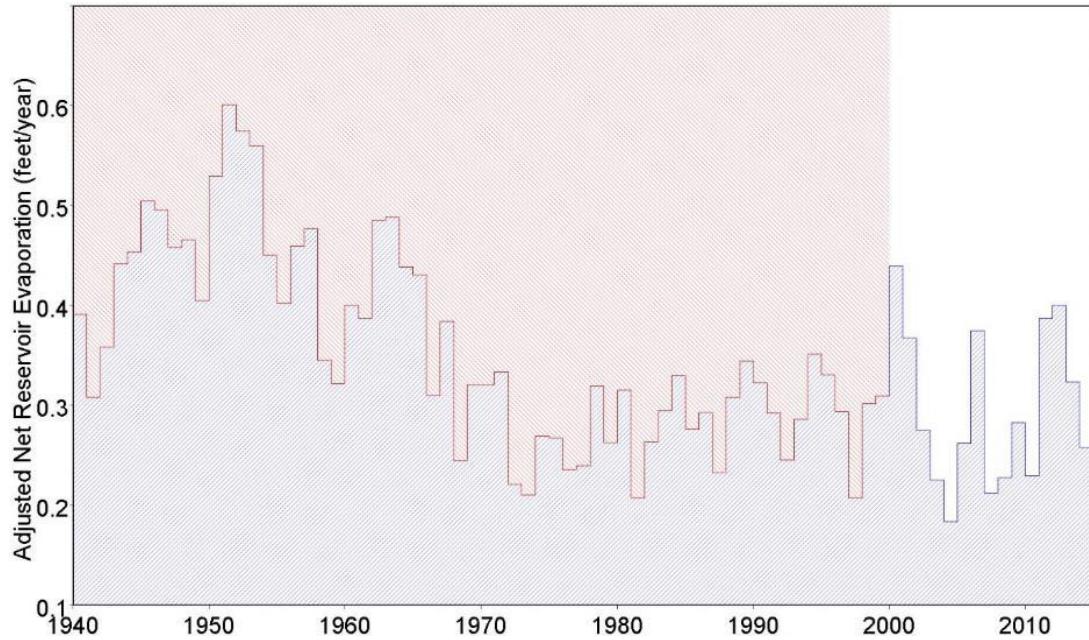


Figure 3.7. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for TEXFAL Reservoir at DT1001

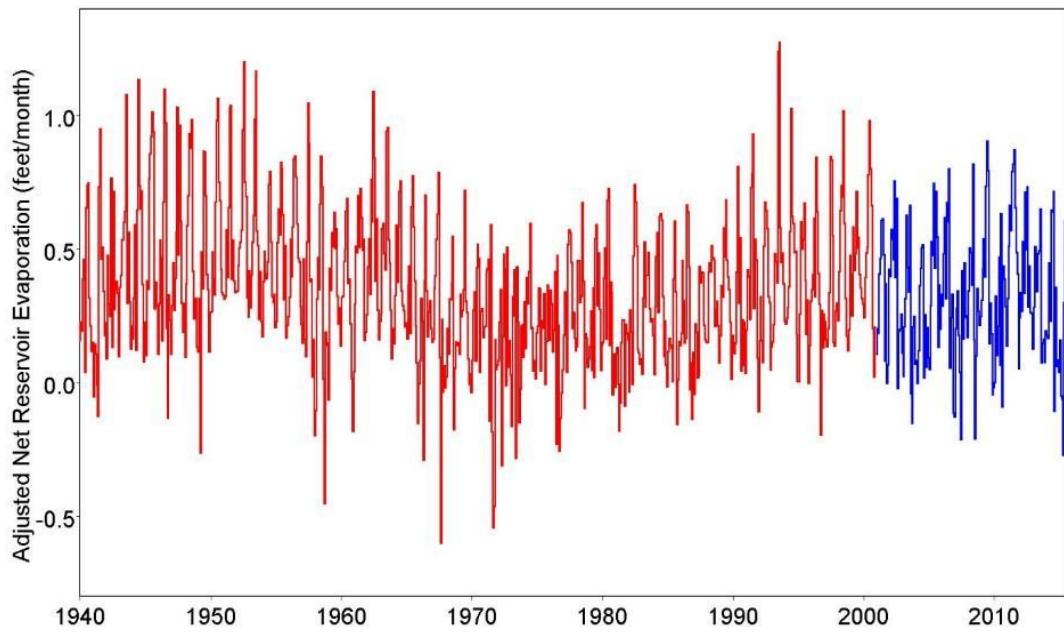


Figure 3.8. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for CASABL Reservoir at DT1230

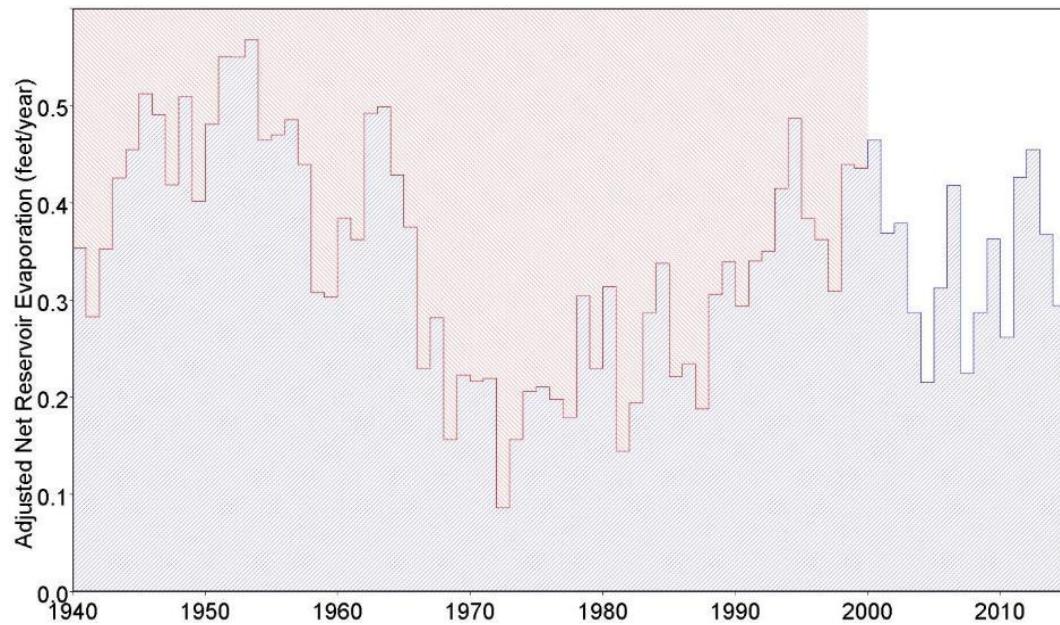


Figure 3.9. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for CASABL Reservoir at DT1230

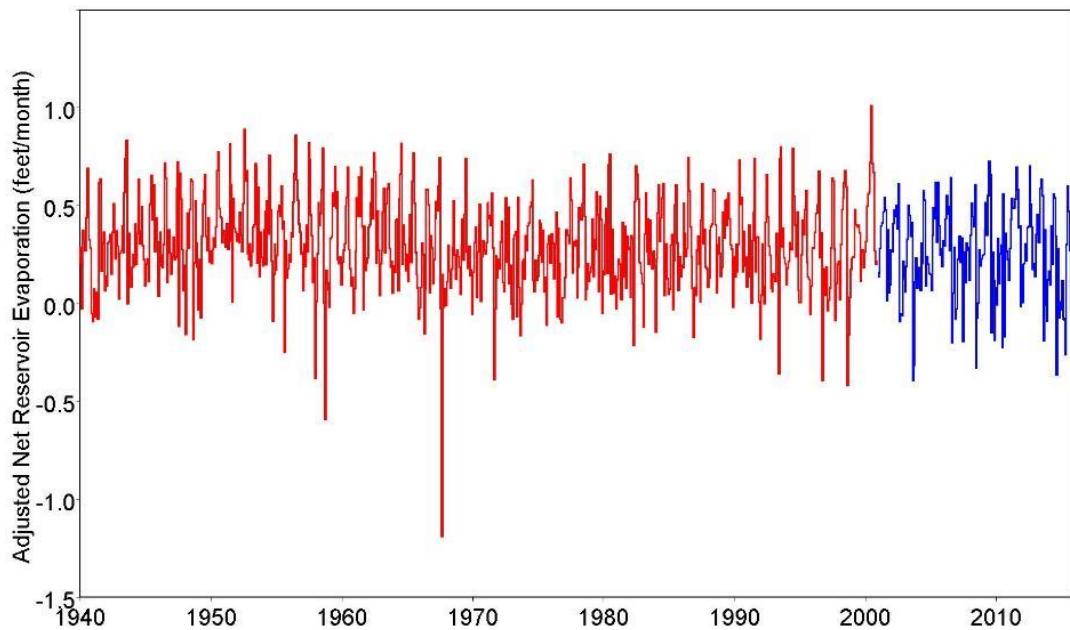


Figure 3.10. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for TEXANZ Reservoir at ET1001

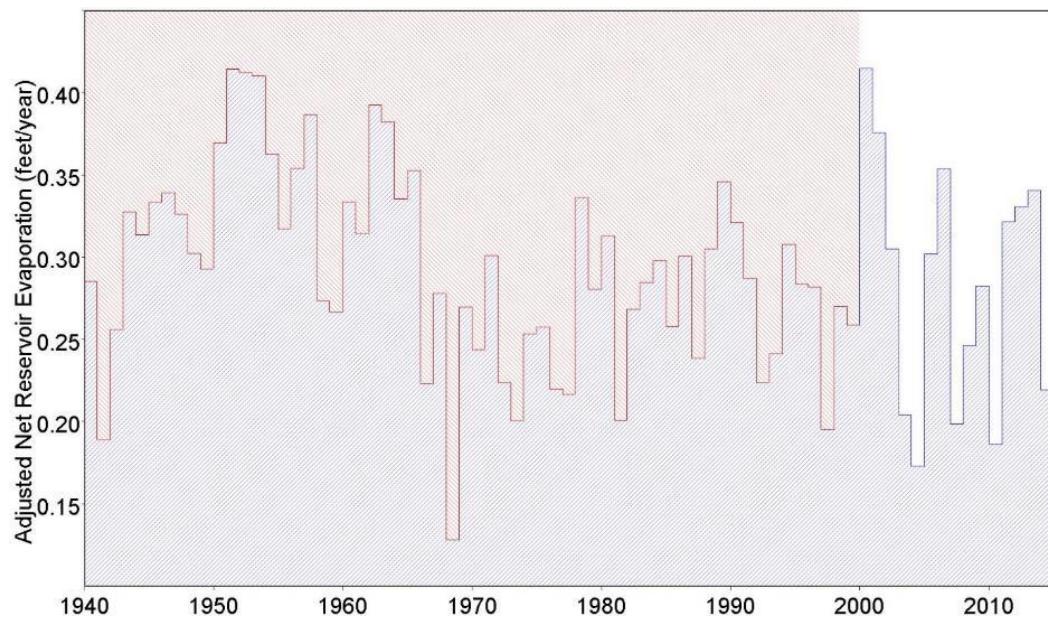


Figure 3.11. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for TEXANZ Reservoir at ET1001

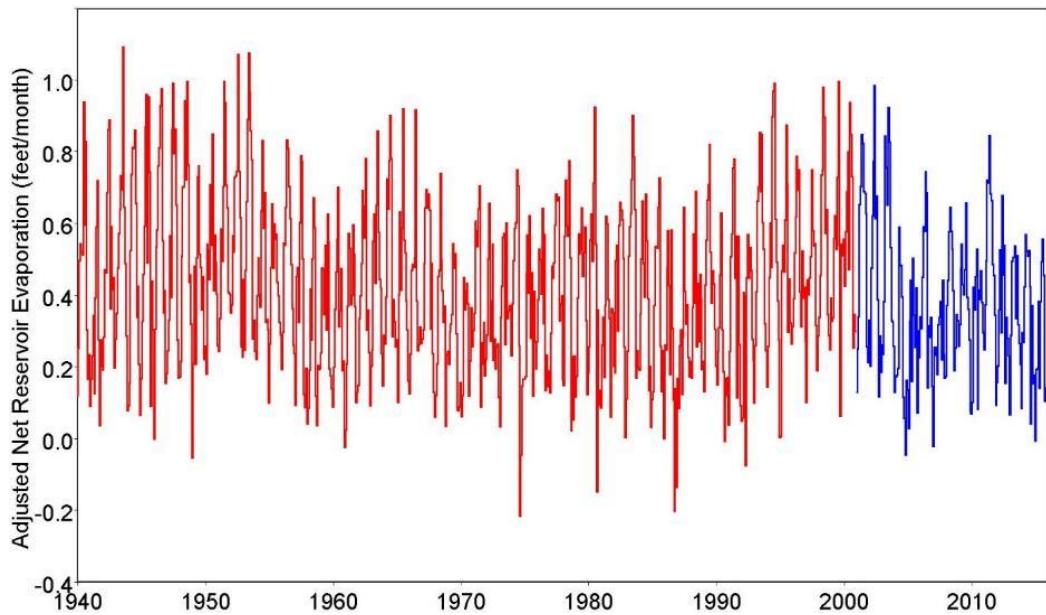


Figure 3.12. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for PECO22 Reservoir at GT2010

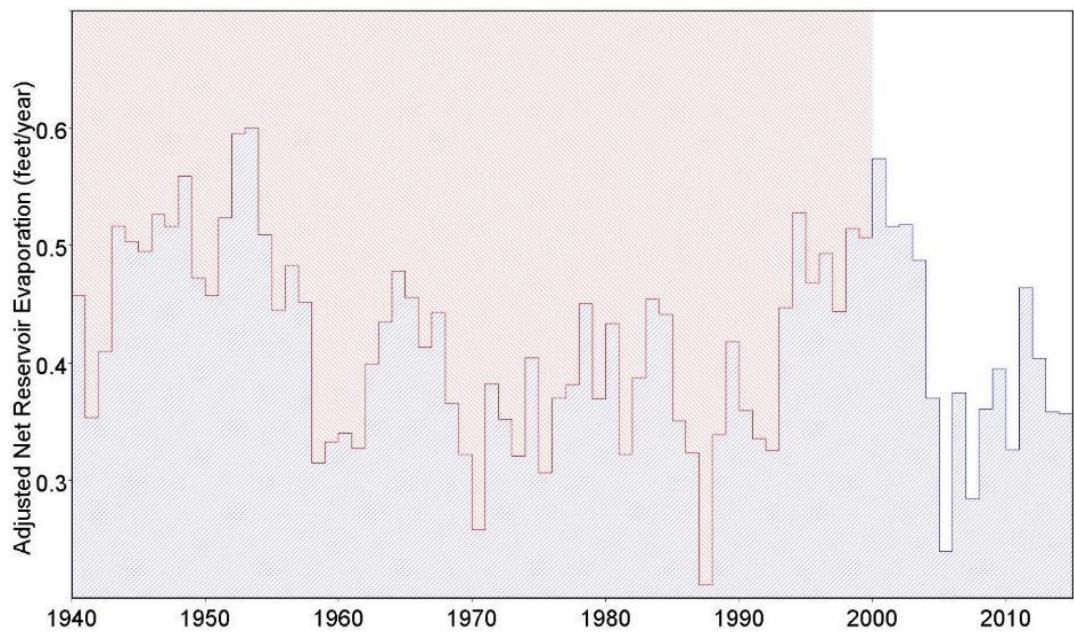


Figure 3.13. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for PECO22 Reservoir at GT2010

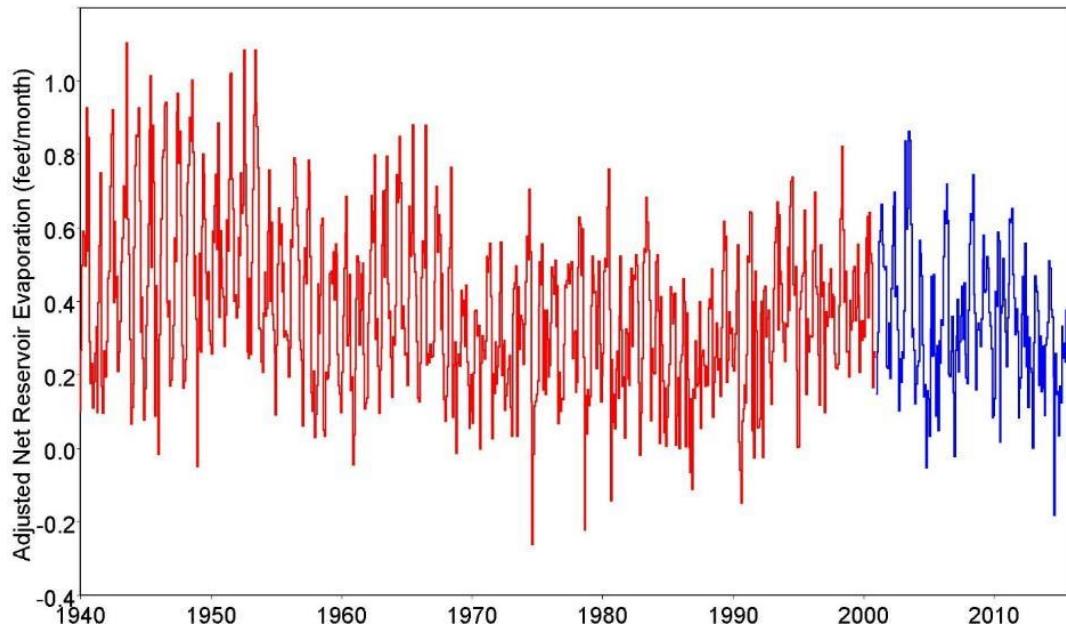


Figure 3.14. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for BALMRH Reservoir at DT2325

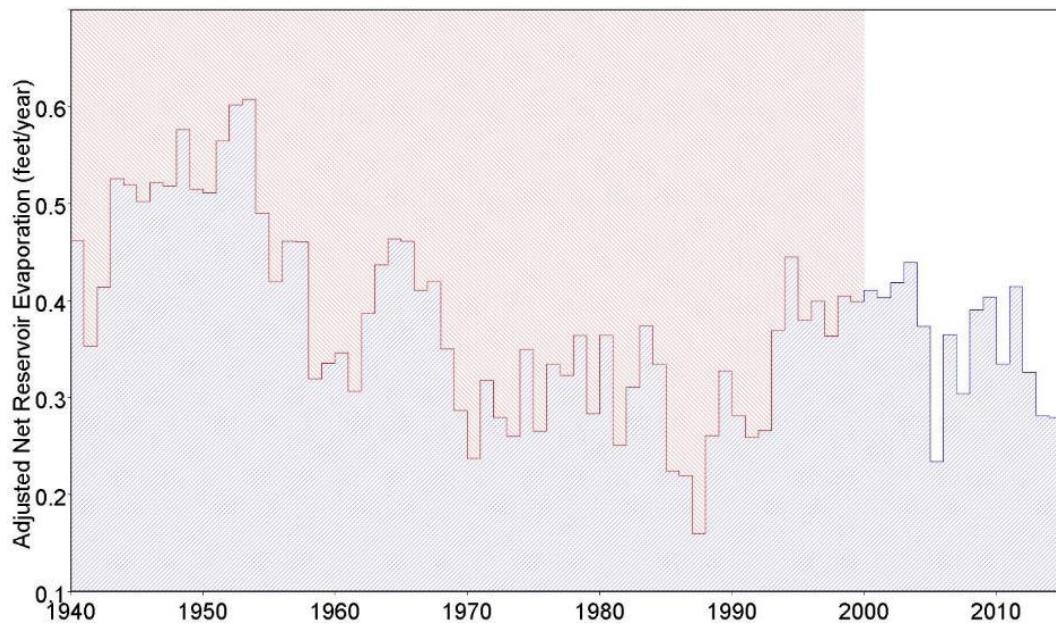


Figure 3.15. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for BALMRH Reservoir at DT2325

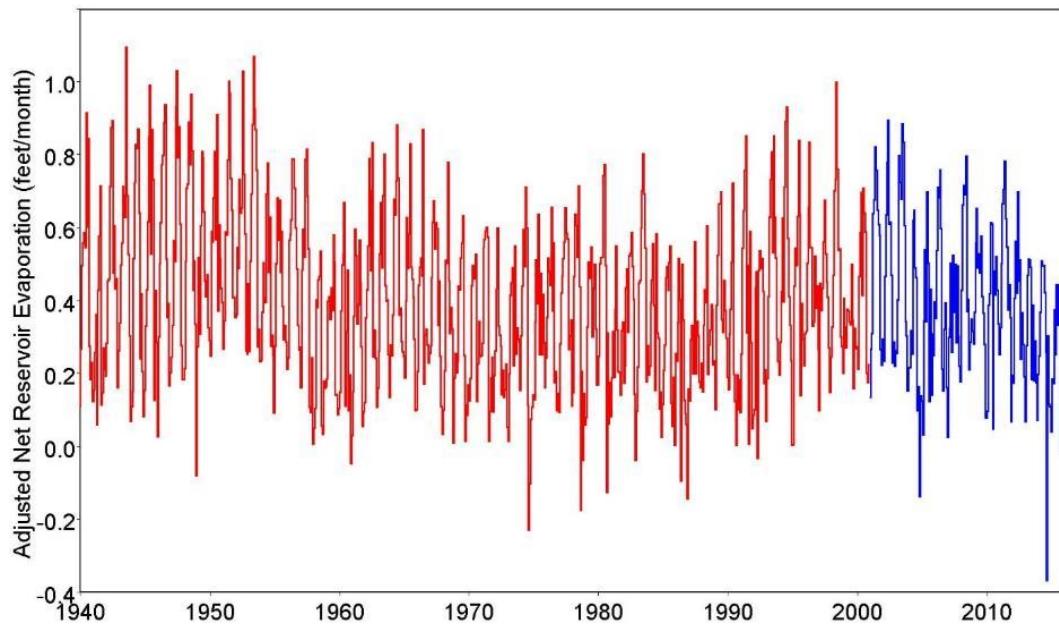


Figure 3.16. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) monthly adjusted net evaporation-precipitation for PECO21 Reservoir at GT3010

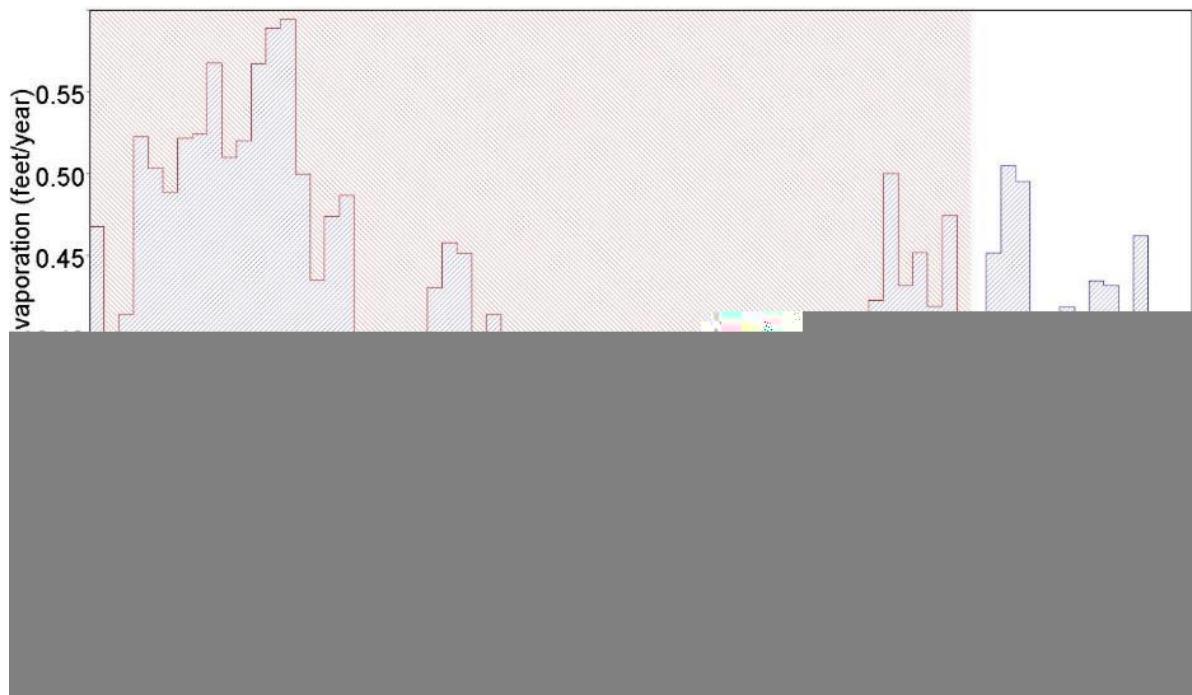


Figure 3.17. Original 1940–2000 (Red) and simulated 1940–2015 (Blue) annual adjusted net evaporation-precipitation for PECO21 Reservoir at GT3010

Extension of the Naturalized Streamflows

The objective of the flow extension process is to reproduce properly the statistical characteristics of the naturalized flows along with reasonable patterns of flow sequences. The synthesized flow in each month is necessarily approximate. However, computed flows in some months that are high will be balanced by flows that are low in other months. The procedure is designed to develop flow sequences with the correct means, standard deviations, frequency relationships, and flow patterns. This is consistent with the fundamental WRAP/WAM modeling strategy of quantifying water supply capabilities regarding diversion reliability and flow and storage frequency metrics.

The recently developed WRAP-program *HYD* methodology described in Chapters 5 and 7 of the *Hydrology Manual* was employed to extend the naturalized flows to cover 2001–2015. *HYD* has a hydrologic watershed rainfall-streamflow model designed for extending monthly naturalized flows. The *HYD* flow-extension model was calibrated for each of the 55 primary control points listed in Tables 3.2 and Table 3.3 using known naturalized flows and concurrent TWDB precipitation and evaporation depths for relevant quadrangles. The calibrated flow extension model was then used to compute naturalized flows for the period from January 2001 through December 2015 using 2001–2015 TWDB precipitation and evaporation depths as input. The final resulting FLO file consists of the known naturalized flows for the period from 1940–2000 and computed flows for the period from January 2001 through December 2015.

Table 3.2. Primary Control Points and Locations on U.S. Portion and the Main Stem of the Rio Grande

CONTROL POINT NO.	C.P. ID	CONTROL POINT LOCATION	UPSTREAM CONTROL POINTS	REACH LENGTH Miles [a]
AT/AM2000	RG-EP	R Grande at El Paso	n/a	n/a
AT/AM1000	RG-FQ	R Grande at Fort Quitman	AT/AM2000	83
BT/BM1000	RG-AC	R Grande abv R Conchos	AT/AM1000	209
CT7000	AC-PR	Alamito Ck nr Presidio	none	82
CT/CM6000	RG-BC	R Grande blw R Conchos	CT7000, AT/AM1000, FM1000	14
CT5000	TC-TE	Terlingua Ck nr Terlingua	none	41
CT/CM4000	RG-JR	R Grande at Johnson Ranch	CT5000, CT/CM6000	88
CT/CM3000	RG-FR	R Grande at Foster Ranch	CT/CM4000	205
GT5000	PR-RB	Pecos R at Red Bluff	n/a	n/a
GT4000	DR-RB	Delaware R nr Red Bluff	none	25
GT3000	PR-OR	Pecos R nr Orla	GT4000, GT5000	31
GT2000	PR-GI	Pecos R nr Girvin	GT3000	136
GT1000	PR-LA	Pecos R nr Langtry	GT2000	160
CT2100	DR-JU	Devils R nr Juno	none	42
CT2000	DR-PC	Devils R at Pafford Crossing	CT2100	33
CT/CM1000	RG-DR	R Grande at Del Rio	CT2000, GT1000, CT/CM3000	96
DT9000	SF-DR	San Felipe Ck nr Del Rio	none	5
DT8000	PC-DR	Pinto Ck nr Del Rio	none	27
DT/DM5000	RG-PN	R Grande at Piedras Negras	DT8000, DT9000, CT/CM1000, DM9500, DM7000, DM6000	64
DT/DM3000	RG-LA	R Grande at Laredo	DT/DM5000, DM4000	137
DT/DM1000	RG-BF	R Grande blw Falcon Dam	DT/DM3000, DM2000	86
ET/EM2000	RG-RG	R Grande at Rio Grande City	DT/DM1000, EM4000, EM3000	40
ET/EM1000	RG-AN	R Grande blw Anzalduas Dam	ET/EM2000	65
ET/EM0100	RG-BR	R Grande blw Brownsville	ET/EM1000	121
ET/EM0000	RG-MO	R Grande at Mouth	ET/EM1000	49

[a] Stream miles from upstream CP on same stream or headwaters to CP of interest

[b] 85% CLF used for Toyah Creek (Balmorhea area)

[c] R. J. Brandes Co.; "Evaluation of Amistad-Falcon Water Supply Under Current and Extended Drought Conditions"; Lower Rio Grande Valley Development Council, Valley Water Policy and Management Council of the Lower Rio Grande Water Committee, Inc.; March 1999.

Source: Brandes 2004

Table 3.3. Primary Control Points and Locations on Mexico Portion of the Rio Grande

CONTROL POINT NO.	C.P. ID	CONTROL POINT LOCATION	UPSTREAM CONTROL POINT(S)	REACH LENGTH Miles
FM5000	RF-CJ	R Florido at Cd. Jimenez, CHIH	none	117
FM6000	RC-BO	R Conchos at Presa La Boquilla, CHIH	none	n/a*
FM4000	SP-VI	R San Pedro at Villalba, CHIH	none	n/a*
FM3000	RC-LB	R Conchos at Las Burras, CHIH	FM4000, FM5000, FM6000	131
FM2000	RC-EG	R Conchos at El Granero, CHIH	FM3000	50
FM1000	RC-OJ	R Conchos nr Ojinaga, CHIH	FM2000	109
DM9500	AV-CA	Arroyo de las Vacas at Cd. Acuna, COAH	none	50
DM7000	SD-JI	R San Diego nr Jimenez, COAH	none	50
DM6000	SR-EM	R San Rodrigo at El Moral, COAH	none	45
DM4000	RE-VF	R Escondido at Villa de Fuente, COAH	none	45
DM2300	RS-SA	R Sabinas at Sabinas, COAH	none	15
DM2200	RN-PR	R Nadadores at Progreso, COAH	none	20
DM2100	RS-RO	R Salado at Rodriguez, NL	DM2200, DM2300	69
DM2000	RS-LT	R Salado nr Las Tortillas, TAMPS	DM2100	71
EM4000	RA-CM	R Alamo at Cd. Mier, TAMPS	none	34
EM3400	SJ-EC	R San Juan at El Cuchillo, NL	none	142
EM3300	RS-CF	R Salinas at Cienega de Flores, NL	none	75
EM3200	RP-LH	R Pesqueria at Los Herrera, NL	EM3300	120
EM3100	SJ-LA	R San Juan at Los Aldamas, NL	EM3200, EM3400	30
EM3000	SJ-CA	R San Juan at Camargo, TAMPS	EM3100	34

* n/a = not applicable. There are no streamflow adjustments within the upstream watershed; therefore, no loss factor is required.

Source: Brandes 2004

The Rio Grande WAM was simulated using a SIM program, which computed the output file containing regulated flows for each control point after simulations of the water rights, reservoir storage, diversion contents, and river management based on the DAT file. The naturalized flows were computed by adding adjustments to actual gaged flows using the HYD program. HYD reads naturalized flows, regulated flows, reservoir storage volumes, and storage capacities from an output file produced by SIM and computes flow adjustments as follows:

$$\text{Naturalized flow} = \text{gaged flow} + \text{flow adjustment} \quad (\text{Eq. 3.3})$$

$$\begin{aligned} \text{Flow adjustment} &= \text{naturalized flow} - \text{regulated flow} \\ &\quad + \text{storage shortage} + \text{diversion shortage} \end{aligned} \quad (\text{Eq. 3.4})$$

SIM simulation output file includes regulated flows, unappropriated flows, and streamflow depletions that were computed based on monthly naturalized flows and reservoir evaporation input files. Regulated and flows are compute from a set of naturalized flows, but regulated flows are required for the flow adjustment used to determine naturalized flows. This can be done with iteration procedure using Equations 3.3. and 3.4 (Wurbs and Kim 2008).

Naturalized Streamflow Equation

Naturalized flows $Q(t)$ are estimated based on known flows, precipitation, and evaporation using the following equations with parameters $U(1)$, BX , DX , $B(m)$, and $X(i,j)$. These formulas and definitions on computing naturalized flows were taken from the *Hydrology Manual* (TR-431, 2012).

$$Q(t) = U(1) \times RP(t)^{U(2)} + BF \quad (\text{Eq. 3.5})$$

$$\begin{aligned} RP(t) &= \sum_{i=1}^N [P(i,t) - X(i,1) \times P(i,t)^{X(1,2)} - X(i,3) \times E(i,t) + PP(i,t-1) - X(i,4) \\ &\quad \times PP(i,t-1)^{X(i,5)}] \end{aligned} \quad (\text{Eq. 3.6})$$

$$PP(i,t) = X(i,1) \times P(i,t)^{X(1,2)} \quad (\text{Eq. 3.7})$$

$$BF(t) = B(m) \times DI(t) \times BX(z) \text{ where } DI(t) \text{ is the lesser of} \quad (\text{Eq. 3.8})$$

$$DI(t) = 1.0$$

or

$$DI(t) = DX \left[\left(\frac{\bar{E}(m-1) + E(m)}{\bar{P}(m-1) + P(m)} \right) \frac{\sum P(1,t-1) + P(i,t)}{\sum E(i,t-1) + E(i,t)} \right]^2 \quad (\text{Eq. 3.9})$$

where

$Q(t)$ = computed naturalized flow volume for month t , which may consist of the weighted average of the $Q(t,z)$ computed for two adjacent overlapping flow zones if flows are categorized by zones (acre-feet/month).

$Q(t,z)$ = naturalized flow computed for either low flow ($z = 1$), medium flow ($z = 2$), high flow ($z = 3$), or flood flow ($z = 4$) zones during month t (acre-feet/month).

$RP(t)$ = summation of runoff from individual quadrangles in current month t resulting from precipitation in the current month t and/or preceding month $t - 1$ (acre-feet/month).

$BF(m, z)$ = base flow in each of the 12 months of the year that may reflect precipitation falling long before as well as during months t and $t - 1$ (acre-feet/month).

$U(k)$ = dimensionless multiplier and exponent coefficients ($0.0 \leq U(1) \leq 1.0$ and $0.7 \geq U(2)$).

N = number of quadrangles included in the watershed ($i = 1, 2, 3, \dots, N$).

$P(i, t)$ = precipitation during month t in quadrangle i (acre-feet/month).

$PP(i, t)$ = portion of precipitation in month t not contributing to $Q(t)$ and becoming streamflow in the next month and/or hydrologic abstractions (acre-feet/month).

$E(i, t)$ = maximum potential evapotranspiration volume estimated based on reservoir surface evaporation rates during month t quadrangle i (acre-feet/month).

$X(i, j, z)$ = model parameters consisting of $5N$ dimensionless coefficients ($j = 1, 2, 3, 4, 5$) that may vary between zones ($z = 1, 2, 3, 4$) that have values ranging between 0.0 and 1.0.

$B(m, z)$ = base flow parameters for the 12 months ($m = 1, 2, 3, \dots, 12$) of the year (acre-feet/month).

$DI(t)$ = dimensionless drought index that varies from 1.0 to 0.0 each month depending on the ratio of precipitation to evaporation volume during the current and preceding months.

$BX(z)$ = dimensionless multiplier factor in the base flow term entered on the UB record with a default of 1.0 ($z = 1, 2, 3, 4$ for low, medium, high, and flood flow zones).

DX = dimensionless multiplier factor entered on the FE record with a default of 1.0.

$\bar{P}(m)$ = monthly means of precipitation volumes for each of the $m = 1, 2, 3, \dots, 12$ months of the year for specified quadrangles (acre-feet/month).

$\bar{E}(m)$ = monthly means of evaporation volumes for each of the $m = 1, 2, 3, \dots, 12$ months of the year for specified quadrangles (acre-feet/month).

Level 1 calibration with HYD consists of automated enumeration and gradient search optimization algorithms that calibrate parameters $U(1)$, BX , DX , $B(m)$, and $X(i, j)$ of the flow

model using the above equations above (3.5–3.9) based on known naturalized flows, $Q(t)_{known}$, for each month t of the original period-of-analysis and corresponding evaporation and precipitation rates. The resulting flow synthesis model is applied to compute flows, $Q(t)_{computed}$, for each month of the original period-of-analysis for use in the Level 2 calibration process.

Level 2 is based on analyzing the period-of-analysis flows, $Q(t)_{computed}$, in Level 1, described above, and adjusting the model to better reproduce the statistical characteristics of known flow— $Q(t)_{known}$.

The automated calibration methodology requires metrics for comparing the optimality of alternative sets of values for the model decision variables. These metrics are called objective functions. The optimization problem consists of finding values for decision variables that minimize a specified objective function defined by equation 3.10 below.

The 16 criteria functions defined by equations 3.10 through 3.14 are computed. The objective function OF and all 16 criterion metrics Z are recorded in the HYD message HMS file for information. The automated parameter calibration optimization procedure incorporates equation 3.9 as its objective function OF (Wurbs, 2012).

Optimization Algorithms

	Low Flows	Medium Flows	High Flows	Flood Flows					
OF =	W1×Z1	+	W2×Z2	+	W3×Z3	+	W4×Z4	+	(Eq. 3.10)
	W5×Z5	+	W6×Z6	+	W7×Z7	+	W8×Z8	+	

$$\begin{aligned} & W9 \times Z9 + W10 \times Z10 + W11 \times Z11 + W12 \times Z12 + \\ & W13 \times Z13 + W14 \times Z14 + W15 \times Z15 + W16 \times Z16 \end{aligned}$$

$$Z1 = Z2 = Z3 = Z4 = \left(\frac{1}{K} \sum_{t=1}^K \left(\frac{100 \times |Q(t)_{known} - Q(t)_{computed}|}{\overline{Q(t)_{known}}} \right)^{E1} \right) \quad (\text{Eq. 3.11})$$

$$Z5 = Z6 = Z7 = Z8 = \left(\frac{1}{K} \sum_{t=1}^K \left(\frac{100 \times |Q(t)_{known} - Q(t)_{computed}|}{ZZZ} \right)^{E1} \right) \quad (\text{Eq. 3.12})$$

where ZZZ is the greater of $Q(t)_{known}$ or $Q(t)_{computed}$

$$Z9 = Z10 = Z11 = Z12 = |N_K - N_C|^{E1} \quad (\text{Eq. 3.13})$$

$$Z13 = Z14 = Z15 = Z16 = \left(\frac{1}{K} \sum_{t=1}^K \left(\frac{100 \times |\sum_{t=1}^K Q(t)_{known} - \sum_{t=1}^K Q(t)_{computed}|}{\overline{Q(t)_{known}}} \right)^{E2} \right) \quad (\text{Eq. 3.14})$$

where

OF = objective function applied in the automated search algorithm procedure.

$W1 - W16$ = dimensionless weighing factors that are provided in FP record.

$Z1 - Z16$ = dimensionless criteria metrics that are recorded in the message HMS file and serve as components of the objective function OF of Equation 10.

$Q(t)_{known}$ = known monthly naturalized streamflows from the TCEQ WAM System dataset at the location of interest in units of acre-feet/month.

$Q(t)_{computed}$ = flows in acre-feet/month computed with the flow model (Equations 3.10-3.14) for each month t where the model parameters are optimization decision variables.

N_K = number of months during which the known flows fall within the specified low, medium, high, or flood flow range.

N_C = number of months during which the computed flows fall within the specified low, medium, high, or flood flow range.

$\overline{Q(t)_{known}}$ = mean of the known flows during the K months used in computing Z for either low, medium, high, flood, or all flows in acre-feet/month.

K = number of months in either low, medium, high, flood, or all flows.

$E1, E2$ = exponents set on FP record with defaults of 2.0 that penalize large differences between computed and known flows more than small differences.

Level 1 Parameter Calibration

Level 1 calibration consists of determining values for parameters recorded on BM , $B4$, XP , $X4$, FR , and UB records using input entered on JC , CP , FE , FN , QD , QA , FP , FZ , and FR records. The entries contained on each of these HYD input records are described in Chapter 7

of the *Hydrology Manual*. Computed flows developed using the Level 1 calibrated flow extension model are used for Level 2 calibration.

Any number of control points can be included in a single HIN file, but the *HYD* computations are performed for each control point in turn, independently of all other control points. The *HYD* input HIN file input records for control point CT2000 are shown in Table 3.4 to illustrate the Level 1 calibration procedure.

Table 3.4. HIN Input File Records for Level 1 Calibration for Control Point CT2000

```
**
JC 1954 47 1 1
** Plan A Calibration for All Flows CT2000
**NE
FECT2000      1954 2000 2 9      -1      1 0 0. -1.0
FN          Level2
QD 4 5     806    706    807    707    606
QA        234.   1269.   499.   1871.   24.
FZ        9867.2  13394.8  20457.4  17700.4
FR        5383.6  7650.2  9867.2  11605.8  13394.8  15571.0  17700.4  20457.4  24269.8  31648.4  44185.2
** Calibration for Flood Flows
FECT2000 1954 2000 1954 2000 2 10
FN  Flood
FP        1.0      3.0      10.      10.      2
ED
```

Three calibration specification plans labeled Plans A, B, and C were defined based on the number of zero flows recorded in the frequency statistics for naturalized flows. Plan A is adopted for control points having no months with zero naturalized flows. Plan B control points have 10 percent or less months with zero naturalized flows. Plan C control points have greater than 10 percent of months with zero naturalized flows. There are 26 control points specified as Plan A, 12 control points specified as Plan B, and seven control points specified as Plan C.

Calibration specification plan A was adopted for control point CT2000. This affected the options selected for *FE* record fields 14, 15, and 16 and *FZ* record fields 4, 6, 8, and 9. Frequency statistics for known naturalized flows for control point CT2000 were used in selecting options on the *FE* and *FZ* records (Table 3.4). The data entered on each of the records in the HIN file of Table 3.4 are described next.

The *FZ* record determines the limits for each flow zone. Because options 9 and 10 were implemented for *FE* record field 8, the low, medium, and high flow zones were combined into a non-flood component model, and the flood zone was evaluated as a flood-flow component model. The values entered in *FZ* record fields 4, 6, 8, and 9 were selected based on flow exceedance frequency values from the known naturalized flows. The flow exceedance frequency values were selected according to Plans A, B, and C described in Table 3.5.

Table 3.5. Exceedance Flow Percentages for Each Flow Zone in *FZ* Record

<i>FZ</i> Record Field, Description	Plan A	Plan B	Plan C
4, Upper limit on low flow zone.	80%	75%	40%
6, Upper limit on medium flow zone.	60%	50%	30%
8, Upper limit on high flow zone.	30%	20%	10%
9, Lower limit on flood flow zone.	40%	30%	20%

The *FR* record defines the flow frequency relationship for naturalized flows. The values listed in the *FR* record are known naturalized flow volumes for the exceedance frequency values recommended in Chapter 7 of the *Hydrology Manual*.

Level 1 Calibration Results

Results from the Level 1 calibration are recorded in HMS and HOT output files. The HOT file contains the *BM*, *B4*, *XP*, and *X4* records, which can be copied and pasted into the Level 2 HIN file. The HOT file also contains information used to adjust the *FE* record and create the *UB* record. Flow frequency metrics for the Level 1 computed flows are used to develop a second *FR* record.

Table 3.6. HYD Input HIN File Records for Level 1 Calibration for Control Point CT2000

```
***  
CT2000  
Multiplier factor U(1) and Exponent U(2) = 0.28000 0.88000  
Base Flow Factor BX = 1.000000  
Drought Index Factor DX = 1.000000  
BM    7330.65 6140.04 5903.34 5749.65 5607.10 5756.47 5567.68 5423.97 6485.34 8240.16 6928.46 7033.91  
XP   806  0.56943005 0.94905001 0.00000000 0.47452500 0.94905001  
XP   706  0.56943005 0.94905001 0.00000000 0.47452500 0.94905001  
XP   807  0.56943005 0.94905001 0.00000000 0.47452500 0.94905001  
XP   707  0.56943005 0.94905001 0.00000000 0.47452500 0.94905001  
XP   606  0.56943005 0.94905001 0.00000000 0.47452500 0.94905001  
CT2000    Flood  
Multiplier factor U(1) and Exponent U(2) = 0.23982 1.18898  
Base Flow Factor BX = 1.000000  
Drought Index Factor DX = 1.000000  
B4    6158.90 5164.43 4922.13 4848.93 4734.67 4779.40 4703.07 4572.87 5314.25 6929.95 5820.99 5915.50  
X4   806  0.46560219 1.00000000 0.18932226 0.93899268 0.99900001  
X4   706  0.58781856 1.00000000 0.39652818 1.01000011 1.00000000  
X4   807  0.80193603 1.00000000 0.39750865 0.98000002 1.00000000  
X4   707  0.99084997 1.00000000 0.00000000 1.00000012 1.00000000  
X4   606  0.35144031 0.19717878 0.00000000 0.98000002 1.00000000
```

Level 2 Parameter Calibration

The first phase of Level 2 calibration involves the determination of values for parameters entered on *FX* records using input from *JC*, *CP*, *FE*, *FN*, *QD*, *QA*, *FZ*, *FR*, *UB*, *BM*, *XP*, *B4*, and *X4* records. *FX* records are used to adjust Level 1 computed flows to reproduce the means of known naturalized flows in each of 12 flow ranges. The HIN input file for the first phase of Level 2 calibration is shown in Table 4.3. The *JC*, *CP*, *QD*, *QA*, and *FZ* records are identical to those used for Level 1 calibration. The *BM*, *XP*, *B4*, and *X4* records are copied and pasted from the HOT output file from Level 1 calibration.

Two *FR* records are used for Level 2 calibration. The first *FR* record is identical to the record used in the Level 1 calibration, except a value of 2 is entered in Field 2. This value signifies that a second *FR* record is implemented. The first *FR* record contains known naturalized flows corresponding to the flow exceedance frequency values identified in Chapter 7 of the *Hydrology Manual*. The second *FR* record contains Level 1 computed flows corresponding to the flow exceedance frequency values identified in Chapter 7 of the *Hydrology Manual*. The *FR* records define flow ranges for development and application of the *FX* record.

Table 3.7. HIN Input File Records for Phase 1 of Level 2 Calibration for Control Point CT2000

JC	1954	47	1	1		1								
** Plan A Calibration for All Flows CT2000														
**NE														
FECT2000	1954	2000	1954	2000	2	1.000000								
FN			Level2											
QD	4	5	806	706	807	707	606							
QA			234.	1269.	499.	1871.	24.							
FZ			9867.2		13394.8	20457.4	17700.4							
FR	2	5383.6	7650.2	9867.2	11605.8	13394.8	15571.0	17700.4	20457.4	24269.8	31648.4	44185.2		
FR		6089.5	9101.3	11986.4	13615.0	15174.0	16591.3	17826.9	20950.4	24347.4	29548.6	40703.2		
UB			0.28000	0.880001	0.000000	0.23982	1.188981	0.000000						
BM			7330.65	6140.04	5903.34	5749.65	5607.10	5756.47	5567.68	5423.97	6485.34	8240.16	6928.46	7033.91
XP	806	0.56943005	0.94905001	0.00000000	0.47452500	0.94905001								
XP	706	0.56943005	0.94905001	0.00000000	0.47452500	0.94905001								
XP	807	0.56943005	0.94905001	0.00000000	0.47452500	0.94905001								
XP	707	0.56943005	0.94905001	0.00000000	0.47452500	0.94905001								
XP	606	0.56943005	0.94905001	0.00000000	0.47452500	0.94905001								
B4		6158.90	5164.43	4922.13	4848.93	4734.67	4779.40	4703.07	4572.87	5314.25	6929.95	5820.99	5915.50	
X4	806	0.46560219	1.00000000	0.18932226	0.93899268	0.99900001								
X4	706	0.58781856	1.00000000	0.39652818	1.01000011	1.00000000								
X4	807	0.80193603	1.00000000	0.39750865	0.98000002	1.00000000								
X4	707	0.99084997	1.00000000	0.00000000	1.00000012	1.00000000								
X4	606	0.35144031	0.19717878	0.00000000	0.98000002	1.00000000								

Results from Phase 1 of Level 2 calibration are recorded in the HOT output file. The HOT output file contains *FX* records, which can be copied and pasted into the HIN file for Phase 2 of Level 2 calibration.

Level 2 Calibration—Phase 2

The second phase of Level 2 calibration involves the incorporation of the *FX* record to reproduce statistical characteristics of the known naturalized flows for 12 flow ranges. The HIN file from Phase 1 of Level 2 is modified in Phase 2 by adding the *FX* record between the *FR* and *UB* records. The *FX* record shown in Table 3.7 was used for control point CT2000.

Table 3.8. HIN Input File Records for Phase 1 of Level 2 Calibration for Control Point CT2000

**	
JC 1954 47 1 1	1
FECT2000 1954 2000 1954 2000 2	1.000000
FN Level12	
QD 4 5 806 706 807 707 606	
QA 234. 1269. 499. 1871. 24.	
FZ 9867.2 13394.8 20457.4 17700.4	
FR 2 5383.6 7650.2 9867.2 11605.8 13394.8 15571.0 17700.4 20457.4 24269.8 31648.4 44185.2	
FR 6089.5 9101.3 11986.4 13615.0 15174.0 16591.3 17826.9 20950.4 24347.4 29548.6 40703.2	
FX 1.13533 0.82739 0.80795 0.83654 0.86214 0.90320 0.95851 0.97629 0.98404 1.00571 1.13566 0.99660	
UB 0.28000 0.880001.000000 0.23982 1.188981.000000	
BM 7330.65 6140.04 5903.34 5749.65 5607.10 5756.47 5567.68 5423.97 6485.34 8240.16 6928.46 7033.91	
XP 806 0.56943005 0.94905001 0.00000000 0.47452500 0.94905001	
XP 706 0.56943005 0.94905001 0.00000000 0.47452500 0.94905001	
XP 807 0.56943005 0.94905001 0.00000000 0.47452500 0.94905001	
XP 707 0.56943005 0.94905001 0.00000000 0.47452500 0.94905001	
XP 606 0.56943005 0.94905001 0.00000000 0.47452500 0.94905001	
B4 6158.90 5164.43 4922.13 4848.93 4734.67 4779.40 4703.07 4572.87 5314.25 6929.95 5820.99 5915.50	
X4 806 0.46560219 1.00000000 0.18932226 0.93899268 0.99900001	
X4 706 0.58781856 1.00000000 0.39652818 1.01000011 1.00000000	
X4 807 0.80193603 1.00000000 0.39750865 0.98000002 1.00000000	
X4 707 0.99084997 1.00000000 0.00000000 1.00000012 1.00000000	
X4 606 0.35144031 0.19717878 0.00000000 0.98000002 1.00000000	
ED	

Extending Hydrologic Period of Analysis

To extend the hydrologic period of records, the HIN file in Phase 2 of Level 2 is repeated, with the exception of the extension period from 2001 to 2015 in the FE record.

Table 3.9. HIN Input File Records of Extension from 2001 to 2015 for Control Point CT2000

**
JC 1954 62 1 1
FECT2000 2001 2015 1954 2000 2
FN Level2
QD 4 5 806 706 807 707 606
QA 234. 1269. 499. 1871. 24.
FZ 9867.2 13394.8 20457.4 17700.4
FR 2 5383.6 7650.2 9867.2 11605.8 13394.8 15571.0 17700.4 20457.4 24269.8 31648.4 44185.2
TP 2000-5 0101-2 11006.4 13615.0 15174.0 16501.3 17026.0 20050.4 21347.4 22540.6 40702.2

Extended Rio Grande WAM

Since the main focus of the research, as mentioned in the previous chapter, was concentrated on the U.S. portion of the Rio Grande, the results of the extended flow frequency statistics are provided only for the U.S. primary control points. However, there are 32 primary control points on the Mexico part of the Rio Grande for which similar results have been developed, but those results are excluded from this chapter as the research focuses on Texas portion of the Basin only.

Table 3.10 below provides monthly flow frequency metrics for calibration and extension for each of the 23 U.S. primary control points. Column 1 in the tables shows mean, standard deviation, flow frequency, and maximums for monthly flow volumes for each of the calibration and extension processes. Column 2 shows the original known monthly flow volumes that were developed by R. J. Brandes as part of the Rio Grande WAM in 2004. Column 4 shows the same original, monthly naturalized flow volumes but covers only the 1954–2000 hydrologic period of analysis. The reason for using this particular period, as explained previously, was due to different methods of evaporation measurements by the

TWDB. Column 4 shows the results of the computed monthly flow volumes in the Level 1 calibration process. The computing process for computing the monthly flow volumes in Level 1 took about 37 hours of computer operation time to simulate the entire Rio Grande WAM. The final computed monthly flow statistics are shown in Column 5, and combined results covering the 1940–2015 hydrologic period are given in Column 6. The extended monthly flow volume statistics covering a hydrologic period of 2001–2015 are given in Column 7.

As mentioned previously, the main objective of the extension process is to statistically reproduce known, monthly naturalized flows as closely as possible. Flow statistical values in Columns 3 and 5 show that the computed monthly flow values covering the 1954–2000 period are reproduced closely to the known monthly flows covering 1954–2000. Figures depicting monthly historical known and computed flows covering 1954–2000 period of record is shown in Appendix A. The 1940–1953 known naturalized flow volumes are added to the final computed flows covering 1954–2000 along with the extended 2001–2015 period that is provided in Column 6. Column 6 depicts the final Rio Grande extended FLO file covering the 1940–2015 hydrologic period of analysis that were used in this research to produce different reservoir firm yield and reliability analysis that will be discussed in subsequent chapters. Based on the final extended monthly flow volumes for the Rio Grande WAM in Column 6, the maximum flow spanning the 76 years of historical hydrologic period record for the primary control point at Fort Quitman (AT1000) is 372,048 acre-feet/month, with the mean and standard deviation of 33,270 acre-feet and 32,954 acre-feet/month, respectively (Table 3.10). Based on the computed monthly flow volumes in column 5, the probability 25 percent of the maximum available flow volumes covering the 76 years of the hydrologic period of record is 43,414 acre-feet/month for the primary control point AT1000 at Fort Quitman (Table 3.10). The monthly flow frequency metrics for calibration and extension for the rest of the 22 U.S. primary control points are shown in Appendix B.

The graphical representations of known, calibrated, and final computed monthly naturalized flow volumes covering the 1954–2000 period are provided in Figure 3.18. The red dashed lines in Figure 3.18 represent the known, monthly naturalized flow volumes covering the 1954–2000 hydrologic period of record. The blue line represents Level 1 calibration, and the dark gray line represents the final computed monthly flow volumes for the primary control

point AT1000 at Fort Quitman. The results of Columns 3, 4, and 5 in Table 3.10 are graphically represented in these figures.

The x-axis in the figure represents exceedance frequencies or likelihood or probability of available flow monthly flow volumes covering the 47 years of the hydrologic period of analysis. The Y-axis represents the monthly flow volumes of the same period of records. As can be seen in Figure 3.18, the chance or probability of water shortage or zero water is high for primary control AT1000, with a slight chance of having significant monthly flow volumes. For example, there is a 75% chance that monthly computed flow volumes covering the 47 years of the historical hydrologic period of record are 10,266 acre-feet/month of the maximum of 205,796 acre-feet/month. These statistical methods play a major role in analyzing reservoir firm yield and reliability analysis as well as the development of drought management plans that will be addressed in the next chapters. The rest of the figures for 22 primary control points are provided in Appendix B.

The 12-month moving average of known and computed monthly flow volumes for CT1000 at Fort Quitman is depicted in Figure 3.19 and the rest of the results for remaining 22 primary control points can be found in Appendix C. According to the figures, known flows (blue line) exceeded computed flows and balanced off in some years (Wurbs, 2013).

Final extended monthly flow volumes for CT1000 is shown in Figure 3.20 that covers the 1940–2015 hydrologic period of records. The 1940s was the wettest period in the Rio Grande, and the region experienced some peak flows during some of those years. However, the 1950s, early 2000s, and 2011—which featured historical records of drought—were the driest periods. The extended DAT includes the dry years after 2000. The Figures depicting extended flows for the remaining 22 primary control points are provided in Appendix D.

Table 3.10. Flow Frequency Metrics in Acre-Feet/Month for Calibration and Extension for the Rio Grande at Fort Quitman AT1000

1	2	3	4	5	6	7
	Original Known 1940- 2000	Original Known 1954- 2000	Level 1 Computed 1954-2000	Final Computed 1954- 2000	Combined 1940-2015	Extension 2001- 2015
Mean	35773	31647	47866	31693	33270	23095
Std Dev	33136	26845	79588	27575	32954	30220
Minimum	0	0	367	183	0	0
99.50%	0	0	458	200	0	0
99%	0	0	692	216	0	0
98%	0	0	1237	231	0	124
95%	0	0	2473	369	135	214
90%	2521	1452	4056	2796	1418	289
85%	5983	3924	5254	4225	3382	1185
80%	9035	6856	6223	8184	6029	1727
75%	12430	10611	7117	10266	9812	2217
70%	15852	13267	8188	12199	12771	3363
60%	23622	20520	11286	19746	19430	9206
50%	29752	27954	15732	27637	27584	14368
40%	37683	34675	21121	33222	35071	21233
30%	46657	43740	30298	40020	43462	31855
25%	51652	46712	44197	43417	48031	33762
20%	55545	52249	66507	51258	53497	38384
15%	62481	56591	105333	60579	59475	42747
10%	68814	63714	149534	69017	67935	55295
5%	85226	76655	228116	79856	83759	77012
2%	114954	104537	310793	102978	114852	131375
1%	160868	119004	364743	120854	166413	184902
0.50%	190321	150355	451597	149632	191083	197884
Maximum	372048	181184	621103	205796	372048	197884

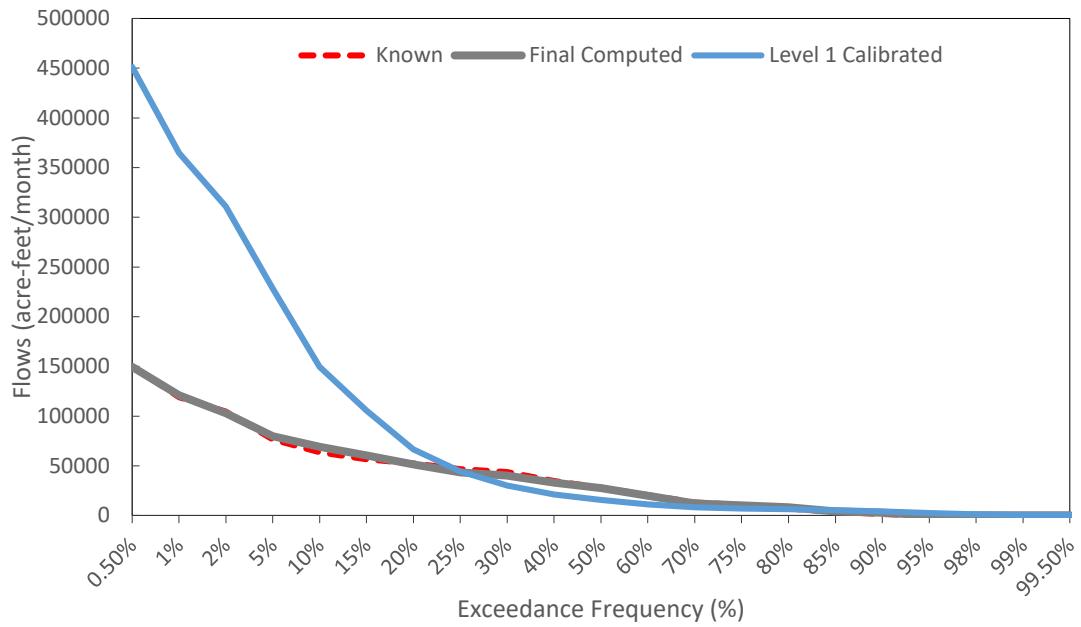


Figure 3.18. Known, Level 1 calibrated, and final computed flow frequencies at AT1000

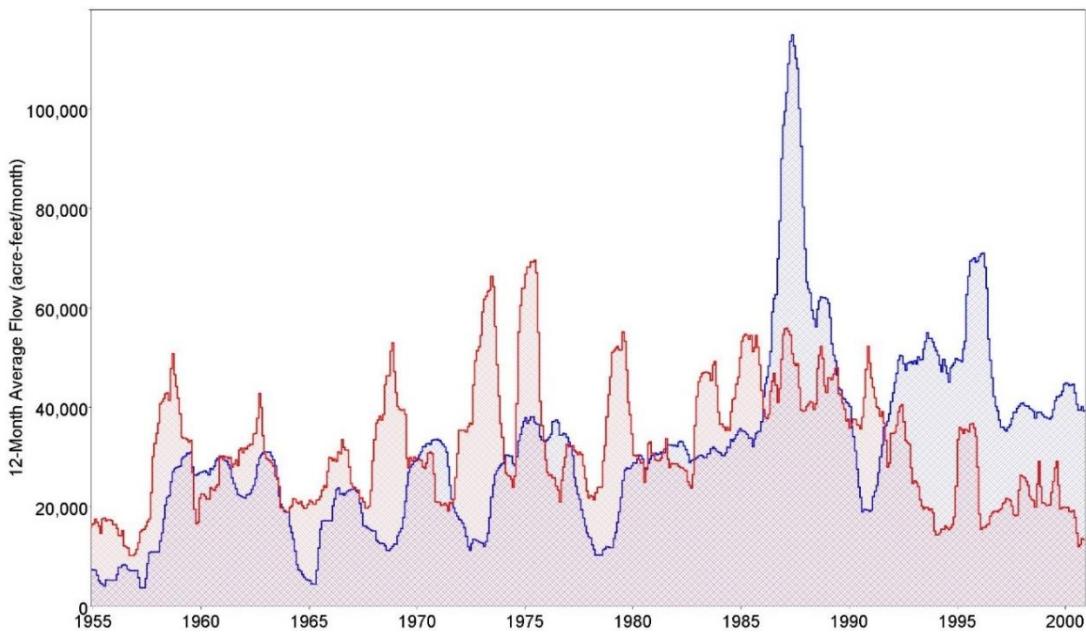


Figure 3.19. Known (Blue) and final computed (Red) 12-month forward moving average flows for the Rio Grande at Fort Quitman AT1000.

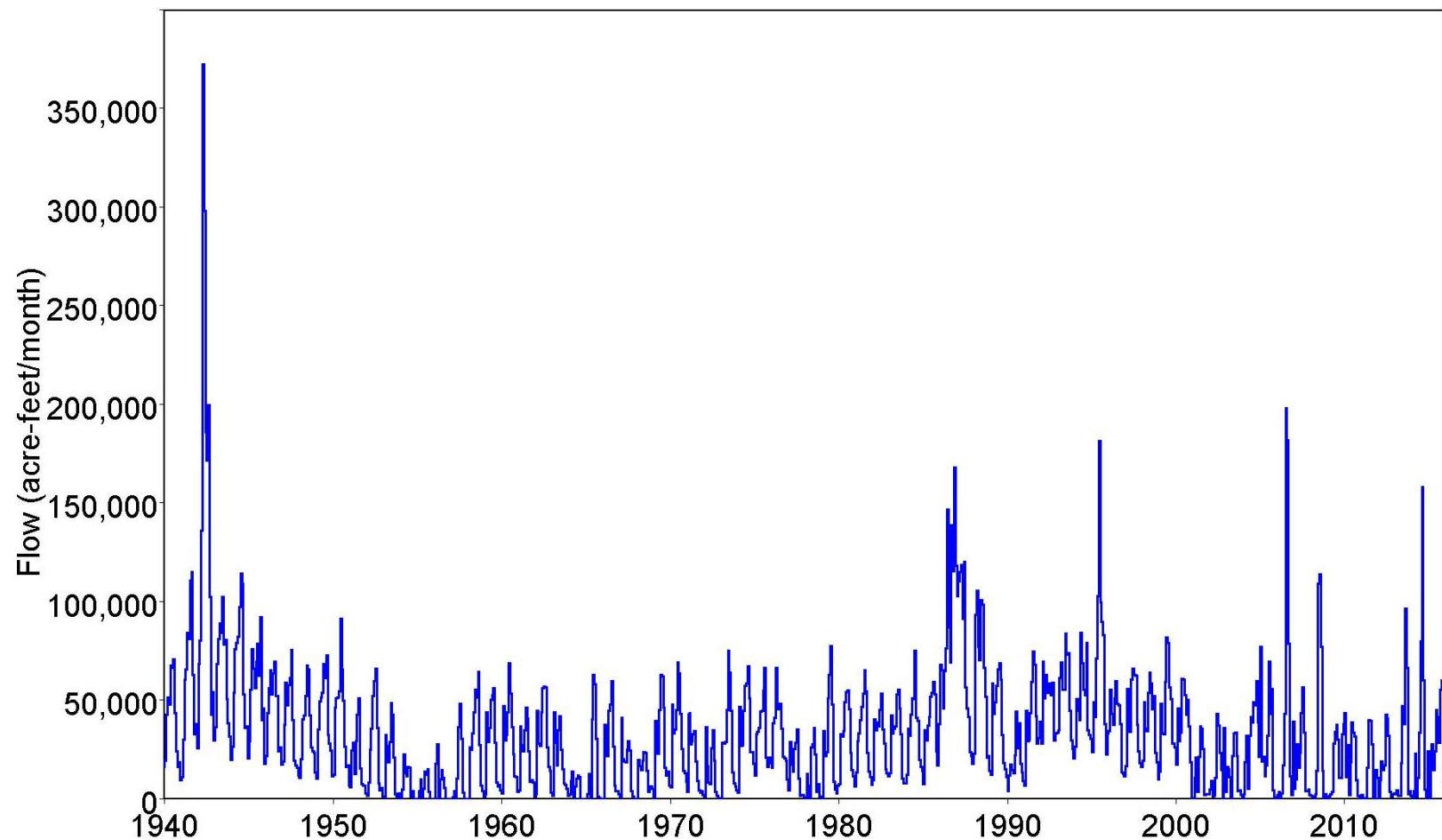


Figure 3.20. Original 1940–2000 and extended 2001–2015 naturalized flows for the Rio Grande at Fort Quitman AT1000.

Extension of the Spring Flow Adjustments

The process of developing the known 1940–2000 naturalized flows documented by the 2004 Brandes Report separated spring flows from the naturalized streamflows. The procedure for dealing with spring flows in the initial development of the naturalized flow dataset was replicated in the flow extension that was described in this chapter. Observed sequences of spring flows at 19 control points are included in the *SIM* input dataset as flow adjustment *FA* records in a FAD file. *SIM* adds these quantities to the naturalized flows at the beginning of each month of the simulation. *FA* records covering January 1999 through December 2012 were added to the FAD file to extend the original *FA* records covering January 1940 through December 1998. There is a single spring-flow control point in the Rio Grande WAM. It consists of monthly flow volumes that were developed by combining San Solomon and Giffin Springs.

San Solomon and Giffin Springs, above Balmorhea reservoir, were combined, and a single control point was included as a FAD file for Rio Grande WAM.

However, the Brandes report (Brandes, 2004) did not provide any details on the type of regression analysis that were used with the monthly flow coefficients and formulas. Therefore, in this research, average flow volumes covering the 1940–2000 hydrologic period for each month were used to extend the Rio Grande FAD file from 2001 to 2015. Figure 3.11 shows the monthly historical spring flow volume for a single control point at GT2390 in time series. With the exception of some peaks in the series, spring flow volumes ranged from 2000 acre-feet/month to 2500 acre-feet/month.

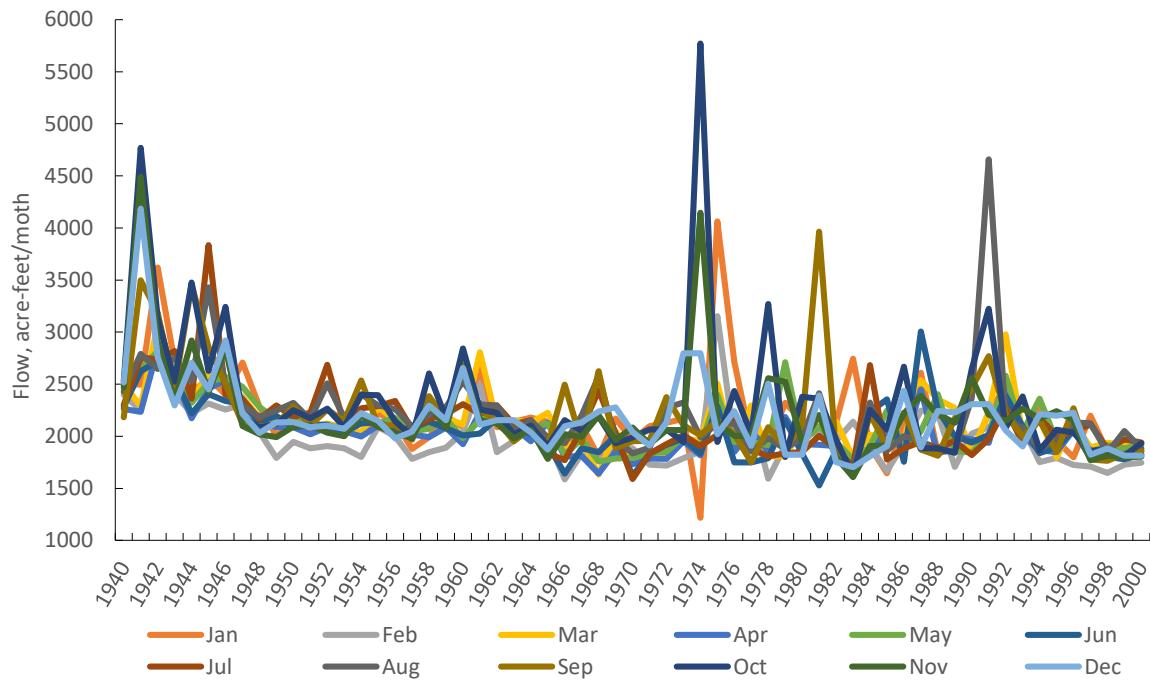


Figure 3.21. Time series of monthly flow volumes in acre-feet/month for San Solomon and Giffin Springs at GT2390 covering 1940–2000.

Updated Rio Grande WAM covering 1940-2015 hydrologic period of analyses will be used to simulate water availability in the next Chapters of this dissertation. The 2011 and 2012 were the driest periods in the Rio Grande and updated WAM datasets show that pattern. The hydrology files were extended using WRAP programs for each of the 55 primary control points based on TWDB quadrangles containing monthly evaporation and precipitation depths. For this research, only Texas portion of the Rio Grande was considered even though extension process was performed for the entire river basin.

CHAPTER IV

LONG-TERM SIMULATION MODELING

Rio Grande WAM Simulations

TCEQ uses the WAM modeling system to evaluate water permit applications based on long-term simulations in which the applicant must demonstrate the availability of water after fully authorized diversion rights for water right holders are met based on the prior appropriation doctrine of Texas. Then, TCEQ may issue a new permit if there is any unappropriated water left on the river. However, this new permit will bear the most junior water right holder status; therefore, the holder of the permit would be the last water user in line for any newly authorized diversions. In addition, TCEQ updates WAM *DAT* files on a regular basis as the use of water rights are being discontinued or as operation policies of local reservoirs are changed. Further, TWDB uses the updated WAM WRAP modeling system to simulate reservoir yield and reliability analysis for future state water planning purposes. The newly extended Rio Grande WAM can be updated annually based on monthly evaporation and precipitation depths, which can easily be obtained from TWDB.

As mentioned in the previous chapters, the Rio Grande is governed by two international treaties and two interstate compacts and managed by the operations of Amistad and Falcon Reservoirs, which are owned and operated by the IBWC. The 1944 treaty defined storage allocations for the Mexican and United States' portions and delineated the operations of these reservoirs as a system. The Lower Rio Grande, which is the main study basin of this research, diverts the largest amount of water from the Amistad-Falcon Reservoir system, primarily to meet Domestic-Municipal-Industrial (DMI) and irrigation demands.

The objective of the study described in this chapter was to develop reservoir firm yield and reliability analysis based on long-term simulations using the updated Rio Grande WAM. Several WRAP simulation scenarios were developed to examine reliabilities for DMI, Class A, and Class B irrigation water rights in the Texas portion of the Middle and the Lower Rio Grande. The extended Rio Grande WAM datasets covering the 1940–2015 hydrologic period of analysis and the October 17, 2014, version of the updated Rio Grande WAM datasets are used in this research. Note that DMI is used to describe the domestic-municipal-industrial pool

in the Amistad-Falcon Reservoir system, but municipal rights are specific annual diversions that are being allocated to the Middle Rio Grande as MUNIMID and the Lower Rio Grande as MUNILWR.

Amistad-Falcon Reservoir System Operations

Amistad and Falcon Reservoirs are owned and operated by IBWC based on the provision of the 1944 treaty signed by the representatives of the United States and Mexico. Falcon Reservoir was built on the main stem of the Rio Grande in 1956 to store river water in order to supply water demands in the Lower Rio Grande Valley following the record historical drought in Texas. Amistad Reservoir was also built on the main stem of the Rio Grande about 45 river miles upstream of Falcon Reservoir in 1968 (Wurbs 1996).

These reservoirs are operated as a system; they move water from upstream toward downstream to supply demands in the Lower Rio Grande. The storage contents in both reservoirs are divided between the United States and Mexico—56% and 58% of the storage in Amistad and Falcon goes to the United States and the remainder to Mexico, respectively—based on financial contributions from both countries for the construction of the reservoirs (Brandes 2004).

TCEQ's watermaster office in the Lower Rio Grande is a state agency responsible for water allocations from the Texas part of the Rio Grande. The agency collects weekly water demands from all water rights holders in the Rio Grande Valley and requests target diversions from IBWC, which in turn makes diversions from Falcon and, if necessary, from Amistad reservoirs (Griffin 2011).

Rio Grande WAM contains the monthly naturalized flow volumes for 23 primary control points and net evaporation minus precipitation depths for seven primary control points in the United States portion of the watershed for 76 years of hydrologic period-of-records covering 1940–2015. TCEQ Run 3, the full-authorized scenario of the Rio Grande WAM, was used throughout the simulations in this research. The purpose of the research scope of this chapter was to demonstrate different water reallocation scenarios from municipal to irrigation pools in Amistad and Falcon Reservoirs. According to research conducted by Griffin et al. (1992) and Chang et al. (1992), storage availability in the municipal pool at Amistad and

Falcon Reservoirs exceeds monthly demand significantly. Therefore, this research aimed to investigate those findings by incrementally reducing storage contents of the municipal pool using the Beginning-Ending-Storage (BES) Option 4 of WRAP program to develop reliability and exceedance frequency tables.

One hundred and thirteen major reservoirs with a total capacity of more than 5,000 ac-ft are included in the Rio Grande WAM. Figure 4.1 shows the locations of the largest reservoirs in the Rio Grande Basin. Eight of the largest reservoirs are included in the Texas portion of the Basin while 18 of the largest reservoirs are included in the Mexico portions of the watershed. Tables 4.1 and 4.2 provide some details on all large reservoirs in the Basin. The reservoirs in the Mexico portion are included only for information purposes because no reliability analysis were carried out on those reservoirs; the focus was on Texas reservoirs only.

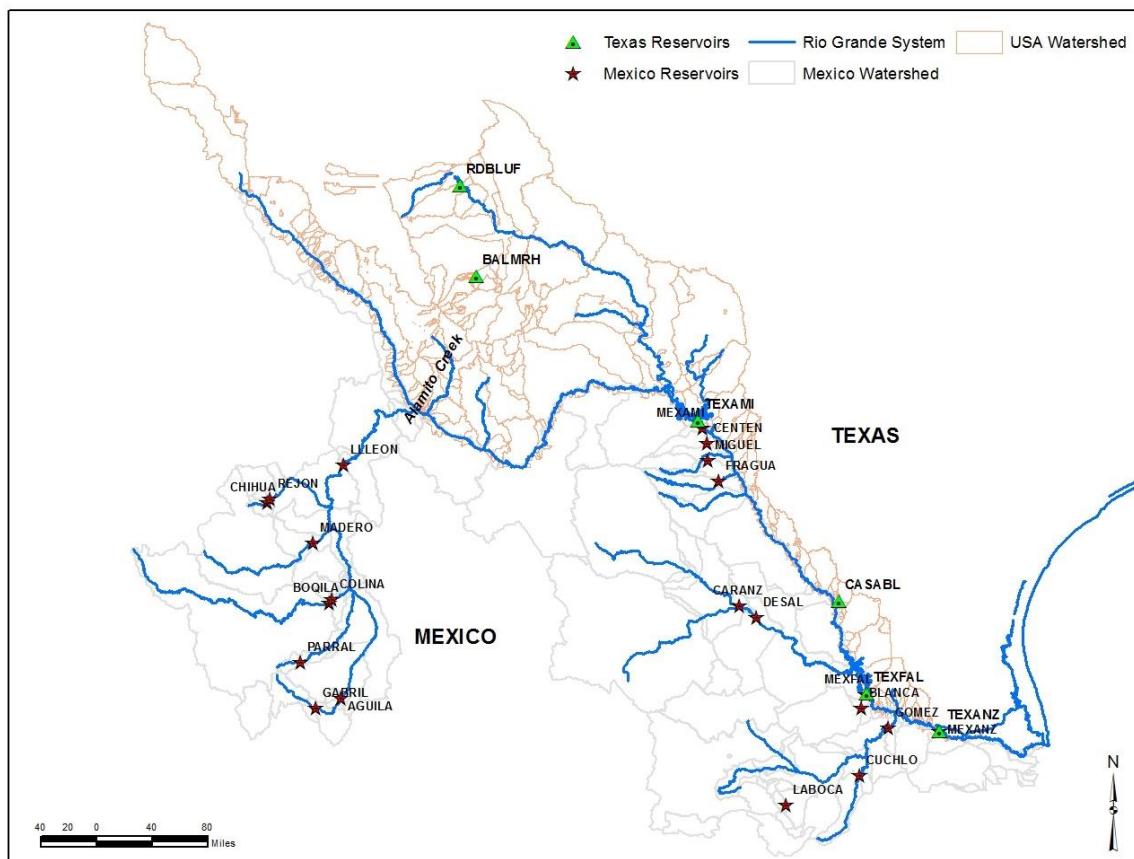


Figure 4.1. Locations of the main reservoirs in the Rio Grande Basin.

Table 4.1. Major Texas Reservoirs in the Rio Grande Basin (reproduced from Brandes, 2004)

#	Full Name	WAM Name	Storage Capacity (Ac-ft)	Date of Impoundment	Contributing Drainage (Area Sq. Mi)
1	Imperial Reservoir*		6,000	1914	48
2	Red Bluff Dam	RDBLF	310,000	1936	20,720
3	Lake Balmorhea	BALMRH	6,350	1917	22
4	Amistad Reservoir	TEXAMI	3,505,238	1968	126,423
5	Casa Blanca Lake	CASABL	20,000	1949	117
6	Falcon Reservoir	TEXFAL	2,371,221	1953	164,482
7	San Esteban Lake	ESTBAN	18,770	1911	500
8	Anzalduas Dam	TEXANZ	13,900	1960	176,112

*Off-channel reservoir

Table 4.2. Major Mexico Reservoirs in the Rio Grande Basin

#	Full Name	WAM Name	Storage Capacity (Ac-ft)	Date of Impoundment	Contributing Drainage (Area Sq. Mi)
1	Pica del Aguila	AGUILA	40,520	1992	1,151
2	San Gabriel	GABRIL	207,027	1979	1,056
3	El Parral	PARRAL	8,187	1952	147
4	La Boquilla	BOQILA	2,353,728	1916	8,113
5	La Colina	COLINA	19,535	1927	8,175
6	Francesco I. Madero	MADERO	282,126	1949	4,163
7	Chihuahua	CHIHUA	20,913	1960	152
8	El Rejon	REJON	7,676	1968	63
9	Luis L. Leon	LLEON	288,574	1968	22,560
10	Centenario	CENTEN	21,322	1985	n/a
11	San Miguel	MIGUEL	16,212	1936	n/a
12	La Fragua	FRAGUA	36,477	1993	680
13	Venustiano Carranza	CARANZ	1,222,182	1930	16,158
14	Laguna de Salinas	DESAL	15,401	1957	25
15	Las Blancas	BLANCA	100,514	2000	4,000
16	La Boca	LABOCA	33,235	1957	107
17	El Cuchillo	CUCHLO	910,304	1993	3,447
18	Marte R. Gomez	GOMEZ	889,228	1943	12,563

Source: Brandes 2004.

The Middle Rio Grande covers the water rights and diversions between Amistad and Falcon Reservoirs, and the Lower Rio Grande covers the water rights between Falcon Reservoir and the Gulf of Mexico in the Lower Rio Grande Valley. The Rio Grande water rights are based on special prior appropriation system in which DMI has seniority over Class A and Class B irrigation and mining rights. Class A rights have 1.7 times of allocations of the Class B rights and 1.4 times of storage in the Amistad-Falcon Reservoir system. The Amistad-Falcon Reservoir system is divided into the dead pool (with 4,600 ac-ft/month storage capacity), conservation pool (comprised of the DMI pool, with 225,000-ac-ft/month storage and 75,000 ac-ft/month as an operational reserves [OR; OP-Reserve – operation storage] pool),

Class A pool, and Class B pool. As per the 1944 treaty, the Amistad-Falcon Reservoir system's accounting was operated by the IBWC in the following order:

- Weekly water demands are submitted to IBWC by the TCEQ watermaster for DMI, Class A, and Class B water right diversions.
- 4,600 ac-ft/month is deducted from the dead pool.
- 75,000 ac-ft/month is deducted for OR (e.g., evaporation and other losses).
- 225,000 ac-ft/month is deducted for DMI reserves (estimated to supply three months of water for municipal use in extreme drought conditions).
- Municipal diversions as requested by the TCEQ watermaster are allocated and deducted from the conservation pool.
- Class A irrigation diversions are allocated and deducted from the conservation pool.
- Class B irrigation diversions are allocated and deducted from the conservation pool.

DMI accounts start over each month, but Class A and Class B rights do not reset until the end of the year.

Concept of Reliability

Reservoir/river systems experience uncertainties involving great variability of streamflows, climatic patterns, reservoir evaporation rates, and other related factors. Because of these uncertainties regarding the future hydrologic character of the system, water supply capabilities must be viewed from a reliability, probability, or percent-of-time perspective (Wurbs, 1996). Reliability is a measure of dependability and can be used to assess the capabilities of a river/reservoir system to satisfy specified water use requirements. Reservoir reliability is an indication of the probability of meeting a given demand. Alternatively, reliability can be expressed as the percent of the time that a given demand can be fulfilled (Santos, 2005).

Reliability indices, such as period reliability and volume reliability, provide a mechanism for evaluating and comparing alternative reservoir storage allocations and operating plans regarding their capabilities for meeting system demand (Wurbs, 1996). Equations determining period and volume reliabilities are provided in the research methods section of Chapter I of this dissertation. Reliability indices in this research were computed from

the results of the Rio Grande water supply simulations based on the extended historical record of flow sequences that preserve selected statistical characteristics of the historical data.

It should be recognized that, in reality, a reliability of 100% does not necessarily mean that the system will always be able to supply all demands without failure. Reliability indices do not provide a perfect appraisal of the system capabilities because they are influenced by modeling assumptions and are based on historical hydrologic data that does not necessarily reflect the entire range of possible future inflow sequences (Santos, 2005). Wurbs (2001) provided the following definitions of reliabilities and exceedance frequencies for reservoir/river simulations in WRAP modeling.

Period reliability is the percentage of months during the simulation for which a specified demand target is met without shortage. Period reliability (R_p) is computed from the results of a simulation as:

$$R_p = \frac{n}{N} \times 100\% \quad (4.1)$$

Where n denotes the number of months during the simulation for which the demand is met, and N is the total months in the simulation, which was 912 months in the case study. Thus, R_p is an expression of the percentage of time that the demand can be met or, equivalently, the likelihood of the demand being fulfilled in any randomly selected months. Reliability table also includes tabulations of both the percentage of months and percentage of years during the simulation for which the amounts supplied equal or exceed specified magnitudes expressed as a percentage of the target demand. Exceedance frequency tables may be developed for naturalized flow, unappropriated flow, instream flow shortages, and reservoir storage. Exceedance Frequency is defined as:

$$\text{Frequency} = \frac{n}{N} \times 100\% \quad (4.2)$$

Where n = a number of months during the simulation that a particular flow or storage amount is equaled or exceeded, and N = total number of months in the simulation. Frequency tables also include the mean, standard deviation, minimum, and maximum of naturalized streamflow volumes.

Volume reliability is the percentage of the total demand volume that can actually be supplied. Volume reliability (R_v) is computed as the ratio of total volume supplied (v) to volume demand (V):

$$R_v = \frac{v}{V} \times 100\% \quad (4.3)$$

or, equivalently, the ratio of the mean actual diversion rate to mean target diversion rate.

The reliabilities computed by WRAP provide meaningful information but are subject to interpretation. The shortages represent a general index of supply failures that could involve emergency demand management measures, negotiation of resource allocations, or similar actions (Wurbs 2005).

The Texas WAM studies indicate that reliabilities are not very sensitive to changes in demand targets. Conversely, the amounts that may be supplied change greatly with relatively small changes in reliability requirements. The amount of water supplied from Texas river systems can be increased significantly by accepting higher risks of shortages or emergency demand reductions (Wurbs, 2005). Reliabilities are also highly dependent on reservoir storage capacity and multiple-reservoir/river system operating rules. The Rio Grande and major reaches of other rivers in the dry western half of the state are over-appropriated. Streamflow in several major urban regions with wetter climates is also either completely appropriated or nearly so. The TCEQ will not issue permits for additional water use from these river reaches. Marketing or transferring of existing water rights among users is encouraged. For other rivers, water is still available for further appropriation. The TCEQ issues or modifies numerous water right permits each year (Wurbs, 2005).

Applications of Reliability

The level of reliability assigned to each water right can be used as a curtailment mechanism during water shortage periods. When a shortage occurs, the water rights with lower reliabilities are curtailed; thus, they absorb the initial effects of droughts, and higher reliability use would only be curtailed under the most severe drought conditions. For example, in the Rio Grande, Class B irrigation rights would automatically be curtailed since they bear the lowest

reliability and the most junior rights' status in the hierarchy of priorities. Then, if necessary, Class A water rights would be curtailed to protect the DMI diversions in the Amistad-Falcon Reservoir system to meet drinking water demands in the Lower Rio Grande Valley. Long-term reliabilities and reallocations of irrigations and municipal pools during drought conditions are explained in the next sections.

In evaluating permit applications, the TCEQ has applied a general rule that municipal supplies should have a volume and period reliability of 100%, and for agricultural supplies, 75% of the permitted demand should be met at least 75% of the time. These guidelines are subject to exceptions and future refinement. Criteria for defining acceptable levels of impact of a proposed plan on the reliabilities of other water users throughout a river basin are also evolving as experience is acquired in applying the modeling system (Wurbs, 2005).

Requiring a reliability of 100% for municipal supplies is common practice since shortages are considered intolerable for purposes of drinking water. For agricultural purposes, shortages are usually acceptable under certain conditions. For instance, a shortage of 10% usually has a negligible economic effect, but shortages as large as 50% can have devastating economic impacts (USACE, 1997). Another important aspect of the relationship between reliability and water availability is how to manage the trade-offs between how much water to commit for beneficial use and the level of reliability that can be attained. Certainly, on many occasions, there will be more water available than the quantity associated with 100% reliability (Santos, 2005).

Wurbs (2002) developed and applied the procedure for estimating the relation between reservoir water-surface elevation and annual exceedance frequency for different operating policies for Addicks and Backers Reservoirs on Buffalo Bayou in Houston. The reservoir/stream system is simulated with the generalized computer program HEC-5 Simulation of Flood Control and Conservation Systems. In addition, the reliability concepts are applied to several river basins in Texas as part of WRAP applications.

Conventional or BES Simulation Options

WRAP SIM provides options with the beginning-ending-storage (BES) parameter in the JO record that allows the model user to either set end-of-storage content in the DAT file manually or set the BES parameter to Option 4, which cycles using end-of-storage of all reservoirs as the beginning of storage automatically for all reservoirs. BES Option 1 was used to develop end-of-storage contents for Amistad and Falcon Reservoirs that were used in the simulation process of this research. Developing reliability tables for each water use group in this manner produces better results than setting all the beginning reservoir content to full (Wurbs 2005).

Rio Grande WAM datasets were developed for both Mexico and Texas watersheds essentially as two parallel river systems following the 1906 Convention, the 1944 treaty on appropriations of the Rio Grande between Mexico and the United States, the Rio Grande Compact between Texas, New Mexico and Colorado, and the Pecos River Compacts between New Mexico and Texas. Simulation modeling and analysis in this research focused on the Texas part of the Rio Grande Watershed excluding Mexico, although the WAM system is deployed all together.

TCEQ applications of WRAP assume that the reservoirs are full at the beginning of the simulation. The rationale behind this is that the results for a long period of analysis are not significantly affected by the initial conditions. However, having full reservoirs at the beginning of the simulation may not be a realistic assumption for arid areas like the Rio Grande Basin (Santos, 2005). The initial storage content minus the storage content at the end of the simulation represents extra water that could result in estimated reliabilities being higher than they should (Wurbs, 2005). Thus, the BES feature in WRAP was used to determine the initial storage conditions. The BES feature is based on setting the beginning and ending storage equal, which reflects the concept of a cycling hydrologic simulation period. The initial storage condition for Amistad Reservoir was determined to be 593,985 ac-ft (32.6% of capacity) and for Falcon Reservoir 276,027 ac-ft (17.8% of capacity).

Several exercises or water reallocation scenarios have been simulated to demonstrate impacts of volume reliabilities on various water right groups in order to identify gainers and losers of particular rights. Numerous studies conducted by Griffin (1999, 2001, 2002)

mentioned how overprotective DMI pools in Amistad and Falcon reservoir system are, and reallocating these excess reserves to irrigation use would technically improve water availabilities for the Lower Rio Grande Valley. Although such simulation results may seem infeasible to implement because it forces some changes to the 1944 treaty, exercising various options for this particular research could spark debate on the improvement of reservoir operations and storage diversions. These options include, but are not limited to, lowering DMI and OR and curtailing Class B water users.

Rio Grande Water Diversions

The Rio Grande, for this research, was divided into middle and lower segments to simplify the modeling analysis. Although the primary focus was to develop reservoir-volume reliability scenarios for DMI, Class A, and Class B irrigation rights in the Lower Rio Grande, the Middle Rio Grande was also included since both segments depend on diversions from the Amistad-Falcon Reservoir system.

Based on the Rio Grande WAM DAT file, annual municipal water demands below Amistad Reservoir are 301,922 ac-ft, or 14% of the total water demands. Seventy-seven percent, or 1,615,089 ac-ft, is diverted to Class A irrigation and mining demands annually, and the other 9%, or 183,203 ac-ft, is allocated to Class B irrigation and mining rights. Table 4.3 shows the breakdown of annual water demand for each water rights' group in the Middle and Lower Rio Grande. Combined Class A and Class B rights equal 86% of the total diversions used in the Rio Grande.

Table 4.3. Summary of Water Demands by Use in the Rio Grande WAM

DMI Water Demands		Class A Irrigation and Mining Demands		Class B Irrigation and Mining Demands	
Middle	Lower	Middle	Lower	Middle	Lower
61,008	240,914	156,226	1,461,009	19,928	167,150

Note: Values are given in ac-ft/year

Annual storage volumes for Class A and Class B water rights in the Amistad-Falcon Reservoir system are defined as 2,280,300 ac-ft/year ($1,617,234 \times 1.41$) and 263,780 ac-ft/year ($187,078 \times 1.41$).

The volume reliability metric was used as the primary criteria for water allocations in this research. Based on the 1944 treaty, Amistad and Falcon Reservoirs are operated as a system with DMI, Class A, and Class B designated pools. The DMI pool must have 225,000 ac-ft of storage each month before the diversions are made. It is shown under DMI reserves in Table 4.4 as 2,700,000 ac-ft per year ($225,000 \times 12$ months). Dead pool or unutilized storage is also listed as 55,200 ac-ft per year ($4,600 \times 12$ months), and OR is 900,000 ac-ft/year ($75,000 \times 12$ months).

Table 4.4. Fully Authorized Diversion Rights and Storage in the Rio Grande WAM

Basin Segment	WAM Name	Full Name	Annual Diversions (ac-ft/year)
Middle Rio Grande	MUNIMID	Municipal	61,008
	MID-A-IRR	Class A Irrigation	151,688
	MID-B-IRR	Class B Irrigation	13,890
Lower Rio Grande	MUNILWR	Municipal	240,914
	LOW-A-IRR	Class A Irrigation	1,460,999
	LOW-B-IRR	Class B Irrigation	163,305
Middle & Lower	DEAD	Dead Storage	55,200
	DMI	Domestic-Municipal-Industrial	2,700,000
	OP-RESERVE	Operational Reserve	900,000

Conventional Long-Term Simulations

All reservoir storage contents were set to 100% capacity at the beginning of 76 hydrologic periods of simulations. Table 4.5 shows the WRAP SIM results using the TABLES program for illustration purposes. The municipal rights have period and volume reliabilities of 100%, which means that the annual target diversions of 61,008 ac-ft and 240,914 ac-ft are being supplied during the 76-year hydrologic period of analysis covering 1940–2015 without

shortages for the Middle and Lower Rio Grande segments, respectively. For the same period of analysis, only 68.29% (with a shortage of 48,099 ac-ft/year) of annual target diversions of 151,688 ac-ft and 44.32% (with a shortage of 7,734 ac-ft/year) of target diversions for Class A and Class B water rights are being supplied.

Thus, the simulation results show that during the period of analysis, Class A irrigation water rights had a 67.14% volume reliability while Class B water rights had only 43.23% reliability in the Lower Rio Grande. The model results show that dead and DMI reserves had 100% reliability for the same period, but OR reserves had a reliability of 92.76%, enduring annual losses of 65,153 ac-ft attributed to evaporation and other losses.

At least 55.9% and 30.2% of the monthly targets for Class A and Class B water rights in the Middle Rio Grande were met during 90% of the 912 months simulated. At least 35.5% and 43.4% of 1,460,999 ac-ft target diversion for Class A water rights in the Lower Rio Grande was supplied during 90% and 75% of the 76 annual sequences. Similar results can be seen for Class A and Class B water rights for the Middle Rio Grande for the 912-month simulations. Total volume reliability for the entire Rio Grande WAM simulations for 76-years of the hydrologic period of analysis covering 1940–2015 was 51.10%, meaning only about half of the total annual diversions were supplied during this period. It shows the impacts of frequent and prolonged droughts in the Rio Grande Basin.

Table 4.5. Summary of Reliabilities for All Water Right Groups Using Conventional Long-term Simulations

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT					PERCENTAGE OF YEARS								
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%			
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0			
MID-A-IRR	151688.0	48099.21	54.28	68.29	54.3	55.2	55.9	58.6	63.9	79.1	93.1	26.3	27.6	28.9	38.2	43.4	67.1
MID-B-IRR	13890.0	7734.40	29.28	44.32	29.3	29.5	30.2	32.8	39.8	52.5	84.6	10.5	10.5	10.5	10.5	13.2	30.3
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
LOW-A-IRR	1460999.4	480049.53	54.28	67.14	54.3	55.2	55.9	58.6	63.9	79.1	93.1	26.3	27.6	28.9	35.5	43.4	67.1
LOW-B-IRR	163305.0	92714.20	29.28	43.23	29.3	29.5	30.2	32.8	39.8	52.5	84.6	10.5	10.5	10.5	10.5	13.2	30.3
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMI	2700000.2	124.10	99.78	100.00	99.8	100.0	100.0	100.0	100.0	100.0	100.0	97.4	100.0	100.0	100.0	100.0	100.0
OP-RESERVE	900000.1	65153.52	83.00	92.76	83.0	84.0	85.3	89.6	94.4	96.2	98.2	25.0	39.5	59.2	73.7	93.4	98.7
Total		91309144.044649944.00		51.10													

The long-term simulations of volume and period reliabilities provide basic information for water managers and users about the likelihood of expected volume that would be received based on simulations of the last 76 annual sequences of the hydrologic period of analysis. TWDB uses the results of long-term reliability analysis for long-term water planning and management purposes.

Long-Term Simulations using BES Option

The BES parameter option in WRAP was used to determine the initial storage contents. The BES parameter is based on setting the beginning and ending storage equal, which reflects the concept of a cycling hydrologic simulation period. The BES parameter with Option 1 of the JO record in the DAT file is used to automatically create and read the initial storage content in Amistad and Falcon as 593,985 ac-ft (32.6% of capacity) and 276,026 ac-ft (17.8 % of capacity), respectively (Table 4.6). The details of the changing BES record are provided on page 42 of the *WRAP Modeling System User's Manual* (Wurbs, 2015). These values have been entered into the WS record and simulated by changing DMI and OR reserves incrementally and analyzing reliability results.

Table 4.6. BES Parameters for Storages in Amistad and Falcon Reservoirs

Reservoir	Storage Capacity	Beginning Storage	Ending Storage	BES
TEXAMI	1,821,502	1,821,502	593,985	32.6%
TEXFAL	1,548,640	1,548,640	276,026	17.8%

Table 4.7 shows the reliability results for municipal, Class A, and Class B irrigation water rights for the Middle and Lower Rio Grande, with slightly lower values than conventional long-term simulation (Table 4.5) in which all reservoirs were full at the beginning of simulations.

Table 4.7 shows the WRAP SIM results using TABLES program for illustration purposes. The municipal rights have period and volume reliabilities of 100%, which means that the annual target diversions of 61,008 ac-ft and 240,914 ac-ft are being supplied during the 76-year hydrologic period of analysis covering 1940–2015 without shortages for the Middle and Lower Rio Grande segments, respectively. For the same period of analysis, only 68.29% (with a shortage of 48,099 ac-ft/year) of annual target diversions of 151,688 ac-ft and 44.32% (with a shortage of 7,734 ac-ft/year) of target diversions for Class A and Class B water rights are being supplied.

Class A irrigation water rights had 67.03% (with a shortage of 480,049 ac-ft/year) volume reliability, while Class B water rights had only 42.91% reliability (with a shortage of 92,714 ac-ft/year) in the Lower Rio Grande. The model results show that Dead and DMI reserves had 100% reliability for the same period, but OR reserves had the reliability of 93.01%, enduring annual losses of 65,153 ac-ft/year attributed to evaporation and other losses. Most losses for Class A and Class B water rights and OP storage reserves in the Lower Rio Grande are characterized by larger water demands than the Middle Rio Grande. As mentioned earlier, in the conventional option, reliabilities are higher because initial reservoir storage contents are assumed to be full at the beginning of simulations. Unlike the conventional option, the BES option produces lower reliabilities, but it is considered more accurate.

At least 55.8% and 29.4% of the monthly targets for Class A and Class B water rights in the Middle Rio Grande are met during 90% of the 912 months simulated. At least 35.5% and 43.4% of 1,460,999 ac-ft target diversion for Class A water rights in the Lower Rio Grande was supplied during 90% and 75% of the 76 annual sequences. The similar results can be seen for Class A and Class B water rights for the Middle Rio Grande for the 912 months of simulations.

Table 4.7. Summary of Reliabilities for all Water Rights Groups Using BES Parameter Record

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS					PERCENTAGE OF YEARS											
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT					100%	95%	90%	75%	50%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	48254.73	54.17	68.19	54.2	54.9	55.8	58.4	64.7	78.2	92.9	25.0	25.0	28.9	38.2	43.4	67.1			
MID-B-IRR	13890.0	7779.09	28.07	44.00	28.1	28.7	29.4	32.2	39.1	53.1	84.6	9.2	9.2	10.5	10.5	11.8	30.3			
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.4	481652.94	54.17	67.03	54.2	54.9	55.8	58.4	64.7	78.2	92.9	25.0	27.6	28.9	34.2	43.4	67.1			
LOW-B-IRR	163305.0	93233.60	28.40	42.91	28.4	28.7	29.4	32.2	39.1	53.1	84.6	9.2	9.2	10.5	10.5	13.2	30.3			
DEAD	552000.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	124.86	99.78	100.00	99.8	100.0	100.0	100.0	100.0	100.0	100.0	97.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	62946.12	81.80	93.01	81.8	84.0	85.7	89.5	94.5	96.8	98.7	15.8	35.5	57.9	72.4	96.1	98.7			
Total		90075304.044648680.00		50.43																

Total target diversions and mean storage volumes at the bottom of Table 4.7 represent the entire Rio Grande WAM, including Mexico. The main purpose of this comparison is to trace any changes in reservoir storage that would likely impact water availability for all major pools listed in the table. Storage reliabilities for the conventional and the BES option for long-term simulations shown in Table 4.7 have some shortages associated with each pool. OR had relatively significant shortages of 62,946.12 (Table 4.5) ac-ft and 65,153.52 ac-ft, respectively, when comparing the two simulation scenarios. These shortages are the evidence of evaporation and other losses that occurred in the Amistad and Falcon reservoir system under long-term simulation scenarios. In addition, lower (less than 100%) reliabilities in the storage pools show the frequency and intensity of the monthly diversions from the pools even though there is no evidence that demonstrates a need for those pools to be full all the time, excluding DMI reserves.

Figure 4.2 shows the frequency exceedance of storage availabilities in Amistad and Falcon Reservoirs using conventional and BES options of Rio Grande WAM for long-term simulations. There is a slight difference between the conventional and BES options of the simulations for the Amistad Reservoir, with maximum total storage of 1,821,311 ac-ft and the likelihood of about 5%. However, deviations converge at about 50% of probability, meaning that there is a 50% chance, based on this simulation scenario, that at the end of any given

month, the Amistad will have a storage of 390,578 ac-ft and 381,581 ac-ft for the conventional and BES option, respectively. However, the probability of available storage in Amistad is 182,311 acre-ft and 175,645 ac-ft under both scenarios, respectively. The maximum storage for Falcon Reservoir is 1,548,640 ac-ft and 1,249,339 ac-ft using simulations with conventional and BES options.

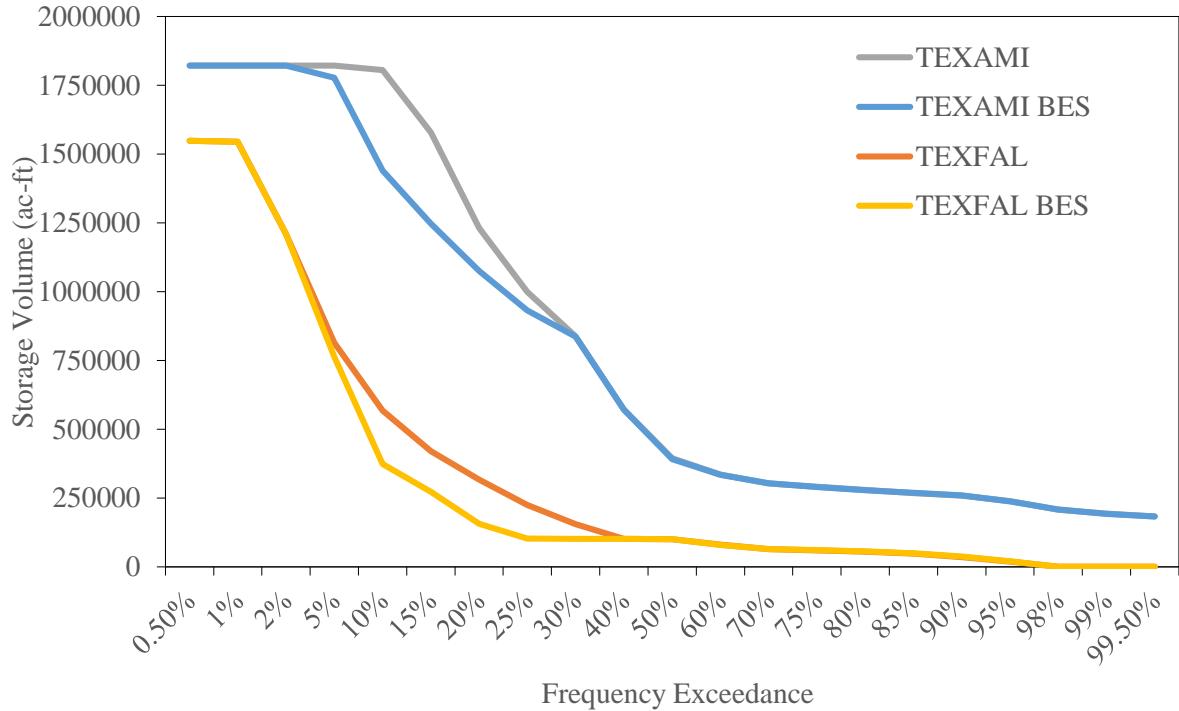


Figure 4.2. Frequency exceedance of storages for Amistad and Falcon Reservoirs with conventional and BES option of long-term simulations.

This difference can be explained by the magnitude of continuous diversion frequency from Falcon Reservoir to meet water demands in the Lower Rio Grande Valley. Storage frequency for the Falcon Reservoir converges at about 40 percent, with 101,371 ac-ft and 101,216 ac-ft for the conventional and BES options. There is about a 99.5 percent chance that storage in Falcon Reservoir will be at 62.0 ac-ft under this simulation scenario.

Assessment of DMI Pool

The objective of this exercise is to lower DMI reserves in the Amistad-Falcon Reservoir system and assess impacts of reliabilities on municipal and Class A and Class B water rights. The municipal pool is reduced until a reliability of less than 100% is reached and analyzed to determine whether lowering this pool is going to increase irrigation reliabilities. This section of the chapter contains series of simulation runs comprised of different scenarios, which are explained below. In this exercise, the October 2014 full authorization scenario (TCEQ Run 3) for the Rio Grande was used as the base model for comparison purposes. The period of analysis extends from 1940 to 2015. The WAM model input data (DAT file) was modified as necessary to represent the different scenarios. The set of runs consisted of the following scenarios:

- Scenario 1: Conventional long-term simulation with full initial storage conditions; DMI = 225,000 ac-ft/month; OR = 75,000 ac-ft/month.
- Scenario 2: Long-term simulation based on BES option; TEXAMI = 593,985 ac-ft/month and TEXFAL = 276,027 ac-ft/month; DMI and OR = full.
- Scenario 3: DMI = 50% of total (112,500 ac-ft/month); OR = 100%.
- Scenario 4: DMI = 25% of total (56,250 ac-ft/month); OR = 100%.
- Scenario 5: DMI = 0% of total (0 ac-ft/month); OR = 100%.

The average volume reliabilities (R_v) for water right groups that are dependent on the Amistad-Falcon Reservoirs system are presented in Table 4.8. Reliabilities for conventional simulations are higher than the reliabilities using BES option. Therefore, determining a beginning-of-period storage as described above, rather than assuming full storage capacity, provides a more realistic analysis of the base conditions in the Basin.

Table 4.8. Summary of Reliabilities Based on Reduced DMI Storage Reserves

Scenario	% of Total of DMI Reserve	% of Total of OR Reserve	Municipal		Class A Irrigation		Class B Irrigation	
			Middle	Lower	Middle	Lower	Middle	Lower
			R _v	R _v	R _v	R _v	R _v	R _v
1	100	100	100	100	68.3	67.1	44.3	43.2
2	100	100	100	100	68.2	67.0	44.0	43.0
3	50	100	100	100	68.6	67.5	44.6	43.6
4	25	100	100	100	69.2	68.1	44.9	44.0
5	0	100	100	100	69.2	68.1	45.0	44.0

Notes: Reliabilities are given in percentages. R_v = Volume Reliability.

The initial simulations in Scenario 1 through Scenario 5 show that volume reliability for municipal rights have been maintained at 100% even though the DMI storage pool is reduced by 25% increments. Reliabilities for Class A and Class B rights show steep increases for each incremental percentage reduction of the DMI pool. However, the reliabilities are the same for Class A irrigation rights at 25% and empty DMI initial reserves, but Class B volume reliabilities for the Middle Rio Grande show very little increase. The detailed reliability results for each water right group for Scenario 3 through Scenario 5 are provided in Table 4.9 through Table 4.11 below.

Table 4.9. Reliabilities for Specific Water Rights Groups and Storages with DMI 50% of Total Storage Capacity

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++								PERCENTAGE OF YEARS -----					
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	47550.51	55.26	68.65	55.3	56.1	56.9	59.9	65.4	78.4	93.1	27.6	27.6	28.9	35.5	44.7	67.1
MID-B-IRR	13890.0	7689.94	29.06	44.64	29.1	29.7	30.2	33.4	39.8	53.0	84.0	10.5	10.5	10.5	10.5	13.2	31.6
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
LOW-A-IRR	1460999.4	474173.25	55.26	67.54	55.3	56.1	56.9	59.9	65.4	78.4	93.1	27.6	27.6	27.6	35.5	44.7	65.8
LOW-B-IRR	163305.0	92133.02	29.17	43.58	29.2	29.7	30.2	33.4	39.8	53.0	84.0	10.5	10.5	10.5	10.5	13.2	34.2
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMI	1350000.1	11.12	99.89	100.00	99.9	100.0	100.0	100.0	100.0	100.0	100.0	98.7	100.0	100.0	100.0	100.0	100.0
OP-RESERVE	900000.1	62707.01	82.13	93.03	82.1	84.2	86.0	90.0	94.6	96.5	98.1	21.1	40.8	60.5	75.0	93.4	100.0
Total	89345576.044598556.00		50.08														

Table 4.10. Reliabilities for Specific Water Rights Groups and Storages with DMI 25% of Total Storage Capacity

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++								PERCENTAGE OF YEARS -----					
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
MID-A-IRR	151688.0	46788.86	55.48	69.15	55.5	55.7	56.8	60.0	66.0	79.8	94.0	27.6	27.6	30.3	35.5	44.7	68.4
MID-B-IRR	13890.0	7658.18	28.95	44.87	28.9	29.9	30.4	33.7	40.2	52.9	85.3	10.5	10.5	10.5	14.5	14.5	34.2
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
LOW-A-IRR	1460999.4	466542.59	55.48	68.07	55.5	55.7	56.8	60.0	66.0	79.8	94.0	27.6	27.6	28.9	36.8	44.7	67.1
LOW-B-IRR	163305.0	91473.05	29.06	43.99	29.1	29.9	30.4	33.7	40.5	53.2	85.6	10.5	10.5	10.5	14.5	14.5	34.2
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMI	67500.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
OP-RESERVE	900000.1	62461.16	83.33	93.06	83.3	84.9	86.1	90.2	94.6	95.9	97.8	27.6	40.8	59.2	76.3	92.1	100.0
Total	87310824.044547240.00		48.98														

Table 4.11. Reliabilities for Specific Water Rights Groups and Storages with DMI 0% of Total Storage Capacity

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								PERCENTAGE OF YEARS					
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	46774.47	55.04	69.16	55.0	55.7	56.7	59.6	65.8	79.8	93.4	27.6	27.6	30.3	35.5	44.7	68.4
MID-B-IRR	13890.0	7652.55	28.95	44.91	28.9	29.8	30.4	33.4	40.4	52.6	85.5	10.5	10.5	10.5	10.5	14.5	34.2
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
LOW-A-IRR	1460999.4	466551.25	55.04	68.07	55.0	55.7	56.7	59.6	65.8	79.8	93.4	27.6	27.6	30.3	36.8	44.7	65.8
LOW-B-IRR	163305.0	91403.87	29.06	44.03	29.1	29.8	30.4	33.4	40.6	53.0	85.9	10.5	10.5	10.5	10.5	14.5	34.2
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMI	This water right has no diversion target.																
OP-RESERVE	900000.1	62047.20	83.22	93.11	83.2	84.5	86.0	90.2	95.0	96.2	98.0	25.0	38.2	57.9	76.3	94.7	100.0
Total	87222080.044543648.00		48.93														

Municipal reliabilities were at 100% even when completely depleting the DMI storage, and reliabilities for Class and Class B rights each improved by the fraction of reduction. Notice that Class B water rights have high reliabilities even though they are subject to curtailment or zero diversion during water shortage periods when the Amistad-Falcon Reservoir system does not contain enough storage to supply. Scenario 9 simulation results, shown below, demonstrate that. Scenarios 6 through 9 will examine impacts of the reduced OR storage on irrigation reliabilities and simulation results that consist of the following:

- Scenario 6: DMI = 0% of total (0 ac-ft/month); OR = 50% of total (37,500 ac-ft/month).
- Scenario 7: DMI = 0% of total (0 ac-ft/month); OR = 0% of total (0 ac-ft/month).
- Scenario 8: DMI = 0% of total (0 ac-ft/month); OR = 100% of total (75,000 ac-ft/month); Class B monthly diversions = 0 ac-ft/month.
- Scenario 9: DMI = 0% of total (0 ac-ft/month); OR = 0% of total (0 ac-ft/month); Class B monthly diversions = 0 ac-ft/month.

Table 12 shows that the reliabilities for Class A and Class B rights increase significantly in each scenario from a reduction of OP storage. However, in Scenario 2, the reliability of the municipal diversions for the Lower Rio Grande is 99.8%, which is unacceptable by the TCEQ since they must always be 100% regardless of reallocation or drought simulations. Completely cutting diversions for Class B rights impacted reliabilities of Class A rights at the cost of less than 100% reliability for Lower Rio Grande municipal diversions in Scenarios 7 and 9. Again, these hypothetical scenarios were simulated for research purposes; in reality, neither DMI nor OP storage reserves can be depleted to improve reliability diversions of irrigation rights.

Table 4.12. Summary of Reliabilities Based on Reduced DMI and OR Storage Reserves

Scenario	% of Total of DMI Reserve	% of Total of OR Reserve	Municipal		Class A Irrigation		Class B Irrigation	
			Middle R _v	Lower R _v	Middle R _v	Lower R _v	Middle R _v	Lower R _v
6	0	50	100	100	69.3	68.2	45.2	44.2
7	0	0	100	99.8	68.7	67.5	53.0	52.3
8	0	100	100	100	71.7	70.6	0.0	0.0
9	0	0	100	99.9	73.4	72.2	0.0	0.0

Notes: Reliabilities are given in percentages. R_v = Volume Reliability

The objective of this exercise is to demonstrate storage reallocations from the municipal pools of Amistad and Falcon Reservoirs to Class A and Class B irrigation rights. As mentioned earlier, the municipal pool contains an excess amount of conservation reserves that can be reallocated to irrigation rights in water shortage periods while maintaining 100 percent reliability. Based on the 1944 treaty, IBWC shall deduct 4,600 ac-ft for dead storage, 225,000 ac-ft for the municipal pool, and 75,000 ac-ft for OR to overcome losses due to reservoir surface evaporation. Then, the remaining storage is allocated to meet DMI followed by Class A and Class B irrigation and mining target diversions. Detailed reliabilities for these simulations are shown in Table 4.13 through Table 4.16.

Table 4.13. Reliabilities for Specific Water Rights Groups and Storages with DMI 0% and OR 50% of Total Storage Capacity

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS															
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	46500.03	55.37	69.34	55.4	56.1	57.6	60.4	66.2	78.9	94.2	27.6	27.6	34.2	36.8	44.7	44.7	68.4									
MID-B-IRR	13890.0	7613.20	29.28	45.19	29.3	30.2	30.5	33.8	40.5	53.5	86.3	10.5	10.5	10.5	10.5	14.5	14.5	34.2									
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.4	464258.59	55.37	68.22	55.4	56.1	57.5	60.3	66.2	78.9	94.2	27.6	27.6	31.6	36.8	44.7	44.7	67.1									
LOW-B-IRR	163305.0	91154.88	29.50	44.18	29.5	30.2	30.5	33.8	40.4	53.5	87.1	10.5	10.5	10.5	10.5	14.5	14.5	35.5									
DEAD	55200.0	344.63	99.23	99.38	99.2	99.2	99.2	99.2	99.3	99.3	99.3	100.0	90.8	90.8	92.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DMI	This water right has no diversion target.																										
OP-RESERVE	450000.1	39953.60	84.65	91.12	84.6	85.4	86.3	88.4	91.4	93.9	96.3	23.7	32.9	42.1	65.8	93.4	100.0										
Total	86687384.044506760.00																										
	48.66																										

Table 4.14. Reliabilities for Specific Water Rights Groups and Storages with DMI 0% and OR 0% of Total Storage Capacity

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS																
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
MID-A-IRR	151688.0	47414.70	52.08	68.74	52.1	53.2	54.4	58.3	65.1	79.9	95.7	23.7	25.0	27.6	31.6	44.7	44.7	67.1										
MID-B-IRR	13890.0	6524.14	34.87	53.03	34.9	35.9	36.5	39.0	49.3	64.0	92.4	13.2	13.2	13.2	14.5	23.7	51.3											
MUNILWR	240914.0	371.94	99.56	99.85	99.6	99.7	99.7	99.8	99.8	100.0	100.0	97.4	97.4	98.7	100.0	100.0												
LOW-A-IRR	1460999.4	474780.62	52.08	67.50	52.1	53.1	53.9	58.2	65.1	79.9	95.7	23.7	25.0	27.6	34.2	44.7	44.7	65.8										
LOW-B-IRR	163305.0	78104.09	34.98	52.17	35.0	35.9	36.5	39.0	49.9	65.1	94.1	13.2	13.2	13.2	14.5	23.7	50.0											
DEAD	55200.0	1549.68	96.49	97.19	96.5	96.5	96.6	96.8	97.0	97.3	99.3	69.7	69.7	72.4	93.4	100.0	100.0											
DMI	This water right has no diversion target.																											
OP-RESERVE	This water right has no diversion target.																											
Total	85728696.044605616.00																											
	47.97																											

Table 4.15. Reliabilities for Specific Water Rights Groups and Storages with DMI 0% and OR 100% of Total Storage Capacity and Complete Depletion of Class B Diversions

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++ -----							PERCENTAGE OF YEARS -----						
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	42904.66	59.54	71.72 59.5	60.0	61.0	63.2	69.5	80.2	94.4 35.5	36.8	38.2	40.8	47.4	71.1		
MID-B-IRR				This water right has no diversion target.													
MUNILWR	240914.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.4	429377.19	59.54	70.61 59.5	60.0	61.0	63.2	69.5	80.2	94.4 35.5	36.8	39.5	40.8	47.4	68.4		
LOW-B-IRR				This water right has no diversion target.													
DEAD	55200.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI				This water right has no diversion target.													
OP-RESERVE	900000.1	57130.49	84.10	93.65 84.1	86.0	87.4	90.9	94.7	96.8	98.2 30.3	43.4	60.5	76.3	96.1	100.0		
Total	108583616.044212052.00			59.28													

Table 4.16. Reliabilities for Specific Water Rights Groups and Storages with DMI 0% and OR 50% of Total Storage Capacity and Complete Depletion of Class B Diversions

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++ -----							PERCENTAGE OF YEARS -----						
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	40422.34	59.54	73.35 59.5	60.1	61.0	63.8	70.4	83.6	96.7 35.5	36.8	36.8	42.1	52.6	71.1		
MID-B-IRR				This water right has no diversion target.													
MUNILWR	240914.0	230.53	99.78	99.90 99.8	99.8	99.8	99.9	99.9	100.0	100.0 97.4	98.7	98.7	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.4	406088.47	59.43	72.20 59.4	59.9	60.9	63.6	70.3	83.6	96.6 35.5	36.8	38.2	42.1	51.3	68.4		
LOW-B-IRR				This water right has no diversion target.													
DEAD	55200.0	950.89	97.70	98.28 97.7	97.8	97.8	98.1	98.2	98.2	99.5 77.6	81.6	82.9	96.1	100.0	100.0		
DMI				This water right has no diversion target.													
OP-RESERVE				This water right has no diversion target.													
Total	94506224.044446724.00			52.97													

Improvement of irrigation reliabilities can also be simulated by equaling DMI reserves to zero and incrementally increasing irrigation diversions (demands) for Class A and Class B water rights in both the Middle and Lower Rio Grande. The following results in Table 4.16 show reliability improvements for irrigation rights by reallocating DMI reserve as it kept at zero storage. Figures 4.3 and 4.4 show the storage changes and exceedance frequency for each scenario in the simulations.

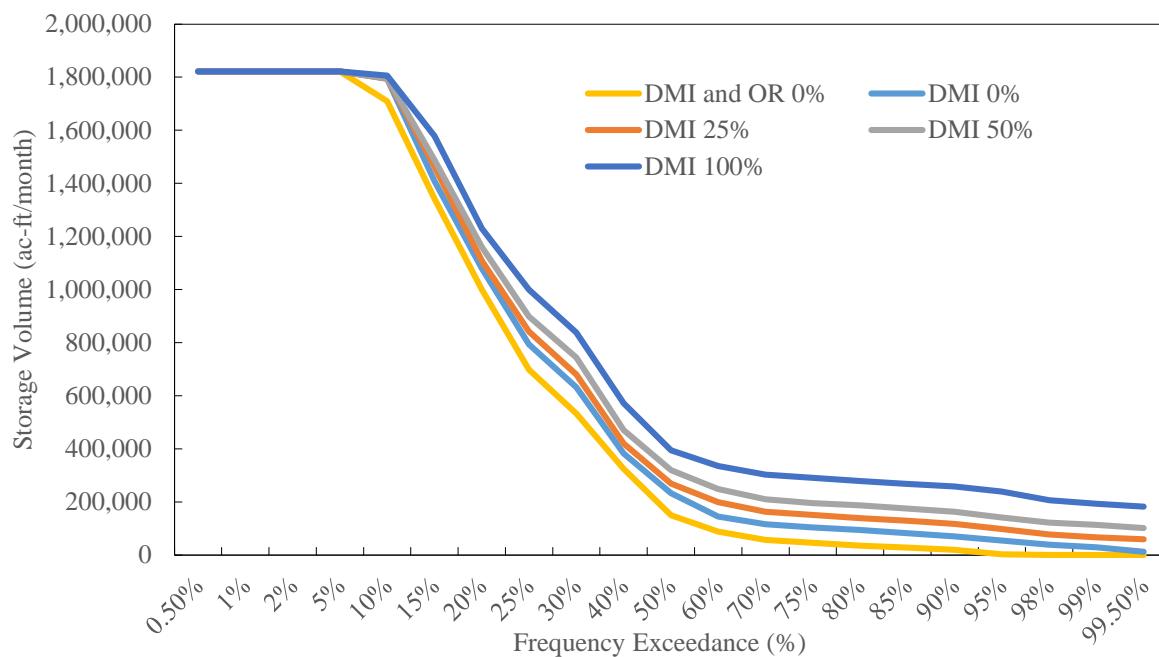


Figure 4.3. Frequency exceedance for various reallocation scenarios for TEXAMI Reservoir.

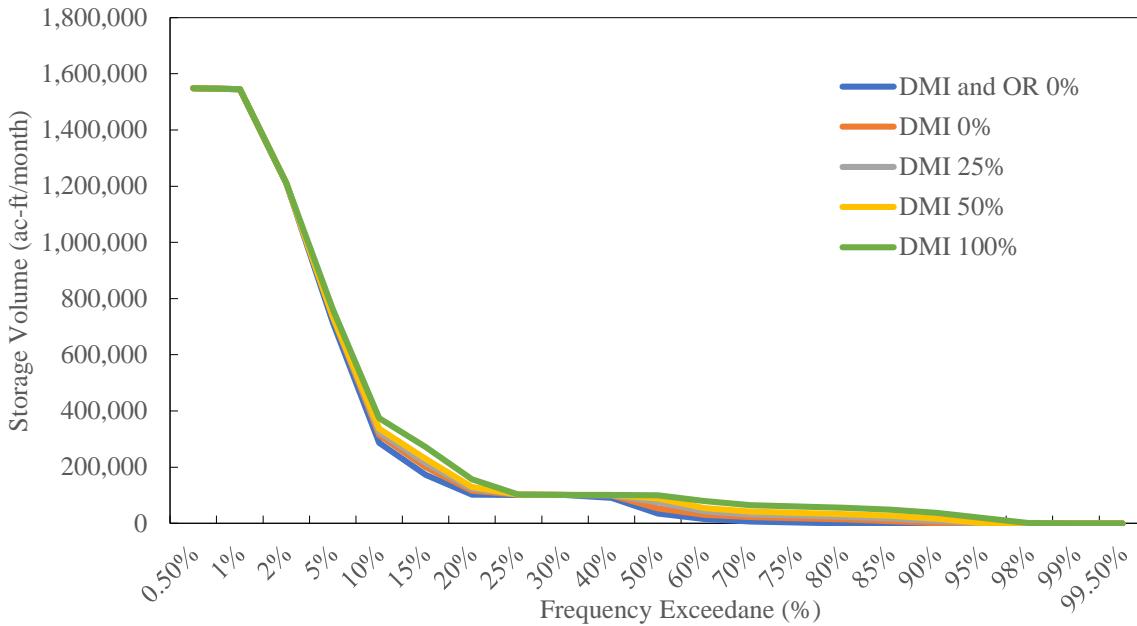


Figure 4.4. Frequency exceedance for various reallocation scenarios for TEXFAL Reservoir.

Drought Management

The water rights in the Rio Grande, along with storage allocations in the Amistad-Falcon Reservoir system, are clearly defined in the 1944 treaty. The IBWC owns and operates Amistad and Falcon Reservoirs along with several others on the Rio Grande. There is no known drought management plan on the Rio Grande because prioritization in water allocations coupled with water rights marketing result curtailment of Class B water rights fully and, if necessary, partial or full curtailment of Class A water rights. This type of water management based on a special water rights system during drought makes the Rio Grande one of the unique river basins in the world. The Class B water rights serve as an initial trigger during the drought because their curtailment frees up 187,078 ac-ft/year. Then, if necessary, some of the Class A water right diversions (1,617,234 ac-ft/year) will be cut depending on the volume needed to preserve municipal uses. Since there is no prioritization among Class A and Class B water right holders, the diversion amount will be distributed equally. Although irrigation diversions make

up 86% of the total demands on the Rio Grande, any water losses due to drought will be distributed to these A and B holders, and they will endure significant economic losses.

The objective discussed in this section was to simulate different hypothetical drought conditions using Class A and Class B water rights as trigger points and examine the changes in reliabilities. First, Class B water rights are completely cut off, and Class A water rights are reduced incrementally while maintaining 100% reliabilities for municipal diversions:

- Scenario 10: DMI = 100%; OR = 100%; Class B = 0%.
- Scenario 11: DMI = 100%; OR = 100%; Class B = 0%; and Class A reduced by 10%.
- Scenario 12: DMI = 100%; OR = 100%; Class B = 0%; and Class A reduced by 20%.
- Scenario 13: DMI = 100%; OR = 100%; Class B = 0%; and Class A reduced by 30%.
- Scenario 14: DMI = 100%; OR = 100%; Class B = 0%; and Class A reduced by 40%.
- Scenario 15: DMI = 100%; OR = 100%; Class B = 0%; and Class A reduced by 50%.

Results of reliability simulations are presented in Table 4.17. The DMI storage was kept at 100%, but diversions for Class B rights were complete cutoff as an initial trigger point during this hypothetical drought condition. Notice that volume reliabilities for Class A water rights increase significantly as the diversions are reduced by 10% of total annual diversions incrementally. As mentioned before, volume reliabilities can be improved significantly as diversion demands are lowered, which is the key concept in reliability analysis. Approximately 23% increase in volume reliabilities for both Middle and the Lower Rio Grande were achieved from 10% to 50% reduction in total Class A water diversions.

Table 4.17. Summary of Reliabilities Based on Reduced DMI Storage, Class A, and Class B Water Rights

Scenario	% of Total of DMI Reserve	% of Total of Class A	Municipal		Class A Irrigation		Class B Irrigation	
			Middle R _v	Lower R _v	Middle R _v	Lower R _v	Middle R _v	Lower R _v
10	100	100	100	100	70.7	69.6	0.0	0.0
11	100	10	100	100	77.3	76.3	0.0	0.0
12	100	20	100	100	84.0	83.2	0.0	0.0
13	100	30	100	100	90.0	89.5	0.0	0.0
14	100	40	100	100	95.1	94.8	0.0	0.0
15	100	50	100	100	98.7	98.6	0.0	0.0

Notes: Reliabilities are given in percentages. R_v = Volume Reliability

The previous simulation scenarios showed that the volume reliabilities for municipal rights had been maintained at 100% even with complete depletion of 225,000 ac-ft/month storage in the Amistad-Falcon Reservoir system. In this example, because of significant cutoff in irrigation diversions, a substantial amount of water is being accumulated in the DMI reserves. They also demonstrate that the Class A water rights that are being converted to municipal rights per free market transactions would impact the reliabilities of the rest of the Class A right holder very positively. For example, if 30% of farmers who possess Class A irrigation rights in the Lower Rio Grande sold their rights to cities, it would improve the volume reliabilities for the rest of the farmers with Class A water rights by 22% from 69.6% in Scenario 10 to 89.5% in Scenario 13 because there is no prioritization among Class A water rights. Thus, conversion of irrigation water rights to municipal rights is the key to alleviating the drought and improving the reliabilities of the rest of the farmers. The details of simulation results for Scenario 11 through Scenario 15 are provided in Table 4.18 through Table 4.23.

The reliability results show that availability reacts to changes in demand rather significantly, as Wurbs (2005) pointed out before: the smaller the diversions, the higher the reliabilities. In addition, this exercise addresses the question of what would be the reliability of farmers who have not been able to sell their water rights. The answer is that their reliability increases significantly due to reduced diversions and low demands. Irrigable lands with high

crop yields holding Class A water rights can benefit from these market transactions significantly.

Table 4.18. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 10

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS																
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	44420.22	58.99	70.72	59.0	59.9	60.7	62.4	67.3	79.2	92.9	34.2	35.5	38.2	40.8	48.7	68.4									
MID-B-IRR			This water right has no diversion target.																							
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.4	443515.94	58.99	69.64	59.0	59.9	60.7	62.4	67.3	79.2	92.9	34.2	35.5	38.2	40.8	47.4	68.4									
LOW-B-IRR			This water right has no diversion target.																							
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	66793.61	82.46	92.58	82.5	84.1	85.7	89.5	93.4	96.3	98.2	25.0	42.1	57.9	73.7	93.4	100.0									
Total		112336528.044352264.00																								

Table 4.19. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 11

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS																
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	136519.0	31022.40	67.00	77.28	67.0	67.8	68.6	70.2	75.4	84.0	97.9	47.4	48.7	51.3	59.2	68.3										
MID-B-IRR			This water right has no diversion target.																							
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1314898.5	311086.91	67.00	76.34	67.0	67.8	68.6	70.2	75.4	84.0	97.9	47.4	48.7	50.0	59.2	72.4										
LOW-B-IRR			This water right has no diversion target.																							
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	0.01	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	64659.80	84.43	92.82	84.4	85.4	87.1	89.9	93.5	96.1	97.9	38.2	48.7	61.8	71.1	94.7	98.7									
Total		124620600.044118524.00																								

Table 4.20. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 12

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS					PERCENTAGE OF YEARS																	
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT					(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	121350.0	19530.11	75.55	83.91 75.5	76.3	76.6	78.4	81.8	89.8	98.8	59.2	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	72.4	84.2				
MID-B-IRR				This water right has no diversion target.																						
MUNILWR	240914.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1168799.2	196000.56	75.55	83.23 75.5	76.3	76.6	78.4	81.8	89.8	98.8	59.2	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	72.4	82.9				
LOW-B-IRR				This water right has no diversion target.																						
DEAD	552000.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	0.02	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	60110.59	84.54	93.32 84.5	85.5	87.5	91.4	94.1	96.2	97.9	39.5	51.3	67.1	76.3	92.1	100.0										
Total		139895296.043563268.00			68.86																					

Table 4.21. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 13

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS					PERCENTAGE OF YEARS																	
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT					(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	106181.0	10669.05	83.77	89.95 83.8	83.9	84.4	85.9	89.0	95.0	99.9	71.1	72.4	72.4	75.0	80.3	94.7										
MID-B-IRR				This water right has no diversion target.																						
MUNILWR	240914.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1022699.2	107286.68	83.77	89.51 83.8	83.9	84.4	85.9	89.0	95.0	99.9	71.1	72.4	72.4	72.4	80.3	90.8										
LOW-B-IRR				This water right has no diversion target.																						
DEAD	552000.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	0.04	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	56976.74	85.64	93.67 85.6	86.6	88.2	90.9	94.3	96.7	98.2	44.7	56.6	72.4	81.6	92.1	98.7										
Total		157674560.043034404.00			72.71																					

Table 4.22. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 14

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN DIVERSION (AC-FT/YR)	SHORTAGE (%)	PERIOD VOLUME (%)	*RELIABILITY* +++++++ PERCENTAGE OF MONTHS +++++++ ----- PERCENTAGE OF YEARS -----											
					100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	61008.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
MID-A-IRR	91013.0	4455.30	91.23	95.10 91.2 91.7 92.1 92.8 94.6 98.0 100.0 85.5 85.5 86.8 86.8 88.2 98.7												
MID-B-IRR				This water right has no diversion target.												
MUNILWR	240914.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
LOW-A-IRR	876599.8	45564.81	91.23	94.80 91.2 91.7 92.1 92.8 94.6 98.0 100.0 85.5 85.5 86.8 86.8 88.2 97.4												
LOW-B-IRR				This water right has no diversion target.												
DEAD	552000.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
DMI	2700000.2	0.06	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
OP-RESERVE	900000.1	37317.89	89.04	95.85 89.0 89.5 90.9 94.3 96.6 98.2 98.8 57.9 68.4 76.3 85.5 97.4 98.7												
Total				178116000.042131328.00												
				76.35												

Table 4.23. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 15

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN DIVERSION (AC-FT/YR)	SHORTAGE (%)	PERIOD VOLUME (%)	*RELIABILITY* +++++++ PERCENTAGE OF MONTHS +++++++ ----- PERCENTAGE OF YEARS -----											
					100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	61008.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
MID-A-IRR	75844.0	969.46	97.59	98.72 97.6 97.7 97.8 98.1 98.6 99.3 100.0 96.1 96.1 96.1 96.1 96.1 100.0												
MID-B-IRR				This water right has no diversion target.												
MUNILWR	240914.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
LOW-A-IRR	730499.9	10126.70	97.59	98.61 97.6 97.7 97.8 98.1 98.6 99.3 100.0 96.1 96.1 96.1 96.1 96.1 100.0												
LOW-B-IRR				This water right has no diversion target.												
DEAD	552000.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
DMI	2700000.2	0.10	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0												
OP-RESERVE	900000.1	21526.75	93.09	97.61 93.1 94.1 94.7 96.7 98.2 98.9 99.6 69.7 82.9 85.5 88.2 100.0 100.0												
Total				196604928.041126088.00												
				79.08												

Reallocation of Municipal Pool to Class A and Class B Irrigation Pools Under Conservative Storage

Griffin (2002) estimated that the DMI pool has grown approximately 350,000 ac-ft/month due to Class A and Class B water right purchases. In the following exercises, the DMI pool is established at 4,200,000 ac-ft/year ($350,000 \times 12$), and storage will be diverted to irrigation rights with the aim of improving reliabilities and supplying water during shortages. The objective is to see how much of the water can temporarily be allocated to the irrigation pool and determine if it is a worth a trade-off.

The following scenarios show the temporary reallocation of the DMI pool to Class A and Class B rights under a conservatively estimated DMI pool account. These hypothetical scenarios are meant to specifically determine if such reallocation is possible or worth doing in order to save irrigation infrastructures as well as help farmers during water shortages to save crops. It can be based on a temporary leasing during which farmers will pay the same amount per ac-ft volume as the price of irrigation rights. If these scenarios create improved reliability while keeping municipal rights at 100% reliability level, then the advantages are self-evident.

- Scenario 16: DMI = 100% of total (320,000 ac-ft/month); OR = 100%.
- Scenario 17: DMI = 100% of total (320,000 ac-ft/month); OR = 100%; Class B monthly diversions = 0 ac-ft/month.
- Scenario 18: DMI = 50% of total (160,000 ac-ft/month); OR = 100%; Class B monthly diversions = 0 ac-ft/month.
- Scenario 19: DMI = 25% of total (80,000 ac-ft/month); OR = 100%; Class B monthly diversions = 0 ac-ft/month.
- Scenario 20: DMI = 0% of total (0 ac-ft/month); OR = 100%; Class B monthly diversions = 0 ac-ft/month.
- Scenario 21: DMI = 0% of total (0 ac-ft/month); OR = 50%; Class B monthly diversions = 0 ac-ft/month.
- Scenario 22: DMI = 0% of total (0 ac-ft/month); OR = 0%; Class B monthly diversions = 0 ac-ft/month.

Table 4.24. summarizes the simulation results for Scenarios 16 through 22 in which water is reallocated from the improved DMI storage (350,000 ac-ft/year) to Class A irrigation

diversions and changes in reliabilities are examined. Notice slight improvements in reliabilities for the Lower Rio Grande Class A irrigation rights with the new DMI storage compared to the reliabilities with conventional DMI storage (225,000 ac-ft/year) that were presented previously. In fact, increased DMI storage, if temporarily reallocated, does provide better reliabilities for Class A water rights during short drought periods and the curtailment of Class B rights. However, regardless of simulation runs, municipal diversions must maintain 100% reliabilities all the time, which is unacceptable in Scenario 22. The simulation results show that reallocations of the DMI pool to Class A irrigation diversions during drought to meet full demands would not be a better trade-off. However, some of the irrigation demands can still be met while draining the DMI pool during extreme shortages. The details of simulation results for each scenario are provided in Table 4.25 through Table 4.31.

Table 4.24. Summary of Reliabilities Based on Reduced DMI Storage, OR, and Class B Water Rights

Scenario	% of Total of DMI Reserve	% of Total of OR Reserve	Municipal		Class A Irrigation		Class B Irrigation	
			Middle R_v	Lower R_v	Middle R_v	Lower R_v	Middle R_v	Lower R_v
16	100	100	100	100	67.6	66.5	43.8	42.8
17	100	100	100	100	70.9	69.8	0.0	0.0
18	50	100	100	100	71.3	70.3	0.0	0.0
19	25	100	100	100	71.8	70.7	0.0	0.0
20	0	100	100	100	72.2	71.1	0.0	0.0
21	0	50	100	100	72.3	71.4	0.0	0.0
22	0	0	100	90.9	73.7	72.5	0.0	0.0

Notes: Reliabilities are given in percentages. R_v = Volume Reliability

As per the 1944 treaty, OR reserves must be subtracted from the IBWC accounting system at 75,000 ac-ft/month, which is primarily designated for evaporation losses from the Amistad-Falcon Reservoir system. Notice that changes in OR storage are linearly correlated to

changes in DMI storage. For example, in Scenario 16, the losses in the OR pool were 74,910 ac-ft/year, but as the DMI pool is reduced, the losses in the OR pool reduced to 55,516 ac-ft/year in Scenario 20. About 26% of reduction due to evaporation losses in the OR pool during water reallocations from DMI to Class A diversions shows that it is a feasible trade-off. Otherwise, that volume would have been lost.

Table 4.25. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 16

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING							PERCENTAGE OF YEARS						
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	49136.81	53.73	67.61	53.7	54.9	55.8	58.6	63.9	77.7	92.4	25.0	25.0	25.0	35.5	43.4	67.1
MID-B-IRR	13890.0	7801.59	28.51	43.83	28.5	29.3	30.0	32.8	39.3	50.9	83.7	10.5	10.5	10.5	10.5	13.2	31.6
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	488842.84	53.73	66.54	53.7	54.9	55.8	58.6	63.9	77.7	92.4	25.0	25.0	26.3	35.5	43.4	65.8
LOW-B-IRR	163305.0	93493.55	28.51	42.75	28.5	29.3	30.0	32.8	39.3	50.9	83.7	10.5	10.5	10.5	10.5	13.2	31.6
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	4200000.5	796.82	99.12	99.98	99.1	100.0	100.0	100.0	100.0	100.0	94.7	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	74910.44	82.13	91.68	82.1	83.0	84.4	87.9	92.8	95.4	97.6	23.7	36.8	57.9	68.4	92.1	98.7
Total		93816912.044713280.00										52.34					

Table 4.26. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 17

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS								
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT														
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	44177.95	59.21	70.88 59.2	60.1	60.7	62.7	67.7	79.1	93.4	34.2	34.2	36.8	40.8	50.0	68.4		
MID-B-IRR				This water right has no diversion target.														
MUNILWR	240914.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	441019.34	59.21	69.81 59.2	60.1	60.7	62.7	67.7	79.1	93.4	34.2	34.2	36.8	40.8	48.7	68.4		
LOW-B-IRR				This water right has no diversion target.														
DEAD	55200.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	4200000.5	0.01	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	67086.36	83.11	92.55 83.1	84.8	86.2	89.7	93.0	96.2	98.1	26.3	43.4	56.6	73.7	94.7	98.7		
Total	114674904.044386772.00			61.29														

Table 4.27. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 18

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS								
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT														
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	
MUNIMID	61008.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	43485.75	59.76	71.33 59.8	60.6	61.2	63.2	68.4	79.3	93.1	35.5	36.8	38.2	40.8	50.0	68.4		
LOW-B-IRR				This water right has no diversion target.														
MUNILWR	240914.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	434665.91	59.76	70.25 59.8	60.6	61.2	63.2	68.4	79.3	93.1	35.5	36.8	38.2	40.8	48.7	68.4		
DEAD	55200.0	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2100000.2	0.00	100.00	100.00 100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	65589.82	82.24	92.71 82.2	84.3	86.0	89.6	93.4	96.6	98.4	25.0	46.1	56.6	73.7	92.1	100.0		
Total	112413272.044304292.00			60.59														

Table 4.28. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 19

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS												
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	42765.30	59.87	71.81	59.9	60.3	61.0	63.5	68.1	80.5	94.2	38.2	39.5	39.5	40.8	50.0	68.4					
MID-B-IRR																						
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	428223.56	59.87	70.69	59.9	60.3	61.0	63.5	68.1	80.5	94.2	38.2	38.2	40.8	40.8	48.7	68.4					
LOW-B-IRR																						
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	1050000.1	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
OP-RESERVE	900000.1	64567.78	83.33	92.83	83.3	84.9	86.0	89.9	93.9	95.9	98.4	26.3	46.1	61.8	71.1	94.7	100.0					
Total		111109576.044248960.00			60.18																	

Table 4.29. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 20

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS						PERCENTAGE OF YEARS												
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%
MUNIMID	61008.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	42155.70	59.87	72.21	59.9	60.0	60.6	63.3	70.0	81.4	94.7	36.8	38.2	39.5	40.8	51.3	71.1					
MID-B-IRR																						
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	422222.12	59.87	71.10	59.9	60.0	60.6	63.3	70.0	81.4	94.7	36.8	38.2	40.8	40.8	50.0	68.4					
LOW-B-IRR																						
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI																						
OP-RESERVE	900000.1	55516.83	84.10	93.83	84.1	86.2	87.4	91.6	95.1	97.1	98.2	31.6	51.3	60.5	76.3	96.1	100.0					
Total		109411544.044186844.00			59.61																	

Table 4.30. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 21

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++							PERCENTAGE OF YEARS -----							
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%		
MUNIMID	61008.0	0.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	41775.11	59.98	72.46	60.0	60.5	61.6	63.8	69.8	80.9	93.9	35.5	38.2	39.5	40.8	51.3	69.7	
MID-B-IRR			This water right has no diversion target.															
MUNILWR	240914.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	417942.88	59.98	71.39	60.0	60.5	61.6	63.8	69.8	80.9	93.9	35.5	38.2	39.5	40.8	50.0	68.4	
LOW-B-IRR			This water right has no diversion target.															
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI			This water right has no diversion target.															
OP-RESERVE	450000.1	38038.26	85.09	91.55	85.1	86.3	86.8	88.9	92.2	94.4	96.1	27.6	36.8	48.7	63.2	92.1	100.0	
Total		107587560.044165200.00		58.95														

Table 4.31. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 22

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS +++++++							PERCENTAGE OF YEARS -----							
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%		
MUNIMID	61008.0	0.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	39963.41	59.76	73.65	59.8	60.3	61.4	64.1	70.3	83.9	96.7	35.5	36.8	38.2	42.1	53.9	72.4	
MID-B-IRR			This water right has no diversion target.															
MUNILWR	240914.0	230.46	99.78	99.90	99.8	99.8	99.9	99.9	100.0	100.0	97.4	98.7	98.7	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	401815.31	59.54	72.50	59.5	60.1	61.2	64.0	70.2	83.9	96.7	35.5	36.8	38.2	42.1	52.6	69.7	
LOW-B-IRR			This water right has no diversion target.															
DEAD	55200.0	925.22	97.81	98.32	97.8	97.9	98.0	98.2	98.2	98.2	99.3	78.9	82.9	82.9	96.1	100.0	100.0	
DMI			This water right has no diversion target.															
OP-RESERVE			This water right has no diversion target.															
Total		95041536.044432984.00		53.25														

Evaluation of Future Municipal Demand

As part of Senate Bill 1 (SB1), which was enacted in 1997 by the 75th Legislature, the TWDB was charged with preparing a comprehensive and flexible long-term plan for the development, conservation, and management of the state's water resources. SB1 established a "bottom up" approach whereby state water plans are based on regional water plans prepared and adopted by the 16 appointed Regional Water Planning Groups (RWPG). The Rio Grande Reginal Water Planning Area (Region M) consists of the eight counties along the Middle and the Lower Rio Grande nearest the river's mouth at the Gulf of Mexico (RGRWP 2016). The population of the region is expected to grow to over 4 million people by the end of the current planning horizon, which represents a 106% population increase from 2020 to 2070 (RGRWP 2016). Increased demand for municipal water diversions puts greater pressure on irrigation uses since it dominates the region with 86% of total annual diversions. As part of water planning, the Region M group uses Rio Grande WAM and WRAP modeling programs to develop firm yield and reliabilities for irrigation uses in the Amistad-Falcon Reservoir system. However, the group has been using the Rio Grande WAM covering the 1940–2000 hydrologic period of analysis because the updated WAM datasets were not developed until this research. The extended WAM covering the 1940–2015 hydrologic period of analysis in this research also covers the 2001 drought, which was considered one of the worst drought periods in the Rio Grande.

The objective addressed in this section was to address future reliabilities for municipal and irrigation diversions while incorporating projected municipal demands for 2020, 2030, 2040, 2050, 2060, and 2070, given in Table 4.32, from the 2016 Rio Grande Regional Water Plan.

Table 4.32. Projected Municipal Demand for the Rio Grande, Combining 2016 Rio Grande Regional Water Plan and Rio Grande WAM

Basin Segment	Water Right	Rio Grande WAM	2020	2030	2040	2050	2060	2070
MIDDLE	Municipal	61,008	71,281	72,546	73,760	75,093	76,438	77,746
	Class A*	156,226	156,226	156,226	156,226	156,226	156,226	156,226
	Class B	19,928	0	0	0	0	0	0
LOWER	Municipal	240,914	542,232	598,373	655,773	715,278	776,314	836,303
	Class A**	1,461,009	1,461,009	876,605	613,624	490,899	392,719	78,544
	Class B	167,150	0	0	0	0	0	0
TOTAL	Municipal	301,922	613,513	670,919	729,533	790,371	852,752	914,049

*Full 100% diversions kept for each decade of projections as it met municipal reliabilities.

**Incrementally reduced each decade to meet projected municipal demands.

Class A water rights are not reduced for the Middle Rio Grande; it met the projected municipal demand for each decade covering 2020 through 2070 based on the 2016 Rio Grande Regional Water Plan. However, in the following scenarios, Class A water rights are incrementally reduced for the Lower Rio Grande to meet the projected municipal demands after all Class B water rights are completely cutoff. The following scenarios will attempt to accomplish these objectives:

- Scenario 23: 2020 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 100%; Class B monthly diversion = 100%.
- Scenario 24: 2020 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 100%; Class B monthly diversion = 0%.
- Scenario 25: 2030 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 40%; Class B monthly diversion = 0%.

- Scenario 26: 2040 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 30%; Class B monthly diversion = 0%.
- Scenario 27: 2050 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 20%; Class B monthly diversion = 0%.
- Scenario 28: 2060 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 100%; Class B monthly diversion = 0%.
- Scenario 29: 2070 Municipal demands incorporated; DMI = 100% of total 225,000 ac-ft/month; OR = 100% of total 75,000 ac-ft/month; Class A monthly diversion = 80%; Class B monthly diversion = 0%.

Simulation results for each scenario from 23 through 29 are summarized in Table 4.33. The reliability analysis in this section focuses on the Lower Rio Grande since there are no shortages to meeting future municipal demands on the Middle Rio Grande. This difference is characterized by the rapid projected population growth in the seven counties in the Lower Rio Valley that force the region to secure water for future municipal use. Only Maverick County, which is located in the Middle Rio Grande, will have some increase in municipal demand, but curtailing the Class B water rights of 19,928 ac-ft/year met the projected municipal demands of 16,738 ac-ft/year by 2070. Table 4.34 summarizes the projected municipal demand for Rio Grande by counties.

As shown in Scenario 23 (Table 4.33), current DMI storage of 225,000 ac-ft/month is not going to be enough to supply 542,232 ac-ft/month in the Lower Rio Grande by 2020 while maintaining low volume reliabilities of 50.3%—down from the original volume reliability of 68.2% (Table 4.12) for Class A water diversions. The only alternative resolution for this problem is to convert all Class B water rights to municipal rights by 2020. Scenario 23 shows improved volume reliability of 53% for Class A diversions and 100% reliability for municipal rights by 2020. However, the pace of free marketing should be expedited in the next five years to convert all Class B water rights in the Lower Rio Grande to municipal rights. In Scenarios 25 through 29, Class A diversions are curtailed in various percentage fractions incrementally for each decade to meet the projected municipal demands. For example, by 2040 the current

Class A diversions of 1,461,099 ac-ft/year for the Lower Rio Grande should be reduced by 40%, or 876,605 ac-ft/year, to meet the municipal demands of 598,373 ac-ft/year. Similar results can be observed for the rest of the decades in Table 4.33. As mentioned earlier, reduction in water demands significantly improves volume reliabilities. For example, volume reliability for Class A diversions in 2020 is 53%, but the expected volume reliability by 2070 is shown to be 97.2%, as annual diversions cut significantly from current 1,461,099 ac-ft/year down to 78,544 ac-ft/year. These simulation results can be used for future water planning purposes by TWDB, the Rio Grande Regional Water Planning Group, and TCEQ. The details for each simulation scenarios are provided in Table 4.35 through Table 4.41.

Table 4.33. Summary of Reliabilities Based on Reduced DMI Storage, OR, and Class B Water Rights (ac-ft/year)

Scenario	Projected Municipal Demands	% of Total Reduced Class A Rights	Municipal		Class A Irrigation		Class B Irrigation	
			Middle R_v	Lower R_v	Middle R_v	Lower R_v	Middle R_v	Lower R_v
23	2020	100	100	99.9	51.4	50.3	34.3	33.5
24	2020	100	100	100	54.0	53	0.0	0.0
25	2030	40	100	100	74.3	73.5	0.0	0.0
26	2040	30	100	100	83.6	83.0	0.0	0.0
27	2050	20	100	100	85.2	85.1	0.0	0.0
28	2060	20	100	100	86.2	86.0	0.0	0.0
29	2070	80	100	100	97.2	97.2	0.0	0.0

Notes: Reliabilities are given in percentages. R_v = Volume Reliability

The Middle Rio Grande includes Val Verde, Kinney, Maverick, Dimmit, and Webb Counties. Current annual municipal diversions in the Rio Grande WAM are 61,008 ac-ft/year. The Lower Rio Grande includes Zapata, Starr, Jim Hogg, Hidalgo, Cameron, and Willacy Counties. Current annual municipal diversions in the Rio Grande WAM are 240,914 ac-ft/year.

Table 4.34. Projected Municipal Demand for the Rio Grande by County

County	2020	2030	2040	2050	2060	2070
Cameron	81,393	92,861	104,873	118,438	132,937	147,932
Hidalgo	158,629	192,687	227,640	263,440	300,014	335,816
Jim Hogg	692	720	746	787	829	871
Maverick	10,273	11,538	12,752	14,085	15,430	16,738
Starr	10,597	11,631	12,620	13,694	14,732	15,689
Webb	43,754	52,567	61,171	69,260	77,161	84,343
Willacy	3,257	3,557	3,871	4,235	4,610	4,982
Zapata	2,996	3,436	3,938	4,509	5,117	5,756
Total	311,591	368,997	427,611	488,448	550,830	612,127

Source: RGRWP 2016

The total annual losses in the OR reserves reduced from 181,226 ac-ft/year (Table 4.35) to 159,802 ac-ft/year (Table 3.41), or about 12%, as DMI reserve was filled in with more allocations.

Table 4.35. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 23

NAME	TARGET (AC-FT/YR)	MEAN (AC-FT/YR)	*RELIABILITY* (%)	PERCENTAGE OF MONTHS										PERCENTAGE OF YEARS							
				WITH DIVERSIONS EQUALING OR EXCEEDING					PERCENTAGE OF TARGET DIVERSION AMOUNT												
				100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%	50%	100%	98%	95%	90%	
MUNIMID	71282.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
MID-A-IRR	151688.0	73761.27	41.34	51.37	41.3	41.8	42.4	44.5	49.0	57.2	74.5	13.2	15.8	15.8	17.1	22.4	48.7				
MID-B-IRR	13890.0	9118.09	23.57	34.36	23.6	24.3	25.0	27.0	31.6	39.6	65.4	5.3	5.3	6.6	7.9	10.5	21.1				
MUNILWR	542232.0	285.18	99.78	99.95	99.8	99.8	99.9	99.9	100.0	100.0	100.0	98.7	98.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	726077.50	41.34	50.30	41.3	41.8	42.4	44.5	49.0	57.2	74.5	13.2	15.8	15.8	17.1	23.7	46.1				
LOW-B-IRR	163305.0	108584.37	23.90	33.51	23.9	24.3	25.0	27.0	31.6	39.6	65.4	5.3	5.3	6.6	7.9	10.5	22.4				
DEAD	55200.0	114.11	99.78	99.79	99.8	99.8	99.8	99.8	99.8	99.8	100.0	98.7	98.7	98.7	98.7	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	42901.91	93.86	98.41	93.9	95.3	96.1	98.0	98.9	99.3	99.8	76.3	88.2	92.1	97.4	98.7	98.7				
OP-RESERVE	900000.1	181226.62	62.39	79.86	62.4	64.6	67.5	73.5	81.8	87.1	90.6	6.6	14.5	19.7	28.9	73.7	92.1				
Total		81626736.045202168.00		44.62																	

Table 4.36. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 24

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS															
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	71281.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	69830.27	43.97	53.96	44.0	44.5	45.0	46.7	51.8	60.9	76.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	30.3	51.3						
MID-B-IRR				This water right has no diversion target.																							
MUNILWR	542232.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	1460999.8	687582.19	43.97	52.94	44.0	44.5	45.0	46.7	51.8	60.9	76.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	28.9	48.7						
LOW-B-IRR				This water right has no diversion target.																							
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	23507.64	98.36	99.13	98.4	98.6	98.6	98.9	99.1	99.5	100.0	94.7	97.4	97.4	97.4	97.4	97.4	97.4	97.4	98.7	98.7						
OP-RESERVE	900000.1	155066.44	64.47	82.77	64.5	67.5	69.7	76.3	85.0	89.6	93.1	9.2	15.8	18.4	30.3	77.6	98.7										
Total	94680256.044849764.00		52.63																								

Table 4.37. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 25

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS															
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	72546.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	39033.37	67.54	74.27	67.5	67.8	68.1	69.7	72.5	78.4	93.6	50.0	50.0	51.3	53.9	60.5	73.7										
MID-B-IRR				This water right has no diversion target.																							
MUNILWR	598372.4	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	876599.8	232316.84	67.54	73.50	67.5	67.8	68.1	69.7	72.5	78.4	93.6	50.0	50.0	51.3	53.9	59.2	73.7										
LOW-B-IRR				This water right has no diversion target.																							
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	23691.10	98.03	99.12	98.0	98.4	98.6	98.8	99.1	99.5	100.0	92.1	97.4	97.4	97.4	97.4	97.4	97.4	97.4	98.7	100.0						
OP-RESERVE	900000.1	173319.27	62.83	80.74	62.8	65.6	68.4	74.7	82.6	87.8	91.8	17.1	23.7	30.3	38.2	63.2	97.4										
Total	123829312.044186488.00		64.32																								

Table 4.38. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 26

NAME	TARGET (AC-FT/YR)	MEAN (AC-FT/YR)	SHORTAGE (%)	PERIOD VOLUME 100% 95% 90% 75% 50% 25% 1%	*RELIABILITY* +++++++ PERCENTAGE OF MONTHS +++++++ ----- PERCENTAGE OF YEARS -----									
					100%	95%	90%	75%	50%	25%	1%	100%	98%	95%
MUNIMID	73760.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
MID-A-IRR	151688.0	24892.58	79.61	83.59 79.6 79.8 79.9 80.9 83.0 86.0 94.0 68.4 69.7 69.7 71.1 77.6 82.9										
MID-B-IRR				This water right has no diversion target.										
MUNILWR	655772.4	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
LOW-A-IRR	613620.0	104091.96	79.61	83.04 79.6 79.8 79.9 80.9 83.0 86.0 94.0 68.4 69.7 69.7 71.1 76.3 81.6										
LOW-B-IRR				This water right has no diversion target.										
DEAD	55200.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
DMI	2700000.2	19810.82	97.48	99.27 97.5 97.6 98.1 98.9 99.3 100.0 100.0 88.2 94.7 97.4 97.4 98.7 100.0										
OP-RESERVE	900000.1	193786.55	61.40	78.47 61.4 63.0 65.4 72.4 79.2 85.5 90.9 25.0 26.3 34.2 38.2 60.5 86.8										
Total	146144016.043487380.00			70.24										

Table 4.39. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 27

NAME	TARGET (AC-FT/YR)	MEAN (AC-FT/YR)	SHORTAGE (%)	PERIOD VOLUME 100% 95% 90% 75% 50% 25% 1%	*RELIABILITY* +++++++ PERCENTAGE OF MONTHS +++++++ ----- PERCENTAGE OF YEARS -----									
					100%	95%	90%	75%	50%	25%	1%	100%	98%	95%
MUNIMID	75093.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
MID-A-IRR	151688.0	21959.37	83.11	85.52 83.1 83.2 83.8 84.9 86.8 93.5 76.3 76.3 76.3 76.3 78.9 84.2										
MID-B-IRR				This water right has no diversion target.										
MUNILWR	715278.8	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
LOW-A-IRR	490896.0	72931.06	83.11	85.14 83.1 83.2 83.8 84.9 86.8 93.5 76.3 76.3 76.3 76.3 77.6 84.2										
LOW-B-IRR				This water right has no diversion target.										
DEAD	55200.0	0.00	100.00	100.00 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0										
DMI	2700000.2	10688.95	97.81	99.60 97.8 98.5 98.8 99.3 99.9 100.0 100.0 90.8 94.7 98.7 98.7 100.0 100.0										
OP-RESERVE	900000.1	211692.44	60.42	76.48 60.4 61.8 63.6 69.0 77.4 83.9 89.5 25.0 27.6 32.9 36.8 57.9 86.8										
Total	154939040.043246548.00			72.09										

Table 4.40. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 28

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS															
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	76438.0	0.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
MID-A-IRR	151688.0	20951.92	83.99	86.19	84.0	84.1	84.2	84.5	85.7	87.9	91.0	77.6	77.6	77.6	78.9	81.6	84.2										
MID-B-IRR																											
MUNILWR	776315.7	0.01	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
LOW-A-IRR	392716.6	55430.68	83.99	85.89	84.0	84.1	84.2	84.5	85.7	87.9	91.0	77.6	77.6	77.6	78.9	81.6	84.2										
LOW-B-IRR																											
DEAD	55200.0	20.26	99.89	99.96	99.9	99.9	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.7	98.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
DMI	2700000.2	63413.76	93.31	97.65	93.3	93.6	94.3	96.5	98.1	99.3	99.9	86.8	89.5	92.1	92.1	96.1	100.0										
OP-RESERVE	900000.1	245745.23	59.43	72.69	59.4	60.7	61.7	65.0	73.5	79.9	85.0	26.3	27.6	32.9	36.8	55.3	81.6										
Total		160215328.043118772.00				73.09																					

Table 4.41. Reliabilities for Specific Water Rights Groups and Storages Performed under Scenario 29

NAME	TARGET	MEAN	*RELIABILITY*	PERCENTAGE OF MONTHS								PERCENTAGE OF YEARS															
	DIVERSION	SHORTAGE	PERIOD VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT								(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	1%	100%	98%	95%	90%	75%
MUNIMID	77746.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
MID-A-IRR	151688.0	4199.39	96.71	97.23	96.7	96.7	96.7	96.7	96.9	97.0	97.6	98.1	94.7	94.7	94.7	94.7	96.1	96.1	97.4								
MID-B-IRR																											
MUNILWR	836303.8	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
LOW-A-IRR	78543.0	2217.86	96.71	97.18	96.7	96.7	96.7	96.7	96.9	97.0	97.6	98.1	94.7	94.7	94.7	94.7	96.1	96.1	97.4								
LOW-B-IRR																											
DEAD	55200.0	0.00	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
DMI	2700000.2	16571.45	98.46	99.39	98.5	98.6	98.8	98.9	99.3	99.9	100.0	97.4	97.4	97.4	97.4	98.7	100.0										
OP-RESERVE	900000.1	159801.69	72.37	82.24	72.4	73.1	74.2	77.4	82.8	87.0	91.3	52.6	53.9	56.6	56.6	67.1	86.8										
Total		195058736.041421056.00				78.76																					

Firm Yield Analysis

Firm yield is defined as the maximum amount of water that can be supplied continuously with period and volume reliability of 100% (Wurbs, 1995). Most reservoir storages that are designed for municipal and industrial water supply are based on supplying the firm yield during the most critical drought of record (USACE 1997). Wurbs (1993) computed yield versus reliability relationships and firm yields for alternative reservoir operating plans based on the 85-year sequence of monthly streamflows and reservoir evaporation rates in the Brazos River Basin. Period reliability was represented in that case study as the percentage of the months during the 85-year simulation period for which a specified firm yield level could be met without a shortage. Firm yield and lesser yields have period and volume reliabilities of 100%. Yields greater than firm yield has reliabilities less than 100%. Wurbs' case study demonstrated the increases in firm yield that can be potentially achieved by a multireservoir system operation rather than operating each reservoir individually. For each USACE/BRA system, the increases in yield can be achieved primarily by properly crediting existing operating policies. Permanent reallocations between flood control and conservation storage capacity result in trade-offs between purposes.

According to Wurbs (1997), if water commitments are limited as required to assure an extremely high level of reliability, the amount of streamflow available for beneficial use is constrained and a greater portion of water flows into the ocean or is lost through reservoir evaporation. Multiple-reservoir system operations can increase reliabilities, as compared to operating the reservoirs independently. Coordinated releases from multiple reservoirs increase reliability by sharing the risks associated with individual reservoirs not being able to meet their individual demands (Wurbs 1996). Brandes and Sullivan (1998) applied a reservoir operation model (ROM)/conditional probability modeling (CPM) system to simulate the annual firm yield for Amistad-Falcon Reservoirs in the Rio Grande. In that study, the 1945–1996 ROM datasets have been used to determine the annual firm yield of the reservoir system. The study concluded that under the reservoir operating procedures as incorporated in the ROM and based on historical river inflows covering 51-year hydrologic sequences at the time, the firm yield for the Amistad-Falcon Reservoir system was determined to be 1,261,670 ac-ft/year. The 2016 Rio Grande Regional Water Plan provided a projected firm yield for the Amistad-Falcon

Reservoir system as 1,060,616 ac-ft/year for 2020 and 1,053,834 ac-ft/year for 2070. However, it was recommended in the 2011 Regional Water Plan that the Rio Grande WAM should be updated regularly (RGRWP, 2016). These firm yield projections were simulated based on the Rio Grande WAM covering the 1940–2000 hydrologic period of analysis.

The objective analyzed in this section was to determine the annual firm yield for each water right group in the Rio Grande WAM based on the 76-year hydrologic sequence covering the 1940–2015 period. The firm yield analysis option activated by the FY record was based on repetitions of the long-term simulation to develop a diversion target (yield) versus reliability table that includes the firm yield if a firm (100% reliability) yield is feasible (Wurbs, 2015). The FY record in WRAP SIM program is entered into the Rio Grande DAT file with the initial value for the annual target amount along with the three, level incremental decreases for iterative simulations.

Table 4.42 shows the results of firm yield analysis for each water rights group in the Rio Grande. Municipal firm yield for the Middle Rio Grande is estimated to be 357,650 ac-ft/year, but no firm yield could be determined for Class A and Class B water right diversions. For the Lower Rio Grande, the municipal pool has a firm yield of 496,790 ac-ft/year with 522,700 ac-ft/year (Figure 4.5) and 29,780 ac-ft/year (Figure 4.6) for Class A and Class B irrigation rights, respectively. It is evident from the analyses that the municipal allocations for the Lower Rio Grande are far more secure than Class A and Class B diversions. Only about 36% of the 1,460,099 ac-ft/year and about 18% of the 163,305 ac-ft/year annual diversions for Class A and Class B irrigation rights can be supplied continuously with volume reliabilities of 100% based on the 76-year hydrologic period of analyses covering 1940–2015 (Table 4.42).

Table 4.42. Summary of Firm Yield Simulation Results for Each Water Right Group in the Rio Grande

Basin Segment	Municipal	Class A	Class B
Middle	357,650	No Firm Yield	No Firm Yield
Lower	496,790	522,700	29,780
Total	1,406,920		

Details of the firm yield simulations are provided in Table 4.43 through 4.48. Figure 4.5 and Figure 4.6 depict reliability versus yield plots for Class A and Class B irrigation rights in the Lower Rio Grande Basin. As volume reliabilities increase, annual yield decreases. The results of this reliability versus yield plots can be used as a water management tool by irrigation districts, TCEQ, and TWDB for future water planning in the Rio Grande.

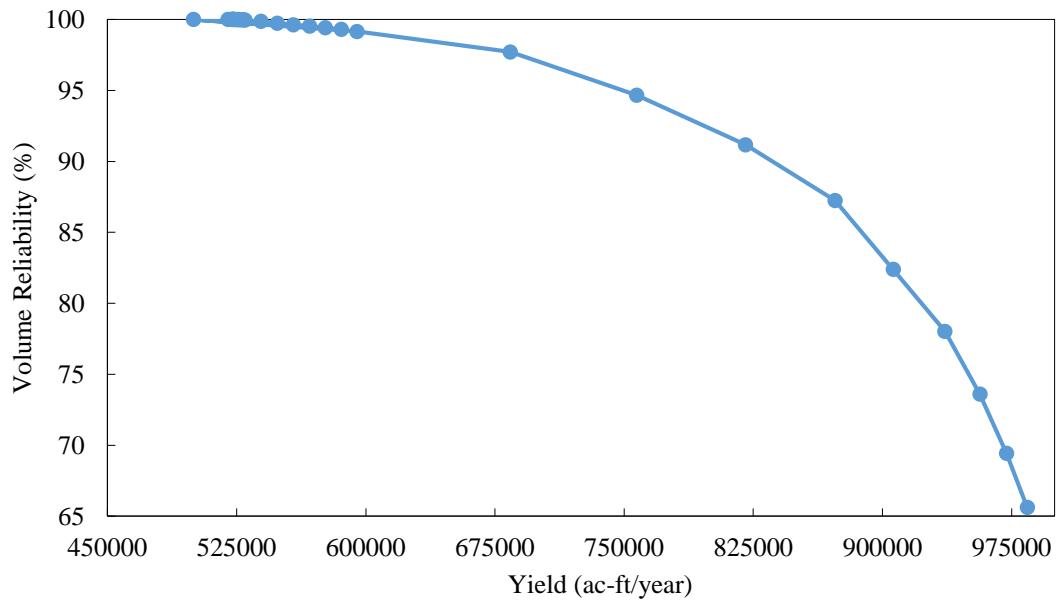


Figure 4.5. Reliability versus yield for Class A irrigation rights in the Lower Rio Grande.

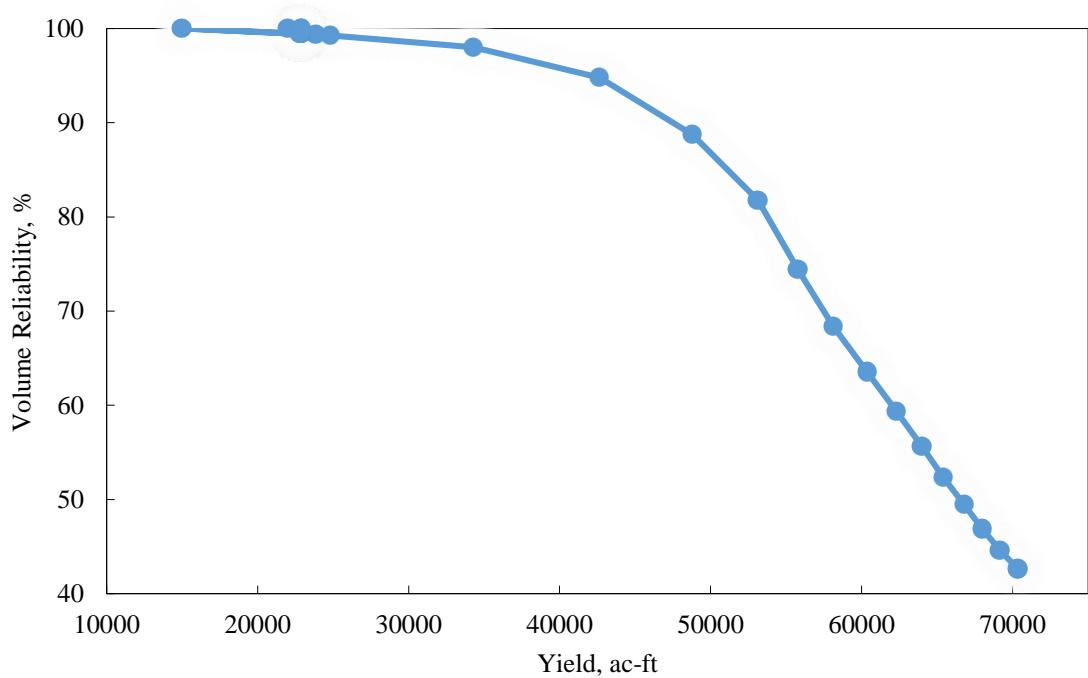


Figure 4.6. Reliability versus yield for Class B water rights in the Lower Rio Grande.

Table 4.43. Yield Reliability Table for Class A Irrigation Rights in the Lower Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):								
		One right (100%): LOW-A-IRR		AL-IRR				
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)	
1	0	1500000.0	515905.2	984094.8	65.61	479	52.52	
2	1	1400000.0	428005.0	971995.0	69.43	525	57.57	
3	1	1300000.0	343378.6	956621.4	73.59	568	62.28	
4	1	1200000.0	263778.6	936221.4	78.02	620	67.98	
5	1	1100000.0	193725.2	906274.8	82.39	666	73.03	
6	1	1000000.0	127551.8	872448.2	87.24	737	80.81	
7	1	900000.0	79482.5	820517.4	91.17	779	85.42	
8	1	800000.0	42732.5	757267.5	94.66	826	90.57	
9	1	700000.0	16030.5	683969.4	97.71	871	95.50	
10	1	600000.0	5100.6	594899.4	99.15	896	98.25	
11	1	500000.0	0.01	500000.0	100.00	912	100.00	

12	2	590000.0	4133.3	585866.7	99.30	900	98.68	
13	2	580000.0	3432.0	576568.0	99.41	901	98.79	
14	2	570000.0	2695.6	567304.4	99.53	903	99.01	
15	2	560000.0	2151.9	557848.1	99.62	904	99.12	
16	2	550000.0	1456.7	548543.2	99.74	907	99.45	
17	2	540000.0	771.4	539228.6	99.86	908	99.56	
18	2	530000.0	200.2	529799.8	99.96	911	99.89	
19	2	520000.0	0.00	520000.0	100.00	912	100.00	

20	3	529000.0	166.7	528833.3	99.97	911	99.89	
21	3	528000.0	65.4	527934.6	99.99	911	99.89	
22	3	527000.0	35.1	526964.9	99.99	911	99.89	
23	3	526000.0	3.69	525996.3	100.00	911	99.89	
24	3	525000.0	33.3	524966.7	99.99	911	99.89	
25	3	524000.0	9.48	523990.5	100.00	911	99.89	
26	3	523000.0	9.82	522990.2	100.00	911	99.89	
27	3	522000.0	0.00	522000.0	100.00	912	100.00	

28	4	522900.0	6.84	522893.2	100.00	911	99.89	
29	4	522800.0	3.67	522796.3	100.00	911	99.89	
30	4	522700.0	0.00	522700.0	100.00	912	100.00	

Table 4.44. Yield Reliability Table for Class B Irrigation Rights in the Lower Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):							
		One right (100%): LOW-B-IRR		BL-IRR			
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)
1	0	163305.0	93233.6	70071.4	42.91	302	33.11
2	1	153305.0	84298.1	69006.9	45.01	315	34.54
3	1	143305.0	75321.5	67983.5	47.44	332	36.40
4	1	133305.0	66650.4	66654.6	50.00	352	38.60
5	1	123305.0	57979.4	65325.6	52.98	384	42.11
6	1	113305.0	49575.9	63729.1	56.25	408	44.74
7	1	103305.0	41331.8	61973.2	59.99	430	47.15
8	1	93305.0	33199.1	60105.9	64.42	459	50.33
9	1	83305.0	25430.0	57875.0	69.47	515	56.47
10	1	73305.0	18260.0	55045.0	75.09	577	63.27
11	1	63305.0	10496.9	52808.1	83.42	687	75.33
12	1	53305.0	5958.1	47346.9	88.82	746	81.80
13	1	43305.0	2030.4	41274.6	95.31	836	91.67
14	1	33305.0	544.1	32760.9	98.37	875	95.94
15	1	23305.0	0.01	23305.0	100.00	863	94.63
<hr/>							
16	2	32305.0	402.7	31902.3	98.75	883	96.82
17	2	31305.0	141.6	31163.4	99.55	893	97.92
18	2	30305.0	54.1	30250.9	99.82	903	99.01
19	2	29305.0	0.01	29305.0	100.00	908	99.56
<hr/>							
20	3	30205.0	45.4	30159.6	99.85	901	98.79
21	3	30105.0	33.5	30071.5	99.89	879	96.38
22	3	30005.0	4.27	30000.7	99.99	907	99.45
23	3	29905.0	22.3	29882.7	99.93	906	99.34
24	3	29805.0	14.6	29790.4	99.95	891	97.70
25	3	29705.0	0.01	29705.0	100.00	904	99.12
<hr/>							
26	4	29795.0	14.1	29780.9	99.95	903	99.01
27	4	29785.0	13.6	29771.4	99.95	902	98.90
28	4	29775.0	0.01	29775.0	100.00	903	99.01

Table 4.45. Yield Reliability Table for Municipal Rights in the Lower Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):							
One right (100%): MUNILWR				MUNLWR			
<p>If more than one right, the target amount is distributed using the priorities shown above. The total number of periods is 912. The period reliability is the percentage of the periods for which at least 100.0 percent (FY record field 2; default=100%) of the target is supplied. The table below ends with the maximum target that results in a mean annual shortage of less than 0.05 units.</p>							
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)
1	0	600000.0	991.4	599008.6	99.83	909	99.67
2	1	590000.0	894.6	589105.4	99.85	910	99.78
3	1	580000.0	785.8	579214.2	99.86	910	99.78
4	1	570000.0	681.3	569318.7	99.88	910	99.78
5	1	560000.0	396.2	559603.8	99.93	911	99.89
6	1	550000.0	293.0	549707.0	99.95	911	99.89
7	1	540000.0	186.1	539813.9	99.97	911	99.89
8	1	530000.0	280.8	529719.2	99.95	911	99.89
9	1	520000.0	189.7	519810.3	99.96	911	99.89
10	1	510000.0	100.2	509899.8	99.98	911	99.89
11	1	500000.0	16.4	499983.6	100.00	912	100.00
12	1	490000.0	0.00	490000.0	100.00	912	100.00

13	2	499000.0	8.43	498991.6	100.00	912	100.00
14	2	498000.0	0.51	497999.5	100.00	912	100.00
15	2	497000.0	1.48	496998.5	100.00	912	100.00
16	2	496000.0	0.00	496000.0	100.00	912	100.00

17	3	496900.0	0.74	496899.2	100.00	912	100.00
18	3	496800.0	0.10	496799.9	100.00	912	100.00
19	3	496700.0	0.00	496700.0	100.00	912	100.00

20	4	496790.0	0.02	496790.0	100.00	912	100.00

Table 4.46. Yield Reliability Table for Class A Irrigation Rights in the Middle Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):								
		One right (100%): MID-A-IRR		AM-IRR				
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)	
1	0	155000.0	49389.8	105610.2	68.14	495	54.28	
2	1	145000.0	45984.3	99015.7	68.29	495	54.28	
3	1	135000.0	42532.9	92467.1	68.49	499	54.71	
4	1	125000.0	39143.0	85857.0	68.69	499	54.71	
5	1	115000.0	35776.9	79223.1	68.89	505	55.37	
6	1	105000.0	32481.0	72519.0	69.07	505	55.37	
7	1	95000.0	29201.7	65798.3	69.26	509	55.81	
8	1	85000.0	26006.5	58993.5	69.40	511	56.03	
9	1	75000.0	22838.5	52161.5	69.55	511	56.03	
10	1	65000.0	19681.8	45318.2	69.72	515	56.47	
11	1	55000.0	16580.1	38419.9	69.85	515	56.47	
12	1	45000.0	13509.5	31490.5	69.98	516	56.58	
13	1	35000.0	10456.9	24543.1	70.12	522	57.24	
14	1	25000.0	7445.8	17554.2	70.22	520	57.02	
15	1	15000.0	4445.5	10554.5	70.36	522	57.24	
16	1	5000.0	1476.6	3523.4	70.47	519	56.91	

17	2	4000.0	1180.7	2819.3	70.48	519	56.91	
18	2	3000.0	884.6	2115.4	70.51	518	56.80	
19	2	2000.0	589.5	1410.5	70.53	516	56.58	
20	2	1000.0	294.7	705.3	70.53	507	55.59	

21	3	900.0	265.2	634.8	70.53	504	55.26	
22	3	800.0	235.7	564.3	70.54	502	55.04	
23	3	700.0	206.2	493.8	70.54	501	54.93	
24	3	600.0	176.8	423.2	70.54	497	54.50	
25	3	500.0	147.3	352.7	70.54	499	54.71	
26	3	400.0	117.8	282.2	70.54	504	55.26	
27	3	300.0	88.4	211.6	70.54	501	54.93	
28	3	200.0	58.9	141.1	70.54	502	55.04	
29	3	100.0	29.5	70.5	70.55	507	55.59	

30	4	90.0	26.5	63.5	70.55	502	55.04	
31	4	80.0	23.6	56.4	70.55	508	55.70	
32	4	70.0	20.6	49.4	70.55	505	55.37	
33	4	60.0	17.7	42.3	70.55	508	55.70	
34	4	50.0	14.7	35.3	70.55	504	55.26	
35	4	40.0	11.8	28.2	70.55	501	54.93	
36	4	30.0	8.84	21.2	70.55	508	55.70	
37	4	20.0	5.89	14.1	70.55	514	56.36	
38	4	10.0	2.95	7.1	70.55	516	56.58	
Routine finished without reaching a firm yield.								

Table 4.47. Yield Reliability Table for Class B Irrigation Rights in the Middle Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):							
		One right (100%): MID-A-IRR		AM-IRR			
If more than one right, the target amount is distributed using the percentages shown above. The total number of periods is 912. The period reliability is the percentage of the periods for which at least 100.0 percent (FY record field 2; default=100%) of the target is supplied. The table below ends with the maximum target that results in a mean annual shortage of less than 0.05 units.							
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)
1	0	155000.0	49389.8	105610.2	68.14	495	54.28
2	1	145000.0	45984.3	99015.7	68.29	495	54.28
3	1	135000.0	42532.9	92467.1	68.49	499	54.71
4	1	125000.0	39143.0	85857.0	68.69	499	54.71
5	1	115000.0	35776.9	79223.1	68.89	505	55.37
6	1	105000.0	32481.0	72519.0	69.07	505	55.37
7	1	95000.0	29201.7	65798.3	69.26	509	55.81
8	1	85000.0	26006.5	58993.5	69.40	511	56.03
9	1	75000.0	22838.5	52161.5	69.55	511	56.03
10	1	65000.0	19681.8	45318.2	69.72	515	56.47
11	1	55000.0	16580.1	38419.9	69.85	515	56.47
12	1	45000.0	13509.5	31490.5	69.98	516	56.58
13	1	35000.0	10456.9	24543.1	70.12	522	57.24
14	1	25000.0	7445.8	17554.2	70.22	520	57.02
15	1	15000.0	4445.5	10554.5	70.36	522	57.24
16	1	5000.0	1476.6	3523.4	70.47	519	56.91

17	2	4000.0	1180.7	2819.3	70.48	519	56.91
18	2	3000.0	884.6	2115.4	70.51	518	56.80
19	2	2000.0	589.5	1410.5	70.53	516	56.58
20	2	1000.0	294.7	705.3	70.53	507	55.59

21	3	900.0	265.2	634.8	70.53	504	55.26
22	3	800.0	235.7	564.3	70.54	502	55.04
23	3	700.0	206.2	493.8	70.54	501	54.93
24	3	600.0	176.8	423.2	70.54	497	54.50
25	3	500.0	147.3	352.7	70.54	499	54.71
26	3	400.0	117.8	282.2	70.54	504	55.26
27	3	300.0	88.4	211.6	70.54	501	54.93
28	3	200.0	58.9	141.1	70.54	502	55.04
29	3	100.0	29.5	70.5	70.55	507	55.59

30	4	90.0	26.5	63.5	70.55	502	55.04
31	4	80.0	23.6	56.4	70.55	508	55.70
32	4	70.0	20.6	49.4	70.55	505	55.37
33	4	60.0	17.7	42.3	70.55	508	55.70
34	4	50.0	14.7	35.3	70.55	504	55.26
35	4	40.0	11.8	28.2	70.55	501	54.93
36	4	30.0	8.84	21.2	70.55	508	55.70
37	4	20.0	5.89	14.1	70.55	514	56.36
38	4	10.0	2.95	7.1	70.55	516	56.58
Routine finished without reaching a firm yield.							

Table 4.48. Yield Reliability Table for Municipal Rights in the Middle Rio Grande

Yield Versus Reliability Table for the Following Water Right(s):							
One right (100%): MUNIMID				MUNMID			
If more than one right, the target amount is distributed using the priorities shown above. The total number of periods is 912. The period reliability is the percentage of the periods for which at least 100.0 percent (FY record field 2; default=100%) of the target is supplied. The table below ends with the maximum target that results in a mean annual shortage of less than 0.05 units.							
Iteration	Level	Annual Target	Mean Shortage	Mean Actual	Volume Reliability (%)	Periods Without Shortage	Period Reliability (%)
1	0	1000000.0	270311.8	729688.2	72.97	463	50.77
2	1	900000.0	194648.4	705351.6	78.37	542	59.43
3	1	800000.0	126383.2	673616.8	84.20	640	70.18
4	1	700000.0	68516.3	631483.7	90.21	727	79.71
5	1	600000.0	26221.9	573778.1	95.63	828	90.79
6	1	500000.0	4341.9	495658.1	99.13	895	98.14
7	1	400000.0	209.6	399790.4	99.95	911	99.89
8	1	300000.0	0.00	300000.0	100.00	912	100.00
9	2	390000.0	339.6	389660.4	99.91	911	99.89
10	2	380000.0	239.2	379760.8	99.94	911	99.89
11	2	370000.0	138.5	369861.5	99.96	911	99.89
12	2	360000.0	17.8	359982.2	100.00	912	100.00
13	2	350000.0	0.00	350000.0	100.00	912	100.00
14	3	359900.0	16.8	359883.2	100.00	912	100.00
15	3	359800.0	15.8	359784.2	100.00	912	100.00
16	3	359700.0	45.6	359654.3	99.99	912	100.00
17	3	359600.0	44.7	359555.3	99.99	912	100.00
18	3	359500.0	43.7	359456.3	99.99	912	100.00
19	3	359400.0	42.7	359357.3	99.99	912	100.00
20	3	359300.0	16.2	359283.8	100.00	912	100.00
21	3	359200.0	15.2	359184.8	100.00	912	100.00
22	3	359100.0	14.2	359085.8	100.00	912	100.00
23	3	359000.0	13.2	358986.8	100.00	912	100.00
24	3	358900.0	12.3	358887.8	100.00	912	100.00
25	3	358800.0	11.3	358788.7	100.00	912	100.00
26	3	358700.0	10.3	358689.7	100.00	912	100.00
27	3	358600.0	9.33	358590.7	100.00	912	100.00
28	3	358500.0	8.35	358491.7	100.00	912	100.00
29	3	358400.0	7.37	358392.6	100.00	912	100.00
30	3	358300.0	6.39	358293.6	100.00	912	100.00
31	3	358200.0	5.41	358194.6	100.00	912	100.00
32	3	358100.0	4.43	358095.6	100.00	912	100.00
33	3	358000.0	3.45	357996.6	100.00	912	100.00
34	3	357900.0	2.47	357897.5	100.00	912	100.00
35	3	357800.0	1.49	357798.5	100.00	912	100.00
36	3	357700.0	0.51	357699.5	100.00	912	100.00
37	3	357600.0	0.00	357600.0	100.00	912	100.00
38	4	357690.0	0.41	357689.6	100.00	912	100.00
39	4	357680.0	0.31	357679.7	100.00	912	100.00
40	4	357670.0	0.22	357669.8	100.00	912	100.00
41	4	357660.0	0.12	357659.9	100.00	912	100.00
42	4	357650.0	0.02	357650.0	100.00	912	100.00

Considering initial storage of Amistad-Falcon reservoir system is important to obtain accurate reliability results. However, TCEQ uses long-term simulation analyses starting the reservoir storage at 100% capacity at the beginning of each simulation to evaluate water right permit applications. The TWDB also uses long-term simulation option of the Rio Grande WAM for future water planning purposes. The BES option along with conventional long-term simulations were applied to the Rio Grande WAM. In the long-term simulation mode, WRAP simulates 76 year of hydrologic record of the Rio Grande WAM in a single sequence. The CRM methodologies of WRAP will be applied to the Rio Grande in the next Chapter of this dissertation. Unlike conventional long-term simulations, in CRM, the WRAP divides the long hydrologic period of records into short sequences subject to initial reservoir storage content at the beginning of month.

CHAPTER V

CONDITIONAL RELIABILITY MODELING

Conditional reliability modeling (CRM) methodologies were evaluated for the Rio Grande Basin using CRM features of WRAP. Key concepts and methodologies concerning CRM are described in this chapter. This study used the updated, fully authorized (RG3) 2014 version of the Rio Grande WAM, with the hydrologic period of record extending from 1940 to 2015. CRM is defined as the process of determining the likelihood of meeting water use requirements after specific circumstance of inflow (the condition) has occurred (Salazar, 2004). Brandes (1998) developed and implemented the conditional probability model (CPM) for Amistad and Falcon Reservoirs in the Rio Grande. The CPM develops yield-reliability relationships based on beginning-of-the-year storage condition. Firm yield and long-term reliabilities for different water rights groups were also developed using the CRM method. The long-term simulations in WRAP described in Chapter IV were implemented for the Rio Grande in order to assess the reliabilities of different water right groups in various water allocation scenarios. Salazar (2002) and Salazar and Wurbs (2004) developed supply reliability indices on the basis of a conditional frequency duration curve to establish probability distributions for naturalized flows conditioned on preceding storage conditions as reflected in discrete storage intervals. This approach was determined to be difficult to apply in practical applications and was never fully implemented in WRAP (Wurbs et. al., 2012).

WRAP was originally developed for and is routinely applied to long-term planning studies and evaluations of water right permit applications. The short-term CRM methodologies described in this chapter use the same input datasets as conventional long-term WRAP applications, except that the hydrologic period of analysis is subdivided into many short simulation sequences (Wurbs, 2012). CRM has been previously applied to river basins in Texas by Salazar (2002), Olmos (2004), Schnier (2010), and Bista (2015), and has been documented by Wurbs (2015). CRM methodologies have been updated since the development of the conditional frequency duration curve (CFDC) described by Salazar (2002), which was not incorporated into WRAP due to complexities in application. The details of the case study applying CFDC to the Brazos River Basin can be found in the publication by Salazar and Wurbs (2009). Olmos (2004) developed a different method for assigning probabilities to each

sequence of streamflows called the storage-flow-frequency (SFF) array. The SFF array uses the log-normal distribution or the Weibull distribution to relate exceedance probabilities to the random variable Q_s and will be explained in the following sections. Schnier (2010) applied firm yield and CRM methodologies to the Brazos River Basin and developed guidelines for real-time decision support during drought and routinely recurring operational planning activities. A case study of the Brazos River drought in 2009 was used to apply CRM features of WRAP. Wurbs et al. (2012) provided details of the development and applications of CRM methods in the Brazos River case study. Bista (2015) applied CRM methods of WRAP to the Colorado River Basin of Texas for both long-term planning and short-term modes to model and develop water management plans that combine interruptible and firm water supply commitments. The *Users and Reference Manuals* (Wurbs, 2015) have been extensively used and consulted in this research.

Conditional Short-Term Simulation

CRM is used to develop short-term reliability and frequency estimates conditioned on preceding reservoir storage. A long hydrologic period of record is divided into short sequences in the SIM simulation model based on specific parameters, and repeated simulations for each sequence are performed starting with the same reservoir content. The output file from the SIM simulation model is then used by the program TABLES to develop flow and storage frequency relationships and water supply reliabilities. The primary purpose of CRM is to establish water supply reliabilities for meeting water need during the near future period months and years. It can be used as a decision support tool for water management during drought and to develop river and reservoir operating policies. The TCEQ Rio Grande watermaster, IBWC, Rio Grande Water Planning Group, TWDB, Lower Rio Grande irrigation districts, and other agencies can use it to determine curtailment or water cut-off actions for water supply and develop seasonal or annual operation plans.

WRAP divides long period of analysis hydrology into several short sequences using the annual cycling and monthly cycling options. The annual cycling option simulates one sequence per year, and each sequence always begins in the same month. The maximum sequence length is equal to the number of months in the period of analysis. For example, a

1940 to 2015 period of analysis for the Rio Grande could be organized into 6-month sequences starting with the month of May that result in the following 76 sequences:

Sequence 1: May 1940 through October 1941

Sequence 2: May 1941 through October 1942

.....

Sequence 76: May 2014 through October 2015

The annual cycling option captures seasonality but is limited by the number of years in the period of analysis.

The monthly cycle simulates one sequence per month; the first sequence begins in the first month of the first year, and the second sequence begins in the next month after completion of the first sequence. The monthly cycle has the length in months specified by the user. After reaching the end of the last year, the sequencing begins again, one month after the preceding cycle began. The number of complete sequences is:

$$\text{Number of sequences} = (12)(\text{number of years}) - \text{length of simulation} + 1 \quad (5.1)$$

Applying the monthly cycle option to the 1940 to 2015 example for the Rio Grande, for a simulation length of 6 months, will result in 905 sequences being computed. The monthly cycle allows up to 12 times more sequences than the annual cycle but loses the seasonal aspect. Both options help improve the accuracy of the reliability and frequency estimates and which option to use should be chosen based on the needs of the user. In this study, seasonality was important due to the significant amount of monthly flow volumes that are allocated to irrigation in the Lower Rio Grande; therefore, the annual cycle option was adopted for CRM simulations. Alternative strategies that assign the probabilities to each of the multiple CRM simulation sequences are outlined in the *WRAP Reference Manual* (Wurbs, 2015).

CRM has two strategies to assign probabilities to each flow sequence: the equal weight option and the probability array option. In the equal weight option, all the simulation sequences are considered equally likely to occur and are assigned probabilities of one out of the total number of simulation sequences (e.g., 1/76 for the Rio Grande WAM). The TABLES program

does not require additional features for the equal weight option because all frequency and reliability computations are the same as for a conventional long-term simulation. The probability array option, on the other hand, assigns probabilities to each hydrological sequence with either a flow-frequency (FF) relationship or storage-flow-frequency (SFF) relationship. Both relationships assign probabilities to naturalized flow volumes directly using either the log-normal probability distribution or the Weibull formula. As the name reflects, the probability array option develops incremental probability arrays and assigns probability to each simulation sequence. The FF relationship assigns exceedance probabilities directly to naturalized flow volumes and can consider preceding storage level by using sequences with preceding storage falling within a specified range. The SFF relationship relates exceedance probabilities to a random variable, $Q\%$, known as the flow ratio of observed flows (Q) over expected flows (Q_s):

$$Q\% = \frac{Q}{Q_s} \quad (5.2)$$

where Q is the naturalized flow volume over a specified length of months observed in CRM simulation results, and Q_s is the corresponding expected value of naturalized flow volume and is determined from a regression equation reflecting preceding storage volume.

The premise behind the SFF option is that naturalized flows are correlated to some extent with preceding storage content. That is, the conditions of the recent past lead to the current storage content, and these conditions are likely to persist in the near future. For example, low reservoir storage contents would not imply dry conditions during preceding months but ongoing dry conditions in upcoming months. Preceding storage can be considered in the FF option only if the analysis is conducted using sequences with preceding storage falling within a specified range. Otherwise, the FF option will assign probability to sequences of naturalized flow regardless of initial storage content.

WRAP has four regression equations to relate the expected naturalized flow (Q_s) to preceding storage volume: linear (Eq. 5.3), combined (Eq. 5.4), exponential (Eq. 5.5), and power (Eq. 5.6).

$$Q_s = a + b \times S \quad (5.3)$$

$$Q_s = a + b \times S^c \quad (5.4)$$

$$Q_S = a \times e^{\frac{S}{b}} \quad (5.5)$$

$$Q_S = b \times S^c \quad (5.6)$$

The coefficients a , b , and c are determined by applying standard least squares regression as follows:

$$E(Y|x) = a + b \times S \quad (5.7)$$

$$b = \frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{n \sum x_i^2 - \sum (y_i)^2} \quad (5.8)$$

$$a = \bar{y} - b \times \bar{x} \quad (5.9)$$

where $E(Y|x)$ is the expected value of Y for a given value of x . The y and x variables adopt values of naturalized flow volumes and preceding reservoir storage volume from a conventional SIM simulation.

The linear correlation coefficient (r) and Spearman rank correlation coefficients are used as an index of goodness to fit between naturalized flows (Q) and preceding storage content or change in storage (S):

$$r = \frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{n \sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_i^2 - (\sum y_i)^2}} \quad (5.10)$$

where Q_S and S represents x and y variables for linear correlation coefficients. The Spearman rank coefficient (r_r) is calculated based on the relative ranks of Q_S and S using the simplified equation below:

$$r_r = \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (5.11)$$

where d_i is the difference between the ranks for each of the paired values, and n is the number of paired values.

The probability array option relates exceedance probability for the FF and SFF option using either the log normal probability distribution or Weibull formula. The log normal probability distribution is defined by the following equation:

$$\log X = \overline{\log X} + z S_{\log X} \quad (5.12)$$

The variable x is the naturalized flow for FF and $Q\%$ for the SFF option. $\log X$ is the mean of $\log X$, $S_{\log X}$ is the standard deviation, and z is computed by linear interpolation from a normal probability table. The Weibull formula is a rank based option to assign exceedance probabilities for the SFF or FF relationship:

$$P = \frac{m}{N+1} \quad (5.13)$$

where P is the exceedance probability, m is the rank of variable Q or $Q\%$, and N is the total number of variables. The probability array option performs reliability and frequency analysis using the conventional computational routine, but it will incorporate an exceedance probability (FF or SFF) relationship to assign an incremental probability to each simulation sequence. The incremental probabilities vary for the sequence and add up to 1.0. To assign probabilities to the simulation sequence, Q or $Q\%$ values are calculated for each hydrologic sequence and combined with the previously created FF or SFF exceedance probability relationship. Thus, exceedance probabilities are assigned to each hydrologic sequence and then ranked in order and converted to incremental probabilities. Extended Rio Grande WAM with an annual cycling option was used in this research to capture seasonality in the basing because it is important for irrigation diversions. The input dataset for the CRM simulations was the same as the one used in the long-term simulation of the preceding section, except that the 1940–2015 hydrologic period of analysis was divided into 76 annual hydrologic simulation sequences.

Conditional Reliability for Rio Grande Basin

CRM methodologies outlined in the previous section were applied to the Rio Grande using updated, fully authorized Rio Grande WAM covering the 1940–2015 hydrologic period of analysis. The annual cycling option was chosen for this research to cover seasonal characteristics of irrigation and municipal water use in the Basin. Short-term reliabilities were developed for municipal and Class A and Class B irrigation rights using initial storage contents or changes to storages of Amistad and Falcon Reservoirs. Control point CT1160 was used for Amistad Reservoir, with a total capacity of 1,821,502 ac-ft, and control point DT1001 was used for Falcon Reservoir, with a total capacity of 1,548,640 ac-ft, to develop exceedance probabilities and reliabilities for municipal, Class A, and Class B water rights. The objective

of this study was to demonstrate short-term reliability analysis in order to develop water planning and management for the Lower Rio Grande using streamflow and reservoir storage relationships to predict the likelihood of meeting water allocation demands for the next few months into the future. The results of this study can be used by irrigation districts in the Lower Rio Grande Valley to improve water management planning, especially given the storage content of Amistad and Falcon Reservoirs. These results supply critical information for farmers and irrigation districts, for there is lack of knowledge about the current storage content in Falcon and Amistad in relation to likelihood or probability of having allocations next month or a few months into the future. The study focused on comparative analysis of equal weight and probability array options for Amistad (TEXAMI) and Falcon (TEXFAL) Reservoirs in the Rio Grande. The different modeling options in CRM were compared by developing storage frequency tables for Amistad and Falcon Reservoirs and employing a combined scenario. Control point CT1160, located downstream of TEXAMI, and control point DT1001, downstream of TEXFAL, were used to develop storage flow frequency analysis. The combined scenario includes both reservoirs and control points that the researcher simulated separately in the TABLES program.

Equal Weight Option

WRAP was originally designed for long-term planning studies and preparation and evaluation of water right permit applications. CRM features expand WRAP capabilities to support short-term drought management and operational planning activities, for which consideration of preceding reservoir storage levels is important. The terms *conditional* and *short-term* modeling are used here interchangeably. Using CRM, the likelihood of meeting reservoir storage, water supply diversion, instream flow, and hydroelectric power generation targets during the next month, next several months, next year, or perhaps next several years is assessed as a function of the amount of water currently in storage along with all the other information otherwise reflected in WRAP. In the short-term, storage and flow frequencies and water supply reliabilities are conditioned on preceding reservoir storage contents.

The equal-weight and probability array options are two alternative CRM approaches. This section focuses on applying the equal-weight method.

The difference between the equal-weight and probability array methodologies is the approach adopted within *TABLES* for assigning probabilities to each hydrologic sequence and corresponding CRM simulations for use in the frequency and reliability analysis computations. The Rio Grande simulation analyses in Chapter 4 and Chapter 5 used 76 annual hydrologic sequences derived from the 1940–2015 period of analysis. With the equal-weight method, each of the 76 simulations are weighted the same in the frequency and reliability analysis, which is equivalent to assigning a probability of 1/76 to each of the 76 simulations. The probability array option is based on assigning varying probabilities to the 76 simulations. The probability array option adds complexity but may improve the accuracy of the probability estimates under certain conditions.

The equal-weight option in CRM, as the name implies, assigns probabilities of meeting specified diversions on an equally likely basis. The Rio Grande WAM hydrologic period of analysis extending from 1940 to 2015 was used to simulate the likelihood of supplying water demands for different water right groups based on initial reservoir storage contents. In addition, a reliability and frequency analysis in terms of naturalized flow volumes and percentages were developed for TEXAMI and TEXFAL reservoirs based on various initial reservoir storage contents. The annual simulation option was chosen in this research to capture seasonality of water allocation reliabilities because of the importance of irrigation demands during the peak irrigation season in the Lower Rio Grande Valley, which starts in April and slows down by the end of September. The *WRAP Reference and Users Manuals* have been used as the main guidelines to develop the simulation modeling. Chapter 7 of the *Reference Manual* (Wurbs, 2015) provides detailed instructions on building CRM modeling features for any river basin with ready-to-use hydrology input files such as the Rio Grande WAM. The *Users Manual* (Wurbs, 2015) provides all WRAP records that need to be included in *SIM* and *TABLES* programs prior to each CRM simulation.

Equal Weight Simulation Results for Amistad Reservoir

The month of April was chosen as the beginning month of simulations using the equal-weight CRM option for the Rio Grande based on 15%, 30%, 50%, 75%, and 100% initial reservoir storage contents in order to determine the likelihood of water allocations at the end

of April, May, June, July, August, and September. CRM equal-weight option produced better results for up to six (6) months into the future simulations, after which the reliability analysis shifts towards conventional simulation results.

The following CR record was inserted into the Rio Grande DAT file for simulations in which the length of simulation was designated as 12 months with a starting month of April (4) and the multiplier factors of 0.15, 0.30, 0.50, 0.75, and 1.0 as initial reservoir storage contents:

CR	12	4	0	0.15.
CR	12	4	0	0.30.
CR	12	4	0	0.50.
CR	12	4	0	0.75.
CR	12	4	0	1.00.

The SIM simulation generates a CRM output file, which is read by the TABLES program in order to develop storage frequency tables. The equal-weight option 5CRM record is activated in the TIN fil along with a 2FRE record to develop the frequency tables. Tables 5.1 through 5.3 show the summary for the end-of-month storage frequencies for Amistad Reservoir using the beginning-of-April simulations with 15, 30, 50, 75, and 100% initial storage levels. The first column in the tables lists the exceedance frequencies, and corresponding end-of-April through September storage contents are tabulated as a percentage of storage capacities. The exceedance frequency values represent the percentage of 76 simulation sequences with the corresponding storage capacity equaled or exceeded. For example, Table 5.1 indicates that with the beginning-of-April storage set to 30% of full capacity, the end of May storage is 46.8% of the 90% exceedance frequency, which means the end-of-May storage equals or exceeds 46.8% of storage capacity for 95% of the 74 annual sequences. The corresponding end-of-April storage capacity is 77.7% of capacity. Similarly, for Amistad Reservoir there is a 60% probability that storage will equal or exceed 61.44% of storage capacity by the end of May if storage is at 50% of full capacity at the beginning of April. The equivalent storage capacity at the end of April is 85.96%. Also, the exceedance frequencies appear to be higher with the high initial reservoir storages on each simulation. It is a testament to the objective of the equal-weight CRM method that high initial reservoir contents will have a higher chance of exceedance frequencies in the next months into the future. The end-of-September and the end-of-August storage capacities vary for Amistad Reservoir,

and, in most cases, the end-of-September values are lower than the end-of-August storage for low frequencies and seem to be lower for high frequencies.

Table 5.1. Equal Weight Storage Frequency for TEXAMI Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	99.64	87.59	82.85	75.29	61.99	98.34	73.53	56.43	44.5	27.32
98	100	87.88	83.27	75.91	62.97	98.4	74.15	57.14	45.36	28.16
95	100	88.57	84.23	77.29	65.03	98.41	74.88	57.99	46.33	29.56
90	100	88.83	84.6	77.77	65.71	98.46	75.2	58.36	46.8	30.69
80	100	89.15	85.07	78.48	66.54	98.62	76.43	59.78	48.41	32.61
70	100	89.39	85.4	78.87	67.18	98.78	77.01	60.46	49.35	33.76
60	100	89.81	85.96	79.46	68.21	99.08	77.86	61.44	50.45	35.17
50	100	90.19	86.52	80.63	69.63	99.33	78.58	62.25	51.34	36.85
40	100	90.67	86.94	80.97	70.19	99.81	79.13	62.9	52.21	38.31
30	100	91.15	87.6	82.16	71.97	100	80	63.91	53.74	39.5
20	100	92.09	89	83.72	74.23	100	81.18	65.17	55.09	42.41
10	100	94.4	92.02	88.11	81.1	100	86.14	70.25	61.55	49.75

Table 5.2. Equal Weight Storage Frequency for TEXAMI Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-June Storage Capacity (%)					End-of-July Storage Capacity (%)				
99	97.34	72.57	47.87	23.43	11.32	95.11	70.34	44.3	13.41	12.19
98	97.71	73.04	48.34	25.84	11.79	96.25	71.29	46.98	13.98	12.43
95	98.27	75.38	50.66	30.01	12.55	98.49	75.54	51.55	18.29	13.28
90	98.57	77.08	52.37	31.62	13.92	98.89	76.98	52.77	19.27	13.84
80	99.12	78.01	53.31	33.19	15.51	99.27	78.09	54.1	22.59	15.78
70	99.47	78.89	54.13	34.17	17.43	99.99	79.49	55.58	24.44	17.24
60	99.65	79.99	55.22	35.3	18.46	100	81.61	57.73	28.48	17.9
50	100	80.77	55.85	36.03	19.35	100	83.61	59.23	31.58	19.4
40	100	82.3	57.59	37.96	20.66	100	85.83	61.96	36.79	21.18
30	100	84.6	59.96	40.35	22.16	100	88.06	64.11	42.8	24.05
20	100	87.02	62.06	42.52	27.86	100	90.89	67.16	48.86	33.48
10	100	92.99	67.54	47.47	32.6	100	100	76.37	56.97	47.7

Table 5.3. Equal Weight Storage Frequency for TEXAMI Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	89.57	60.42	31.2	10.37	11.66	81.75	56.69	22.87	10.66	10.1
98	93.72	62.5	36.75	11.57	12.73	85.1	60.21	28.71	11.4	10.84
95	97.04	63.63	41.68	13.06	14.4	90.05	65.24	36.22	12.07	12.2
90	98.17	67.15	43.44	13.93	16.4	93.08	66.84	38.01	12.59	13.45
80	99.25	69.94	46.65	16.1	18.01	98.65	70.82	44.47	14.45	14.88
70	100	72.9	46.83	19.01	19.28	99.24	72.82	47.33	17.59	16.1
60	100	75.05	49	22.82	21.12	99.83	76.43	49.14	20.68	17.68
50	100	79.25	53.42	27.33	22.19	100	79.95	54.57	24.71	19.72
40	100	82.23	56.06	32.82	24.45	100	84.14	58.39	32.63	22.42
30	100	87.19	62.05	42.69	27.36	100	93.41	64.8	41.81	28.49
20	100	94.12	68.49	56.38	36.47	100	100	74.42	53.04	37.41
10	100	100	76.82	70.01	57.06	100	100	85.13	66.29	51.72

Figures 5.1 through 5.5 depict the end-of-the-month exceedance frequencies versus storage volumes (ac-ft) for the Amistad Reservoir with initial reservoir contents of 15, 30, 50, 75, and 100% at the beginning of April. As the initial storage content at the beginning of April increases, the likelihood of storage volume available for allocations at the end of April, May, June, July, August, and September increase accordingly. Significant withdrawal from Amistad happens during the months of July, August, and September due to increased demands during summer time, especially in the arid Rio Grande Valley. There is a 70% likelihood that the storage level in Amistad Reservoir will have 260,730 ac-ft of water by the end of July given the 15% total storage capacity at the beginning of April (Figure 5.1). Also, there is a 40% chance that Amistad will have 1,019,815 ac-ft of storage at the end of August given that the reservoir is half full at the beginning of April (Figure 5.3). These simulation results show that if the water storage at Amistad Reservoir falls below 75% of the total capacity at the beginning of April, the reliabilities for irrigation diversions during peak irrigation season may be significantly lower, which may lead to curtailment of some of the allocations.

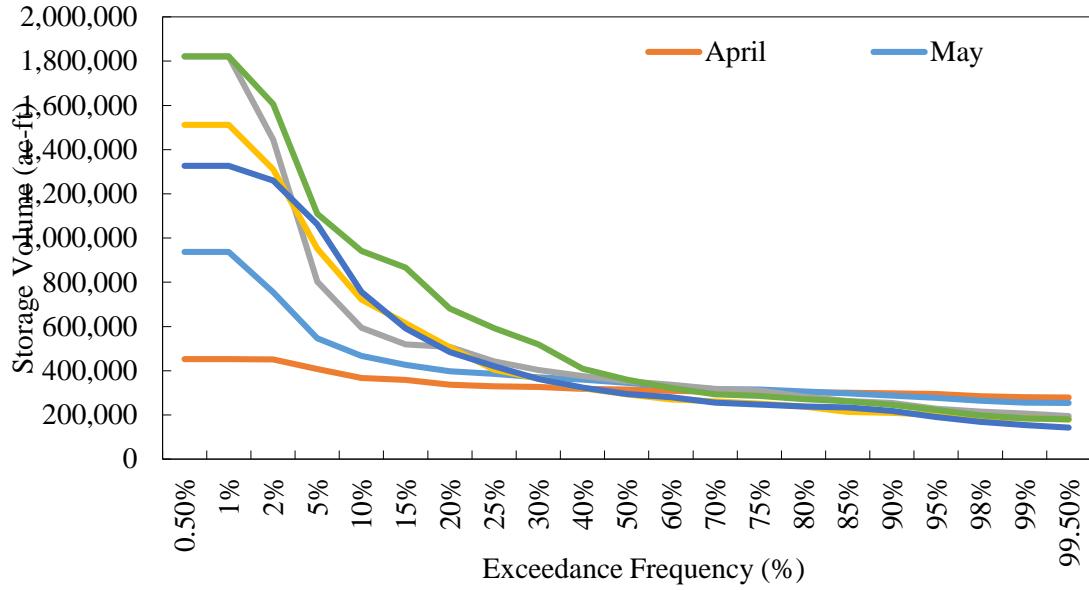


Figure 5.1. End-of-the-month storage exceedance frequency for TEXAMI Reservoir with 15% of initial reservoir content.

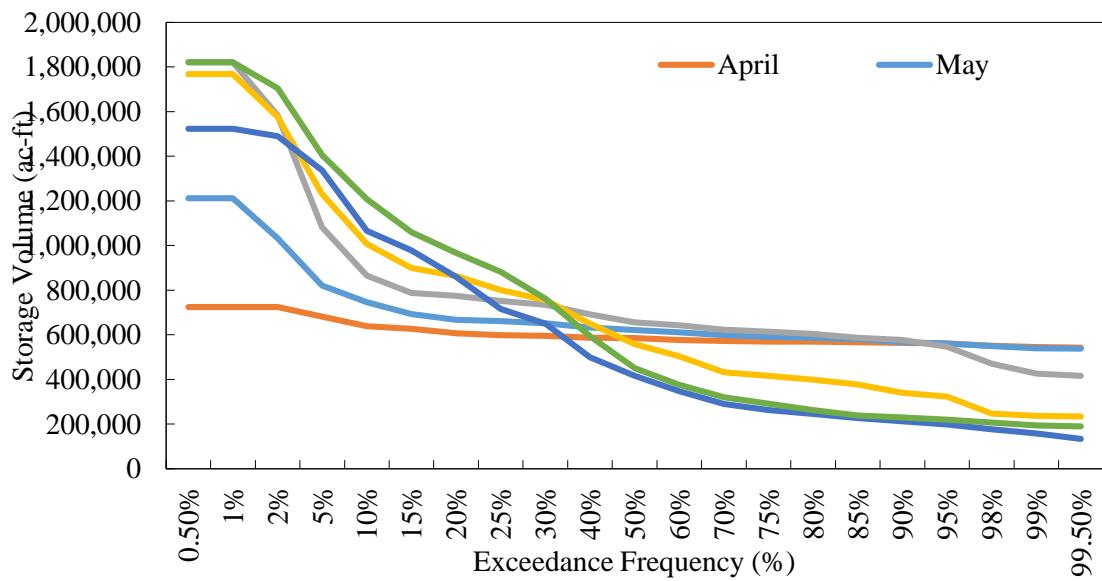


Figure 5.2. End-of-the-month storage exceedance frequency for TEXAMI Reservoir with 30% of initial reservoir content.

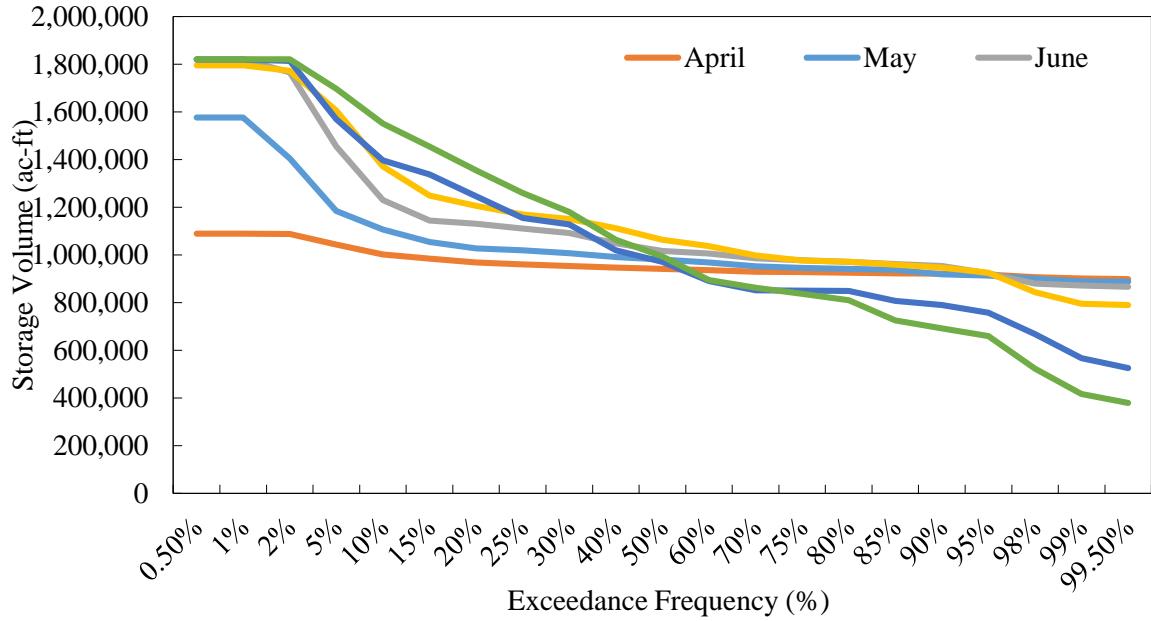


Figure 5.3. End-of-the-month storage exceedance frequency for TEXAMI Reservoir with 50% of initial reservoir content.

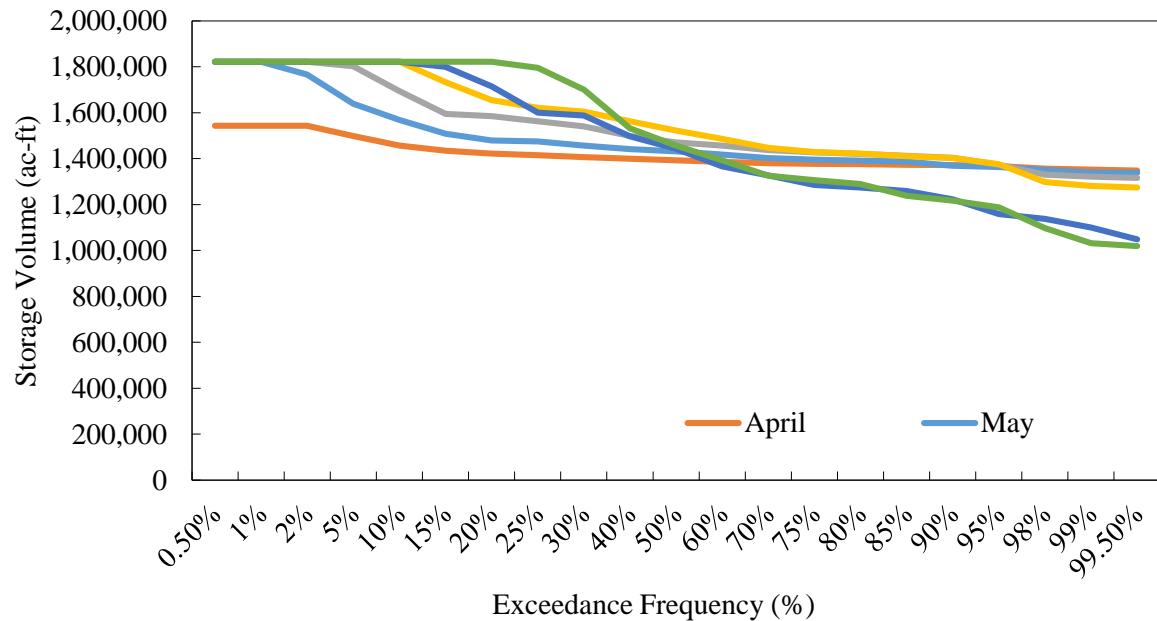


Figure 5.4. End-of-the-month storage exceedance frequency for TEXAMI Reservoir with 75% of initial reservoir content.

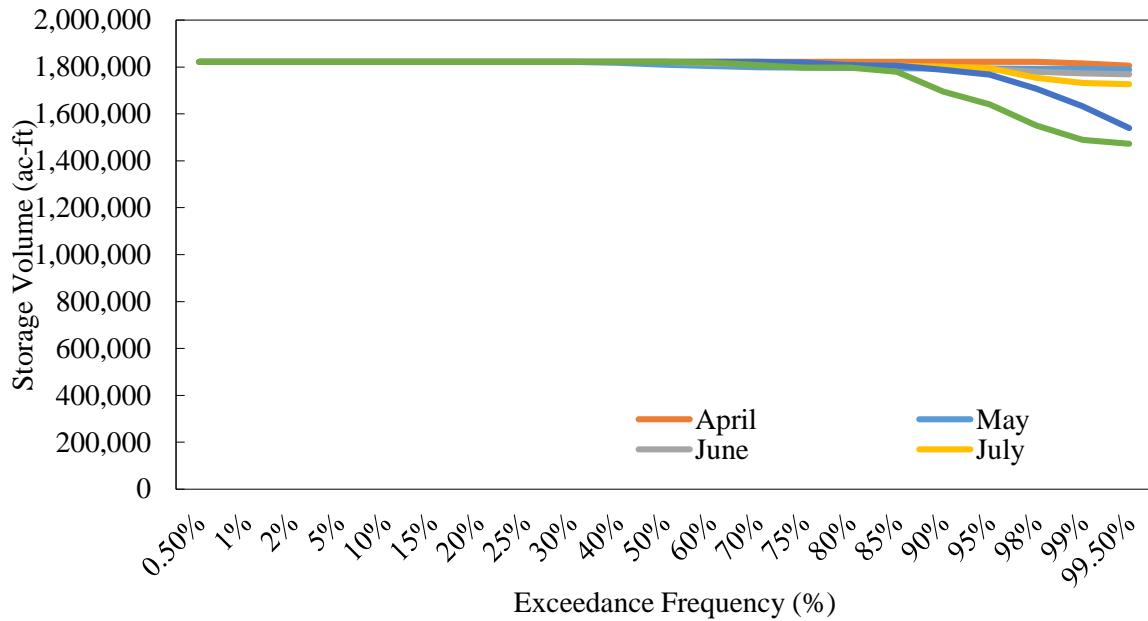


Figure 5.5. End-of-the-month storage exceedance frequency for TEXAMI Reservoir with 100% of initial reservoir content.

Equal Weight Simulation Results for Falcon Reservoir

Tables 5.4 through 5.6 show the simulation results for beginning-of-April simulations for the Falcon Reservoir with the same initial storage contents and end-of-the-month reliabilities as in the case of the Amistad Reservoir storage. End-of-the month storage exceedance frequencies are significantly lower for the Falcon Reservoir compared to the Amistad Reservoir because of the significant demands of the Lower Rio Grande Valley. The summer months were chosen to develop the likelihood of storage levels in Falcon based on various initial storage content at the beginning of April in order to analyze the impacts of storage allocations during the peak irrigation season. The results of these analyses can be used by farmers and irrigation districts to improve water deliveries and plan irrigation scheduling ahead of time. For example, Table 5.5 shows that 50% of the time, storage levels at Falcon Reservoir equal or exceed 11.31% of the total storage capacity by the end of July, given a reservoir storage level of 15% at the beginning of April. Knowing the likelihood of storage levels in Falcon Reservoir by the end of June or August based on the storage levels in April is

a useful water allocations tool for farmers. There is a 60% chance that the storage content of Falcon Reservoir will equal or exceed only 11.85% of total capacity by the end of September if the reservoir level was at 30% of capacity at the beginning of April. In addition, Table 5.5 indicates that with the beginning-of-April storage set to 75% of full capacity, the end of July storage is 32.27% of the 80% exceedance frequency, which means the end-of-July storage equals or exceeds 32.2% of storage capacity for 80% of the 74 annual sequences. Corresponding end-of-June storage capacity is 44.3% of capacity. Similarly, for Falcon Reservoir, there is a 50% probability that storage will equal or exceed 51.09% of storage capacity by the end of May if storage is at 50% of full capacity at the beginning of April. The equivalent storage capacity at the end of April is 69.17%.

Table 5.4. Equal Weight Storage Frequency for TEXFAL Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity					End-of-May Storage Capacity (%)				
	100	75	50	30	15	100	75	50	30	15
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	86.79	73.68	65.3	53.18	35.32	75.22	51.64	42.77	24.18	4.26
98	87.3	73.98	65.66	53.57	35.8	76.57	52.3	43.66	25.34	4.57
95	87.63	74.28	66.13	54.33	36.92	77.28	53.08	44.94	27.23	6.64
90	88.3	74.65	66.58	54.9	37.66	78.52	53.91	46.05	28.69	8.66
80	88.54	75.32	67.48	56.01	39.12	79.71	54.58	47	29.89	10.06
70	89.18	75.9	68.18	56.95	40.44	81.1	55.16	47.62	30.68	11.38
60	89.43	76.41	68.91	58.03	41.85	82.07	56.05	48.88	32.33	12.4
50	90.13	76.62	69.17	58.38	42.36	83.87	57.65	51.09	35.32	14.32
40	90.77	76.94	69.59	59.12	43.57	86.41	59.03	53.23	38.37	17.77
30	91.71	77.48	70.3	59.86	44.64	88.02	61.24	56.3	42.41	23.62
20	93.87	78.69	71.94	62	47.25	91.32	63.12	58.82	45.22	26.85
10	95.98	81.47	75.53	66.92	54.15	99.37	67.01	64.36	52.73	36.99

Table 5.5. Equal Weight Storage Frequency for TEXFAL Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-June Storage Capacity (%)					End-of-July Storage Capacity (%)				
99	62	39.86	27.52	12.5	0	47.8	26	8.95	0	0
98	64.2	40.63	28.54	12.96	0	49.83	27.83	9.78	5.32	0
95	67.56	42.1	30.76	13.01	0	54.79	29.73	11.9	10.68	1.46
90	68.81	42.79	31.75	13.04	2.25	56.28	30.46	13.2	10.7	4.06
80	70.7	44.3	33.62	13.15	5.03	60.33	32.27	15.15	10.78	6.38
70	74.01	46.66	37.11	15.53	7.76	62.47	34.05	17.71	13.12	8.33
60	76.18	47.75	38.67	18.11	10.26	66.22	36.64	20.29	13.15	10.32
50	77.83	50.05	42.3	23.45	12.05	69.68	38.64	23.79	13.19	11.31
40	81.52	52.19	45.25	26.97	14.61	72.56	41.01	26.88	13.23	13.1
30	86.37	55.31	49.88	33.13	16.47	81.9	44.27	30.69	13.3	14.11
20	92.76	59.34	55.58	40.6	24.44	91.58	52.86	42.19	27.49	15.58
10	99.82	66.4	62.54	49.66	38.68	100	60.4	51.15	40.71	28.17

Table 5.6. Equal Weight Storage Frequency for TEXFAL Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	43.47	20.01	10.62	0	0	39.61	18.49	7.33	0	0.03
98	44.71	20.71	10.63	0	0	42.54	20.45	7.58	1.65	2.61
95	44.96	22.56	10.64	0	2.23	44.98	22.75	7.83	4.86	6.44
90	46.66	23.48	10.67	1.17	4.13	48.06	24.41	7.84	6.65	6.88
80	51.87	30.29	10.7	10.53	7.04	51.68	26.69	7.86	7.88	8.07
70	55.27	32.02	11.57	10.67	7.97	55.57	29.98	9.33	10.12	9.19
60	58.4	33.41	17.47	10.71	9.01	62.74	32.62	13.77	11.85	11.81
50	63.95	36.88	25.36	12.4	10.91	66.91	35.59	19.19	11.9	13.71
40	70.86	38.21	28.82	13.23	13.6	74.48	41.4	23.71	12.37	13.8
30	74.94	42.13	33.68	13.28	16.16	91.01	46.74	27.86	19.66	16.27
20	87.3	48.41	38.67	19.71	16.69	100	59.78	38.54	31.5	28.03
10	97.65	62.62	51.85	30.84	29.34	100	72.11	45.15	40.59	42.74

Exceedance frequencies versus storage volume relationships for Falcon Reservoir are provided in Figures 5.6 through 5.10. These figures depict the probabilities or likelihoods of end-of-the-month storage volumes in Falcon Reservoir given initial reservoir contents at the

beginning of April. For example, with a 30% reservoir capacity at the beginning of April, there is a 40% chance that the reservoir will have 100,149 ac-ft of storage at the end of July.

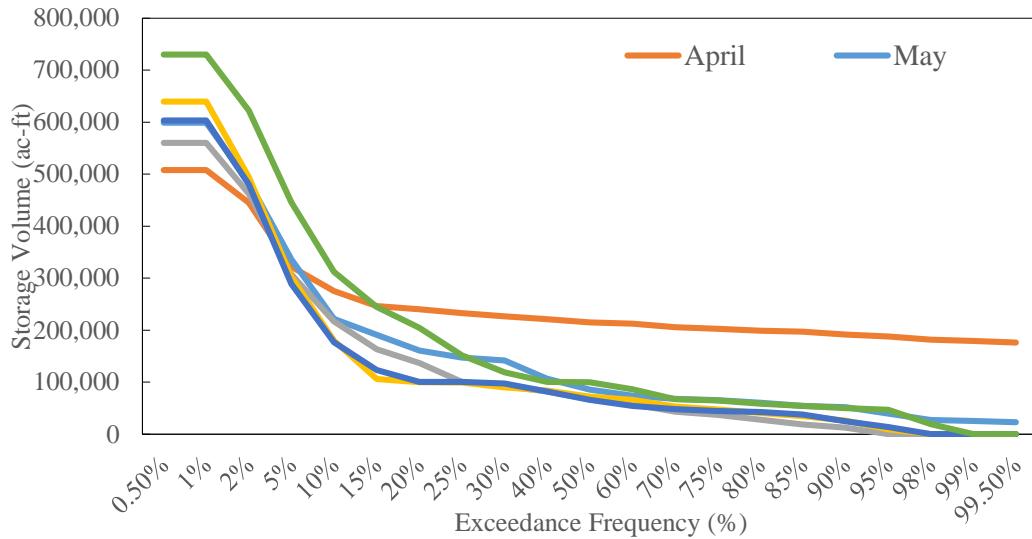


Figure 5.6. End-of-the-month storage exceedance frequency for TEXFAL Reservoir with 15% of initial reservoir content.

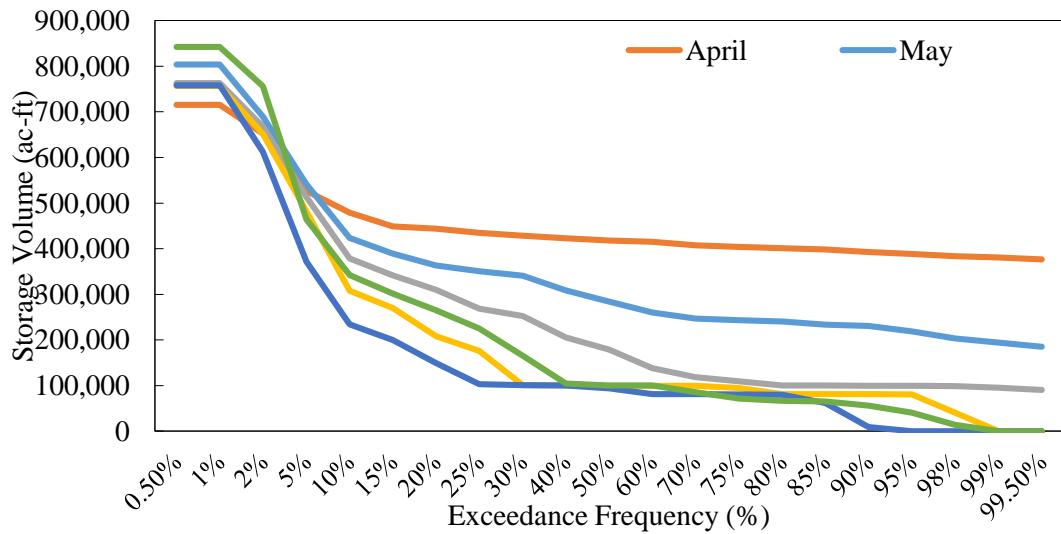


Figure 5.7. End-of-the-month storage exceedance frequency for TEXFAL Reservoir with 30% of initial reservoir content.

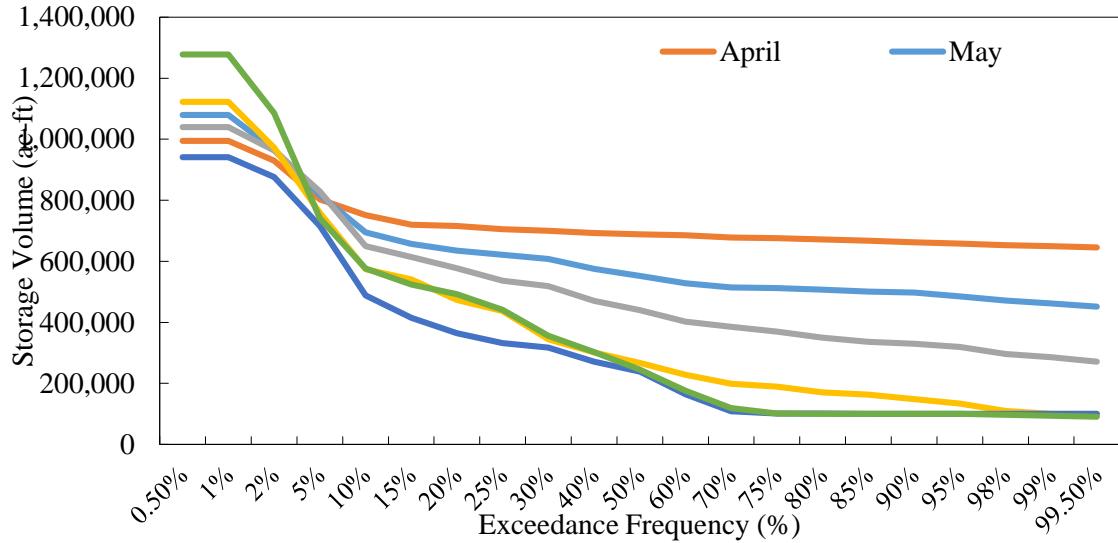


Figure 5.8. End-of-the-month storage exceedance frequency for TEXFAL Reservoir with 50% of initial reservoir content.

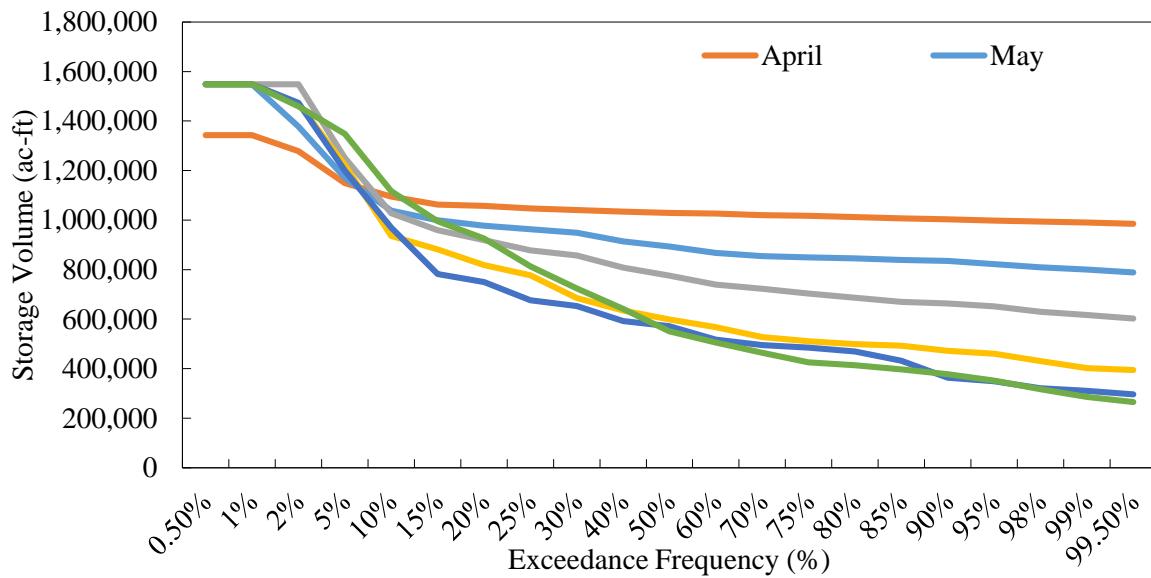


Figure 5.9. End-of-the-month storage exceedance frequency for TEXFAL Reservoir with 75% of initial reservoir content.

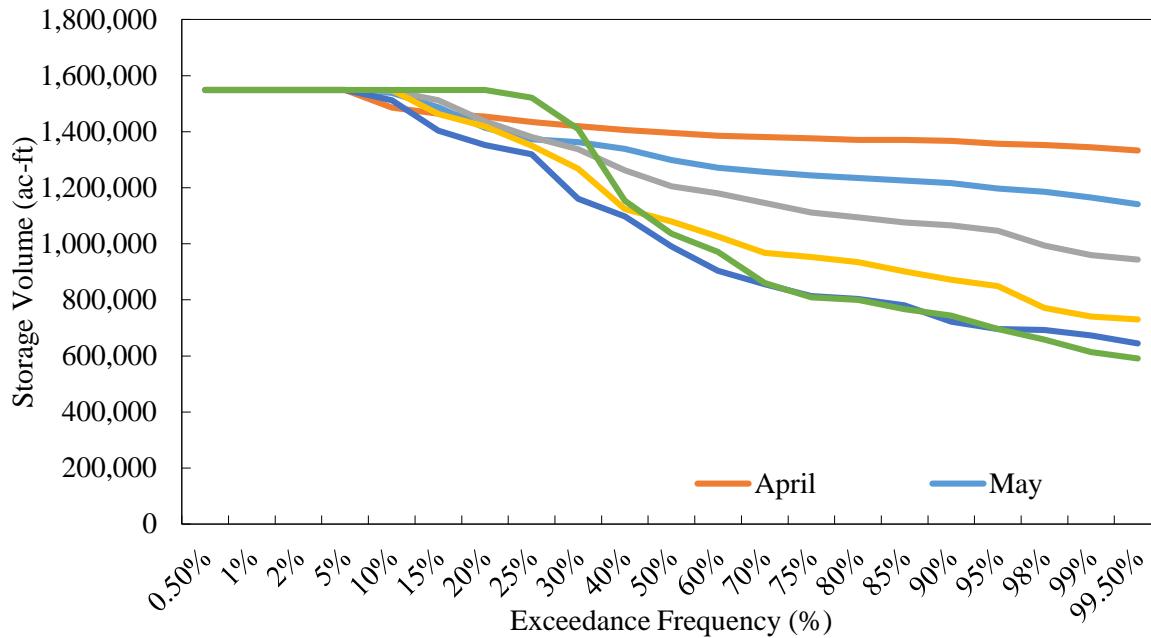


Figure 5.10. End-of-the-month storage exceedance frequency for TEXFAL Reservoir with 100% of initial reservoir content.

Although CRM analysis is widely used to determine the likelihood of water allocations for certain water rights given the initial storage contents of reservoirs during a drought in order to develop curtailment scenarios or drought management plans, the equal-weight option results can be used for water management planning. The detailed drought management scenarios using CRM methods for the Rio Grande will be discussed in Chapter VI of this dissertation.

Probability Array with Total Reservoir Storage Options

As noted in the previous sections, the probability array methodology establishes a correlation between naturalized flow and preceding storage content in which high correlation yields a better prediction of flows. It provides multiple options to compute variable Q_s , and all of those options are evaluated in the following sections.

Flow-Frequency Correlation Comparisons

The probability array option assigns probabilities to sequences based on the relationship between preceding storage condition and naturalized flow volume. Higher correlation values between the preceding storage and flow volume values suggest the potential for improved accuracy with the probability array approach relative to the equal-weight option. The correlation analyses presented here were developed for preceding storage at 100% capacity at the beginning of months February, April, June, August, and October. Naturalized flow volumes were summed for 1, 3, 6, and 12 months following the preceding storage. Simulations were developed for three scenarios: (1) TEXAMI separately, (2) TEXFAL separately, and (3) TEXAMI and TEXFALL combined. Control points CT1160 and DT1001 were used for Amistad and Falcon reservoirs, respectively. Tables 5.7 to 5.10 provide linear and Spearman correlation coefficients for all the combinations of naturalized flow versus preceding storage volume. The linear correlation coefficients tend to be variable for each month of the simulations, in most cases being close to values of 0.1 and 0.4. The Spearman correlation coefficient values are relatively higher in comparison to linear correlation coefficients. This result implies that the correlation between preceding storage and flow volume may be greater than that indicated by the linear correlation coefficient. The Spearman correlation coefficients compares the storage and flow volumes based on a ranking system and a standard statistic commonly to assess linear or nonlinear relationships between the variables. The tables show that the Spearman correlation coefficients have decreasing values, with increases in months for which flow volume is summed. These results are expected since initial storage is more closely related to nearer months than months farther in the future (Bista, 2015).

Table 5.7. Correlation Coefficients for February

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	No. of months for naturalized flows volume					No. of months for naturalized flows volume				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.4361	0.4594	0.4223	0.194	0.2322	0.6031	0.5672	0.4984	0.4158	0.2584
TEXFAL	0.3256	0.4319	0.2771	0.3049	0.2971	0.4829	0.471	0.4193	0.4028	0.2839
Combined	0.4147	0.4784	0.3745	0.2646	0.2753	0.6153	0.5729	0.4823	0.3971	0.2501

Table 5.8. Correlation Coefficients for April

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	No. of months for naturalized flows volume					No. of months for naturalized flows volume				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.2229	0.2841	0.0861	0.1382	0.2055	0.4	0.4522	0.3712	0.1898	0.2284
TEXFAL	0.055	0.1845	0.2335	0.2769	0.29	0.277	0.4063	0.3394	0.2938	0.2817
Combined	0.1544	0.243	0.1663	0.2047	0.2519	0.3535	0.4114	0.3593	0.2176	0.2412

Table 5.9. Correlation Coefficients for June

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	No. of months for naturalized flows volume					No. of months for naturalized flows volume				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.0455	0.1099	0.1412	0.2091	0.2592	0.3568	0.4187	0.4539	0.2779	0.2479
TEXFAL	0.3112	0.3265	0.2901	0.3104	0.3374	0.4655	0.4906	0.4804	0.357	0.3246
Combined	0.1373	0.2034	0.213	0.2597	0.301	0.4392	0.497	0.5073	0.3355	0.2864

Table 5.10. Correlation Coefficients for August

Reservoir	Linear Coefficient No. of months for naturalized flow volume					Spearman Coefficient No. of months for naturalized flow volume				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.4361	0.4594	0.4223	0.194	0.2322	0.6031	0.5672	0.4984	0.4158	0.2584
TEXFAL	0.3256	0.4319	0.2771	0.3049	0.2971	0.4829	0.471	0.4193	0.4028	0.2839
Combined	0.4147	0.4784	0.3745	0.2646	0.2753	0.6153	0.5729	0.4823	0.3971	0.2501

Table 5.11. Correlation Coefficients for October

Reservoir	Linear Correlation Coefficient No. of months for naturalized flows volume					Spearman Correlation Coefficient No. of months for naturalized flows volume				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.3995	0.4027	0.4197	0.4375	0.3117	0.3155	0.3173	0.3441	0.3881	0.2803
TEXFAL	0.3932	0.3818	0.3977	0.3882	0.3294	0.2943	0.2908	0.3003	0.3159	0.2746
Combined	0.4053	0.4069	0.4257	0.4389	0.3485	0.303	0.3041	0.3207	0.3646	0.305

Regression Analysis

The probability array SFF option assigns probabilities to each of the simulation sequences based on the basic correlation between preceding storage volume and the variable $Q\%$. $Q\%$ represents the deviation of flow volume from the expected values of flow volume condition on preceding storage volume as modeled by the regression equation (Wurbs, 2013). The exponential, combined, and power correlation coefficients are presented below for simulation sequences starting at the five months mentioned earlier. The linear correlation

coefficients are obtained by using equation 5.10, where x and y are log transformed values of Q_s and storage S . Tables 5.12 to 5.26 provide both the two reservoirs' scenarios and the combined scenario; the power correlation coefficient has relatively higher correlation values for all months. Exponential correlation coefficients are comparatively higher than linear and combination correlation coefficients. The power correlation appears to be higher in all simulation months, but the exponential correlation coefficient is also higher for some months. Linear correlation seems to be high for the first month, but it decreases over the 12-month period. Also, linear correlations show decreases from higher values for February and April and significant decreases for June. August and October values are almost the same following the higher values in the first month and decrease toward the twelfth month.

Table 5.12. Exponential Correlation Coefficient for Beginning of February

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.4393	0.464	0.4262	0.3204	0.2649
TEXFAL	0.3491	0.4107	0.3115	0.3145	0.2726
Combined	0.4356	0.4754	0.3979	0.3386	0.2825

Table 5.13. Combined Correlation Coefficient for Beginning of February

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.4501	0.4803	0.4443	0.1903	0.2093
TEXFAL	0.3995	0.4867	0.3439	0.3061	0.2439
Combined	0.4479	0.5104	0.4154	0.2593	0.2425

Table 5.14. Power Correlation Coefficient for Beginning of February

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.4567	0.4969	0.4563	0.3329	0.2557
TEXFAL	0.4423	0.4782	0.3978	0.3762	0.2586
Combined	0.4776	0.5201	0.4494	0.3634	0.2716

Table 5.15. Exponential Correlation Coefficient for Beginning of April

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2856	0.3559	0.2322	0.2034	0.228
TEXFAL	0.128	0.2584	0.2729	0.2615	0.2637
Combined	0.2247	0.3237	0.2666	0.2329	0.2514

Table 5.16. Combined Correlation Coefficient for Beginning of April

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2482	0.2866	0.0834	0.1236	0.1932
TEXFAL	0.0374	0.1165	0.1484	0.1994	0.1887
Combined	0.1965	0.2507	0.1626	0.1781	0.2348

Table 5.17. Power Correlation Coefficient for Beginning of April

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.3239	0.3778	0.2516	0.2038	0.2282
TEXFAL	0.0869	0.1735	0.1683	0.2077	0.1864
Combined	0.2815	0.3561	0.2871	0.232	0.2538

Table 5.18. Exponential Correlation Coefficient for Beginning of June

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2126	0.2704	0.2862	0.2342	0.27
TEXFAL	0.3578	0.3558	0.3387	0.2777	0.3055
Combined	0.2938	0.3284	0.3267	0.2612	0.2925

Table 5.19. Combined Correlation Coefficient for Beginning of June

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.0677	0.1347	0.1614	0.2069	0.245
TEXFAL	0.3382	0.3393	0.2818	0.2805	0.314
Combined	0.1549	0.2226	0.2248	0.2473	0.2815

Table 5.20. Power Correlation Coefficient for Beginning of June

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2521	0.322	0.3251	0.2568	0.2661
TEXFAL	0.434	0.4313	0.3774	0.2978	0.31
Combined	0.3424	0.3894	0.3693	0.2852	0.2916

Table 5.21. Exponential Correlation Coefficient for Beginning of August

Reservoirs	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2456	0.1362	0.1936	0.2232	0.2285
TEXFAL	0.2006	0.1838	0.2411	0.2635	0.2661
Combined	0.228	0.1548	0.212	0.2412	0.2544

Table 5.22. Combined Correlation Coefficient for Beginning of August

Reservoirs	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.1439	0.0424	0.1424	0.1799	0.1611
TEXFAL	0.1515	0.1214	0.2179	0.2098	0.1619
Combined	0.16	0.0697	0.177	0.2101	0.1987

Table 5.23. Power Correlation Coefficient for Beginning of August

Reservoirs	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.2797	0.2797	0.1995	0.2188	0.1747
TEXFAL	0.1524	0.1469	0.2165	0.1921	0.1378
Combined	0.2665	0.1414	0.2095	0.2246	0.1942

Table 5.24. Exponential Correlation Coefficient for Beginning of October

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.4079	0.406	0.4237	0.4378	0.312
TEXFAL	0.3572	0.352	0.3646	0.3499	0.2924
Combined	0.3962	0.3936	0.4094	0.4201	0.3263

Table 5.25. Combined Correlation Coefficient for Beginning of October

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.3705	0.3773	0.3932	0.4153	0.2684
TEXFAL	0.3213	0.3124	0.3218	0.3164	0.2964
Combined	0.3731	0.3776	0.3942	0.4145	0.3197

Table 5.26. Power Correlation Coefficient for Beginning of October

Reservoir	No. of month summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.3909	0.3902	0.4027	0.4199	0.2722
TEXFAL	0.2654	0.2668	0.2773	0.2675	0.257
Combined	0.377	0.3726	0.3819	0.3975	0.2994

Storage Flow Frequency Option Using Total Storage

Storage frequency tables were developed using the probability array SFF option, and the power regression was chosen to compute Q_s values. The SFF was developed considering total storage at the beginning of April for Amistad and Falcon Reservoirs. As shown in the previous sections, there is enough correlation coefficient values between initial storage and flow volumes to justify use of the probability array option. For the storage frequency tables, the initial storage contents were set to 100%, 75%, 50%, 30%, and 15% of their full capacity at the beginning of April, and naturalized flows were summed for 12 months to develop a SFF array. The Weibull formula was chosen to assign exceedance probabilities to the flow ratio $Q\%$ since flows were summed for 12 months.

Storage flow frequency analyses were simulated using CRM SFF with total storage option with the beginning of April and predicting storage contents for Amistad and Falcon reservoirs for the next six months into the future. As Table 5.27 shows, with the beginning-of-April storage set at 15% of full capacity, the end of May storage is 30.38% of capacity at 90% exceedance frequency. Similarly, for Falcon Reservoir, there is a 40% probability that storage will equal or exceed 40.61% of storage capacity by the end of September if storage is at 75% of full capacity at the beginning of April (Table 5.32).

Table 5.27. SFF Total Storage Frequency for TEXAMI Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	98.59	87.15	82.23	74.48	60.95	98.15	73.43	56.31	44.34	26.92
98	99.8	87.73	83.05	75.56	62.34	98.4	73.57	56.47	44.56	27.57
95	100	88.56	84.23	77.25	64.85	98.41	74.75	57.84	46.19	29.25
90	100	88.78	84.54	77.63	65.67	98.45	75.14	58.3	46.68	30.38
80	100	89.15	85.07	78.48	66.54	98.62	76.43	59.78	48.41	32.55
70	100	89.38	85.39	78.82	67.11	98.74	76.92	60.36	49.24	33.7
60	100	89.81	85.96	79.46	68.21	99.02	77.86	61.44	50.45	35.17
50	100	90.18	86.51	80.62	69.62	99.24	78.52	62.21	51.29	36.25
40	100	90.67	86.94	80.97	70.19	99.57	79.06	62.65	52.15	37.84
30	100	91.11	87.56	82.15	71.65	100	79.91	63.8	53.56	39.1
20	100	92.09	89	83.72	74.23	100	81.18	65.17	55.09	42.41
10	100	94.33	91.91	87.95	80.87	100	85.92	69.84	60.92	49.71

Table 5.28. SFF Storage Frequency for TEXAMI Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End of June Storage Capacity (%)					End of July Storage Capacity (%)				
99	96.9	72.01	47.3	21.12	10.43	94.37	69.48	42	10.24	10.57
98	97.49	72.76	48.06	22.71	10.51	95.34	70.62	42.91	11.84	11.5
95	98.12	74.29	49.58	28.78	12.4	98.47	74.17	50.11	16.43	13
90	98.52	76.86	52.16	30.43	13.13	98.88	76.76	52.75	17.44	13.87
80	99.12	78.01	53.31	32.6	15.05	99.27	78.05	54.1	20.91	16.09
70	99.38	78.85	54.07	33.86	15.89	99.98	79.24	55.14	23.28	17.25
60	99.62	79.99	55.15	34.82	17.89	100	81.59	57.58	26.83	17.58
50	99.91	80.5	55.62	35.97	19.15	100	83.31	58.99	29.62	19.28
40	100	82.3	57.59	37.95	20.64	100	85.18	61.11	35.22	21.2
30	100	84.57	59.93	40.34	21.62	100	87.28	63.38	41.34	23.7
20	100	87.02	62.06	42.52	27.45	100	90.85	67.12	48.11	31.77
10	100	92.18	66.43	46.33	31.56	100	100	76.37	56.67	46.22

Table 5.29. SFF Storage Frequency for TEXAMI Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	79	54.28	24.55	9.98	10.13	79.52	54.82	16.42	8.97	9.84
98	92.42	61.08	30.67	11.81	12.18	81.43	56.25	22.75	10.16	10.78
95	96.9	61.83	39.42	12.46	14.37	88.09	63.51	31.91	10.28	11.24
90	97.96	64.25	41.24	13.45	15.11	90.43	65.18	35.26	13.02	13.25
80	99.25	69.23	44.56	15.82	17.45	97.8	68.7	42	15.25	14.72
70	99.95	72.25	46.8	18.55	18.99	98.79	71.8	46.18	16.4	15.4
60	100	75.7	48.48	21.41	19.61	99.83	75.36	49.6	19.92	17.14
50	100	79.55	53.88	24.84	20.93	100	79.64	54.93	22.43	18.26
40	100	83.06	56.88	30.66	24.37	100	82.7	58.71	30.24	20.48
30	100	87.6	62.57	40.21	26	100	94.13	65.59	38.62	26.05
20	100	95.21	67.46	56.18	37.66	100	99.31	73.53	52.99	36.49
10	100	100	75.09	65.37	54.12	100	100	84.87	64.99	50.1

Table 5.30. SFF Storage Frequency for TEXFAL Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	85.11	72.93	64.3	51.83	33.38	71.61	49.55	40.32	20.97	1.91
98	86.95	73.81	65.42	53.23	35.19	75.59	51.51	42.91	24.04	3
95	87.32	74.09	65.75	53.57	35.56	76.48	52.04	43.82	25.49	4.32
90	88	74.49	66.35	54.57	36.96	77.88	53.23	45.48	27.8	7.17
80	88.47	75.23	67.33	55.73	38.57	79.08	54.03	46.56	29.04	8.61
70	88.82	75.78	67.98	56.65	39.84	80.39	54.52	47.23	29.83	10.06
60	89.25	76.33	68.77	57.77	41.33	81.72	55.42	48.42	31.52	11.47
50	89.9	76.53	69	58.1	41.84	83.17	56.94	50.6	34.54	13.52
40	90.47	76.86	69.45	58.86	43.06	86.01	58.46	52.82	37.62	16.96
30	91.37	77.32	70.1	59.56	44.13	87.14	60.53	55.83	41.58	22.36
20	93.57	78.61	71.81	61.75	46.77	90.7	62.49	58.45	44.56	25.66
10	95.28	81.27	75.2	66.42	53.31	98.79	66.03	63.49	51.51	35.28

Table 5.31. SFF Storage Frequency for TEXFAL Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-June Storage Capacity (%)					End-of-July Storage Capacity (%)				
99	58.92	36.94	23.63	11.33	0	45.23	23.6	9.11	0	0
98	61.75	39.59	27.46	13.21	0	46.9	25.11	9.13	6.2	0
95	65.99	40.93	29.2	13.24	0	52.83	28.21	10.46	10.87	0
90	67.66	41.86	30.73	13.29	1.97	54.99	28.64	11.14	10.93	4.28
80	69.75	43.35	32.68	13.39	5.08	58.98	30.94	13.59	10.97	6.87
70	73.18	45.62	36.22	13.79	7.98	60.92	32.77	16.42	13.26	7.65
60	75.3	46.84	37.96	16.92	10.5	64.87	35.32	19.6	13.42	8.95
50	76.94	48.88	41.12	21.31	11.54	68.05	37.64	22.73	13.45	9.88
40	80.57	51.25	44.65	25.73	14.62	71.39	40.29	26.09	13.49	11.37
30	84.9	53.9	48.58	31.48	16.55	79.45	42.65	29.5	13.58	13.54
20	91.97	58.53	55.01	39.45	22.45	90.83	51.69	41.1	25.29	15.76
10	98.96	64.85	61.09	47.73	36.81	100	58.95	49.37	38.7	26.72

Table 5.32. SFF Storage Frequency for TEXFAL Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	38.5	16.99	10.92	0	0	35.16	14.25	7.09	0	0
98	42.99	21.15	10.93	0	0.96	39.28	18.19	7.1	1.35	5.24
95	43.31	21.43	10.94	0	2.99	45.23	20.57	7.7	1.98	5.66
90	44.48	22.73	10.96	2.44	4.64	46.61	23.34	8.03	5.51	6.23
80	50.15	28.51	11	7.49	6.76	49.39	25.44	8.05	8.01	7.85
70	53.43	29.8	11.04	10.82	8.81	52.72	29.18	8.09	10.15	9.1
60	56.69	31.27	14.68	10.89	9.68	60.74	32.04	13.04	12.25	12.8
50	61.82	34.6	19.42	11.04	10.85	64.51	33.47	15.97	12.31	14.02
40	69.14	36.92	25.19	13.5	13.11	72.29	40.61	22.31	12.78	14.12
30	73.28	39.06	28.69	13.55	15.2	87.79	45.38	25.95	17.9	16.37
20	86.27	43.42	36.8	17.46	17.09	100	55.02	37.46	30.15	27.72
10	95.56	60.48	52.03	28.47	29.44	100	69.64	43.25	40.25	43.89

Probability Array Storage Change Option

In the previous section, the total storage option with the preceding storage volume at the beginning of month was used to develop the SFF probability array. This section demonstrates how the SFF array is developed from change in storage contents of reservoirs during one or multiple preceding months. Change in storage over a specified length of time can be considered from the beginning of the starting months. An increase in storage content indicates wet hydrologic conditions, while a decrease represents dry conditions (Bista, 2015). As with the total storage option, correlation between naturalized flow volume and storage condition is important in order for the probability array option to provide meaningful estimates of future conditions.

Change in Storage Correlation Analysis

Linear correlation and Spearman rank correlation analysis were performed to analyze the relationship between different naturalized flow volumes and change in storage during preceding months. Naturalized flow volumes summed over 1-, 2-, 3-, 6-, or 12-month periods were considered in combination with 1, 2, 3, 6, or 12 preceding months of change in storage. Exponential and combined regression relations between storage content and flow volume with the same five preceding months were also developed. The Linear and Spearman correlation coefficient along with exponential and combined regressions are presented in Tables 5.32 to 5.42. The linear correlation coefficients provide a comparative measure of how closely the simulated preceding change in storage versus flow volume quantities can conform with a linear equation. The Spearman coefficients provide a comparative measure of how closely the storage change versus flow volume relationship can be described based on a ranking system without regard to the linearity or nonlinearity of the function.

Table 5.33. Correlation Coefficients for 1-Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	Change in storage for preceding months					Change in storage for preceding months				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.0638	0.1884	0.1964	0.1683	0.0987	0.3052	0.1833	0.1172	0.1461	0.2905
TEXFAL	0.187	0.0632	0.0351	0.0415	0.0719	0.1875	0.0602	-0.005	0.074	0.2269
Combined	0.1252	0.1868	0.1677	0.1349	0.1197	0.2395	0.1339	0.0944	0.1156	0.282

Table 5.34. Exponential Correlation Coefficients for 1-Month Naturalized Flow Summation

Reservoir	Change in storage for preceding months				
	1	2	3	6	12
TEXAMI	0.2156	0.2368	0.1798	0.1652	0.1818
TEXFAL	0.258	0.0899	0.0485	0.0838	0.1041
Combined	0.2785	0.2147	0.1455	0.1447	0.1811

Table 5.35. Combined Correlation Coefficients for 1-Month Naturalized Flow Summation

Reservoir	Change in storage for preceding months				
	1	2	3	6	12
TEXAMI	0.1021	0.1443	0.1678	0.1801	0.1899
TEXFAL	0.0897	0.0375	0.011	0.0288	0.2115
Combined	0.1353	0.1524	0.1279	0.1609	0.2131

Table 5.36. Correlation Coefficients for 2-Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	Change in storage for preceding months					Change in storage for preceding months				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.062	0.189	0.156	0.171	0.101	0.205	0.13	-0.08	0.065	0.192
TEXFAL	0.073	-0.028	-0.031	-0.039	0.082	0.046	0.023	-0.03	-0.03	0.151
Combined	0.076	0.145	0.11	0.107	0.114	0.089	0.077	-0.02	0.033	0.203

Table 5.37. Exponential Correlation Coefficients for 2-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.1343	0.1652	0.0612	0.1139	0.1414
TEXFAL	0.1075	0.0086	0.0263	0.0149	0.0535
Combined	0.1388	0.12	0.0337	0.0563	0.1272

Table 5.38. Combined Correlation Coefficients for 2-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.1136	0.1813	0.1095	0.1972	0.1884
TEXFAL	0.0057	0.0132	0.0121	0.0623	0.1812
Combined	0.1064	0.1453	0.1027	0.1508	0.2256

Table 5.39. Correlation Coefficients for 3-Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	Change in storage for preceding months					Change in storage for preceding months				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.059	0.2	0.164	0.205	0.122	0.127	0.183	-0.04	0.149	0.203
TEXFAL	0.02	-0.07	-0.07	-0.06	0.088	-0.01	-0.07	-0.07	-0.09	0.192
Combined	0.047	0.133	0.086	0.109	0.145	0.024	0.075	-0.04	0.026	0.22

Table 5.40. Exponential Correlation Coefficients for 3-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.096	0.175	0.0829	0.1636	0.2482
TEXFAL	0.0338	0.0886	0.0902	0.0754	0.0917
Combined	0.0706	0.0969	0.0147	0.0589	0.1796

Table 5.41. Combined Correlation Coefficients for 3-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.1088	0.1594	0.08	0.2394	0.1891
TEXFAL	0.0095	0.01	0.0218	0.1301	0.1692
Combined	0.0869	0.1676	0.0598	0.1287	0.2138

Table 5.42. Correlation Coefficients for 6-Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	Change in storage for preceding months					Change in storage for preceding months				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.077	0.183	0.1	0.103	0.019	0.102	0.167	-0.016	0.077	0.076
TEXFAL	0.103	-	0.043	0.035	-	0.049	-0.04	0.044	-0.014	0.011
Combined	0.1	0.107	0.05	0.035	0.013	0.015	0.106	0.006	0.045	0.1

Table 5.43. Exponential Correlation Coefficients for 6-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.0858	0.1539	0.0443	0.068	0.0485
TEXFAL	0.0895	0.0245	0.0181	0.0142	0.0019
Combined	0.0941	0.0973	0.0242	0.0287	0.0348

Table 5.44. Combined Correlation Coefficients for 6-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.0366	0.091	0.014	0.0483	0.1026
TEXFAL	0.1147	0.0455	0.0294	0.1019	0.0826
Combined	0.0426	0.1114	0.0356	0.003	0.0857

Table 5.45. Correlation Coefficients for 12-Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient					Spearman Correlation Coefficient				
	Change in storage for preceding months					Change in storage for preceding months				
	1	2	3	6	12	1	2	3	6	12
TEXAMI	0.11	0.183	0.089	0.077	-0	0.082	0.115	-0.04	0.033	0.003
TEXFAL	0.101	-0.04	-0.02	-0	-0.03	0.048	-0	0.011	0.043	0.046
Combined	0.133	0.108	0.047	0.034	-0.02	-0.02	0.036	-0.04	-0	-0

Table 5.46. Exponential Correlation Coefficients for 12-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.1049	0.1545	0.0522	0.0528	0.0094
TEXFAL	0.0767	0.0231	0.011	0.0246	0.0284
Combined	0.1151	0.0959	0.0272	0.0307	0.0112

Table 5.47. Combined Correlation Coefficients for 12-Month Naturalized Flow Summation

Reservoir	No. of months summed for naturalized flows				
	1	2	3	6	12
TEXAMI	0.0359	0.0701	0.0367	0.0435	0.0581
TEXFAL	0.1277	0.0711	0.0225	0.0497	0.0544
Combined	0.0505	0.1014	0.0706	0.013	0.0412

The correlation coefficients varied for all periods of naturalized flows considered in simulations and characterized—with a minimal degree of linear correlation—the change in storage. Correlations for 1- and 2-month summations appear to be higher compared to 3-, 6-, and 12-month summations. The correlation trend tends to decrease as the preceding storage and summation month are simulated for the longer periods of simulations. Naturalized flow volume for 2 and 3 months shows significant correlation to all preceding periods of change in storage that were considered. Naturalized flow volume for 1 month has a linear correlation coefficient of 0.1964 for a change in storage period of 3 months. The exponential and combined correlation coefficients for the same period are 0.2147 and 0.1524, respectively. The other periods of analysis show insignificant correlations.

Storage Flow Frequency Using Change in Storage

Storage frequency tables were developed using the probability array SFF option with change in storage, and combined regression was chosen to compute Q_S values. The initial reservoir storage contents were set to 100%, 75%, 50%, 30%, and 15% of their full capacity at the beginning of April, and naturalized flows were summed for 12 months. The Weibull formula was chosen to assign exceedance probabilities to the flow ratio $Q\%$ because flows were being summed for 12 months. The storage frequency tables were developed with initial storage at 50% capacity for a naturalized flow volume of 12 months starting in April. The change in storage period of 3 months showed the best correlation with naturalized flows of 12 months, and it was used in this analysis. As Table 5.43 shows, with the beginning-of-April storage set at 30% of full capacity, the end of May storage is 47.83% of capacity at 95% exceedance frequency for Amistad Reservoir. Similarly, for Falcon Reservoir, there is a 50% probability that storage will equal or exceed 11.89% of storage capacity by the end of September if storage is at 30% of full capacity at the beginning of April (Table 5.48). The storage frequency exceedance for the rest of the months are provided in Tables 5.43 to 5.48.

Table 5.48. SFF Storage Frequency for TEXAMI Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	98.65	88.34	83.48	75.75	62.26	97.85	73.12	57.64	45.45	28.1
98	98.8	88.97	84.38	76.92	63.79	98.37	73.58	58.19	46.14	28.11
95	98.8	89.62	85.3	78.3	65.8	98.37	74.85	59.71	47.83	30.03
90	98.8	89.81	85.57	78.65	66.46	98.37	74.97	59.85	48.04	31.13
80	99.34	90.05	85.91	79.07	67.06	98.37	75.76	60.78	49.16	32.51
70	99.87	90.42	86.44	79.84	68.05	98.38	76.38	61.52	50.19	33.98
60	99.87	90.64	86.75	80.31	68.85	98.38	76.88	62.12	50.93	35.31
50	99.87	90.93	87.16	80.92	69.58	98.38	77.46	62.81	51.68	37
40	99.87	91.2	87.54	81.52	70.82	98.38	78.24	63.74	52.83	38.48
30	99.87	91.56	88.05	82.21	72.01	98.39	78.72	64.31	53.7	39.22
20	99.87	92.06	88.76	83.4	74.14	99.87	79.87	65.67	55.42	42.54
10	99.87	94.92	92.82	89.28	82.95	99.87	85.6	72.5	64.23	53.99

Table 5.49. SFF Storage Frequency for TEXAMI Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-June Storage Capacity (%)					End-of-July Storage Capacity (%)				
99	96.91	72.12	48.15	23.93	10.87	94.11	69.39	42.33	9.72	10.77
98	97.08	72.36	48.4	26	12.26	94.24	69.44	43.58	12.34	11.04
95	98.15	75.67	51.76	31.17	12.48	97.69	74.39	50.48	15.38	12.47
90	98.46	76.02	52.12	33.61	13.82	98.04	75.48	51.56	17.21	13.59
80	98.46	76.71	52.82	35.87	15.61	98.25	75.92	52.01	20.9	15.71
70	98.46	77.2	53.32	36.83	17.13	98.41	78.13	54.02	24.31	17.01
60	98.46	78.1	54.23	38.02	17.88	98.42	79.37	55.24	25.85	18.5
50	98.46	79.02	55.17	39.08	18.8	98.42	81.38	57.03	30.08	19.63
40	98.46	80.69	56.86	40.85	19.95	98.42	83.33	58.55	34.23	21.34
30	98.47	82.39	58.59	42.86	21.67	98.42	84.66	60.9	40.93	22.39
20	98.93	85.21	61.45	45.9	26.28	99.32	88.6	64.92	46.47	30.72
10	99.88	91.31	67.62	52.68	32.42	99.88	98.41	75.3	58.47	45.25

Table 5.50. SFF Storage Frequency for TEXAMI Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	89.15	56.98	24.2	12.22	13.54	78.36	53.66	15.55	11.6	11.16
98	91.6	60.5	30.78	12.22	14.62	80.4	56.59	22.54	12.5	13.27
95	95.89	64.49	38.24	12.67	15.48	87.33	62.82	32.92	13.15	13.4
90	96.69	65.35	40.77	13.54	16.78	88.46	64.2	36.23	14.36	14.01
80	96.87	69.89	45.54	16.63	18.17	96.25	67.57	40.75	15.34	14.99
70	98.03	73.27	47.37	18.59	19.92	97.67	71.27	45.04	16.38	16.18
60	98.46	75.3	48.11	21.09	21.07	98.62	73.21	47.71	17.79	17.16
50	98.46	77.66	52.59	24.71	21.57	98.63	75.37	53.04	20.69	18.6
40	98.46	80.79	57.05	29.27	23.83	98.63	81.77	57.15	31.39	22.34
30	98.46	84.49	60.61	34.43	26.39	98.63	89.44	64.58	38.41	27.63
20	98.47	90.71	66	53.1	35.54	99.89	97.65	73.2	53.46	36.56
10	99.88	98.58	72.65	65.24	51.9	100	98.63	83.49	65.89	57.03

Table 5.51. SFF Storage Frequency for TEXFAL Reservoir for April and May

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100	75	50	30	15	100	75	50	30	15
	End-of-April Storage Capacity (%)					End-of-May Storage Capacity (%)				
99	85.13	72.72	64.06	51.57	33.17	71.84	50.22	40.29	21.15	3.04
98	87.28	73.89	65.53	53.31	35.32	75.5	52.44	43.2	24.64	4.03
95	87.33	74.19	65.93	53.88	36.15	75.63	52.91	43.96	25.9	5.22
90	87.71	74.37	66.18	54.28	36.8	77.89	54	45.37	27.78	7.55
80	88.04	75.06	67.06	55.48	38.53	78.32	54.58	46.41	29.33	8.63
70	88.43	76.05	68.36	56.88	40.39	79.67	55.49	47.36	30.08	10.39
60	88.84	76.32	68.8	57.83	41.81	80.78	56.68	49.21	32.95	11.66
50	89.18	76.54	69.07	58.25	42.25	83.47	58	50.98	35.15	14.32
40	89.6	76.8	69.38	58.62	42.76	85.74	60.04	53.59	38.7	18.78
30	90.3	77.38	70.16	59.69	44.24	87.17	61.65	55.99	42	23.38
20	91.81	77.85	70.82	60.68	45.65	89.15	63.72	59.02	45.91	28.46
10	94.36	81.34	75.33	66.64	53.75	96.82	67.75	64.28	52.27	35.93

Table 5.52. SFF Storage Frequency for TEXFAL Reservoir for June and July

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-June Storage Capacity (%)					End-of-July Storage Capacity (%)				
99	59.4	37.42	23.99	11.11	0	46.45	24.78	9.14	0	0
98	61.92	39.87	27.66	12.94	0	47.31	25.62	9.15	8.74	0
95	65.44	41.46	29.74	12.97	0	51.78	28.85	11.06	12.41	0
90	66.82	42.49	31.24	13.03	2.38	54.78	29.68	12.7	12.46	2.48
80	69.62	43.69	32.93	13.15	5.11	58.22	31.92	15.49	12.52	5.48
70	72.05	45.81	36.22	15.4	7.62	61.47	33.83	17.34	15.17	7.24
60	76.03	48.72	39.95	19.65	9.2	64.13	36.2	20.28	15.31	8.96
50	76.36	50.32	42.82	23.47	11.97	67.72	37.88	22.81	15.34	9.7
40	78.88	51.73	44.67	26.34	14.3	71.5	41.02	27.43	15.37	12.01
30	85.9	55.69	50.48	34.35	17.65	75.64	41.98	28.96	15.45	13.62
20	89.86	59.25	55.7	41.32	24.78	87.79	54.34	45.32	35.82	15.67
10	96.57	67.56	66.28	54.08	37.25	97	61.21	53.1	48.8	22.57

Table 5.53. SFF Storage Frequency for TEXFAL Reservoir for August and September

Exceedance Frequency (%)	Beginning-of-April Storage as Percentage of Capacity									
	100 75 50 30 15					100 75 50 30 15				
	End-of-August Storage Capacity (%)					End-of-September Storage Capacity (%)				
99	35.1	14.61	10.93	0	0	35.33	14.48	7.25	0	3.29
98	37.79	19.91	10.94	0	0	38.59	17.27	7.26	2.01	3.29
95	41.8	21.97	10.97	0	2.3	42.25	22.35	8.21	2.02	5
90	43.37	22.56	10.98	0	3.5	43.98	23.49	8.21	3.61	6.36
80	48.41	27.01	11.01	7.98	5.77	47.46	25.62	8.23	7.1	7.67
70	51.89	31.6	11.03	12.52	7.32	51.45	28.43	8.24	10.27	9.14
60	55.79	32.66	12.31	12.6	8.93	56.82	30.68	9.88	10.49	10.05
50	61.94	34.13	16.47	12.71	10.33	63.84	33.14	13.76	11.89	12.72
40	66.96	38.96	26.04	15.58	12.31	68.46	38.29	20.01	11.98	13.52
30	72.31	41.37	29.81	15.67	15.21	85.23	45.41	27.37	19.52	17.34
20	82.73	46.93	39.76	23.89	16.96	97.11	59.94	37.69	28.04	26.73
10	88.75	62.55	56.45	38.42	30.55	100	69.53	48.03	47.36	44.79

The storage capacity frequency for the end of May and end of August has significant variations for Falcon Reservoir. For example, there is a 50% likelihood that storage in Falcon Reservoir will equal or exceed 12.71% capacity given 30% of reservoir capacity at the beginning of April, and the capacity is slightly lower (11.89%) for the same period at the end of September. However, there is a 60% chance that predicted storage equals or exceeds 48.72% capacity at the end of June for Falcon Reservoir given the 75% storage capacity at the beginning of April compared to 36.2% for the same condition at the end of July. Table 5.45 shows the end-of-September storage capacity is at 22.54% of total capacity at 98% exceedance frequency. Similarly, Table 5.47 indicates a probability of 98% for storage capacity at the end of July to equal or exceed 25.62%.

Comparison between Equal Weight and Probability Array Methods

Equal weight and probability array methods were applied for the Amistad-Falcon Reservoir system. The correlation coefficients seem to be acceptable to use SFF options. Probability array SFF options with total storage and change of storage appear to produce improved storage exceedance frequency results for Amistad and Falcon Reservoirs compared to the equal-weight option. The difference in storage frequency relationships for preceding storage levels set at 75% and 15% of storage capacity does not appear to be significant. The equal-weight option shows slightly lesser values of storage capacity than the probability array option when initial storage level is at 100% of capacity. In addition, relatively smaller values of storage appear for the probability array option with initial storage content of 15% of capacity. The high probabilities assigned to high flow simulation sequences when storage is at full capacity and higher probabilities to low flow simulation sequences when storage is at the lowest capacity are decisive factors in using the probability array option (Bista, 2015).

The content of initial reservoir levels are critical for developing likelihood scenarios of storage exceedance into future months. Higher initial storage capacities imply wet hydrologic conditions, and storage exceedance for near preceding months will have higher probabilities compared to probabilities for more distant preceding months. The low preceding storage levels suggest dry hydrologic conditions for the future predicted probability of exceedance. These can be seen in storage frequencies developed using the equal-weight, total storage, and storage

change scenarios of the probability array SFF option. The naturalized flow volume seems to correlate better with a longer preceding month of change in storage for 1, 2, and 3 months, whereas 6 and 12 months of naturalized flow volumes have better correlation for shorter preceding months of change in storage. Even though the equal-weight option has slightly higher probabilities with higher storage exceedance when reservoirs are at full capacity, the probability array option produces better results for lower initial reservoir storage in both shorter and longer preceding months. Hence, the probability array option is the better alternative for modeling Amistad and Falcon Reservoirs in the Rio Grande.

CHAPTER VI

DROUGHT MANAGEMENT

The Rio Grande Valley is prone to inconsistent precipitation and frequent and prolonged drought that cause water shortages in the region. The international Amistad and Falcon Reservoirs supply almost all water demands in the Lower Rio Grande Valley (LRGV) based on a special prior appropriation doctrine in which “purpose of use” sets priorities among various water right groups. Municipal rights have the highest priority, with buffer storage of 225,000 ac-ft/month in the DMI pool of the Amistad-Falcon Reservoir system, and they are designated with 240,914 ac-ft/year diversion rights in the Rio Grande WAM. Class A and Class B irrigation have the biggest diversion rights—86% of the total allocations in the LRGV—with annual diversions of 1,460,998 ac-ft and 163,305 ac-ft for Class A and Class B irrigation rights, respectively. (Mining rights receive a negligible amount; therefore, was eliminated from the simulation analyses.) The IBWC owns and operates Amistad and Falcon Reservoirs (along with several others in the Basin) as a system based on designated conservation pools allocated for Mexico and United States separately in accordance with the 1944 treaty. The Rio Grande watermaster office collects requests for weekly or monthly water demands for each water right group from irrigation districts and submits them to the IBWC for storage releases from Falcon Reservoir. The IBWC allocates requested diversions only after assessing current U.S. storage volume in the Amistad-Falcon Reservoir system and subtracting DMI (225,000 ac-ft/month), dead pool (4,600 ac-ft/month), and operating reserves (75,000 ac-ft/year). The municipal diversions are allocated fully first, then Class A, if surplus storage is available, followed by Class B. In times of drought conditions, Class B rights will be curtailed first, if necessary. Class A rights are pursued depending on the diversion needs. As noted in Chapter V, the municipal pool is conservatively protected by IBWC with large purchases of irrigation rights by cities. Extreme and prolonged drought in the Valley fuels the urgency of municipal storage accumulation and necessitates a well-established water marketing system in the region. During the drought, all accrued shortages are shared among the Class A and Class B water right holders, leaving farmers and irrigation districts uncertain about the likelihood of receiving any water allocation in upcoming months. The Rio Grande WAM covering the 1940–2015 hydrologic period of analyses are described in Chapter IV of this research, and the annual end-

of-period storage and evaporation volumes for Amistad and Falcon Reservoirs are shown in Figures 6.1 through 6.4. Amistad Reservoir had low storage volumes from 1993 through 2001 and from 2009 through 2013. The drought period in the 1950s is considered the “drought of record” in the state of Texas and is used as a benchmark in preparation of state water planning. However, the Amistad Reservoir had the lowest storage in 2011 and 2012, with 269,055 ac-ft and 290,546 ac-ft, respectively. Unlike Amistad, the Falcon Reservoir experienced severe and prolonged water shortages for the periods of 1944–1957, 1960–1970, and 1977–2015, with very few years of higher storage volumes. As with Amistad, Falcon Reservoir had the lowest storage volumes in 2011 and 2012 with 38,344 ac-ft and 43,473 ac-ft, respectively. However, the lower storage contents at Falcon reservoirs does not carry any beneficial information to irrigation districts unless both Amistad and Falcon storages considered as a system. The lowest storage content at Falcon is designated to be at 6% or 100,000 ac-ft of capacity but the lowest storage at Amistad is designated to be at 47% or 850,000 ac-ft or capacity. These values are included in OR record in the Rio Grande WAM DAT file and used to balance the system per IBWC reservoir operation policy.

The Lower Rio Grande Basin experiences frequent and prolonged drought, especially during irrigation season when diversions for agricultural use become critical. Although water rights priorities in the Basin are well established for allocation scheduling, lack of knowledge relating initial reservoir storage at Amistad-Falcon reservoir system to usage in subsequent months based on likelihood predictions persists among irrigation water right holders in the Lower Rio Grande Valley. In the CRM mode, WRAP divides a period of hydrologic analyses into small sequences of simulation while establishing linear correlations between storage and flow volumes of the particular reservoir of interest based on either preceding months’ storage or full storage options. As demonstrated in Chapter V, the CRM SFF option with full storage level produces better correlation results for the Rio Grande. Hence, it was used in this study to perform drought analyses, the results of which are discussed here.

The objective examined in this chapter was to examine the likelihood of meeting water demands in the next few months into the future for the LRGV subject to initial storage contents in the Amistad-Falcon Reservoir system. Reliability and exceedance frequency analyses were developed using CRM with the SFF option predicting flow volumes for three months into the future beginning in May, June, and July while constrained by various initial reservoir or

drought storage triggers. The WRAP BES option was used throughout the simulations to accurately represent reservoir storage contents instead of using maximum conservation levels. Two types of drought scenarios were developed based on the following constructs: (a) the State Drought Preparedness Plan (SDPP) and (b) the Municipal Drought Plans (MDP) in the LRGV.

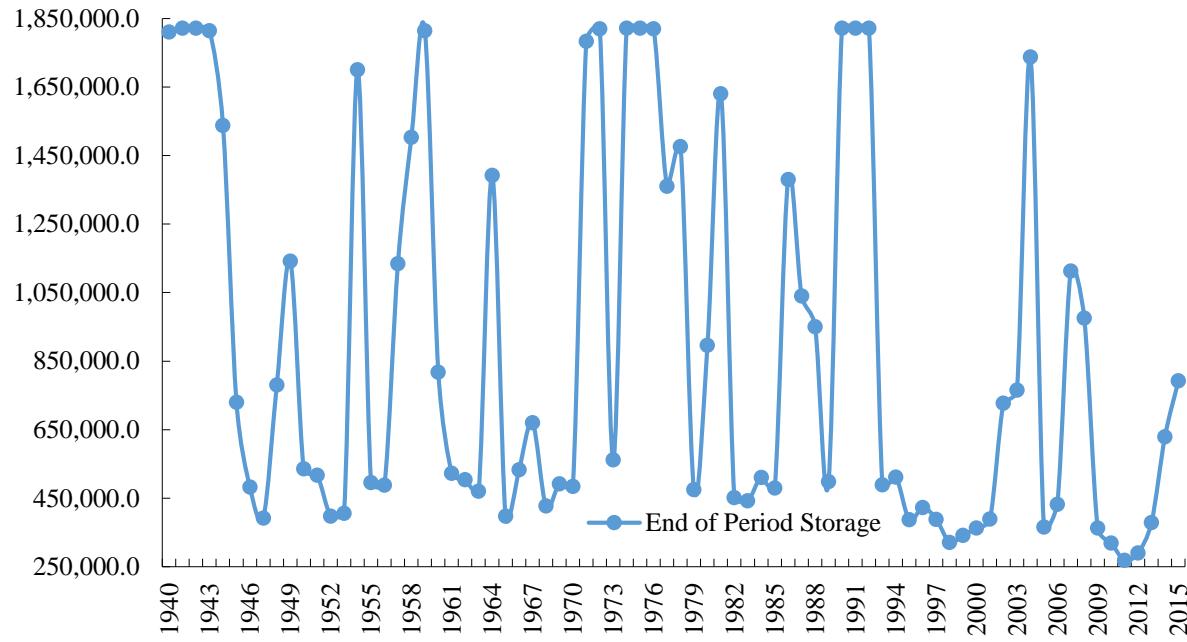


Figure 6.1. Annual end-of-period storage volume (ac-ft) for Amistad Reservoir for each end of period covering the 1940–2015 hydrologic period of analysis.

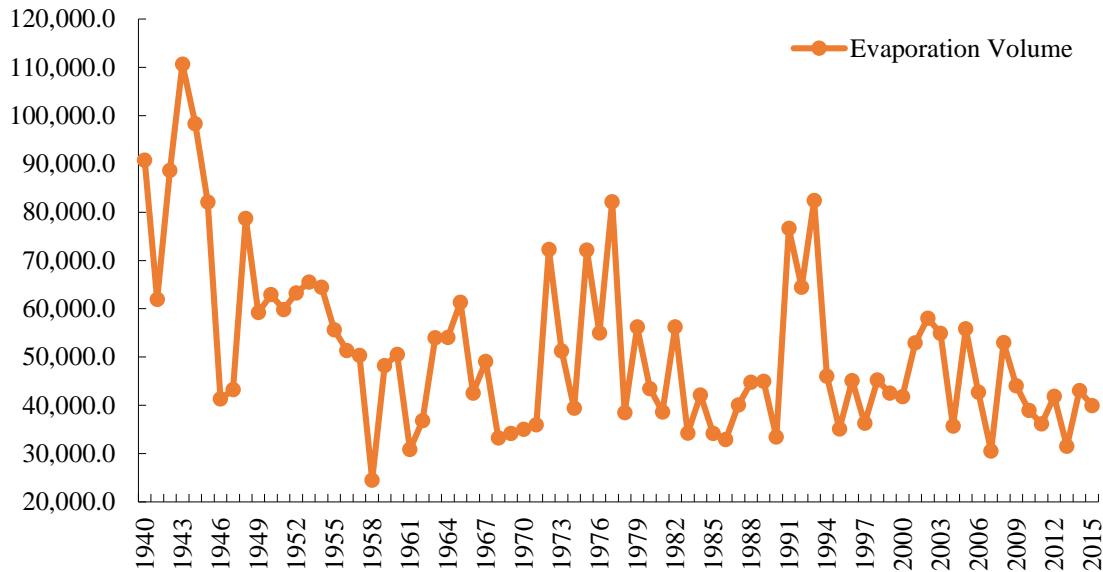


Figure 6.2. Annual end-of-period evaporation volume (ac-ft) for Amistad Reservoir covering the 1940–2015 hydrologic period of analysis.

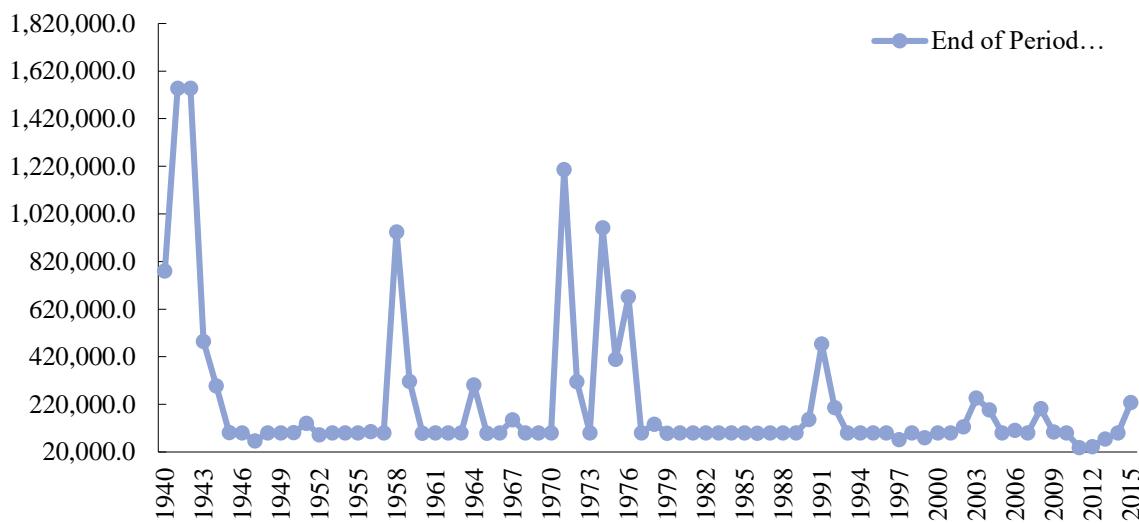


Figure 6.3. Annual end-of-period storage volume (ac-ft) for Falcon Reservoir for each end of period covering the 1940–2015 hydrologic period of analysis.

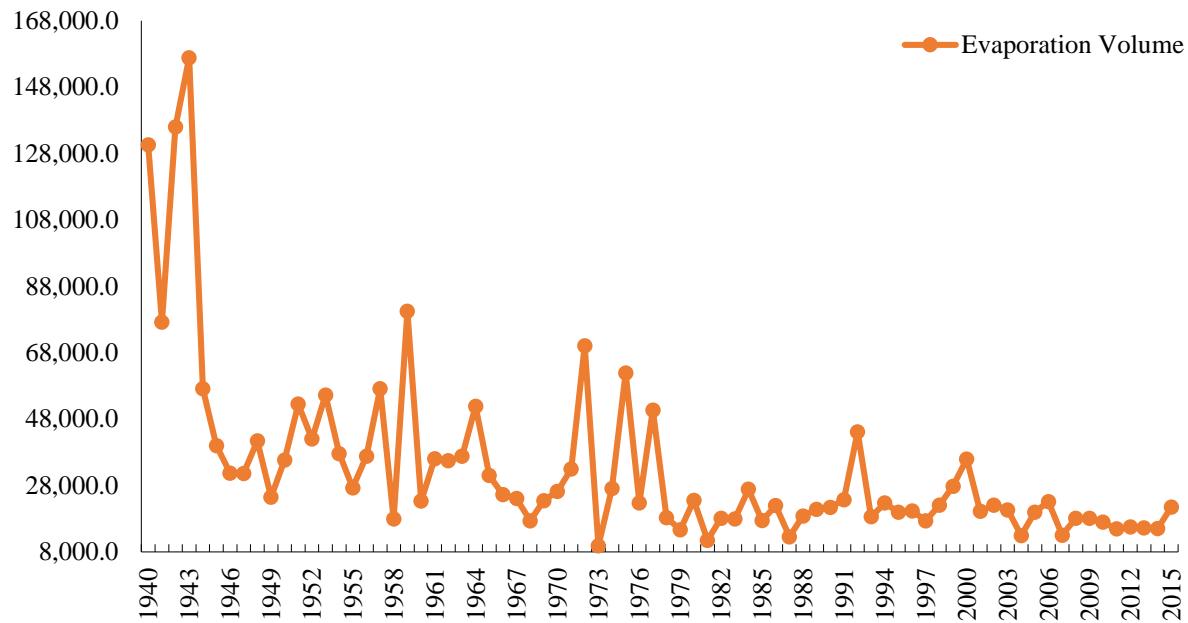


Figure 6.4. Annual end-of-period evaporation volume (ac-ft) for Amistad Reservoir covering the 1940–2015 hydrologic period of analysis.

State Drought Preparedness Plan

The IBWC does not have specific drought contingency or mitigation plans for the Rio Grande since allocation priorities among the water rights groups are already firmly established; Class B rights are automatically subject to curtailment, followed by Class A rights, in order to protect municipal rights. The IBWC determines these curtailment actions based on current reservoir storage after conducting allocation assessments and informs the Rio Grande watermaster of the decision. Although there are no drought contingency plans for water allocations in the Rio Grande, the state and regional drought contingency plans are examined using various initial storage volumes as storage triggers. The Texas Drought Preparedness Plan, developed in 2005 by the State Drought Preparedness Council, includes five different drought stages: (1) abnormally dry, (2) first-stage drought, (3) severe drought, (4) extreme drought, and (5) exceptional drought, with reservoir storage contents of 10%, 20%, 40%, 60%, and 70% of capacities, respectively (SDPC 2005). Possible impacts of each drought stage along

with streamflow percent exceedance and reservoir conservation storages within a region are explained in detail in the Drought Preparedness Plan. The objective of part of this research was to use those five drought stages and reservoir contents as triggers and develop a storage exceedance frequency analysis for Falcon Reservoir and reliabilities for municipal, Class A, and Class B irrigation rights.

Beginning-of-May Simulations

All simulation scenarios were run using the BES option of SIM beginning with the May storage content and predicting the likelihood of exceeding maximum flow volumes for three months (May, June, and July) into the future using the CRM SFF option. The linear and Spearman correlation coefficients and the exponential regression option to determine Q_s are provided in Table 6.1. The correlation coefficients are high enough to allow the use of the CRM option for drought management simulations. However, the correlation and regression coefficients are higher (except the Spearman correlation coefficient in June) at the beginning of May simulations compared to June and July.

Table 6.1. Correlations and Exponential Regression for Rio Grande Drought Simulations Using CRM SFF Option

Beginning Month	Linear Correlation	Spearman Correlation	Exponential Regression
May	0.2544	0.4734	0.3308
June	0.2130	0.5073	0.3267
July	0.1911	0.1875	0.2333

Table 6.2 shows the summary of likelihood for exceeding initial reservoir storage in various drought conditions at Falcon Reservoir. There is only a 10% likelihood that the reservoir exceeds the maximum capacity of 1,548,640 ac-ft at the end of May if storage was at 100% at the beginning of the month. If Falcon Reservoir is at 10% of capacity or in exceptional

drought condition at the beginning of May, then there is 68.1% likelihood that 23,982.3 ac-ft is exceeded by the end of the month. It continues to increase by 88.3% and 87.4% by the end of June and July, respectively. It shows that due to curtailment of Class A and Class B rights, the storage will only be used to meet the municipal demands of the LRGV. Hence, the likelihood of exceeding initial storage at the end of June and July increase. However, if the reservoir is at 40% capacity at the beginning of May, the likelihood of exceeding 223,493.5 ac-ft by the end of the month is 34.6% and decreases to 14.7% and 13.1% by the end of June and July. It can be concluded that if Falcon is at 30% capacity at the beginning of May, then there is a 40.3% chance that 126,601 ac-ft storage is equaled or exceeded by the end of the month and a probability of 78.9% and 85.9% that the same storage will not be exceeded by the end of June and July. These significant changes in storage may be attributed to some diversions for meeting Class A irrigation demands in the LRGV. In that case, 30% initial storage at the beginning of May can be used as a cutoff point between complete curtailment of Class A and Class B rights and some diversions to meet irrigation demands.

Table 6.2. End-of-Month Storage Exceedance Frequency for Initial Storage Volume at the Beginning of May

Initial Storage (%)	Storage (ac-ft)	May (%)	June (%)	July (%)
100	1,548,640.0	10.0	25.0	10.0
10	23,982.3	68.1	88.3	87.4
15	35,737.4	50.7	81.4	80.4
20	57,616.5	49.2	69.4	46.7
30	126,601.0	40.3	21.1	14.1
40	223,493.5	34.6	14.7	13.1
50	349,151.9	30.0	13.2	12.9
60	503,066.5	20.1	15.0	14.3
70	686,223.9	16.2	16.8	17.1

The volume reliabilities for the three major water right groups for the end of May is provided in Table 6.3. The exceptional drought condition is activated when Falcon Reservoir is at 10% storage level at the beginning of May, and by the end of the month, the volume

reliabilities for Class A and Class B irrigation rights would be at 11.09% and 8.98%, respectively. Both Class A and Class B rights would completely be curtailed at this storage level because the municipal water supply becomes the highest priority. The municipal reliability for the LRGV is maintained at 100%. As the severity of drought conditions reduces from an exceptional drought to abnormally dry, the volume reliabilities for Class A and Class B irrigation rights increase significantly by the end of May. As noted in the reliability analysis in the previous chapters, initial storage content is critical to meeting water demands. At 40% storage content of Falcon Reservoir, the volume reliabilities for Class A and Class B irrigation rights are at 77.94% and 64.12%, respectively. These amounts would be considered a better condition for the LRGV since both irrigation rights will receive about 78% and 64% of the demand by the end of May.

Table 6.3. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation Rights in May

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
10	100.00	11.09	8.95
20	100.00	25.20	17.79
40	100.00	77.94	64.12
60	100.00	86.29	86.29
70	100.00	89.72	89.72

Table 6.4 shows the summary of storage exceedance frequencies for the end of May given initial trigger contents that activate different drought conditions at the beginning of May. There is an 80% chance that only 4.09% of the maximum storage content is exceeded by the end of May during exceptional drought conditions given an initial reservoir level at 10% of capacity at the beginning of the month. As initial storage content increases or drought conditions are lessened, the frequency exceedance of storage volume increases. There is a 90% probability that 57.93% of the maximum storage will be exceeded by the end of May under abnormally dry conditions if there exists 70% of the initial reservoir storage in Falcon

Reservoir at the beginning of May. However, end-of-month storage contents are higher with smaller exceedance frequencies. Thus, the probability of exceeding maximum storage volume is very small. Figure 6 depicts the end-of-May storage and frequency exceedance analysis in terms of storage volumes. Storage volumes increase proportionally to the initial reservoir content with the same likelihood. However, the maximum storage for the end of May, June, and July are different. There is a 60% probability that only 10.99% and 15.96% of the maximum storage volumes will be exceeded by the end of May (439,084 ac-ft) and June (401,372 ac-ft), respectively, given that the initial storage level at Falcon is 20% capacity at the beginning of May. However, under the same probability, only 9.59% of the maximum storage volume at the end of July (576,128 ac-ft) can be exceeded (Figure 6).

Table 6.4. Exceedance Frequencies for Predicting the End-of-May Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-May Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-May Storage Capacity (%)				
99	55.04	45.85	23.7	4.35	1.27
98	55.45	47.12	24.89	4.35	2.43
95	56.55	47.79	25.38	4.68	2.73
90	57.93	48.06	25.59	5.25	3.1
80	59.34	49.78	27.56	6.98	4.09
70	61.53	51.13	30.85	9.11	4.89
60	62.22	52.49	31.53	10.99	7.68
50	63.06	54.15	32.85	12.77	9.52
40	65.85	55.5	35.9	15.87	10.53
30	67.6	58.92	40.45	19.29	19.32
20	68.57	61.67	45.39	23.58	20.47
10	71.41	65.45	49.44	31.95	32.17

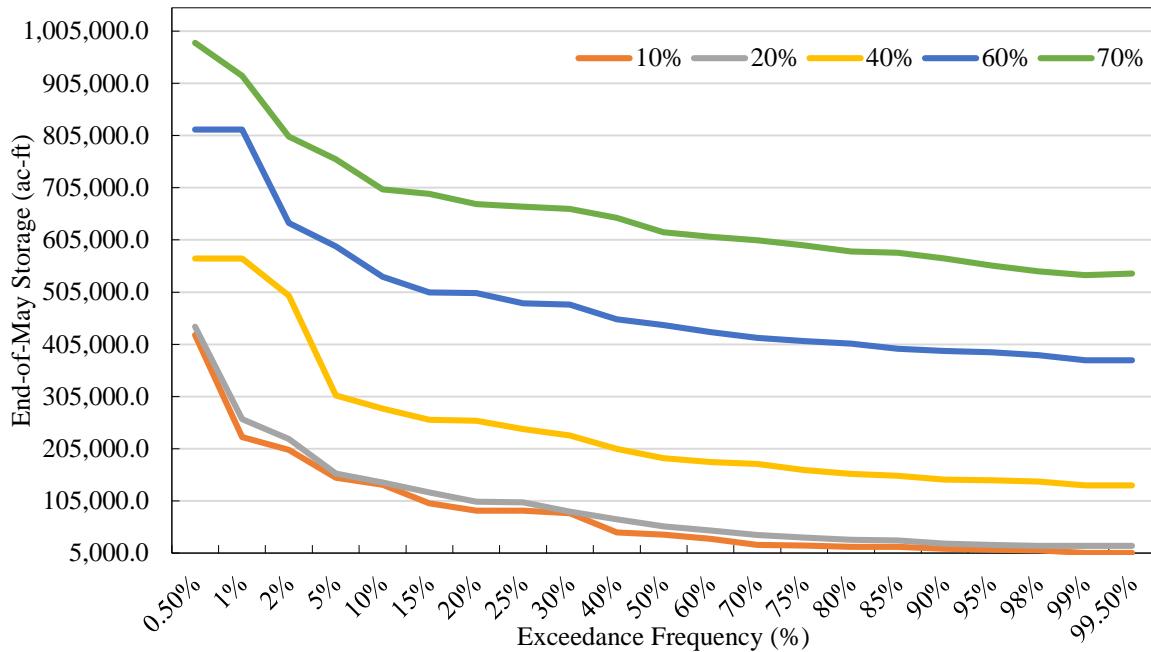


Figure 6.5. End-of-May Storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

Predicted storage exceedance frequency analyses were extended to June and July with the same initial reservoir contents at beginning of May. According to Tables 6.5 and 6.6, under the same likelihood, the exceeding maximum storage volume by the end of June and July is lower than that of in May. For example, there is a 70% chance that only 18.81% and 12.68% of maximum storage volumes for June (533,751 ac-ft) and July (703,154 ac-ft) will be exceeded given an initial storage at 40% capacity at the beginning of May. It is evident that maximum end-of-the-month storage is higher for July than it is for June. Figures 6.6 and 6.7 depict the exceedance frequency and end-of-month storage volumes for June and July.

Table 6.5. Exceedance Frequencies for Predicting the End-of-June Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-May Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-June Storage Capacity (%)				
99	36.16	24.56	15.93	4.99	0
98	36.73	28.06	15.93	4.99	0
95	41.6	29.39	15.95	6.23	0
90	45.38	32.98	15.99	9.91	3.13
80	47.15	34.6	16.03	11.57	8.18
70	50.04	37.88	18.81	14.21	11.41
60	54.13	40.75	18.82	15.96	13.26
50	57.22	46.67	18.9	18.18	17.14
40	61.47	51.27	22.13	23.42	24.59
30	64.4	58.69	30.17	29.94	31.99
20	68.63	63.86	39.41	35.99	41.11
10	71.61	67.57	49.14	51.61	58.54

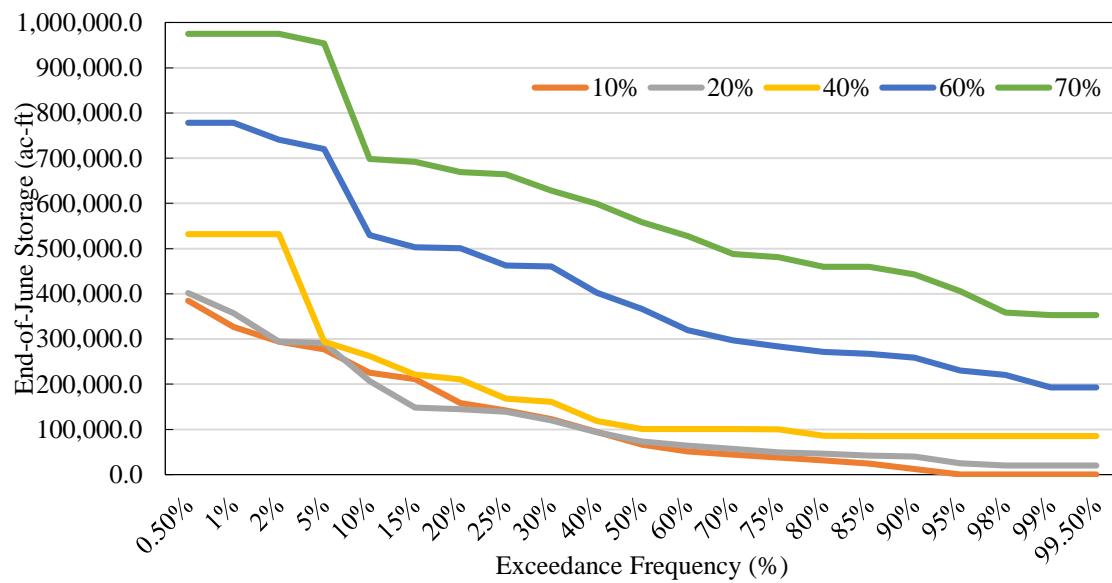


Figure 6.6. End-of-June storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

Table 6.6. Exceedance Frequencies for Predicting the End-of-July Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-May Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-July Storage Capacity (%)				
99	16.01	11.65	0.01	0	0.66
98	19.41	11.66	0.01	0.14	0.9
95	22.19	11.68	0.02	4.05	1.54
90	25.34	11.7	0.04	5.71	3.68
80	29.64	14.47	9.97	6.66	5.38
70	31.65	17.16	12.68	7.94	6.64
60	32.93	24.19	13.14	9.59	8.94
50	38.13	27.91	13.68	9.87	12.78
40	42.7	36.77	14.28	10.62	13.33
30	47.87	43.34	14.38	12.08	18.23
20	51.25	51.35	15.06	15.87	25.53
10	68.6	69.63	34.36	35.92	30.7

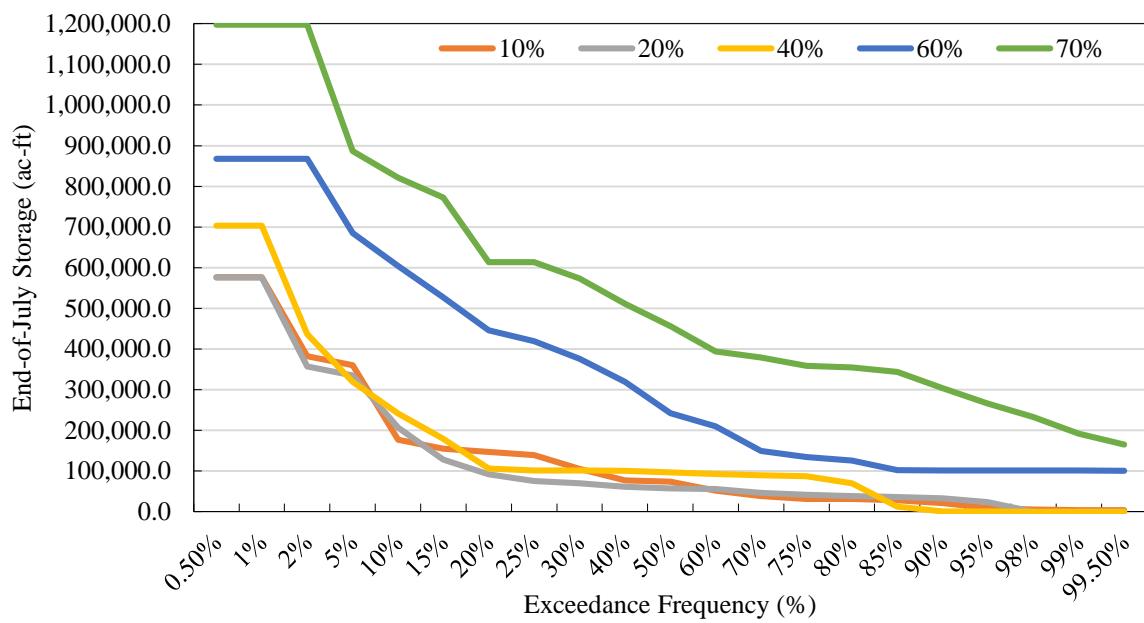


Figure 6.7. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

Beginning-of-June Simulations

The same CRM methodology that is described in section 6.1.1 applies to this section, which discusses the beginning of June at various storage trigger levels to predict storage conditions for the end of June, July, and August using exceedance frequency analysis. The likelihood of initial reservoir contents for the next three months was simulated, and the exceedance frequency analysis is shown in Table 6.7. There is a 58.4% probability that initial storage of 26,154.4 ac-ft is exceeded by the end of June and a probability of 70.8% and 76.5% that the same initial storage is exceeded by the end of July and August, respectively. The probability of exceeding 70% (or 543,347 ac-ft) of initial storage for the end of May is 21.7% and 18.3% and 9.2% for the end of June and July, respectively.

Table 6.7. End-of-Month Storage Exceedance Frequency for Initial Storage Volume at the Beginning of June

Initial Storage (%)	Storage (ac-ft)	June (%)	July (%)	August (%)
10	26,154.4	58.4	70.8	76.5
15	47,187.1	54.1	55.1	57.2
20	43,664.4	47.2	47.6	64.1
30	68,568.6	46.8	30.0	40.0
40	143,783.4	36.7	8.4	4.6
50	247,172.1	24.3	9.1	8.7
60	380,115.9	33.5	12.7	5.1
70	543,346.9	21.7	18.3	9.2

The volume reliabilities for the three major water rights groups were simulated using various initial reservoir contents at the beginning of June. Table 6.8 provides volume reliabilities in June for Class A and Class B irrigation rights and municipal rights for the LRGV. The largest water supply shortages occur when the reservoir is at 10% and 20% capacity while meeting only 11.09% and 25.20% of target diversions for Class A irrigation rights. The municipal rights have 100% volume reliability regardless of the initial storage

content at the beginning of June simulations. The table also shows that curtailment actions may be implemented by IWBC when reservoir storage at the beginning of June is less than 40% of capacity. As the reservoir storage increases to 70% capacity, 89.72% and 89.72% of the target diversions for June for Class A and Class B rights are met with less shortages compared to initial storage volumes of 10% and 20% at the beginning of June.

Table 6.8. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation in June

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
10	100.00	11.09	8.95
20	100.00	25.20	17.79
40	100.00	77.94	64.12
60	100.00	86.29	86.29
70	100.00	89.72	89.72

Predicted flow frequency exceedance analyses were simulated for the end of June, July, and August from the beginning of June using various trigger storage levels for the Amistad-Falcon system. Tables 6.9 through 6.11 show the likelihood of exceeding maximum reservoir storage at the end of June, July, and August given different initial storage contents at the beginning of June. There is a probability of 70% that only 7.88% of the maximum storage volume will be exceeded at the end of June during exceptional drought conditions. The probability of exceeding 53.68% of the maximum storage volume for the end of June is 70% during a first-stage drought. During extreme drought conditions at the beginning of June, the probability of exceeding maximum storage by the end of July and August by 7.89% and 9.34%, respectively, is 60% and 40%. Figures 6.8 through 6.10 depict exceedance frequency of maximum storage volumes for each of the drought trigger categories.

Table 6.9. Exceedance Frequencies for Predicting the End-of-June Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-June Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-June Storage Capacity (%)				
99	51.09	46.73	15.9	2.66	0.13
98	51.09	46.73	15.9	4.09	2.09
95	52.86	48.47	27.14	5.33	2.37
90	52.94	49.22	27.21	5.47	3.04
80	54.8	50.79	27.34	8.2	5.32
70	55.71	52.68	28.94	9.12	7.88
60	58.58	54.84	29.05	11.59	9.29
50	60.96	59.21	33.87	13.55	12.33
40	64.37	65.13	37.08	18.75	20.64
30	66.81	69.7	46.7	22.33	22.76
20	69.73	72.8	52.23	33.66	33.29
10	75.78	85.15	65.54	46.89	46.66

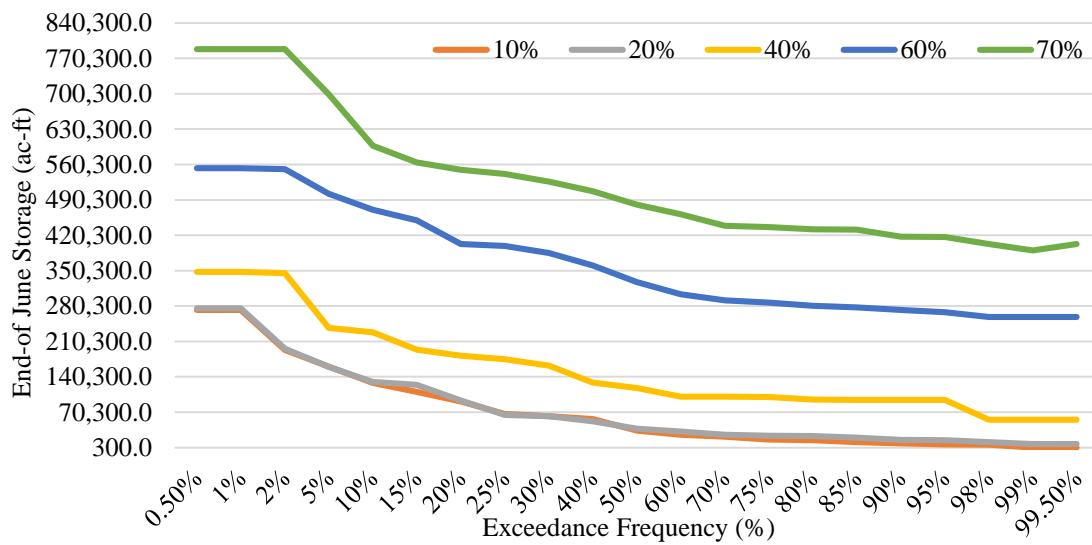


Figure 6.8. End-of-June storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-June storage.

Table 6.10. Exceedance Frequencies for Predicting the End-of-July Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-June Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-July Storage Capacity (%)				
99	20.85	14.65	0.05	0.86	0.04
98	21.53	14.66	0.06	0.86	0.04
95	21.7	14.66	0.06	2.44	0.09
90	23.1	14.71	8.2	3.83	1.52
80	26.67	15.58	14.24	4.61	3.17
70	27.86	18	14.39	6.85	5.71
60	30.01	21.3	14.53	7.89	7.58
50	33.21	23.28	14.88	8.88	8.75
40	36.06	28.93	15.1	10.22	9.86
30	37.05	31.58	15.68	12.59	15.6
20	50.54	46.78	17.44	18.82	20.86
10	58.24	57.71	20.88	29.21	35.44

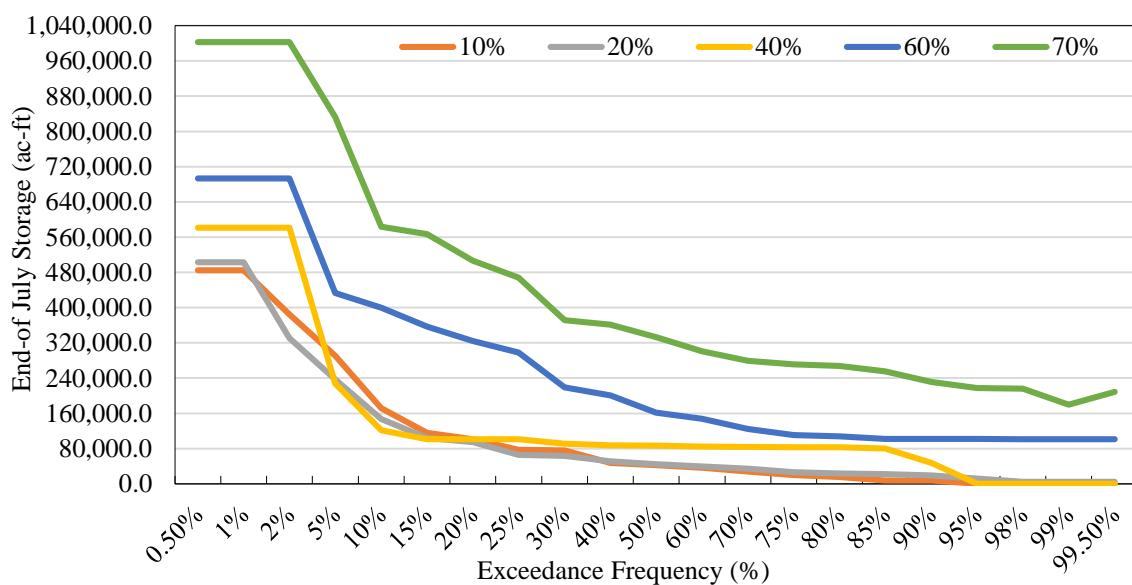


Figure 6.9. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-June storage.

Table 6.11. Exceedance Frequencies for Predicting the End-of-August Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-June Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-August Storage Capacity (%)				
99	9.57	13.45	0.01	0	2.93
98	9.89	13.48	0.03	0.07	2.93
95	13.96	13.52	0.03	3.48	3.26
90	17.15	13.55	0.34	5.72	3.91
80	20.31	13.58	4.64	6.48	4.55
70	26.31	13.65	12.4	7.75	6.07
60	26.87	13.7	14.43	9.34	7.39
50	30.27	13.82	18.28	11.43	9.79
40	32.5	22.81	19.99	12.07	12.33
30	34.3	26.07	21.7	12.83	14.62
20	40.33	30	22.02	20.24	25.4
10	48.8	40.07	42.92	29.32	31.01

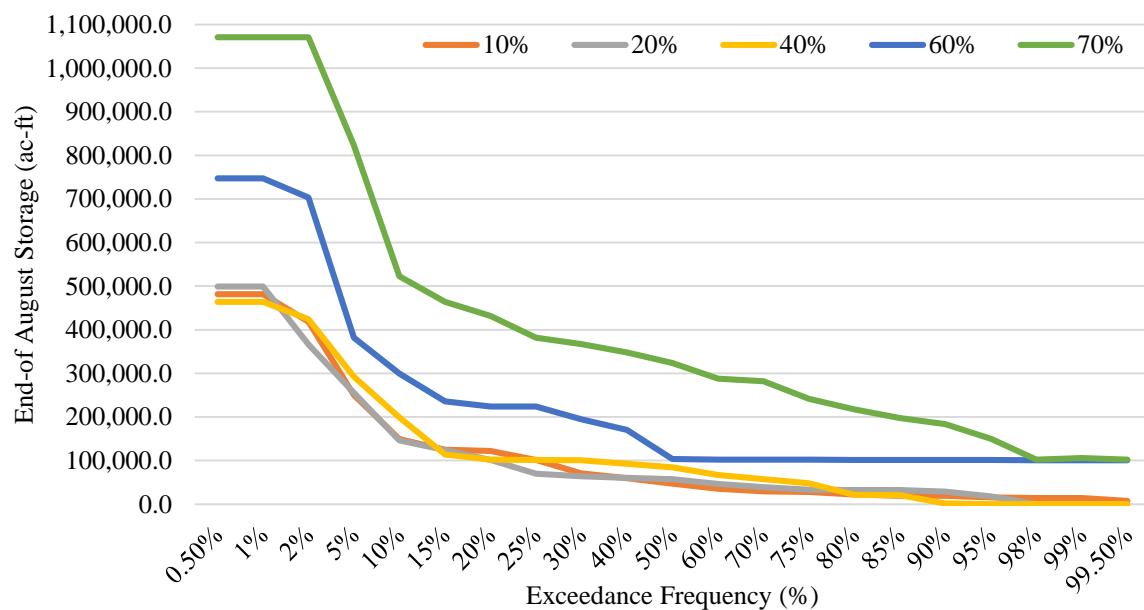


Figure 6.10. End-of-August storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-June storage.

Beginning-of-July Simulations

Exceedance frequency and volume reliability analyses were performed by simulating various drought conditions using various trigger levels with initial reservoir volumes starting in July to predict storage volumes for the end of July, August, and September. Table 6.12 shows the probability of the reservoirs exceeding initial storage volumes starting in July and extending through July, August, and September. During extreme drought conditions, there is 27.5% chance that the 34,848 ac-ft storage volume will be exceeded at the end of July, but the probability of exceeding the same storage volume increases to 60% by the end of August and to 82.4% at the end of September. The reservoir system gains more volume by the end of September if initial storage at the beginning of July increases from 15% to 20%. The irrigation diversions take effect once the reservoir gains more than 30% storage content at the beginning of July, which can be seen in Table 6.12; as abnormally dry conditions ensue, only 9.8% of the initial storage volume will be exceeded by the end of July and August. However, the probability of exceeding initial storage at the end of September is higher than that of July and August because of the impending irrigation season in the LRGV. The main purpose of Table 6.12 is to demonstrate the likelihood of exceeding initial reservoir storage by the end of July, August, and September with the various drought conditions activated at the beginning of July.

Table 6.12. End-of-Month Storage Exceedance Frequency for Initial Storage Volume at the Beginning of July

Initial Storage (%)	Storage (ac-ft)	July (%)	August (%)	September (%)
10%	27,317.3	29.2	50.0	78.3
15%	44,908.2	22.4	45.1	72.4
20%	34,848.0	27.5	60.0	82.4
30%	66,183.4	18.2	38.8	68.3
40%	139,924.7	12.1	8.7	24.9
50%	240,778.1	14.8	9.8	15.7
60%	370,268.1	9.9	10.0	12.5
70%	529,165.9	9.8	9.8	21.6

The volume reliabilities for Class A and Class B irrigation rights are lower for July than for May and June. Table 6.13 shows the volume reliabilities for the major water rights groups during various drought conditions. If exceptional drought conditions are activated for the Rio Grande at the beginning of July, volume reliabilities for Class A and Class B irrigation rights are 9.24% and 7.72%, respectively. It means that only about one-tenth of Class A diversions in July can be supplied during such drought conditions. As the reservoir system replenishes by gaining increased storage volume, the reliabilities for supplying irrigation demand in the LRGV increases. Curtailment actions may be more severe during the month of July than May or June during the same drought conditions.

Table 6.13. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation in July

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
10	100.00	9.24	7.72
20	100.00	14.50	12.29
40	100.00	59.80	47.45
60	100.00	81.02	79.72
70	100.00	84.82	84.82

The probability of exceeding maximum storage volumes at the end of July, August, and September becomes lower given the various trigger storage at the beginning of July. Tables 6.14 through 6.16 show that there is a 90% probability that only 12.54% of the maximum storage volume is exceeded at the end of July given that the initial storage at the beginning of July is 40% capacity. Under the same scenario, 0% and 5.01% of the maximum storage volume is exceeded at the end of August and September, respectively. Figures 6.11 through 6.13 depict the exceedance frequency for storage volumes at the end of July, August, and September.

Table 6.14. Exceedance Frequencies for Predicting the End-of-July Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-July Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-July Storage Capacity (%)				
99	47.80	36.55	10.17	1.4	0.02
98	47.80	36.55	10.17	1.4	0.02
95	48.18	37.16	10.75	1.43	0.03
90	48.62	37.8	12.54	2.33	1.28
80	50.57	39.76	18.2	4.4	2.09
70	51.59	40.4	22.93	5.13	3.84
60	52.30	41.38	23	6.8	4.61
50	53.03	42.64	23.01	7.3	5.02
40	54.63	43.63	23.1	8.12	6.18
30	57.22	47.46	24.75	9.31	7.34
20	59.16	50.14	24.89	12.57	11.07
10	75.59	61.97	36.59	18.11	17.74

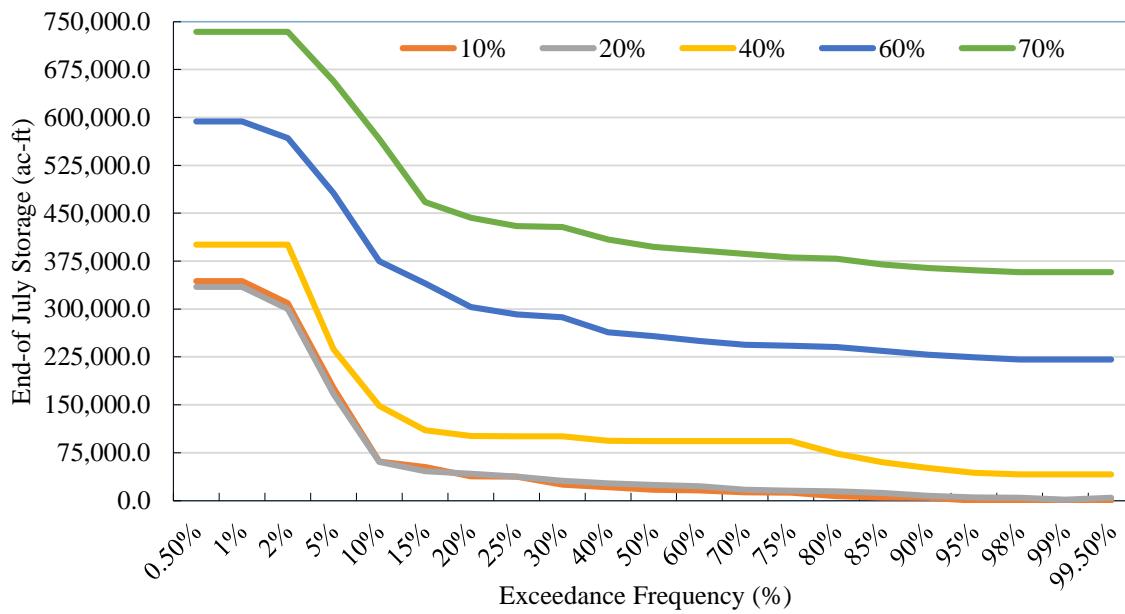


Figure 6.11. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

Table 6.15. Exceedance Frequencies for Predicting the End-of-August Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-July Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-August Storage Capacity (%)				
99	19.73	16.86	0	0.09	0
98	20.36	16.9	0	0.09	0.02
95	21.76	16.95	0	0.24	0.04
90	23.14	16.97	0	1.5	0.06
80	24.67	17.02	0.09	4.15	3.52
70	26.67	17.08	16.41	7.01	4.78
60	28.20	17.11	18.68	9.64	6.34
50	30.57	17.16	23.4	10.93	6.98
40	38.62	17.3	23.88	11.88	11.1
30	48.85	22.46	25.17	14.71	15.21
20	55.49	29.92	25.34	24.45	18.29
10	64.42	62.01	29.38	32.66	31.59

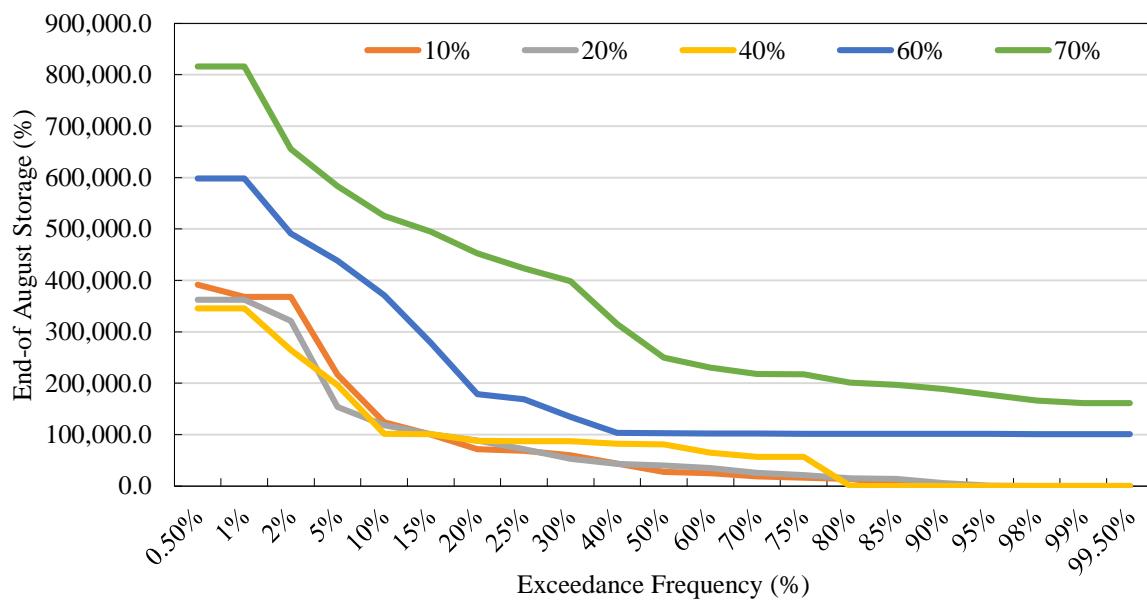


Figure 6.12. End-of-August storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

Table 6.16. Exceedance Frequencies for Predicting the End-of-September Storage at Various Drought Trigger Storages

Exceedance Frequency (%)	Beginning-of-July Storage as Percentage of Capacity				
	70	60	40	20	10
	End-of-September Storage Capacity (%)				
99	7.93	10.04	0.02	1.2	0
98	10.62	10.04	2.03	1.2	0
95	12.75	10.09	4.09	2.55	1.27
90	14.12	10.15	5.01	4.45	2.96
80	16.77	10.2	7.14	5.71	3.73
70	20.28	10.25	8.68	7.54	5.43
60	23.31	10.3	12.18	11.27	9.2
50	25.42	13.43	14.2	13.73	12.59
40	29.44	20.73	14.69	15.5	13.84
30	34.04	26.92	16.27	17.98	16.68
20	47.59	30.73	22.8	24.77	22.04
10	55.19	47.24	43.92	48.95	37.54

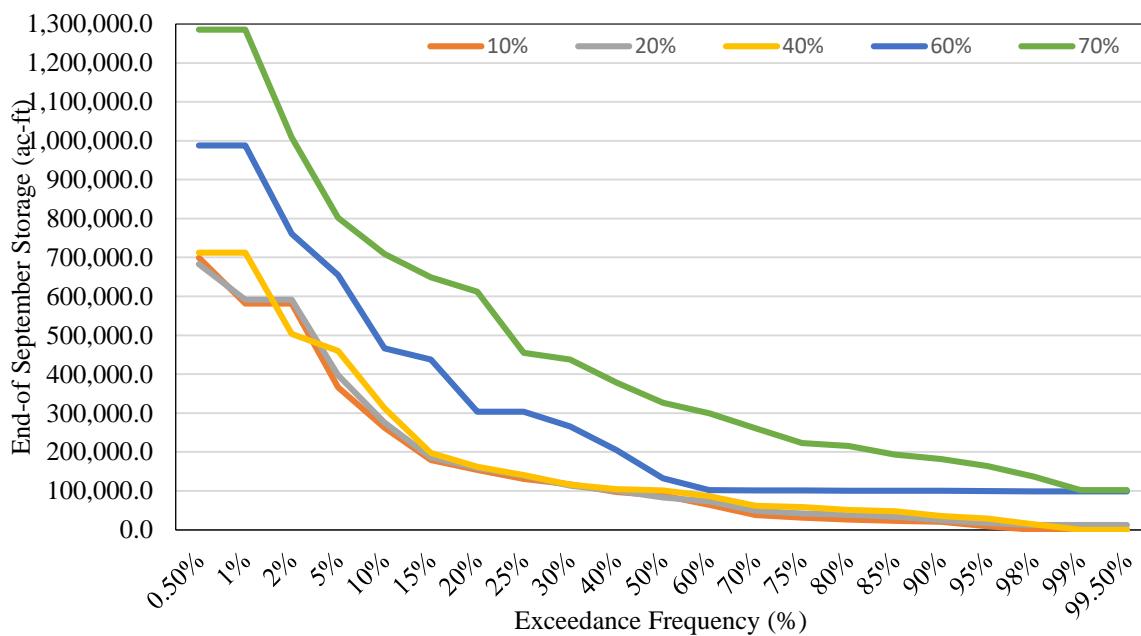


Figure 6.13. End-of-September storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

The exceedance frequency analyses show that drought at the beginning of May has lesser impact on water allocations in the next three months compared to the beginning of June and July. It is evident that the beginning of drought in summer in the LRGV continues to get worse toward the end of September before the reservoir system replenishes and irrigation season slows down. The curtailment actions are well established and executed in a timely manner by the IBWC, the Rio Grande watermaster, irrigation districts, and municipal water suppliers.

LRGV Municipal Drought Plan

The Lower Rio Grande municipal water suppliers also have their own drought contingency plans that include 15%, 30%, and 50%, which are also included in the simulation process. Each of those storage contents are used as trigger contents that activate various hypothetical drought conditions. Exceedance frequencies and reliability analyses were developed for each scenario. Simulations were run and storage frequency exceedance were developed beginning in May, June, and July that extended for three consecutive months.

Beginning-of-May Simulations

The probability of exceeding maximum reservoir storage volumes by the end of months follows the decreasing pattern from May through July. For example, Table 6.17 shows that there is a 90% probability that end-of-storage volume by the end of May exceeds by 15.09% at an initial storage level of 30% capacity. However, under the same scenario, only 0% and 2.39% of the maximum storage volume are exceeded at the end of June and July. Figures 6.14 through 6.16 depict changes in storage volumes for each end of the period and the likelihood of exceeding maximum storage constrained to various initial storage contents at the beginning of simulations in May.

Table 6.17. Exceedance Frequencies for Predicting the End-of-Month Storage at Various Drought Trigger Storages Beginning in May

Exceedance Frequency (%)	Beginning-of-May Storage as Percentage of Capacity								
	50 30 15			50 30 15			50 30 15		
	End-of-May Storage Capacity (%)			End-of-June Storage Capacity (%)			End-of-July Storage Capacity (%)		
99	35.42	12.93	2.15	15.66	0	0.27	13.55	0.04	1.06
98	36.43	12.93	2.15	15.66	0	0.27	13.59	0.04	1.06
95	36.71	14.53	3.77	15.69	0	1.45	16.53	0.93	3.6
90	37.87	15.09	3.98	15.74	0	6.95	16.59	2.39	5.31
80	39.89	15.79	5.77	21.1	0.1	11.19	16.6	3.75	6.68
70	41.77	18.05	7.13	25.42	2.52	12.97	16.61	5.05	7.72
60	43.26	20.45	8.31	29.1	5.12	15.26	16.66	6.23	9.68
50	44.78	21.75	10.18	34.5	12.01	19.65	16.68	9.08	11.88
40	46.77	25.74	12.93	40.63	15.11	25.13	16.78	11.1	14.01
30	51.44	31.1	19.89	44.15	20.61	33.17	31.77	14.67	17.25
20	54.26	33.89	21.13	50.81	29.85	41.95	46.73	15.97	22.89
10	58.85	38.88	32.64	57.08	41.31	58.01	69.96	41.42	38.39

During a severe drought condition when initial reservoir storage is at 15% of capacity, only 16.57% and 12.66% of the target diversion is supplied for Class A and Class B irrigation rights, while 100% reliability for municipal rights is maintained (Table 6.18).

Table 6.18. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation in May

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
15	100.00	16.57	12.66
30	100.00	55.55	34.91
50	100.00	82.86	82.86

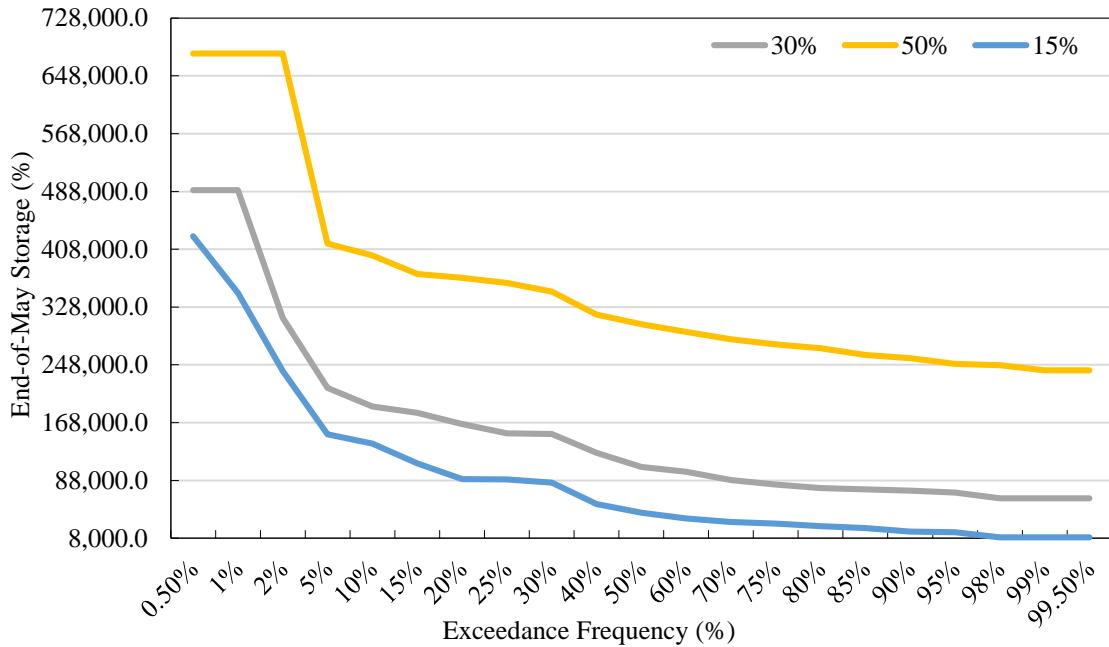


Figure 6.14. End-of-May storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

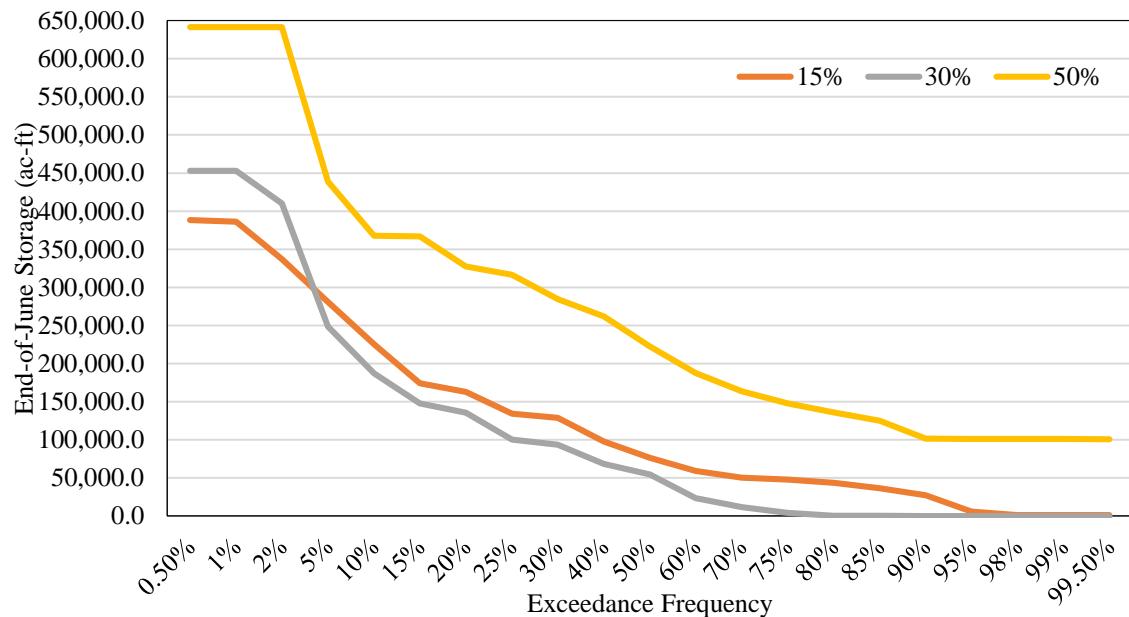


Figure 6.15. End-of-June storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

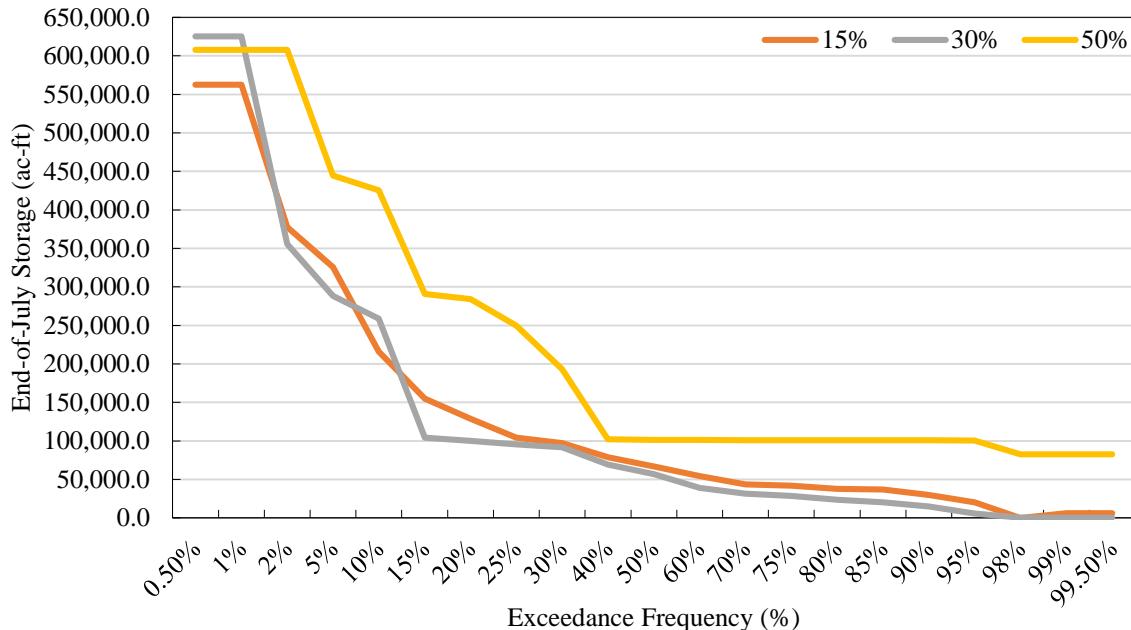


Figure 6.16. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

Beginning-of-June Simulations

The beginning of June simulation follows the same methodology described in the previous section. Volume reliabilities for Class A and Class B irrigation rights are lower in June compared to May simulations under the same drought conditions. In order to supply 85.10% and 81.45% of the target supplies for Class A and Class B irrigation rights in June, the initial reservoir storage should be at 50% capacity at the beginning of the month (Table 6.19).

Table 6.19. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation in May

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
15	100.00	12.58	9.60
30	100.00	34.56	23.82
50	100.00	85.10	81.45

Exceedance frequencies of maximum storage volume at the end of June and July tends to be lower because of the initial reservoir storage at the beginning of June. However, by the end of August, the exceedance frequency of maximum storage tends to be higher than that of July. For example, there is a 70% chance that the maximum storage volume can be exceeded by 18.16% at the end June but by 6.13% and 7.38% at the end of July and August given a 30% initial storage at the beginning of June (Table 6.20). Figures 6.17 through 6.19 depict changes in storage volume versus exceeding frequency analysis for the end of June, July, and August.

Table 6.20. Exceedance Frequencies for Predicting the End-of-Month Storage at Various Drought Trigger Storages Beginning in June

Exceedance Frequency (%)	Beginning-of-June Storage as Percentage of Capacity								
	50 30 15			50 30 15			50 30 15		
	End-of-June Storage Capacity (%)			End-of-July Storage Capacity (%)			End-of-August Storage Capacity (%)		
99	30.57	10.82	1.9	12.14	0	0.05	0	0	1.45
98	30.57	11.87	1.9	12.14	0	0.07	0	0.04	1.45
95	33.09	12.1	2.13	14.69	0.05	1.55	13.97	2.46	3.89
90	34.12	13.25	4.97	14.75	2.32	2.52	14.04	3.55	4.73
80	37.48	16.1	7.78	14.8	6.13	4.33	14.19	7.38	5.59
70	39.58	18.16	9.93	14.82	8.69	6.02	14.27	9.12	8.41
60	42.5	19.58	12.63	14.83	9.93	7.94	14.58	11.37	8.96
50	46.69	21.82	18.36	14.88	11.33	10.81	17.13	12.08	11.82
40	48.67	23.08	24.26	14.9	11.45	11.51	17.21	13.01	12.72
30	54.75	25.65	26.18	14.91	13.18	15.05	17.36	14.89	14.27
20	63.62	40.62	36.36	15.05	15.34	22.09	17.45	17.98	22.65
10	72.77	49.32	49.03	35.13	19.48	34.11	36.59	30.12	31.61

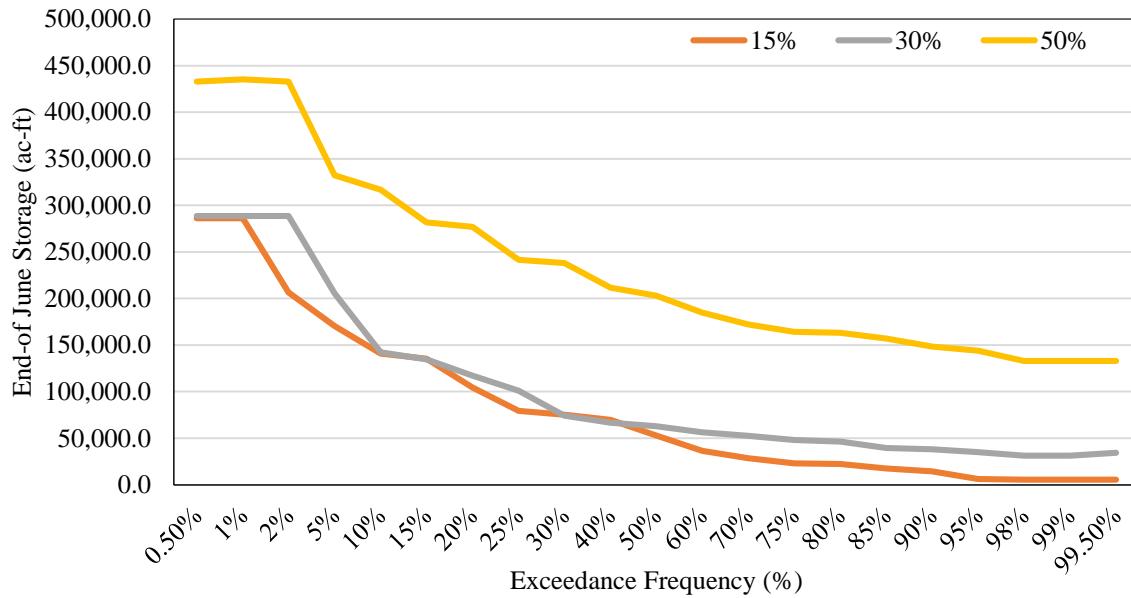


Figure 6.17. End-of-June storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-May storage.

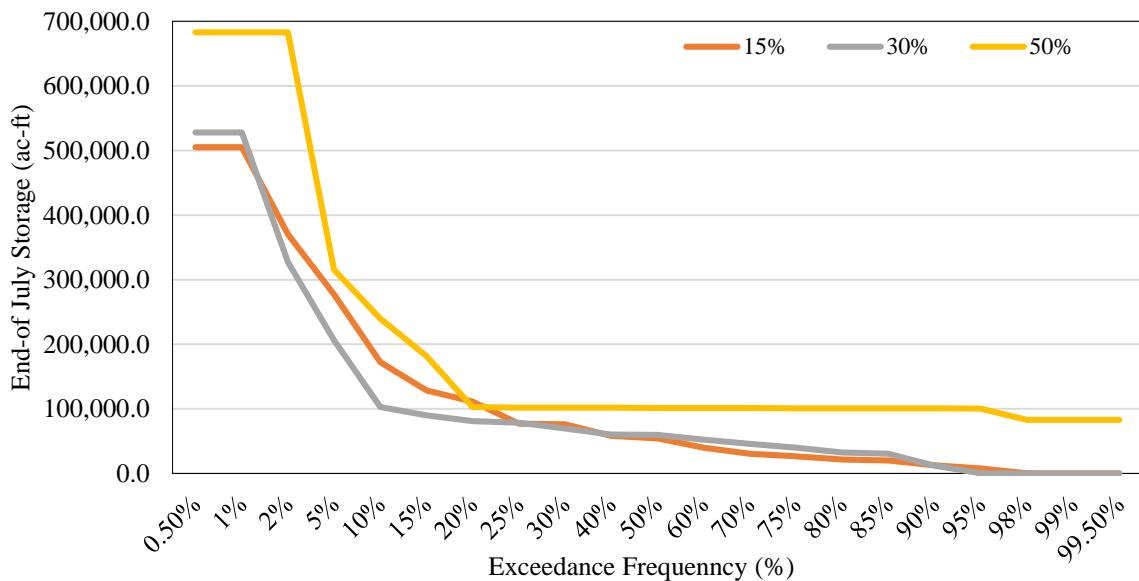


Figure 6.18. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-June storage.

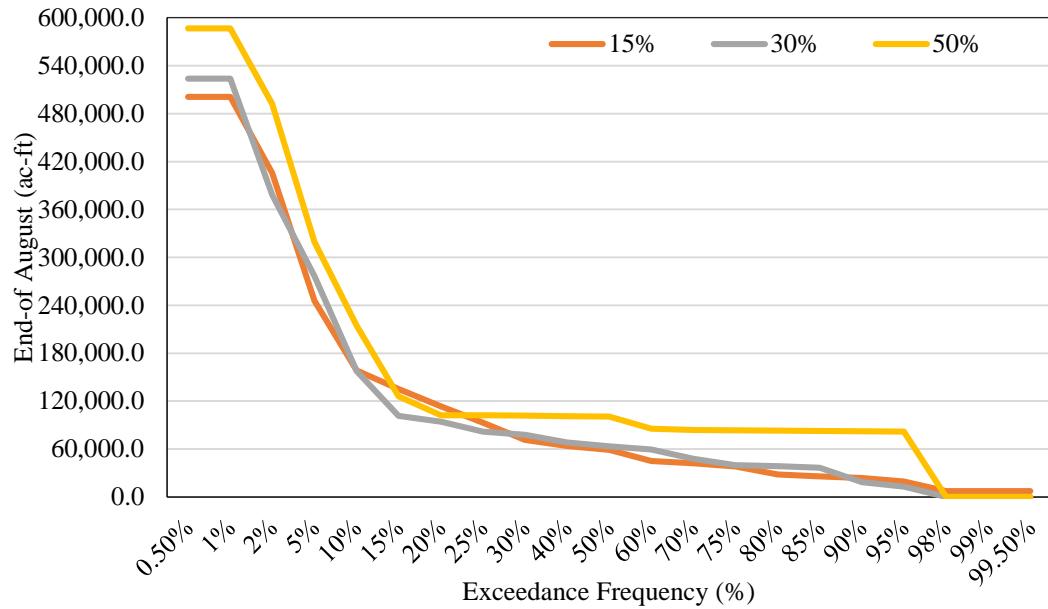


Figure 6.19. End-of-August storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-June storage.

Beginning-of-July Simulations

Although volume reliabilities tend to be lower for July than June or May, exceeding maximum storage volume by the end of September shows higher values. Table 6.21 shows the results of volume reliability analysis for Class A and Class B irrigation rights while municipal right is maintained at 100%. With 30% capacity at the beginning of July, only 26.66% and 21.51% of target diversions of the Class A and Class B irrigation rights are supplied by the end of the month. According to Table 6.22, there is an 80% chance that the maximum end-of-August storage is exceeded by 11.12% and 9.46% at the end of August and September given the storage at the beginning of July is at 30% capacity. However, the probability that the maximum storage can be exceeded by 12.19% and 9.34% at the end of September and August, respectively, is 50%. Tables 6.20 through 6.22 depict the end-of-period storage volume and exceedance frequency for July, August, and September given different drought triggers at the beginning of July.

Table 6.21. Volume Reliability Analysis for Municipal, Class A, and Class B Irrigation in July

Initial Storage (%)	Volume Reliability by Water Right Groups (%)		
	Municipal	Class A Irrigation	Class B Irrigation
15	100.00	11.79	9.98
30	100.00	26.66	21.51
50	100.00	81.02	79.72

Table 6.22. Exceedance Frequencies for Predicting the End-of-Month Storage at Various Drought Trigger Storages Beginning in July

Exceedance Frequency (%)	Beginning-of-July Storage as Percentage of Capacity								
	50 30 15			50 30 15			50 30 15		
	End-of-July Storage Capacity (%)			End-of-August Storage Capacity (%)			End-of-September Storage Capacity (%)		
99	23.02	5.24	0.03	18.38	0	0	0.01	4.37	1.86
98	23.02	5.37	0.03	18.41	0	0.06	0.01	5.5	1.86
95	23.63	5.41	1.87	18.44	7.31	2.23	1.08	5.6	2.52
90	24.49	9.06	2.06	18.48	8.79	3.92	7.9	7.34	3.61
80	26.2	10.85	3.7	22.53	11.12	5.13	10.57	9.46	5.67
70	27.3	12.27	3.95	22.61	12.52	7.22	10.7	10.36	7.13
60	28.12	13.19	5.97	22.67	15.52	8.14	12.03	11.66	10.69
50	30.07	14.05	6.76	22.68	17.28	9.34	12.04	14.26	12.19
40	31.81	14.93	8.52	22.75	20.07	14.19	12.15	16.38	14.73
30	35.23	15.7	9.07	22.83	22.35	15.8	15.03	19.34	16.68
20	39.22	18.54	13.18	23	23.64	20.51	25.47	25.94	23.29
10	54.13	23.46	21.7	44.97	32.15	32.48	46.71	50.07	40.37

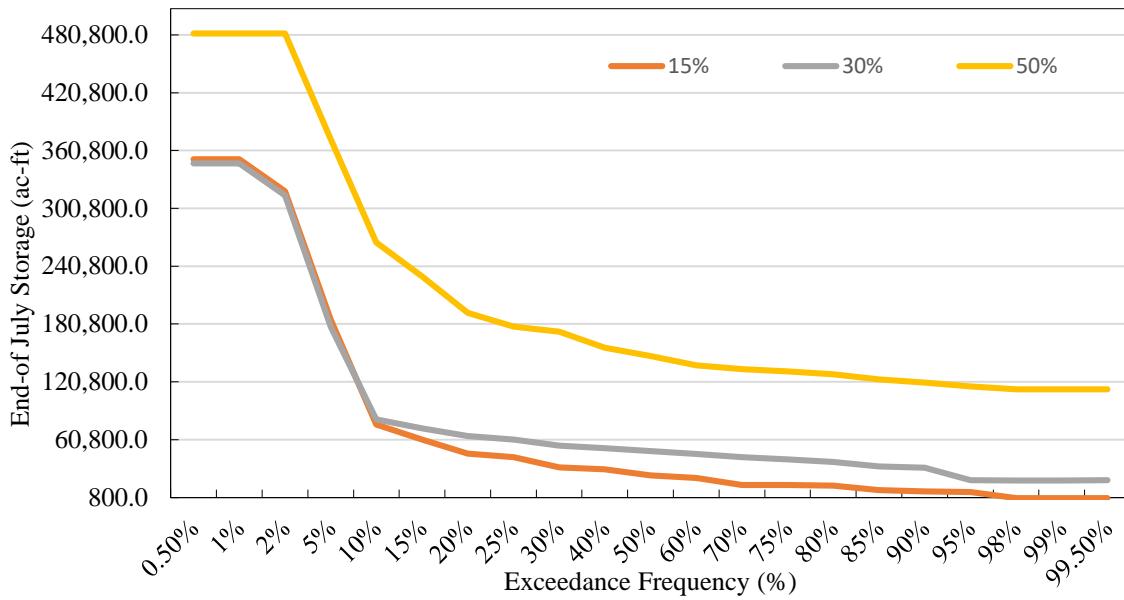


Figure 6.20. End-of-July storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

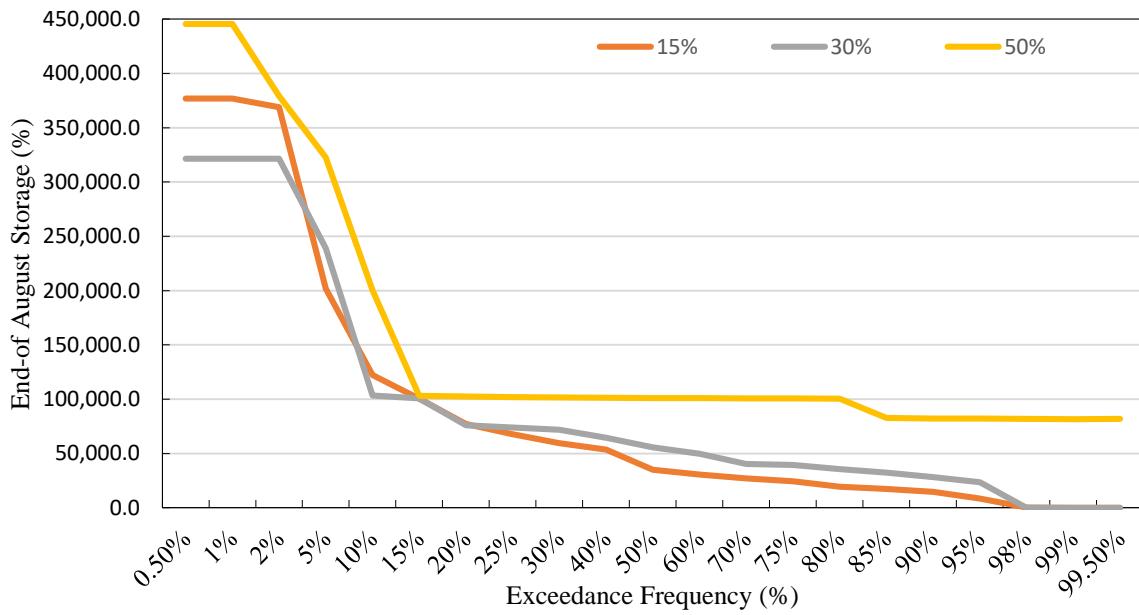


Figure 6.21. End-of-August storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

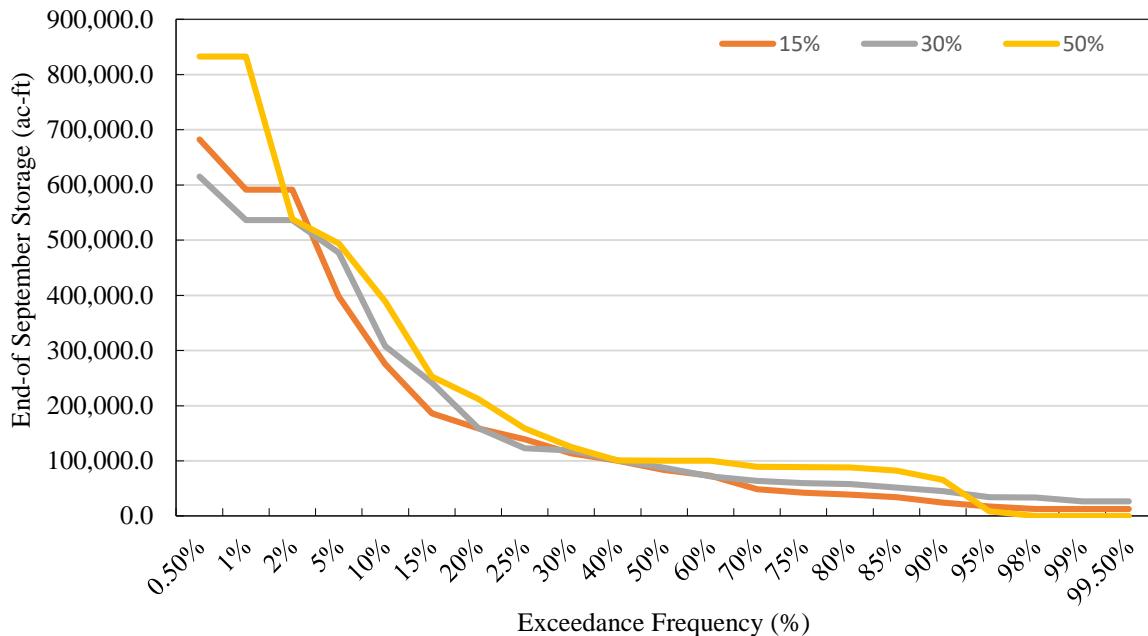


Figure 6.22. End-of-September storage volume and exceedance frequency analyses at different drought triggers with the beginning-of-July storage.

Region M Drought Contingency Plans

TWDB develops a State Water Plan every five years in order to ensure future water supply by projecting water demands using population growth projections. It divides the state by 16 water planning groups that are responsible for development and submission of future water plans to TWDB. Region M is the water planning group responsible for the Rio Grande and covers eight counties along the river. The group released the 2016 Rio Grande Regional Water Plan, which includes Drought Preparation and Response (TWDB 2016, Chapter 7), that outlines the reservoir storage triggers and mitigation plans both for irrigation and municipal uses.

The Rio Grande watermaster notifies each irrigation district about possible drought conditions based on an assessment of storage in the Amistad-Falcon Reservoir system. The board of directors of each district convenes special meetings and issues specific curtailment measures among the Class A and Class B irrigation rights. As mentioned before, all water shortages will be absorbed and distributed equally among the irrigation users to ensure

protection of municipal water supplies. Table 7-2 on page 7-5 of the 2016 Rio Grande Regional Water Plan (TWDB, 2016) provides a summary of irrigation district drought triggers and responses. Though each individual district issues different drought contingency plans, the process is the same; the board of directors makes a formal decision on curtailment and mitigation options. For example, during a drought, the Harlingen Irrigation District issues triggers if either (a) the storage balance in the district's irrigation water rights accounts has declined to one irrigation-per-acre level or (b) the board of directors determines that there is not sufficient water to complete the traditional crop year. In order to mitigate a solution, the total water allocated to the irrigation district by the watermaster will be divided among flat-rate customers evenly so that no one can irrigate more than his or her portion. The TWDB requires the municipal water supplier to have drought contingency plans. Tables 7-3 through 7-9 in the 2016 Rio Grande Regional Water Plan (TWDB, 2016) provide detailed drought stage triggers and mitigation plans for selected municipal water suppliers in the LRGV.

Drought simulation analyses for the Rio Grande carry useful quantitative information for irrigation districts and municipal users in the LRGV. The probability of exceeding specific storage volumes in the Amistad-Falcon Reservoir system by the end of the next few months in the future based on beginning-of-month storage helps irrigators to plan for potential curtailment actions ahead of time. The simulation results show that during exceptional and extreme drought conditions, Class B water rights should completely be curtailed along with Class A rights in order to ensure guaranteed municipal water supplies in the LRGV.

The CRM method of WRAP was applied to the Amistad-Falcon Reservoir system to predict the likelihood of maximum storage volume exceedance during drought conditions when specific storage triggers and volume reliabilities were analyzed. The beginning of May, June, and July storages were chosen, and a BES simulation option was used to predict storage volume exceedance for the next three consecutive months. The simulation results show that the CRM method can be useful to predict drought conditions based on probability analyses for the next three months into the future. Any type of drought tends to continue into the next few months and gets worse during the summer months when the peak irrigation season in the LRGV is in full swing. The beginning of May simulations shows a lesser degree of drought impact by the end of June and July. However, the beginning-of-June and July simulations have a more severe impact by the end of July, August, and September. Conversely, the end-of-

September storage tends to increase as the severity of drought lessens and the slow irrigation season begins.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Research Summary

The Rio Grande Basin WAM consists of complex modeling parameters that incorporate two inter-state compacts and two international agreements on allocations of water between three states and two countries. Amistad and Falcon Reservoirs, owned and operated as a system by IBWC, are the main impoundments that store and allocate water diversions between Mexico and the United States to meet municipal and irrigation demands of the LRGV in accordance with the 1944 treaty provisions. The Conchos River basin in Mexico and the Pecos River Basin in Texas are the main contributors of storage to Amistad Reservoir. Falcon Reservoir is primarily used to supply water demands of the LRGV, and because of that, most of the time it has lower storage volumes than Amistad Reservoir. However, both of these reservoirs are operated as a system; therefore, lower storage volumes in Falcon do not translate to water shortages in the LRGV unless reservoir storage dries up in Amistad simultaneously. The Texas WAM system is routinely used to evaluate permit applications and determine unappropriated and regulated flows. In this study, the Rio Grande WAM was extended using WRAP WAM extension methodologies from 2001 to 2015 and the final 1940–2015 hydrologic period of analyses were used to simulate different water allocation scenarios.

Unlike any other river basin in Texas, water in the Rio Grande is allocated based on special prior appropriation doctrine in which municipal and industrial rights have seniority over Class A and Class B irrigation and mining rights. Water rights in the Rio Grande are grouped into three major groups by the following priority: (a) domestic-industrial-municipal (DMI); (b) Class A irrigation and mining; and (c) Class B irrigation and mining. Total Class A and Class B mining rights are about 1% of the total water use; therefore, they were not considered in this research. Combined Class A and Class B rights in the Rio Grande WAM are about 86% of the total diversions. Class A rights have 1.7 times more allocation than Class B rights. The storage volume in the Amistad-Falcon Reservoir system should not exceed 1.4 total allocations for Class A and Class B irrigation rights. When Class A or Class B rights are acquired by the cities and converted to municipal rights, it leaves the rest of the users with less reliability. Future water allocations are handled by the IBWC accounting system.

Priority among irrigation rights does not exist, and water shortages accrued during the drought periods is shared equally. Irrigation rights can be sold or leased between irrigation and municipal or industrial rights. When sold to municipal use, Class A and Class B irrigation rights can only be converted by 50% and 40% per ac-ft of their market values, respectively. However, the municipal right holder acquires full volume of the irrigation rights. This special water marketing system is created to protect municipal water demands in the LRGV from future water shortages. Several research findings show that the DMI pool in the Amistad-Falcon system acquired more water rights from irrigation districts, which led to conservative protection of these rights. The modeling analyses in this dissertation research showed that the firm yield for municipal rights is about 456,893 ac-ft while the annual combined demand for the Lower and Middle parts of the Rio Grande WAM is 351,922 ac-ft/year. This volume does not account for the 225,000 ac-ft/month protection in the Amistad-Falcon Reservoir system that is left in the DMI pool.

Long-term simulations were performed and volume reliabilities for each water right group in the Middle and Lower Rio Grande were determined in order to guide regional water planning groups and irrigation districts. Conditional reliability modeling (CRM) with equal weight and storage flow frequency (SFF) options were applied to the Amistad-Falcon Reservoir system to determine the probability of exceeding maximum storage contents subject to initial reservoir volumes. CRM with SFF option was applied to simulate drought conditions for the Rio Grande.

Major Research Findings and Conclusions

Original Rio Grande WAM datasets were developed by Brandes (2004) in contractual agreement with TCEQ as part of Senate Bill 1 provisions. The Rio Grande is modeled as essentially two parallel rivers; one represents Mexico, and the other represents the United States' parts of the basin. Amistad and Falcon Reservoirs, the main water storage impoundments, were built with the sole purpose of meeting water demands from each country. Hydrology files of Rio Grande WAM consisted of monthly naturalized flow volumes and reservoir net evaporation minus precipitation depths covering the 1940–2000 hydrologic period of analysis. The monthly naturalized flow volumes were developed for 23 primary

control points on the U.S. parts of the watershed and 32 primary control points on the Mexico parts of the watershed. Net evaporation minus precipitation depths were developed for seven control points on the U.S. portion of the Basin and 18 control points on the Mexico portions of the Basin.

Although the hydrologic extension methodologies have not been officially accepted by TCEQ, they have been applied to several river basins in Texas. TCEQ still uses original WAM datasets for permit evaluation applications. The updated 2014 Rio Grande WAM original files along with TWDB's monthly evaporation and precipitation depths covering 1940–2015 were used to extend the hydrology input datasets from 2001–2015. This was done by several calibration steps in order to compute monthly naturalized flow volumes and net evaporation minus precipitation depth based on known naturalized flow volumes.

Monthly computed versus known naturalized flow volumes were compared after calibration, and plots show that flows had higher and lower peaks in some periods. Higher flow volumes in some periods will essentially be balanced with the low flow volumes. The objective of the flow extension process is to replicate known naturalized flows as closely as possible. However, monthly naturalized flow statistics are the most important part of the extension process. There were several quadrangles with missing evaporation and precipitation data prior to 1954. Also, the monthly evaporation depth from reservoir surface areas were measured using different methodology prior to 1954. Hence, the calibration and computing flows for the Rio Grande were based on known naturalized flow volumes covering 1954–2000. The known naturalized flow volumes covering 1940–1953 hydrologic period was added back to the newly extended naturalized flow data. Known monthly naturalized flow data are a critical part of the flow extension process, along with TWDB's monthly evaporation minus precipitation depths.

One of the biggest challenges of the flow extension process was to calculate contributing drainage areas based on sub-watersheds—created for the entire basin using ArcGIS mapping tools and methodologies—because each sub-watershed within each specific quadrangle had to be determined to incorporate evaporation and precipitation data for each drainage area. Four different flow zones in FP and FZ records were assigned specific percentages of zero flows for each period to improve the accuracy of the computed flows. The initial calibration process required significant computer simulation time. For the future period of extension, TWDB quadrangle data can be added to existing EVA file of the Rio Grande

WAM, and it should allow water users to have the most up-to-date datasets. The necessity of updated Rio Grande WAM datasets is mentioned several times in the Rio Grande Water Planning Group's reports.

2011 and 2012 are the years for the drought of record for the Rio Grande; Falcon Reservoir had only 38,453 ac-ft of water, while Amistad storage was at 45,873 ac-ft. In 2013, the reservoir system began regaining storage volume due to rainfall following the drought. The extended Rio Grande WAM captured that period, which is important for water planning activities. The EVA file can be used to remove reservoir surface areas from the naturalized flow process in order to determine streamflows. Spring flow adjustments for a single control point were extended using monthly averages for 1940–2000 because there were no stream gaging data that could have been used to extend this file.

Long-Term Simulations

Texas WAM datasets are used to evaluate permit applications for Texas rivers by TCEQ and for long-term water planning by TWDB. The updated Rio Grande WAM, with 76-year sequences of hydrologic period analysis covering 1940–2015, was used to simulate long-term reliability and end-of-reservoir storage frequency analysis for the Amistad-Falcon Reservoir system. The purpose of the long-term simulation option was to investigate water allocation reliabilities for irrigation and municipal water right groups. TCEQ applications of WRAP assume that the reservoirs are full at the beginning of the simulation. The rationale behind this assumption is that the results for a long period of analysis are not significantly affected by the initial conditions. However, having full reservoirs at the beginning of the simulation may not be a realistic assumption for arid areas like the Rio Grande Basin (Santos, 2005). The BES feature is based on setting the beginning and ending storage equal, which reflects the concept of a cycling hydrologic simulation period. Volume reliability and exceedance frequency analysis were performed for both middle and lower segments of the Rio Grande. The Middle Rio Grande includes all water rights between Amistad and Falcon Reservoirs, and the Lower Rio Grande includes all water rights below Falcon Reservoir.

In evaluating permit applications, TCEQ applies a general rule that municipal supplies should have a volume and period reliability of 100%, and for agricultural supplies, 75% of the

permitted demand should be met at least 75% of the time. The simulation results show that municipal rights had maintained 100% reliability while irrigation Class A had 67.14% and 68.29% reliability and Class B had 43.23% and 44.32% reliability for the Middle and Lower Rio Grande, respectively. DMI reserves were lowered from 100% to 0%, but volume reliabilities for irrigation rights were only increased to about 2% while 100% of municipal reliabilities were maintained. However, when Operation Reserve (OR) at the Amistad-Falcon Reservoir system was lowered to 0% storage, the volume reliabilities for Lower Rio Grande were at 99.85%, which is not acceptable by TCEQ. The simulation results showed that the volume reliabilities for municipal water rights with 0% DMI storage can still be maintained at 100%, but if combined with 0% OR storage, a reliability of less than 100% is achieved. Curtailing all Class B irrigation rights significantly improves volume reliabilities for Class B rights. The DMI and OR storage reserves were used in combination to reallocate waters to Class A irrigation diversions while curtailing Class B rights during drought periods. The results show a 6.8% increase in volume reliabilities for Class A irrigation rights and 100% reliability for municipal rights. The DMI pool of the Amistad-Falcon Reservoir system is extremely protected, with excess volume of storage due to conversion of irrigation rights to municipal rights based on the water marketing in the LRGV. This protection was evidenced by 100% volume reliability for municipal water rights in all simulation scenarios with various initial storages. Although prohibited, some of the water in the DMI pool can be temporarily released to irrigation purposes during severe drought to prevent water conveyance infrastructure from deteriorations.

The 2016 Rio Grande Regional Water Planning Group's projected water demands from 2020 to 2070 were also incorporated and simulated to evaluate potential curtailment or water transfer options. The results show that based on the current water rights in the Rio Grande WAM, the incorporated projected municipal demands for 2020 would have less than 100% municipal volume reliability. Curtailment of Class B irrigation rights would meet 2020 municipal demand and maintain a volume reliability of 53% for Class A water rights. Additionally, Class A irrigation rights should be reduced by 20% each decade in order to meet future municipal demands in the LRGV. These reductions will be achieved by purchasing and converting irrigation rights to municipal rights based on a water marketing system in the

region. In addition, the 2016 regional water-planning group report projects a decrease in current agricultural land due to population growth and water shortages.

Conditional Reliability Modeling

CRM is used to predict the likelihood of meeting water supply demands in the near future, which is highly dependent on current reservoir storage levels. In CRM, naturalized flows and net evaporation rates are divided into short sequences that begin with the same initial reservoir storage. CRM can be used to support operational planning, drought management plans, and many other applications.

Equal weight and probability array options of CRM were applied to the Amistad-Falcon Reservoir system, and the probability of exceeding maximum storage contents based on initial storage at the beginning of April were developed. Then, the probability of exceedance for the next six months for Amistad and Falcon Reservoirs was developed. The equal weight option, as expected, produced higher exceedance frequencies for Amistad and Falcon Reservoirs since it assigns probabilities of meeting or exceeding specific diversions on an equally likely basis. This method can be used for long-term water planning purposes, but the CRM method would be a better option for short-term drought management or reservoir operations.

CRM with the SFF option using storage changes was also demonstrated in this research. The linear and Spearman correlation coefficients were developed for each scenario. However, the combined Amistad and Falcon Reservoir with full storage option in SFF appears to be a better option to apply for the Rio Grande. Power and exponential regression analysis were used because they demonstrated a better fit in relating storage to naturalized flows in simulations.

Drought Management

CRM methods were applied to simulate different drought conditions based on the storage trigger percentages developed by the Texas State Drought Preparedness Council and Rio Grande Municipal Use. The probability of exceeding maximum end-of-storage for the next

three months into the future for three months beginning with May, June, and July based on initial reservoir triggers were presented. The simulation results show that drought at the beginning of month continues to be persistent in the next three months with the initial reservoir storages. CRM methods were applied with different initial reservoir storage contents to the Amistad-Falcon Reservoir system. The beginning of May, June, and July were selected to determine likelihood of water allocations for the next three months. Peak irrigation season for the LRGV begins in May and ends by September. The end-of-month probability of exceeding maximum storage volumes from May to September were developed for the LRGV. Volume reliabilities for irrigation rights appeared to be lower with the low initial storage contents of the Amistad-Falcon Reservoir system at the beginning of each period. The probability of severe drought occurring at the beginning of May appeared to continue through the end of July. If irrigation districts and farmers anticipate lower storage levels in the Amistad-Falcon system at the beginning of May, the water shortage will continue into the next three months and curtailment of some of the irrigation rights will be enforced by IBWC.

Future Research

Irrigation district operations are somewhat unknown. For instance, it is not clear which Class A or Class B water right holders should get their allocations first since priorities among the same group does not exist. Detailed account holders are maintained by the irrigation district's database, and the watermaster office only maintains municipal, Class A, and Class B rights along with annual authorized diversions for each irrigation district. When developing reliability analysis for drought conditions, the IBWC uses the Amistad-Falcon system storage before issuing any drought condition triggers. However, based on simulation results, it is evident that both Amistad and Falcon Reservoirs have significantly different storage volumes. This difference can also be seen from the historical data on the IBWC website. In addition, there is no release schedule from Amistad to Falcon to meet water demands in the LRGV. Also, the accounting systems of prior diversions are also unknown. There is very limited literature on specific operation policies of the Amistad-Falcon Reservoir system. Future research should focus on examining and understanding these parameters in order to improve the understanding of reliability and exceedance frequency analysis for the LRGV. Since

Amistad and Falcon Reservoirs operate as a system, it is difficult to identify specific minimum storage capacity at which certain reliabilities can be expected. The available storage in Amistad Reservoir is usually higher than it is in Falcon Reservoir. For example, when Falcon is at 34% capacity, Amistad might be at 71% capacity. In this case, it will be difficult for an irrigation district manager or a farmer to make any water plans because Falcon Reservoir can be filled by Amistad at any time in order to meet the water demands of the LRGV. IBWC makes the final decision on the amount of water to be diverted to the LRGV per request from the Rio Grande watermaster. Once finalized, the watermaster informs each irrigation district about the allocations for the next weeks. Water allocations within irrigation districts are governed by the board of directors comprised of farmers. The board makes a decision on who gets the appropriated water for the next week.

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APPENDIX A

Known and Computed Naturalized Flow Volumes for the Rio Grande Texas Primary Control Points Covering 1954-2000

Hydrologic Period of Analysis

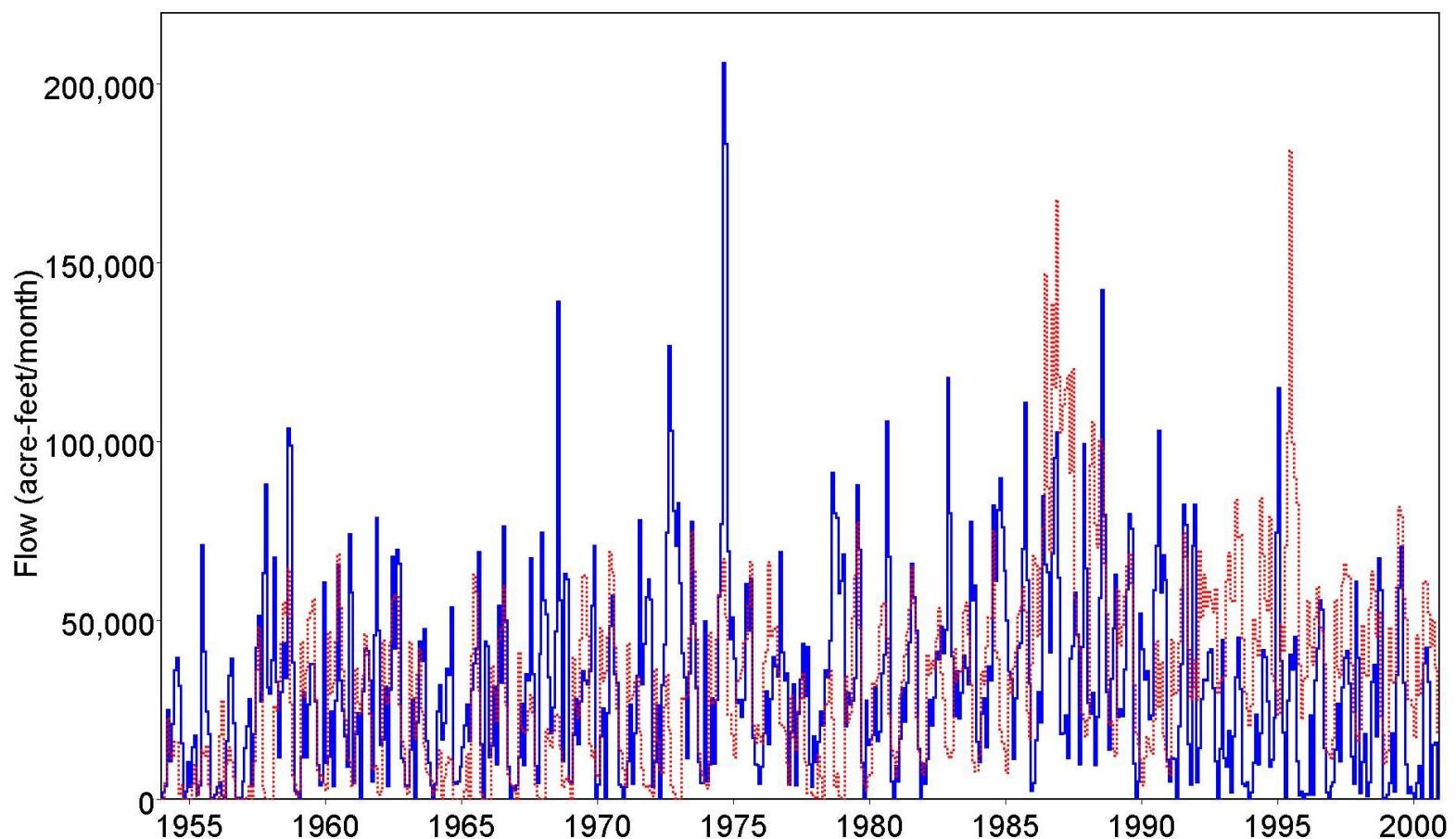


Figure A1. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Fort Quitman AT1000

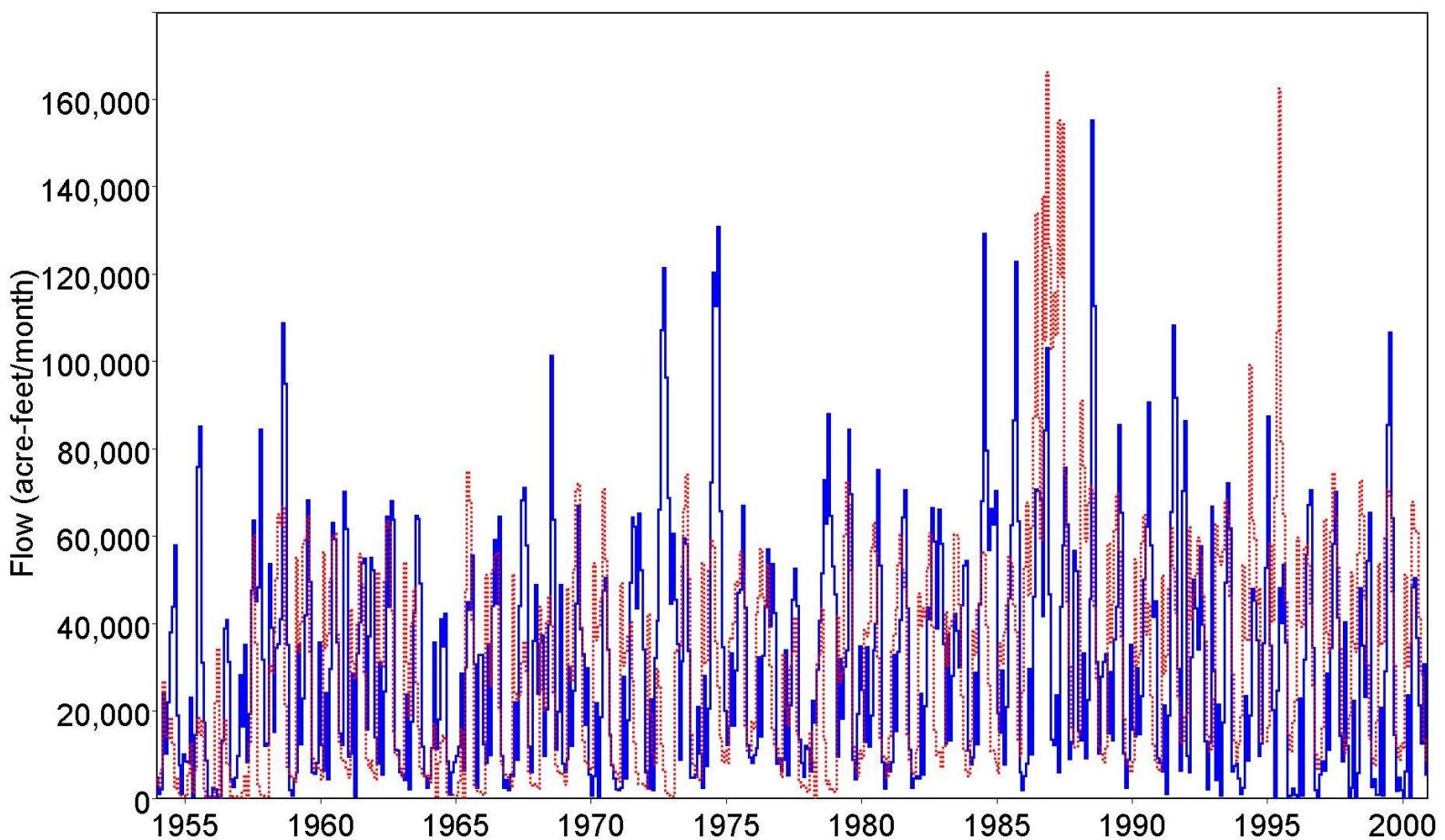


Figure A2. Known (Red) and Final Computed (Blue) Flows for Rio Grande at El Paso AT2000

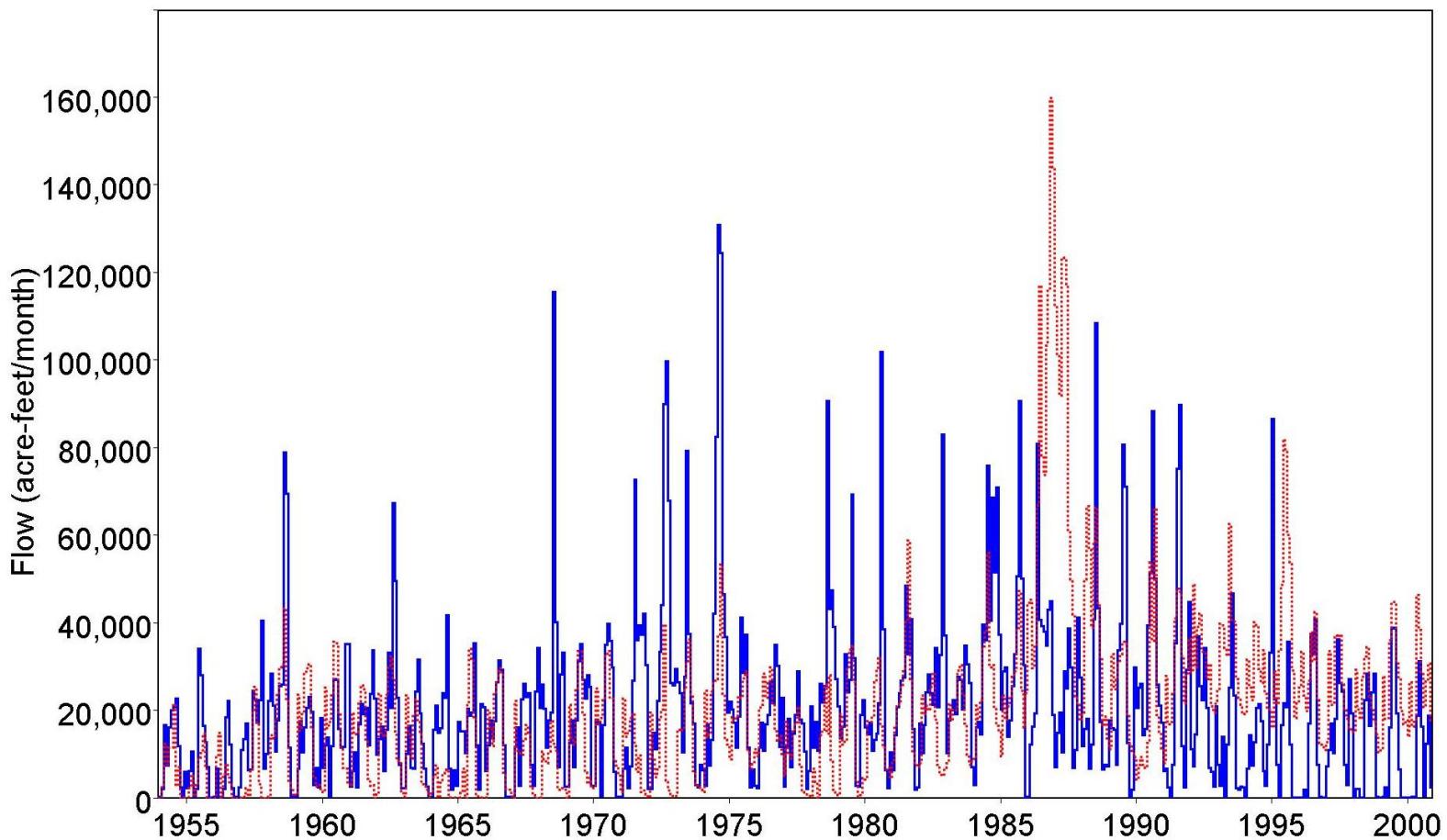


Figure A3. Known (Red) and Final Computed (Blue) Flows for Rio Grande above Conchos River BT1000

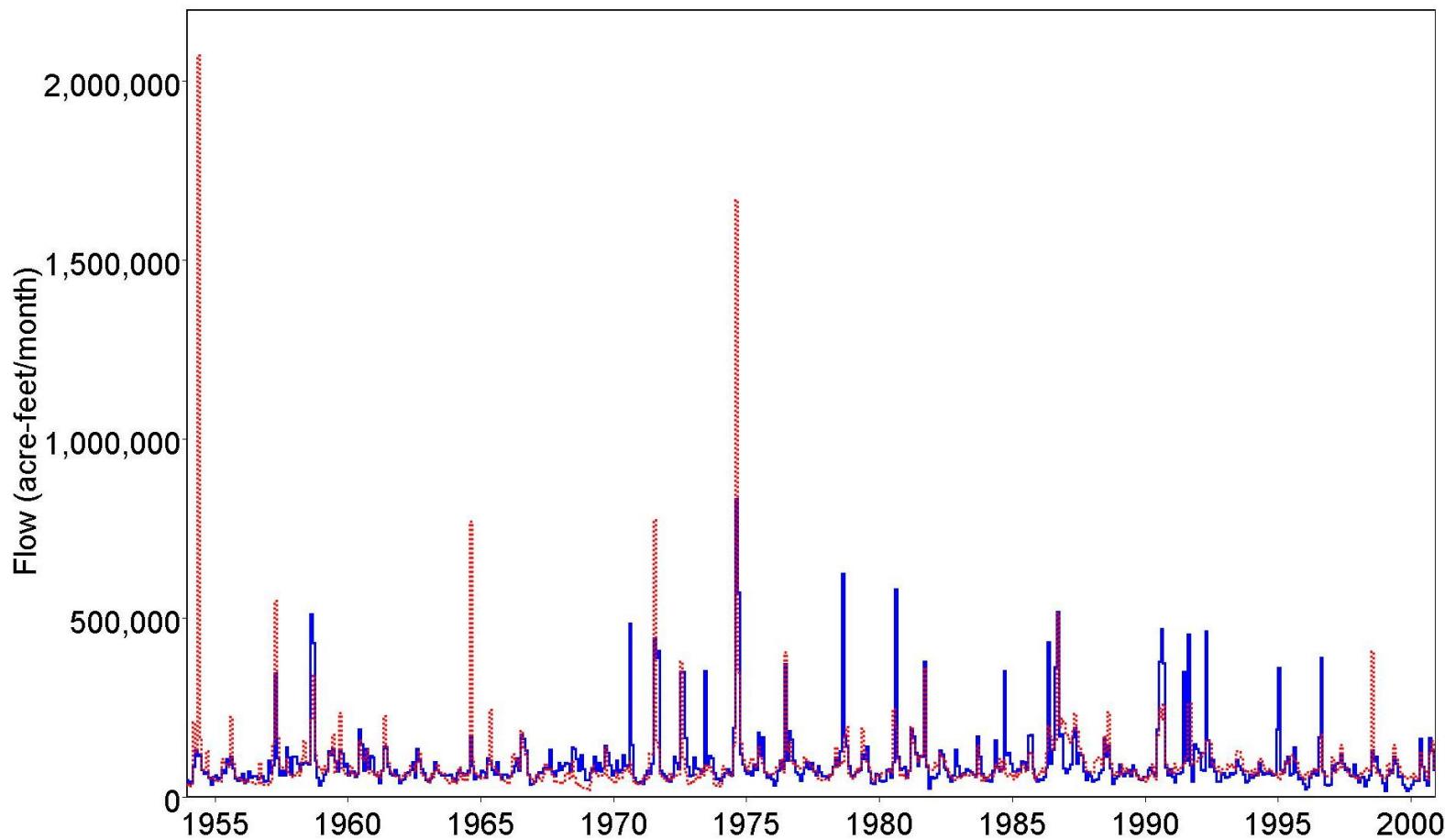


Figure A4. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Del Rio CT1000

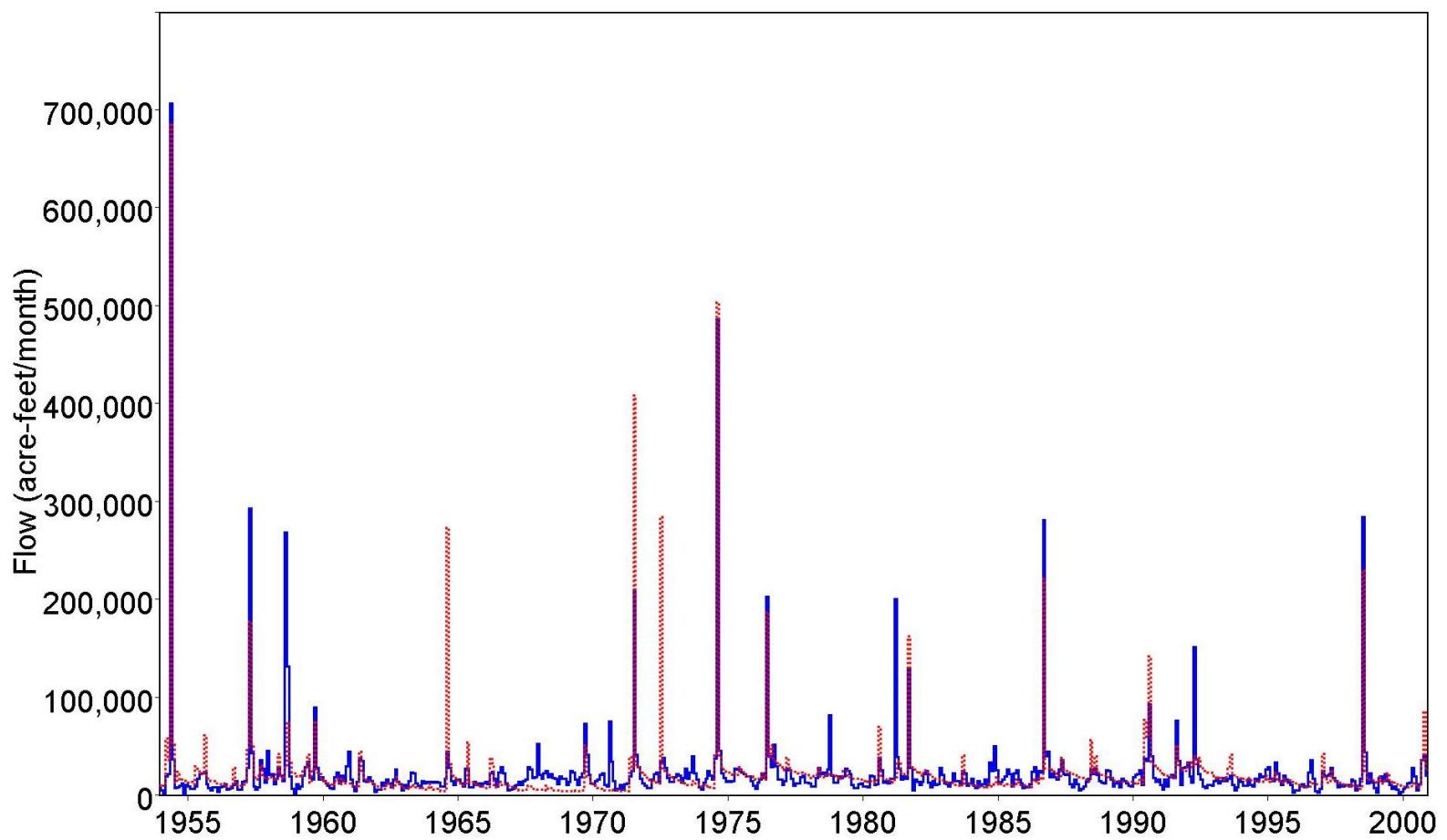


Figure A5. Known (Red) and Final Computed (Blue) Flows for Devils River at Pafford Crossing CT2000

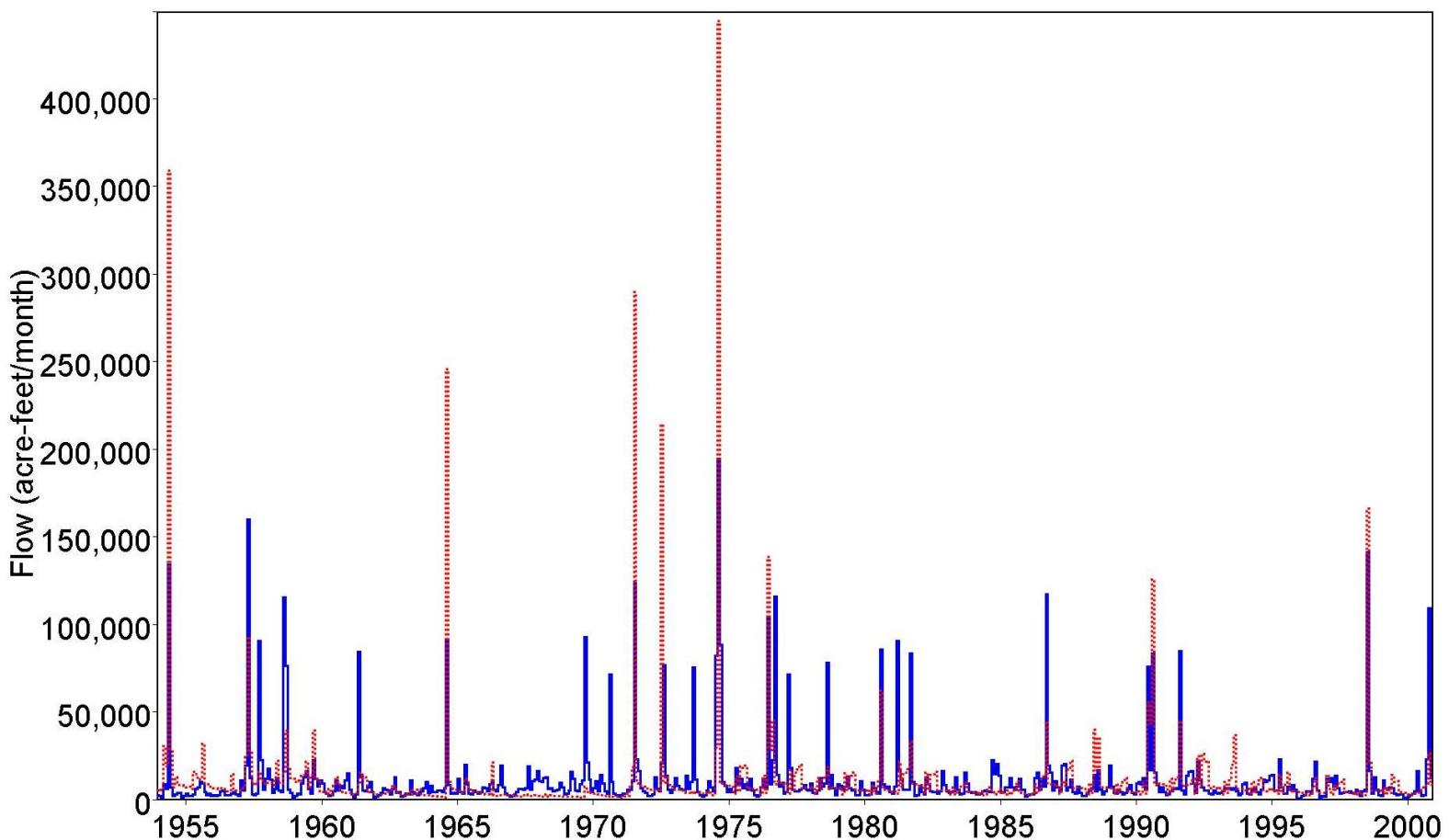


Figure A6. Known (Red) and Final Computed (Blue) Flows for Devils River near Juno CT2100

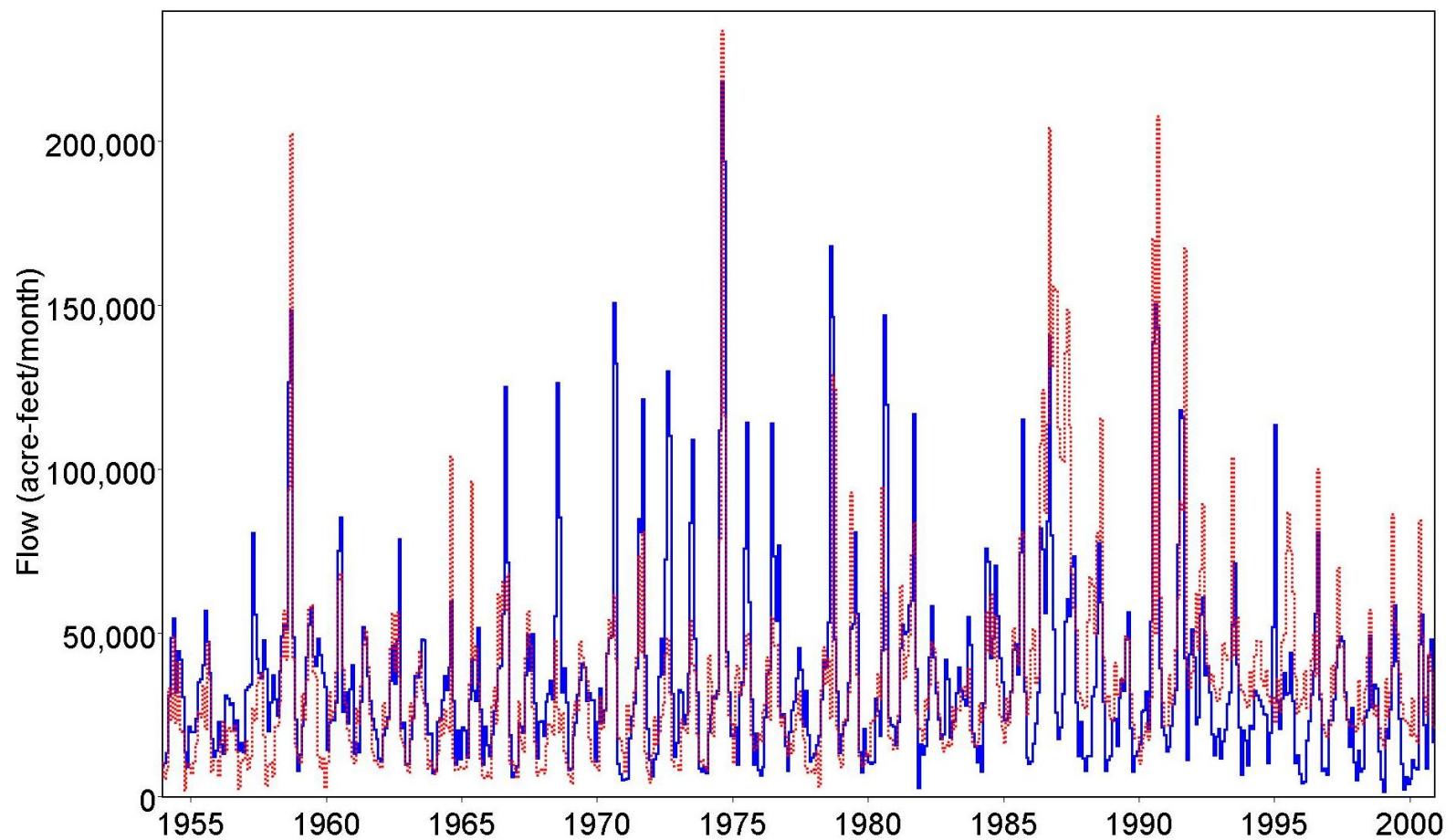


Figure A7. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Foster Ranch CT3000

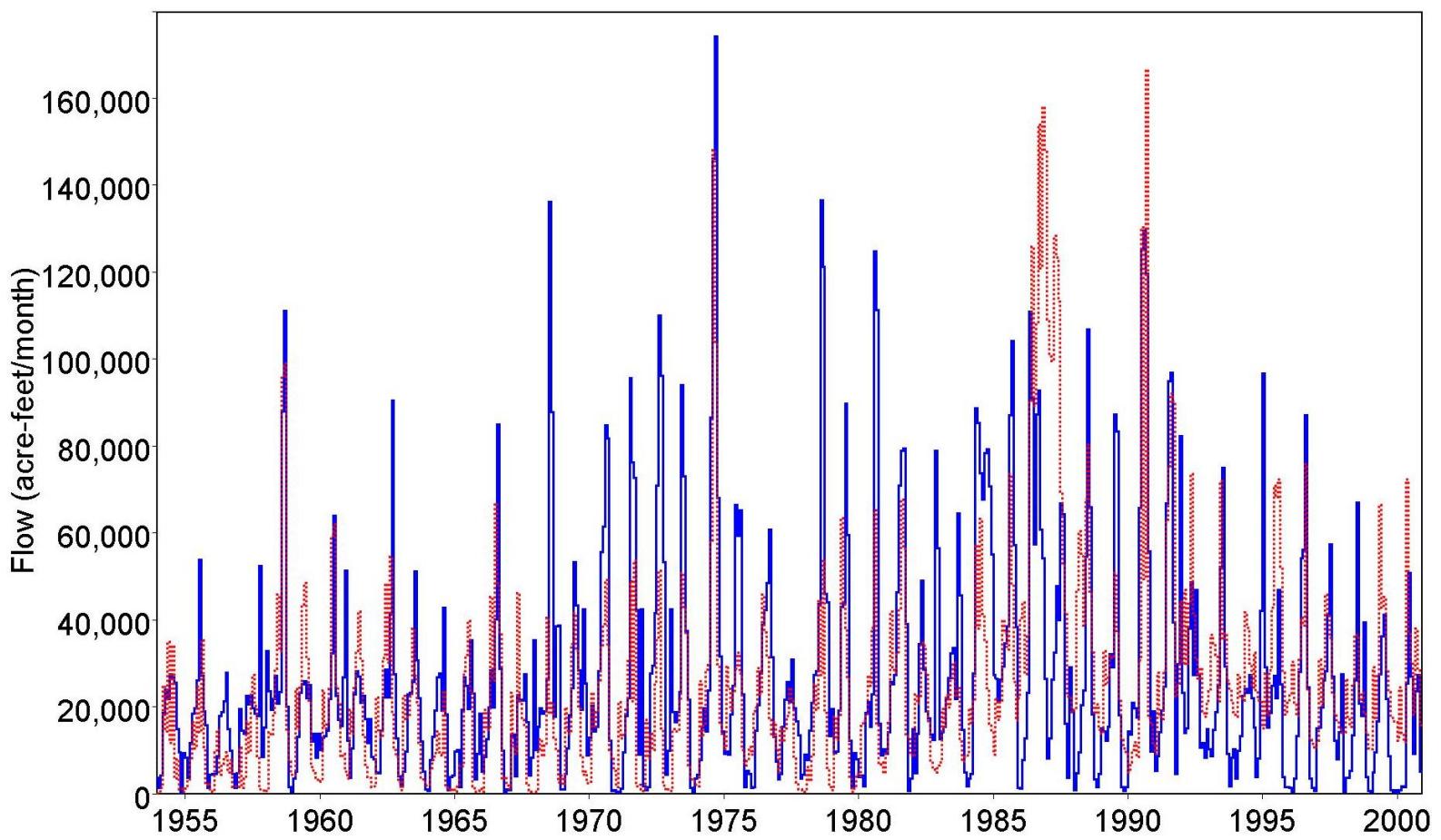


Figure A8. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Johnson Ranch CT4000

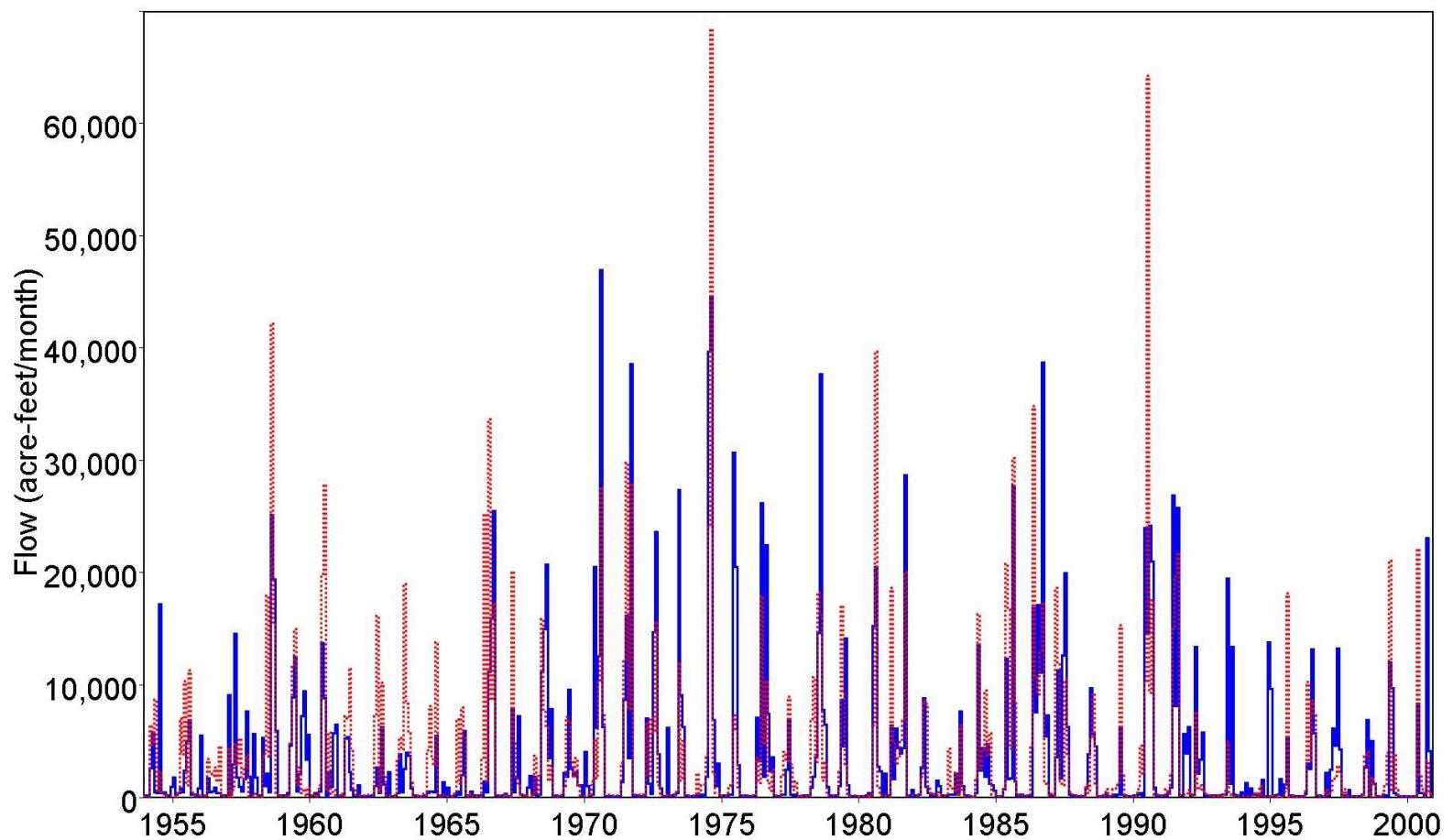


Figure A9. Known (Red) and Final Computed (Blue) Flows for Terlingua Creek near Terlingua CT5000

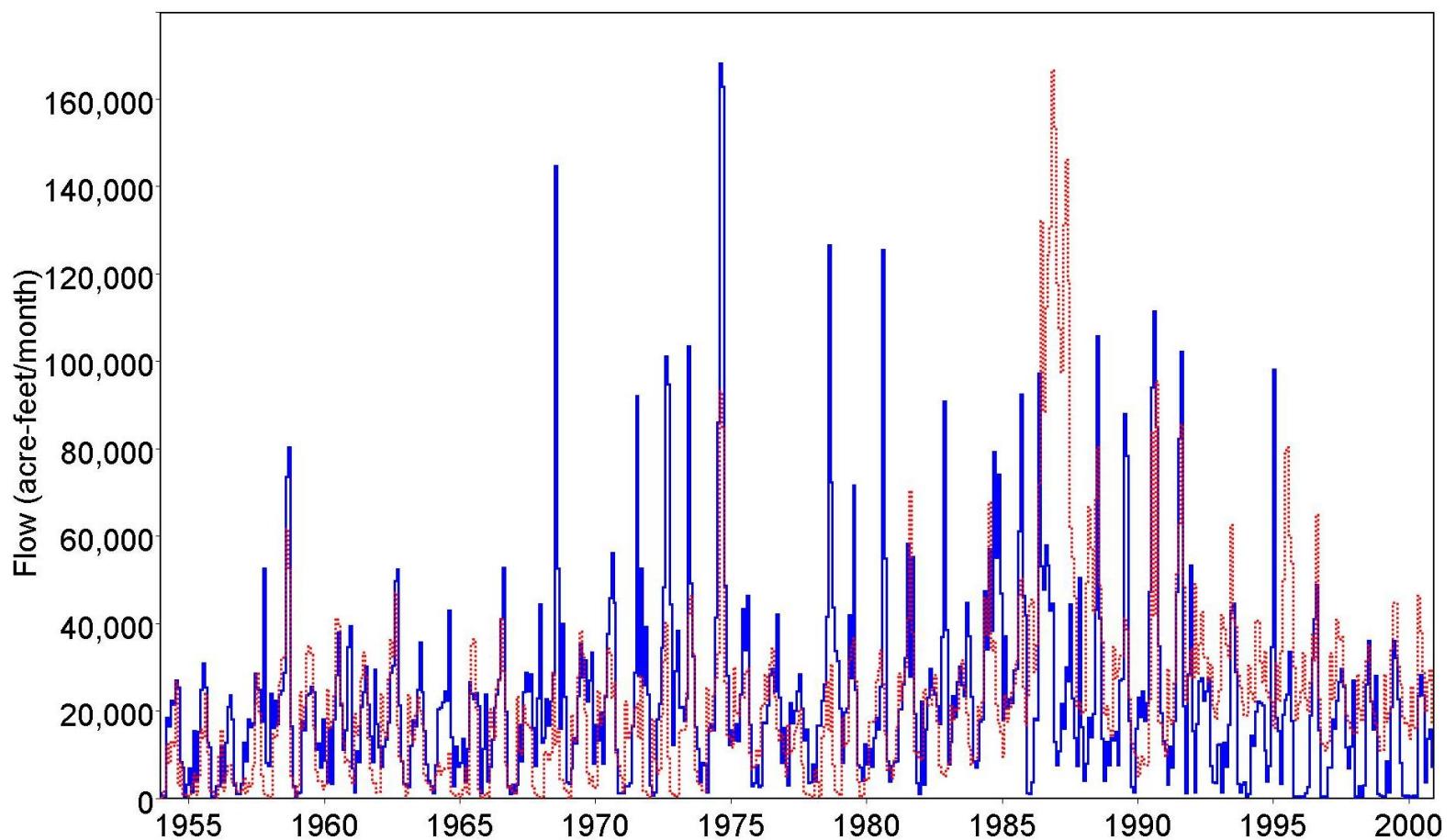


Figure A10. Known (Red) and Final Computed (Blue) Flows for Rio Grande below Rio Conchos CT6000

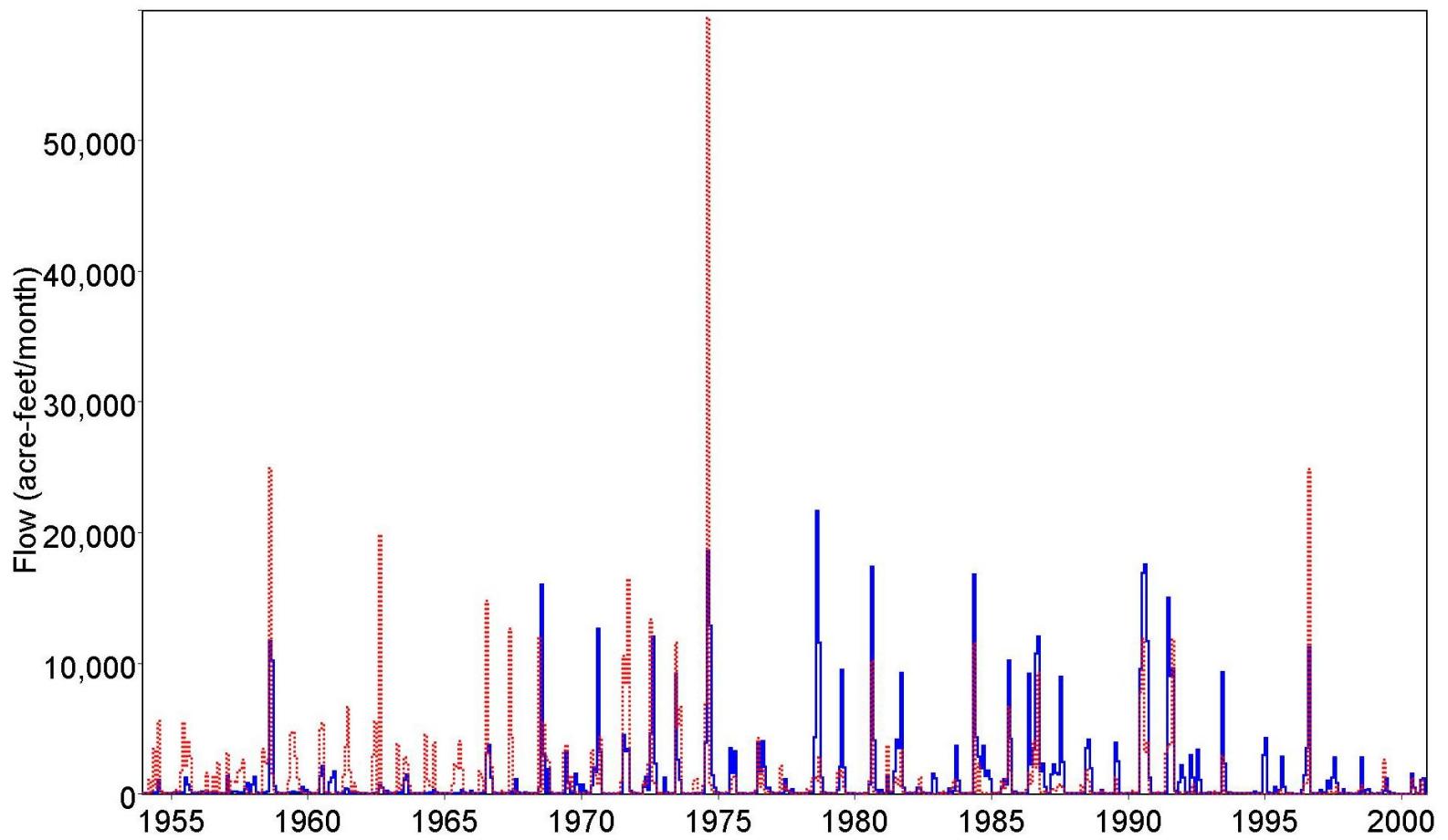


Figure A11. Known (Red) and Final Computed (Blue) Flows for Alamito Creek near Presidio CT7000

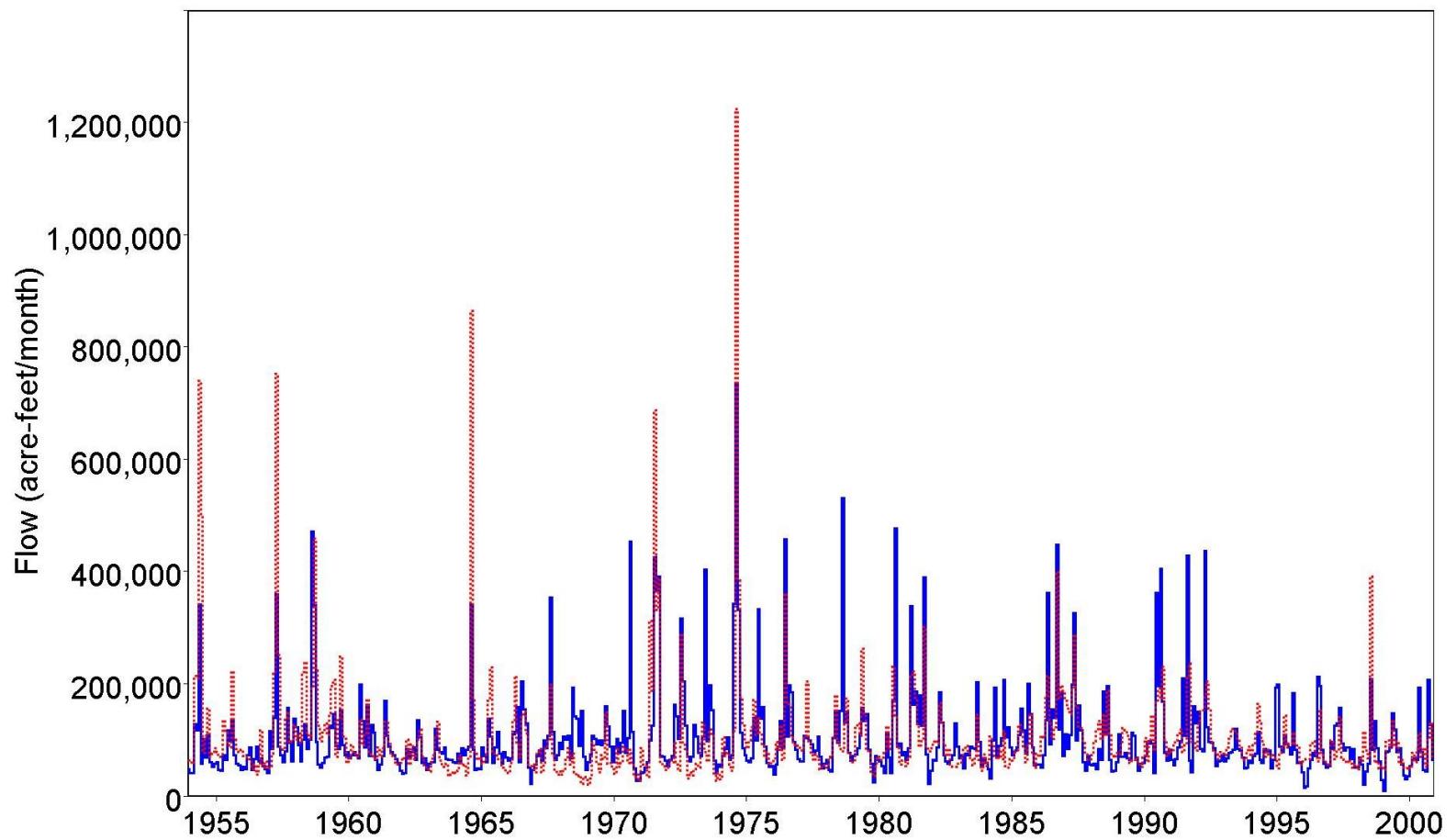


Figure A12. Known (Red) and Final Computed (Blue) Flows for Rio Grande below Falcon Reservoir DT1000

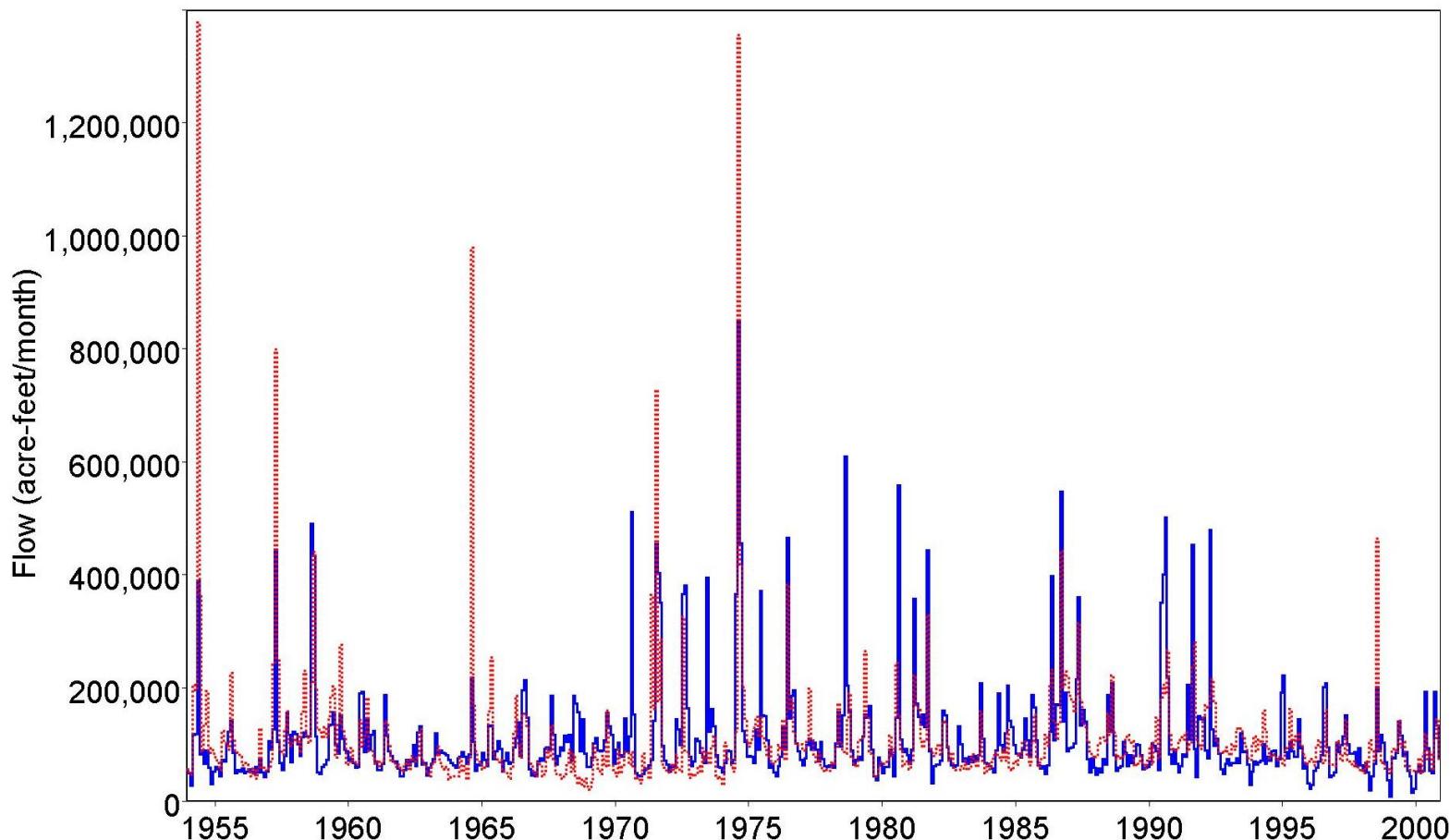


Figure A13. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Laredo DT3000

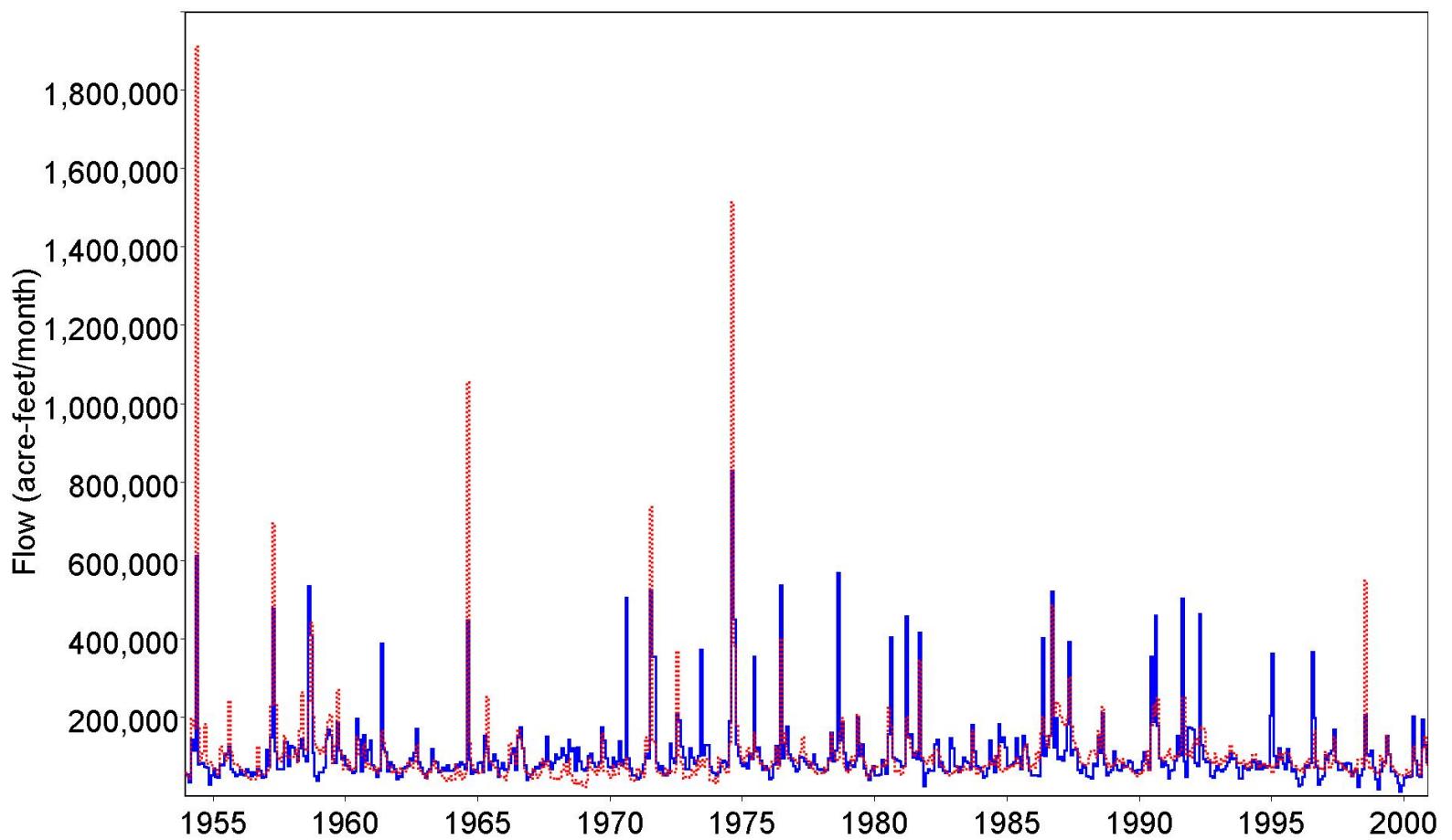


Figure A14. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Piedras Negras CT5000

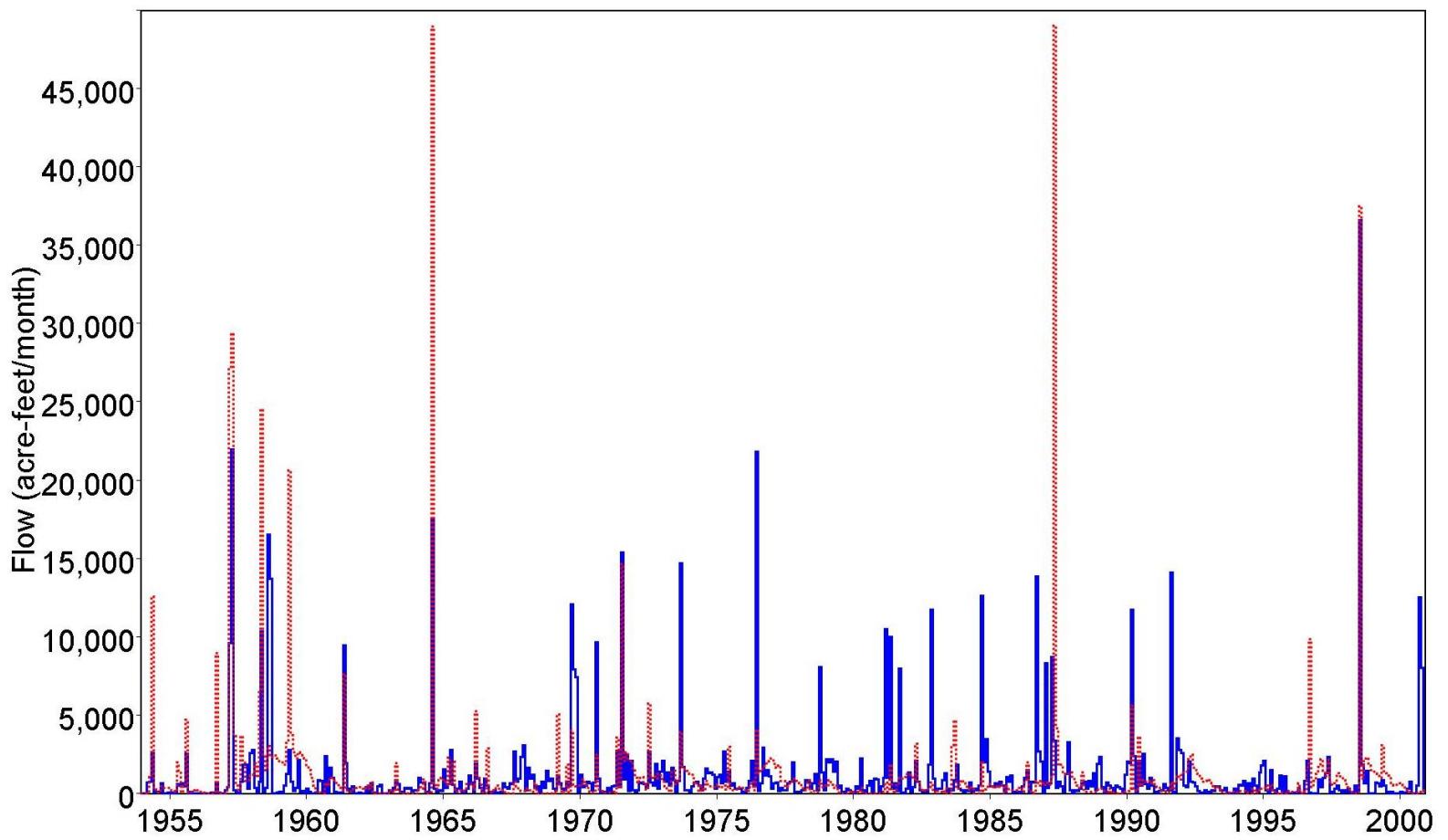


Figure A15. Known (Red) and Final Computed (Blue) Flows for Pinto Creek near Del Rio CT8000

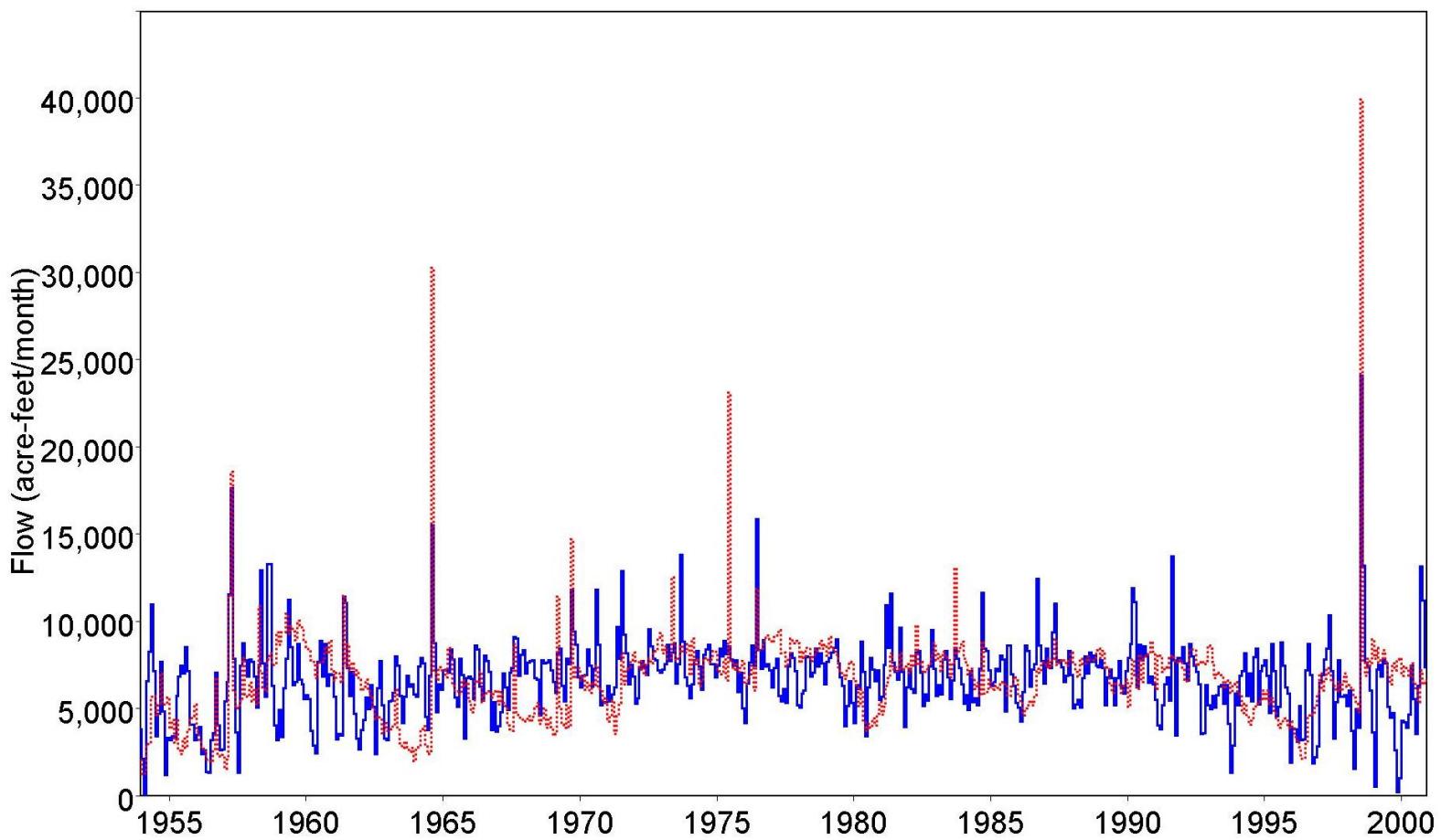


Figure A16. Known (Red) and Final Computed (Blue) Flows for San Felipe Creek near Del Rio CT9000

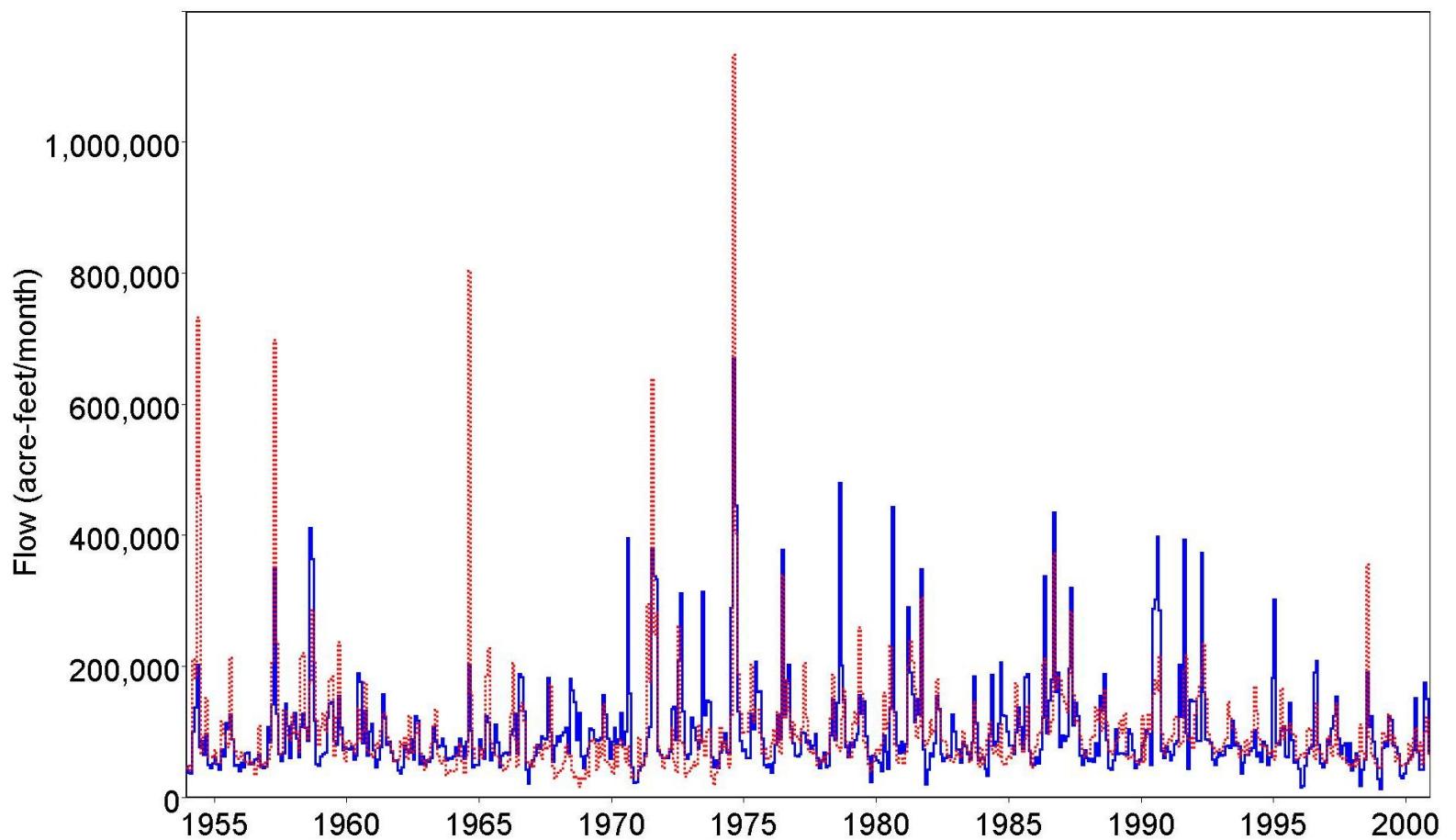


Figure A17. Known (Red) and Final Computed (Blue) Flows for Rio Grande below Anzalduas Reservoir ET1000

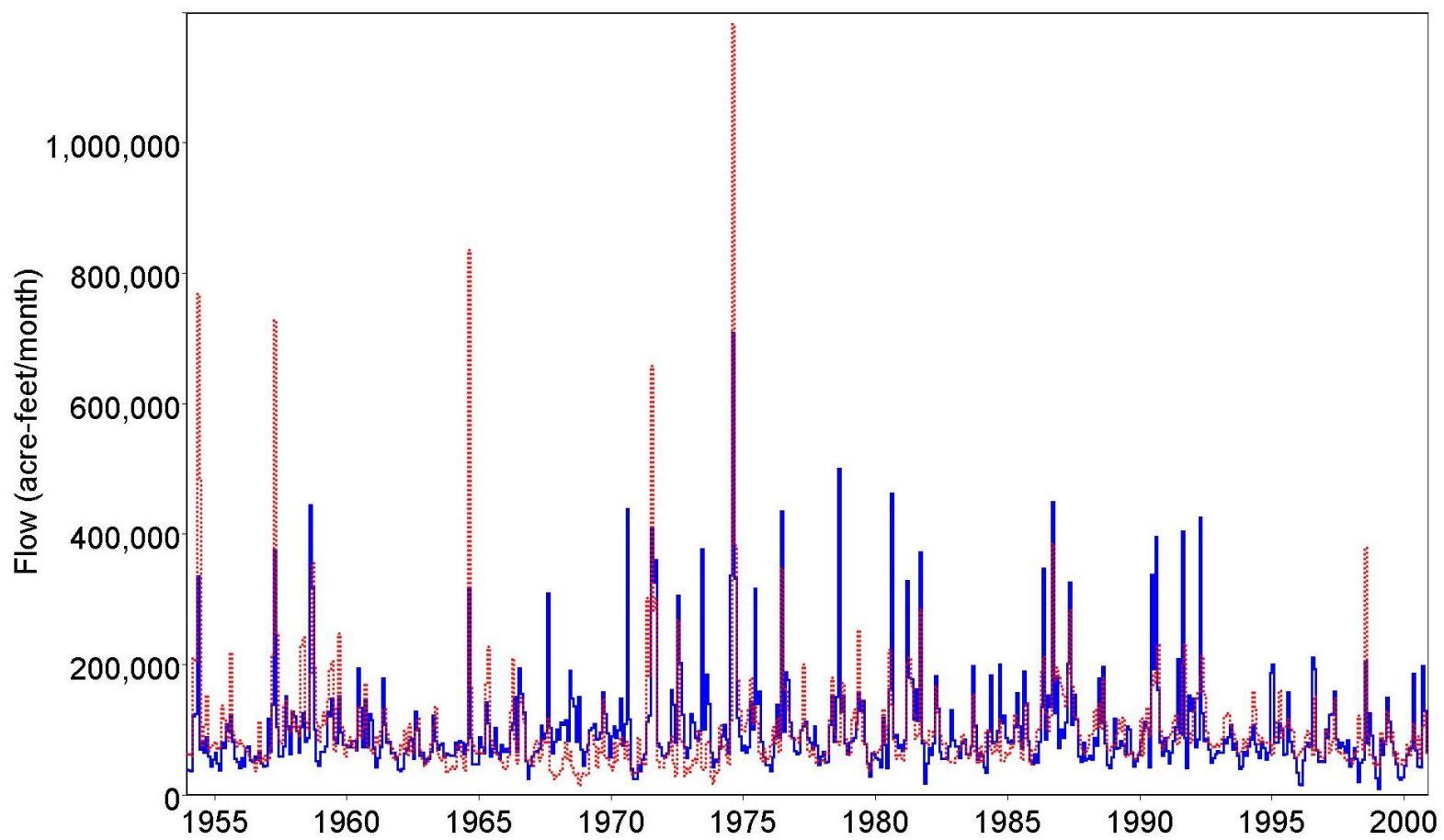


Figure A18. Known (Red) and Final Computed (Blue) Flows for Rio Grande at Rio Grande City ET2000

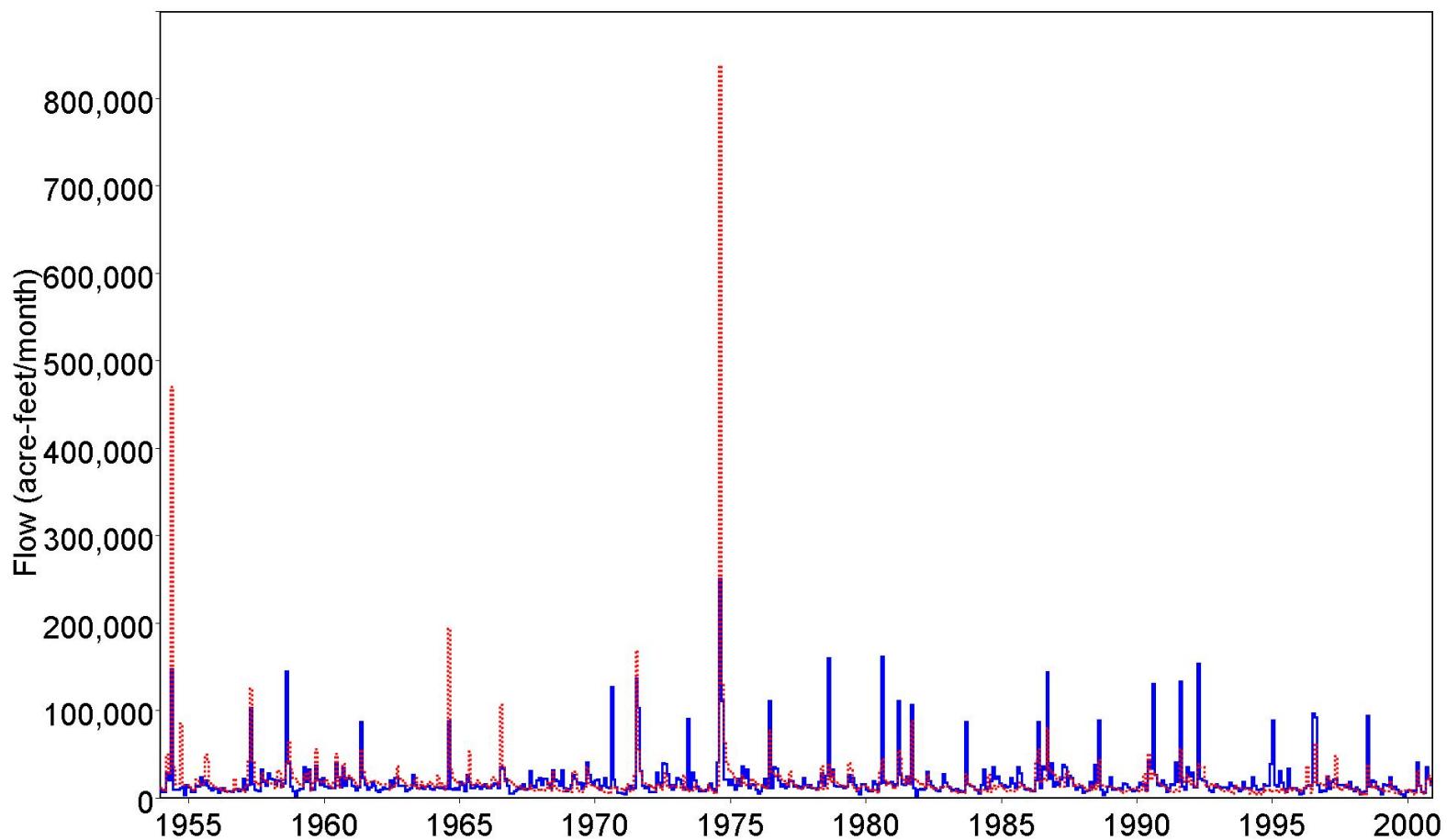


Figure A19. Known (Red) and Final Computed (Blue) Flows for Pecos River near Langtry GT1000

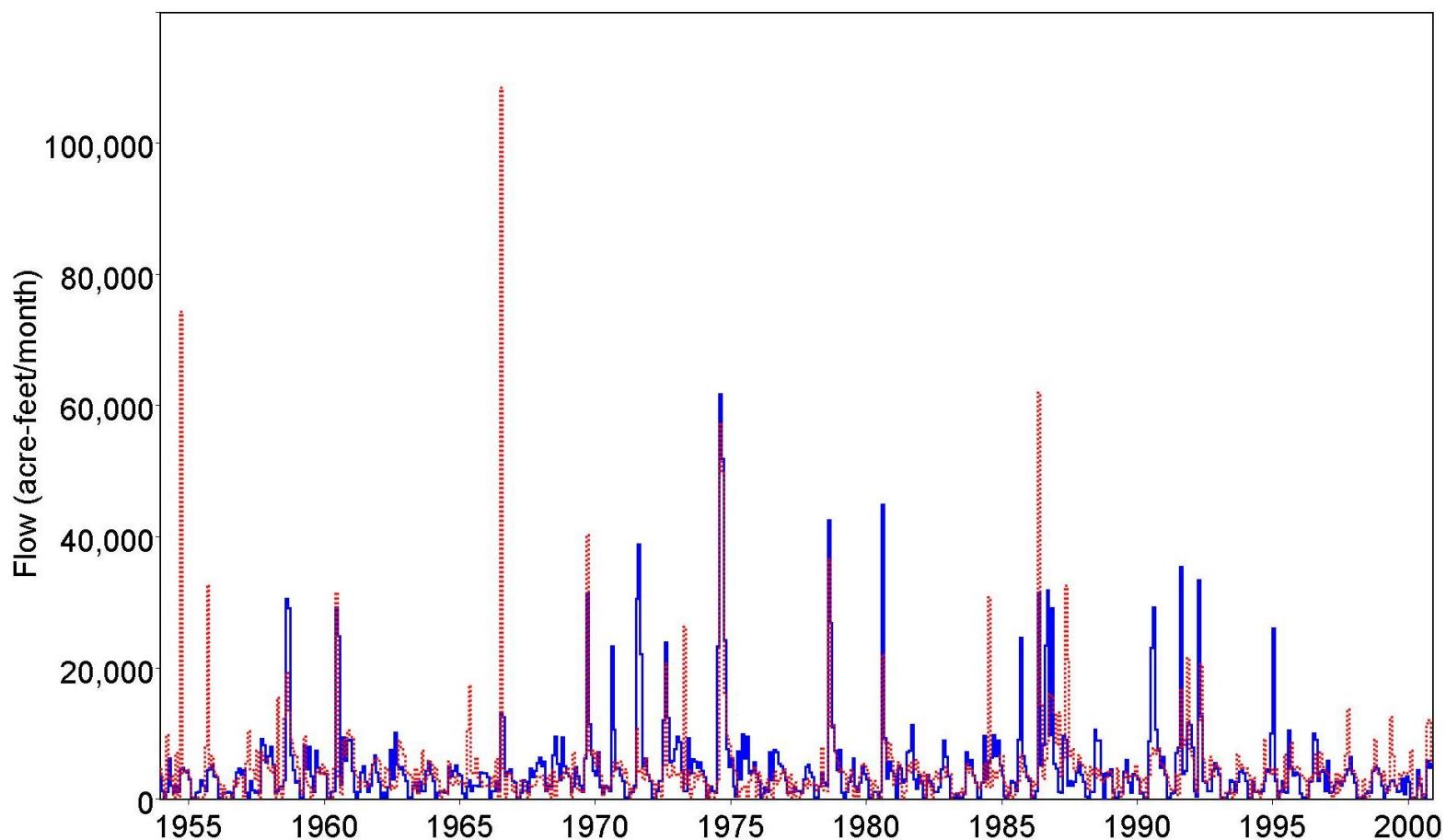


Figure A20. Known (Red) and Final Computed (Blue) Flows for Pecos River near Girvin GT2000

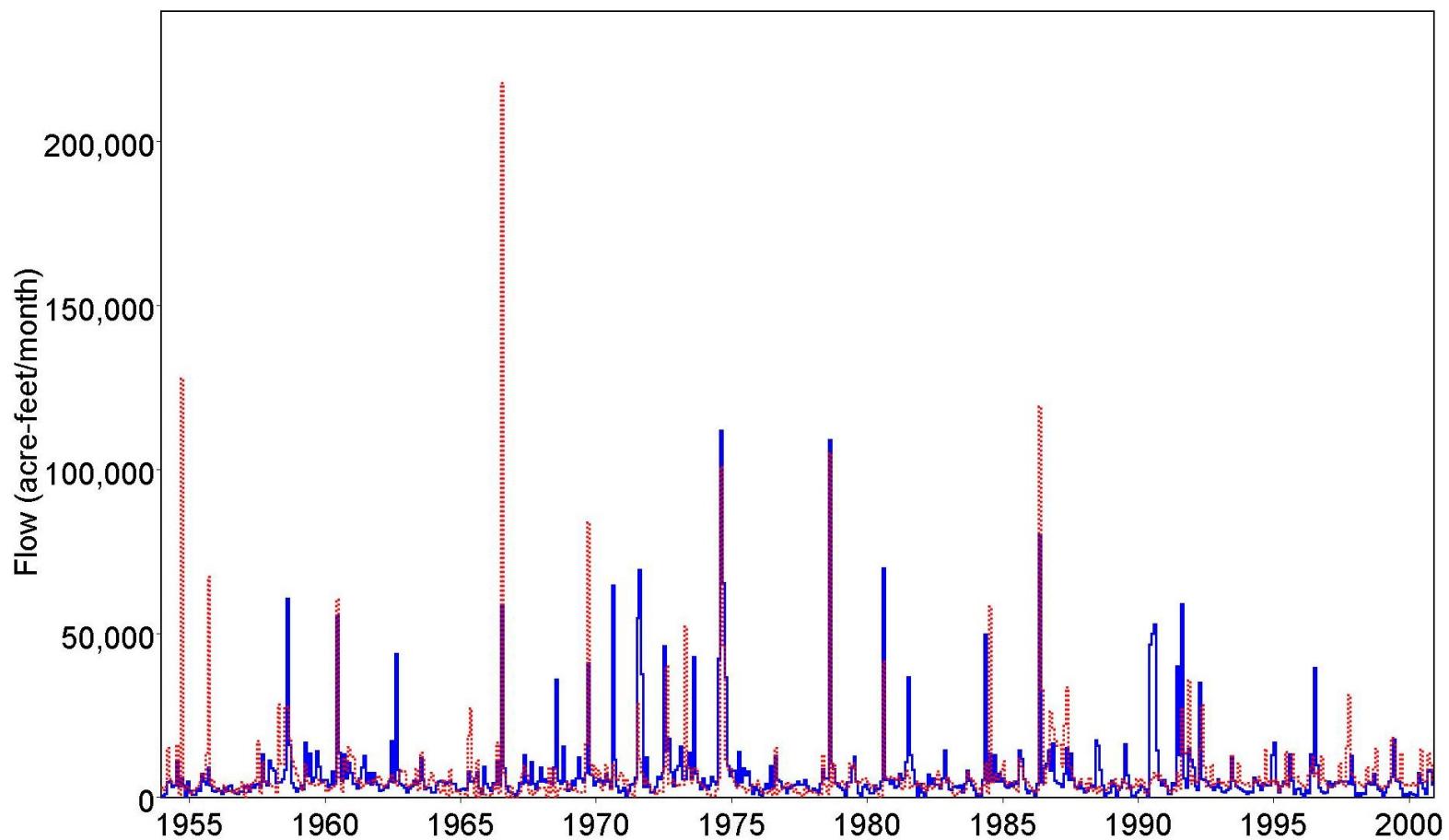


Figure A21. Known (Red) and Final Computed (Blue) Flows for Pecos River near Orla GT3000

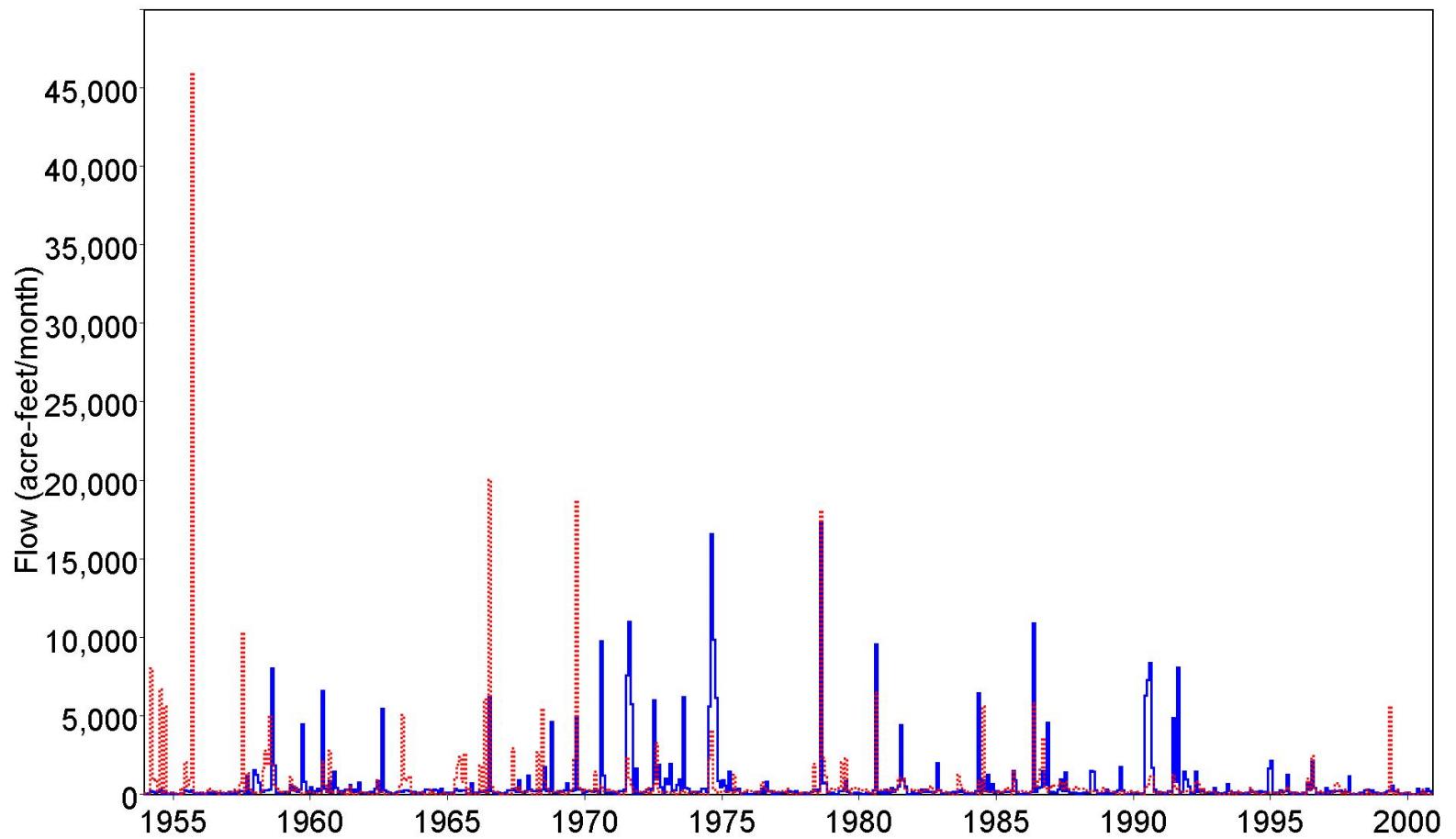


Figure A22. Known (Red) and Final Computed (Blue) Flows for Delaware River near Red Bluff GT4000

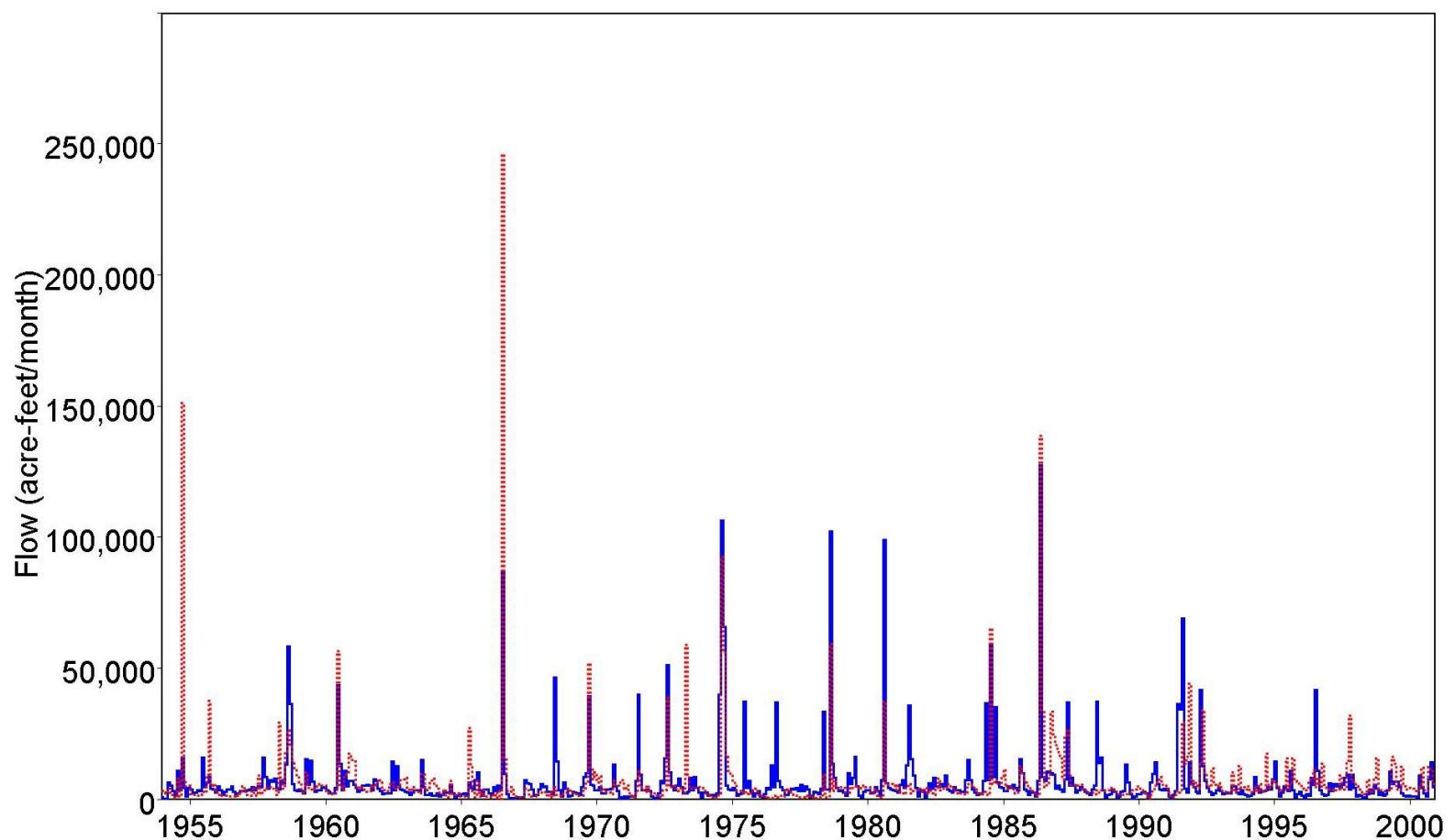


Figure A23. Known (Red) and Final Computed (Blue) Flows for Pecos River at Red Bluff GT5000

APPENDIX B

Rio Grande WAM Flow Frequency Metrics

Table B1. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande at El Paso AT2000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	34335	31176.77	42956.33	31176.83	32425.29	24659.07
Std Dev	32199.52	26947.79	59577.51	26788.47	32632.84	33316.85
Minimum	0	0	0	0	0	0
99.50%	180.3	145.14	114.11	48.24	0	0
99%	351	302.76	427.59	180.71	76.19	0
98%	473.32	424.08	756.01	319.57	299.16	0
95%	1581.4	837.8	2255.1	1114.37	614.28	114.4
90%	4562.2	3229.2	3265.78	3179.54	2160.2	394.2
85%	6497.6	5538.2	4273.12	5360.02	4788.2	668.4
80%	8235.2	6963.4	5126.64	7207.89	6537.2	908.4
75%	10683	8612	6051.5	8736.1	8538	1932.6
70%	12412.41	10975.6	7139.72	10434.85	10945.58	4114.9
60%	17994	14992.39	10333.64	16191.7	15454.2	7808.2
50%	30115	28419	15687.4	27803.2	26327	13260.1
40%	38573.2	35937.2	21175.94	34443.22	36091	21666.3
30%	47348.8	43963.2	37224.88	43031.65	44488.2	35589.1
25%	52708	48672	52576.1	46718.5	48999	39224.8
20%	56184.4	53517.8	76080.7	53274.56	54121.6	42835.8
15%	60490.4	57699.39	106416.97	61672.48	59477.92	46632.1
10%	66993	62196.4	132231.12	66391.58	65027.8	55423.1
5%	76552.2	70737.4	184951.59	83354.3	76402.4	75949
2%	117065.84	105728.76	235887.28	107083.41	120501.86	137807.92
1%	154936.52	135296.33	265717.81	120625.27	156305.75	210267.66
0.50%	178681.48	156548.56	285315.88	129522.02	197139.3	239951.91
Maximum	356367	166173	341837.31	155180.5	356367	239951.91

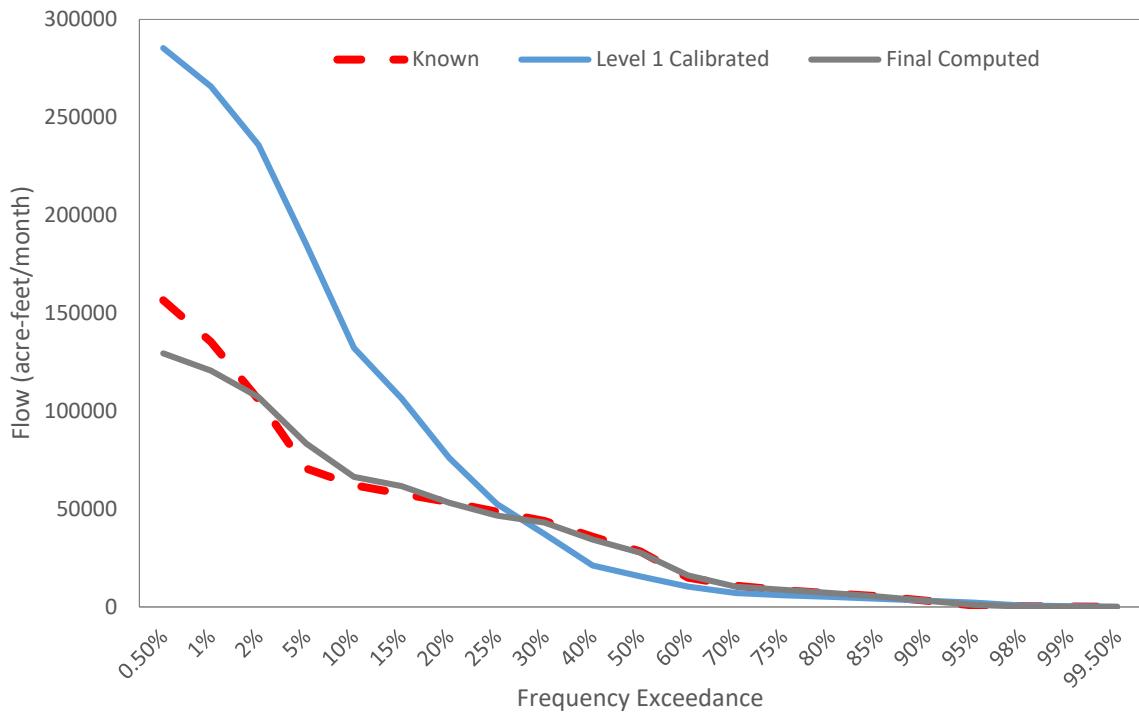


Figure B1. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at AT2000

Table B2. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Rio Grande above Rio Conchos BT1000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	23495.07	20429.85	25141.09	20417.82	21442.66	13096.17
Std Dev	25784.07	20358.18	33930.12	19753.45	24690.46	17329.81
Minimum	0	0	294.3	0.4	0	0
99.50%	0	0	550.77	0.78	0	0.09
99%	0	0	940.25	1.36	0	0.18
98%	0	0	1158.3	1.7	0	0.2
95%	137	10.6	1809.88	56.82	1.66	0.6
90%	1394.8	773.4	2518	977.06	318.34	1.2
85%	3089.6	2212.8	3200.86	2375.96	1910.2	1.7
80%	6060.19	4476.6	3961.58	5332.08	2939	2.2
75%	8016	6851	4499.6	6735.4	6333	326.1
70%	10462.2	8926.6	5097.34	8068.45	7903.4	2002.3
60%	15276.2	14019.4	6598.34	13054.83	13126.6	2852.3
50%	19006	17610	8983.4	17018.3	17484	7306.5
40%	23152	21077.2	13931.08	20491.66	21244	13712.2
30%	27451	24807	22644.24	24230.14	25403.7	18194.3
25%	29804	27321	32218.9	26944	28645	20129.7
20%	33269.4	29850.6	44488.54	30367.02	31009.48	22316.3
15%	37200.8	33481.4	59666.28	35163.4	35360.2	24546.3
10%	44295.59	38961.4	72895.52	39931.16	40998.6	30850
5%	62611.6	53669.8	102576.78	64207.48	59064.6	36092.3
2%	101910.48	89098.12	134171.53	87750.89	100672.08	87258.56
1%	137385.09	117084.56	153633.97	100479.68	122327.84	105671.8
0.50%	176548.16	127082.08	179112.75	117143.38	167019.33	110654.2
Maximum	271634	159846	199994.59	130800.5	271634	110654.2

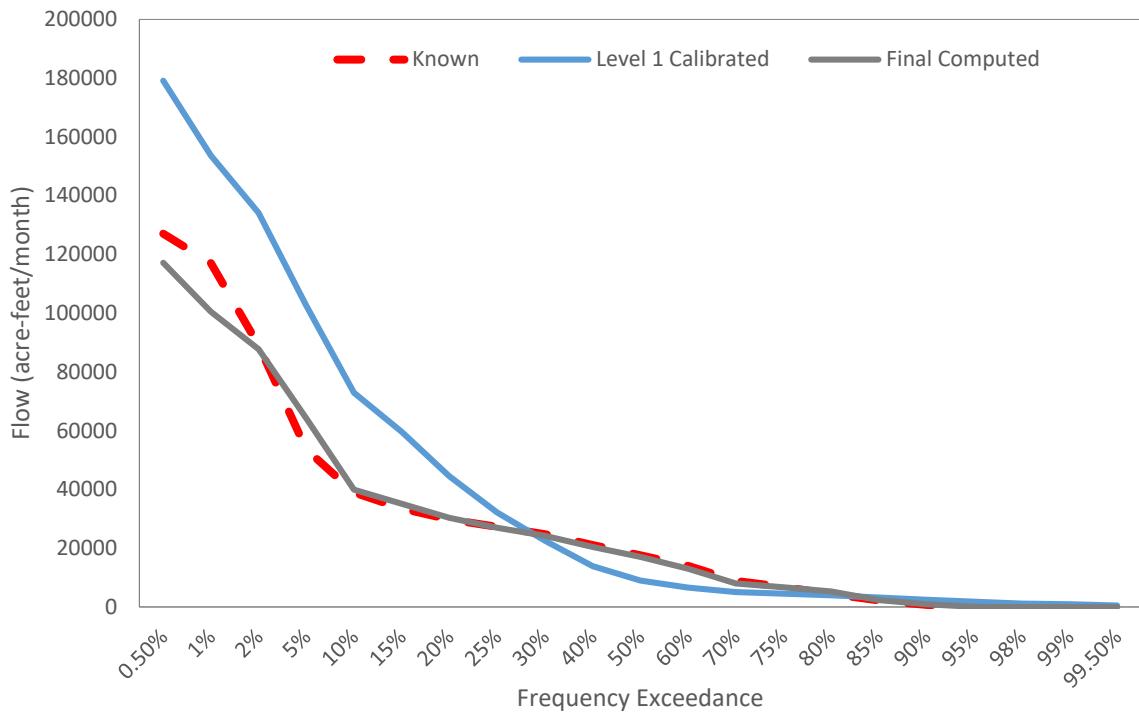


Figure B2. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at BT1000

Table B3. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande at Del Rio CT1000

1	2	3	4	5	6	7
	Original Known 1954-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	100068.38	96112.54	97469.89	96322.2	97429.08	86695.96
Std Dev	125746.8	127756.04	68485.43	88346.7	117362.79	73368.38
Minimum	19293.64	19293.64	8784.52	16179.42	8210.7	8210.7
99.50%	28871.43	25802.55	12201.46	22342.76	13792.33	10753.38
99%	31897.24	31296.69	14682.76	26948.72	18513.59	11609.36
98%	35123.36	34304.49	18051.55	32857.7	28926.82	13620.44
95%	37882.98	38631.4	25582.64	38408.14	36604.45	18466.4
90%	45317.52	45265.77	37130.9	44749.57	43478.55	33106.17
85%	49857.69	49694.42	44705.61	49530.08	49028.31	44422.9
80%	53967.05	53329.39	51905.12	53922.7	52659.05	49050.37
75%	57564.92	56898.9	57132.95	57379.38	56860.18	52652.71
70%	60293.04	59556.68	60619.07	60238.62	59562.36	56181.1
60%	66568.2	65788.82	66479.89	65461.93	65813.21	61800.37
50%	72133.26	70855.3	74313.32	72065.52	71481.76	67133.99
40%	80543.16	78920.4	82646.32	76924.6	79148.14	74858.59
30%	93716.2	90344.02	107477.9	91137.96	92486.55	87541.07
25%	101769.52	98510.45	126117.76	98124.86	100958.67	95907.38
20%	114823.84	107436.23	144815.62	111411.85	114133.45	113893.35
15%	134584.02	123829.8	162833.19	124853.2	132537.16	127406.29
10%	167413.12	151533.48	190841.61	153067.45	165141.12	159452.09
5%	223127.33	205122.91	234718.03	314935.56	216284.33	181218.27
2%	351109.78	344362	298817.5	439259.09	366399.34	414791.97
1%	536015.62	525037.56	347851.03	511322.62	468075.62	456756.66
0.50%	940945.56	934335.88	399561.06	587368.5	811541.44	470073.09
Maximum	2071248.3	2071248.25	566155.81	832314	2071248.25	470073.09

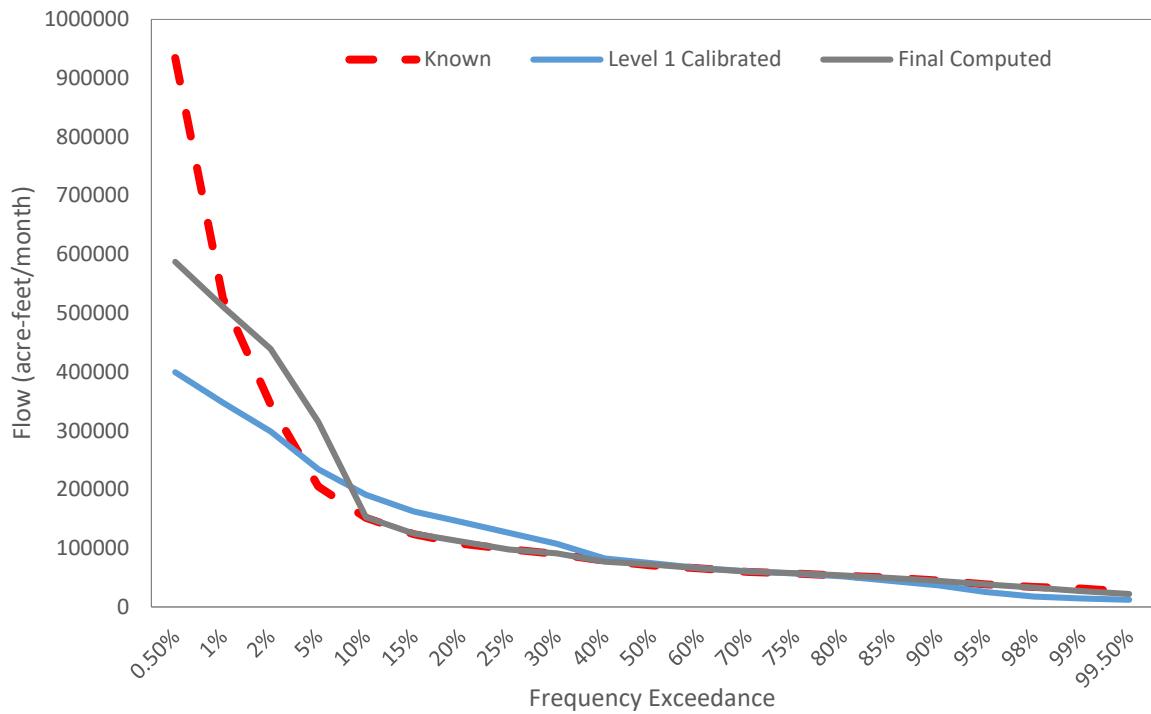


Figure B3. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT1000

Table B4. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Devils River at Pafford Crossing CT2000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	21860	23111.66	25074.94	23107.87	21662.32	20858.42
Std Dev	41668.62	46162.21	48190.14	45631.28	40064.35	32830.4
Minimum	3955	3955	939.9	1067.1	1918.3	1918.3
99.50%	4143.8	4108.34	1971.53	2290.41	2926.15	1952.14
99%	4308.28	4204.4	2597.55	3023.8	3724.8	2497.9
98%	4748.4	4545.44	4058.74	4607.67	4227.08	2911.44
95%	6075.6	5383.6	5841.36	5938.26	5390.8	3702.1
90%	8035.6	7650.2	9101.3	7461.46	7665.4	5534.3
85%	9297.2	8936.2	11998.02	8828.06	9078.6	7370
80%	10015.8	9867.2	13290.98	9958.72	9907	9184.1
75%	10735	10668	14257.6	10742.2	10673	10275.9
70%	11559.4	11605.8	14855.82	11459.24	11487.2	11224.9
60%	12961.6	13394.8	16405.16	13456.04	12875.12	12591.7
50%	14821	15571	17817.5	14985.3	14442	14085.5
40%	16672.4	17700.4	19688.68	17214.36	16599	16195.4
30%	19269.8	20457.4	21718.92	20583.64	19425.4	20378.1
25%	21181	22186	22378.2	22149.1	21187	21277.2
20%	23086	24269.8	24503.14	24065.36	23010.6	22920.4
15%	25626.8	26567	27228.66	27152.72	25567.2	25455.2
10%	30031.2	31648.4	30264.62	32024.04	30031.2	34416.4
5%	42687.6	44185.2	39449.64	42553.24	43482	48641.9
2%	75900.8	126311.17	140969.97	130777.88	76412.8	125570.98
1%	226846.16	245376.69	291693.16	273302.56	228648.56	281390.88
0.50%	326510.47	425644.44	345478.38	327858.09	289468.62	296185.59
Maximum	685973	685973	754183.88	706194.19	685973	296185.59

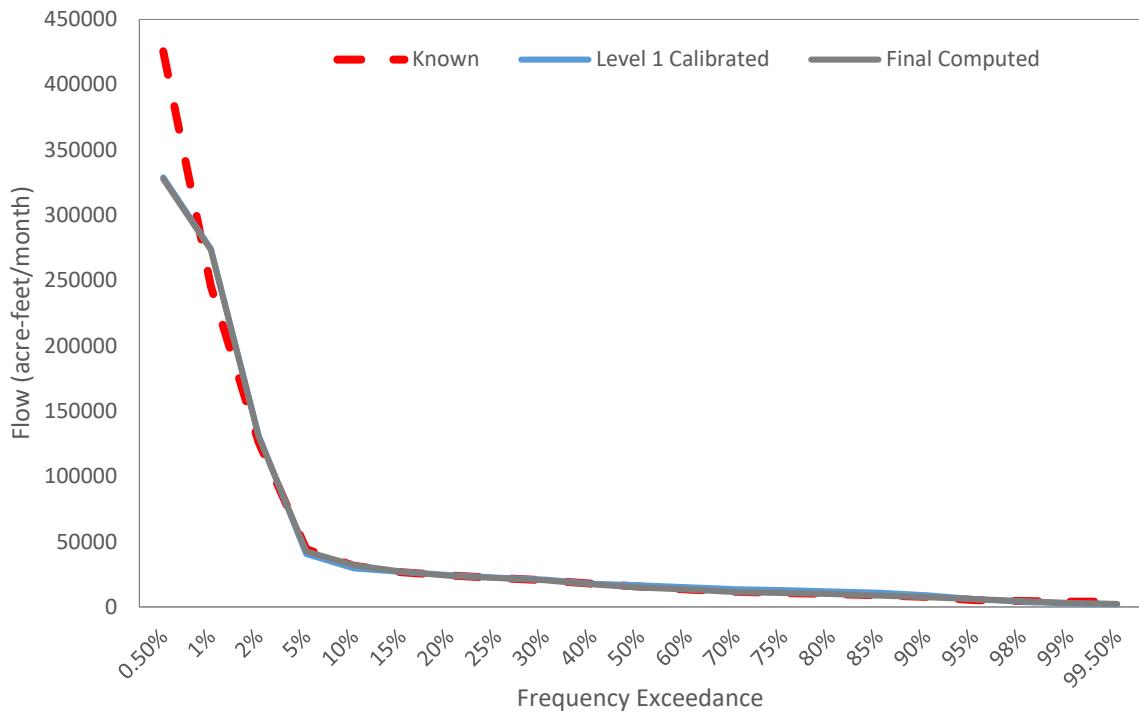


Figure B4. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT2000

Table B5. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Devils River near Juno CT2100

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	10638.19	11344.06	14933.6	11342.3	10545.27	10167.38
Std Dev	29331.4	32076.92	21899.47	21712.75	27643.11	19375.61
Minimum	1093	1093	347.1	693.9	440.7	440.7
99.50%	1259.3	1254.92	407.1	813.82	1061.66	563.73
99%	1355.4	1336.84	489.61	978.88	1143.82	847.56
98%	1551.08	1483.8	750.16	1499.78	1377.18	1001.08
95%	2088.8	1857.6	1170.42	2003.54	1858.8	1152.7
90%	2818.2	2491.2	1575.22	2467.52	2624.4	1998.8
85%	3106	2947.6	1953.02	2917.96	3057.8	2638.8
80%	3522.6	3141.8	2297.5	3205.02	3392.6	3105.5
75%	3854	3543	2721.5	3483.7	3781	3327.3
70%	4174.2	3884.4	3207.28	4007.24	4085.6	3850.2
60%	4947.6	4792.2	3889.92	4738.1	4815.68	4403.9
50%	5476	5652	4815.8	5514.4	5425	5183
40%	6478.8	6714	6337.3	6437.94	6424.2	6252
30%	7887	8340.2	13946.64	8440.66	7861.6	7633.1
25%	8682	9310	18456.2	10013.8	8764	9378.4
20%	9991	10745.8	25378.66	11368.34	10214.2	11331.5
15%	12045.4	12768.2	32164.62	12823.72	12205.4	12962.7
10%	15058.4	15804.8	42493.64	16325.34	15140.78	16098.9
5%	23896	26248.4	61450.02	61732.66	22635.4	20366.6
2%	45183.36	52289.4	79218.82	92000.01	60321.12	110610.3
1%	157157.38	183280.2	102808.3	119395.38	127571.91	120555.56
0.50%	260600.36	302029.41	124499.74	144586.59	228064.41	127855.4
Maximum	444373	444373	167591.2	194630.41	444373	127855.4

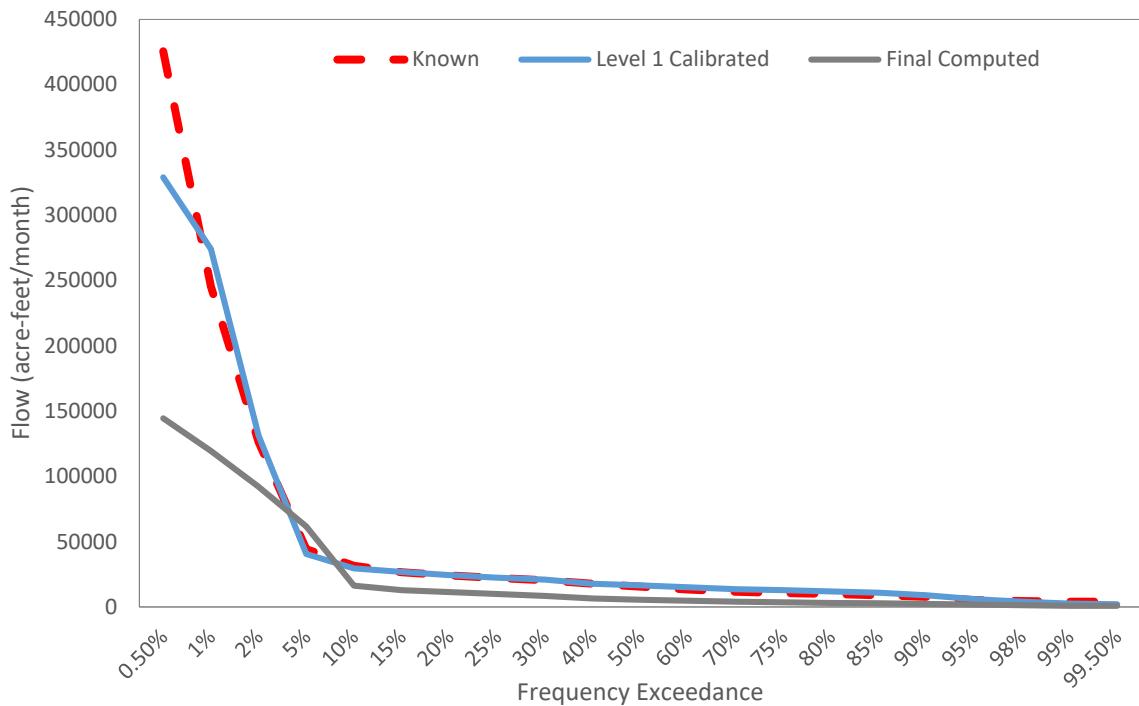


Figure B5. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT2100

Table B6. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Rio Grande at Foster Ranch CT3000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	38682.97	35380.24	36602	35380.24	36789.73	29090.54
Std Dev	44082.7	29784.17	29288.51	29055.08	40965.52	23035.34
Minimum	464	2122	938.8	1486	464	615
99.50%	2614.24	3006.64	2308.47	3654	1440.64	786.63
99%	4119.96	4192.92	3106.82	4917.79	1987.54	1106.42
98%	6112.52	6284.56	3560.6	5636.08	3527.92	1467.56
95%	8103.8	8048.8	5541.28	7891.16	7201.44	2824.3
90%	10378.4	9990.2	8652.4	10104.62	9680.4	5904.3
85%	12938.6	11959.4	10735.54	12318.68	11421	8384.2
80%	16338.6	15410.4	12490.76	15006.63	15030.39	11219.7
75%	18558	17942	14868.8	18063.3	17730	13336.8
70%	21236.4	20136.6	17169.96	20338.04	20207.6	16841.3
60%	25024	23714.2	21232.08	23432.3	23801.4	20807.2
50%	29922	28353	28725.3	29112.4	28638	23710.2
40%	34258.4	32943	33170.22	32232.12	33179.8	28669.8
30%	40702	39289.6	45691.76	39321.56	39472.6	36492.69
25%	44014	42848	52689.2	42656.9	42804	38996.3
20%	48874	46654.8	60612.66	48243.56	47300.6	41739.6
15%	55922.8	52010.19	67480.92	53030.54	53544.4	46819.2
10%	70933.59	64678.4	77766.78	66608.51	67708.99	53101.9
5%	100887.2	93520.2	94537.94	104128.59	95684.2	77584.8
2%	146505.64	130705.72	119127.89	137095.97	134460.53	111300.42
1%	203532.92	168366.23	129548.38	149088.17	169748.92	130342.1
0.50%	236083.73	204815.48	150111.05	172752.33	230672.92	131662.91
Maximum	715646	233819	189727.3	218343.91	715646	131662.91

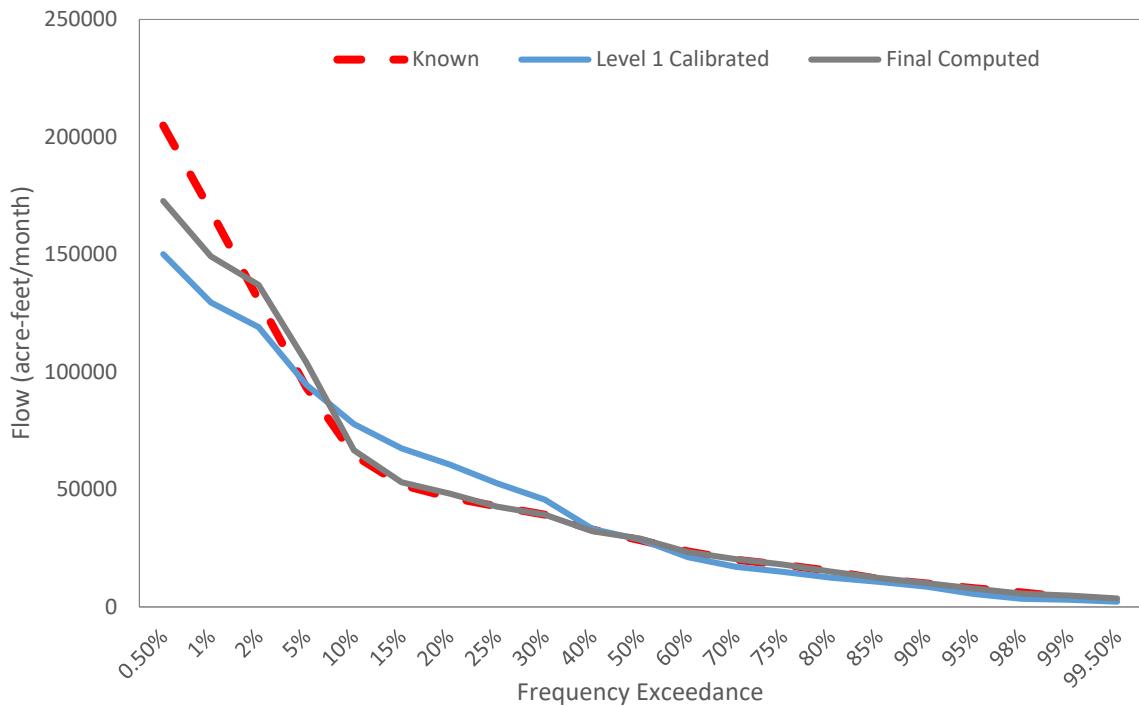


Figure B6. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT3000

Table B7. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande at Johnson Ranch CT4000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	28433.74	25009.52	28228.25	26865.24	27060.79	21477.44
Std Dev	41431.69	25245.13	35598.23	27407.89	38324.68	20638.55
Minimum	112	112	664.8	262.1	0	0
99.50%	332.46	394.44	843.78	332.63	120.17	0
99%	430.88	433.76	1098.99	433.24	175.68	55.52
98%	518.84	506.6	1393.42	549.28	415.41	120.22
95%	1059.6	997.8	2451.2	1010.44	834.84	222.4
90%	2551.2	2045.2	3593.7	2377.6	2012	637.7
85%	4861.2	4057.4	4629.64	4314.32	4124.6	1680.1
80%	7909.8	7069.4	5585.4	6993.99	7268	4035.3
75%	10036	9037	6811.1	9073.8	9173	5004.2
70%	12543	10949.2	7900.22	10721.57	11797.4	8650.9
60%	16244.2	15281.4	10583.78	14972.9	15534.6	14553.4
50%	20112	18957	14701.7	19206.4	19674	18251.5
40%	24065	23164.4	18570.54	22969.68	23278.6	21357.6
30%	29490.6	28448.2	24329.38	27365.94	28359.4	25127.2
25%	33165	31333	29163.9	29828.5	31941.6	27593.4
20%	38055.8	36512.6	43397.02	41156.66	37046.4	31137.6
15%	44032	41783.2	61034.98	52256.96	43295.68	36038.8
10%	56672.8	50204	77967.02	66753.8	55158.6	50476.7
5%	82539	72348.8	109225.9	87670.32	80629.72	72218.1
2%	126711.76	112103.12	145935.61	111071.62	122543.24	86325.12
1%	153650.41	136584.88	166555.88	126765.7	148044.72	92260.28
0.50%	219719.62	154650.31	181631.86	138240.02	188428.72	108628.6
Maximum	733162	166566	228894.8	174211.8	733162	108628.6

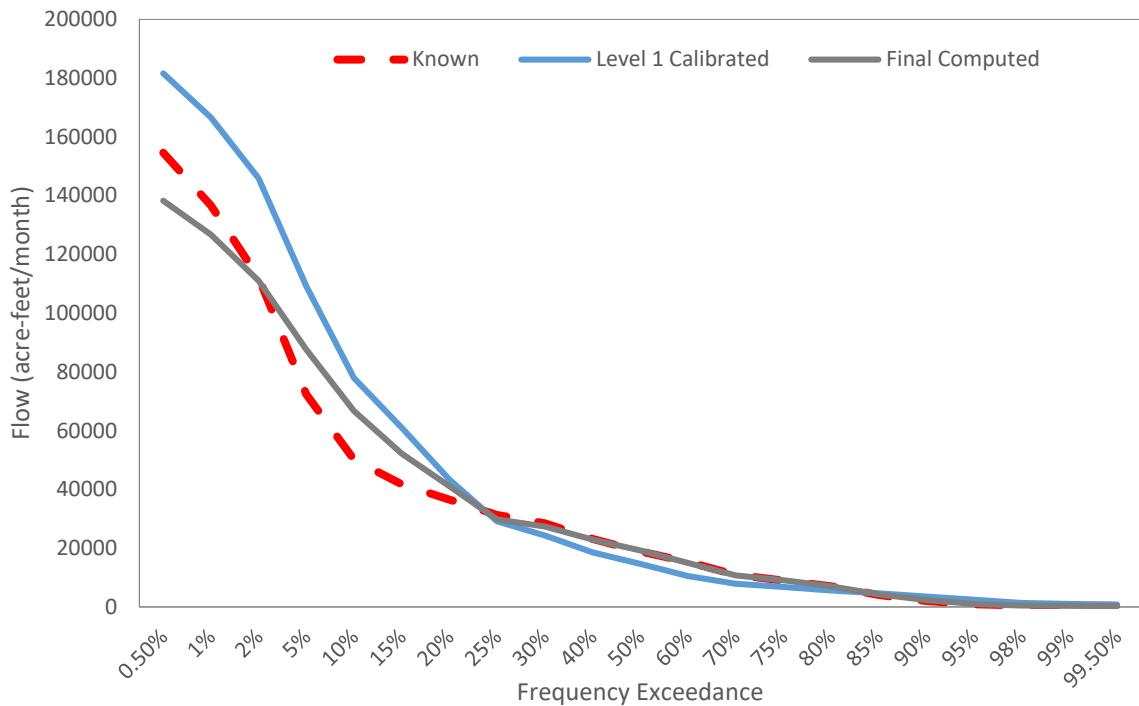


Figure B7. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT4000

Table B8. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Terlingua Creek near Terlingua CT5000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	3032.89	3374.5	3622.43	3373.97	2859.25	2153.14
Std Dev	6535.77	7120.61	6855.51	6751.99	6139.23	4092.71
Minimum	20	20	0	0	0	0
99.50%	22	21.82	1.07	5.1	0.68	0
99%	30.64	22	5.19	24.03	20.82	0
98%	70.28	65.56	9.62	44.96	29.47	0.24
95%	87	87	26.1	83.5	82.18	28.6
90%	109	106	44.88	102.94	103.2	81.7
85%	123.4	118	68.88	115.76	117.64	99
80%	131	130	91.22	132.94	130	113
75%	144	143	112.9	144.3	140.9	126.3
70%	157	156	134.02	162.6	155	140.9
60%	192.8	192.6	173.42	191.3	190	182.9
50%	295	302	259.4	335.6	265	233.9
40%	781.6	816	931.86	878.72	737	424.4
30%	1878.2	2152.2	2474.4	2108.06	1800.8	1450.5
25%	2973	3504	4120	3510.1	2682	2049.8
20%	4091.6	4715.2	6361.66	5355.74	4091.6	4259
15%	5973.8	7047.6	8482.88	6914	5676.72	5368.4
10%	9143.8	10294.6	12050.08	10546.54	8661.6	7456.9
5%	16248.6	17808.8	18910.96	18965.02	15155.3	9561.5
2%	22787.8	26896.52	26029.92	26671.79	21567.6	14723.2
1%	30073.76	34051.92	37081.83	37996.3	28739.76	24050.16
0.50%	40517.2	46148.26	39542.48	40517.59	36947.16	28740
Maximum	68402	68402	45824.3	46954.4	68402	28740

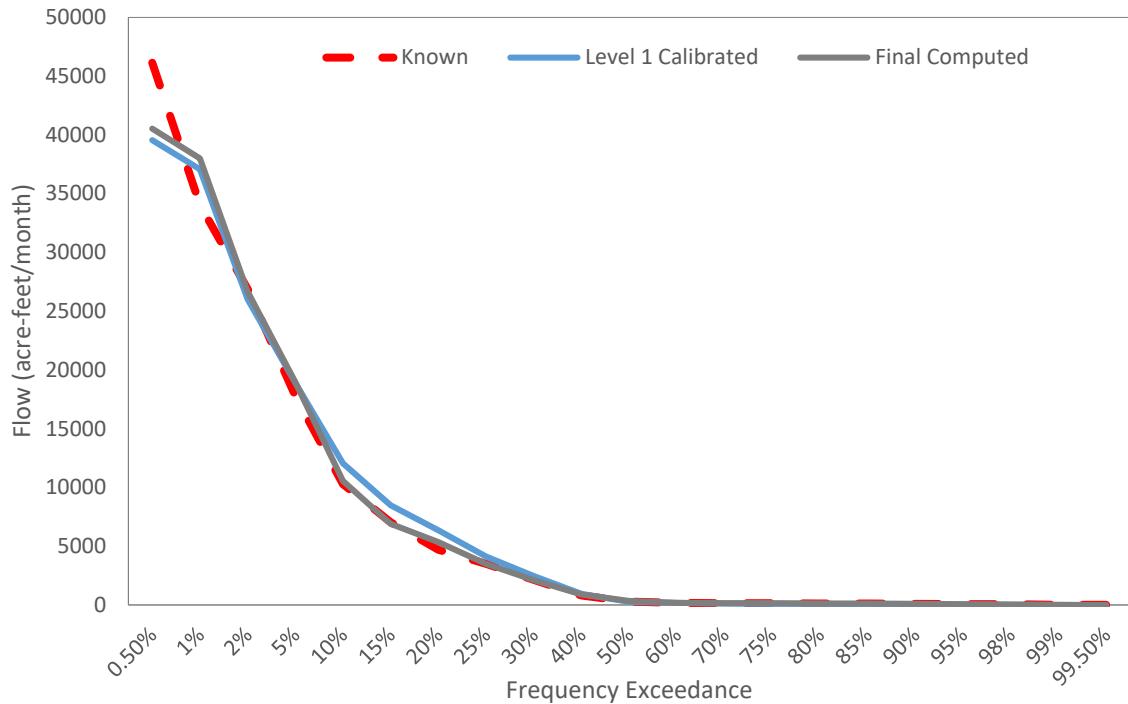


Figure B8. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT5000

Table B9. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Rio Grande below Rio Conchos CT6000

1	2	3	4	5	6	7
	Original Known 1954-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	25767.82	22456.93	27755.71	22450.42	23567.05	14617.24
Std Dev	38940.14	22825.73	45248.64	22811.93	35831.43	15539.02
Minimum	48	48	356.7	107.4	0	0
99.50%	117.84	121.68	995.78	299.92	46.64	25.56
99%	245.08	251.16	1101.78	331.83	86.42	28.72
98%	337.6	332.2	1324.1	398.77	234.27	42.66
95%	865.4	765.4	1891.04	634.44	428.94	149.9
90%	1748.6	1630.4	2909.24	1859.75	1202.6	350.9
85%	3851.4	3308	3616.58	3215.58	2717.6	429.9
80%	6670.2	5405	4492.36	6273.89	4084.2	1138.4
75%	8811	7565	4929.3	7508.9	7178	1249.4
70%	11170.8	9939.8	5700.94	9103.85	9440.4	2852.9
60%	15700.8	15006	7565.88	14884.76	13907.56	7389.7
50%	19156	17968	9076	17778	17599.5	12008.8
40%	23044.2	22125.2	12709.6	21846.7	22054.4	16776.2
30%	27212.6	26566.4	18940.78	24761.98	26036.24	21781
25%	29873	28737	23804.3	27502.2	28340	23076.4
20%	33316.6	32378	36553.12	30139.08	31858.4	24638.1
15%	38413.2	35282.8	56904.38	38390.34	36183	28066.5
10%	46953.8	41958.8	87660.02	46290.74	44037.3	30138.6
5%	70375.4	62476.2	131616.66	69438.15	64858.4	43295.3
2%	118456.72	104883.12	181970.55	97871.03	108350.84	59631.74
1%	153502.56	130909.8	216554.88	116471.91	144402.84	82048.68
0.50%	237785.64	147456.95	275108.19	147964.16	194380.77	100074.2
Maximum	693166	166527	312534.09	168093.41	693166	100074.2

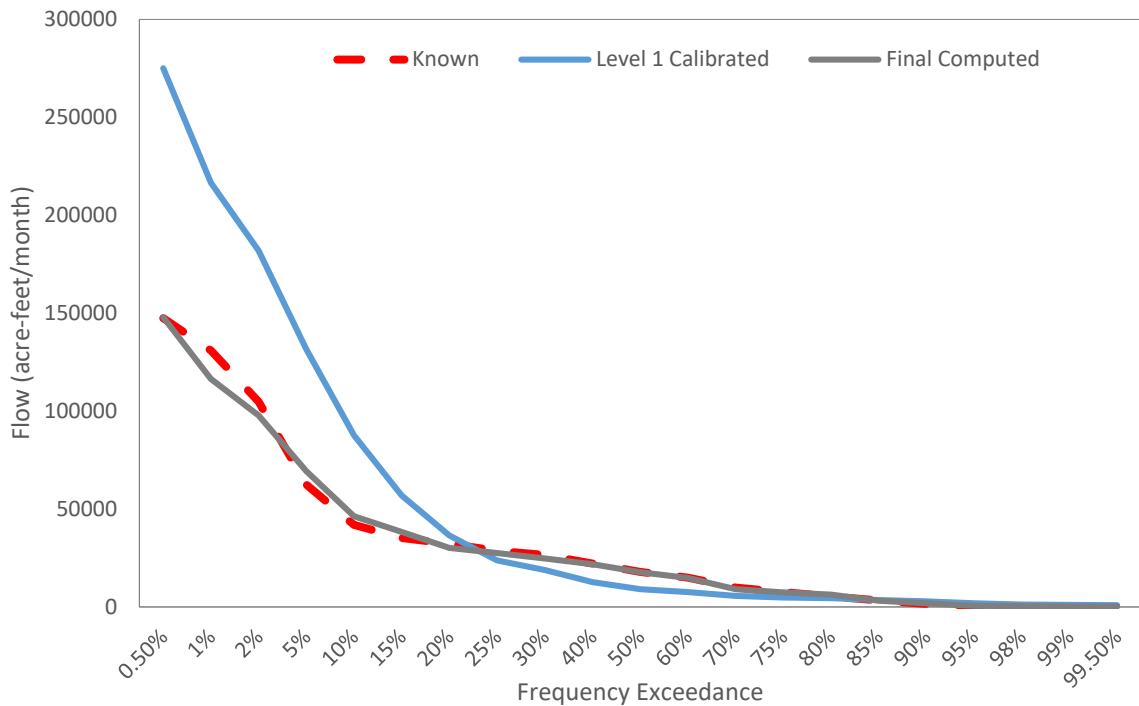


Figure B9. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT6000

Table B10. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Alamito Creek near Presidio CT7000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	1136.43	1132.55	1356.13	1132.26	1068.65	793.01
Std Dev	3413.02	3627.42	2835.56	2881.03	3157.61	1754.38
Minimum	12	12	0	0	0	0
99.50%	21	21	3	7.05	3.85	0
99%	22	21	4.78	11.23	12.12	0
98%	28	22.84	10.66	25.04	22	1.5
95%	41.6	37.2	21.92	36.34	37.88	16.1
90%	53	44.8	35.78	48.48	49.3	40.9
85%	63.8	59	45.66	57.38	61	50.1
80%	69	65	54.58	64.26	65.82	53.8
75%	78	70	64.4	70.9	75	61.4
70%	86	78	72.24	78.52	81.24	65.7
60%	102	91.6	86	90.16	97	79.7
50%	135	106	105.1	104.3	123	96
40%	211.2	134.4	141.96	138.84	210	130.7
30%	383	328.8	380.24	325.7	390.2	401.6
25%	711	671	837.1	573.3	705	678.2
20%	1173	1093.6	1907.26	1226.08	1172.64	1178.4
15%	1909.4	1794	3076	1736.96	1881.94	1861.2
10%	3050.2	2953	5306.2	3105.06	2844.6	2431.1
5%	4950.2	5138.2	7860.06	8093.6	4641.16	3706.5
2%	11666.8	11758.6	10645.94	12084.6	10654.43	9813.14
1%	15930.12	15407.24	14836.76	16841.69	13304.88	10785.06
0.50%	21537.26	24870.02	15642.53	17756.32	19527.76	11246.9
Maximum	59362	59362	19081.2	21659.6	59362	11246.9

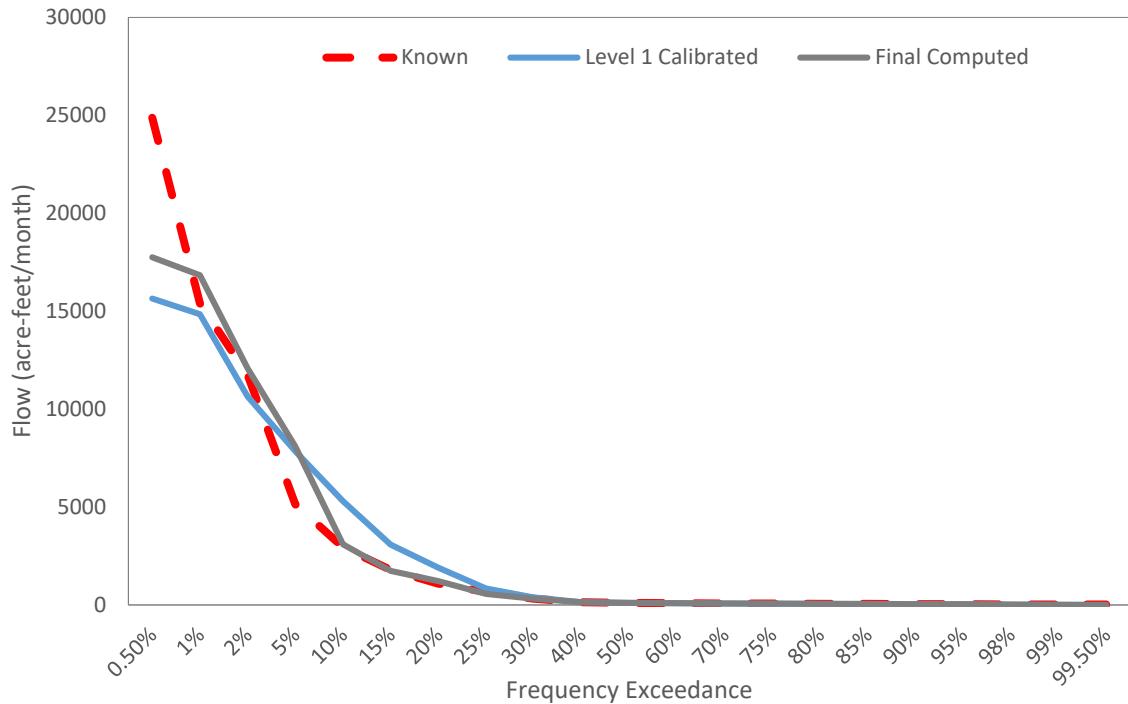


Figure B10. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at CT7000

Table B11. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande below Falcon Dam DT1000

	1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015	
Mean	110733.05	103147.39	110032.45	103274.58	108293.41	98372.16	
Std Dev	102256.26	94587.94	81258.8	80690.57	98108.22	78495.48	
Minimum	6886.82	20314.72	4756.62	8745.32	6886.82	6963.96	
99.50%	24642.24	27307.51	10505.04	19422.02	14029.24	7023.58	
99%	29051.03	30555.17	12904.6	23796.11	21780.01	7645.42	
98%	33962.57	35095.55	17566.5	32559.11	30449.42	14462.22	
95%	42068.63	42028.2	28348.05	43712.29	39349.77	35855.16	
90%	50000.09	49966.86	38347.37	48939.09	47258.08	42532.62	
85%	55050.34	54741.59	48818.03	55294.49	52837.73	45962.95	
80%	58285.77	57444	53917.66	58879.96	57458.55	50974.35	
75%	62838.77	61293.82	59558.3	61533.01	61320.34	57668.38	
70%	65737.62	64969.28	63185.34	64382.82	64938.85	62517.32	
60%	72571.72	71065.84	72780.36	71582.01	71826.44	67394.18	
50%	82632.84	79576.62	81832.1	79290.4	80692.48	73225.05	
40%	94367.42	90027.15	90173.2	87180.54	93463.4	84395.22	
30%	108876.51	100568.84	120902.66	102603.49	107268.99	103117.78	
25%	121918.62	111618.07	142984.16	112976.45	120326.77	108606.68	
20%	135439.39	124822.87	163156.38	126083.47	134136.72	127665.8	
15%	155640.38	142898.55	196066.55	146238.33	152543.69	138146.89	
10%	188580.44	172686.84	227154.31	174785.22	187366.42	165010.39	
5%	270002.34	221379.58	272445.09	295490.5	283518.12	340388.38	
2%	401112.78	377167.19	348998.75	404485.38	387305.66	366287.59	
1%	626939.94	566694.25	392013.81	454345.78	482320.09	394316.03	
0.50%	790051.75	772016.12	419755.09	486498.75	751488.94	473843.59	
Maximum	1223481.62	1223481.62	632329.31	732886	1223481.62	473843.59	

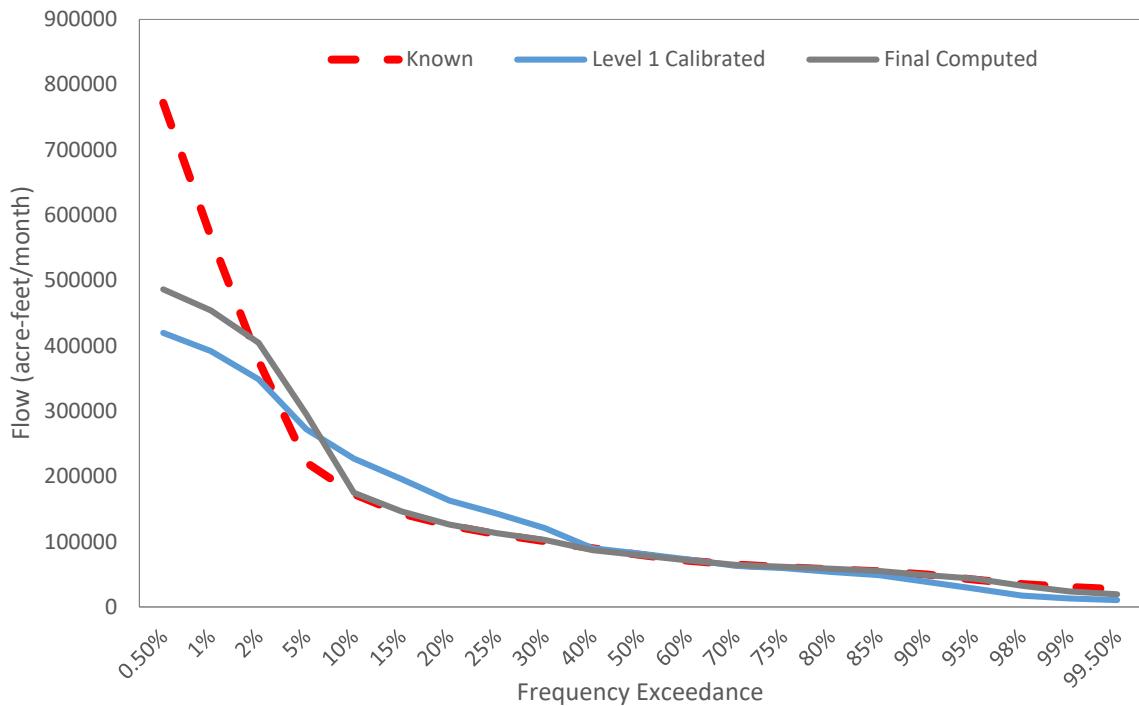


Figure B11. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at DT1000

Table B12. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande at Laredo DT3000

	1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015	
Mean	112243.51	107718.5	115714.97	108294.27	109188.86	96766.52	
Std Dev	112244.39	110369.7	84817.05	90203.89	106583.96	78560.95	
Minimum	20706.16	20706.16	4448.73	7549.53	5976.77	5976.77	
99.50%	28570.84	27961.73	12065.54	20626.15	15823.05	6997.76	
99%	33530.28	32262.78	16091.52	27527.64	19827.43	11924.87	
98%	39182.27	38761.35	21125.49	36209.12	28206.7	15256.04	
95%	45100.59	44049.22	32100.02	44926.06	42304.93	19707.61	
90%	51618.11	51489.57	43318.82	51759.77	48834.79	31272.78	
85%	56125.29	56123.35	53011.04	57177.36	54733.68	44672.06	
80%	60283.56	59562.42	58155.11	60545.97	58532.64	48986.75	
75%	64184.71	63256.93	63152.61	63499.81	62120.86	55548.98	
70%	67815.48	66235.79	66516.61	66268.48	65833.31	60361.18	
60%	74489.57	73037.91	75215.83	74093.14	73262.28	69189.31	
50%	84825.55	83096.97	84140.61	82860.8	82750.34	77593.55	
40%	95708.29	92447.99	96196.95	90468.48	93957.87	88150.77	
30%	109915.92	105354.4	131878.44	105020.36	107671.23	100827.55	
25%	121504.67	113051.4	153886.73	116276.28	118508.12	109709.32	
20%	138350.09	126782.5	177208.75	131528.06	134959.14	122677.16	
15%	158285	147348.8	200344.12	147636	157441.09	148875.23	
10%	185382.94	176238.9	235502.14	180377.64	184855.36	168276.73	
5%	243091.98	228893.7	284447.44	324658.62	237438.08	218145.16	
2%	371027.84	363343.7	368861.44	453663.12	386612.5	416255.88	
1%	661130.62	559129.1	410386.06	504736.03	494160	434486.88	
0.50%	990816.56	1046583	461516.78	567629.62	906460.94	498188.25	
Maximum	1377071.4	1377071	691534.88	850553.69	1377071.38	498188.25	

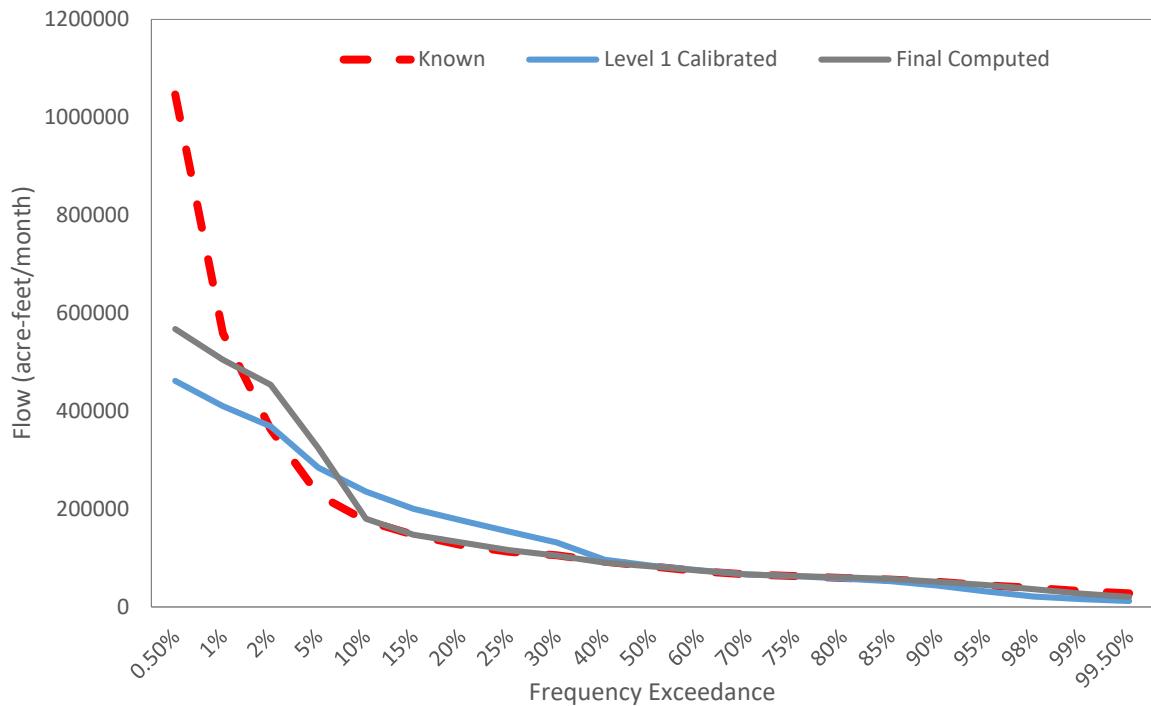


Figure B12. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at DT3000

Table B13. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Rio Grande at Piedras Negras DT5000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	109647.9	106145.38	109400.01	106416.84	107197.56	97232.87
Std Dev	123530.05	125029.82	80230.16	90567.66	116554.35	81835.45
Minimum	22171.64	22171.64	5798.79	11123.19	4988.04	4988.04
99.50%	33305.27	32541.58	12568.06	23770.81	15743.12	10099.37
99%	36067.85	35562.7	14496.11	27681.6	20057.72	12428.02
98%	40319.89	39813.68	20188.62	38445.43	31707.81	14641.81
95%	45593.84	44730.91	28135.24	47032.98	42919.36	19935.82
90%	52327.2	52292.14	37956.11	51635.09	50879.46	37894.57
85%	57251.3	57414.31	49269.13	58155.41	55727.37	47562.42
80%	61174.38	61341.27	58033.18	62638.68	60590.35	54010.38
75%	63990.06	63869.88	63521.52	65526.59	63218.68	61691.04
70%	67507.99	67360.62	66450.52	67658.8	66656.63	63425.53
60%	74444.2	74154.65	75277.17	74849.64	73417	68201.02
50%	82339.84	81293.09	83278.94	81865.94	80716.91	77390.34
40%	92228.8	90499.01	90640.82	88951.27	90579.02	85888.35
30%	104353.41	102394.16	117687.44	101664.17	103632.15	100685.52
25%	113318.6	107514.43	137591.84	109448.23	110934.12	106766.65
20%	124507.31	117761.93	157005.61	121360.52	123769.13	114905.34
15%	149372.72	133233.05	185364.95	139808.17	142464.42	131900.75
10%	177615.38	164880.47	214812.78	165421.25	176006.03	174464.89
5%	232701.59	221019.56	273592.28	325133.59	232701.59	362840.91
2%	360839.06	361927.34	358631.69	462051.5	379377.72	384919.66
1%	658865.69	600826.81	409812.56	528012.56	576716.81	440551.38
0.50%	1056464.3	1137590.4	446857	575745.56	938522.62	586353.94
<u>Maximum</u>	<u>1910749</u>	<u>1910749</u>	<u>643887.5</u>	<u>829631.19</u>	<u>1910749</u>	<u>586353.94</u>

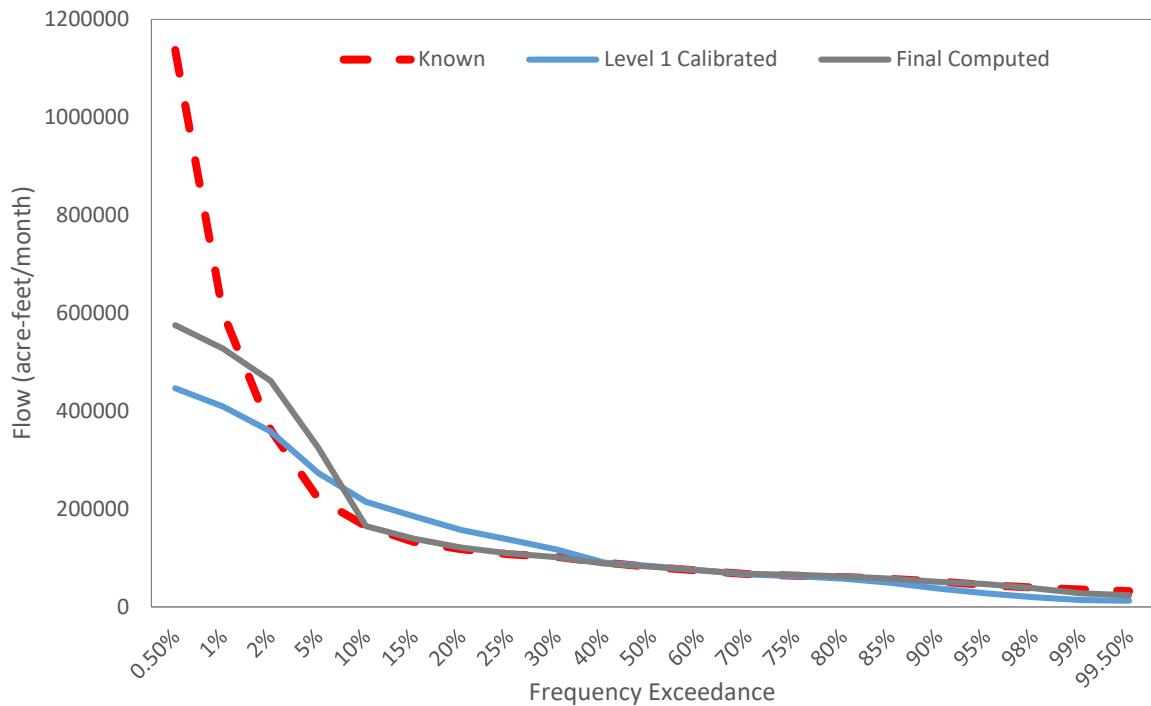


Figure B13. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at DT5000

Table B14. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Pinto Creek near Del Rio DT8000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	1149.44	1230.82	1799.69	1234.33	1139.76	1100.43
Std Dev	4187.37	4081	4083.66	3071.71	4014.02	3224.08
Minimum	0	0	0.5	0.5	0	4.6
99.50%	0	0	5.23	5.23	0	6.85
99%	0	0	10.48	6.96	0	7.34
98%	0	0	28.68	8.23	0	7.7
95%	0	1	69.96	10.38	0	8.4
90%	1	22	122.16	43.1	7.46	11.1
85%	22	50	178.16	55.12	21.86	21.3
80%	50	96.2	210.42	96.34	47	41.2
75%	90	121	251.1	123	69	47.5
70%	116.6	161	284.82	186	106	57.7
60%	188.8	269.2	370.24	308.22	172.8	116.5
50%	319	412	438	436.6	289	207.6
40%	482.2	576	554.9	581.8	463.44	324.9
30%	721.4	838.4	728.9	770.54	690.4	550.7
25%	875	1002	942.7	941.4	845	752.1
20%	1149	1263.6	1470.86	1210.64	1106.96	895.7
15%	1489.4	1678.8	3108.46	1676.02	1486.84	1490.2
10%	2084	2164.6	5239.24	2192.6	2104.28	2236.8
5%	3211.2	3524.8	9420.9	6660.04	3142.4	2681.4
2%	6952.52	8581	15945.92	12586.63	8874.27	15393.58
1%	23290.12	25480.88	20023.99	15805.58	22693.68	23143.86
0.50%	41364.22	39526.94	27679.19	21847.97	32938.56	23829.3
Maximum	56767	48980	46332.9	36572	56767	23829.3

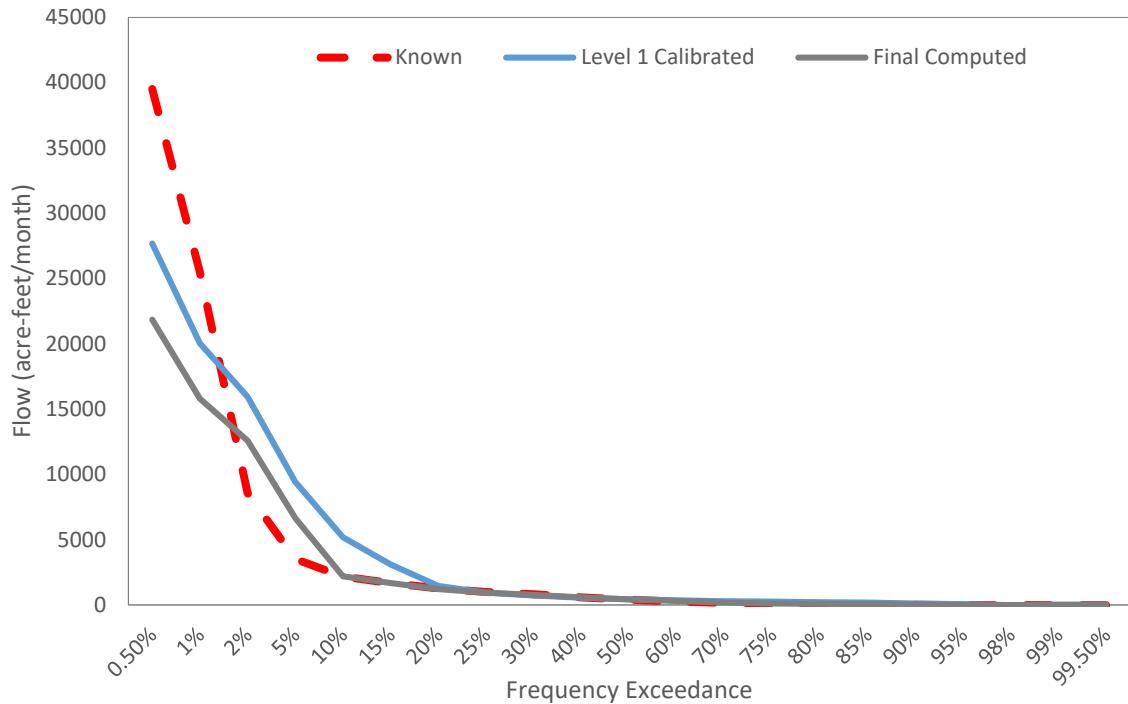


Figure B14. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at DT8000

Table B15. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for San Felipe Creek near Del Rio DT9000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	5887.67	6664.76	6913.21	6664.76	5907.46	5987.95
Std Dev	2953.52	2709.01	3452.42	2330	2914.75	2757.87
Minimum	863	1221	27.9	78.4	225.9	225.9
99.50%	1000.66	1858.64	320.87	902.32	906.5	647.55
99%	1103.76	2016.48	470.87	1324.16	946.12	724.72
98%	1228.92	2266.68	697.18	1960.46	1211.12	916.16
95%	1571.8	2798.8	1536.92	3192.58	1571.8	1717.5
90%	2211.4	3887.2	2629.26	3722.28	2267.4	2842.7
85%	2763.8	4368.4	3748.12	4548.46	2855.92	3369.4
80%	3358	4955.8	4556.52	5112.46	3532.8	3723.5
75%	3994	5318	4985.9	5397.4	3991.2	3991.2
70%	4422.4	5778.4	5308.74	5711.32	4422.4	4474.7
60%	5396.6	6319.8	6081.5	6312.64	5390.4	5373
50%	6163	6780	6811.8	6847.1	6136	5996.7
40%	6779.2	7313.6	7314.04	7238.14	6779.2	6859.2
30%	7392.4	7663.8	8051.34	7611.24	7372.4	7301.4
25%	7631	7791	8420.6	7758.4	7622	7556.3
20%	7816.6	8016.2	9277.86	7976.76	7788.76	7777
15%	8120.2	8260	9971.46	8352.44	8149	8249.2
10%	8428.8	8617	10739	8648.04	8461.8	8717.2
5%	8983	9092.8	12823.1	10199.56	9086.4	10433.2
2%	10584.76	11205.96	16050.89	12905.08	11401.15	13372.86
1%	12877	13634.6	17102.02	13750.16	13502.17	17180.34
0.50%	20109.78	24378	20121.97	16178.28	18248.14	17992.1
Maximum	39909	39909	29968.4	24094.9	39909	17992.1

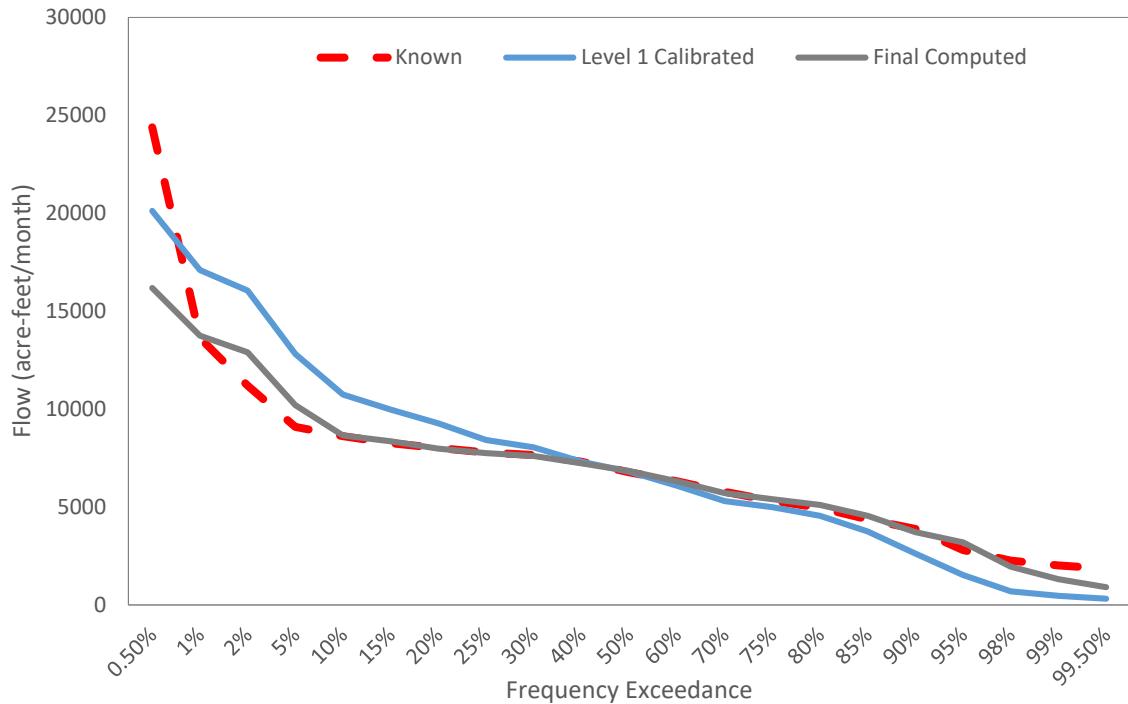


Figure B15. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at DT9000

Table B16. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande below Anzalduas Dam ET1000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	109118.1	100629.88	107771.91	99777.48	106382.59	93102.48
Std Dev	100776.9	88000.91	79658.37	73685.99	95883.84	68466.94
Minimum	15344.51	15482.51	7156.55	12147.45	6544.27	6544.27
99.50%	28315.21	28779.34	10315.6	17532.86	16305.67	6761.02
99%	30248.01	30681.42	12972.73	21894.81	22886.07	6998.77
98%	33021.57	32989.89	19035.27	32449.18	30774.29	13182.91
95%	40667.55	40708.05	27327.99	41994.77	39171.79	26533
90%	47877.24	48097.81	37221.48	47247.72	46066.6	41509.05
85%	52604.13	52923.04	44948.6	52175.95	51271.93	44753.22
80%	56627.12	56825.76	52227.31	57129.52	55017.82	49427.09
75%	60491.86	60017.44	58665.2	60263	59407.58	54131.99
70%	63927.06	62722.69	62837.11	63196.57	63197.83	57835.55
60%	71539.66	70080.81	68784.23	69075.91	70821.88	67057.72
50%	81068.12	79400.85	78395.14	78795.73	80218.55	74019.3
40%	91829.02	88076.55	89231.74	86516.3	90410.18	82756.37
30%	109289.8	101632.92	119649.07	101248.2	105875.17	97044.25
25%	123419.8	112917.87	142164.48	110928.28	121663.4	106720.02
20%	133993.1	124462.47	165185.66	126461.42	132197.8	122448.93
15%	163022.8	136301.17	195090.17	144401.77	157908.27	147112.34
10%	187610.4	174264.23	219891.38	169965.84	185291.05	160308.72
5%	253998.2	214867.53	261523.64	207843.16	254687.61	291256.66
2%	384790.2	301930.75	347245	376561.44	367661.88	346637.44
1%	672224.7	524531	386555.88	419191.56	505820.81	367221.34
0.50%	817142	744926.06	415959.91	451065.38	783518.88	392709.25
Maximum	1122537	1132885.5	616778.25	668860.94	1132885.5	392709.25

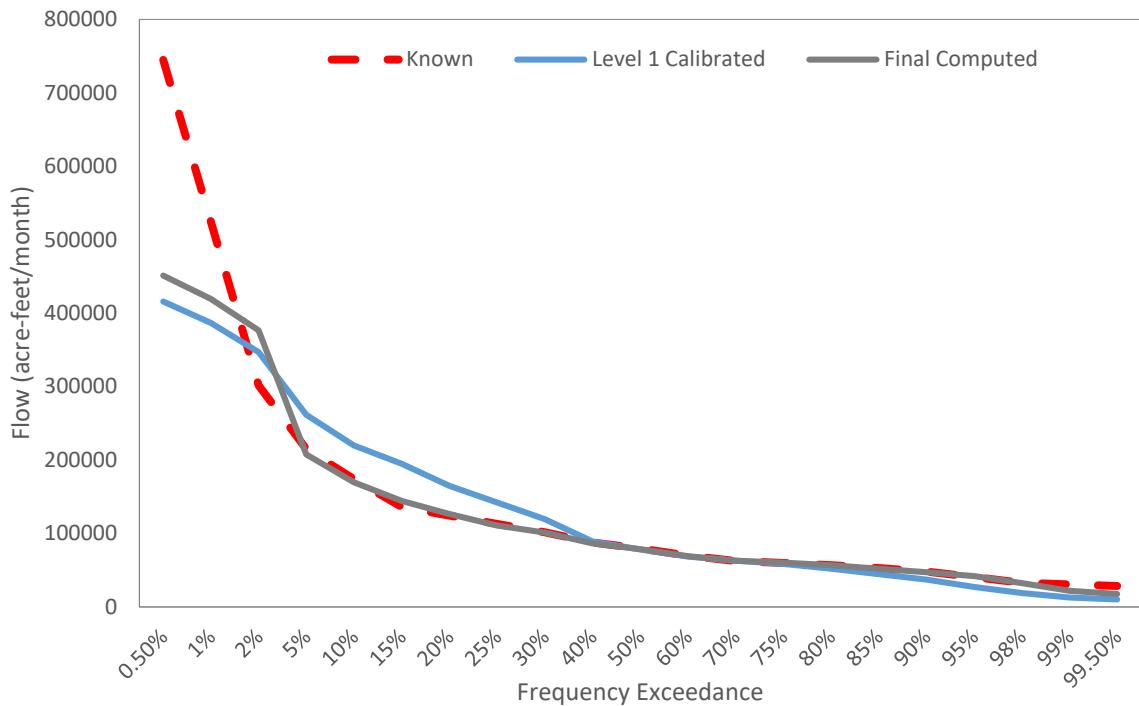


Figure B16. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at ET1000

Table B17. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Rio Grande at Rio Grande City ET2000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	112635.04	101138.45	109461.95	101151.49	109222.7	95345.84
Std Dev	108301.68	91180.46	81522.89	77403.51	102719.09	74552.05
Minimum	15373.23	15373.23	5163.09	8404.29	5970.19	5970.19
99.50%	25433.37	25570.75	10519.77	17078.59	15536.96	6183.95
99%	29688.18	29209.06	14674.81	23843.49	19960.59	7107.98
98%	31200.4	30884.04	16672.78	27362.49	29926.51	13049.93
95%	40374.8	38532.2	27016.11	41040.42	37195.89	28728.8
90%	49174.42	48494.38	38310.8	47022.75	46142.41	37626.34
85%	53254.32	52873.96	46108.48	53463.98	51901.06	42570.1
80%	57144.76	56402.27	51602.55	57374.83	56329.32	49564.84
75%	62166.05	61609.68	57869.41	61484.91	60739.38	56879.07
70%	65247.5	64047.42	62086.34	64370.17	64445.98	59223.14
60%	74464.73	71252.69	71940.96	72060.91	72288.89	67698.27
50%	81838.86	79185.64	80099.01	79811.73	80141.91	73481.7
40%	93802.91	87814.65	88147.53	86163.33	91291.45	81626.84
30%	109347.16	99801.38	125913.56	104135.02	106953.69	98564.87
25%	125296.69	110484.91	142800.28	110737.98	120863.8	110348.38
20%	137729.31	122842.71	163754.81	123569.52	134978.7	124347.63
15%	164966.39	137459.42	195912.17	143285.14	158535.3	137809.64
10%	195035.98	169638.78	226299.91	170913.95	189227.05	175085.11
5%	282516.38	214588.83	273530.09	286297.31	284475.12	312031.31
2%	404255.78	334550.31	349375.16	389679.09	384584.47	342500
1%	705248.81	545722.81	394593.88	440118.19	535971.19	375072.53
0.50%	910012.5	779920.19	420579.03	469102.31	864298.44	452984.03
Maximum	1181282.1	1181282.1	635301.75	708606.81	1181282.12	452984.03

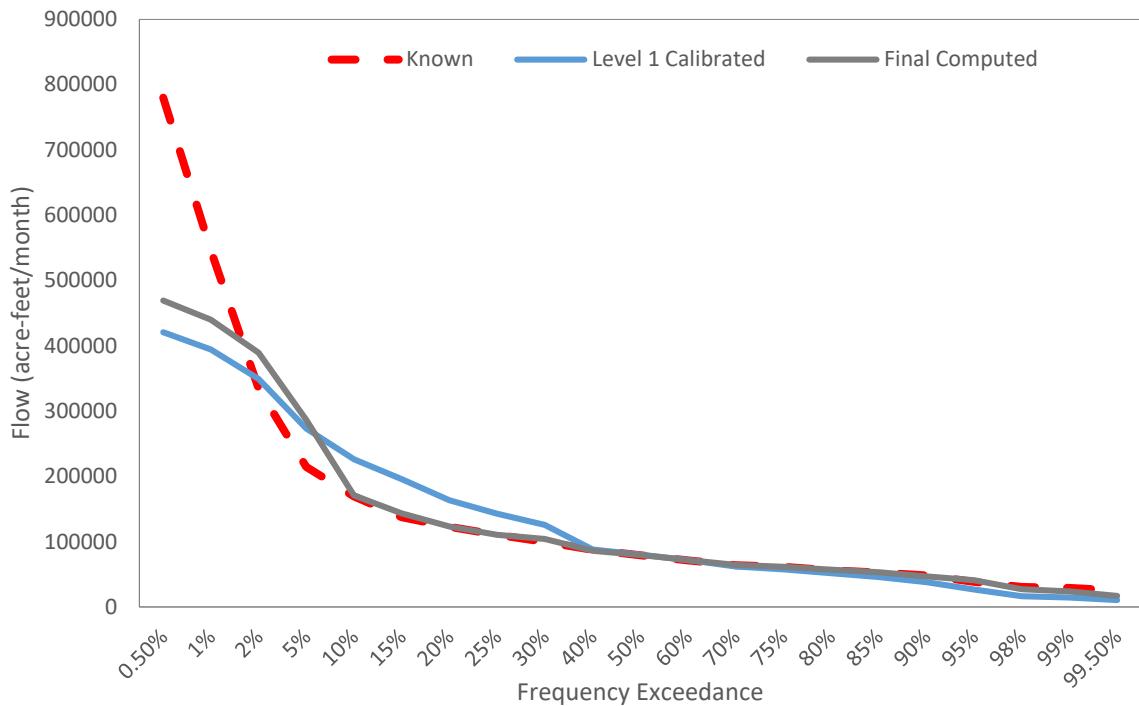


Figure B17. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at ET2000

Table B18. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Pecos River near Langtry GT1000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	22461.08	20020.74	23472.51	20106.74	21987.62	20062.21
Std Dev	44686.61	42851.89	25700.43	24852.94	41314.62	22967.51
Minimum	2963.21	2963.21	1150.31	1906.64	1586.8	1586.8
99.50%	4271.38	4216.81	1635.99	3067.31	2657.44	1757.59
99%	4959.89	4813.46	2023.65	3688.85	3740.24	1948.59
98%	5470.15	5204.03	2599.65	4675.31	4738.66	2523.34
95%	6897.06	6390.23	4158.28	6513.4	6260	4277.3
90%	8005	7665.77	5753.99	7702.42	7741.93	5928.27
85%	8911.51	8414.54	7365.33	8612.09	8727.06	7557.64
80%	9694.34	9146.43	8339.78	9378.81	9507.06	9348.26
75%	10398.82	9788.45	9204.53	9929.61	10296.96	9919.14
70%	11236.99	10402.32	10046.79	10697.71	11043.81	10631.6
60%	13045.96	12046.2	11514.57	12026.52	12734.9	12050.09
50%	14723.49	13415.07	12885.85	13433.05	14469.92	13548.7
40%	16577.77	15278.12	14460.32	14718.1	16251.72	14878.4
30%	19692.45	17318.48	23124.64	17926.37	19703.75	20078.35
25%	21898.48	19256.54	28146.38	20213.61	21825.51	21216.39
20%	24560.78	21593.89	35101.3	22070.31	24279.13	23615.7
15%	28338.69	26166.31	45128.89	25427.95	28240.57	27037.44
10%	35654.35	31024.59	58904.4	32914.7	35371.71	32603.5
5%	51333.8	43928.18	75369.75	41072.79	51846.15	88930.54
2%	85533.02	73660.21	108116.59	122555.12	101109.55	110719.82
1%	175798.88	127261.7	128441.77	145595.97	146444.78	124630.15
0.50%	300485.75	243365.44	141126.84	159980.98	206697.27	148577.19
Maximum	837192.69	837192.69	220559.8	250043.2	837192.69	148577.19

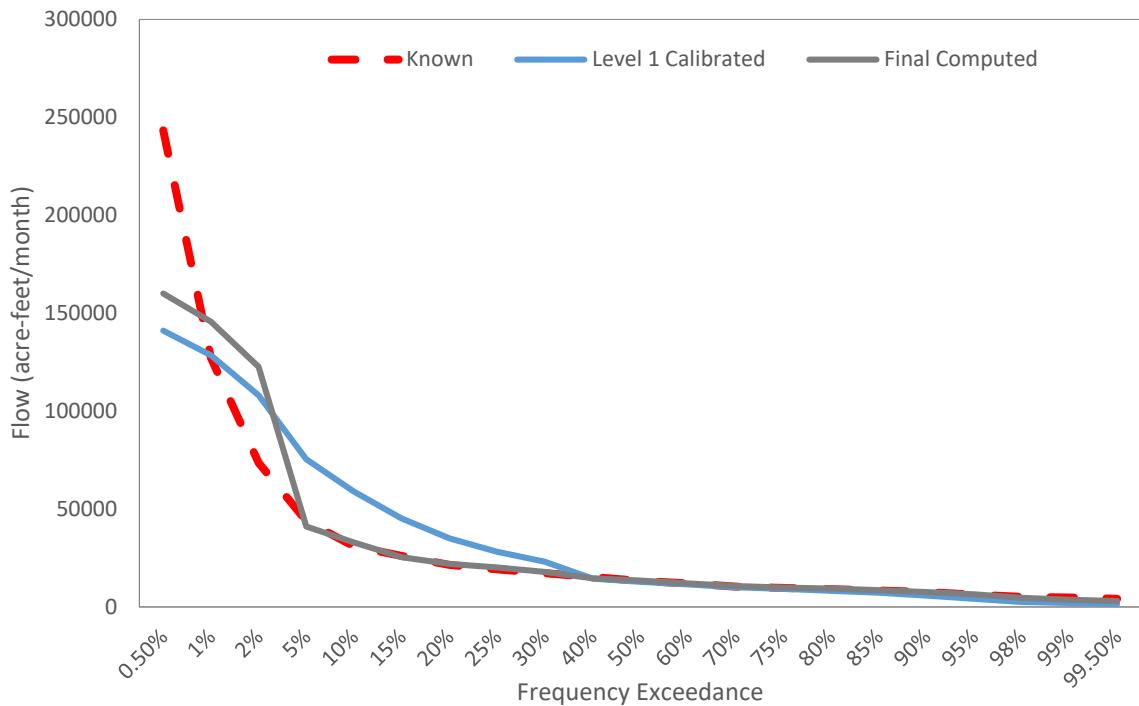


Figure B18. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at GT1000

Table B19. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Pecos River near Girvin GT2000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	7661.81	4879.53	6134.82	4748.15	7011.72	4368.02
Std Dev	24185.49	8016.7	10183.9	6871.15	21897.4	6543.49
Minimum	223.1	223.1	197.57	38.17	223.1	298.11
99.50%	260.43	260.02	402.64	271.12	261.87	299.91
99%	266.44	263.8	429.94	273.89	267.94	300.78
98%	270.6	269.24	490.89	279.39	274.2	302.23
95%	289.07	281.07	593.73	288.53	299.73	309.11
90%	339.06	318.33	772.48	321.92	324.95	317.7
85%	960.21	763	942.23	942.23	729.13	323.4
80%	1472.79	1339.67	1105.2	1051.89	1170.82	338.3
75%	1947.33	1733.16	1206.18	1135.51	1592.32	1042.28
70%	2411.86	2105.41	1333.31	1253.9	2028.99	1124.57
60%	3277.65	2868.17	1613.36	2395.25	2999.05	1305.98
50%	3938.27	3545.06	1851.2	2943.76	3755.57	2689.47
40%	4587.49	4021.25	2288.24	3846.89	4433.72	3795.45
30%	6042.7	4613.74	3369.77	4659.28	5532.75	4491.18
25%	6814.15	5079.02	4955.83	5118.79	6601.43	5080.32
20%	8009.72	5846.75	8999.81	5926.35	7452.32	5782.4
15%	9603.25	6761.38	13581.26	7322.89	9273.24	7216.1
10%	12480.4	8426.71	18996.39	9236.56	11671.87	9423.11
5%	19814.14	13102.58	28443.65	13043.51	17655.79	12140.35
2%	50414.41	29530.29	40530.02	30560.79	39860.23	33626.28
1%	75163.59	43697.14	48631.25	36661.38	64462.85	36499.65
0.50%	163981.62	64129.5	61276.57	46181.57	129361.49	45324.39
Maximum	522870.31	108412.23	81944.66	61696.87	522870.31	45324.39

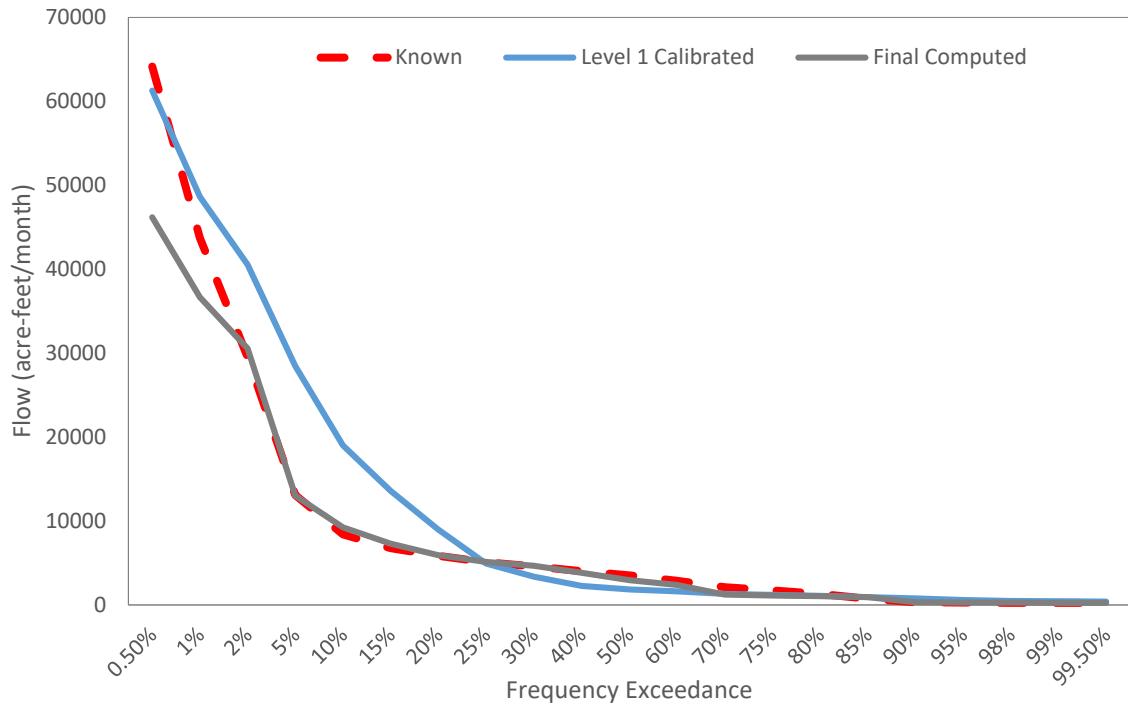


Figure B19. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at GT2000

Table B20. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Pecos River near Orla GT3000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	10364.81	7362.01	8086.58	7362.01	9598.87	6484.05
Std Dev	29783.37	14985.71	12051.27	12193.09	27179.02	11173.06
Minimum	0	0	89.9	94.6	0	0.9
99.50%	0	0	274.28	288.33	0	14.94
99%	3.2	6.4	350.84	368.85	10.24	20.58
98%	489.92	434.84	427.26	449.21	93	33.44
95%	1002	938.8	704.52	784.2	707.38	234.8
90%	1611.6	1452.6	1061.84	1426.86	1367.04	537.4
85%	2076.8	1823.4	1429.06	1911	1864.6	1166.1
80%	2471	2228.8	1699.1	2274.64	2313.2	1785.9
75%	2962	2653	1968.2	2635.6	2722	2035.3
70%	3408.6	3009.2	2234.06	2995.8	3136.76	2371.7
60%	4032.8	3660.6	2779.44	3584.14	3850.8	3065.5
50%	4671	4215	3422.5	4157.8	4371	3681.6
40%	5536.6	4807.4	4527.44	4782.1	5245.6	4191.4
30%	7314.6	5629.8	5673.86	5471.66	6841.9	4935.9
25%	8612	6427	7818.8	6397.8	8077	5404.3
20%	9940	8133	11797.5	8072.88	9451.4	7174.9
15%	12563.6	9816	16579.6	9753.26	11811.2	8948.9
10%	15104	12840	22409.9	13131.52	14917.8	12833.6
5%	29676.79	18705.2	31170.7	31612.81	31069.6	36267.1
2%	69392.68	44672.68	49131.2	55191.52	65490	44154.28
1%	114506	89848.72	59487.38	66825.16	99810.08	73697.32
0.50%	261656.5	120599.34	75820.54	85173.08	208790.84	87530.6
Maximum	429255	217925	99504.1	111777.9	429255	87530.6

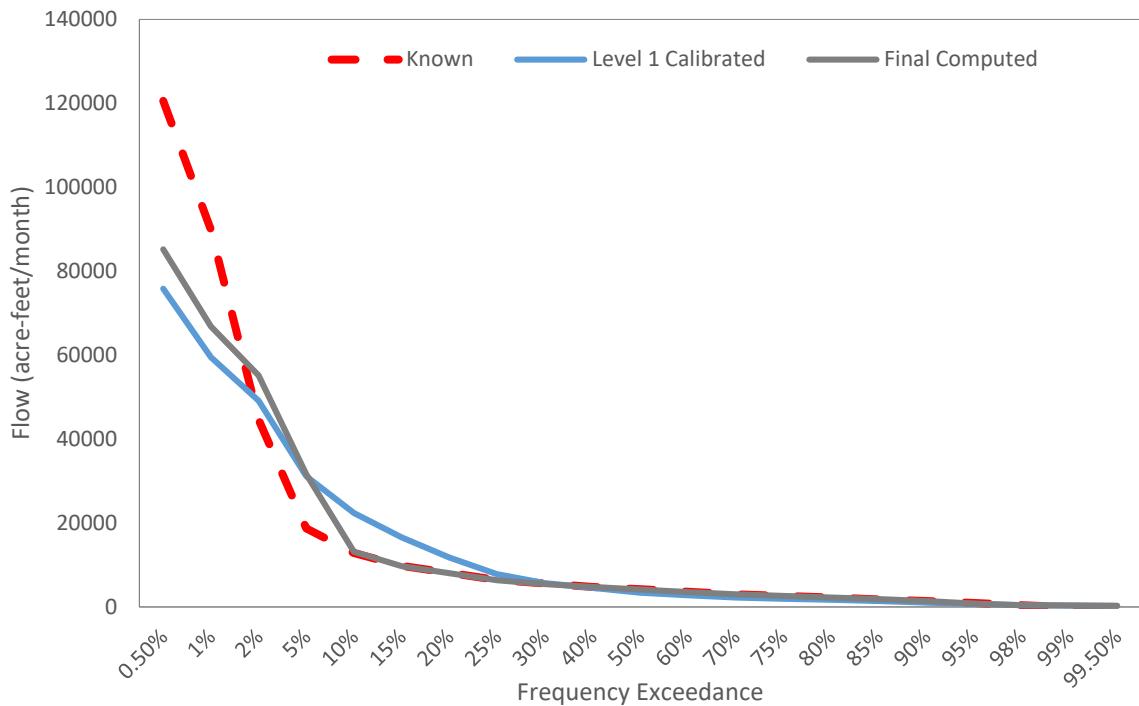


Figure B20. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at GT3000

Table B21. Flow Frequency Metrics in acre-feet/month for Calibration and Extension
for Delaware River near Red Bluff GT4000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	627.57	636.01	746.42	635.61	589.06	432.45
Std Dev	2358.3	2555.15	1790.07	1782.4	2195.04	1333.59
Minimum	0	0	1	0.4	0	0
99.50%	0	0	5.4	2.2	0	0
99%	0	0	6.16	2.46	0	0
98%	0	0	8.97	3.58	0	0.16
95%	12	12.2	15.4	7.84	4.72	1.1
90%	37.2	38	33.78	35.74	25.36	4.3
85%	57.8	58	44.78	57.14	49.8	19.2
80%	76	74.8	56.48	74.7	67.2	44.9
75%	94	94	70.4	94	88	56.4
70%	105.6	106.2	81.36	104	101	78.4
60%	135	139	108.86	135.14	129.52	102.5
50%	165	169	152.3	168	159	132.1
40%	206.2	204.4	201.44	207.04	195.6	166
30%	285.4	278	269.6	268.74	264	201
25%	334	322	315.5	310.2	317	244.7
20%	419.6	408	445.68	360.62	396	287.5
15%	587.2	546.8	1275.1	609.58	553.2	341.7
10%	1116.6	989.2	2159.9	1089.08	1002.8	646.9
5%	2336.8	2328.2	4201.56	3967.56	2244	1737.6
2%	5614.16	5619.92	7147.49	7486.72	5611.04	5389.22
1%	9499.64	8851.16	9349.83	9793.6	7967.3	8542.5
0.50%	18270.16	18952.24	11437.14	11979.92	15709.72	12946.5
Maximum	45939	45939	16546.1	17331.4	45939	12946.5

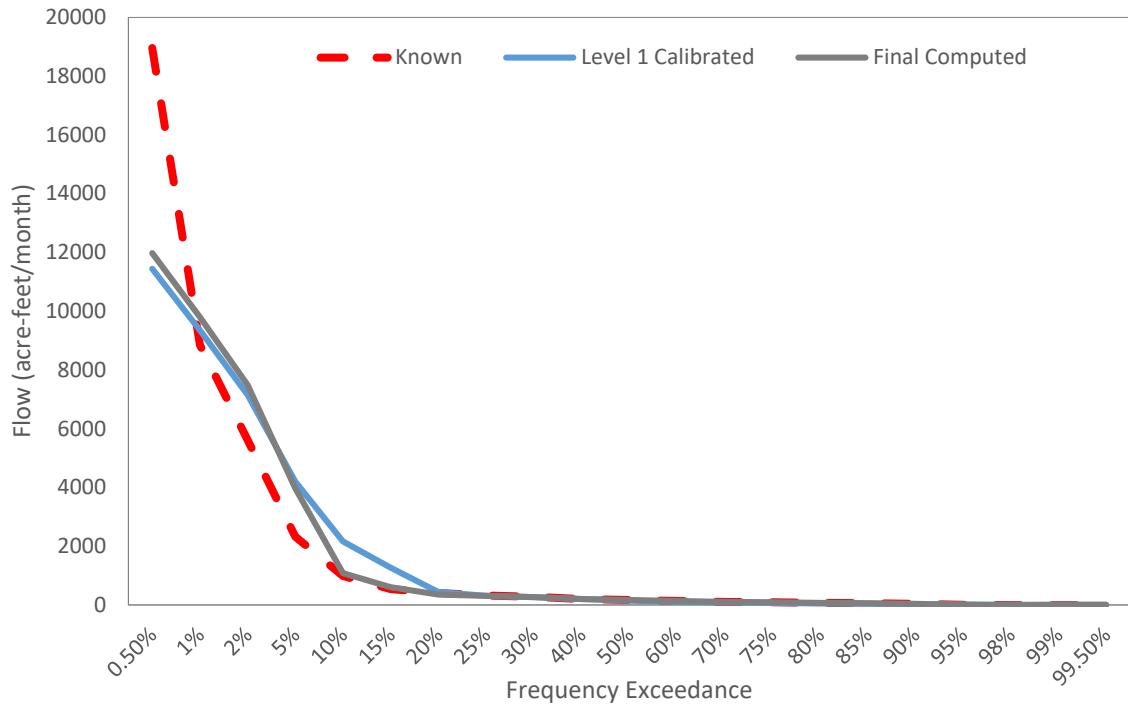


Figure B21. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at GT4000

Table B22. Flow Frequency Metrics in acre-feet/month for Calibration and Extension for Pecos River at Red Bluff GT5000

1	2	3	4	5	6	7
	Original Known 1940-2000	Original Known 1954-2000	Level 1 Computed 1954-2000	Final Computed 1954-2000	Combined 1940-2015	Extension 2001-2015
Mean	9663.41	6751.15	8375.46	6750.21	9104.67	6832.46
Std Dev	29376.75	15647.8	12929.84	12650.63	26948.21	12852.34
Minimum	149	149	7.1	15.4	0	0
99.50%	402.3	365.64	114.72	247.56	113.68	0
99%	495.2	476.4	148.59	320.72	170.42	0.16
98%	649.04	626.28	226.51	488.92	508.48	76.38
95%	886.6	816.2	548.06	837.18	826.1	233.6
90%	1351	1148.8	908.98	1193.3	1229.8	872.4
85%	1774.6	1505	1231.22	1549.18	1626	1212.4
80%	2188.8	1928.8	1489.4	1907.32	2063	1614.8
75%	2517	2273	1716.9	2208.2	2406	2039.2
70%	2909.2	2535.2	1979.54	2548.48	2740.2	2473.2
60%	3500	3196	2462.22	3128.06	3370	3009.8
50%	4229	3650	2952.6	3533.6	4001	3428.5
40%	5044.8	4336.2	4338.72	4222.36	4757.56	3766.3
30%	6307.4	5172.6	7462.44	5036.44	5751.56	4700.2
25%	7269	5562	9827.8	5715.4	6899	5131.5
20%	8598.8	6613.4	12810.16	6945.88	8029.4	5926.6
15%	10971.4	8089.6	17712.22	8325.28	10175.6	7901.2
10%	14901.6	11399.8	23435.82	11950.74	14533.78	10371.8
5%	29219	18249.2	30543.38	29809.23	30871.6	35445.1
2%	61285.56	42493.36	41988.25	45507.68	58212.84	55363.36
1%	127664.77	61285.56	69341.86	75154.05	99726.85	73995.28
0.50%	272172.84	140870.77	95003.5	102966.69	214209.44	100745.6
Maximum	427555	245934	117540.5	127392.7	427555	100745.6

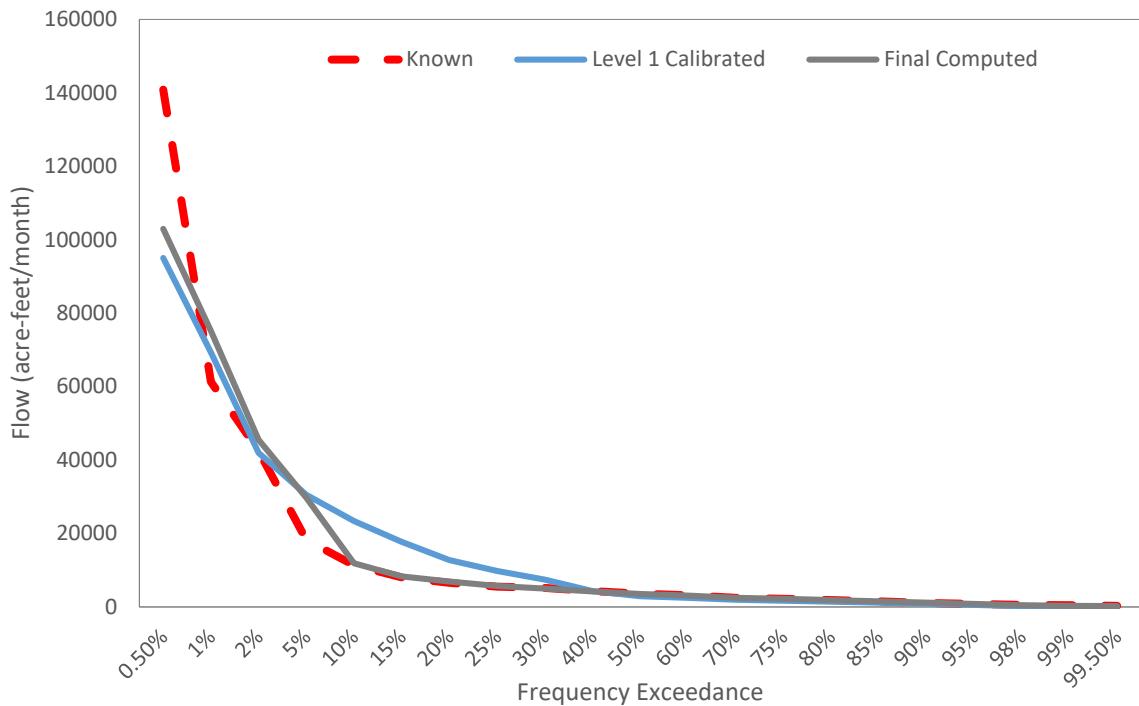


Figure B22. Known, Level 1 Calibrated, and Final Computed Flow Frequencies at GT5000

APPENDIX C

Known and Computed 12-Month Forward Moving Average Flow Volumed for Rio Grande Texas Primary Control Points

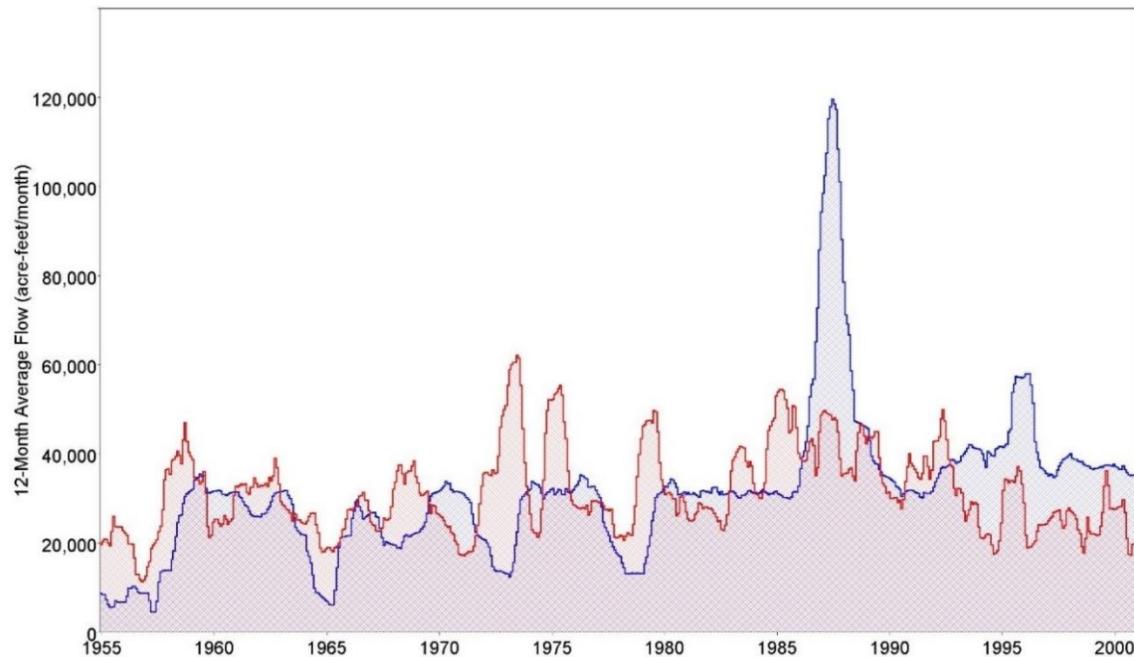


Figure C1. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at El Paso AT2000

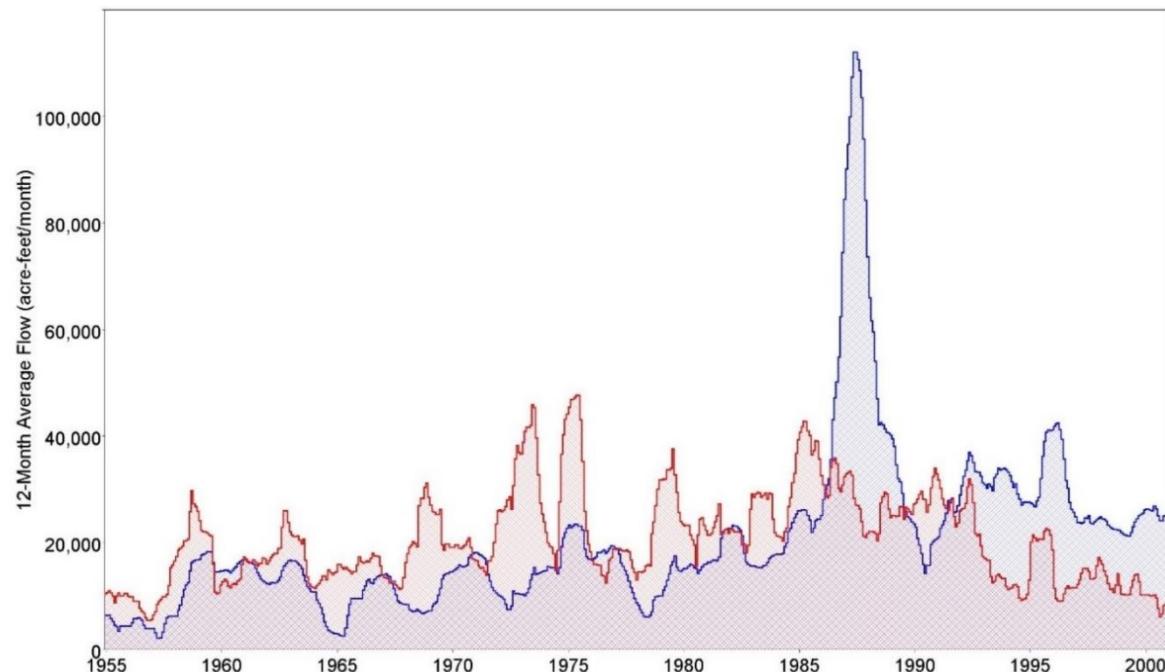


Figure C2. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande above Rio Conchos BT1000

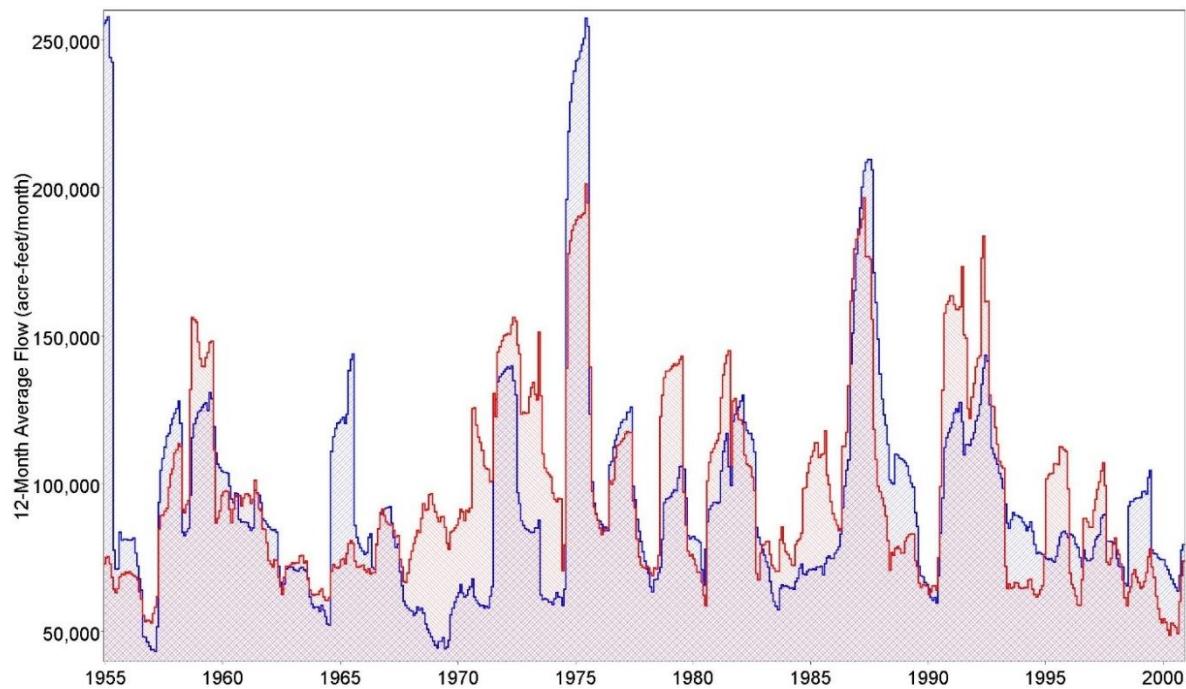


Figure C3. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Del Rio CT1000

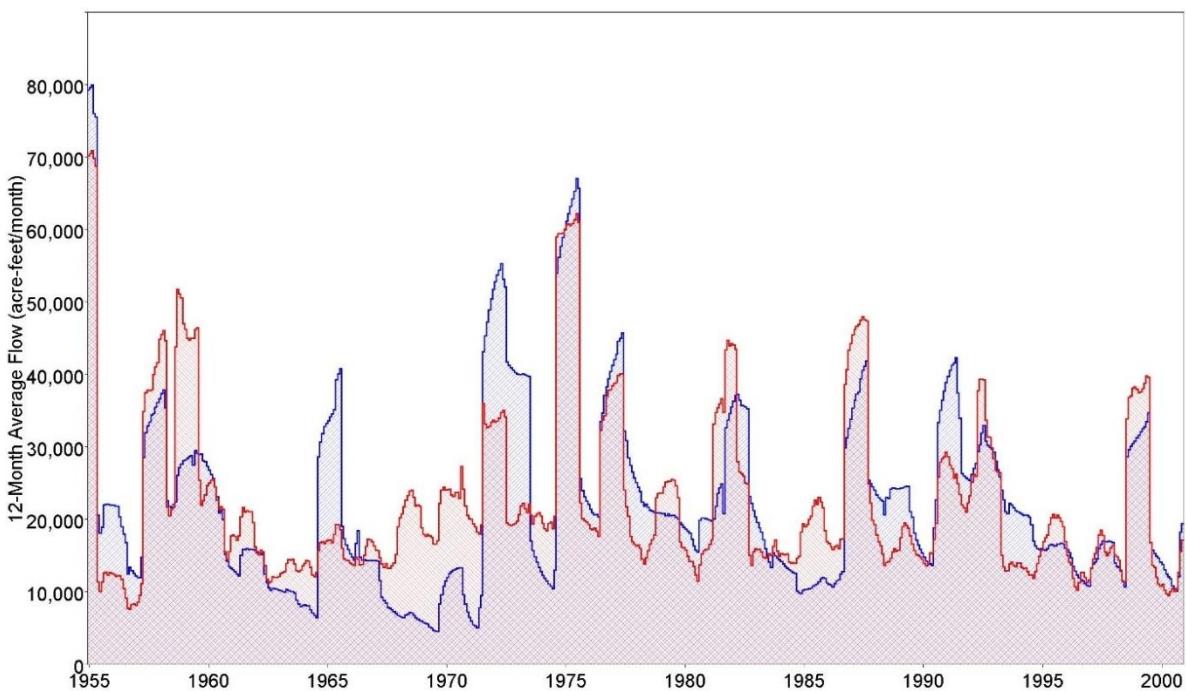


Figure C4. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Devils River at Pafford Crossing CT2000

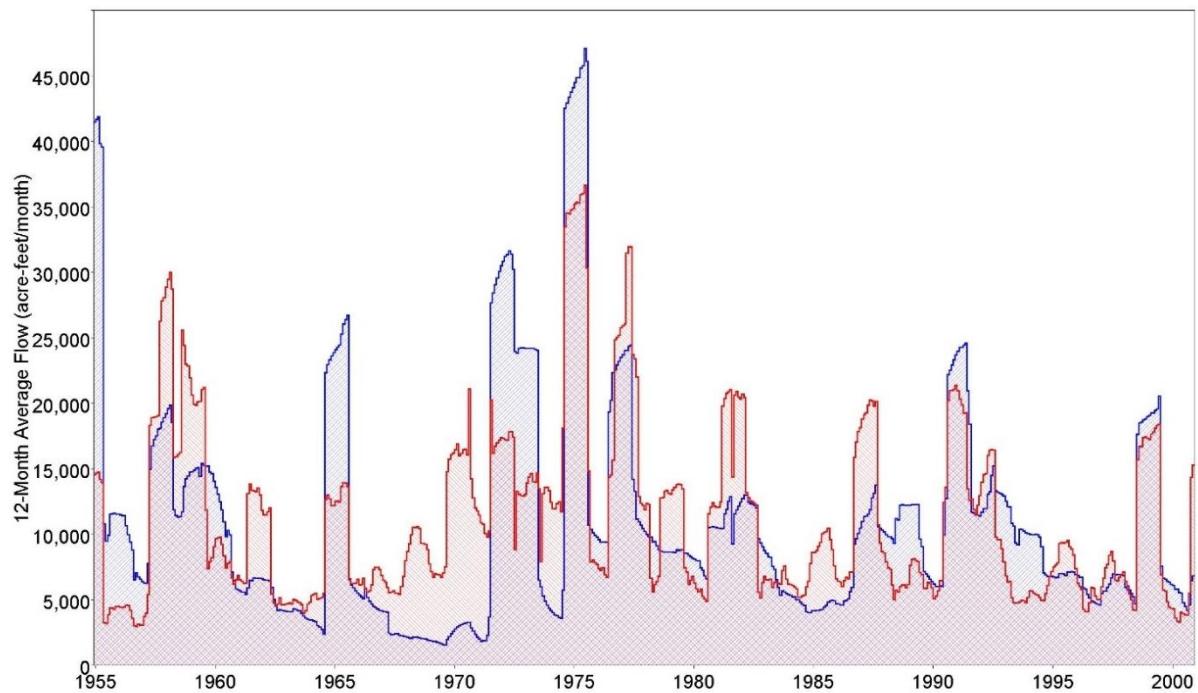


Figure C5.Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Foster Ranch CT3000

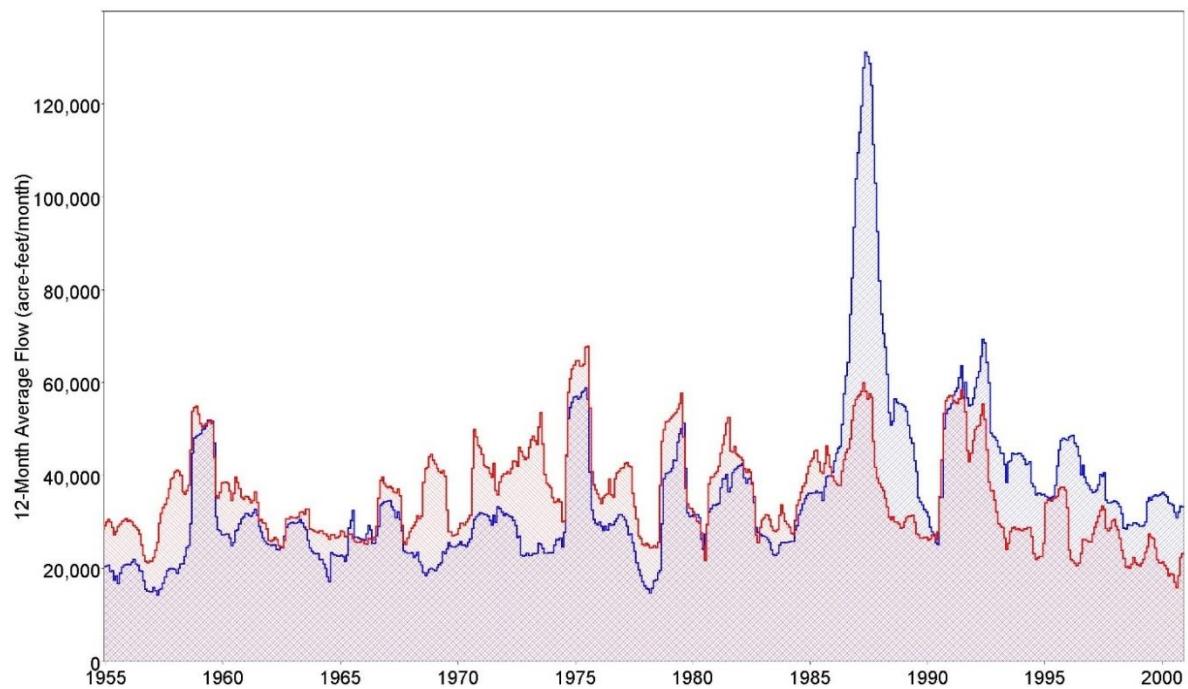


Figure C6. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Johnson Ranch CT4000

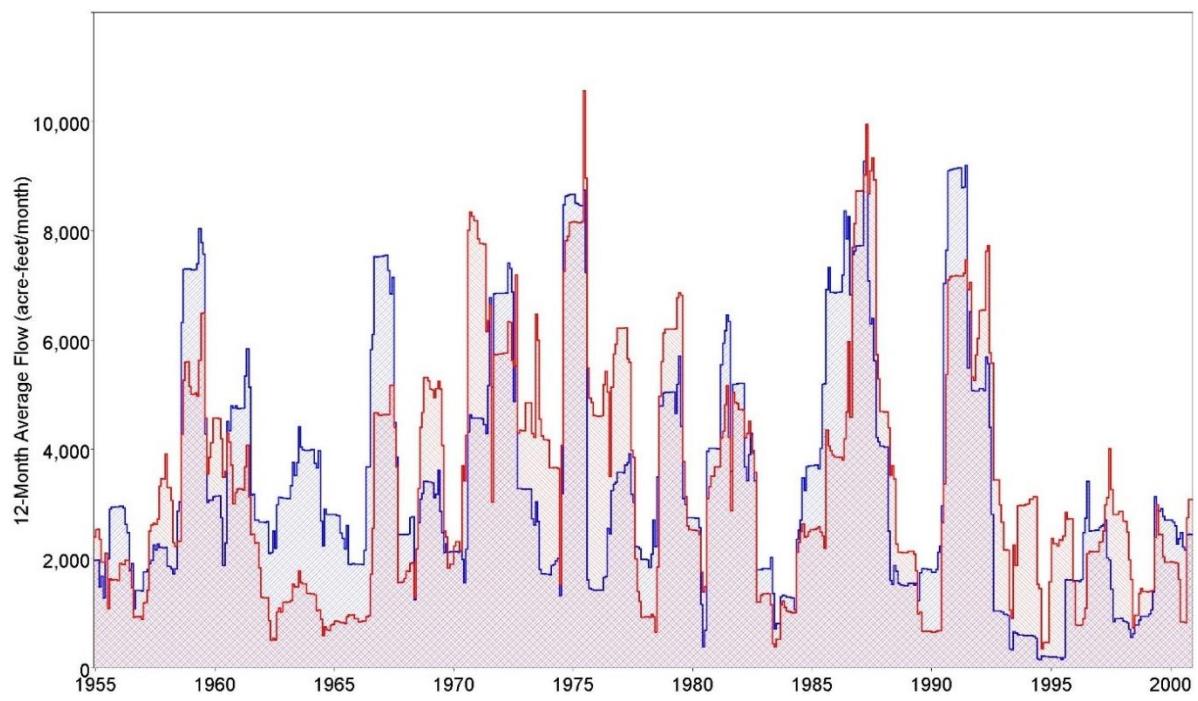


Figure C7. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Terlingua Creek near Terlingua CT5000

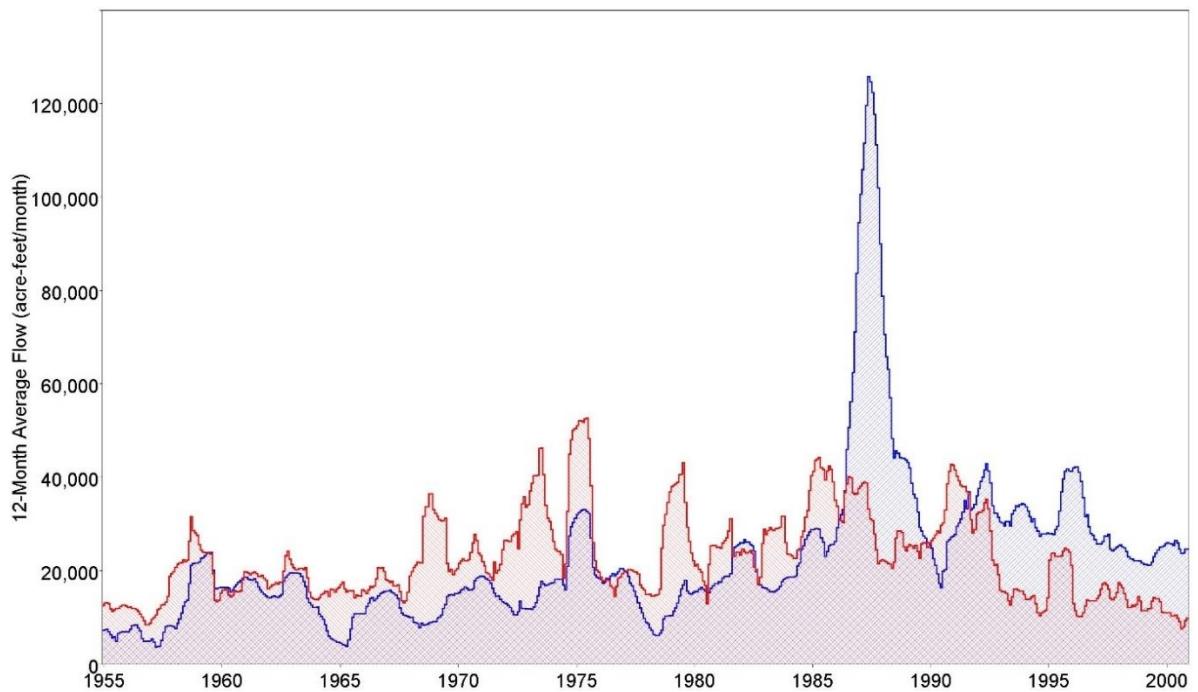


Figure C8. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande below Rio Conchos CT6000

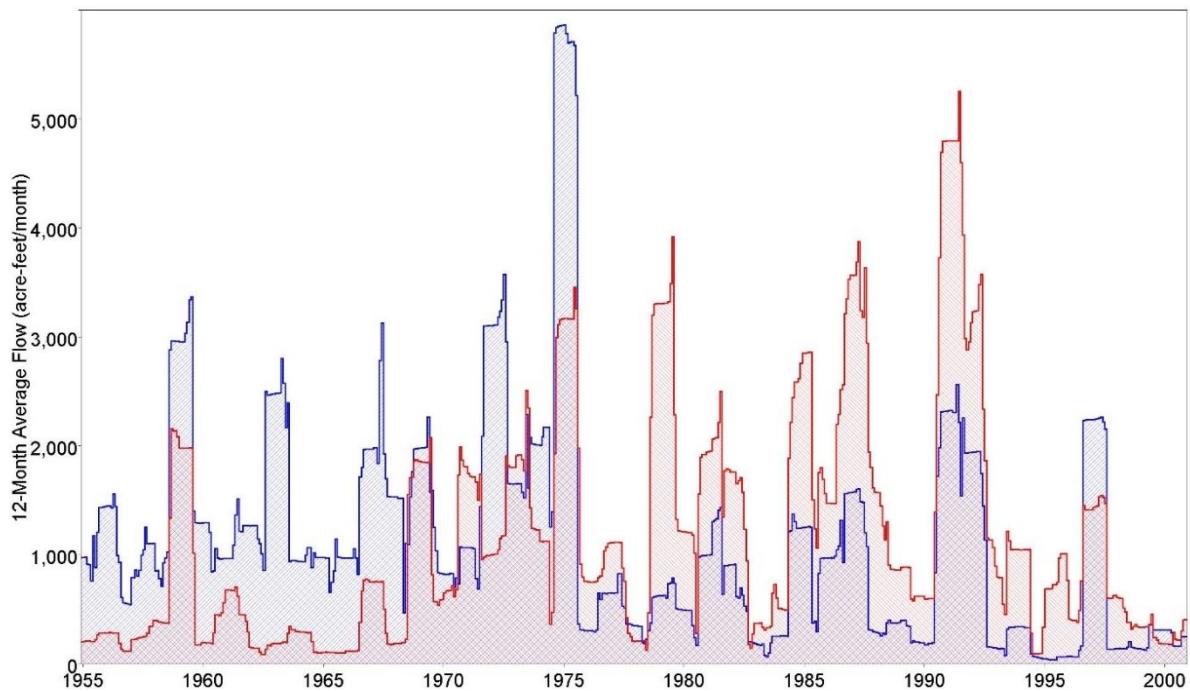


Figure C9. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Alamito Creek near Presidio CT7000

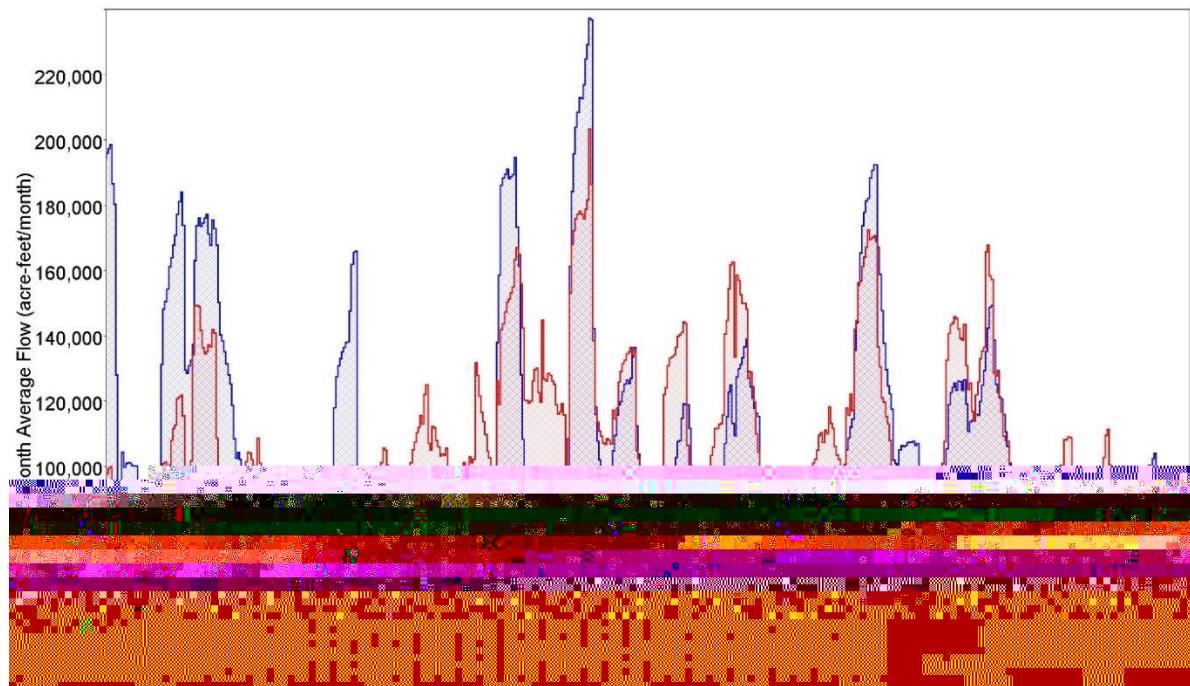


Figure C10. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande below Falcon Dam DT1000

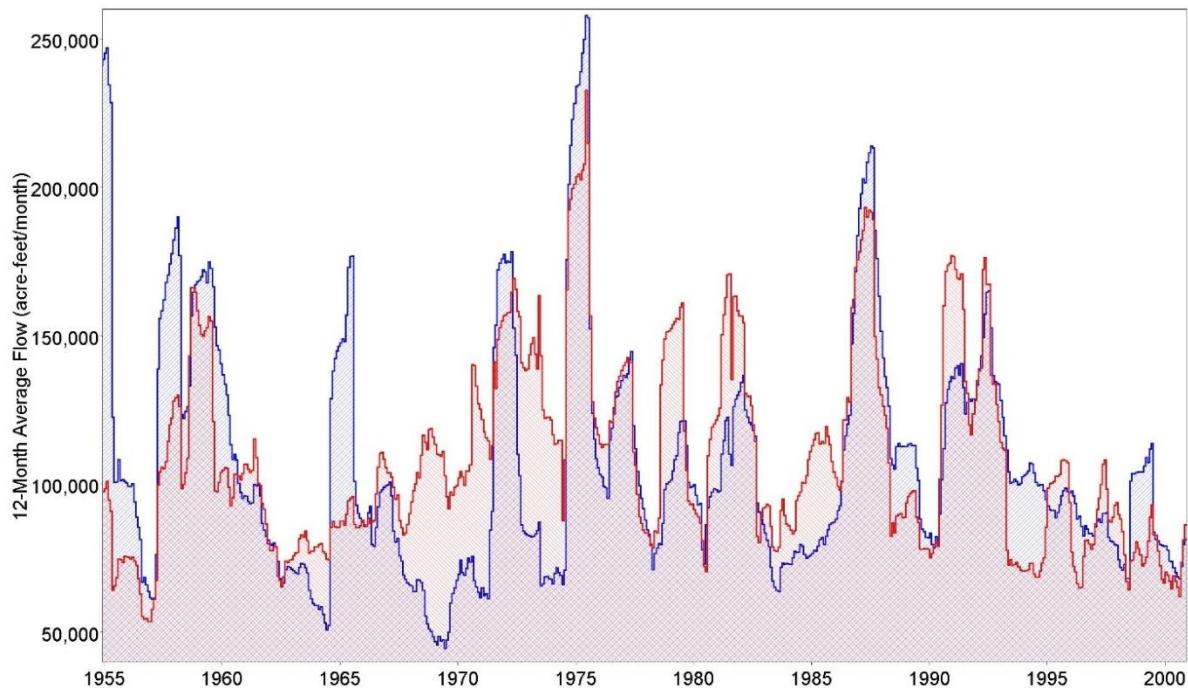


Figure C11. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Laredo DT3000

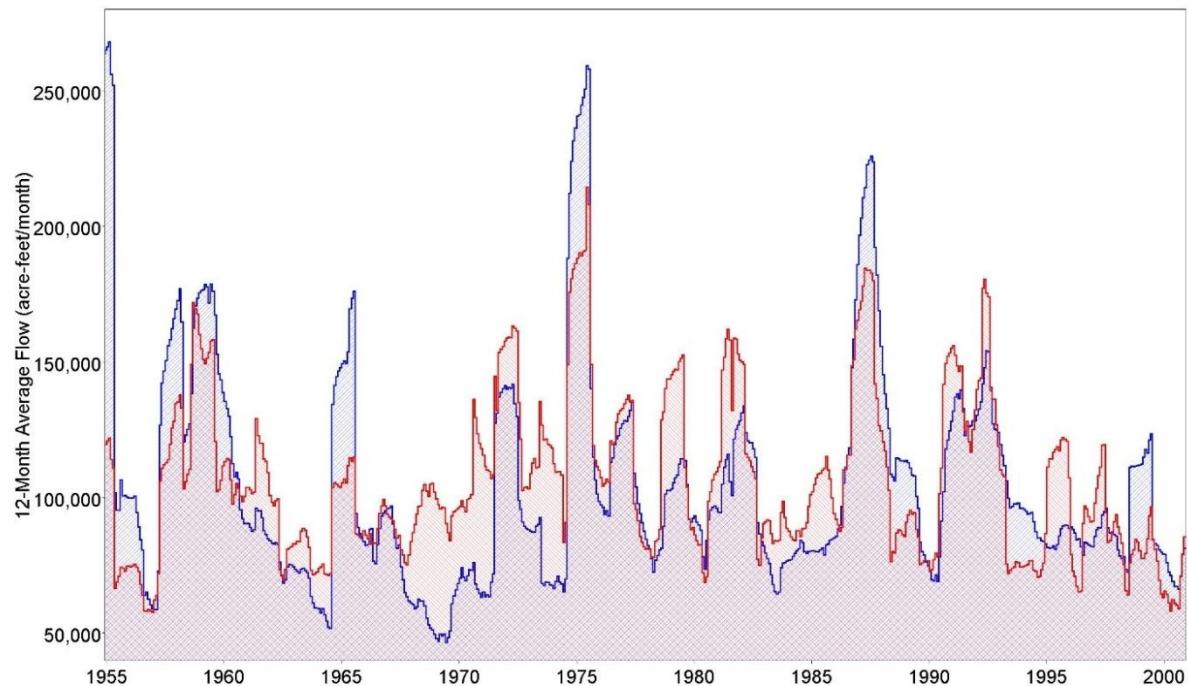


Figure C12. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Piedras Negras DT5000

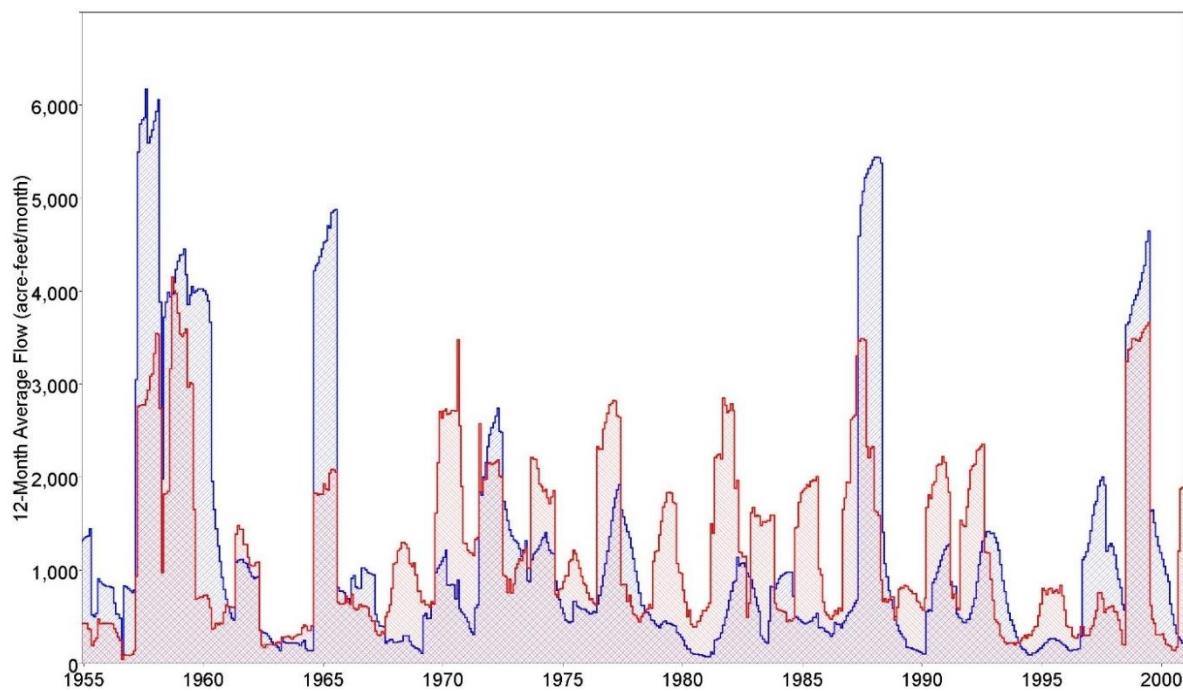


Figure C13. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Pinto Creek near Del Rio DT8000

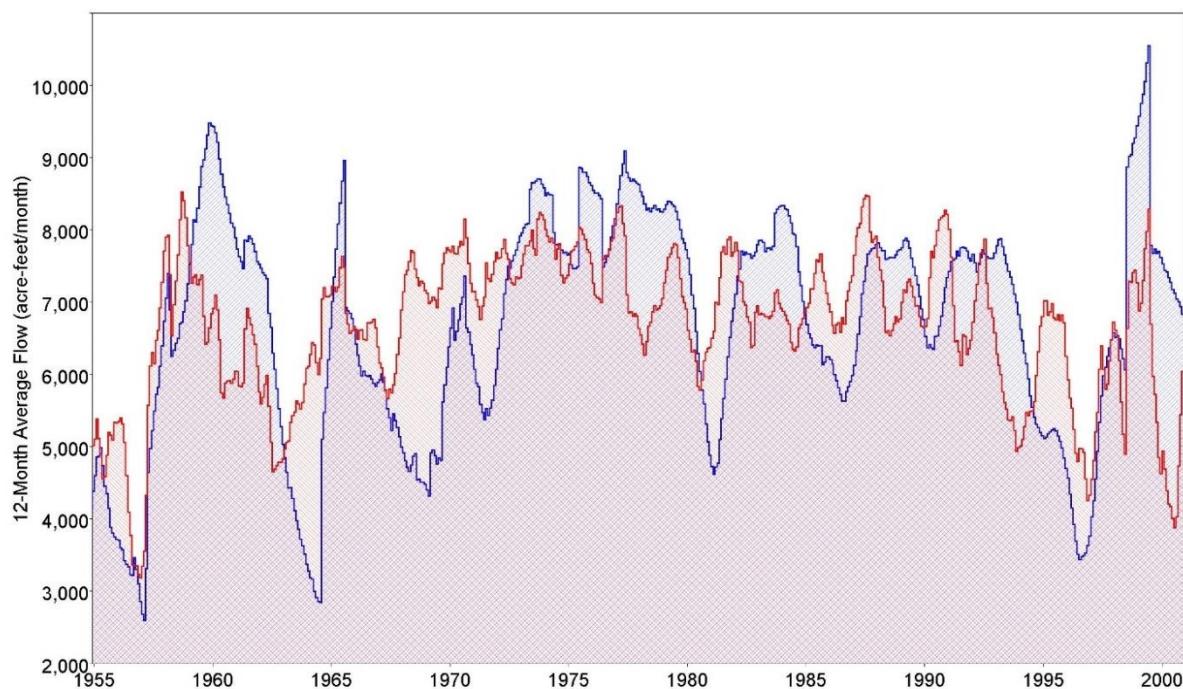


Figure C14. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for San Felipe Creek near Del Rio DT9000

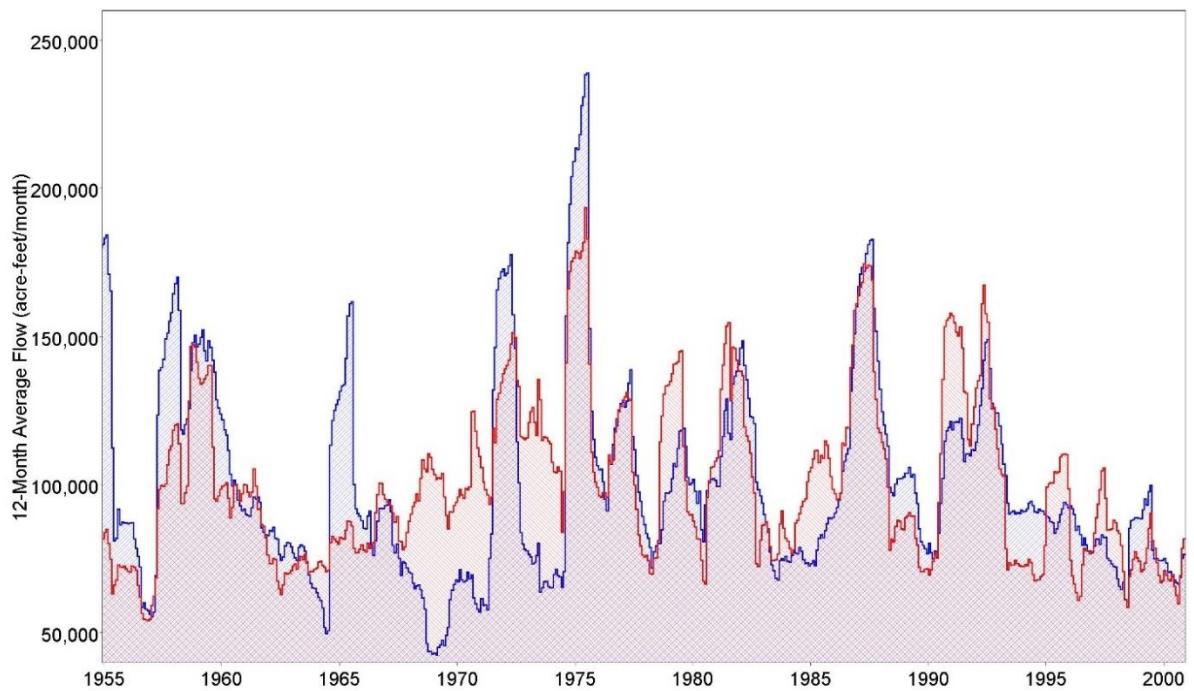


Figure C15. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande below Anzalduas Dam ET1000

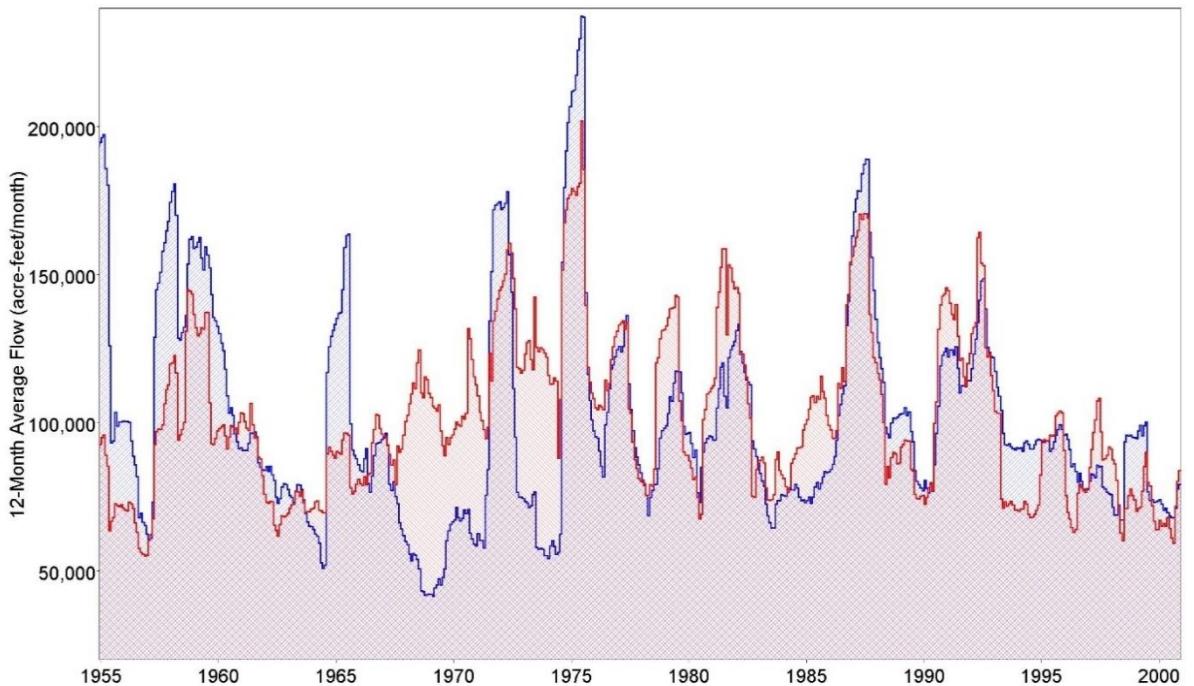


Figure C16. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Rio Grande at Rio Grande City ET2000

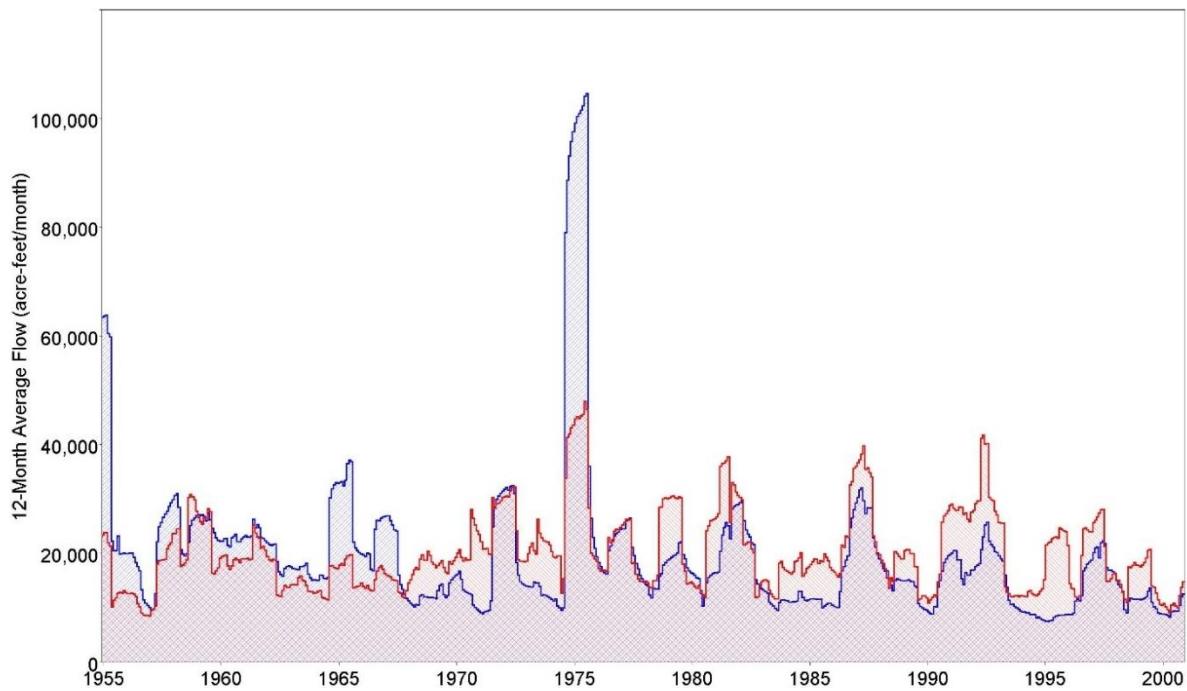


Figure C17. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Pecos River near Langtry GT1000

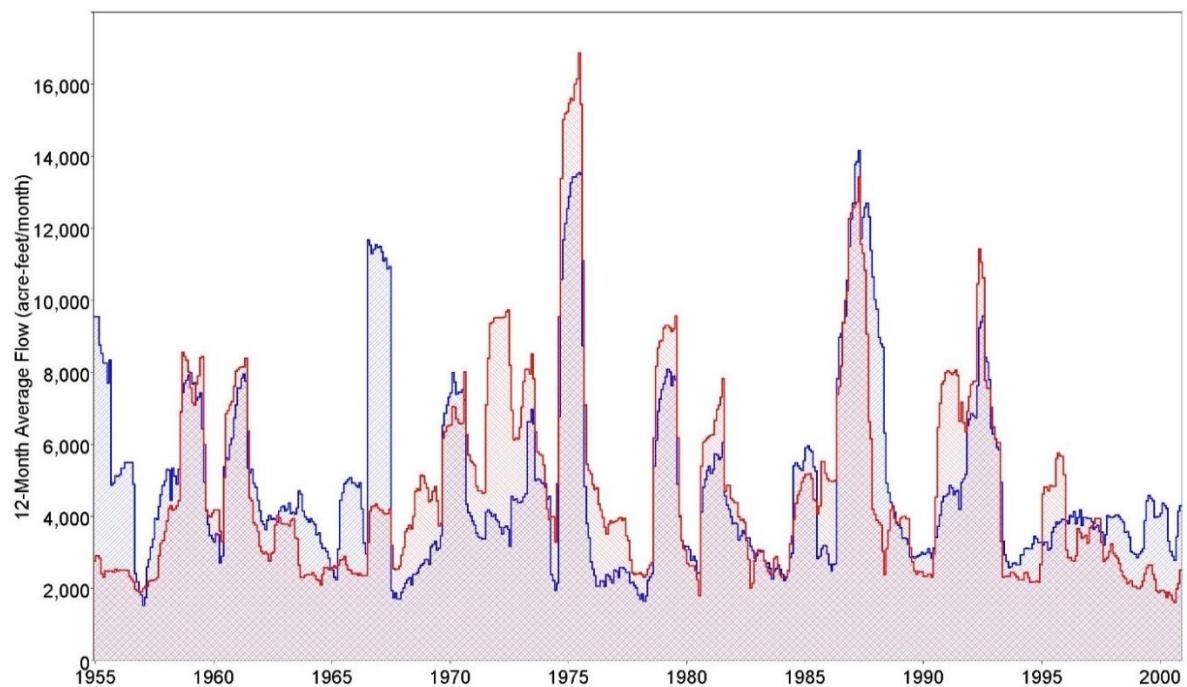


Figure C18. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Pecos River near Girvin GT2000

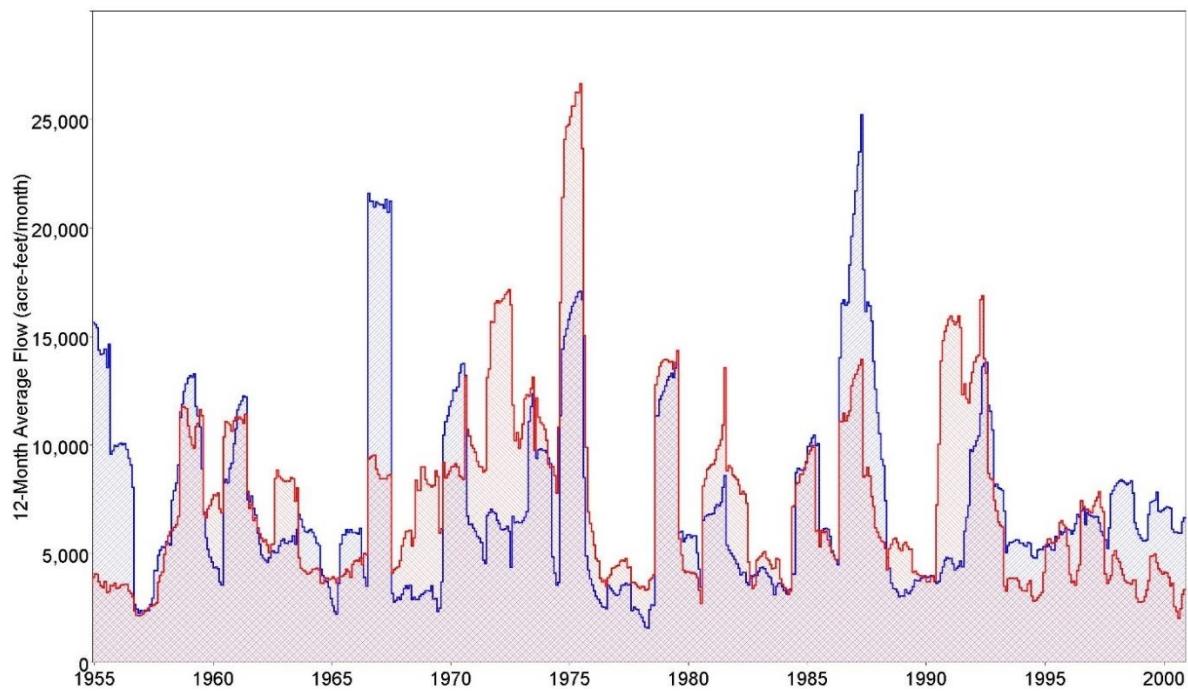


Figure C19. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Pecos River near Orla GT3000

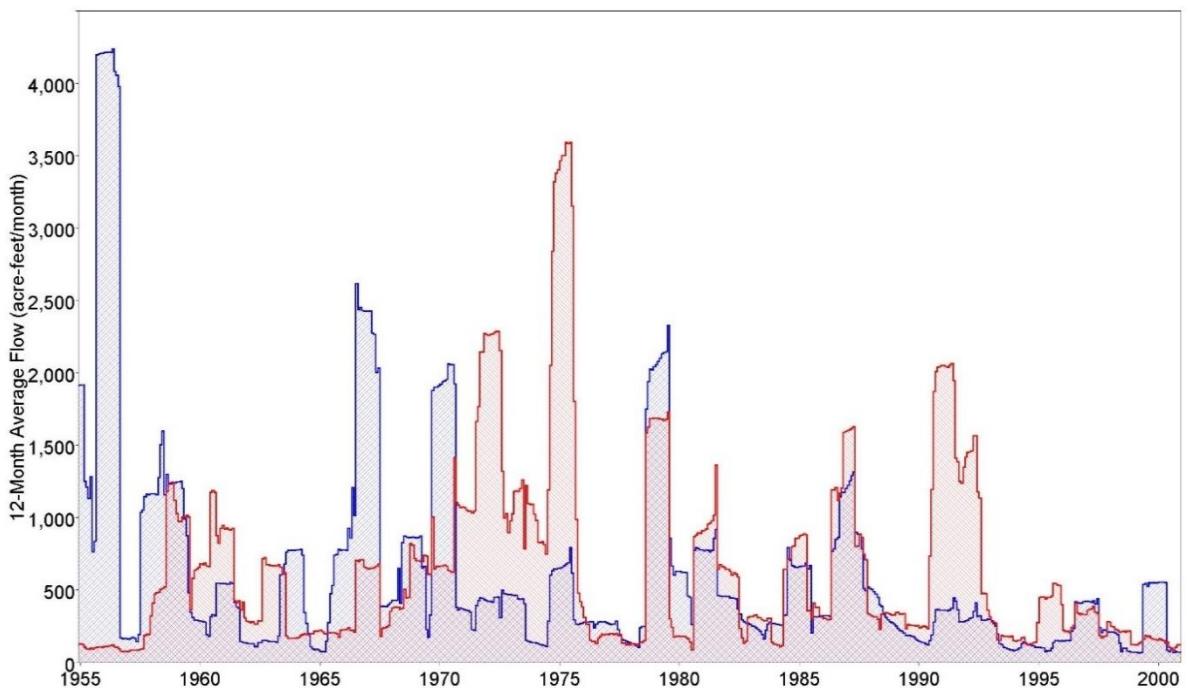


Figure C20. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Delaware River near Red Bluff GT4000

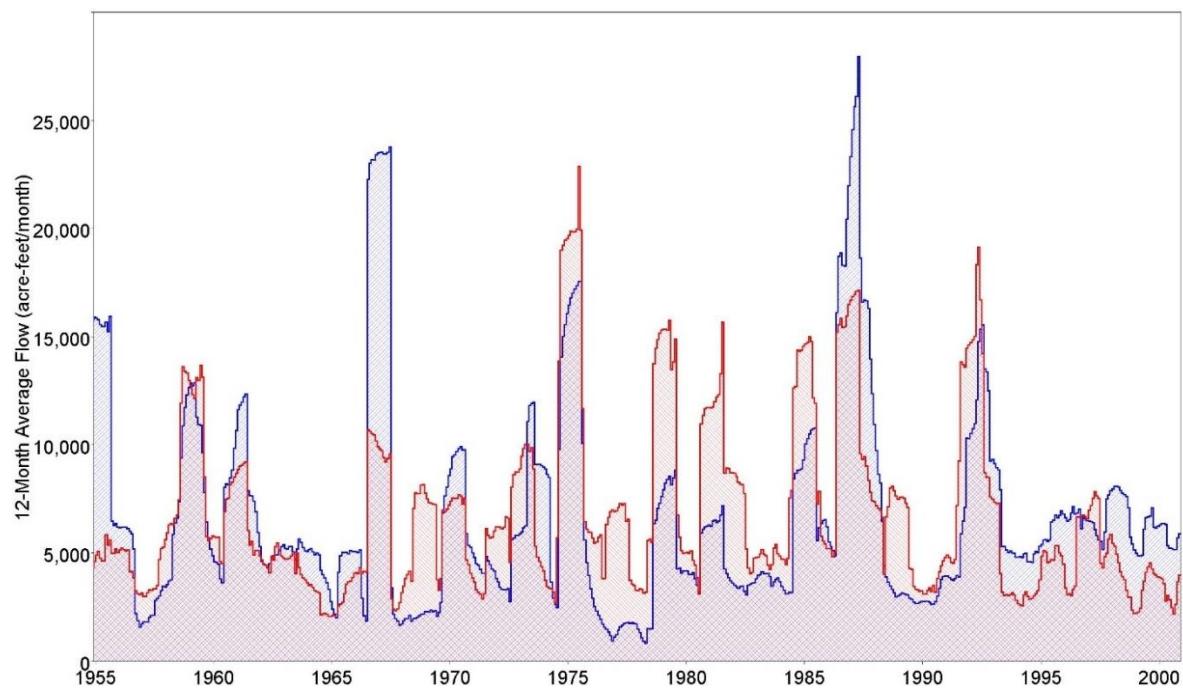


Figure C21. Known (Blue) and Final Computed (Red) 12-Month Forward Moving Average Flows for Pecos River at Red Bluff GT5000

APPENDIX D

Original and Extended Naturalized Flow Volumes for the Rio Grande Texas Primary Control Points

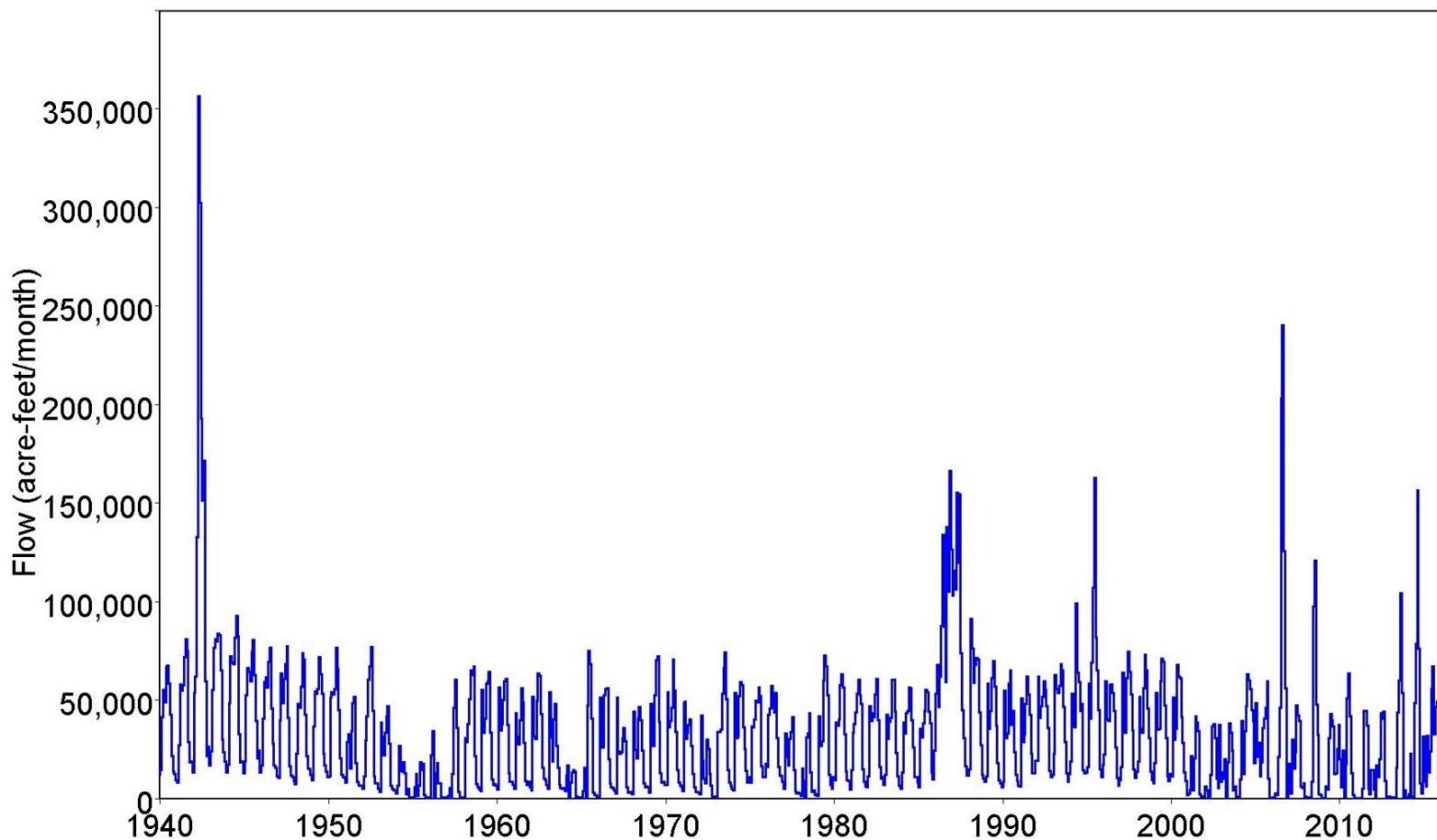


Figure D1. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at El Paso AT2000

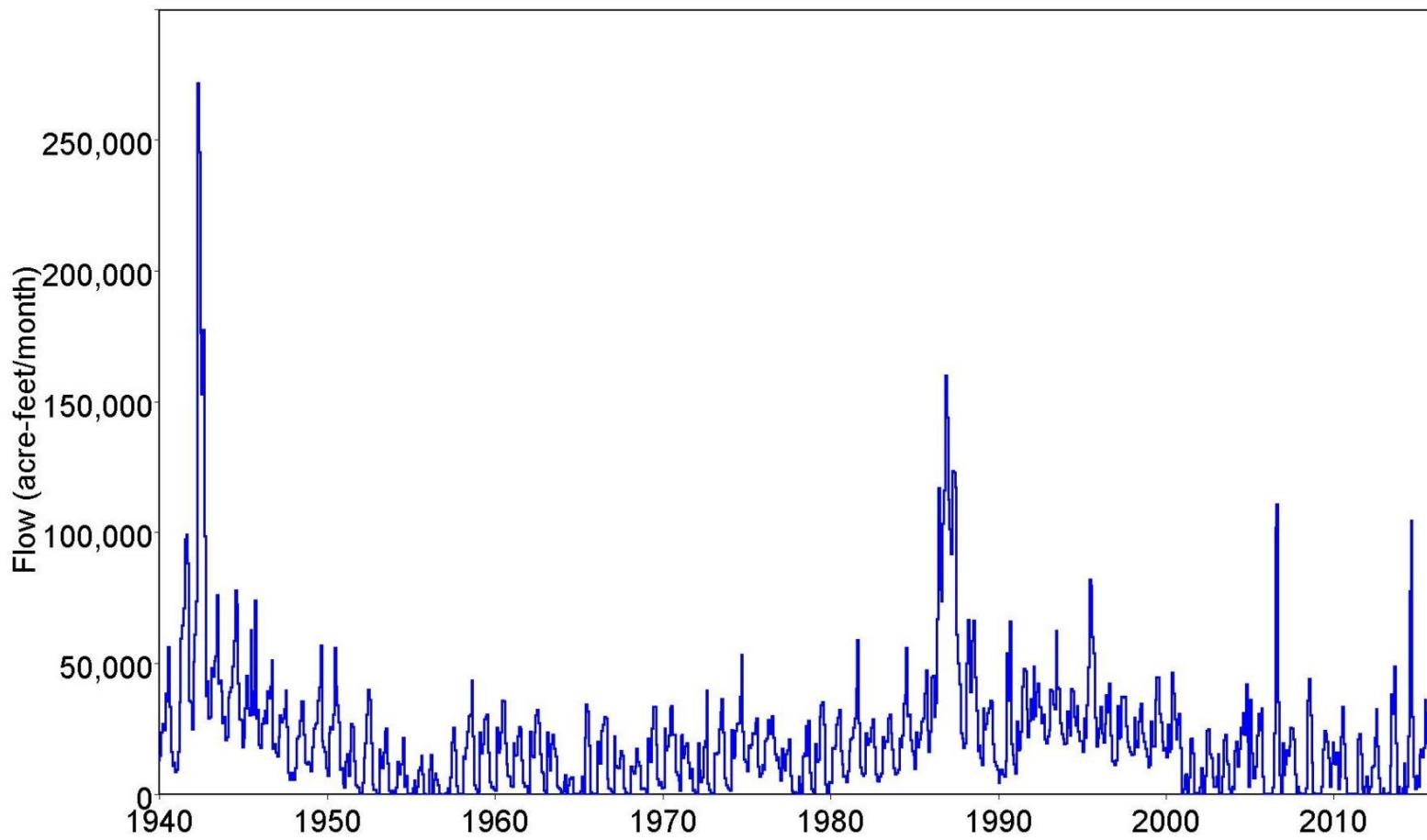


Figure D2. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande above Rio Conchos BT1000

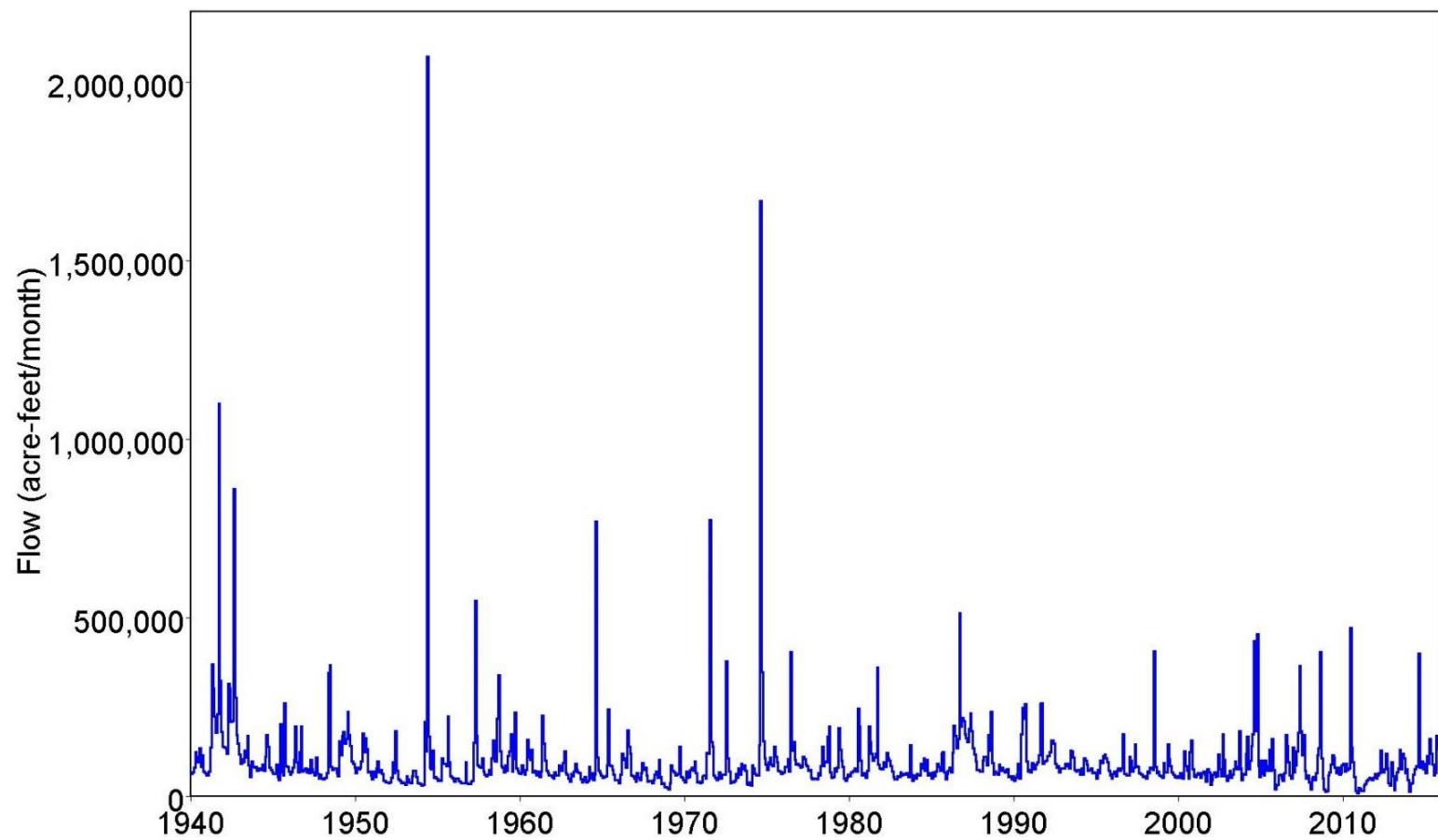


Figure D3. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Del Rio CT1000

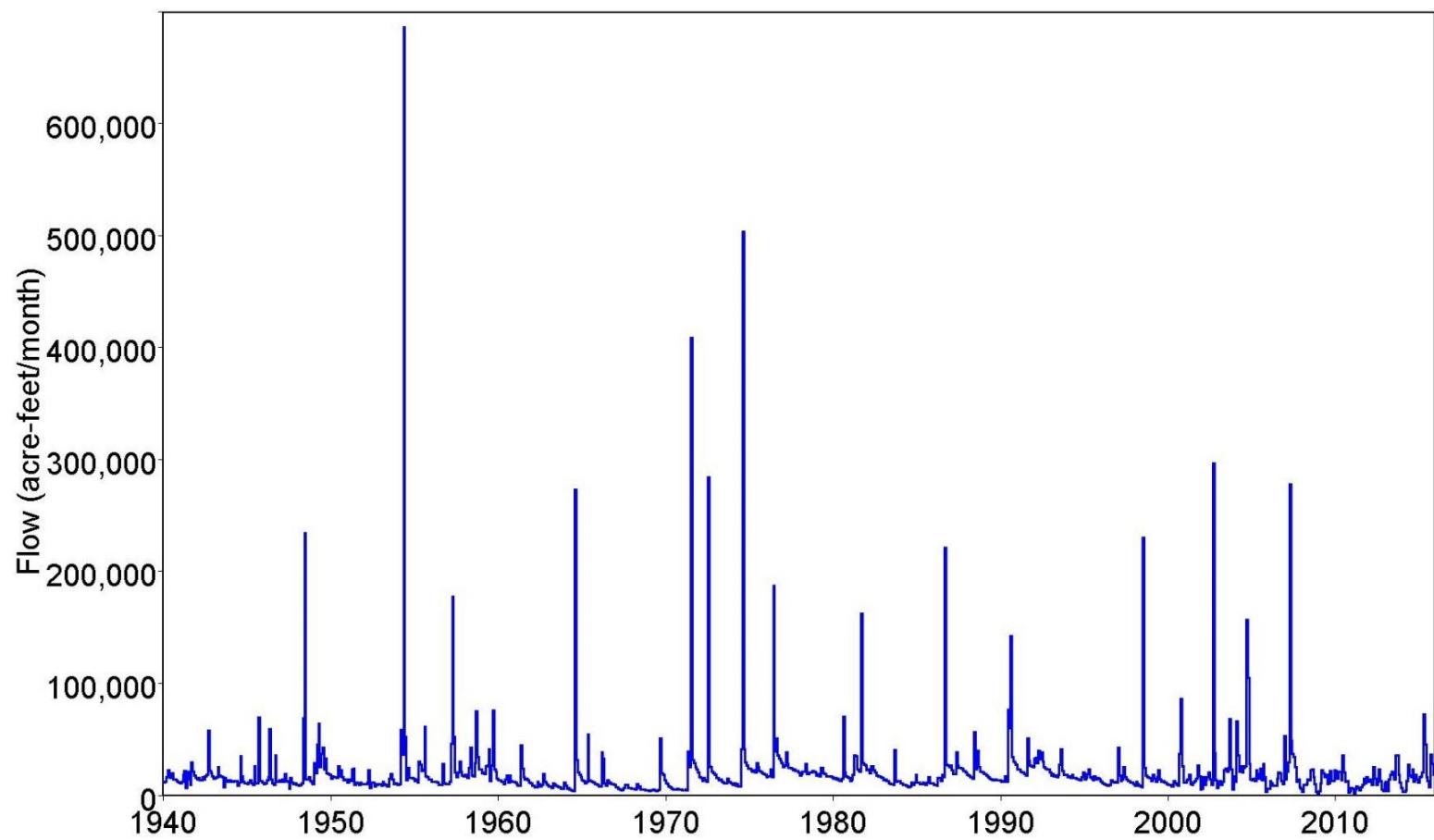


Figure D4. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Devils River at Pafford Crossing CT2000

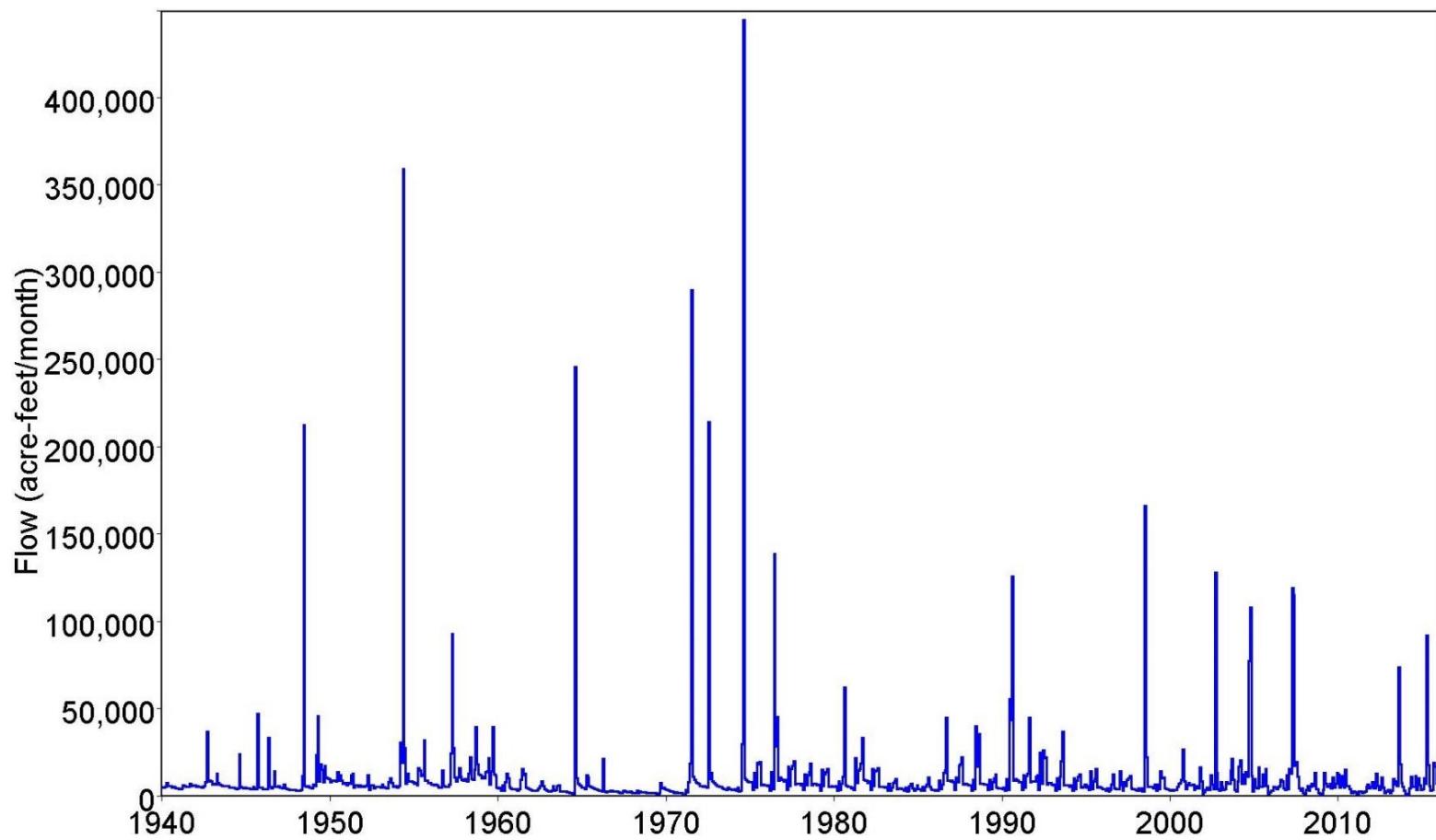


Figure D5. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Devils River neat Juno CT2100

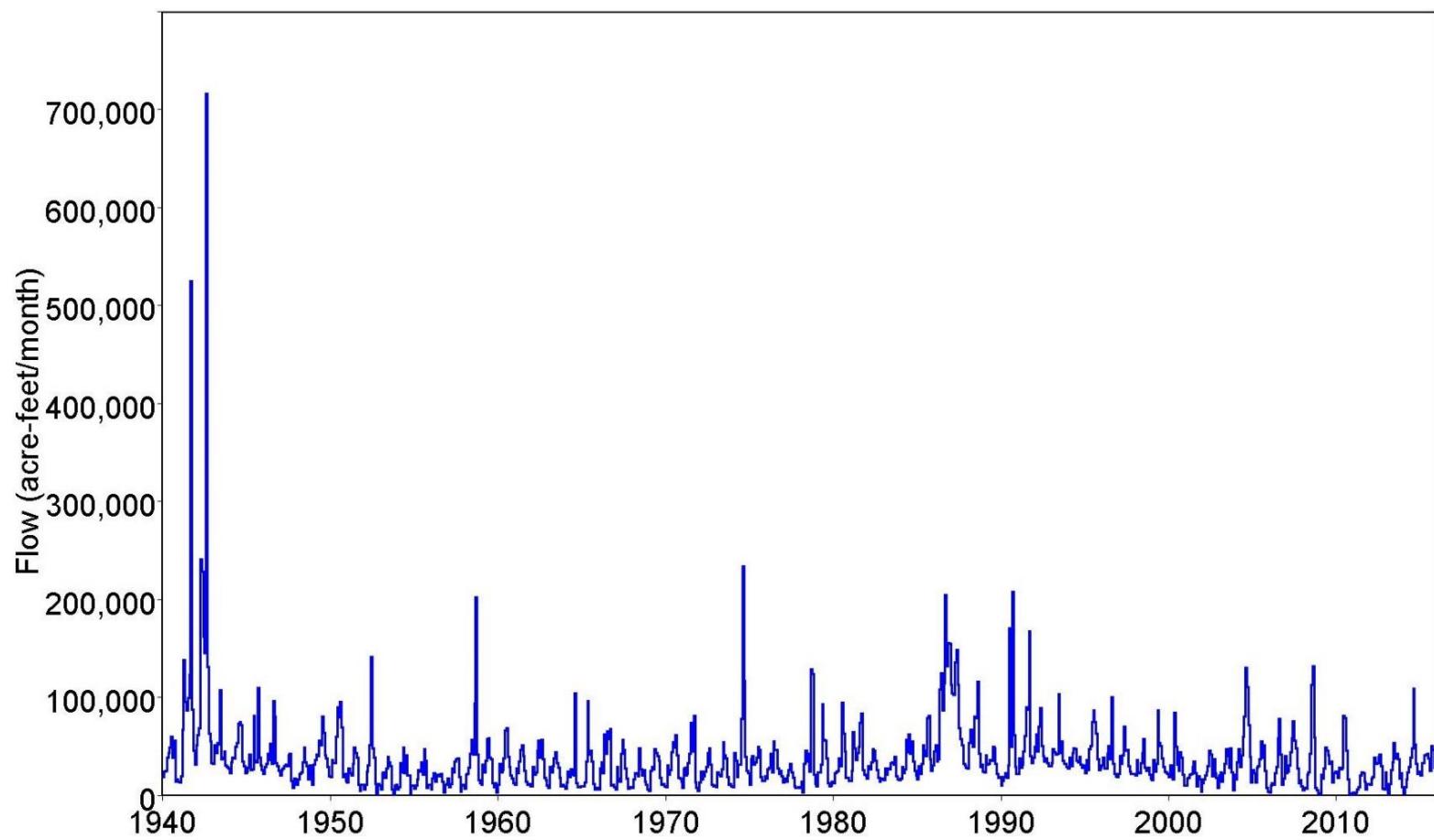


Figure D6. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Forest Ranch CT3000

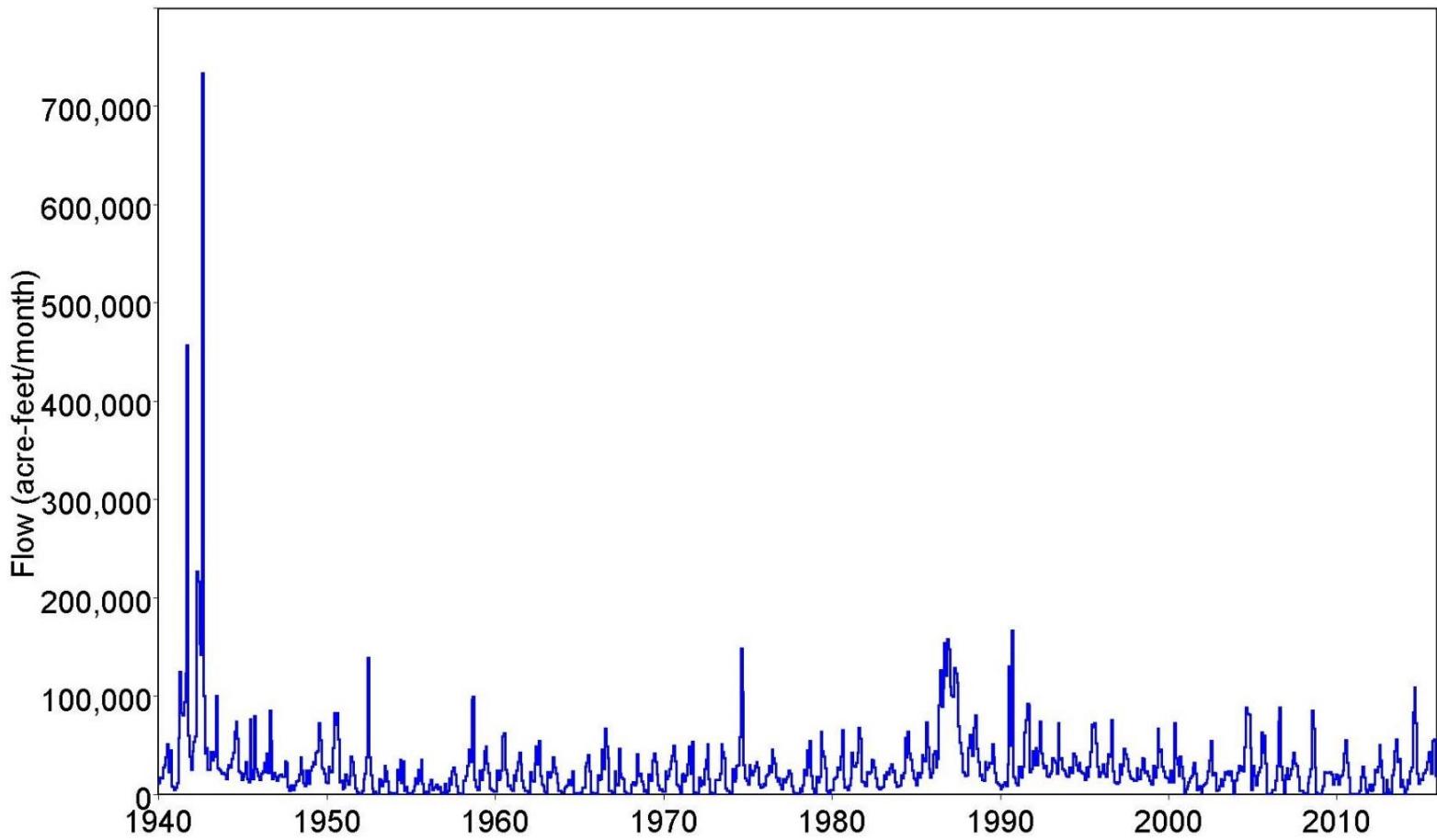


Figure D7. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Johnson Ranch CT4000

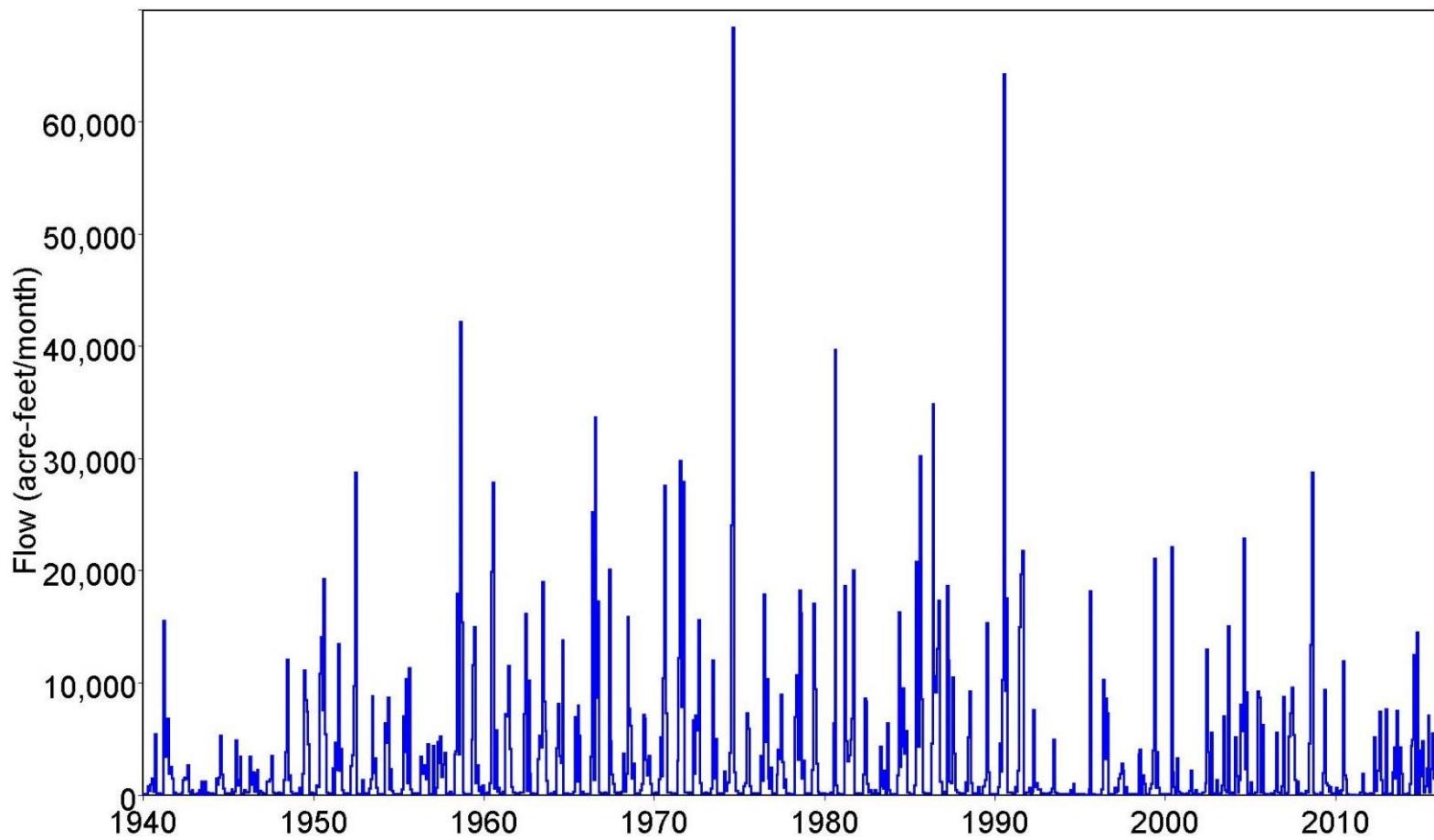


Figure D8. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Terlingua Creek near Terlingua CT5000

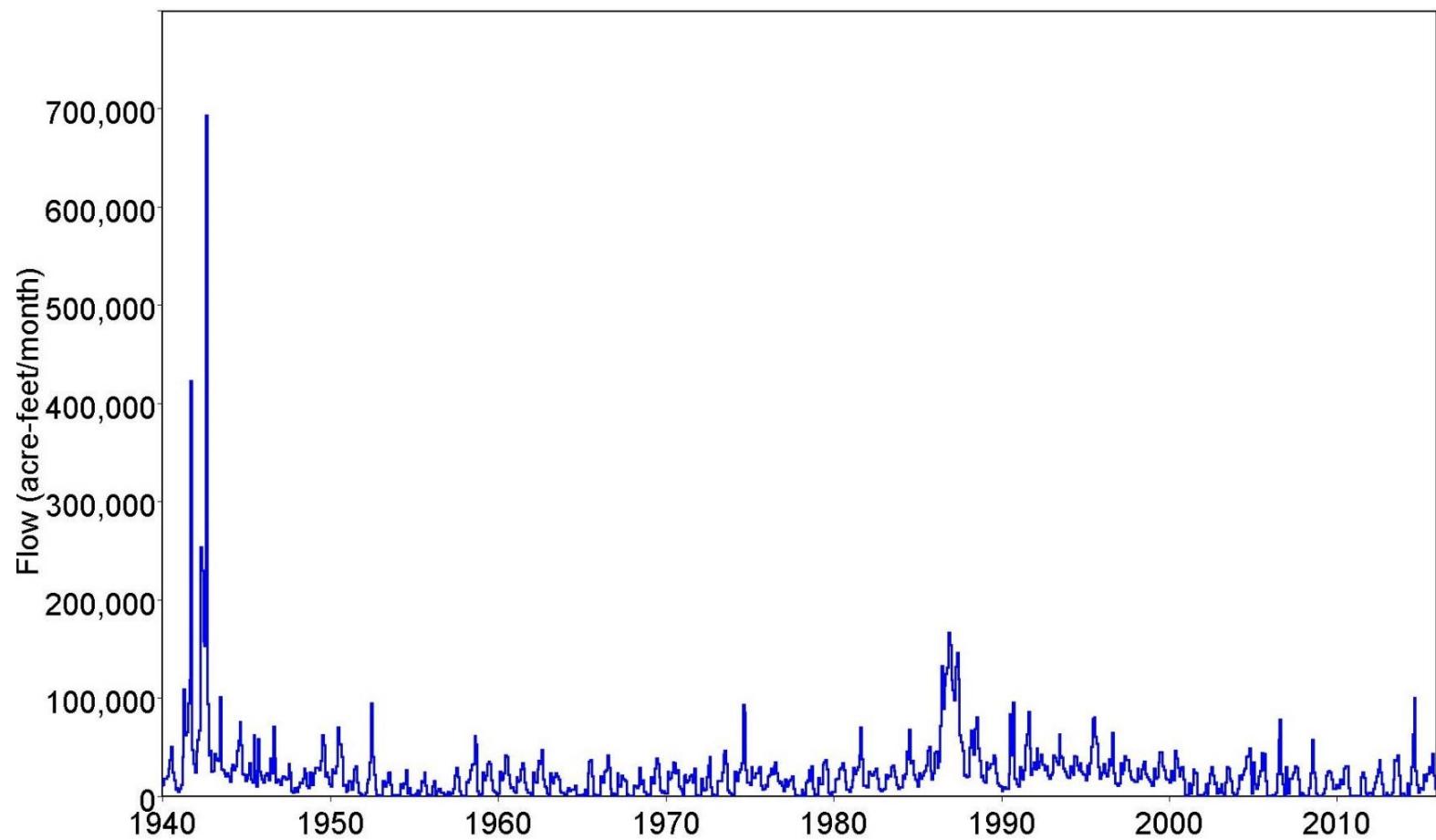


Figure D9. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande below Rio Conchos CT6000

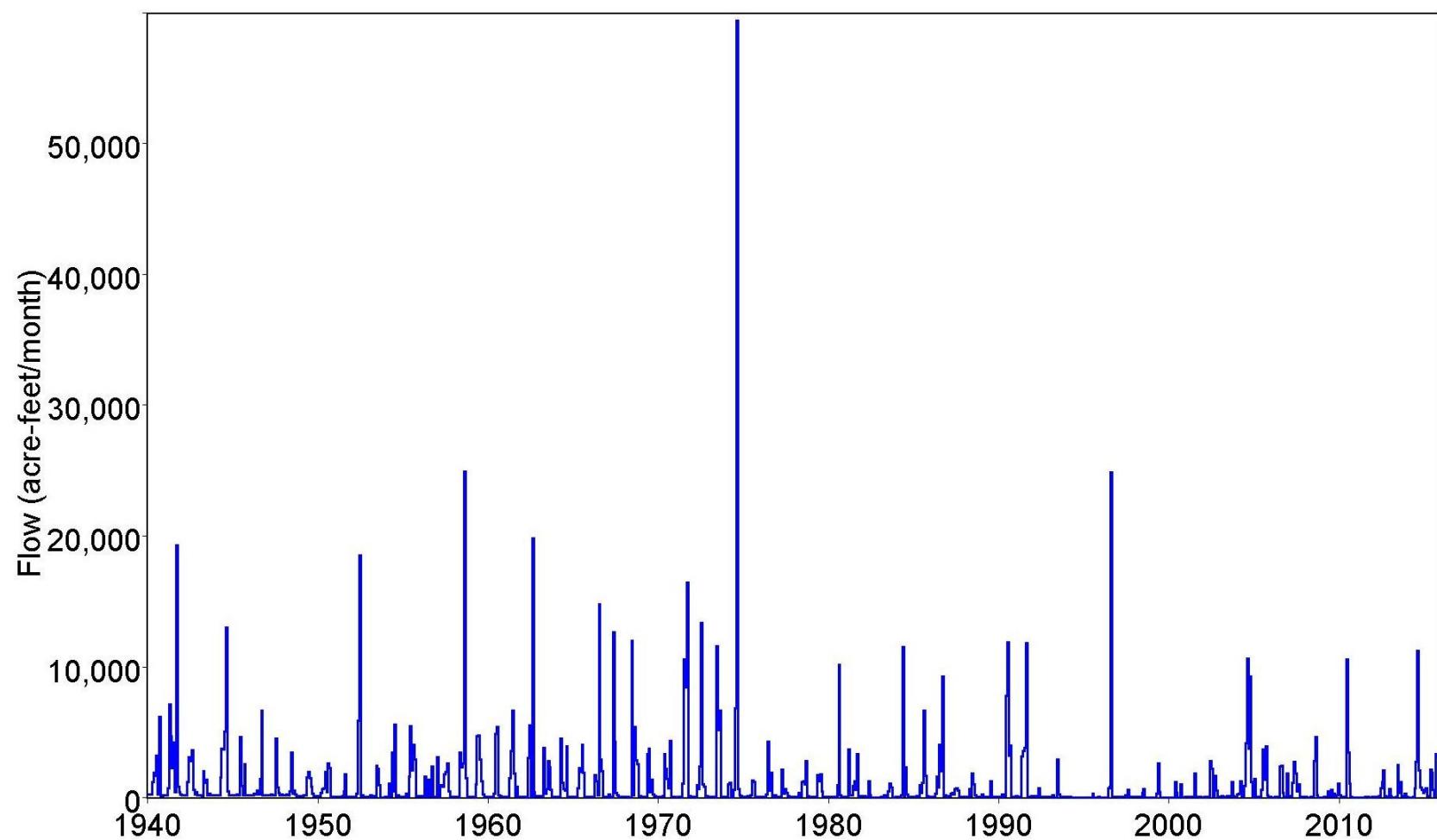


Figure D10. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Alamito Creek near Presidio CT7000

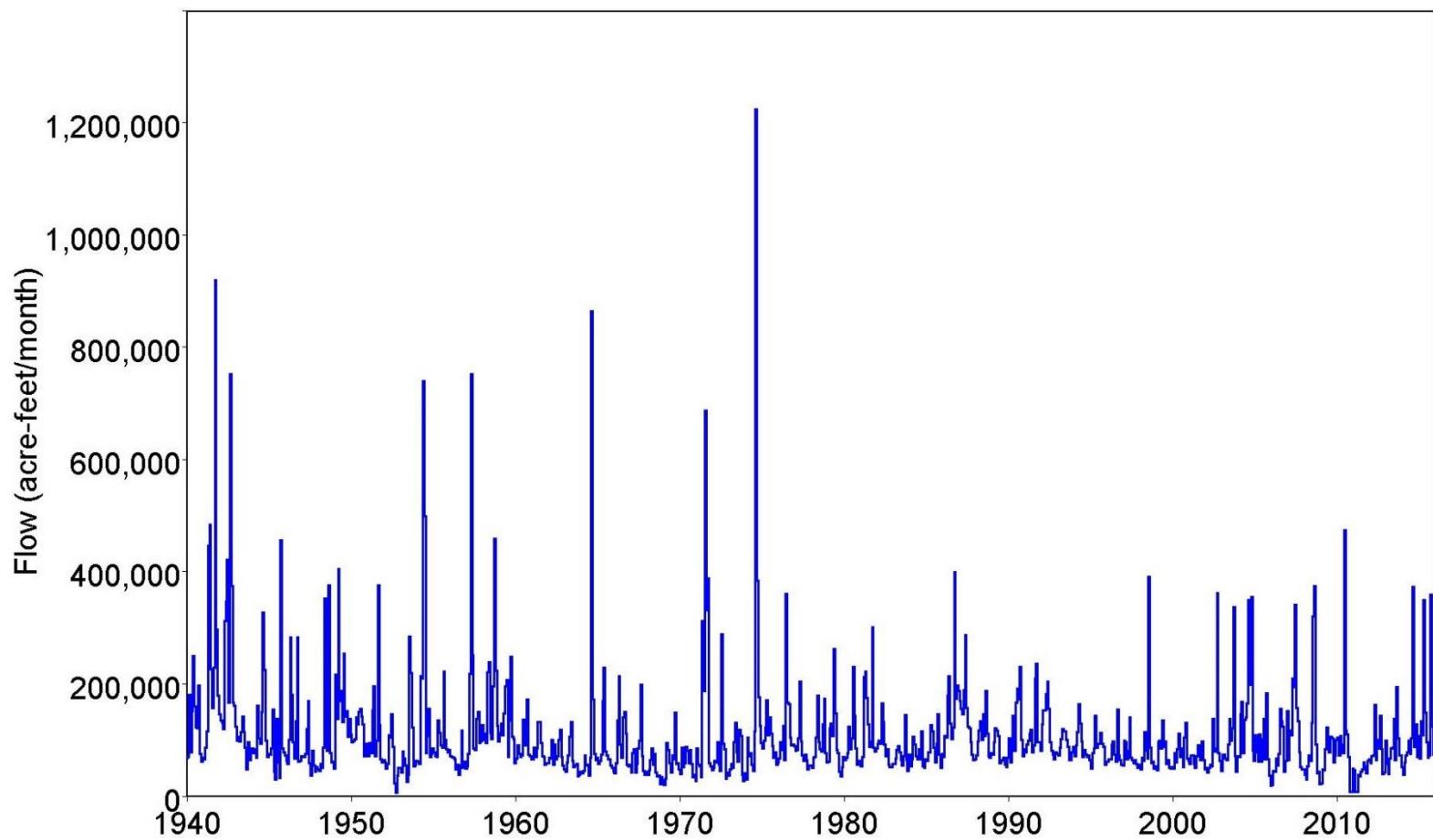


Figure D11. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande below Falcon Dam DT1000

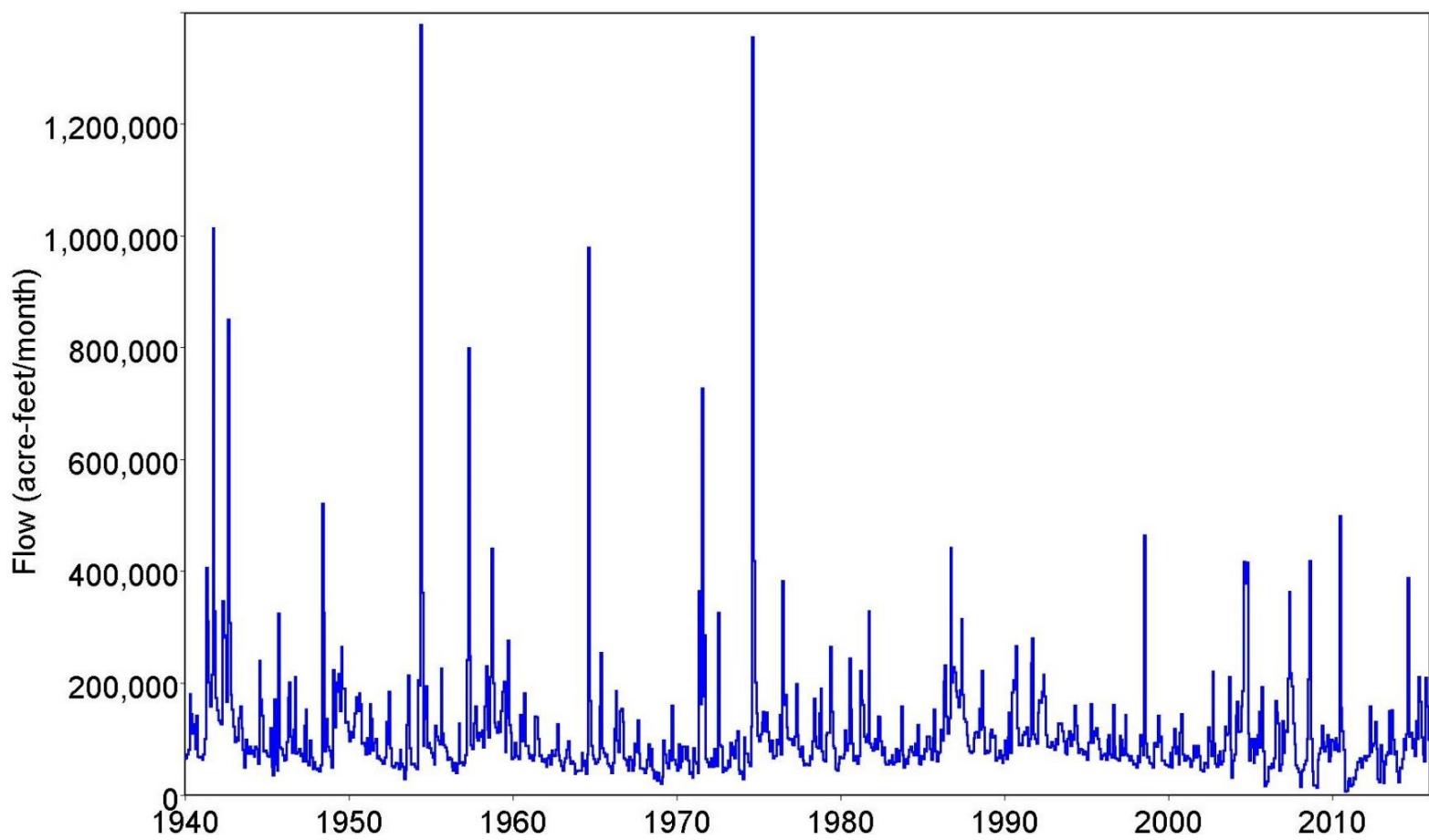


Figure D12. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Laredo DT3000

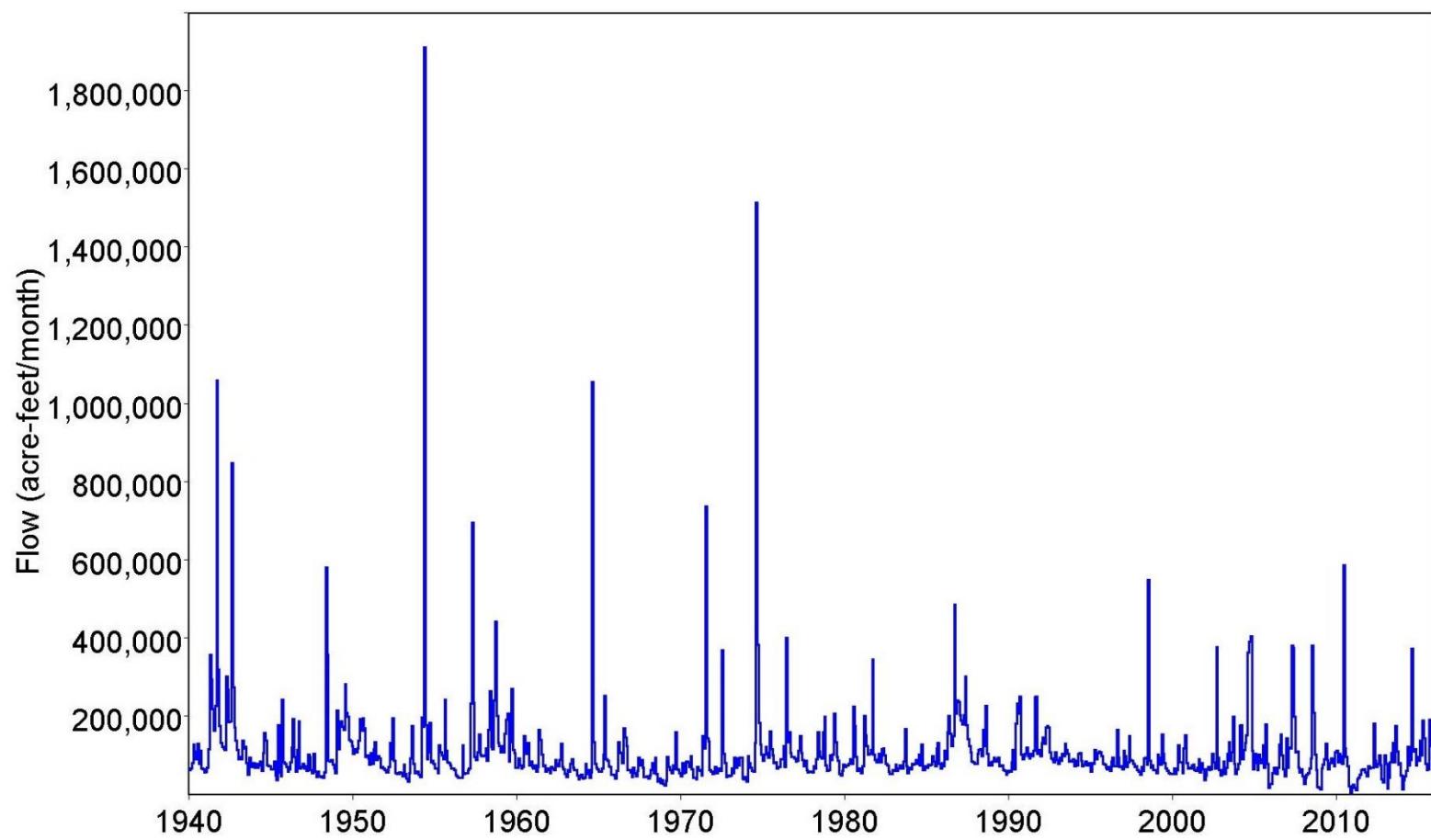


Figure D13. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Piedras Negras DT5000

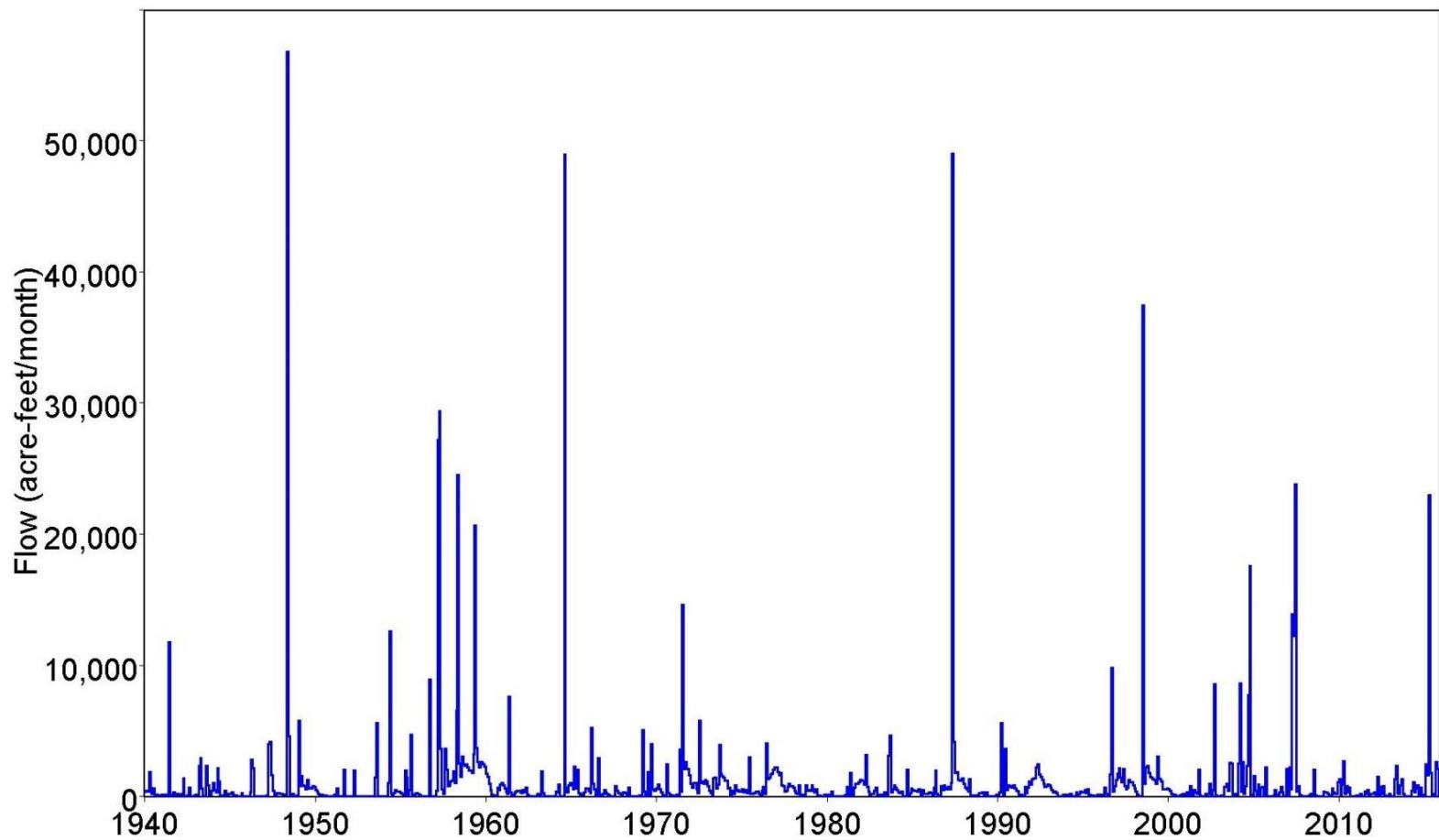


Figure D14. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pinto Creek near Del Rio DT8000

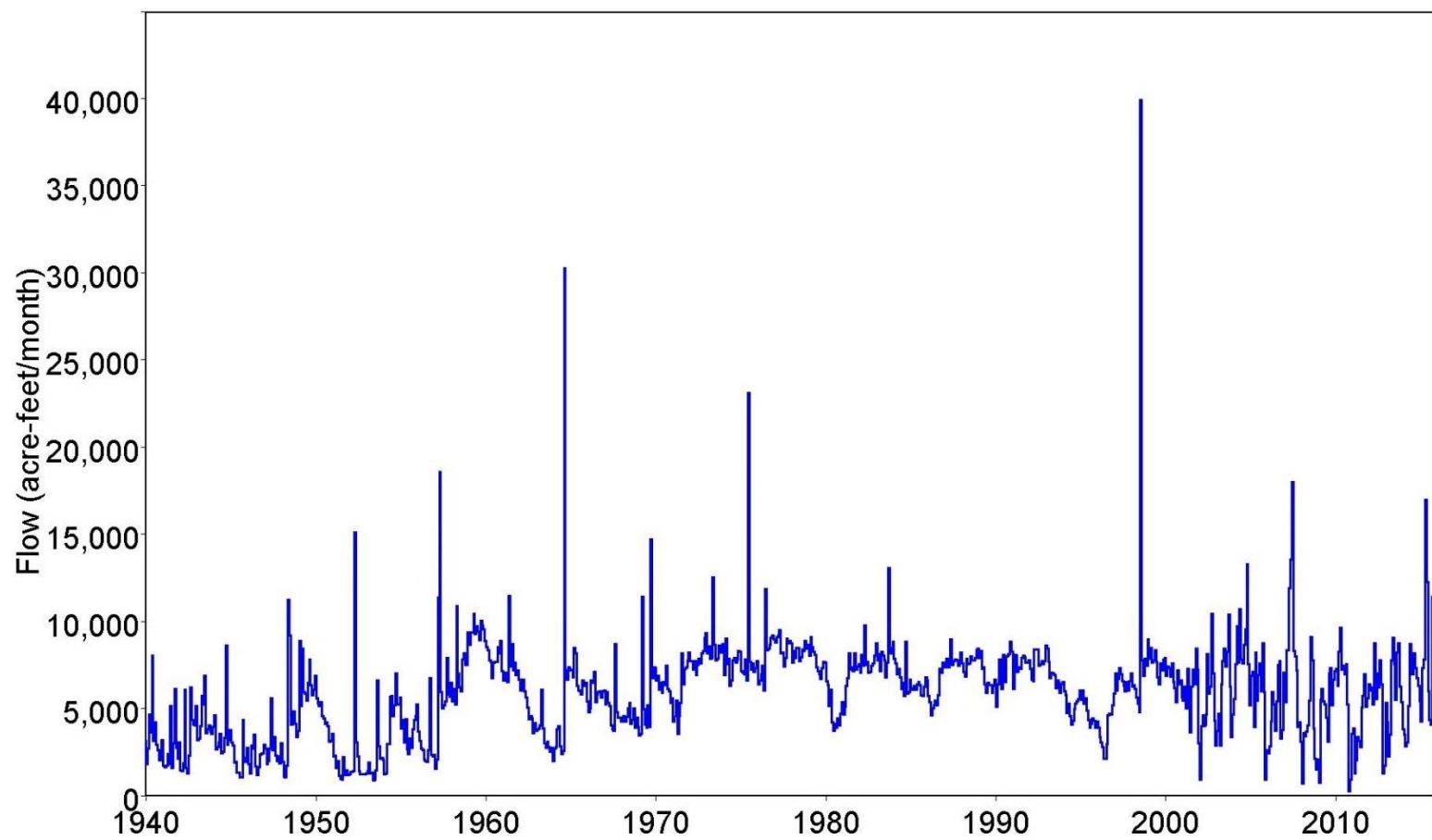


Figure D15. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for San Felipe Creek near Del Rio DT9000

Figure D16. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande below Anzalduas Dam ET1000

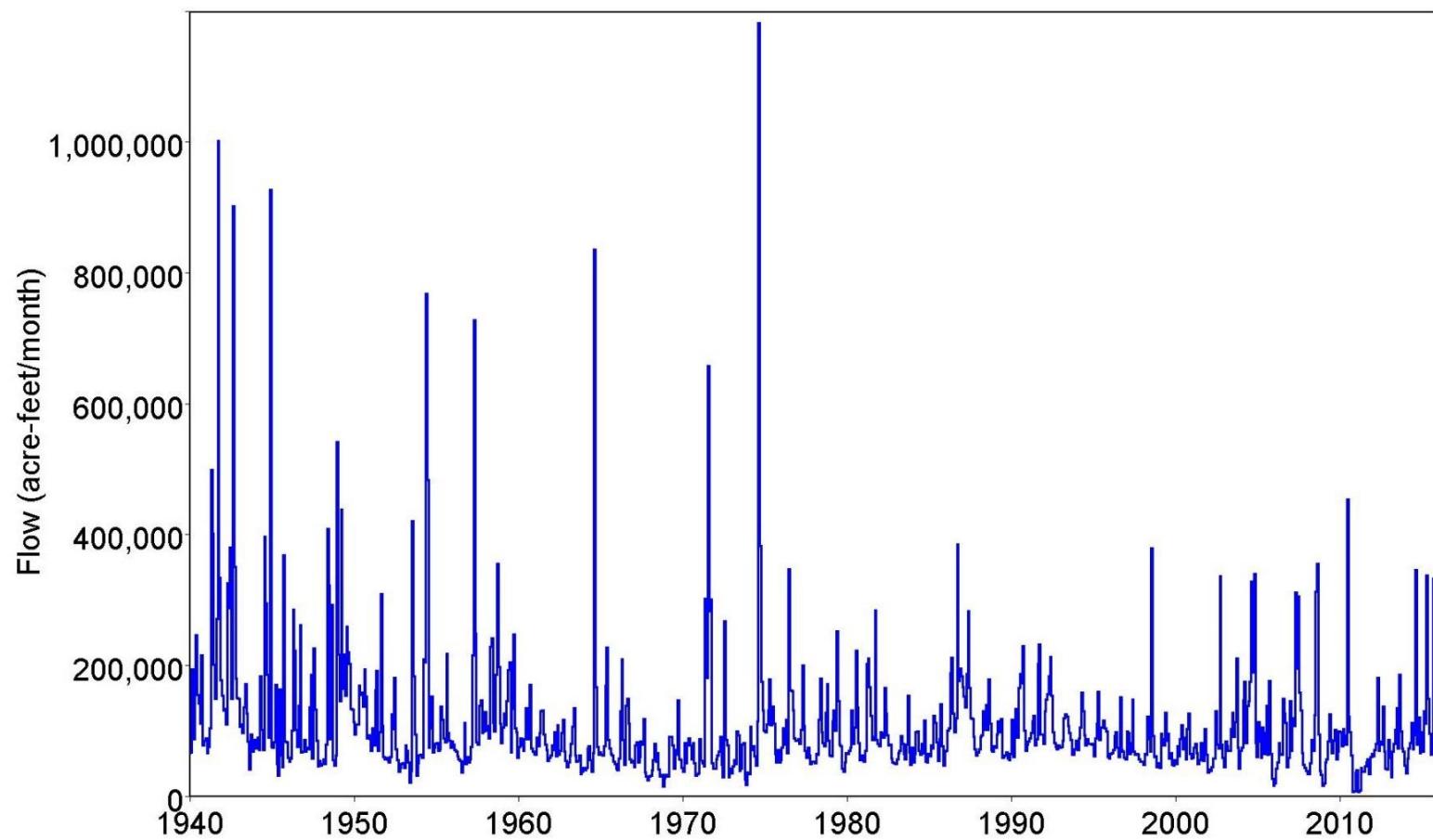


Figure D17. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Rio Grande at Rio Grande City ET2000

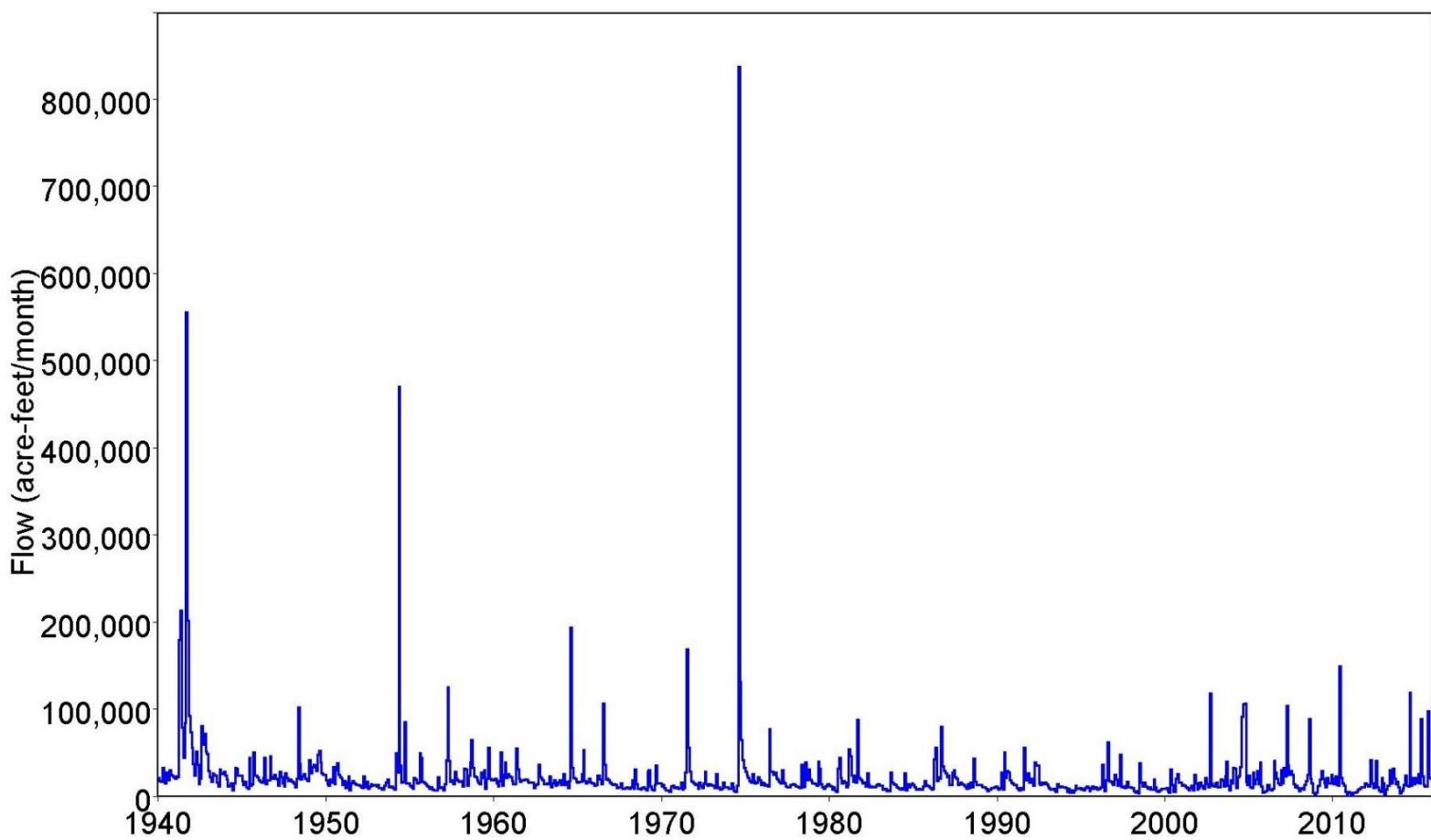


Figure D18. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pecos River near Langtry GT1000

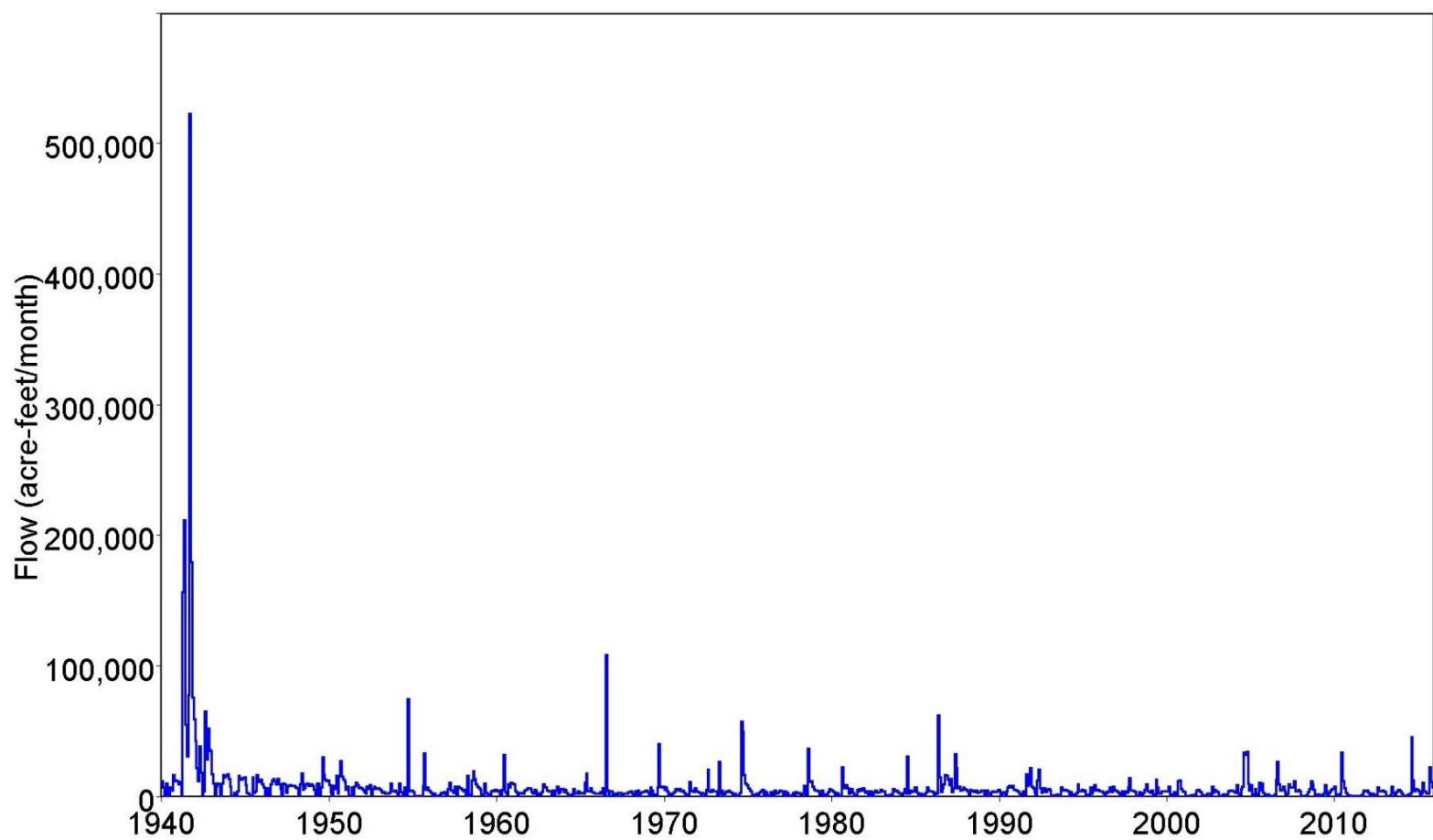


Figure D19. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pecos River near Girvin GT2000

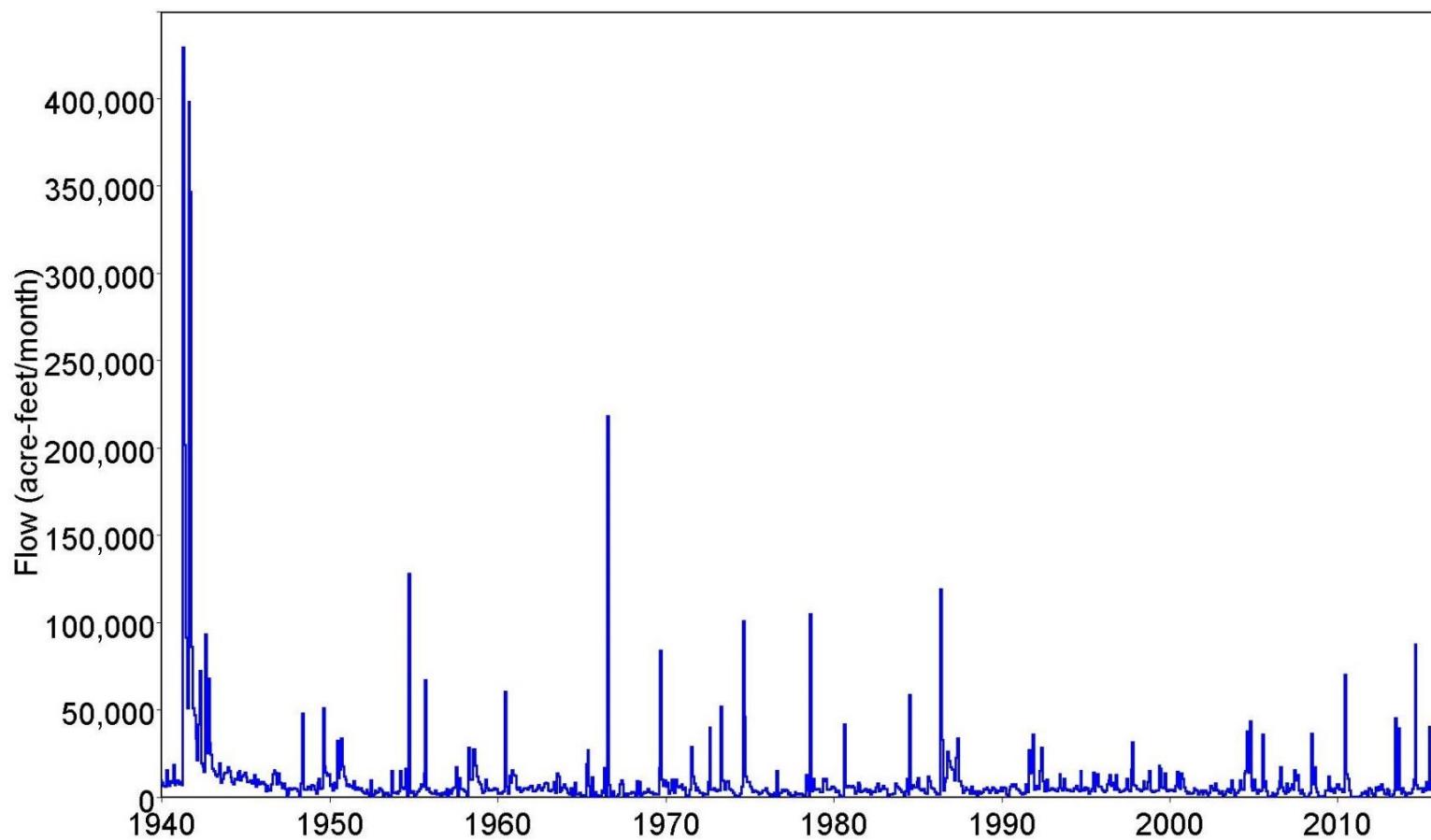


Figure D20. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pecos River near Orla GT3000

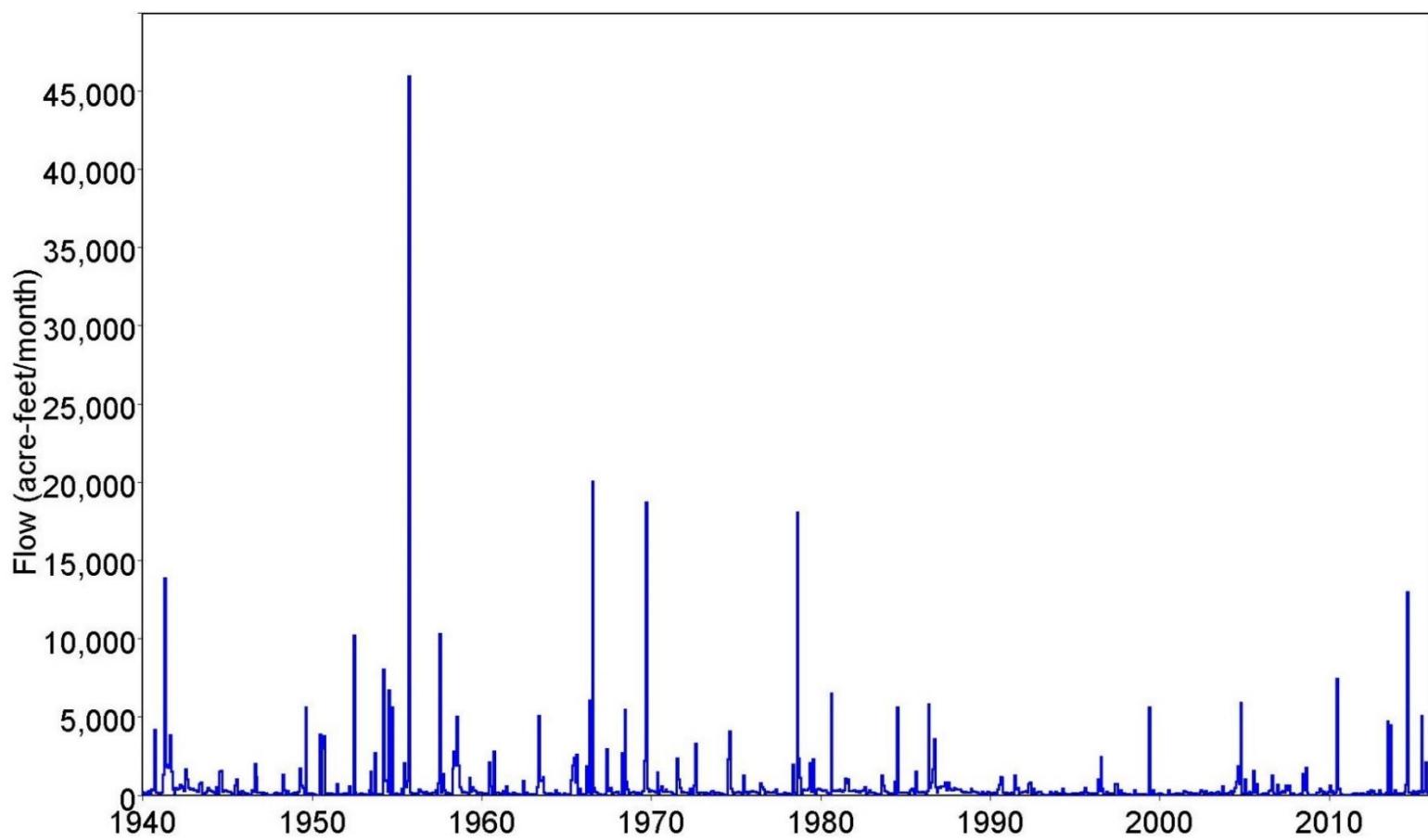


Figure D21. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pecos River near Red Bluff GT4000

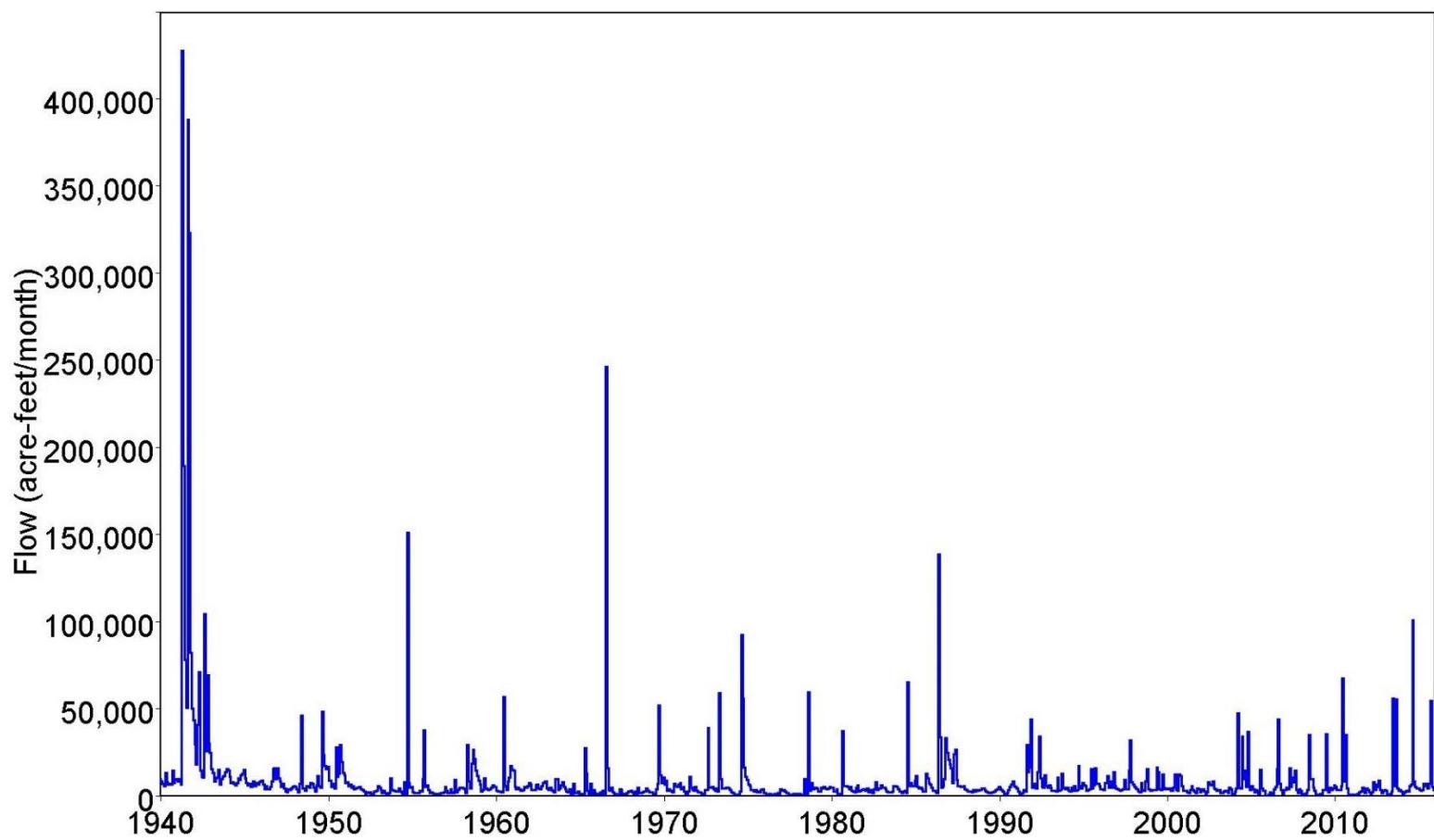


Figure D22. Original 1940-2000 and Extended 2001-2015 Naturalized Flows for Pecos River at Red Bluff GT5000