ASSESSMENT OF FLOOD CONTROL CAPABILITIES FOR ALTERNATIVE RESERVOIR STORAGE ALLOCATIONS

A Thesis

by

MUSTAFA DEMIREL

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Ralph A. Wurbs
Committee Members,	Anthony T. Cahill
	Clyde L. Munster
Head of Department,	Robin Autenrieth

August 2015

Major Subject: Civil Engineering

ABSTRACT

Reservoir operation and storage allocation are important duties for agencies and water management professionals in Texas and elsewhere responsible for supplying water for municipal, industrial, and agricultural uses, hydroelectric power generation, recreation, navigation, and maintenance of instream flow for fish and wildlife, and protecting human lives and properties from flooding. Flood control capabilities for alternative reservoir storage allocations are assessed in the thesis research using the Water Rights Analysis Package (WRAP) with a daily version of the WRAP input dataset for the Trinity River Basin from the Texas Water Availability Modeling (WAM) System expanded to incorporate flood control operations. Tradeoffs between flood control and water supply in multiple-purpose reservoirs are analyzed. A system of eight multiple-purpose reservoirs operated by the United States Army Corps of Engineers (USACE) in the Trinity River Basin serves as a case study for this research.

WRAP/WAM capabilities for simulating reservoir system operations for flood control were tested and improved. Frequency analyses of maximum annual storage levels were performed for both actual observed storage and storage computed by the simulation model for alternative modeling premises and reservoir operating strategies. The frequency analyses focused on determining the probability of exceeding flood control storage capacities. The Hydrologic Engineering Center (HEC) Statistical Software Package (SSP) was used to apply the log-normal and log-Pearson type III probability distribution functions. Various issues in simulating multiple-purpose reservoir systems and performing storage frequency analyses were investigated.

Reallocations of storage capacity in the eight reservoirs from water supply to flood control can be implemented by raising the designated top of conservation pool. Impacts on flood control are evaluated in this study in terms of probability of overtopping the flood control pool. Impacts on water supply are quantified based on changes in reliability metrics.

Alternative nine simulations are performed in WRAP for the eight Trinity River Basin Reservoirs. Three of the nine simulations are reallocation of storage capacities from flood control pool to conservation pool. Storage capacities, flood frequency analyses, and water supply reliabilities are compared and assessed for both actual observed storage capacities and simulation results.

DEDICATION

To my lovely wife, Esra, and our son, Zekeriya

and

To my beloved parents, Nazife and Zekeriya

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Ralph A. Wurbs as my advisor, professor, and advisory committee chair. He always supported, guided and encouraged me to complete this thesis. I would also like to thank to Dr. Cahill and Dr. Munster for accepting to serve as committee members. I appreciate my all professors at Texas A&M University.

I owe great thanks to my wife, Esra, for her support and encouragement. I would also like to thank my family and my friends.

I also want to extend my gratitude to the Republic of Turkey Ministry of National Education and the Republic of Turkey Ministry of Forestry and Water Affairs, which have provided me funding to pursue the Master of Science Degree in the United States.

NOMENCLATURE

BRA	Brazos River Authority
FFA	Flood Frequency Analysis
FSE	Flood Storage Efficiency
GEV	Generalized Extreme Value
HEC	Hydrologic Engineering Center
HEC-SSP	Hydrologic Engineering Center Statistical Software Package
ICOLD	International Commission on Large Dams
MFSE	Marginal Flood Storage Efficiency
TCEQ	Texas Commission on Environmental Quality
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

The research focuses on assessing flood risk mitigation capabilities of reservoir systems with flood control pools controlled by gated outlet structures based on the results of a reservoir/river system simulation model. Flood control capabilities were analyzed within the broader framework of evaluating permanent or seasonal reallocation of storage capacity between flood control and conservation pools in multipurpose reservoirs. However, the research is also relevant to analyses of reservoirs operated solely for flood control. A system of eight multiple-purpose reservoirs in the upper Trinity River Basin owned by the U.S. Army Corps of Engineers (USACE) serves as a case study. These reservoirs are operated to reduce flood damages and supply water for the Dallas and Fort Worth Metropolitan Area.

1.1 Background

Population and economic growth place intensifying demands on limited water sources. Reservoir storage capacity becomes increasingly more important with increasing municipal, agricultural, industrial, and energy needs. According to the Texas Water Development Board (TWDB), the population of Texas will increase 82% from 2010 to 2060 and population of growth will be 25.4 million to 46.3 million people. Growth rates are different across the states, with some areas more than doubling while others increase slightly or not at all. The TWDB (Vaughan et al. 2012) notes that current water sources are expected to decrease 10% from 17.0 to 15.3 acre-feet between 2010 and 2060 respectively. Water needs exceed supplies during severe droughts. On the other hand, floods are another important issue that must be considered. Because of floods, people face difficulties such as losses of properties and lives. Increased impervious areas such as houses, roads, industrial places, increase runoff volume and cause flash floods. Therefore, water management plans and operations should consider both water needs and flood events.

Numerous small flood control and stormwater detention structures with uncontrolled (ungated) outlet structures are found throughout Texas. However, most of the flood control storage capacities in the state are contained in 33 large federal reservoirs which include the multiple-purpose Amistad and Falcon Reservoirs on the Rio Grande operated by the International Boundary and Water Commission, Addicks and Barker Reservoirs in Houston operated by the USACE solely for flood control, and 30 multiple purpose reservoirs in several river basins operated by the USACE for water supply and flood control. The flood control pools of these federal reservoirs are controlled with gated outlet structures following specified operating rules. The thesis research dealt with this type of reservoir/river system operations.

Reservoir operation is based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space available for storing future flood waters to reduce downstream damages (Wurbs 1996). Many reservoirs are operated either for only flood control or for only conservation purposes. Most of the reservoirs in Texas containing flood control capacity controlled by gated outlet structures are also operated for conservation purposes, with separate pools designated for conservation and flood control. The conservation and flood control pools are defined by a designated top of conservation pool elevation, which also serves as the bottom of the flood control pool. Conservation pools may be shared by various purposes, such as municipal and industrial water supply, agricultural irrigation, hydroelectric power, recreation, and maintenance of environmental flow requirements. Converting portions of the large volumes of flood control storage capacity to conservation storage represents a potential strategy for meeting intensified demands for supplying water for human and environmental needs. Storage reallocations consist of permanent or seasonal raising or lowering of designated top of conservation pool elevations.

The Texas Water Availability Modeling (WAM) System consists of the Water Rights Analysis Package (WRAP) simulation model and input datasets for the 23 river basins of Texas (Wurbs 2005). The WRAP/WAM System has been applied in Texas since about 2000 to support regional and statewide planning and water allocation activities focused on water supply for municipal, industrial, agricultural, and environmental needs. The WAM System is based on a monthly time step. Daily WRAP/WAM capabilities have recently been developed that include flow forecasting and routing, simulation of environmental high pulse flow requirements, and simulation of reservoir flood control operations (Wurbs and Hoffpauir 2013).

The WRAP modeling system with a daily version of the WAM system dataset for the Trinity River Basin was applied in the thesis research to evaluate flood control capabilities and the effects of storage reallocations on flood control capabilities of eight multiple-purpose USACE reservoirs. WRAP/WAM simulation and flood control storage frequency analysis capabilities are applied in the research to assess reallocations between flood control and conservation purposes. Water supply capabilities for alternative storage allocations were quantified in the study using conventional WRAP/WAM reliability metrics. The research was particularly concerned with investigating and improving capabilities for evaluating the risk of exceeding flood control capacity associated with alternative storage allocations.

1.2 Dams and Reservoirs in the USA

Tremendous variability in precipitation, seasonal and annual fluctuations in stream flows, long duration droughts, and severe floods are major problems in water management. Reservoirs are essential to regulate streamflow fluctuations, develop reliable water supplies, decrease flood damages, and maintain instream flow requirements (Wurbs and James 2002). Dams, outlet structures, channel improvements canals, pipelines, pumping plants, hydraulic power plants, recreation facilities, fish ladders and various other structures constitute reservoir projects.

Numerous reservoir projects were constructed during the period from 1900 through the 1970s (Wurbs 1996). These projects are operated by the United States Army Corps of Engineers (USACE), United States Bureau of Reclamation (USBR), state and regional agencies, water districts, cities, private industries and other agencies. After the 1970s, optimization of the operation of existing reservoirs became more important than before. Public needs and objectives and many other factors subject to change impact reservoir operations.

Throughout the United States, numerous dam and reservoir projects regulate stream flows by storing water from small creeks to major rivers as shown in Table 1. Many of them not only store water for beneficial use but also prevent flooding by holding water in flood control pools. Lake Mead and Lake Powel, located on the Colorado River, are the largest reservoirs in the nation, owned by the USBR. Oahe, Fort Peck, and Sakakawea Reservoirs, located on the Missouri River, owned by the USACE are the 3nd, 4th, and 5th largest in terms of total storage capacity (Wurbs 1996). In terms of power capacity, Grand Coulee (6180 megawatts), John Day (2160 megawatts), Chief Joseph (2069 megawatts) Dams, constructed on the Columbia River are the largest hydroelectric power projects on the Unites States.

Table 1. Reservoirs in the United States by ranges of storage capacity

Storage Capacity Range (acre-feet)	Number Of Reservoirs	Storage	
		(acre-feet)	(10^9 m^3)
Greater than 10,000,000	5	107,655,000	133
100,000-10,000,000	569	322,852,000	398
50,000-100,000	295	20,557,000	25
25,000-50,000	374	13,092,000	16
5,000-25,000	1411	15,092,000	19
Total	2654	479,788,000	592

Source: (Wurbs 1996)

1.2.1 United States Bureau of Reclamation (USBR) Reservoirs

The United States Bureau of Reclamation was founded in order to develop water projects needed to support and help economic growth in the arid western United States

(Wurbs 1996). As shown in Figure 1, 17 western states, divided into the 5 regions, have USBR projects. These projects include dams, dikes, channels, tunnels, pipelines, pumping plants, as well as hydroelectric power for various purposes.

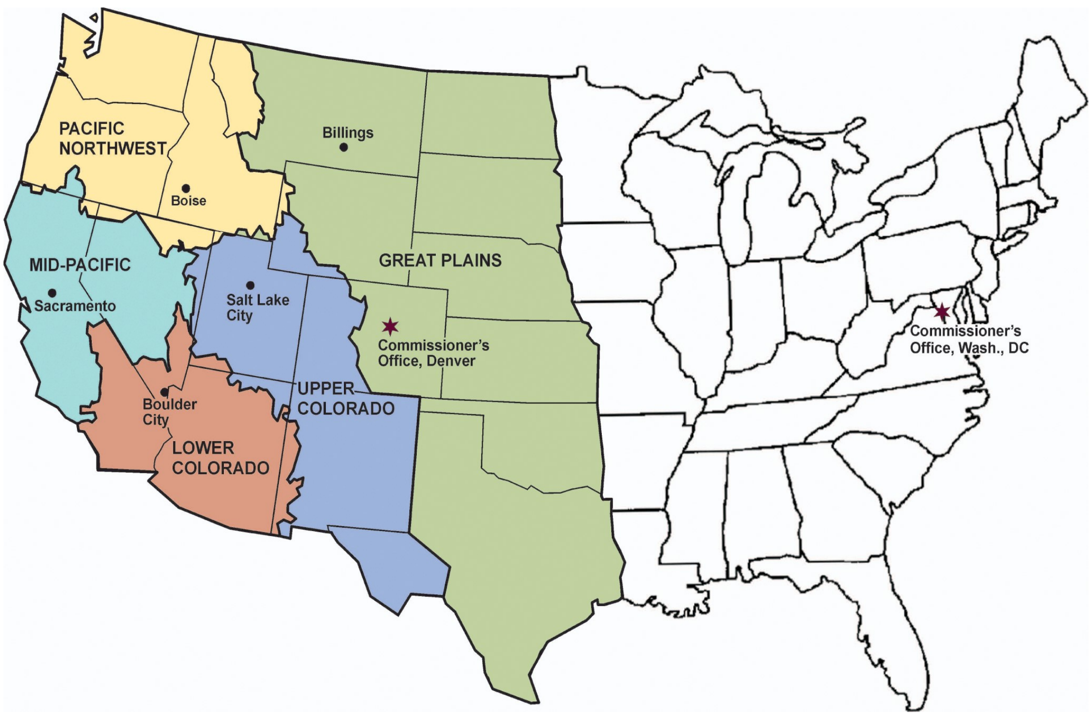

Figure 1. Bureau of Reclamation Region (USBR 2014)

Throughout the nation, USBR involves 343 reservoir projects but some of them are turned over to local irrigation, water districts or other entities for operation, which leaves only 130 of them operated by the USBR. Most of these projects were constructed for multi-purposes; however, the main purpose is irrigation. 28% of them are for irrigation purposes.

1.2.2 United States Army Corps of Engineers (USACE) Reservoirs

The United States Army Corps of Engineers (USACE) is one of the largest and oldest water management agency in the nation (Wurbs 1996). The main purpose of the agency has been to improve the nation`s rivers and harbors, flood control and navigation since 1800s. The USACE`s work programs include planning, design, construction, operation, maintenance, water management and regulatory functions. The 516 USACE reservoirs, as shown in Table 2, have 272,100 million m^3 total storage capacity. About 117,100 million m^3 (43%) of storage capacity was specifically designed for flood control. 151,600 million m^3 (56%) storage capacity is for multi-purpose usage. The remaining 1.1% and 0.2% storage capacities were only designed for navigation and hydroelectric power respectively. The 330 reservoirs were solely designed for flood control purposes.

Table 2. Storage capacity of the USACE reservoirs

Storage Allocation	Number of Reservoirs	Storage Capacity	
		(million m^3)	(acre-feet)
Exclusive flood control	330	117,100	94,950,000
Exclusive navigation	135	2,900	2,354,000
Exclusive hydropower	5	475	385,000
Multi-purpose use	385	151,600	122,926,000
Total storage in 516 reservoirs		272,100	220,615,000

Source: (Wurbs 1996)

The 237 reservoirs (46%) of the 516 reservoirs were constructed during the 1950s and 1960s. These reservoirs` storage capacity constitutes 69% of the 516 USACE reservoirs. Construction of the USACE dams decreased after the 1960s. Table 3 provides detailed information about construction dates.

Table 3. USACE and USBR reservoirs completion dates in the US

Construction Decade	USACE		USBR	
	Reservoirs	Percent (%)	Reservoirs	Percent (%)
Before 1900	9	1.7	1	0.3
1900-1909	3	0.6	6	1.8
1910-1919	3	0.6	30	9
1920-1929	8	1.6	20	6
1930-1939	67	13	35	10.5
1940-1949	58	11.2	31	9.3
1950-1959	88	17.1	82	24.7
1960-1969	149	28.9	74	22.3
1970-1979	96	18.6	32	9.6
1980-1989	35	6.8	18	5.4
After 1989	-	-	3	0.9
Total	516	100	332	100

Source**:** (Wurbs 1996)

1.2.3 Reservoirs in Texas

Reservoirs in Texas are owned and operated by variety of entities (Wurbs 1987). Texas has 6000 reservoirs with surface areas greater than 10 acres; however, as shown in Table 4, 189 of them constitute 95% of total storage capacity (Wurbs 1996). Total conservation and flood control storage capacity are 49,450 and 22,880 million m^3 respectively. As shown in Figure 2, the three largest reservoirs of Texas, located at its borders with Louisiana, Oklahoma, and Mexico have been operated by interstate compacts and the International Boundary and Water Commission. Toledo Bend Reservoir on the Sabine River, which has 4,477,000 acre-feet conservation pool, is the largest conservation pool capacity in the southern United States. In terms of total storage capacity, Lake Texoma, owned by the USACE, on the Red River is the largest reservoir in Texas; capacities of the conservation and flood control pools are 2,772,000 and 2,660,000 acre-feet respectively. One of the largest total controlled storage capacities is Amistad Reservoir, owned by the International Boundary and Water Commission, on the Red River that has 4320 and 2150 million m^3 conservation and flood control storage capacities respectively.

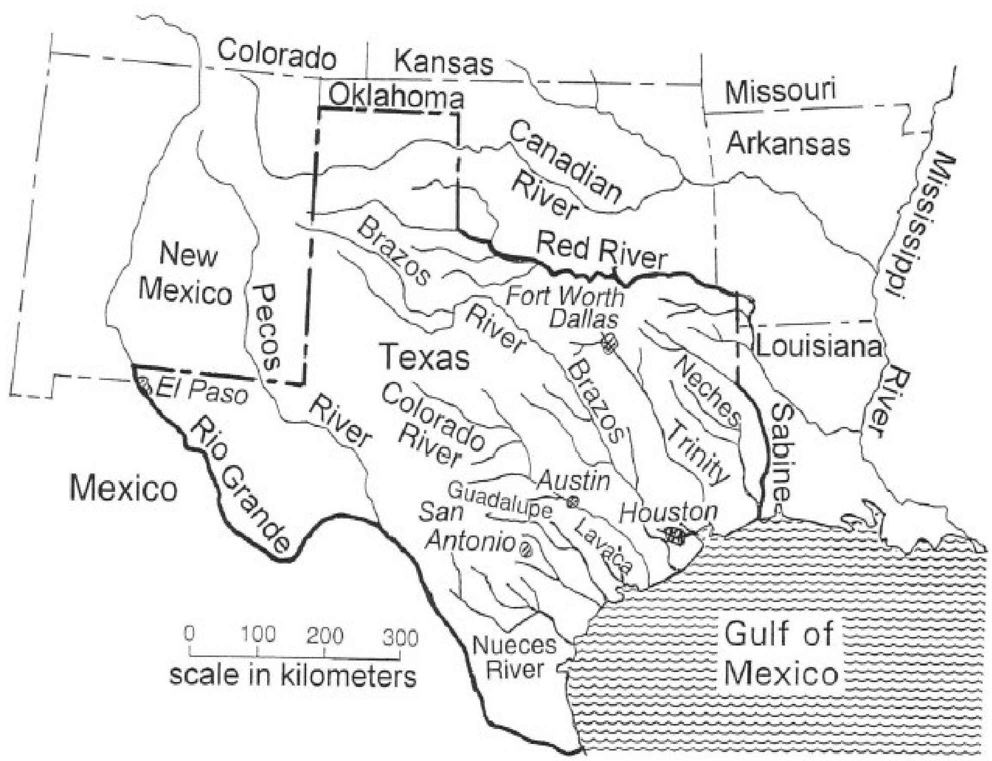

Figure 2. Major rivers in Texas (Wurbs 2013b)

Table 4. In terms of storage capacity, reservoirs in Texas

Storage Capacity Range (acre-feet)	Number of Reservoirs
>5,000,000	2
2,000,000-5,000,000	4
1,000,000-2,000,000	7
500,000-1,000,000	15
100,000-500,000	39
50,000-100,000	12
5,000-50,000	110
Total	189

Source: (Wurbs 1996)

1.3 Scope and Objectives

The research focused on evaluating and improving capabilities for modeling flood control reservoir operations and quantifying the risk of exceeding flood control storage capacities. However, flood control operations were addressed in the research within the framework of comprehensive multiple-purpose reservoir/river system operations. The research was concerned with both reservoir/river system management and modeling/analysis thereof. The objectives of the research were to:

1. Investigate and improve WRAP/WAM capabilities for simulating reservoir system operations for flood control.
2. Investigate frequency analysis capabilities for analyzing the risk of exceeding flood control storage capacities based on observed storage in eight reservoirs in the Trinity River Basin.

3. Investigate frequency analysis capabilities for analyzing the risk of exceeding flood control storage capacities based on the results of a WRAP/WAM simulation.
4. Formulate and apply methodologies for modeling and analysis of storage reallocation plans that provide meaningful quantitative information for assessing tradeoffs between flood control and conservation purposes.
5. Assess the potential of permanent or seasonal storage reallocations between flood control and conservation purposes as a strategy for enhancing the operations of reservoirs in the Trinity River Basin and elsewhere.
6. Assess the effects of flood control storage on water supply reliability and environmental flows and the effects of conservation storage operations on flood control capabilities.

1.4 Literature Review

A number of studies reported in the literature deal with modeling reservoir storage reallocations and other operational modifications, flood frequency analysis, reservoir storage analysis, long-term and short-term storage frequency analyses, failure of dams, and effects of climate change on flood analysis. Also, many studies were performed to assess causes of flood events, while other studies evaluated the results of flood events. According to the International Commission on Large Dams (ICOLD 1973), about 35% of all earth dam failures are caused by overtopping, while the rest of failure are caused by seepage, piping and other causes. Generally, failure of dams are triggered by flood events, which may possibly be accompanied by strong winds (Hsu et al. 2010). Several studies related to storage reallocation and analysis of risk of overtopping flood control storage capacities are cited as follows.

1.4.1 Reservoir Operations and Storage Reallocations

Wurbs and Carriere evaluated storage reallocation strategies in conjunction with optimizing reservoir system operations in Texas (Wurbs and Carriere 1988). They modeled permanent and seasonal reallocation plans and other related modifications. Twelve reservoirs in the Brazos River Basin owned by the USACE served as a case study. The HEC-3 and HEC-5 software packages were used to simulate an 85-year period-of-record sequence of monthly streamflows. System firm yield for the 12-reservoir system was found to be much greater than the summation of individual reservoir firm yield. Moreover, they found that after reallocating the storage capacity of flood control pool to the conservation pool, firm yield was significantly increased. However, because of diminished flood control storage capacity, the risk of exceeding flood control capacity significantly increased during an extreme flood event.

Kim reports another study related to modeling reallocation of storage capacity between flood control pool and conservation pool that was previously performed at Texas A&M University (Kim 2009). The system of 12 reservoirs in the Brazos River Basin with storage reallocations involving tradeoffs between flood control and conservation purposes was simulated with the WRAP/WAM system (Kim 2009). This research also includes the conversion from a monthly to daily time step.

Hui and Lund performed a flood control storage allocation study examining flood hydrograph effects on flood operation for parallel reservoirs (Hui and Lund 2014).

Oroville Reservoir and New Bullards Bar Reservoir in the Sacramento River Basin of California served as a case study. These reservoirs were built for multiple purposes. An uncertain storm and single flood data from 1977 were analyzed in the case study. They found that, for flood management, parallel reservoirs should be managed together in order to protect downstream from flood damages. Allocation of flood control pool storage capacity for parallel reservoirs minimizes peak inflows which are affected by hydrograph shape and timing, channel capacity, characteristics of damages, as well as flood duration. They defined two terms for their study; Flood Storage Efficiency (FSE) is reduction of peak flow per unit flood storage volume and Marginal Flood Storage Efficiency (MFSE) is the derivative of FSE which represents changes of peak flow reduction. For parallel reservoirs, the ideal allocation of total flood control storage capacity should have the same MFSEs. The main purpose of the study is minimizing damage of downstream caused by maximum flow by determining ideal allocation of flood control storage capacity for parallel reservoirs. In order to achieve this goal the worst case should be considered.

1.4.2 Flood Frequency Analysis and Risk of Overtopping

Dam overtopping probability induced by flood and wind was evaluated in Taiwan (Hsu et al. 2010). Their study constitutes a probability-based methodology to assess dam overtopping probability which has uncertainties from wind speed and peak flow. Their study based on maximum monthly and annual basis to calculate probability of overtopping. As a case study, they used Shihmen Dam on the Dahan River in Taiwan and they tested Log-normal, Pearson type III, Log-Pearson type III, Weibull and Gumbel distribution for 3-day average flow. However, they found that Gumbel, Log-normal, and

Log-Pearson type III which have better fit than others. They also found that maximum monthly flood data series are higher than annual maximum flood data except Gumbel distribution, because its right-end tail probability is much smaller than the other two. Furthermore, wind has crucial impact on overtopping probability that is 113-119% greater than the case without considering wind effect. Moreover, in Shihmen reservoir on the Tahan River, Lee and You evaluated long-term overtopping and optimal termination time of the dam under climate change (Lee and You 2013). They developed a methodology to assess cause of sedimentation and hydrological condition and their impacts on dam failure, and in the meantime benefit-cost evaluation was done. They determined that the major source of risk is extreme hydrological condition while reservoir sedimentation is not very strong in most cases.

Burn and Goel made a study on flood frequency analysis for the Red River at Winnipeg (Burn and Goel 2001). Their study started after the spring of 1997 flood at parts of southern Manitoba, North Dakota, and Minnesota. There are also some historical records for floods from 1826, 1852, 1861, 1950, 1979, 1996, and 1997. Their goal was to determine return period of extreme flood events and quantify the uncertainty associated with flood quantile estimates on the Red River. Their first step was to evaluate flood series for nonstationarity by using Consolidated Frequency Analysis package. The second step was conducting a standard frequency analysis on the available data which includes 1826, 1852, 1861 as flood events and the Rannie data. The last step was to examine impact of any dependencies on the extreme flow estimates by using a noise model (Booy and Lye 1989). The result of statistical tests, which are the Spearman and Mann-Whitney tests, indicated that nonstationarity flood occurs. As a second step, estimation of flood quantiles was done with three set of data which were recorded data (systematic gauged record) from 1875 to1998 included 11 flood events, the Rannie Data (excluded the 11 flood data), and recorded data from 1875 to1998. These data were plotted in a box plot as a final step of the study data generation approach to create likely data. 5000 sets of data were created with lengths of 115 years. The mixed noise model generated normally distributed data which should be transformed to generalized extreme value (GEV) and log-Pearson III distribution. In this study, GEV fitted better than log-Pearson III distribution. In the last step, generated data gave larger mean and standard deviation than gauging record. As a conclusion of this study, they suggested that expected flood magnitude has uncertainty. These researches were inadequate to make a decision about new flood control infrastructure, so this issue required further study.

Another study related to risk analysis for dam overtopping was completed by Kuo et al (Kuo et al. 2007). Risk and uncertainty analysis were performed in this study with three major steps: identifying and evaluating important factors such as reservoir routing and overtopping; data collection and analysis for reservoir routing and uncertainty analysis; evaluating uncertainty and risk analysis. Annual maximum peak discharge data were used to analyze five flood events of Feitsui Reservoir in northern Taiwan. They performed five uncertainty analysis methods which are Rosenblueth`s point estimation method, Harr`s point estimation method, Monte Carlo Simulation, Latin hypercube sampling, and mean-value first-order second-moment method. In order to perform FFA, 70-year annual peak discharges were used from 1912 to 1981. Log-normal, Pearson Type

III, Log-Pearson Type III and Gumbel distribution were tested and it was determined that Gumbel distribution fits better than others. As a result of their study, they found that different methods of uncertainty analyses gave basically similar results for flood return period and overtopping risk. However, mean-value first-order second-moment overtopping risk was higher than those computed other methods. They assumed that the cause of the differences might be due to its inability to perform well for a nonlinear model.

1.5 Water Availability Modelling (WAM)

1.5.1 Texas Commission on Environmental Quality (TCEQ) WAM Datasets

The WAM System maintained by the Texas Commission on Environmental Quality (TCEQ) consists of the WRAP modeling system and datasets containing hydrology and water rights input files for all of the river basins of Texas. WAM datasets are available for each of the river basins delineated in Figure 3 (Wurbs 2005). The TCEQ as lead agency, Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), and their contractors consisting of two universities and ten consulting engineering firms originally implemented the WAM system during 1997-2002. WRAP and the WAM System continue to be expanded and updated.

The TCEQ WAM System supports regional and statewide planning, administration of water rights permit system with over 6000 active permits, and other water management activities. The WAM datasets include about 3,400 reservoirs, but most of the storage capacity is contained in the 200 largest reservoirs.

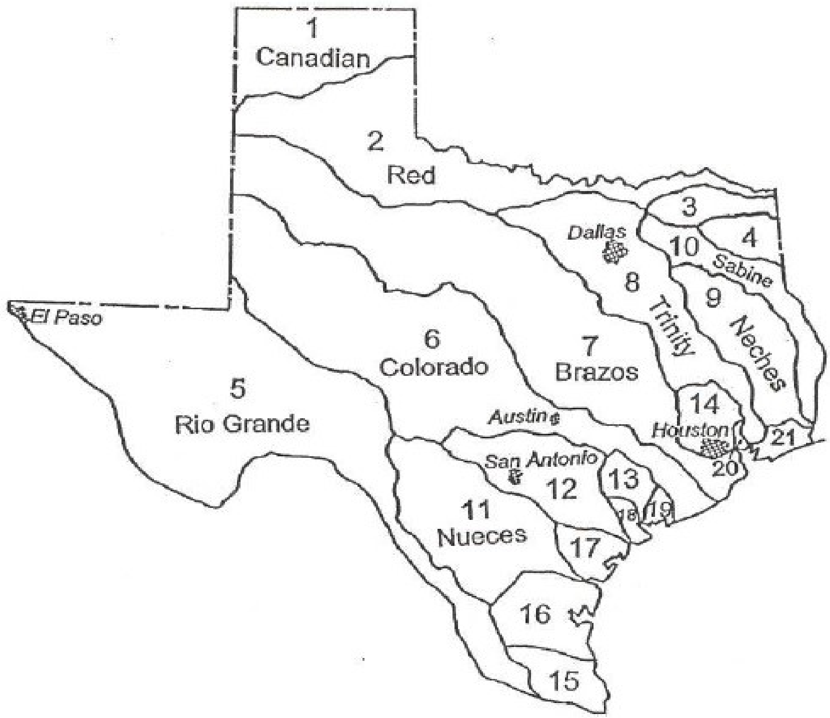

Figure 3. Texas WAM System river basins

1.5.2 Water Rights Analysis Package (WRAP)

The WRAP modeling system simulates water development, management, regulation, and use in a river basin or multiple-basin region under a priority-based water allocation system. The generalized model is designed for assessing hydrologic and institutional water availability and reliability for water supply diversions, environmental instream flows, hydroelectric energy generation, and reservoir storage. The original WRAP/WAM system is based on a monthly computational time step. A daily version of the modeling system was recently developed with capabilities for simulating reservoir flood control operations. WRAP is documented in detail by a set of manuals (Wurbs 2013a; Wurbs 2013b; Wurbs 2013c; Wurbs and Hoffpauir 2013).

A simulation study of WRAP includes evaluating capabilities to meet specified water management and also uses requirements during historical hydrology`s hypothetical repetition. The overall modelling process involves the flowing tasks:

1. Monthly naturalized flow sequences which cover the hydrologic period of analysis at chosen gauging stations are developed.
2. Naturalized flows are distributed from gauged to appropriate ungauged locations.
3. The simulation of the water management system is executed, with water being allocated in priority order to each water right.
4. Simulation results are organized and water supply reliability flow, storage frequency relationships and indices and also other summary statistics are calculated.

Task 1 has been completed for all of the river basins in the state for monthly datasets. Daily datasets are currently being developed for selected river basins. Tasks 2 and 3 occur each time when WRAP SIM is executed. Task 4 consists of various post-simulation analyses of simulation results including reliability and frequency analyses.

An expanded version of WRAP allows use of a daily time step and provides additional features for simulating flood control reservoir operations and environmental instream flow requirements. Future time steps extending over a forecast period are considered in the simulation model in determining both water availability from a supply perspective and remaining flood control channel capacity (Wurbs and Hoffpauir 2013). Calibration methods for determining routing parameters are included in the WRAP package.

Both gated and ungated outlet structures can be included in the WRAP simulation of flood control reservoirs. Operation of reservoirs with gated outlets may consider multiple reservoir system operations. Uncontrolled (ungated) storage pools are always operated individually. The WRAP simulation model includes features for modeling multiple-purpose, multiple-reservoir system operations. Flood control operations are based on minimizing the risk of flooding at downstream locations. Operation rules are based on emptying flood control pool expeditiously while making sure that water does not exceed flood flow limit at downstream control points. Reservoir operations are based on flow limits at downstream locations as long as flood control capacity is not exceeded (Wurbs and Hoffpauir 2013). When the water storage level at a reservoir exceeds the top of flood control pool, emergency releases are made as necessary to prevent dam overtopping and downstream flooding may occur.

Post-simulation analysis capabilities include frequency analyses of annual peak naturalized flow, regulated flow, and reservoir storage volumes that may be performed based on the log-normal or log-Pearson type III probability distributions. Storage can be combined with spills from a full flood control pool.

1.6 Research Methodology

The research explored and improved capabilities for incorporating flood control operations in WRAP/WAM simulations, evaluating flood control capabilities, and evaluating tradeoffs between flood control and conservation purposes for alternative storage reallocations. The simulation study of the Trinity River Basin provided an enhanced understanding of flood control and multiple-purpose water management. The simulation study addressed the following issues: flood control capabilities, effects of conservation pool on the flood control operation, effects of flood control operations on water supply, effects of water supply operations on flood control, and tradeoffs associated with storage reallocations and other modifications in operating procedures.

The literature review presented in the thesis covers the following topics: multiple-purpose reservoir system operations, flood control operations, storage reallocation and related operational modifications, simulation of reservoir system operations, flood risk analysis methods, and statistical and probability analysis methods applied reservoir storage. Information regarding water management and reservoir operations in the Trinity River Basin was obtained from publications websites, and other materials available from USACE, TCEQ, and TWDB.

The system of eight reservoirs in the Trinity River Basin served as a case study. Research findings provide an enhanced understanding of reservoir system operations and associated modeling and analysis capabilities that also relevant to similar reservoir systems in other river basins in Texas and elsewhere.

The recently developed daily WRAP modeling system was applied with a recently developed daily version of the Trinity River Basin dataset from the TCEQ WAM System. The new WRAP capabilities for simulating flood control operations were tested and refined. The daily WAM dataset for the Trinity River Basin was tested and improved.

The WRAP/WAM simulation model combines specified conditions of water resources development and management with historical natural hydrology. The simulation study was based on a 1940-2012 hydrologic period-of-analysis. Simulated stream flows and storage levels were analyzed to develop an understanding of flood characteristics and the effects of flood control system operations on flood flows. The sensitivity of stream flows and storage contents to various aspects of system operations were explored in the simulation study.

Historically observed storage levels in the eight reservoirs were analyzed. Comparisons between observed and simulated storage levels contributed to analyses of the validity of the simulation model and the post-simulation storage frequency analyses.

The annual exceedance probability for overtopping controlled flood control pool storage capacities were adopted as the primarily metric for assessing flood control capabilities. Other possible metrics for quantifying flood control capabilities also were investigated. Relative advantages of alternative probability distributions and frequency analysis methods were explored.

The HEC-SSP Statistical Software Package (HEC 2010) available from the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers was used to perform frequency analyses based on the log-normal and log-Pearson type III probability distributions. Conventional water supply reliability, flow frequency, and storage frequency analysis methods incorporated in the WRAP software were applied in evaluating alternative storage reallocation plans and other revisions to reservoir system operating procedures.

CHAPTER II

TRINITY RIVER BASIN AND RESERVOIR OPERATION

2.1 Overview of Trinity River Basin

The Trinity River Basin extends 400 miles across Texas from north of the Dallas-Fort Worth metropolitan area to Galveston Bay, east of the city of Houston, as shown in Figures 2 and 3. Average annual rainfall ranges from 53 inches near Galveston Bay to 29 inches in the northwestern extreme of the upper basin (Hoffpauir et al., unpublished report., 2014). The Trinity River basin`s area is approximately 18,000 square miles. Major tributaries of the Trinity River are West Fork, Elm Fork, Cedar Creek, East Fork, Richland Creek, and Chamber Creek. Figure 4 shows Trinity River Basin`s tributaries, and reservoirs as well as cities where a river basin is located.

The Trinity River Authority, Tarrant Regional Water District, North Texas Municipal Water District, Dallas Water Utilities, and several other cities have contracted with USACE for the conservation storage capacity of the eight USACE reservoirs adopted as the case study for the thesis research project. Several of these nonfederal agencies own their own reservoirs, as well as contracting for storage capacity in federal reservoirs. The conservation storage capacity is used primarily for municipal and industrial water supply. Recreation is popular at all eight federal reservoirs and most of the nonfederal reservoirs in the Trinity River Basin.

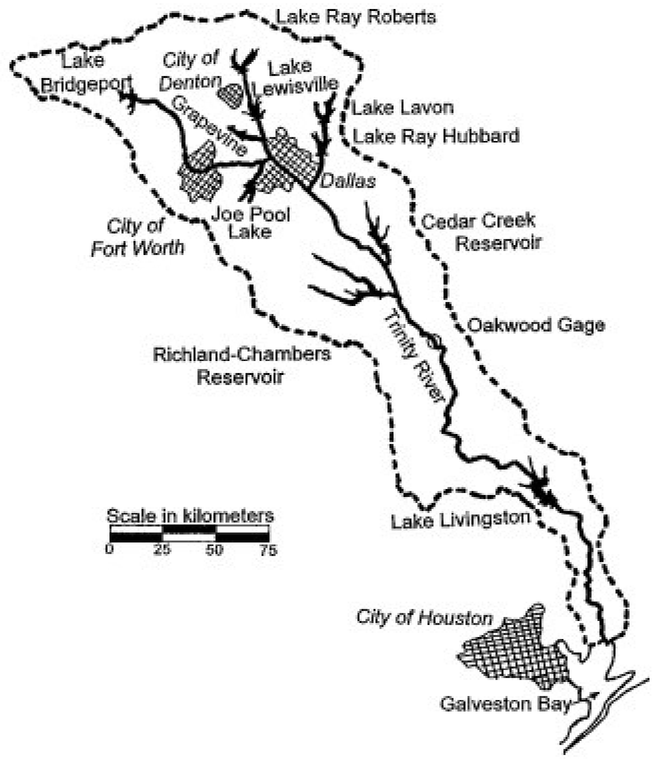

Figure 4. Trinity River Basin

A system of eight reservoirs owned and operated by USACE Fort Worth District served as a case study for the thesis research project. These are the only federally owned and only controlled (gated outlets) flood control reservoirs in the Trinity River Basin. All eight are located in the upper basin in or near the Dallas and Fort Worth Metropolitan Area. The USACE operates the flood control pools. Nonfederal sponsors have contracted for the conservation pool storage capacity. The following information describing each of the eight multiple-purpose reservoirs is gathered from the USACE Fort Worth District website and a Texas Water Development Board (TWDB) Report (Dowel and Petty 1973).

The TWDB also maintains a website with information regarding about 200 major reservoirs in Texas.

2.2 The Eight USACE Reservoirs in the Trinity River Basin

2.2.1 Benbrook Reservoir

Location of the Benbrook Dam is 15.0 river mile on Clear Fork of Trinity River, 10 miles southwest of Fort Worth, in Tarrant County near the City of Benbrook. Drainage area of the reservoir is 429 square miles and correspondingly one inch runoff is 22,880 acre-feet. The construction of the dam started on May, 27 1947 and completed in Dec 1950. Deliberate impoundment began on Sept, 29 1952. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 9130, 130, and 20 feet respectively. Table 5 demonstrates technical features and Figure 5 shows daily observed storage elevation of Benbrook Dam.

Table 5. Technical features of the Benbrook Dam

Features	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway& Notch Cap. (cfs)
Top of Dam	747			
Max. Design Water Surface	741	410,000		172,000
Spillway Crest	724	258,600	170,350	17,000
Top of Flood Control pool	710	164,800	76,550	
Top of Conservation Pool	694	88,250	72,500	
Sediment Reserve			15,750	
Streambed	617			

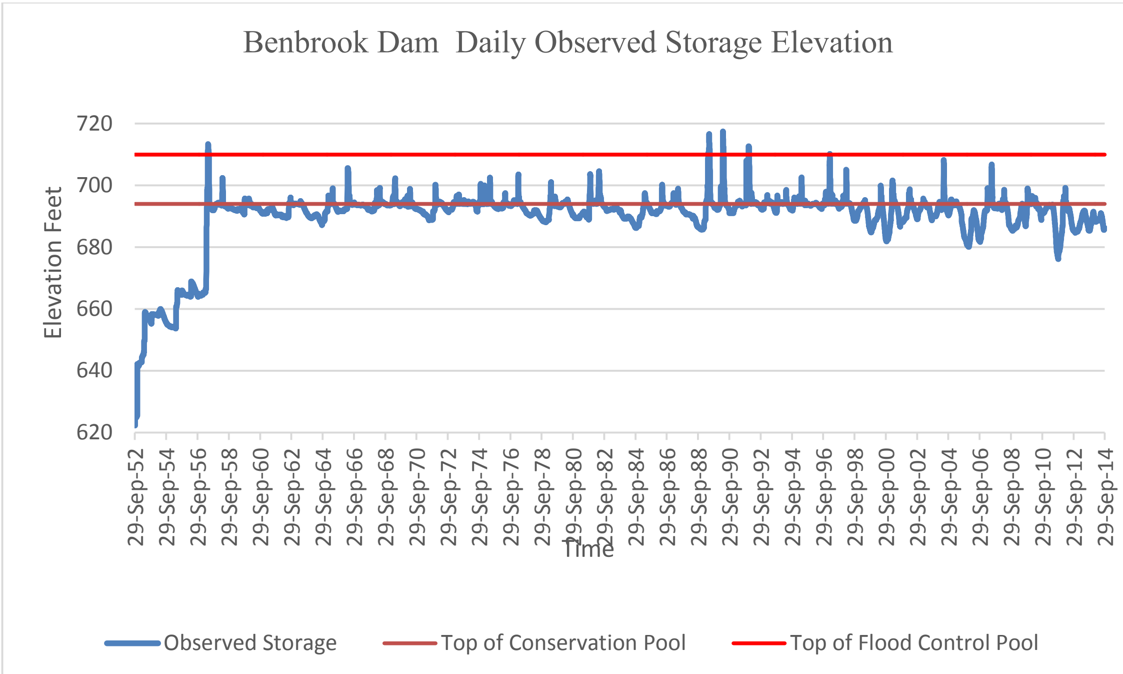

Figure 5. Benbrook Dam daily observed storage elevation

2.2.2 Joe Pool Reservoir

Location of the Joe Pool Dam is 11.2 river mile on Mountain Creek om Trinity River, 10 miles southwest of Dallas, in Tarrant and Ellis Counties. Drainage area of the reservoir is 232 square miles and correspondingly one inch runoff is 12,373 acre-feet. The construction of dam started in 1977 and completed in 1985. Deliberate impoundment began in 1985. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 24200, 108.5, and 30 feet respectively. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table 6 demonstrates technical features and Figure 6 shows daily observed storage elevation of Joe Pool Dam

Table 6. Technical features of the Joe Pool Dam

Feature	Elevation (Ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway Cap. (cfs)
Top of Dam	564.5			
Max. Design Water	559.5	642,400	279,700	11,900
Spillway Crest	541	362,700	58,700	
Top of Flood Control Pool	536	304,000	123,100	
Top of Conservation Pool	522	176,900	142,900	
Sediment Reserve			38,000	
Streambed	456			

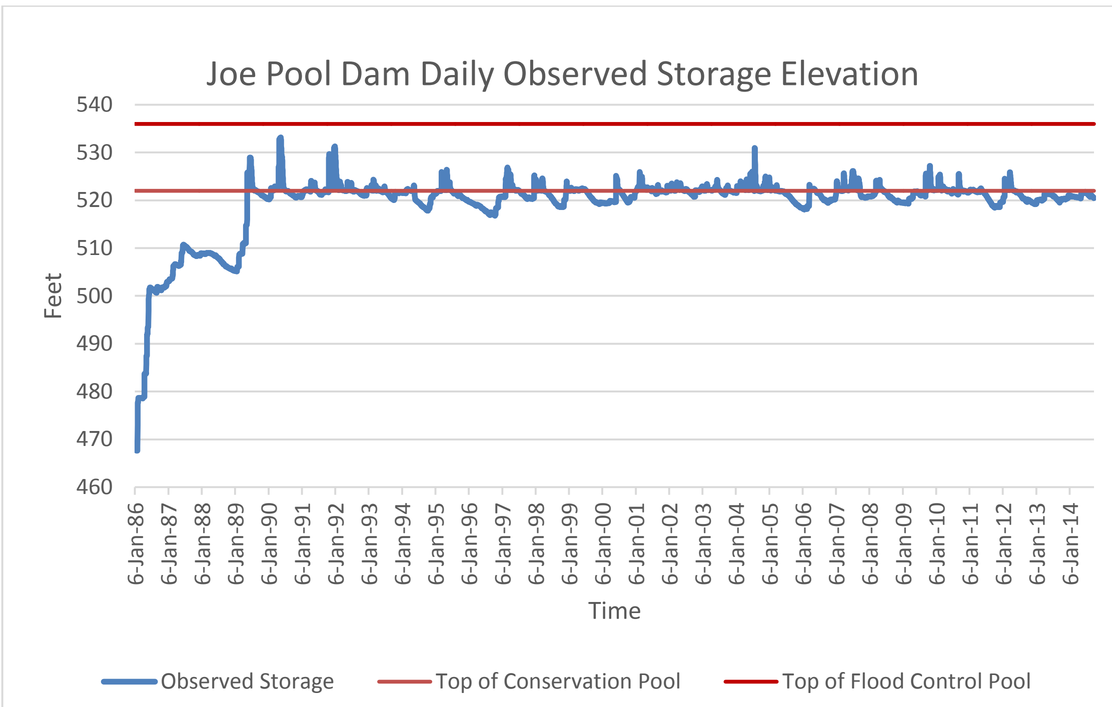

Figure 6. Joe Pool Dam daily observed storage elevation

2.2.3 Ray Roberts Reservoir

Location of the Ray Robert Dam is 60 river mile on Elm Fork of Trinity River, 30 miles upstream of Lewisville Dam, in Denton County. Drainage area of the reservoir is 691 square miles and correspondingly one inch runoff is 36,907 acre-feet. The construction of the dam started on May, 31 1982 and completed on June, 30 1987. Deliberate impoundment began on June, 30 1987. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 15250, 131, and 44 feet respectively. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table 7 demonstrates technical features and Figure 7 shows daily observed storage elevation of Ray Roberts Dam.

Table 7. Technical features of the Ray Robert Dam

Feature	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Outlet work Cap (cfs)
Top of Dam	665			
Max. Design Water Surface	658.8	1,931,900		7,600
Spillway Crest	645.5	1,261,000		7,100
Top of Flood Control Pool	640.5	1,064,600	265,000	6,900
Top of Conservation Pool	632.5	799,600	745,000	6,600
Sediment Reserve		54,600	54,600	
Streambed	524			

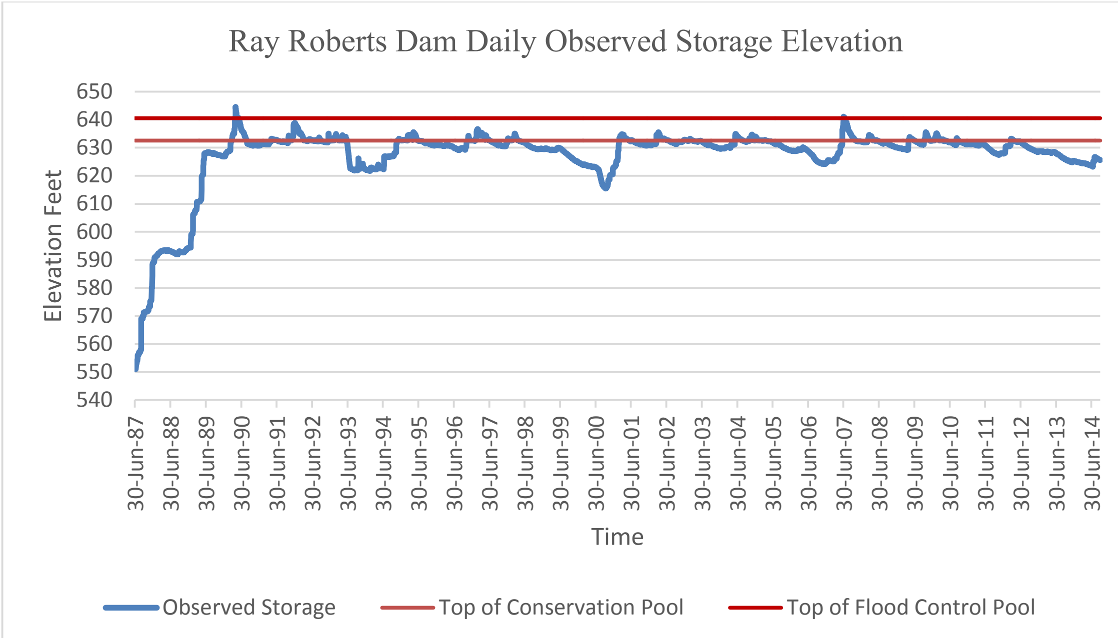

Figure 7. Ray Roberts Dam daily observed storage elevation

2.2.4 Lewisville Reservoir

Location of the Lewisville Dam is 30.0 river mile on Elm Fork of Trinity River, 22 miles northwest of Dallas, in Denton County near the City of Lewisville. Drainage area of the reservoir is 1,660 square miles and correspondingly one inch runoff is 88,533 acre-feet. The construction of dam started on Nov, 28 1948 and completed in Aug, 1955. Deliberate impoundment began on Nov, 1 1952. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 33888, 125, and 20 feet respectively. The top of conservation pool elevation was raised 515.00 ft to 522.00 ft on November 30, 1988. Based on the sediment survey conservation and flood control pool capacity decreased from 640,986 to 618,400 ac-ft and 981,763 to 959,177 ac-ft respectively. 22,586 ac-ft storage capacity has been decreased. Table 8 demonstrates technical features and Figure 8 shows daily observed storage elevation of Lewisville Dam.

Table 8. Technical features of the Lewisville Dam

Feature	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Outlet Work Cap. (cfs)
Top of Dam	560			
Max. Design Water Surface	553	2,082,800	1,101,037	12,300
Spillway Crest	532	959,177		
Top of Flood Control Pool	532	959,177	340,777	11,000
Top of Conservation Pool	522	618,400	618,400	10,200
Streambed	435			

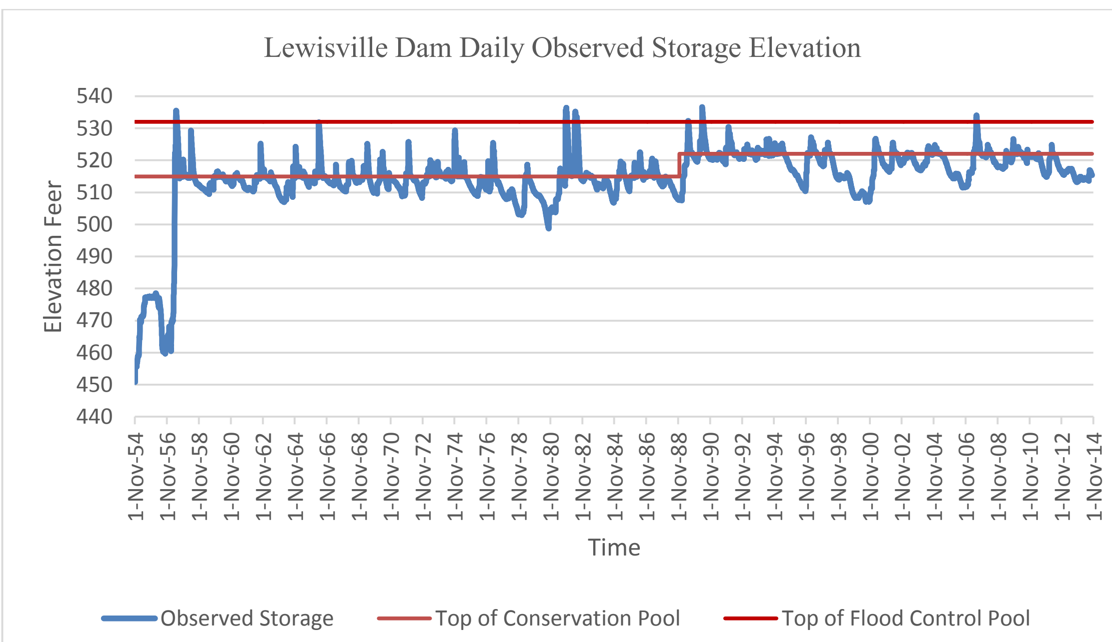

Figure 8. Lewisville Dam daily observed storage elevation

2.2.5 Grapevine Reservoir

Location of the Grapevine Dam is 11.7 river mile on Denton Creek of Trinity River, 20 miles northwest of Dallas, in Denton and Tarrant Counties near the City of Grapevine. Drainage area of the reservoir is 695 square miles and correspondingly one inch runoff is 37,067 acre-feet. The construction of the dam started in Jan, 1948 and completed in Jun 1982. Deliberate impoundment began on Jul, 3 1952. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 12850, 137, and 28 feet respectively. Based on the sediment survey conservation and flood control pool capacity decreased from 181,100 to 162,500 ac-ft and 425,500 to 406,900 ac-ft respectively. 18,600 ac-ft storage capacity has been decreased. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table 9 demonstrates technical features and Figure 9 shows daily observed storage elevation of Grapevine Dam.

Table 9. Technical features of the Grapevine Dam

Feature	Elevation (Ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway Cap. (cfs)
Top of Dam	588			
Max. Design Water Surface	581.9	788,000	363,000	191,310
Spillway Crest	560	406,900		
Top of Flood Control Pool	560	406,900	244,400	
Top of Conservation Pool	535	162,500	126,500	
Sediment Reserve			36,000	
Streambed	451			

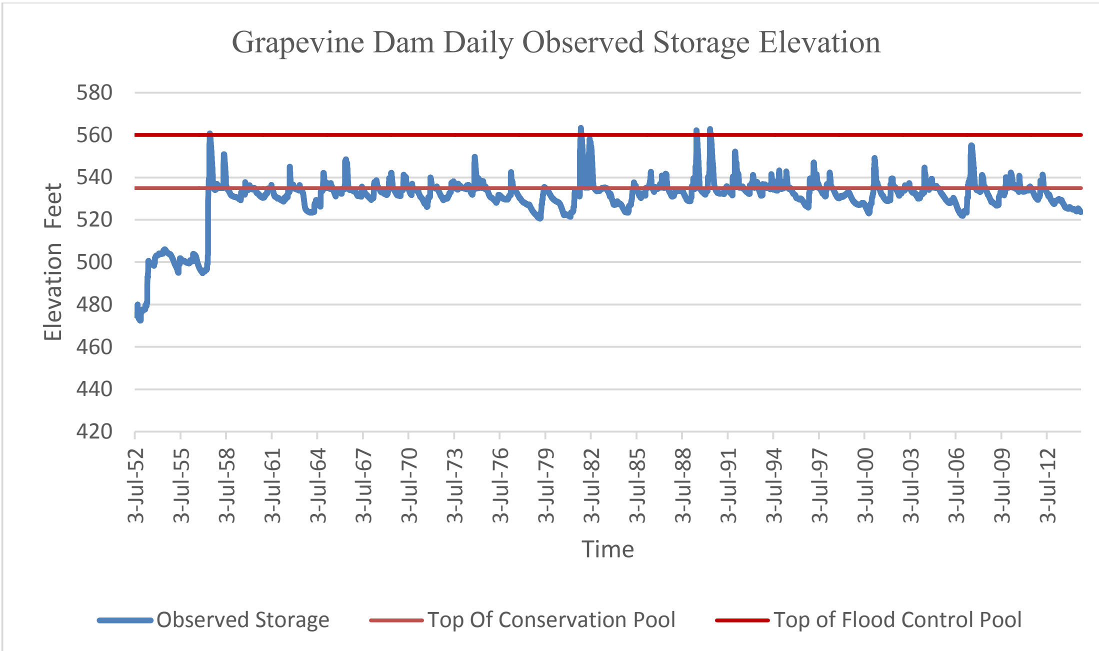

Figure 9. Grapevine Dam daily observed storage elevation

2.2.6 Lavon Reservoir

Location of the Lavon Dam is 55.9 river mile on East Fork of Trinity River, 22 miles northeast of Dallas, in Collin County near the City of Benbrook. Drainage area of the reservoir is 770 square miles and correspondingly one inch runoff is 41.067 acre-feet. The construction of the dam started in Jan, 1948 and completed on Dec, 1 1975. Deliberate impoundment began on Sep, 14 1953. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 19493, 81, and 30 feet respectively. The top of conservation pool elevation was raised 472 ft to 492 ft on December 01, 1975. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table

10 demonstrates technical features and Figure 10 shows daily observed storage elevation of Lavon Dam.

Table 10. Technical features of the Lavon Dam

Feature	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway Cap.(cfs)
Top of Dam	514			
Max. Design Water Surface	509	921,200		357,700
Spillway Crest	503.5	748,200		
Top of Flood Control Pool	503.5	748,200	291,700	
Top of Conservation Pool	492	456,500	380,000	
Sediment Reserve			92,600	
Streambed	433			

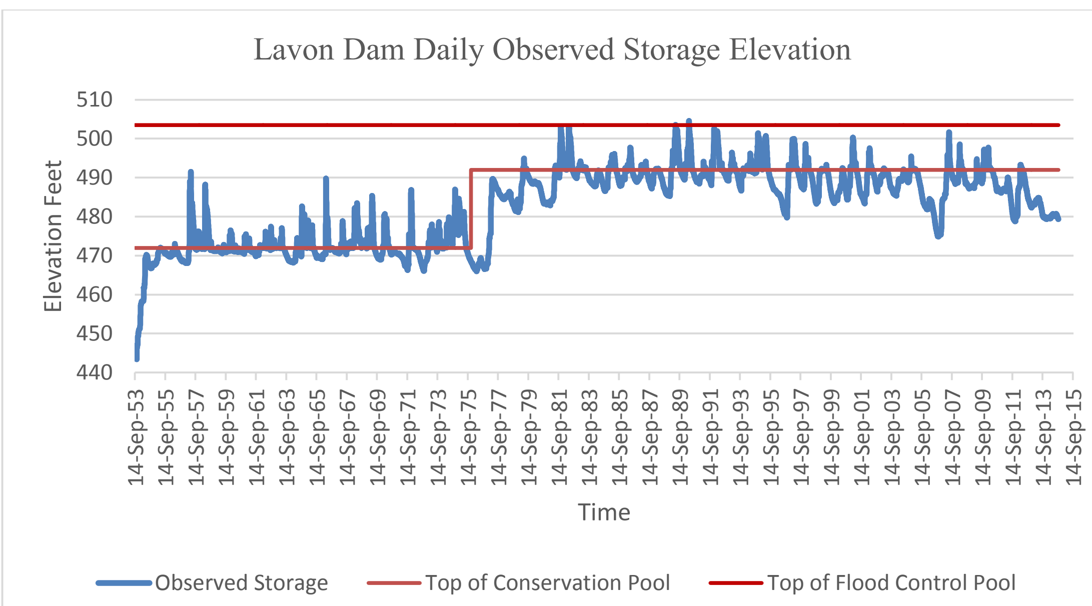

Figure 10. Lavon Dam daily observed storage elevation

2.2.7 Navarro Mills Reservoir

Location of the Navarro Mills Dam is 63.9 river mile on Richland Creek of Trinity River, 16 miles southwest of Corciscana, in Navarro County. Drainage area of the reservoir is 320 square miles and correspondingly one inch runoff is 17,067 acre-feet. The construction of the dam started on Jun, 14 1960 and completed on Mar, 15 1963. Deliberate impoundment began on Mar, 15 1963. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 7570, 81.7, and 20 feet respectively. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table 11 demonstrates technical features and Figure 11 shows daily observed storage elevation of Navarro Mills Dam.

Table 11. Technical features of the Navarro Mills Dam

Feature	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway Cap. (cfs)
Top of Dam	457			
Max. Design Water Surface	451.9	335,800		224,000
Spillway Crest	443	212,200		
Top of Flood Control Pool	443	212,200	148,900	
Top of Conservation Pool	424.5	63,300	53,200	
Sediment Reserve			15,800	
Streambed	375.3			

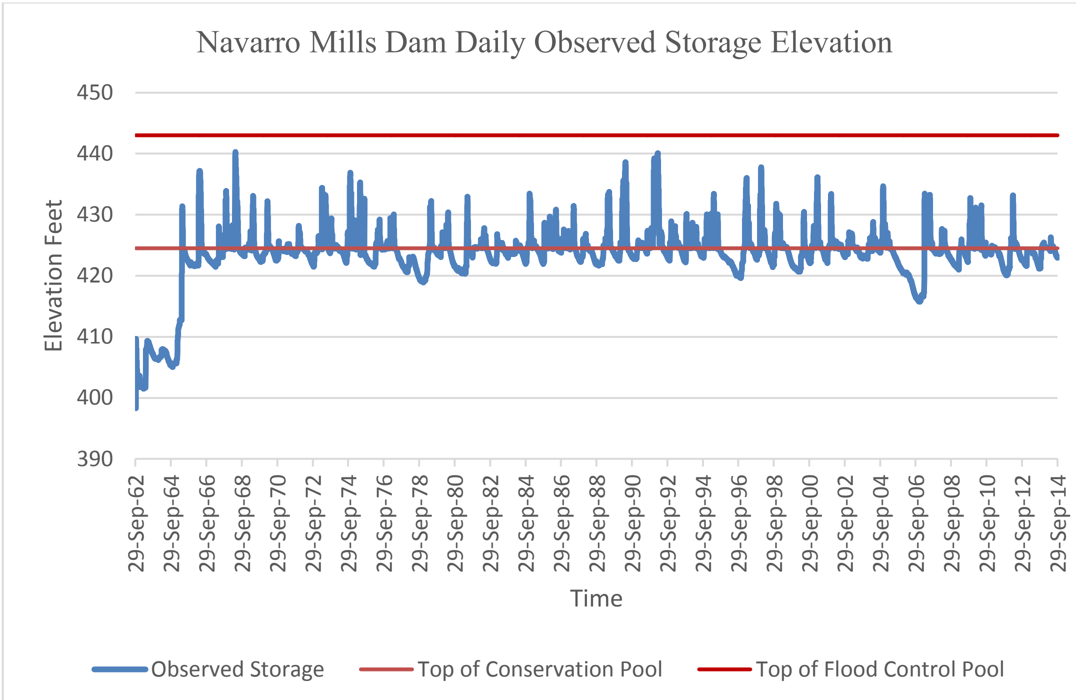

Figure 11. Navarro Mills Dam daily observed storage elevation

2.2.8 Bardwell Reservoir

Location of the Bardwell Dam is 5.0 river mile on Waxahachie of Trinity River, 5 miles south of Corsicana, in Ellis County. Drainage area of the reservoir is 178 square miles and correspondingly one inch runoff is 9,493 acre-feet. The construction of the dam started in Aug, 1963 and completed on Nov, 20 1965. Deliberate impoundment began on Nov, 20 1965. The dam type is rolled earth fill. Length of dam including spillway, max height, and top width are 15400, 82, and 20 feet respectively. The technical information about reservoir and reservoir storage data as a daily time step are available in the United States Army Corps of Engineer Fort Worth District website. Table 12 demonstrates technical features and Figure 12 shows daily observed storage elevation of Bardwell Dam.

Table 12. Technical features of the Bardwell Dam

Feature	Elevation (ft)	Accumulative (ac-ft)	Incremental (ac-ft)	Spillway Cap. (cfs)
Top of Dam	460			
Max. Design Water Surface	455.9	268,400		78,000
Spillway Crest	439	140,000		
Top of Flood Control pool	439	140,000	85,100	
Top of Conservation Pool	421	54,900	42,800	
Sediment Reserve			17,600	
Streambed	377.6			

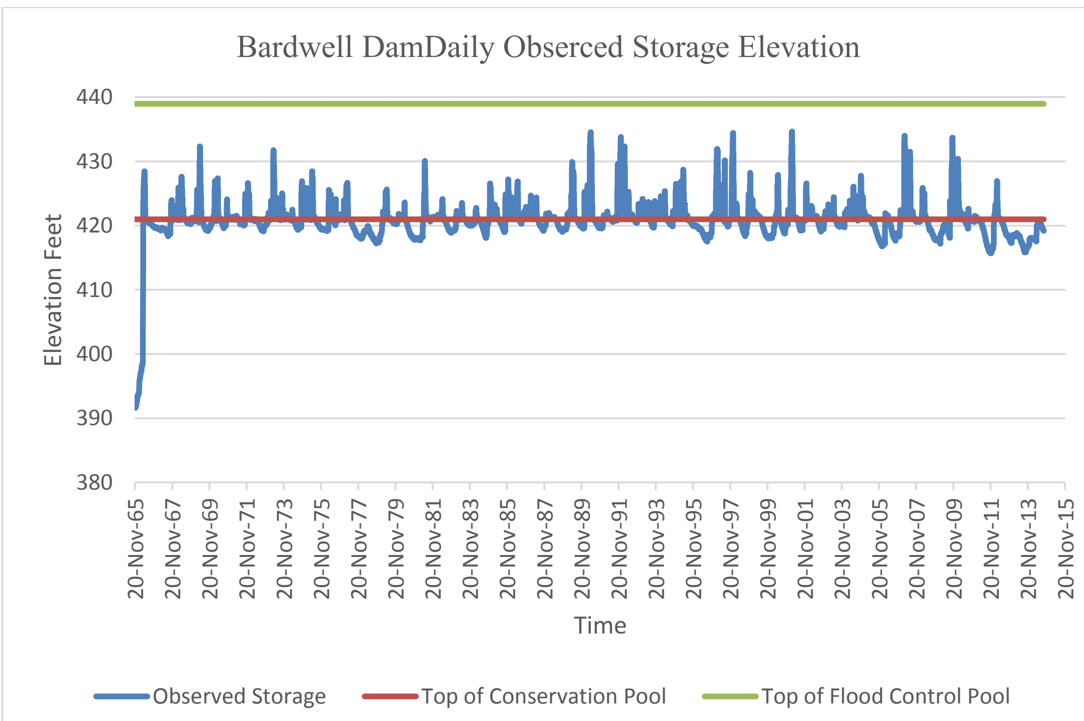

Figure 12. Bardwell Dam daily observed storage elevation

2.3 Sedimentation

Sediment transport causes decreases in reservoir storage capacity over time. Various factors such as reservoir site characteristics, flow rate, watershed canopy, sediment loads in creeks, rivers flowing into reservoirs, slope of watershed, and slope of streambed have an impact on sediment rate. During a flood event, sediment transportation reaches peak level. Decrease in velocity of upstream of reservoir ends up with deltas since there is not enough energy to carry sediment to downstream. For sediment reserve in reservoirs, as shown on Figure 13, inactive pool is allocated. Over time, capacity of an inactive pool decreases which then affects reservoir operation. Based on sediment surveys, Lewisville and Grapevine reservoirs storage capacities decreased 22,586 ac-ft and 18,600 ac-ft respectively because of sedimentation. However, many big reservoir sediment reserves are unknown because of the difficulties and expenses of surveying bottom elevation.

For federal and other large reservoirs for sediment reserve, inactive pools are designed to fill up within 50 to 100 years (Wurbs 1996). USACE and USBR agencies have methods to predict future sediment deposition while designing a reservoir. However, smaller local entities, such as farmers and private reservoirs do not have special provisions to design inactive pools.

2.4 Reservoir Pools

Reservoirs are operated based on storage capacity of designated zones. A typical large multi-purpose reservoir consists of vertical zones such as inactive pools, conservation pools, flood control pools and surcharge storage as illustrated in Figure 13. Storage capacity of pools might be allocated either seasonally or permanently.

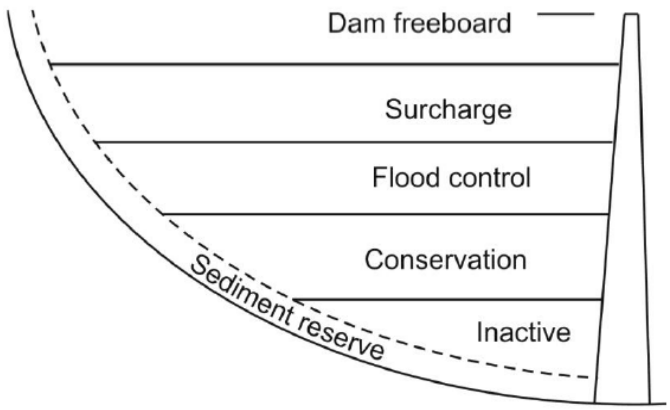

Figure 13. Reservoir pools

2.4.1 Inactive Pool

Inactive pools, also known as a dead storage, are located at the bottom of the reservoirs. The purposes of inactive pools are sediment reserve, fish and wildlife, recreation, and head for hydroelectric power. Except for seepage and the natural process of evaporation, water cannot be withdrawn from dead storage. At the top of the dead storage, elevation level might be located an outlet structure or hydroelectric turbines for hydroelectric dams. For large multi-purpose federal dams, the top of the inactive pool level is the bottom of the conservation pool.

2.4.2 Conservation Pool

Conservation pools are designed to meet municipal, irrigation, and industrial water demand, as well as hydroelectric power, navigation, instream flow maintenance, among other purposes. Conservation pools also serve recreational purposes. During operation of reservoirs, the level of the water in reservoirs is wanted to be as close possible as to the top of conservation pool in order to meet water demands. For many multi-purpose federal large dams, the top of the conservation pool`s level is the bottom level of the flood control pool.

2.4.3 Flood Control Pool

Flood control pools are designed to store excessive water during high flows. Ideally, the flood control pool should remain empty except during a flood event. Generally, the top of the flood control pool is set by emergency spillways. When water exceeds the top of the flood control pool, uncontrolled emergency spillways withdraw water from dam and prevent overtopping and dam failure. Some dams have gated spillways before an ungated flood control pool. During an extreme flood event when water exceeds the top of the flood control elevation, ungated spillways automatically withdraw water. At that time, downstream might be under flood. In order to store water for the next flood, operation procedures should include the emptying of the flood control pool as quickly as possible without contributing to downstream flooding.

2.5 Reservoir Operation

Estimating the probability of exceeding the storage capacity of the flood control pools of the eight reservoirs is a central focus of the research. Permanent or seasonal reallocation of storage capacity between flood control and conservation purposes is also a major topic addressed by the research.

Reservoirs are divided into the following three vertical zones called pools: conservation, flood control, and surcharge (Wurbs 1996). Operations are based on maintaining reservoir contents at the elevation of the top of the conservation pool or as close thereto as feasible while supplying the needs of water users. Water use demands are supplied by releases or withdrawals from conservation storage. Flood control operations are activated whenever high inflows result in storage levels rising above the top of the conservation pool. USACE flood control operations are based on two sets of procedures referred to as regular and emergency.

Regular flood control operations are in effect whenever the storage level is within the flood control pool. Releases are based on emptying flood control pools as expeditiously as feasible without contributing to flows at designated downstream gaging stations exceeding maximum non-damaging flow levels. Multiple reservoirs share the same downstream gaging stations and stream flow limits. In many cases, the maximum allowable non-damaging flow levels vary depending on storage contents of the flood control pools.

Emergency procedures are activated only during extreme flood events when the flood control storage capacity is exceeded, with the storage level encroaching into the surcharge pool. Emergency operations are based on assuring that the total surcharge capacity is never exceeded. Releases and uncontrolled spills from the surcharge pool, above the top of flood control pool, may contribute to flows at downstream locations exceeding non-damaging levels.

The eight Trinity River Basin Dams all have flood control pools. These flood control pools are operated by USACE as a multiple-reservoir system. In the WRAP simulation model, a flood control pool is modeled as two components. First one is controlled (gated) pool. A gated flood control pool located between conservation pool and uncontrolled flood control pool. If water level is in the controlled flood control, release is made by taking into account downstream control points in order to keep water level under the max allowable level. Thus downstream areas are protected from floods. The system of the eight Trinity River Basin Reservoir release are made based on pertinent datasheet that is in Figure 14.

An uncontrolled flood control pool is located between spillway and top of controlled pool if there is a gate system. Otherwise uncontrolled flood control pool starts after conservation pool. When water level in this pool, hydraulic structure makes release based on the dimension of notch, conduit, or spillway. People cannot manage uncontrolled pool. A top of uncontrolled flood control pool generally ends with a big spillway. Whenever water levels exceed top of uncontrolled pool, outflow is equal to inflow.

PROJECT	ELEVATIONS	% FLOOD STORAGE	CLEAR FK TRINITY R.	WEST FK TRINITY R.	WEST FK TRINITY R.	MOUNTAIN CREEK	DENTON CREEK	ELM FORK TRINITY R.	ELM FORK TRINITY R.	TRINITY RIVER	EAST FK TRINITY R.	TRINITY RIVER	RICHLAND CREEK	WAXAHACHIE CREEK	CHANMBERS CREEK	LONG LAKE
Location			FWHT2	Ft Worth FWOT2	Grand Prairie GPRT2	Grand Prairie GPAT2		Above Lewisville Lake	Carrollton CART2	Dallas DALT2	Crandall CNLT2	Rosser RSRT2	Dawson DWST2	Bardwell BRDT2	Rice RCET2	LOLT2
Benbrook BNBT2	694.0 - 696.0	0 - 10	600		6000					13000		15000				24000
	696.0 - 697.1	10 - 16		3000	6000					13000		15000				24000
	697.1 - 710.0	16 - 100			6000					13000		15000				24000
Joe Pool JPLT2	522.0 - 524.0	0 - 10			6000	1000				13000		15000				24000
	524.0 - 536.0	10 - 100				4000				13000		15000				24000
										13000		15000				24000
Ray Roberts RRLT2	632.5 - 633.5	0 - 11						2000	4000	13000		15000				24000
	633.5 - 636.0	11 - 41						4000	5500	13000		15000				24000
	636.0 - 640.5	41 - 100						6000	7000	13000		15000				24000
Lewisville LEWT2	522.0 - 523.0	0 - 10							4000	13000		15000				24000
	523.0 - 526.0	10 - 35							5500	13000		15000				24000
	526.0 - 532.0	35 - 100							7000	13000		15000				24000
Grapevine GPVT2	535.0 - 538.2	0 - 10					2000		4000	13000		15000				24000
	538.2 - 542.0	10 - 23					2000		5500	13000		15000				24000
	542.0 - 560.0	23 - 100					2000		7000	13000		15000				24000
Lavon LVNT2	492.0 - 503.5	0 - 100									8000	15000				24000
Navarro Mills DAWT2	424.5 - 427.3	0 - 10											1200			24000
	427.3 - 443.0	10 - 100											2000			24000
Bardwell BDWT2	421.0 - 423.3	0 - 10												600	4000	24000
	423.3 - 427.4	10 - 30												1200	4000	24000
	427.4 - 439.0	30 - 100												2000	4000	24000

Figure 14. USACE flood control pertinent datasheet for Trinity River Basin (USACE 2015)

CHAPTER III

FREQUENCY ANALYSIS OF OBSERVED RESERVOIR STORAGE

3.1 Overview of Flood Frequency Analysis

Frequency analysis is performed for many types of planning, management, and design situations in hydrology and reservoir system management (Wurbs 1996). This research particularly focused on flood storage frequency analysis. The log-normal and log-Pearson type III probability distribution functions were applied with the Hydrologic Engineering Center Statistical Software Package (HEC-SSP) to calculate annual exceedance probabilities and recurrence intervals for reservoir storage content volumes as outlined in this chapter. The results of frequency analyses of actual observed storage is presented in this chapter. The results of frequency analyses of simulated storage are presented in Chapter IV. Water supply reliability metrics are also computed as discussed in Chapter V.

The annual exceedance probability (P) is probability that a specified storage magnitude will be equaled or exceeded in any year. The return period or the recurrence interval (T) is the mean interval, in years, between occurrence of flood events equaling or exceeding a specified storage magnitude. The relationship of between annual exceedance probability (P) and recurrence interval (T) in years is

$$T = \frac{1}{P} \ or\ P = \frac{1}{T} \qquad (1)$$

3.2 Analytical Probability Distributions

3.2.1 Log-normal Distributions

The normal probability distribution, also known as the Gaussian distribution, has two parameters, the standard deviation and mean. The normal probability distribution function is bell-shaped and symmetrical to the mean. The sample standard deviation (S) and the sample mean ($\overline{X}$) are used to predict population standard deviation (σ) and population mean (μ). The general formula for normal distribution is as follows;

$$X = \mu + K\sigma \tag{2}$$

where

K is standard variant from normal distribution table.

The log-normal probability distribution is transferring random variable X to logarithm and applying normal distribution. The logarithm transfer is convenient to reduce outlier effects on the calculation. The standard deviation (σ) and mean (μ) need to be transfer logarithm and K again, the same as the normal distribution table. The general formula for log-normal distribution is as follows:

$$\log X = \mu_{logX} + K\sigma_{logX} \tag{3}$$

3.2.2 Log-Pearson Type III

The Pearson probability distribution, also known as Pearson type III distribution, has three parameters which are the skew coefficient, mean, and standard deviation. Equation 2 is used for Pearson type III calculation. K value is found from Pearson type III distribution table. Skew coefficient (G) can be calculated from observed annual max flow or reservoir storage, and called station skew in flood frequency analysis. In order to perform Pearson type III probability distribution, adequate sample size should be used, otherwise, results might be inaccurate. When skew coefficient (G) is equal to zero, K value becomes exactly normal probability distribution.

Logarithmic transform of Pearson type III distribution is called log-Pearson type III distribution. The federal water agencies use log-Pearson type III distribution for performing FFA (Wurbs 1996). The standard deviation (σ) and mean (μ) need to be transferred logarithm and K again, the same as the log-Pearson type III distribution table. In order to find right K value from table, skew coefficient (G) must be known. The Equation 3 formula is used for log-Pearson type III distribution.

3.2.3 Expected Probability and Confidence Limits

The Hydrology Committee of the former U.S Water Resources Council developed a guideline that was published as Bulletin 17 in 1976 and revised as Bulletin 17B in 1982, for flood frequency analysis (Wurbs and James 2002). Bulletin 17B was developed for peak flows and adopted with log-Pearson type III distribution; however, in this research, it is used for reservoir storages. HEC-SSP provides an option that calculate expected probability and confidence limit for flood frequency analyses. The expected probability is described as the average of all magnitude estimates' true probabilities for any designated flood frequency which might be calculated from successive samples of a specified size (Miller et al. 1981). The expected probability is the representation of value, which tend to be in the central of the confidence limits.

Confidence limit can be calculated with defined limits in the HEC-SSP. By default and in this research, confidence limit is the 90% confidence interval (5%-95% confidence limits). The frequency estimates depend on sample size. A large sample size provides lower confidence limit. Likewise, a small sample size provides higher confidence limit. There are always uncertainties for frequency analyses and confidence limits with log-Pearson type III distribution. Confidence limits are calculated with the following equations in Bulletin 17B.

$$P\left(U_{P,C} \geq X_P^*\right) = C \qquad (4)$$

$$P\left(L_{P,C} \geq X_P^*\right) = C \qquad (5)$$

where

X_P^* true or population discharge that has exceedance probability

C confidence level

$U_{P,C}$ upper confidence limit

$L_{P,C}$ lower confidence limit

$U_{P,C}$ and $L_{P,C}$ are called one-sided confidence limits since only one side has limit. A two-sided confidence interval is as follows.

$$P\left(L_{P,C} \leq X_P^* \leq U_{P,C}\right) = 2C - 1 \tag{6}$$

Confidence limits are computed with the following equations.

$$U_{P,C} = \bar{X} + SK_{P,C}^{U} \tag{7}$$

$$L_{P,C} = \bar{X} + SK_{P,C}^{L} \tag{8}$$

$$K_{P,C}^{U} = \frac{K_p + (K_P^2 - ab)^{0.5}}{a} \tag{9}$$

$$K_{P,C}^{L} = \frac{K_p - (K_P^2 - ab)^{0.5}}{a} \tag{10}$$

$$a = 1 - \frac{Z_C^2}{2(N-1)} \tag{11}$$

$$b = K_P^2 - \frac{Z_C^2}{N} \tag{12}$$

where

P specified annual exceedance probability

C specified confidence level

Z_C standard normal deviate from normal probability table

$U_{P,C}$ upper confidence limit

$L_{P,C}$ lower confidence limit

$K_{P,C}^{U}$ upper confidence limit coefficient

$K_{P,C}^{L}$ lower confidence limit coefficient

$\bar{X}$ mean of annual peak flows or storage

S standard deviation of logarithms annual peak flows or storage

K_P frequency factor from K values table

N record length

3.3 Hydrologic Engineering Center Statistical Software Package (HEC-SSP)

The Statistical Software Package (HEC-SSP) was developed by the USACE Hydrologic Engineering Center (HEC 2010). The software package allows users to perform hydrologic statistical analysis. It has capabilities to perform flow frequency analysis (Bulletin 17B), general frequency analysis, volume frequency analysis, duration analysis, coincident frequency analysis as well as curve combination analysis. In order to perform one of these analysis, a few steps must be followed.

First of all, data must be added to perform frequency analysis. The software package provides various ways to input data. The HEC-SSP allows users to input data from HEC-DSS, USGS website, Microsoft Excel, text file, and manually. In this study, annual maximum reservoir storage data was added to software packages from a Microsoft Excel file.

Next, after data is available to perform frequency analysis, frequency analysis could be performed under the analysis tab. Several methods are available under the analysis tab, allowing it to perform statistical analysis for different probability distributions. In this study, log-normal and log-Pearson type III distributions were employed and compared to find the best fit. After frequency analysis results were plotted with observed values, 5% and 95% confidence limit, computed curves, and expected probability curves for both log-normal and log-Pearson type III distributions were plotted.

3.4 Flood Frequency Analysis for Trinity River Basin Reservoirs

In this research, risk of the exceedance probability of the flood control pool capacity of the Trinity River Basin dams were analyzed based on observed annual maximum reservoir storage. The data for this study is available on the USACE Fort Worth District website as a daily measurement. From observed reservoir storage data, annual maximum storage values were found for each year and each reservoir. Afterwards, the data was added to the HEC-SSP software and frequency analyses were performed.

After obtaining the report of analyses, interpolation was done in order to find the exact risk of exceedance probability based on reservoirs` flood control storage capacity. After obtaining the percent chance of exceedance values, Equation 1 was used to calculate recurrence time for exceeding flood control pool capacity in years. Wurbs (1996) noted that for federal reservoirs, flood control storage capacities typically were designed for at least 50-year recurrence interval; in addition to that, most projects` flood control pools were sized for 100-year recurrence interval. For each reservoirs, detailed results and plots are as follows.

3.4.1 Benbrook Reservoir FFA Based on Observed Annual Storage

A frequency analysis for peak annual storage contents of Benbrook Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. The total storage capacity of Benbrook Reservoir below the top of flood control pool is 164,800 acre-feet, which can be to the storage-frequency relationships presented in Tables 13 and 14 and Figures 15 and 16.

Table 13. Benbrook Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence 0.05 (ac-ft)	Limits 0.95 (ac-ft)
226,597	235,244	0.2	262,153	202,948
209,852	215,901	0.5	239,725	189,637
196,970	201,409	1	222,717	179,275
183,797	186,908	2	205,567	168,552
165,670	167,426	5	182,422	153,544
151,070	152,077	10	164,231	141,181
135,103	135,571	20	144,920	127,266
109,106	109,106	50	115,334	103,215
88,112	87,808	80	93,538	82,144
78,799	78,277	90	84,319	72,485
71,855	71,101	95	77,530	65,257
60,437	59,105	99	66,402	53,450

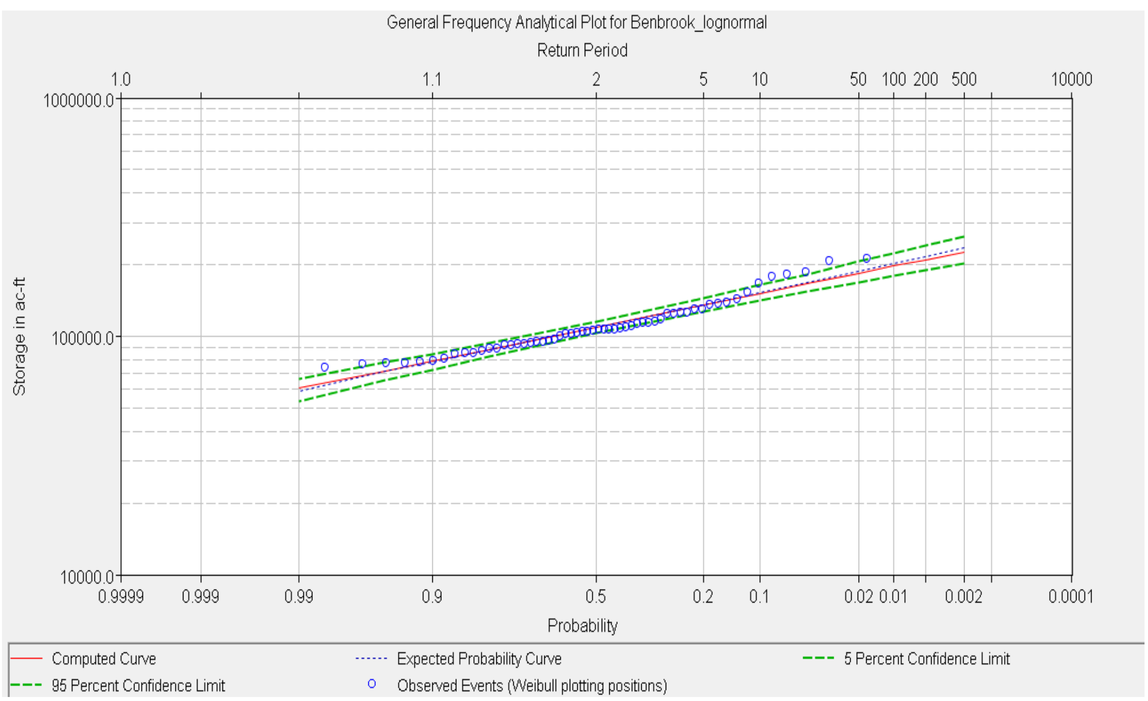

Figure 15. Benbrook Reservoir FFA log-normal probability distribution

Table 14. Benbrook Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence 0.05 (ac-ft)	Limits 0.95 (ac-ft)
290,532	311,578	0.2	350,631	252,474
253,354	266,527	0.5	298,667	223,901
227,566	236,324	1	263,461	203,713
203,545	209,127	2	231,371	184,578
174,101	176,798	5	193,116	160,565
153,195	154,613	10	166,850	142,998
132,979	133,563	20	142,406	125,376
105,485	105,485	50	111,442	99,682
87,792	87,579	80	93,217	81,813
81,174	80,845	90	86,654	74,955
76,728	76,277	95	82,289	70,329
70,347	69,703	99	76,060	63,689

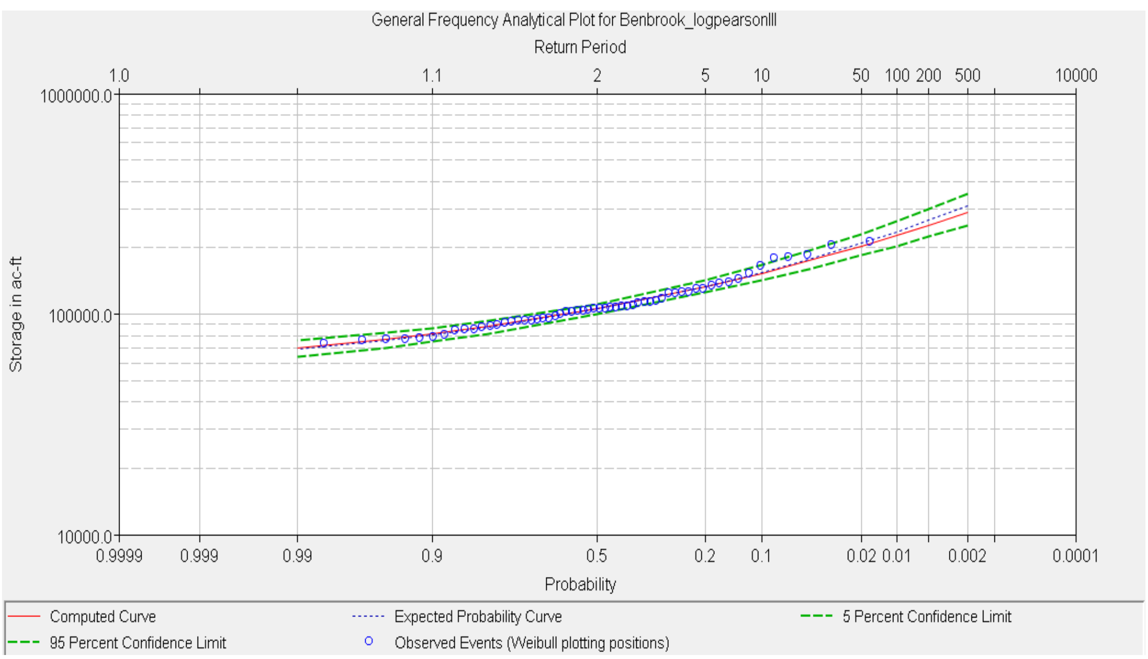

Figure 16. Benbrook Reservoir FFA log-Pearson type III probability distribution

3.4.2 Joe Pool Reservoir FFA Based on Observed Annual Storage

A frequency analysis for peak annual storage contents of Joe Pool Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The total storage capacity of Joe Pool Reservoir below the top of flood control pool is 304,000 acre-feet, which can be to the storage-frequency relationships presented in Tables 15 and 16 and Figures 17 and 18.

Table 15. Joe Pool Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
295,971	309,601	0.2	334,038	273,518
284,748	294,550	0.5	317,942	264,812
275,808	283,173	1	305,294	257,796
266,361	271,661	2	292,110	250,289
252,793	255,909	5	273,550	239,300
241,319	243,173	10	258,267	229,750
228,120	229,023	20	241,293	218,337
204,847	204,847	50	213,721	196,341
183,948	183,222	80	192,190	173,905
173,887	172,561	90	182,642	162,476
165,994	163,973	95	175,354	153,398
152,142	148,185	99	162,773	137,448

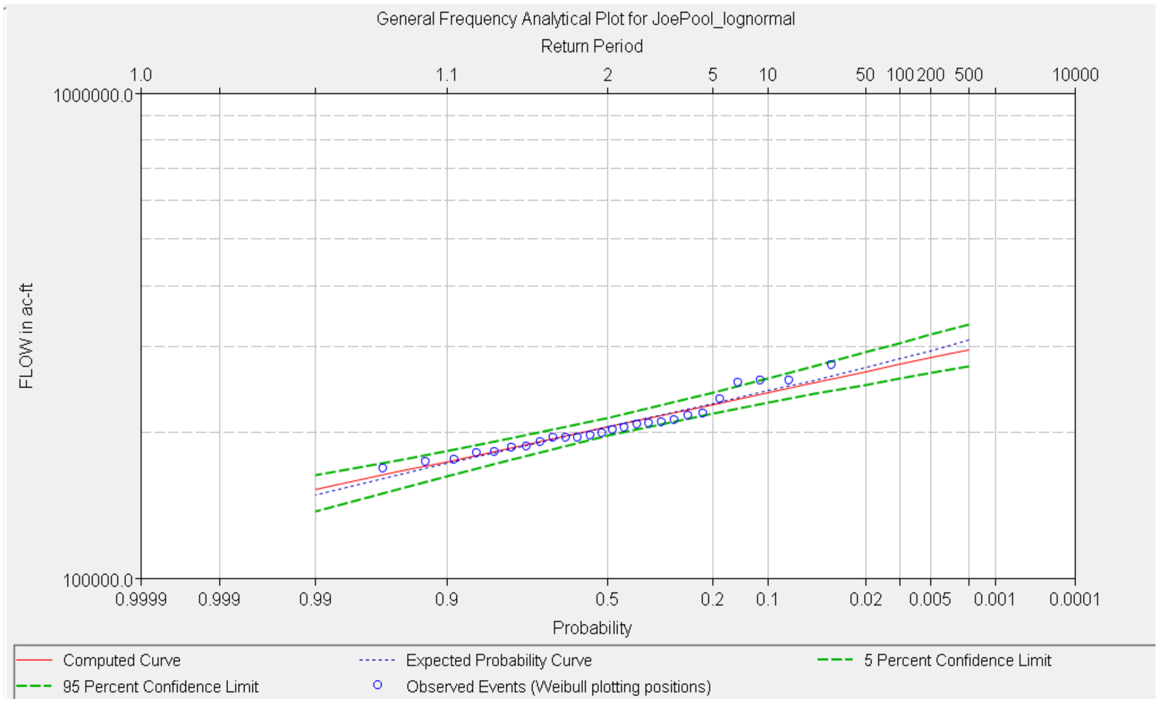

Figure 17. Joe Pool Reservoir FFA log-normal probability distribution

Table 16. Joe Pool Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
332,121	360,468	0.2	387,348	300,956
310,778	329,387	0.5	355,618	284,858
294,965	307,969	1	332,587	272,743
279,341	288,070	2	310,273	260,578
258,755	263,300	5	281,647	244,163
242,954	245,490	10	260,419	231,129
226,497	227,617	20	239,263	216,892
201,663	201,663	50	210,247	193,083
183,595	183,069	80	191,849	173,509
176,247	175,384	90	184,851	165,176
171,076	169,837	95	180,032	159,250
163,240	161,301	99	172,836	150,222

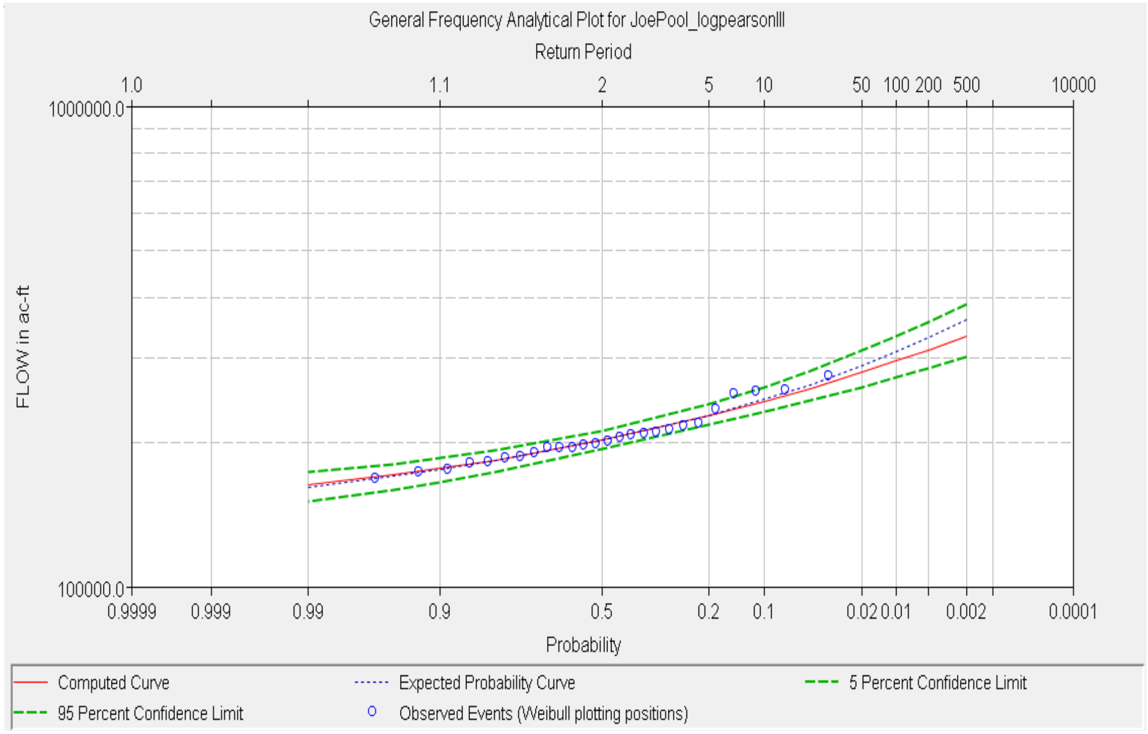

Figure 18. Joe Pool Reservoir FFA log-Pearson type III probability distribution

3.4.3 Ray Roberts Reservoir FFA Based on Observed Annual Storage

The frequency analysis for peak annual storage contents of Ray Roberts Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The total storage capacity of Ray Roberts Reservoir below the top of flood control pool is 1,064,600 acre-feet, which can be to the storage-frequency relationships presented in Tables 17 and 18 and Figures 19 and 20.

Table 17. Ray Roberts Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
1,320,245	1,395,437	0.2	1,532,155	1,198,126
1,258,927	1,312,454	0.5	1,441,834	1,151,380
1,210,479	1,250,365	1	1,371,594	1,113,965
1,159,670	1,188,126	2	1,299,091	1,074,192
1,087,428	1,103,944	5	1,198,299	1,016,465
1,027,026	1,036,744	10	1,116,469	966,792
958,357	963,031	20	1,026,893	908,046
839,521	839,521	50	884,486	796,843
735,421	731,852	80	776,168	686,338
686,250	679,817	90	729,005	631,272
648,131	638,435	95	693,380	588,164
582,246	563,672	99	632,691	513,852

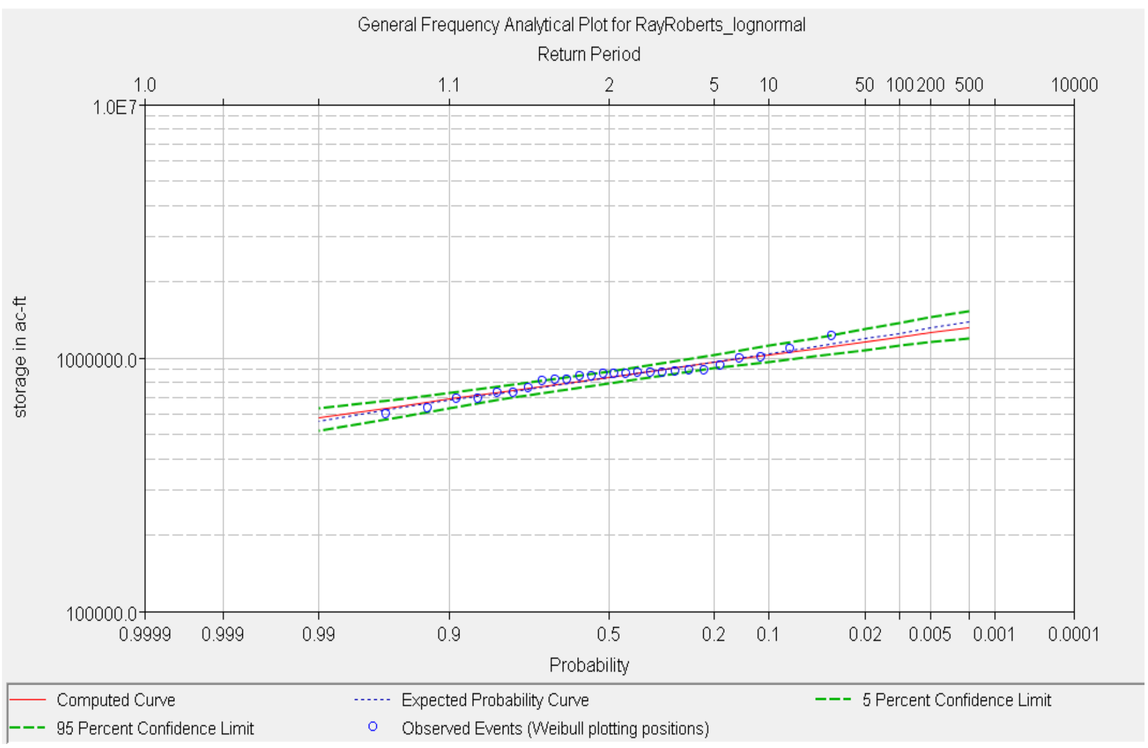

Figure 19. Ray Roberts Reservoir FFA log-normal probability distribution

Table 18. Ray Roberts Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedence	Confidence Limits 0.05 (ac-ft)	0.95 (ac-ft)
1,309,392	1,380,625	0.2	1,516,058	1,189,897
1,250,890	1,301,964	0.5	1,430,111	1,145,205
1,204,407	1,242,680	1	1,362,866	1,109,243
1,155,408	1,182,859	2	1,293,066	1,070,827
1,085,287	1,101,364	5	1,195,357	1,014,730
1,026,244	1,035,748	10	1,115,426	966,138
958,651	963,253	20	1,027,267	908,304
840,473	840,473	50	885,546	797,798
735,683	732,059	80	776,425	686,629
685,771	679,208	90	728,554	630,733
646,898	636,985	95	692,236	586,768
579,346	560,216	99	630,030	510,603

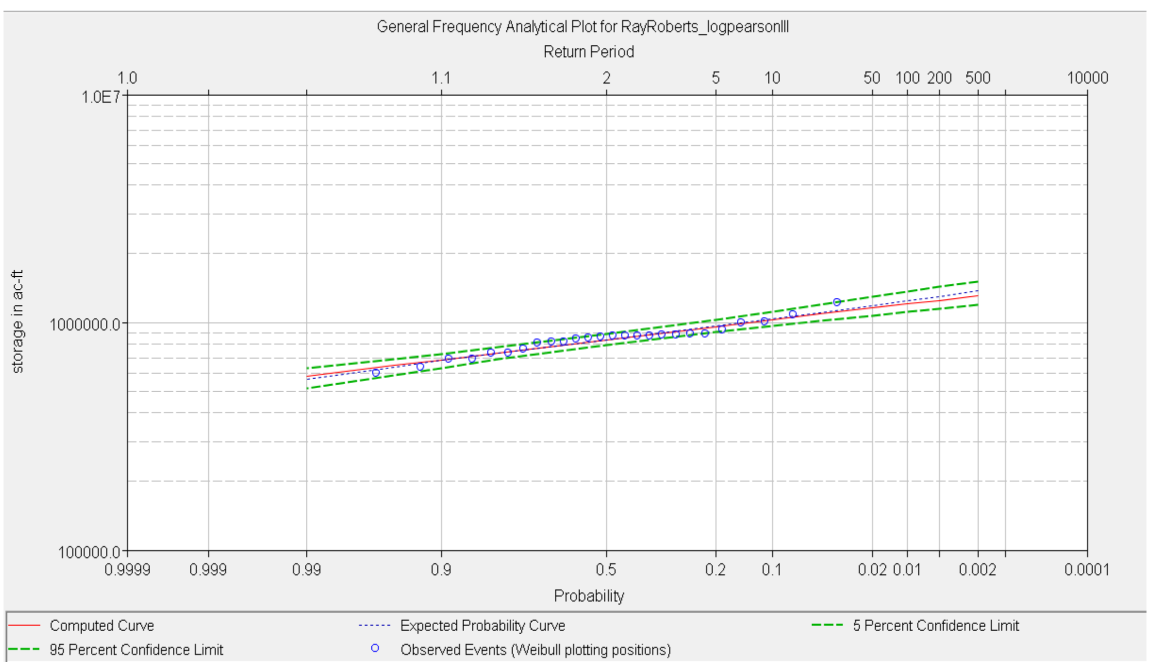

Figure 20. Ray Roberts Reservoir FFA log-Pearson type III probability distribution

3.4.4 Lewisville Reservoir FFA Based on Observed Annual Storage

A frequency analysis for peak annual storage contents of Lewisville Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The total storage capacity of Lewisville Reservoir below the top of flood control pool is 959,177 acre-feet, which can be to the storage-frequency relationships presented in Tables 19 and 20 and Figures 21 and 22.

Table 19. Lewisville Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
1,429,681	1,570,231	0.2	1,831,081	1,218,466
1,323,698	1,420,303	0.5	1,658,496	1,142,641
1,242,185	1,312,177	1	1,528,893	1,083,289
1,158,846	1,207,304	2	1,399,434	1,021,514
1,044,203	1,071,123	5	1,226,930	934,311
951,895	967,144	10	1,093,438	861,635
850,971	857,982	20	954,261	778,550
686,748	686,748	50	748,628	629,983
554,217	549,689	80	605,770	494,228
495,457	487,645	90	547,358	431,321
451,658	440,307	95	504,781	384,393
379,672	359,420	99	435,362	308,473

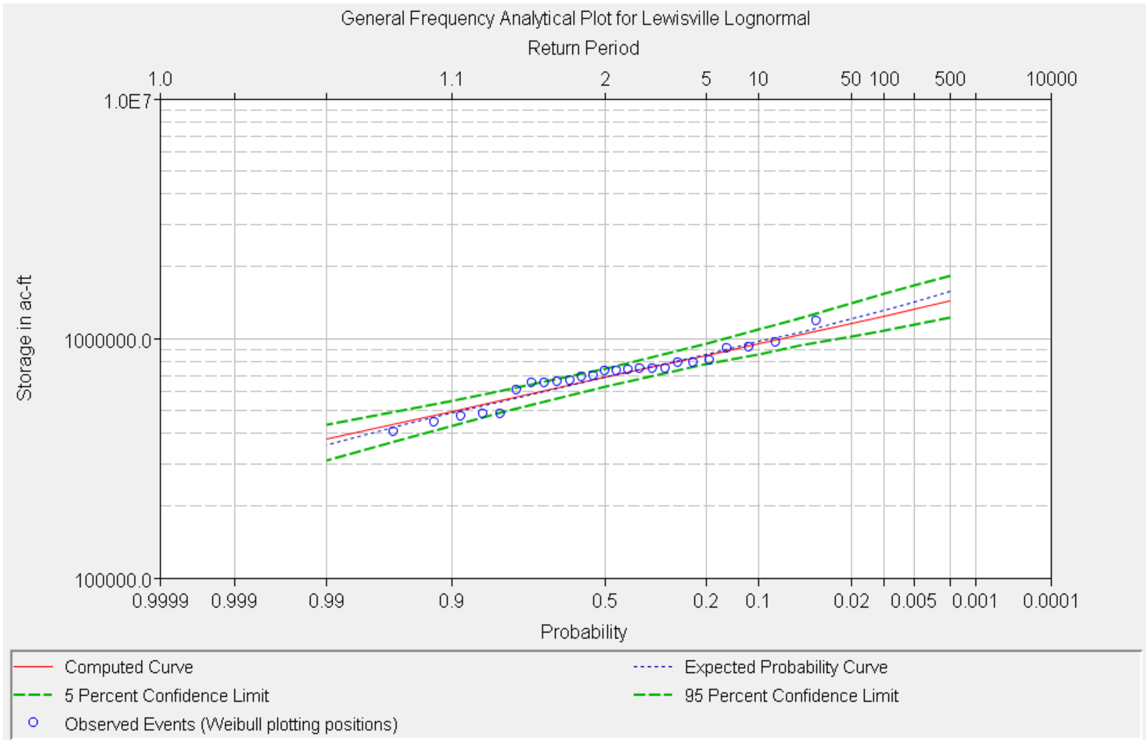

Figure 21. Lewisville Reservoir FFA log-normal probability distribution

Table 20. Lewisville Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
1,294,355	1,380,292	0.2	1,611,515	1,121,387
1,224,742	1,288,255	0.5	1,501,535	1,070,457
1,168,179	1,216,803	1	1,413,771	1,028,493
1,107,415	1,142,865	2	1,321,200	982,749
1,018,579	1,040,003	5	1,189,350	914,391
942,267	954,952	10	1,079,831	853,894
853,531	859,733	20	957,689	780,718
696,276	696,276	50	759,693	639,205
557,006	551,946	80	608,597	497,194
491,728	482,762	90	543,710	427,318
441,757	428,636	95	495,217	373,835
357,545	333,450	99	413,962	285,651

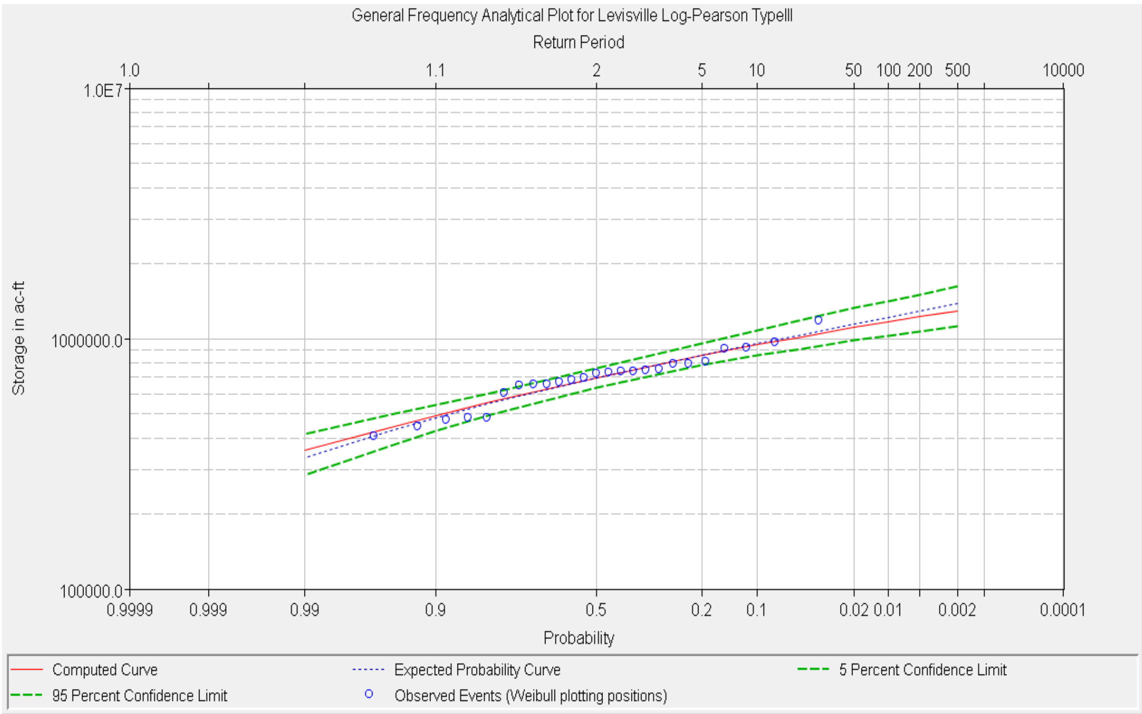

Figure 22. Lewisville Reservoir FFA log-Pearson type III probability distribution

3.4.5 Grapevine Reservoir FFA Based on Observed Annual Storage

A frequency analysis for peak annual storage contents of Grapevine Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The total storage capacity of Grapevine Reservoir below the top of flood control pool is 406,900 acre-feet, which can be to the storage-frequency relationships presented in Tables 21 and 22 and Figures 23 and 24.

Table 21. Grapevine Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	0.95 (ac-ft)
573,600	602,236	0.2	693,347	496,982
519,086	538,634	0.5	617,201	455,006
478,025	492,086	1	560,857	422,935
436,864	446,508	2	505,341	390,330
381,671	386,943	5	432,617	345,738
338,511	341,449	10	377,364	309,973
292,728	294,049	20	320,694	270,837
221,683	221,683	50	238,281	206,241
167,881	167,127	80	181,450	153,241
145,175	143,926	90	158,541	130,228
128,759	127,005	95	142,141	113,596
102,805	99,868	99	116,196	87,622

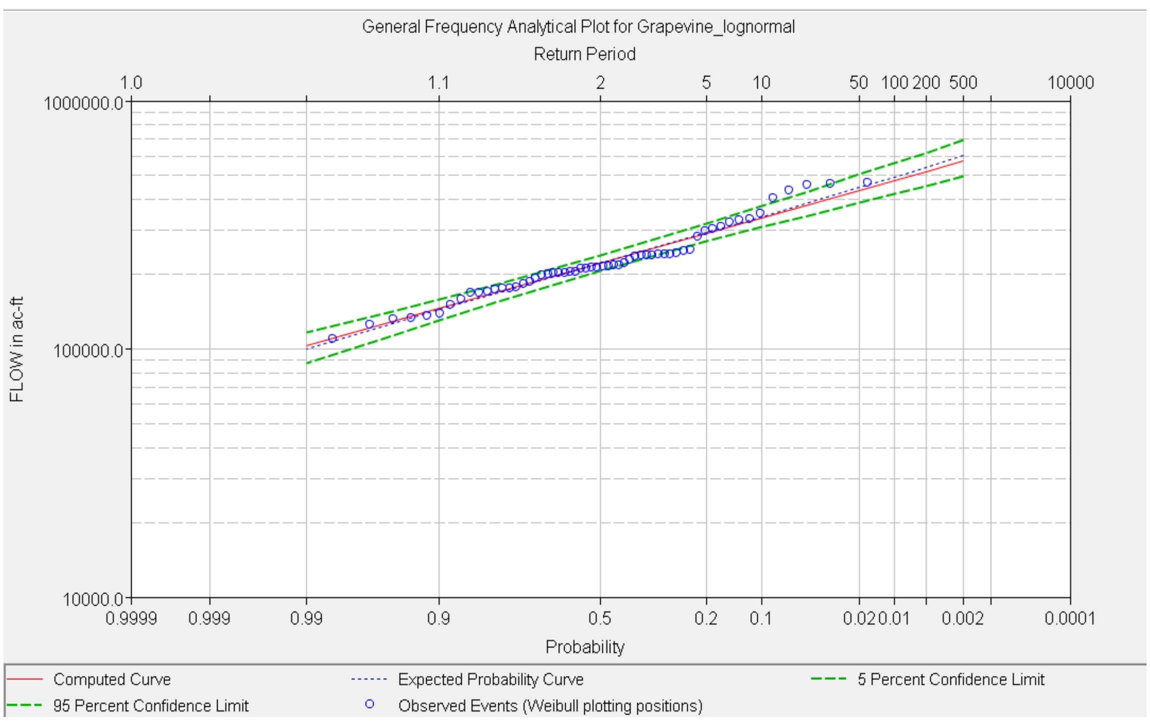

Figure 23. Grapevine Reservoir FFA log-normal probability distribution

Table 22. Grapevine Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
683,862	734,157	0.2	851,506	580,143
593,785	625,656	0.5	721,904	512,370
530,429	551,907	1	632,923	463,794
470,693	484,531	2	550,895	417,163
396,368	403,214	5	451,773	357,723
342,731	346,338	10	382,695	313,512
290,012	291,517	20	317,407	268,466
216,431	216,431	50	232,524	201,218
167,107	166,475	80	180,662	152,459
147,882	146,879	90	161,253	132,975
134,553	133,164	95	147,922	119,457
114,436	112,264	99	127,846	99,192

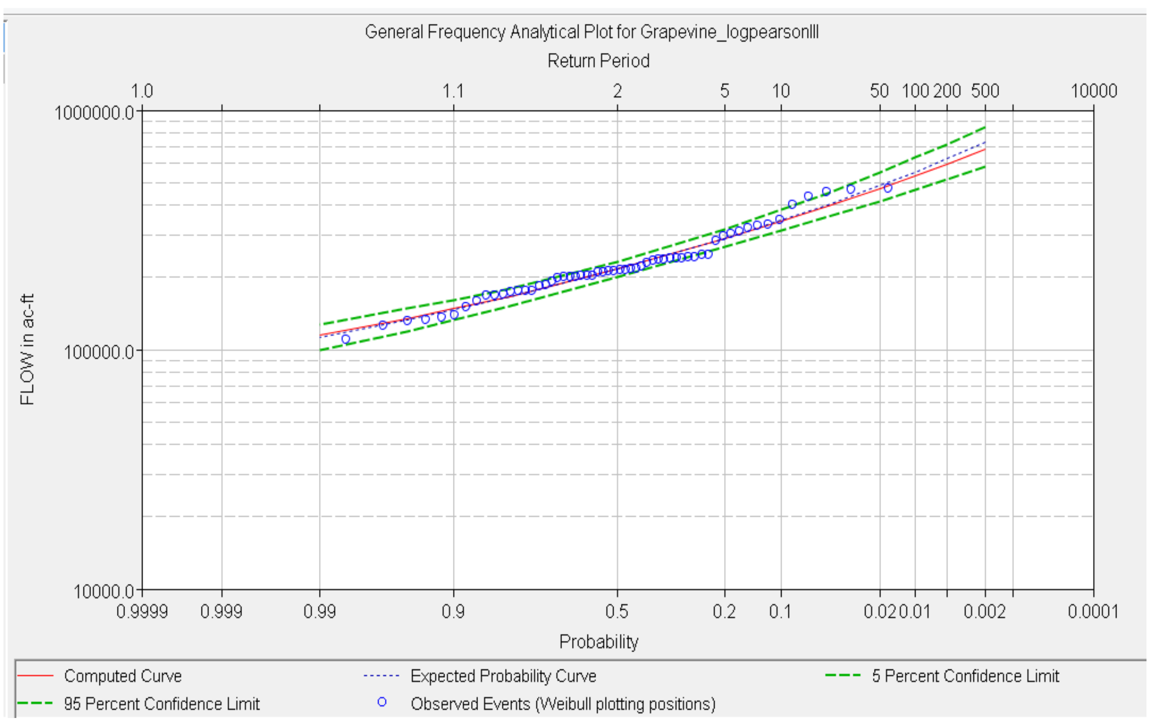

Figure 24. Grapevine Reservoir FFA log-Pearson type III probability distribution

3.4.6 Lavon Reservoir FFA Based on Observed Annual Storage

A frequency analysis for peak annual storage contents of Lavon Reservoir was performed in HEC-SSP alternatively applying the log-normal and log-Pearson type III probability distributions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The total storage capacity of Lavon Reservoir below the top of flood control pool is 748,200 acre-feet, which can be to the storage-frequency relationships presented in Tables 23 and 24 and Figures 25 and 26.

Table 23. Lavon Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
1,080,481	1,143,310	0.2	1,294,885	950,938
1,003,639	1,047,445	0.5	1,183,846	892,438
944,364	976,440	1	1,099,700	846,673
883,591	906,034	2	1,014,917	799,080
799,685	812,330	5	900,644	732,006
731,844	739,087	10	811,006	676,271
657,352	660,721	20	716,134	612,873
535,313	535,313	50	572,027	500,956
435,932	433,709	80	467,569	400,149
391,559	387,722	90	423,736	353,339
358,342	352,764	95	391,473	318,173
303,443	293,475	99	338,455	260,581

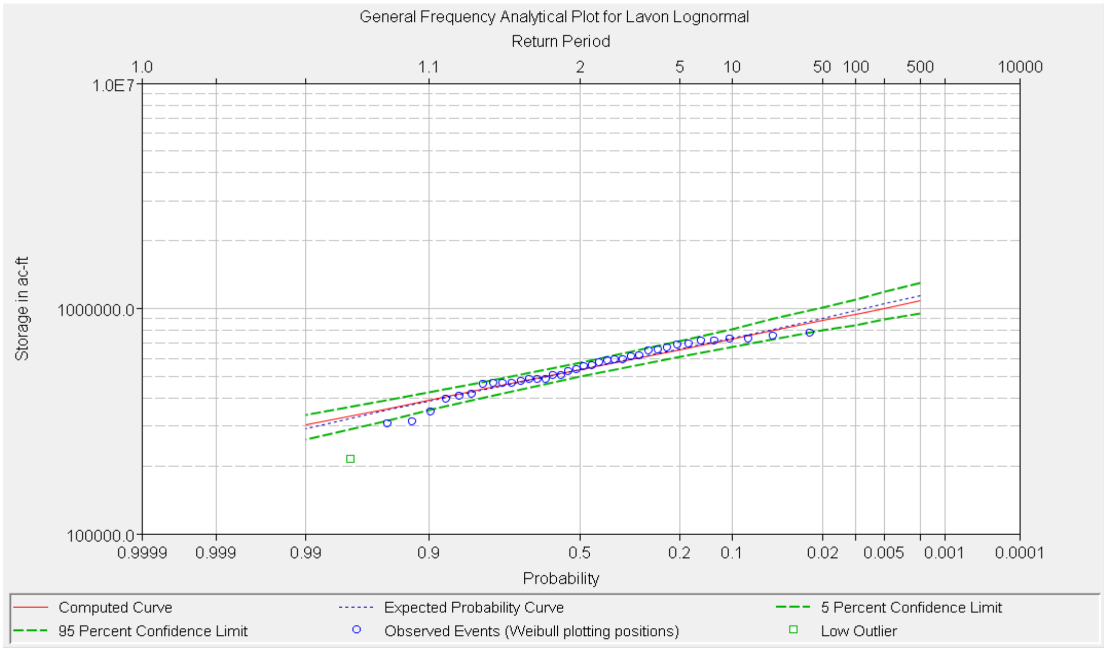

Figure 25. Lavon Reservoir FFA log-normal probability distribution

Table 24. Lavon Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
927,871	955,698	0.2	1,076,537	833,828
890,349	911,888	0.5	1,024,267	804,409
858,533	875,846	1	980,434	779,230
823,025	836,239	2	932,081	750,846
768,633	777,219	5	859,277	706,690
719,555	724,849	10	795,075	665,993
659,774	662,505	20	719,150	614,980
546,824	546,824	50	584,877	512,072
439,731	437,089	80	471,381	404,128
387,481	382,725	90	419,757	349,020
346,713	339,720	95	380,234	305,895
276,776	263,722	99	312,605	233,087

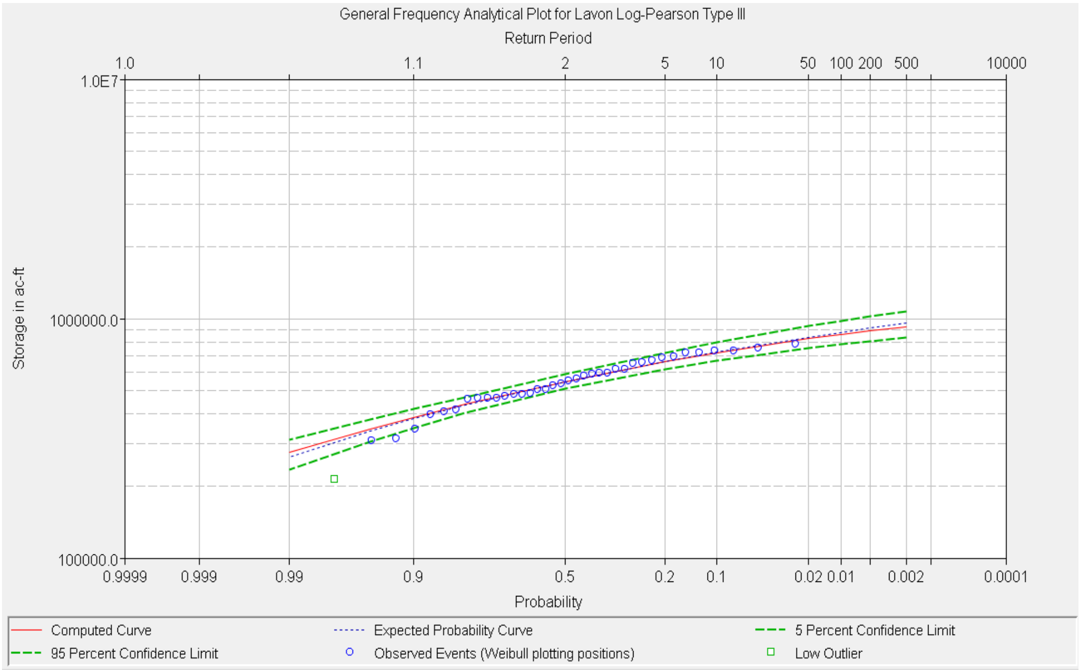

Figure 26. Lavon Reservoir FFA log-Pearson type III probability distribution

3.4.7 Navarro Mills Reservoir FFA Based on Observed Annual Storage

Total storage volumes associated with specified exceedance probabilities for Navarro Mills Reservoir were likewise estimated with the HEC-SSP program based on both the log-normal and log-Pearson type III probability distribution functions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The flood control capacity of Navarro Mills Reservoir is 212,200 acre-feet which can be to the storage-frequency relationships presented in Tables 25 and 26 and Figures 27 and 28.

Table 25. Navarro Mills Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
255,572	270,758	0.2	315,223	218,851
230,991	241,320	0.5	279,743	200,298
212,497	219,907	1	253,568	186,124
193,979	199,048	2	227,850	171,712
169,183	171,943	5	194,287	151,998
149,824	151,357	10	168,897	136,179
129,323	130,010	20	142,981	118,854
97,592	97,592	50	105,605	90,188
73,648	73,258	80	80,135	66,612
63,570	62,926	90	69,940	56,391
56,296	55,392	95	62,661	49,022
44,821	43,311	99	51,172	37,561

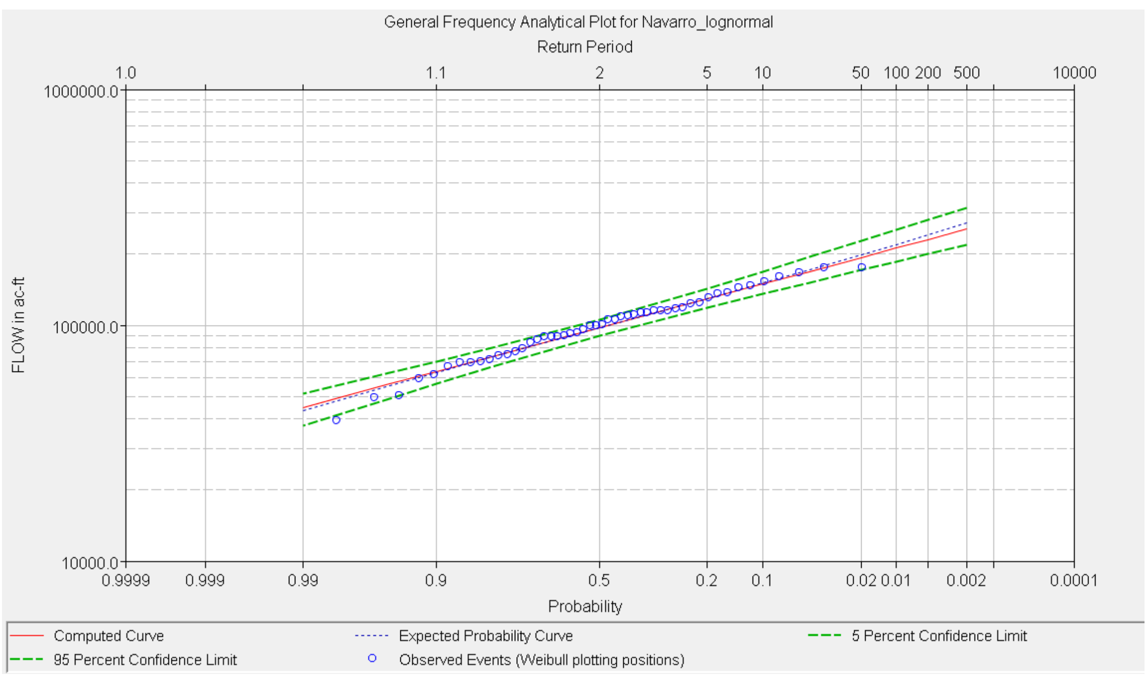

Figure 27. Navarro Mills Reservoir FFA log-normal probability distribution

Table 26. Navarro Mills Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
213,763	221,150	0.2	255,345	187,101
200,785	206,300	0.5	237,242	177,036
190,131	194,437	1	222,573	168,686
178,598	181,788	2	206,904	159,546
161,618	163,592	5	184,272	145,868
146,969	148,143	10	165,223	133,806
129,936	130,514	20	143,740	119,383
100,050	100,050	50	108,353	92,514
74,368	73,914	80	80,871	67,340
62,763	61,990	90	69,130	55,572
54,136	53,048	95	60,503	46,845
40,238	38,381	99	46,543	33,080

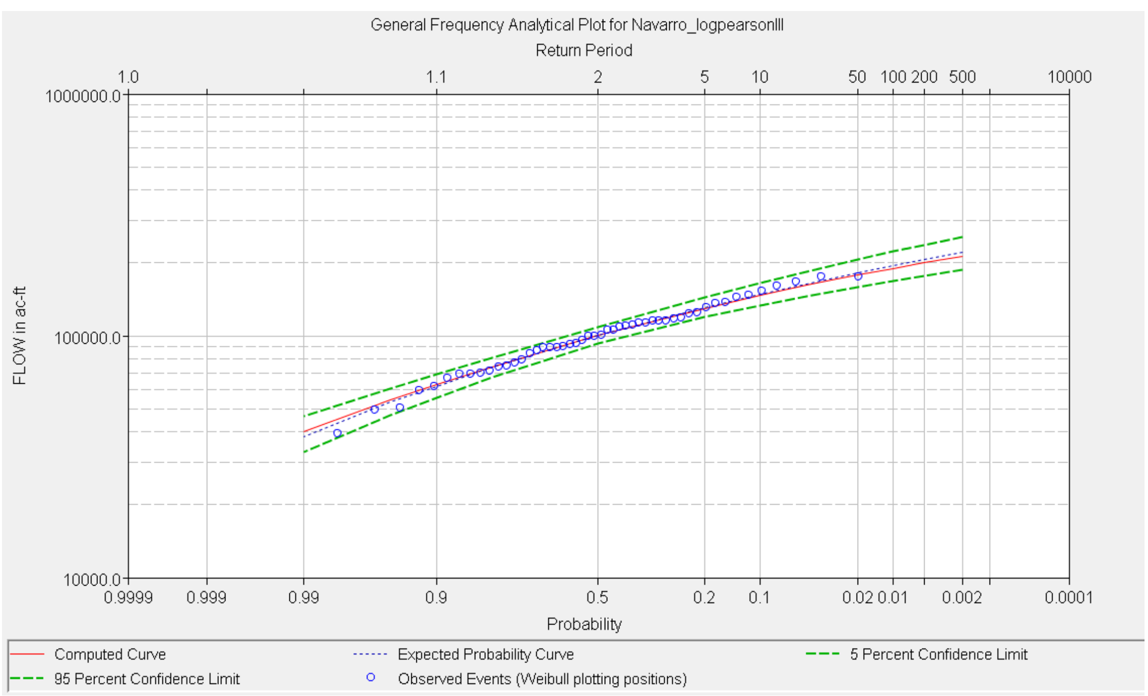

Figure 28. Navarro Mills Reservoir FFA log-Pearson type III probability distribution

3.4.8 Bardwell Reservoir FFA Based on Observed Annual Storage

Total storage volumes associated with specified exceedance probabilities for Bardwell Reservoir were likewise estimated with the HEC-SSP program based on both the log-normal and log-Pearson type III probability distribution functions. Annual observed maximum reservoir storage data was used in order to perform flood frequency analysis which are available USACE Fort Worth website. The flood control capacity of Bardwell Reservoir is 140,000 acre-feet which can be to the storage-frequency relationships presented in Tables 27 and 28 and Figures 29 and 30.

Table 27. Bardwell Reservoir FFA log-normal probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
148,308	154,975	0.2	173,750	131,974
137,537	142,197	0.5	158,922	123,549
129,241	132,659	1	147,677	116,977
120,746	123,142	2	136,338	110,162
109,040	110,392	5	121,038	100,597
99,595	100,370	10	109,018	92,689
89,246	89,607	20	96,266	83,752
72,349	72,349	50	76,781	68,174
58,652	58,415	80	62,499	54,375
52,557	52,151	90	56,473	48,014
48,004	47,417	95	52,034	43,246
40,501	39,458	99	44,748	35,445

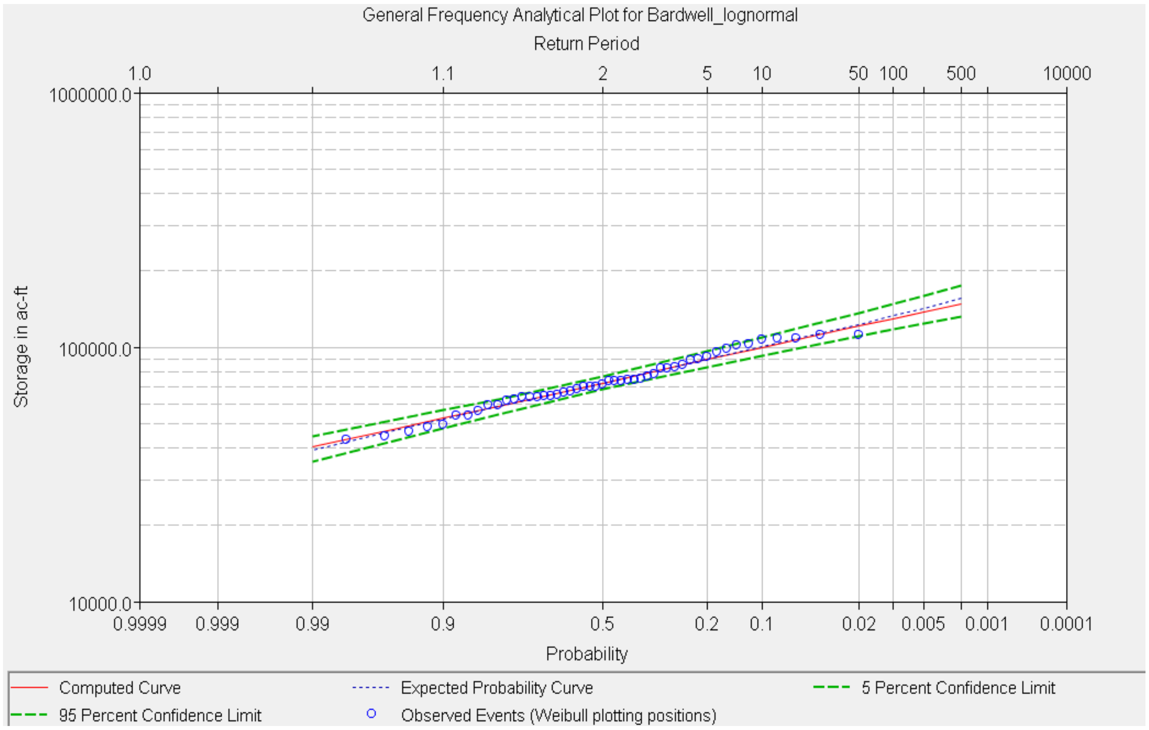

Figure 29. Bardwell Reservoir FFA log-normal probability distribution

Table 28. Bardwell Reservoir FFA log-Pearson type III probability distribution

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence	Limits
			0.05 (ac-ft)	0.95 (ac-ft)
146,708	153,066	0.2	171,532	130,729
136,384	140,854	0.5	157,350	122,640
128,389	131,685	1	146,532	116,298
120,164	122,484	2	135,567	109,691
108,758	110,079	5	120,675	100,363
99,495	100,256	10	108,893	92,605
89,282	89,638	20	96,309	83,783
72,457	72,457	50	76,898	68,278
58,679	58,440	80	62,527	54,403
52,509	52,096	90	56,426	47,964
47,884	47,286	95	51,917	43,120
40,236	39,169	99	44,490	35,172

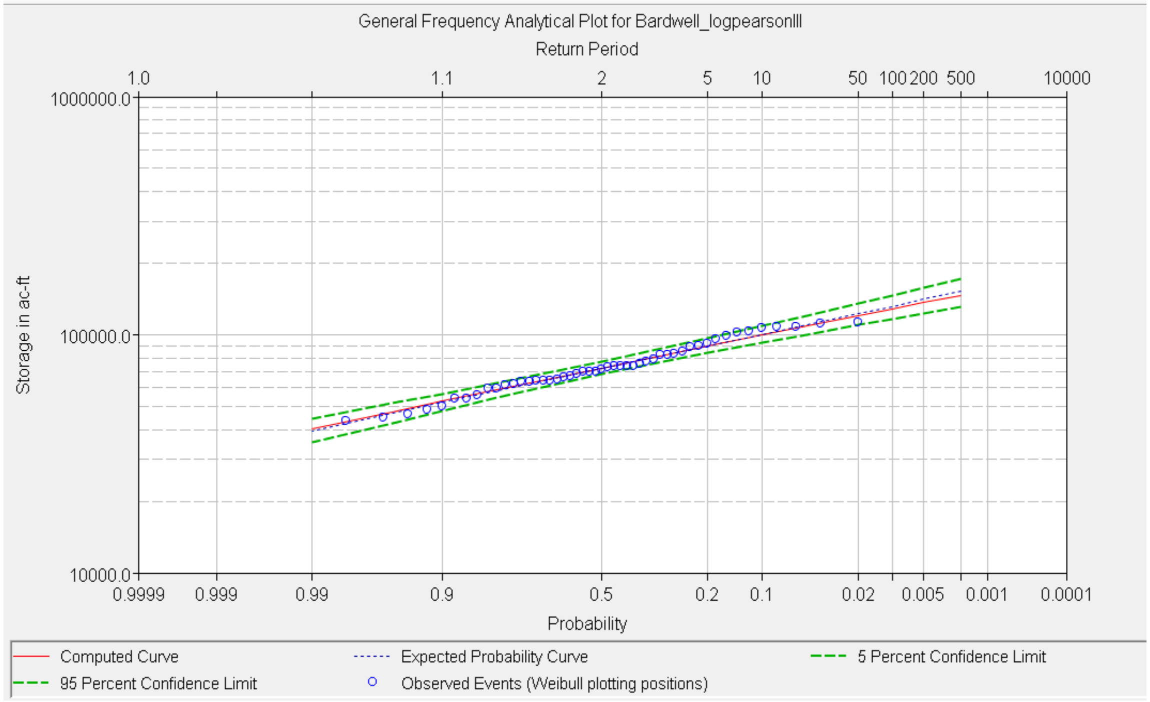

Figure 30. Bardwell Reservoir FFA log-Pearson type III probability distribution

3.5 Discussion of the Frequency Analysis Results

Total storage volumes associated with specified annual exceedance probabilities are presented in the preceding Tables 13-28 and Figures 14-32 for each of the eight reservoirs. HEC-SSP was applied alternatively using the log-normal and log-Pearson type III probability distribution for comparison. The frequency analyses are based on the maximum actual observed storage volume for each year since the reservoir initially filled after construction.

The estimated probability of overtopping the top of flood control pool shown in Table 29 for each of the eight reservoirs is based on linear interpolation of the storage volume versus exceedance probability columns of Tables 13 through 28. The total storage capacity below the top of flood control pool is tabulated in the third column of Table 29.

Although the reservoirs are in the same river basin and operated by the same agency, results of the frequency analyses of observed annual maximum storage are significantly different between the reservoirs. These differences might be the cause of different reservoir operation strategies. As shown in the Table 29, return periods vary between 10 to 1,000 years and 11 to 416 years based on log-normal and log-Pearson type III distributions, respectively. According to Wurbs, federal dams are typically designed for at least a 50-year recurrence interval (Wurbs 1996). Unfortunately, as these results show us, in reality, return period is as low as 10 years for log-normal and 11 years for log-Pearson type III probability distributions for Lewisville Dam. On the other hand, some of them have over 100-year return periods.

The log-normal and log-Pearson type III yield similar results for six of the results. However, the two alternative probability distributions result in very different probability estimates for Joe Pool and Navarro Mills Reservoirs. The return periods shown in Table 29 for Joe Pool and Navarro Mills Reservoirs are 1,000 years and 98 years based on the log-normal distribution and are 140 years and 416 years based the log-Pearson type III distribution, respectively. The plots of Figures 15 through 30 show that the log-Pearson type III probability distribution fits the data better than the log-normal probability distribution. Samples are generally between confidence intervals in the log-Pearson type III probability distribution. Different periods-of-analysis (sample sizes) might cause large differences between the log-normal and log-Pearson type III distributions. The analyses for Benbrook, Joe Pool, Ray Roberts, Lewisville, Grapevine, Lavon, Navarro Mills, and Bardwell Reservoirs have periods-of-analyses of 58, 26, 26, 25, 58, 38, 50, 49 years.

Storage reallocations have been implemented in the past for Lewisville and Lavon Reservoirs. Flood control pool capacity was transferred to conservation purposes by raising the designated top of conservation pool elevations. The top of conservation pool for Lewisville Reservoir was raised from 515 feet to 522 feet on November 30, 1988. Likewise, Lavon Dams` top of conservation pool elevation was raised from 472 feet to 492 feet on December 1, 1975. The flood frequency analyses for these reservoirs are based on storage data for the periods after the reallocations.

Table 29. Recurrence interval of exceeding top of flood control pools

No	Reservoirs	Top of Flood Control (ac-ft)	Percent Chance Exceedance (log-normal)	Return Period (log-normal) (year)	Percent Chance Exceedance (log-Pearson Type III)	Return Period (log-Pearson Type III) (year)
1	Benbrook	164,800	5.30	18.87	7.22	13.85
2	Joe Pool	304,000	0.10	1000.00	0.71	140.85
3	Ray Roberts	1,064,600	6.89	14.51	6.75	14.81
4	Lewisville	959,177	9.60	10.42	8.89	11.25
5	Grapevine	406,900	3.63	27.55	4.57	21.88
6	Lavon	748,200	8.79	11.38	7.08	14.12
7	Navarro Mills	212,200	1.02	98.04	0.24	416.67
8	Bardwell	140,000	0.43	232.56	0.39	256.41

CHAPTER IV

THE WRAP SIMULATIONS AND STORAGE REALLOCATIONS FOR TRINITY RIVER BASIN RESERVOIRS

4.1 Water Availability Model (WAM) for the Trinity River Basin

The Texas Commission on Environmental Quality (TCEQ) maintains a Water Availability Modeling (WAM) system that consists of the generalized Water Right Analysis Package (WRAP) modeling system and WRAP input datasets for all the river basins of Texas. The WRAP input dataset for the Trinity River Basin from the TCEQ WAM system is called the Trinity WAM. The original WRAP and WAM datasets are based on a monthly computational time step. WRAP has been expanded to include daily modeling capabilities, and several WAM datasets including the Trinity WAM have been converted to daily. Flood control operations have been added to the daily models.

The WRAP input dataset for the Trinity River Basin used in this study has a hydrologic period-of-analysis of 1940-2012. Naturalized flows at 40 primary control points are included in the dataset. With the exception of control point 8TRGB on Trinity River at Galveston Bay which represents the basin outlet, all of the primary control points are located at USGS gaging stations. Naturalized flows at secondary control points are calculated within the simulation model based on watershed parameters and primary control point stream flow data. During the execution of simulation, naturalized flows for over 1,300 secondary control points are computed. Figure 31 is a map showing the 40 primary control points.

Figure 31. Map of primary control points in the Trinity WAM (Hoffpauir et al., unpublished report., 2014)

The Trinity WAM has 697 reservoirs which includes 32 major reservoirs with permitted storage capacities exceeding 5,000 acre-feet. The total permitted conservation pool capacity of the 697 reservoirs is 7,596,677 acre-feet. The 32 major reservoirs contain 7,447,970 acre-feet of conservation storage capacity, which is 98 percent of the total in the Trinity WAM. The United States Army Corps of Engineers (USACE) Fort Worth District (FWD) operates the eight reservoirs that have flood control pools.

In the original WAM dataset, Ray Roberts, Lewisville, Lavon, Grapevine, and Benbrook Reservoirs are modeled as component reservoirs representing multiple owners as shown in Table 30. The USACE has more than one contract between different cities or agencies on each reservoir. Thus, reservoir storage capacities are modeled as divided pools and named multiple-owner reservoirs. Three of eight reservoirs Joe Pool, Navarro Mills and Bardwell, are single-owner and modeled as undivided storage capacity.

Table 30. Multiple-owner reservoirs

Reservoir	Control Point	Identifier for Component Reservoirs
Ray Roberts	B2335A	ROBDEN, ROBDAL
Lewisville	B2456A	LEWDE1, LEWDE2, LEWDA1, LEWDA2, LEWDA3
Lavon	B2410A	LAVON0, LAVON1, LAVON2, LAVON3
Grapevine	B2362A	GPVGP1, GPVGP2, GPVDPC. GPVDAL
Benbrook	B5117P	BENBRK, BENBR1, BENBR2, BENBR3, BENBR4

The system of eight reservoirs in the Trinity River Basin originally was designed as multiple-owner (component) reservoirs. Multiple-owner reservoirs system constrains usage of extra water for permits. Thus, each water right can withdraw water from reservoir that specified in the contract. However, in daily time step with flood control operation, component reservoirs did not work in WRAP. Because of that, component reservoirs were changed as single-owner reservoirs. Each reservoir has single conservation pool and flood control pool. By changing this, flood control simulation and flood frequency analysis were performed accurately. This change might affect water reliability for some water rights in the simulation. Table 31 shows single-owner reservoirs on the Trinity River Basin.

Table 31. Single-owner reservoirs on the Trinity River Basin

Reservoir	Reservoir Identifier	Control Point	Storage (acre-feet)	
			Conservation	Flood Control
Benbrook	BENBRK	B5157P	88,250	76,550
Joe Pool	JOPOOL	B3404A	176,900	127,100
Ray Roberts	ROBDEN	B2335A	799,600	265,000
Lewisville	LEWDE1	B2456A	618,400	340,777
Grapevine	GPVGP1	B2362A	162,500	244,400
Lavon	LAVON0	B2410A	456,500	291,700
Navarro Mills	NAVARO	B4992A	63,300	148,900
Bardwell	BARDWL	B5021A	54,900	85,100

The TCEQ WAM system involves variation of datasets for alternative scenarios. Full authorized water use (run 3) and current water use (run 8) are two scenarios that were simulated for water usage. Full authorized scenario (run 3) are performed based on all water right permit holders which withdraw full amount of water that they authorized in their permit and there is not return flow. On the other hand, current water use (run 8) are performed based on water right permit holders which withdraw less amount of water than authorized.

4.2 Simulation of Flood Control Operations in WRAP

Within WRAP, flood control reservoirs operations are processed as a form of water rights in the SIMD file. Flood control rights are activated by FR and WS records, they are simulated with all other water and instream flow rights in a multiple-reservoir operation system. FR record, flood flow (FF) record and flood volume and outflow (FV/FQ) records are specifically for flood control operations. In addition to that SIMD creates an optional output named AFF with annual series peak flows, excess flows and storages. The SIMD AFF file is read by the WRAP program TABLES and performs flood frequency analyses controlled by a 7FFA record in TIN file.

Flood control rights are junior to all other water rights. Decisions about water storing and releasing are made in priority order in FR record fields 3-4 as shown in Table 32. In order to set up a multiple reservoir system, reservoirs share the same priority numbers to store and release water. Thus, reservoirs work as a system. The rank index (Equation 13) is computed to make a decision to store or release water. At the beginning of the each day, rank index is calculated and decision is made for multiple reservoirs. In making decision to store water, the reservoir with the smallest rank index is considered first. In contrast, in making decision to release water, the reservoir with the largest rank index is considered first. The multiplier factor and the addition factor are 1.0 and 0.0 by defaults respectively.

$$rank\ index = (multiplier\ factor)\left[\frac{storage\ content\ in\ FC\ pool}{storage\ capacity\ in\ FC\ pool}\right] + add.\ factor \quad (13)$$

A flood control pool is modeled as two section, controlled (gated) flood pool and uncontrolled (ungated) flood control pool as shown in Figure 32. Controlled means that water releases are done by opening and closing gates at the same time without contributing to downstream flooding. Uncontrolled means that releases are controlled by hydraulic design of outlet structures and there are not any gates operated by people. When water level exceed the top of gated flood control pool, downstream control points are not taken into consideration to release. The zones are defined in the FR record by entering storage capacity values into field 8, 9, and 10.

Table 32. Flood control reservoirs FR record

```
**  CPID STORAGE RELEASE FFNUM     FCMAX   FCTOP  FCGATE FCBOTOM   FCMUL   FCADD    STORAGE WRID     RELEASE WRID
**      |       |       |     FCDEP    |       |       |       |       |       |               |               |
FRB5157P9100000092000000       2          410000  164800   88250          BENBRK-FRSTOR   BENBRK-FRREL
WSBENBRK                                                       4
FRB3404A9100000092000000       2          642400  304000  176900          JOPOOL-FRSTOR   JOPOOL-FRREL
WSJOPOOL
FRB2335A9100000092000000       2         1931900 1064600  799600          ROBDEN-FRSTOR   ROBDEN-FRREL
WSROBDEN                                                       1
FRB2456A9100000092000000       2         2060214  959177  618400          LEWDE1-FRSTOR   LEWDE1-FRREL
WSLEWDE1                                                       2
FRB2362A9100000092000000       2          769400  406900  162500          GPVGP1-FRSTOR   GPVGP1-FRREL
WSGPVGP1                                                       3
FRB2410A9100000092000000       2          921200  748200  456500          LAVON0-FRSTOR   LAVON0-FRREL
WSLAVON0                                                       5
FRB4992A9100000092000000       2          335800  212200   63300          NAVARO-FRSTOR   NAVARO-FRREL
WSNAVARO
FRB5021A9100000092000000       2          268400  140000   54900          BARDWL-FRSTOR   BARDWL-FRREL
WSBARDWL
```

In WRAP terminology, flood control operation is made by defining zones in FR record in DAT file as shown in Table 32. Field 8 of FR record is defined as FCTOP which is cumulative storage volume that correspond maximum allowable water level on the dams. Field 9 of FR record is defined as FCGATE which is cumulative storage volume that correspond to top of the controlled flood control pool level. FCGATE value separates gated and ungated flood control pool. Field 10 of FR record is defined as FCBOTTOM which is top of conservation (bottom of gated flood control pool).

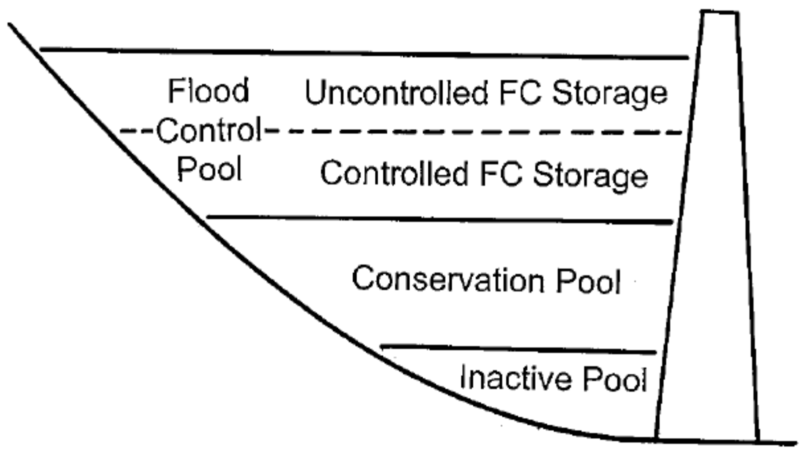

Figure 32. Reservoir pools

When the water level is between FCBOTTOM and FCGATE, which is the controlled (gated) flood control pool, FF and FV/FQ records are applied in order to release water. Table 33 and 34 show FF and FV/FQ records. FF record defines maximum release limit at downstream control points in order to prevent flooding at downstream. FV/FQ records define maximum release that can be made based on the outlet structures. When water is in that level, SIMD calculates both FF and FV/FQ record and makes release by choosing minimum of them. Thus, release is made by checking downstream control points and hydraulic structure capacity. However, when water level is between FCGATE and

FCTOP, which is uncontrolled (ungated) flood control pool, only FV/FQ records are calculated to release water.

The excess flow can be defined as; a max daily flow volume release in a year from the reservoir at which water level above the FCGATE (top of controlled flood control pool) level. In the last column of the AFF file, excess flows are tabulated. If the excess flow is zero that means in that year water has never exceeded the controlled flood control capacity. 7FFA record in the TIN file reads to AFF file and flood frequency tables can be created. Flood frequency tables can be performed only for reservoir storage and also can be performed for summation of storage and excess flow.

A storage volume and surface area relationship is required for evaporation computations. The storage-area relationship is created with SV/SA records as shown in Table 35. Coefficients can be associated in WS records. The maximum number of storage volume and surface area points in SV/SA record can be set in JD record in the field 11. For Trinity WAM, it was defined as 13 points.

Table 33. Flood flow limit FF records

FF 8CTFW	434380.	NDAYS		FFLIM- 8CTFW
FF 8WTFW	2171901.	NDAYS		FFLIM- 8WTFW
FF 8WTGP	4343802.	NDAYS		FFLIM- 8WTGP
FF 8MCGP	2895868.	NDAYS	6	FFLIM- 8MCGP
FF 8DNGR	1447934.	NDAYS		FFLIM- 8DNGR
FF 839	4343802.	NDAYS	7	FFLIM- 839
FFB2457C	5067769.	NDAYS		FFLIM-B2457C
FF 8TRDA	9411570.	NDAYS		FFLIM- 8TRDA
FF 8ETCR	5791736.	NDAYS		FFLIM- 8ETCR
FF 8TRRS	10859504.	NDAYS		FFLIM- 8TRRS
FF 8RIDA	1447934.	NDAYS	11	FFLIM- 8RIDA
FF 8WABA	1447934.	NDAYS	12	FFLIM- 8WABA
FFB5023A	2895868.	NDAYS		FFLIM-B5023A
FF 8TROA	17375207.	NDAYS		FFLIM- 8TROA

Table 34. Flood control reservoir storage volume-outflow FV/FQ records

FVBENBRK	0	88250	164800	258600	410000
FQ	0	23088	25944	60892	319719
FVJOPOOL	0	176900	304000	362700	642400
FQ	0	6863	7696	7696	32455
FVROBDEN	0	799600	1064600	1261500	1931900
FQ	0	13090	13686	14083	43834
FVLEWDE1	0	618400	959177	2060214	
FQ	0	20231	21818	454413	
FVGPVGP1	0	162500	406900	769400	
FQ	0	11683	14360	379458	
FVLAVON0	0	456500	748200	921200	
FQ	0	1983	2579	712066	
FVNAVARO	0	63300	212200	335800	
FQ	0	444297	444297	444297	
FVBARDWL	0	54900	140000	268400	
FQ	0	4681	6188	154711	

Table 35. Storage volume-surface area (SV/SA) records for flood control reservoirs

SVROBDEN	0	5000	20000	65000	110000	210000	340000	380000	480000	630000	730000	799600	1064601
SAROBDEN	0	800	2500	4900	7400	11000	14500	16500	20000	24000	28000	29350	36900
SVLEWDE1	0	510	3824	39399	86203	138752	206931	291014	358343	441620	537846	648418	981764
SALEWDE1	0	100	1400	4630	7750	9740	12850	15920	18170	22630	25500	29700	39168
SVGPVGP1	0	104	515	1421	3441	7990	15986	28203	45537	77128	129291	181259	425501
SAGPVGP1	0	30	86	216	537	979	1686	2420	3358	4518	5901	7190	12710
SVLAVON0	0	1520	5660	12700	41100	72800	115900	171900	240400	321500	415200	456500	748201
SALAVON0	0	910	1810	2870	5190	7470	9970	12500	15000	17500	20000	21400	29450
SVJOPOOL	0	2500	5160	11180	24620	37620	54460	75260	100100	129000	162300	176900	304001
SAJOPOOL	0	430	650	1170	2230	2990	3760	4560	5360	6220	7110	7470	10940
SVNAVARO	0	2370	6960	12900	17100	22100	27900	34600	42400	51300	60800	63300	212201
SANAVARO	0	530	1070	1950	2310	2690	3100	3610	4200	4570	4600	5070	11700
SVBARDWL	0	1077	3074	7270	23467	35867	54900	140001					
SABARDWL	0	215	610	1082	2201	2800	3570	6040					
SVBENBRK	0	145	696	1400	6200	9911	15750	32400	44169	59800	73897	88251	164801
SABENBRK	0	28	102	270	720	1050	1360	2120	2520	2960	3400	3770	5820

4.3 Types of Storage Reallocation

Reservoir storage reallocation and operation of dams are becoming more important than before because of increasing population, water demands, global warming as well as flood events. Reservoir reallocation between purposes might be categorized as follows: first, reallocation between flood control pool and conservation pool, second, reallocation between different conservation purposes, and lastly, temporary use of sediment reserve (Wurbs and Carriere 1988). The most common reallocation is reallocation between conservation pool and flood control pool. This research particularly focused on reallocation from flood control pool to conservation pool.

Reallocation between conservation pool and flood control pool is implemented by raising or lowering the existing top of conservation pool level. Frequent flood events, flash floods, or extra water in the conservation might lead reallocation from storage capacity conservation pool to flood control pool. Physically, lowering top of conservation pool automatically increase storage capacity of flood control pool. During a flood event, more water can be stored and downstream flooding risk decreases. On the other hand, increase of water demand, extreme droughts, less frequent flood events might lead reallocation from flood control pool to conservation pool. In order to increase water reliability, more water must be stored in the conservation pools.

Reallocation between flood control and conservation pool also affects recreation facilities and roads around lakes. By increasing top of conservation pool level, some facilities might be under water. Also, it might affect roads around lakes. Likewise, lowering top of conservation pool elevation might affect dockside, natural habitat for fish as well as other recreational facilities.

Storage reallocations between conservation and flood control pool can be permanent or seasonal. A permanent reallocation between conservation pool and flood control pool is raising or lowering top of conservation level for good. Permanent reallocation might be needed for high water demand for all seasons. Moreover, if precipitation time is various and has different intensity among seasons for each year, permanent reallocation works better. In this research, permanent reallocations from flood control pool to conservation pool for different capacity were simulated.

Seasonal reallocation between flood control and conservation pool is temporary raising or lowering top of conservation elevation. In other words, in a year, top of conservation pool changes based on water demand and flood threat. To illustrate, if summers or certain period of time has drought in a year and spring has a flood threat, during the flood months, top of conservation pool elevation stays lower in order to protect downstream by storing water. Beginning of drought season, top of conservation pool is raised that helps to store more water. To determine seasonal reallocation, observed flows or storage levels of reservoirs should be closely monitored for each month in a year and they should be compared same month with previous year`s level. In this research seasonality study was analyzed in the following pages.

4.3.1 Alternative Permanent Reallocation Simulation Plans and Runs

The simulations were performed with WRAP for Trinity WAM. This research includes three alternative permanent reallocations from flood control storage capacity to conservation storage capacity simulations. Reallocation simulations were executed by converting 10%, 20%, and 50% of the flood control pool to the conservation pool. The current storage capacities and alternative reallocated storage capacities are shown in the Table 36. Simulation time step was daily and simulation period was from 1940 to 2012. The flood control and conservation storage capacity frequency analyses were performed. In the following pages, simulation runs are explained in details. Post simulation studies provided water reliability tables and flood frequency analyses tables.

Table 36. Reservoirs storage capacity with alternative reallocations

Reservoirs		Benbrook	Joe Pool	Ray Roberts	Lewisville	Grapevine	Lavon	Navarro Mills	Bardwell
Reservoir Identifier		BENBRK	JOPOOL	ROBDEN	LEWDE1	GPVGP1	LAVON0	NAVARO	BARDWL
Control Point		B5157P	B3404A	B2335A	B2456A	B2362A	B2410A	B4992A	B5021A
Existing Capacity (D1) (ac-ft)	Conservation	88250	176900	799600	618400	162500	456500	63300	54900
	Flood Control	76550	127100	265000	340777	244400	291700	148900	85100
	Total	164800	304000	1064600	959177	406900	748200	212200	140000
10 % S. Reallocation (D4) (ac-ft)	Conservation	95905	189610	826100	652478	186940	485670	78190	63410
	Flood Control	68895	114390	238500	306699	219960	262530	134010	76590
	Total	164800	304000	1064600	959177	406900	748200	212200	140000
20 % S. Reallocation (D5) (ac-ft)	Conservation	103560	202320	852600	686555	211380	514840	93080	71920
	Flood Control	61240	101680	212000	272622	195520	233360	119120	68080
	Total	164800	304000	1064600	959177	406900	748200	212200	140000
50 % S. Reallocation (D6) (ac-ft)	Conservation	126525	240450	932100	788789	284700	602350	137750	97450
	Flood Control	38275	63550	132500	170389	122200	145850	74450	42550
	Total	164800	304000	1064600	959177	406900	748200	212200	140000

4.3.2 Evaluation of Seasonal Reallocation

The system of eight USACE Reservoirs on the Trinity River Basin was assessed in this research. Kim and Wurbs and Carriere investigated seasonal operation for Brazos River Basin in Texas (Kim 2009; Wurbs and Carriere 1988). They simulated by raising top of conservation pool elevation in summer and fall and lowering top of conservation pool elevation in winter and spring in order to store more water to use in drought seasons.

As first step, daily observed storages were assessed to decide seasonality. To determine drought and rainy months, daily observed storage values were split up each year and plotted to compare reservoir storage elevation each month for all years and reservoirs.

Figure 33-40 provide a better understanding of seasonality. According to plots, the Trinity River Basin reservoirs storage levels were above the top of conservation pool at least one year except for Benbrook Reservoir. Benbrook Reservoir`s water levels are very close to top of conservation pool elevation from July to October and there was not any release because of flood. In other words, flood control storage has not been used to store water. However, the seven reservoirs` water level passed to top of conservation level and flood control pool stored water.

All in all, plots of reservoirs` elevations clearly show that flood can occur any time of the year in the Trinity River Basin. The seven of eight reservoirs` flood control pools were used all months in different years. Only Benbrook Reservoir was convenient to raise top of conservation pool elevation between July and October. Also return period of exceeding flood control pool values were as low as 10-year for some dams. Therefore, in this study, seasonal reallocation was not suggested for these reservoirs.

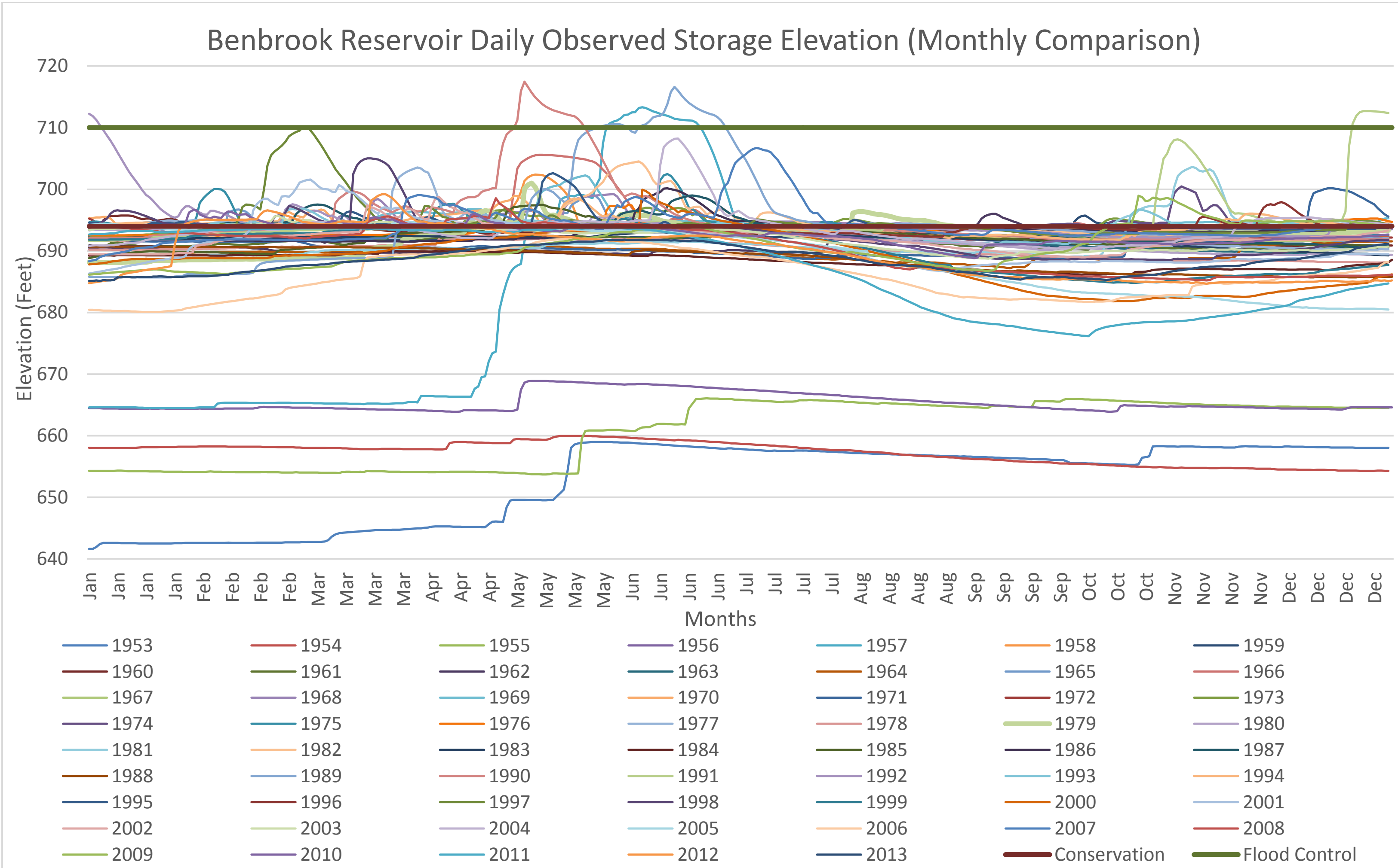

Figure 33. Benbrook Reservoir daily observed storage elevation (monthly comparison)

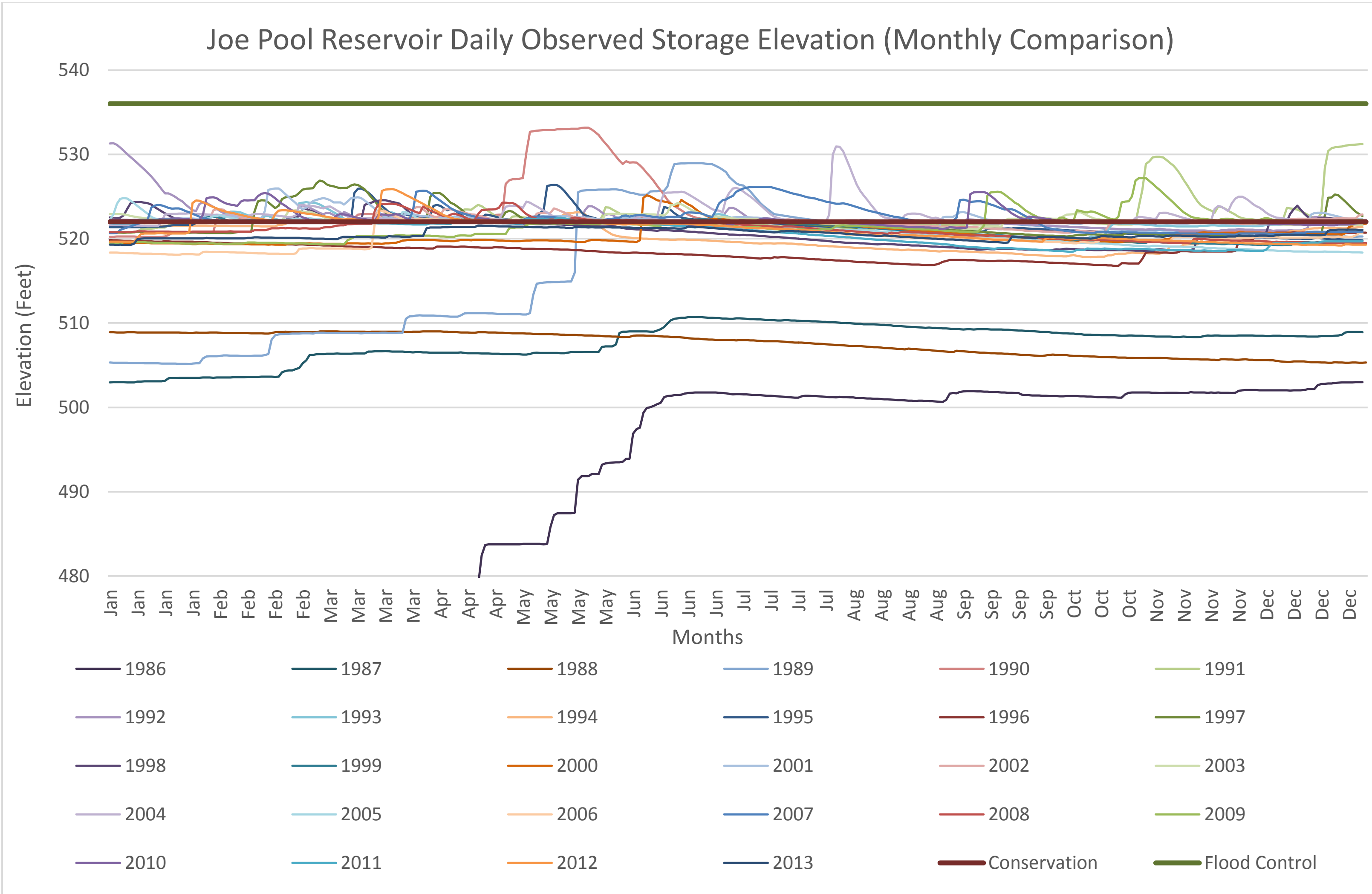

Figure 34. Joe Pool Reservoir daily observed storage elevation (monthly comparison)

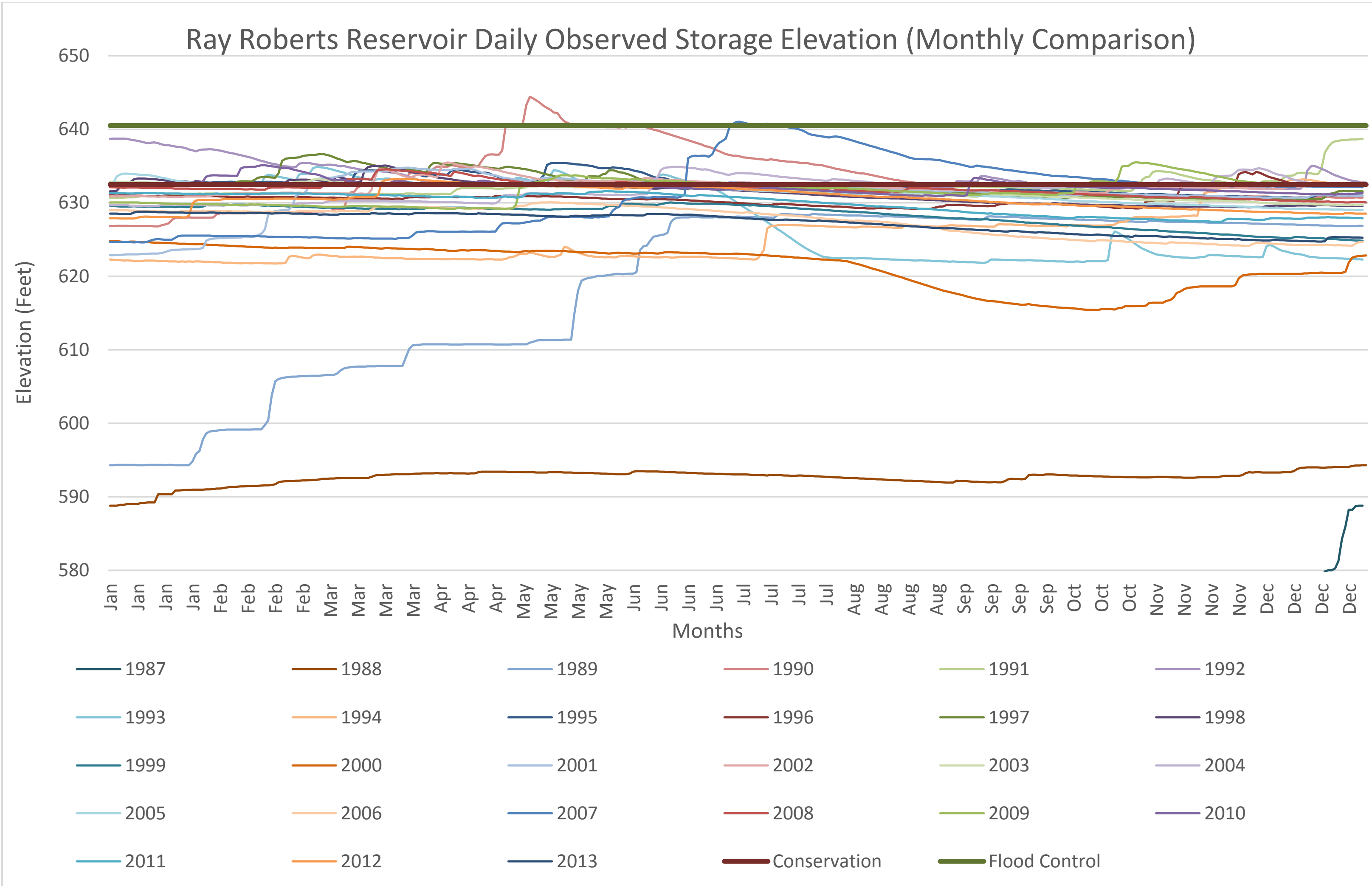

Figure 35. Ray Roberts Reservoir daily observed storage elevation (monthly comparison)

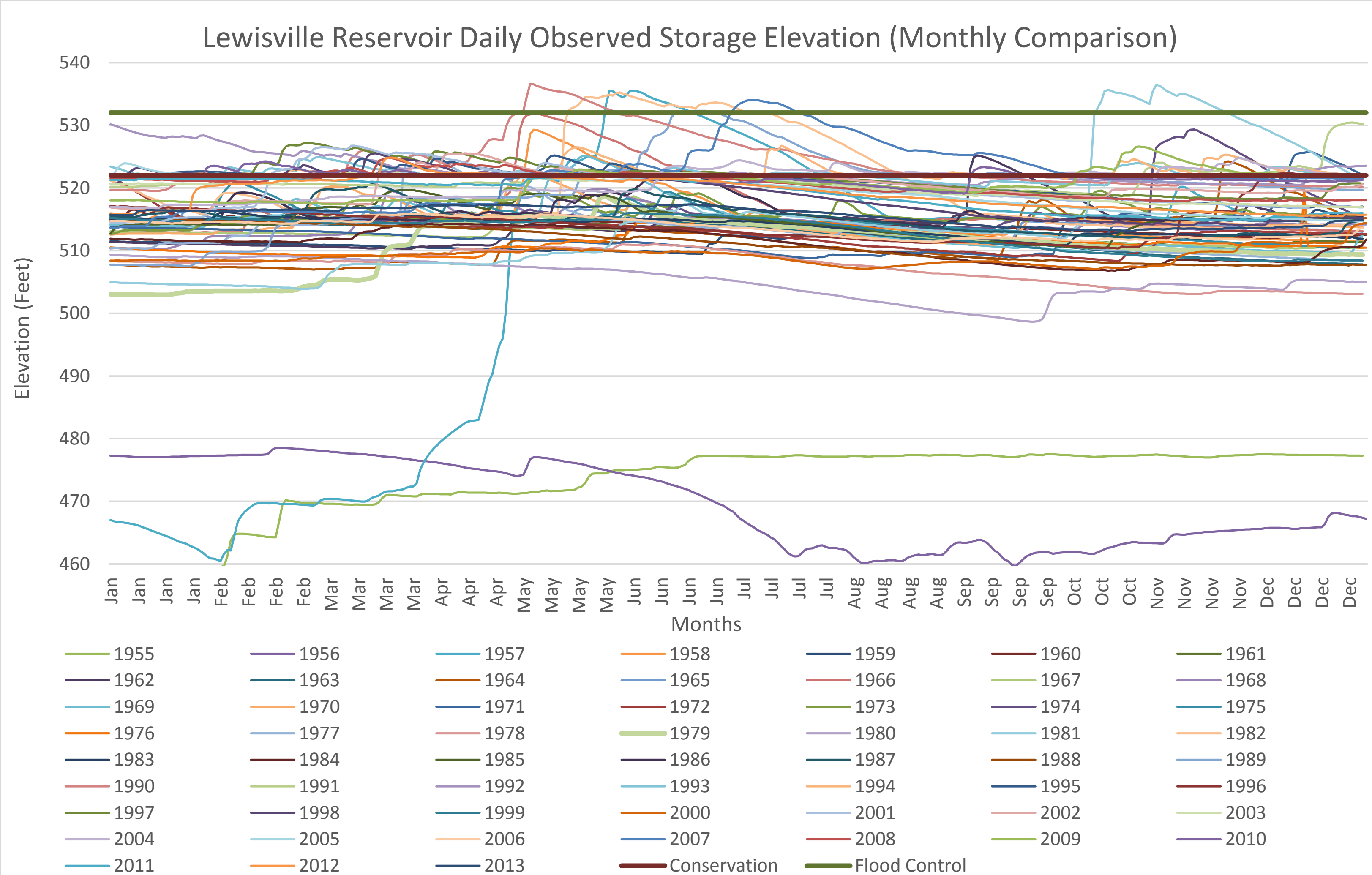

Figure 36. Lewisville Reservoir daily observed storage elevation (monthly comparison)

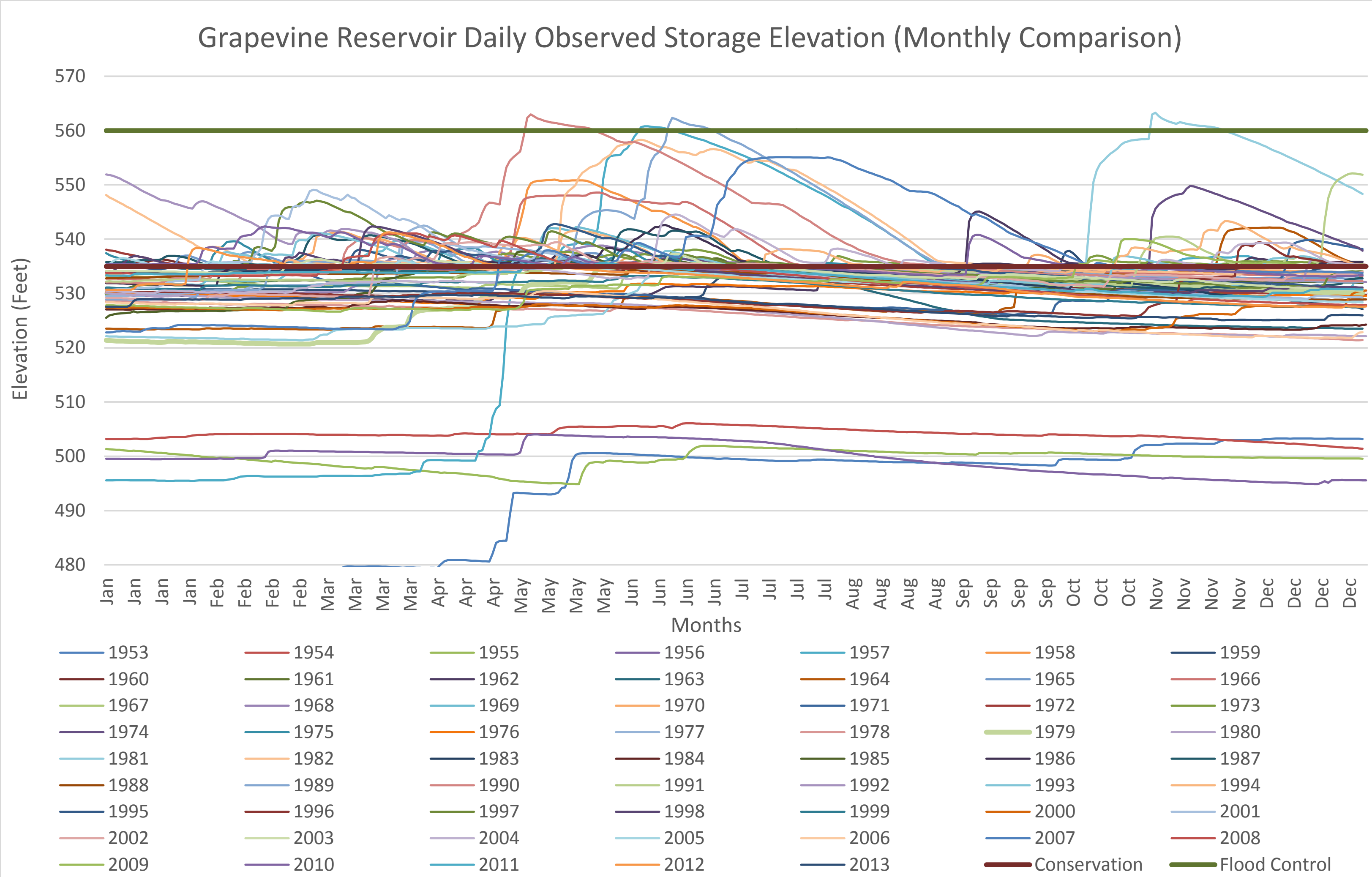

Figure 37. Grapevine Reservoir daily observed storage elevation (monthly comparison)

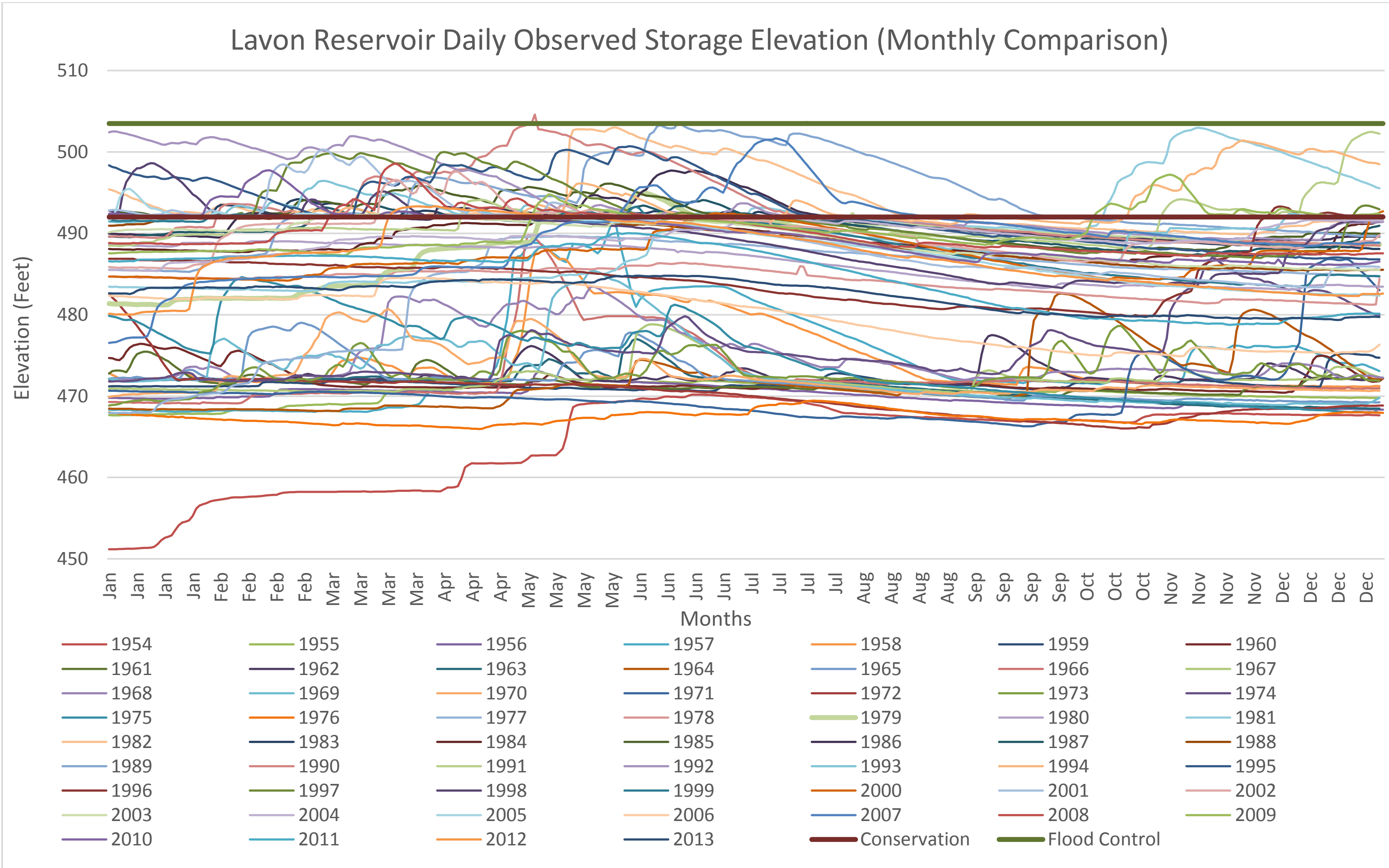

Figure 38. Lavon Reservoir daily observed storage elevation (monthly comparison)

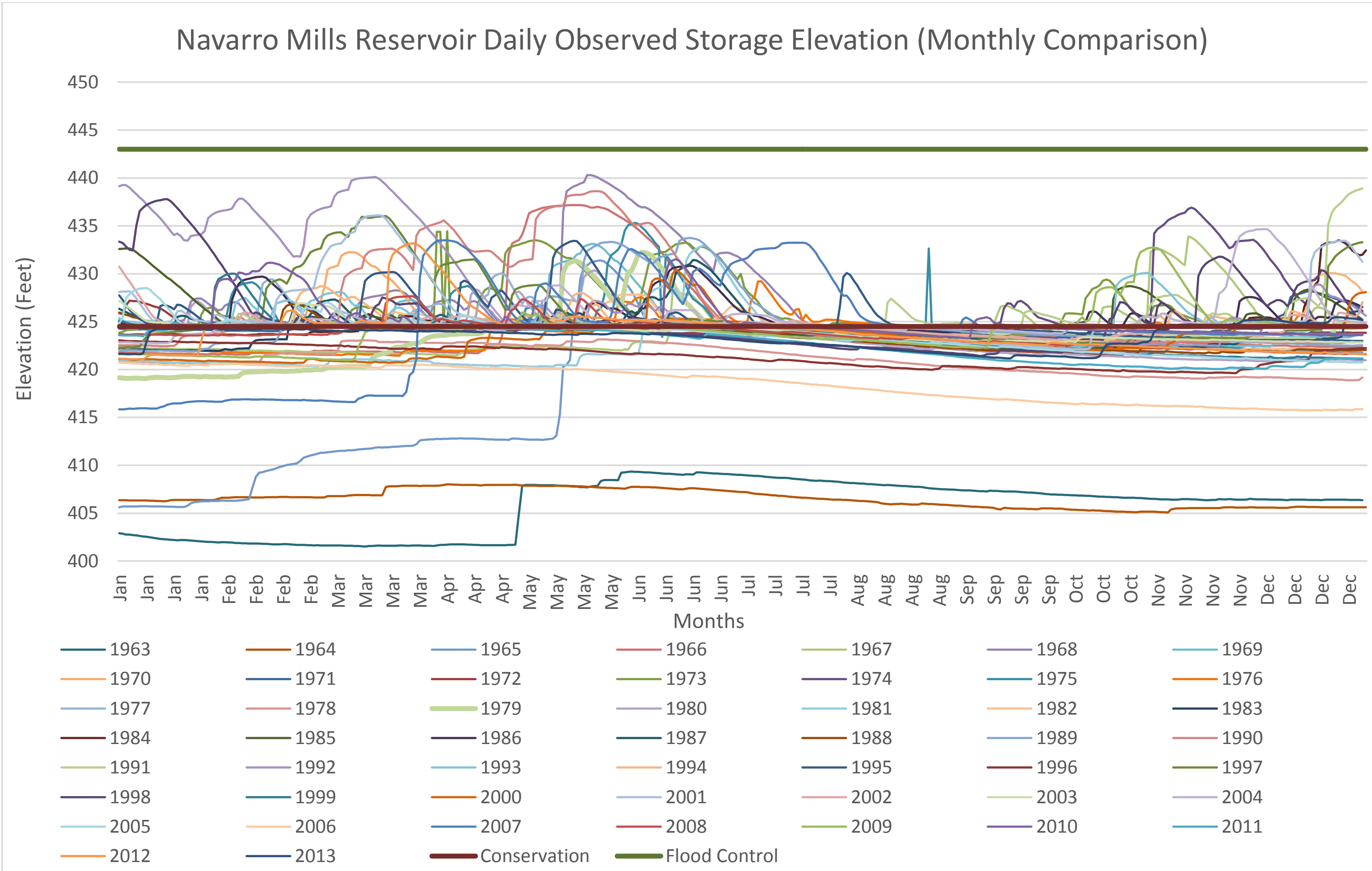

Figure 39. Navarro Mills Reservoir daily observed storage elevation (monthly comparison)

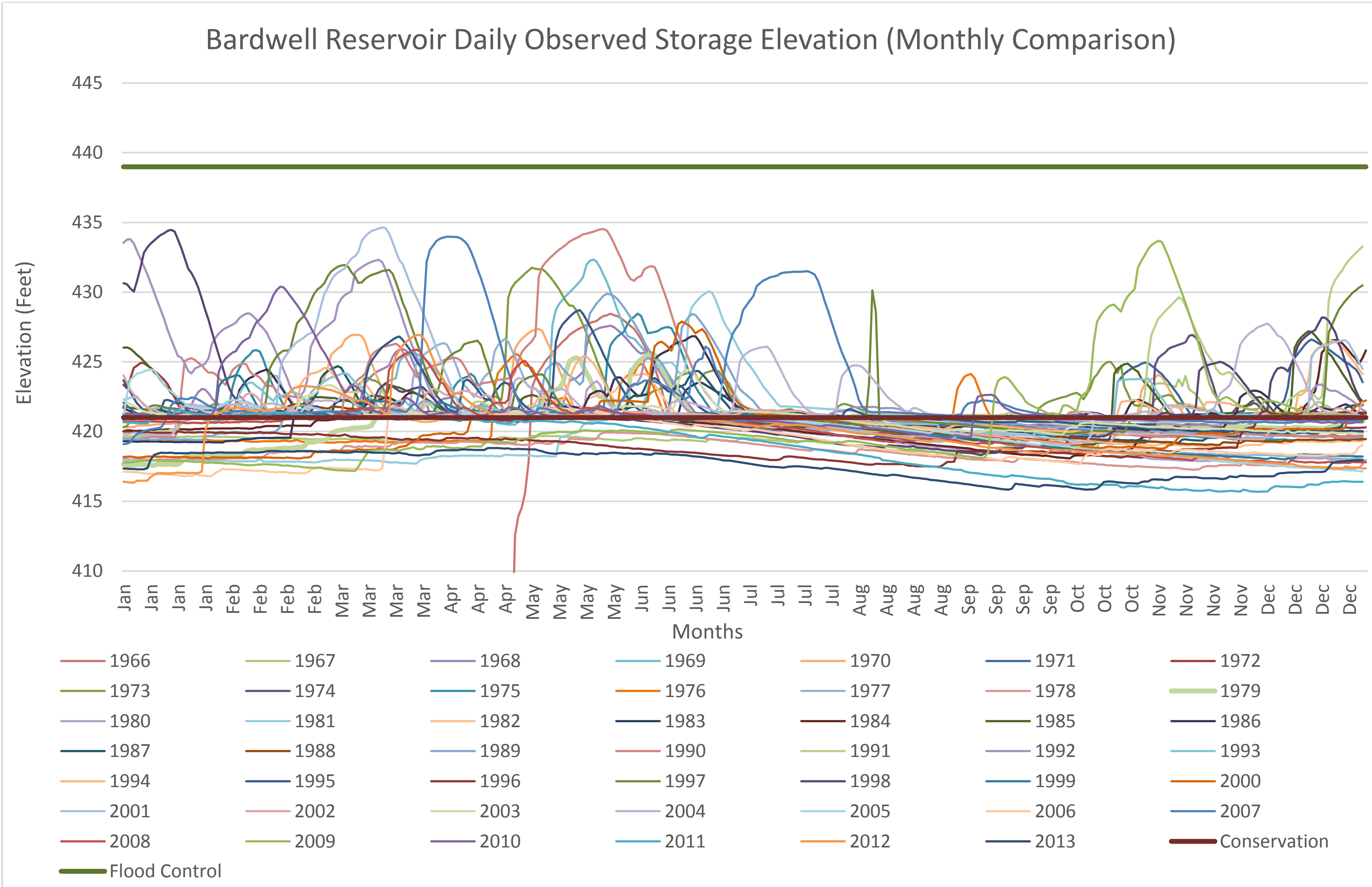

Figure 40. Bardwell Reservoir daily observed storage elevation (monthly comparison)

4.4 Alternative Simulation Runs

The objective of the WRAP simulation study was to assess impact permanent storage reallocation between flood control and conservation pool on the flood frequency analyses and water supply reliabilities. The Trinity WAM data set was modeled in WRAP and developed for flood control operation in daily time step. The WRAP post simulation, which are tables and graphs, provided basic data for output such as, reservoir storage levels, regulated flows, flood frequency tables and water reliability tables.

The thesis research involved nine alternative simulation runs in order to enhance understanding impacts on permanent storage reallocation on water supply and flood frequency analysis and confirm its validity. Daily and monthly time step simulations` hydrologic period-of-analysis were 1940 through 2012. Alternative simulation runs, as shown in Table 37, include six daily time step and three monthly time step. Daily time step simulations have flood control operation, although monthly time step simulations don't have flood control operation. Some of reservoirs were simulated as component (multiple-owner) reservoirs while rest of them were simulated as single owner reservoirs. Also, simulations included current water use and full authorized water use scenarios. Three of six daily time step runs were performed for storage reallocation. Permanent reallocations simulations involved three alternative scenarios which were allocating reservoir storage from flood control pool to conservation pool with amount of 10%, 20%, and 50% for eight reservoirs in the Trinity River Basin.

Alternative simulation runs are defined as follows.

Table 37. Alternative simulation runs

Simulation Label	Time Step	Water Use Scenario	Flood Control Operation	Component Reservoir	Reallocation
D1	Daily	Authorized	Yes	No	No
D2	Daily	Authorized	Yes	Yes	No
D3	Daily	No Withdrawn	Yes	No	No
D4	Daily	Authorized	Yes	No	Yes (10%)
D5	Daily	Authorized	Yes	No	Yes (20%)
D6	Daily	Authorized	Yes	No	Yes (50%)
M1	Monthly	Authorized	No	Yes	No
M2	Monthly	Authorized	No	No	No
M3	Monthly	Current	No	Yes	No

Simulation D1: Simulation D1 was performed in daily time step and water use scenario was full authorized. There was flood control operation and designed as single owner reservoirs for eight Trinity River Basin Reservoirs.

Simulation D2: Simulation D2 was performed in daily time step and water use scenario was full authorized. There was flood control operation and designed as multiple-owner (component) reservoirs for eight Trinity River Basin Reservoirs.

Simulation D3: Simulation D3 was performed in daily time step and there was not water use scenario, water rights for eight reservoirs, were changed to zero. There was flood control operation and designed as single owner reservoirs for eight Trinity River Basin Reservoirs.

Simulation D4: Simulation D4 was performed in daily time step and water use scenario was full authorized. There was flood control operation and designed as single owner reservoirs for eight Trinity River Basin Reservoirs. In addition, there was storage reallocation from flood control pool to conservation pool the amount of 10% of flood control storage capacity for eight reservoirs.

Simulation D5: Simulation D5 was performed in daily time step and water use scenario was full authorized. There was flood control operation and designed as single owner reservoirs for eight Trinity River Basin Reservoirs. In addition, there was storage reallocation from flood control pool to conservation pool the amount of 20% of flood control storage capacity for eight reservoirs.

Simulation D6: Simulation D6 was performed in daily time step and water use scenario was full authorized. There was flood control operation and designed as single owner reservoirs for eight Trinity River Basin Reservoirs. In addition, there was storage reallocation from flood control pool to conservation pool the amount of 50% of flood control storage capacity for eight reservoirs.

Simulation M1: Simulation M1 was performed in monthly time step and water use scenario was full authorized. There was not flood control operation and designed as multiple-owner (component) reservoirs for eight Trinity River Basin Reservoirs.

Simulation M2: Simulation M2 was performed in monthly time step and water use scenario was full authorized. There was not flood control operation and designed as single-owner reservoirs for eight Trinity River Basin Reservoirs.

Simulation M3: Simulation M3 was performed in monthly time step and water use scenario was current use. There was not flood control operation and designed as multiple-owner (component) reservoirs for eight Trinity River Basin Reservoirs.

CHAPTER V

EVALUATION OF SIMULATION RESULTS

The nine alternative simulation runs were evaluated by comparing simulation results and observed data in order to enhance understanding the impact of alternative permanent storage reallocations on water reliabilities and flood frequency analyses for the system of eight reservoirs in the Trinity River Basin. In Section 4.4 alternative simulation runs were described in detail. Simulation D1 is main run which was in daily time step, modeled as full authorized water use, set up as existing storage allocation, has flood control operation and designed as single-owner reservoirs. Simulation D2 is identical with D1 except reservoirs were modeled as multiple-owner. D3 is identical with D1 except water rights were entered as zero in order to see flood frequency changes when conservation pool is full. Three of six daily time step simulations, D4, D5, and D6 were only for alternative permanent storage reallocation for eight reservoirs. Simulation M1, M2, and M3 are monthly time step runs and include current water use and full authorized water use; however, there is not flood control operation in monthly time step simulations.

The main D1 simulation`s results were compared with all other daily time step simulations and M1 simulation`s results in order to show effects of alternative simulation changes. Likewise, Simulation M1`s results were compared with all other monthly time step simulations` results. Comparisons were made based on storage level of reservoirs, flood frequency analyses, return period of flood event, and water reliabilities. Flood frequency analyses and return period of floods also were compared with actual observed reservoirs data and HEC-SSP results.

5.1 Simulation D1 versus Observed Annual Maximum Reservoirs Storage

The simulation D1 represents existing reservoir storage, full authorized water use, daily time step, single-owner, and has flood control operation. The simulation D1 was considered as base simulation and compared with other alternative simulation runs. In order to check it`s validity, D1 storage capacity, flood return periods were compared with observed values. In addition to that, water reliability summary table was developed to compare with other simulations result in order to show differences.

Flood control reservoir operations are processed as water rights and activated by FR and WS records in WRAP. As described in the Chapter 4, if FR record shares same priority number, reservoirs become multiple-reservoir system to store and release water. Then, rank indices make decision to release and store water. If rank indices are same, first FR record order in DAT file has priority. In the simulation D1, reservoirs were listed from upstream to downstream in DAT file. Alternatively, order of FR records were changed and simulations were run. As a result, original simulation D1 and alternative simulations changed around 1% in reservoir storages. The reason for this little change was, each day rank index was calculated and priority of the reservoir was changed to store and release water. The changes were very small because one day simulation time step was short enough to keep reservoirs water level in balance.

5.1.1 Comparison of Reservoirs Storage

The system of eight Trinity River Basin reservoirs storage capacities for simulation D1 were compared with maximum annual observed storage capacities. As shown in Figures 41-48, straight blue line represents D1 likewise, red points and green lines represent annual maximum observed storage levels and top of controlled flood control pool level respectively. As a result of this comparison, Benbrook, Joe Pool, Lavon, Navarro Mills and Bardwell Reservoirs storage levels matched with D1 and annual maximum observed data. However, simulation results of Ray Roberts, Lewisville, and Grapevine Reservoirs` storage levels were lower than observed values. Reason for these differences might be simulation duration (1940-2012) longer than observed data. Another reason might be, D1 simulation represents full authorized scenario, and contractors do not use all water that they authorized.

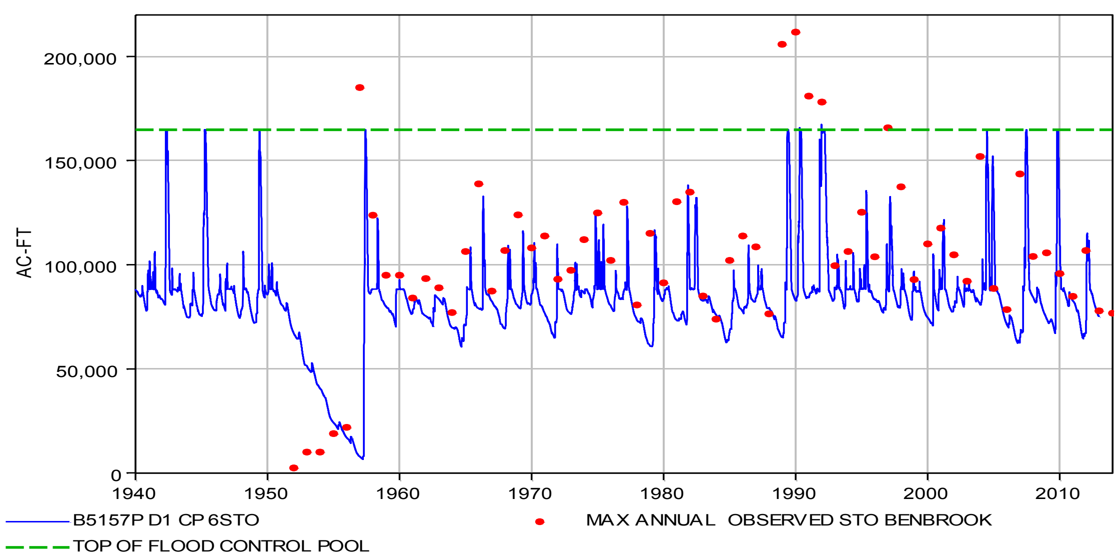

Figure 41. Benbrook Reservoir simulation D1 versus max annual observed storage

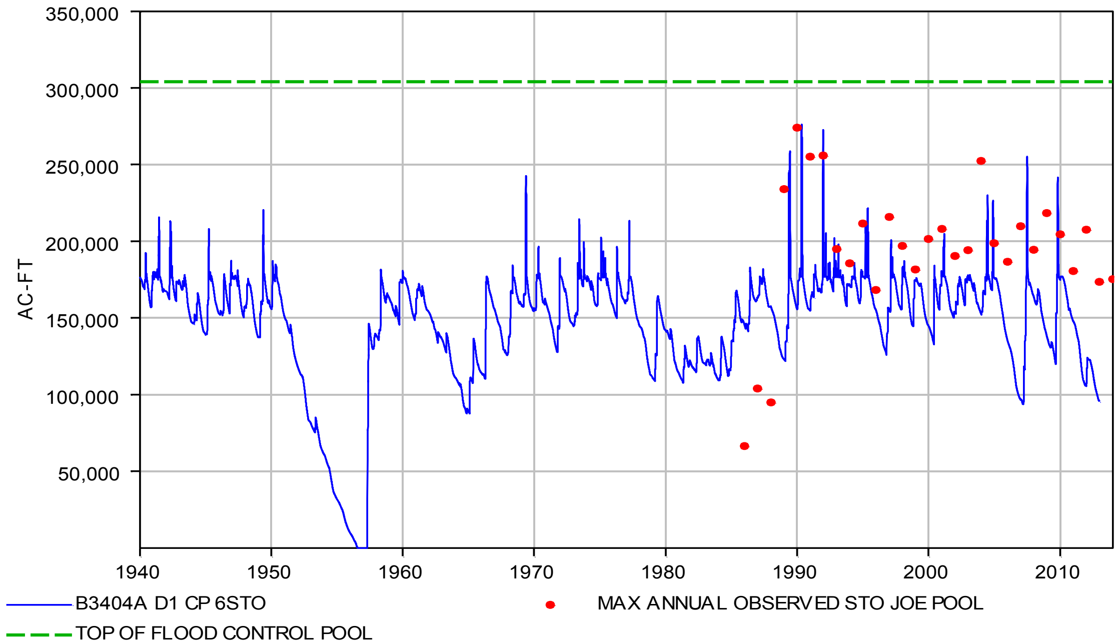

Figure 42. Joe Pool Reservoir simulation D1 versus max annual observed storage

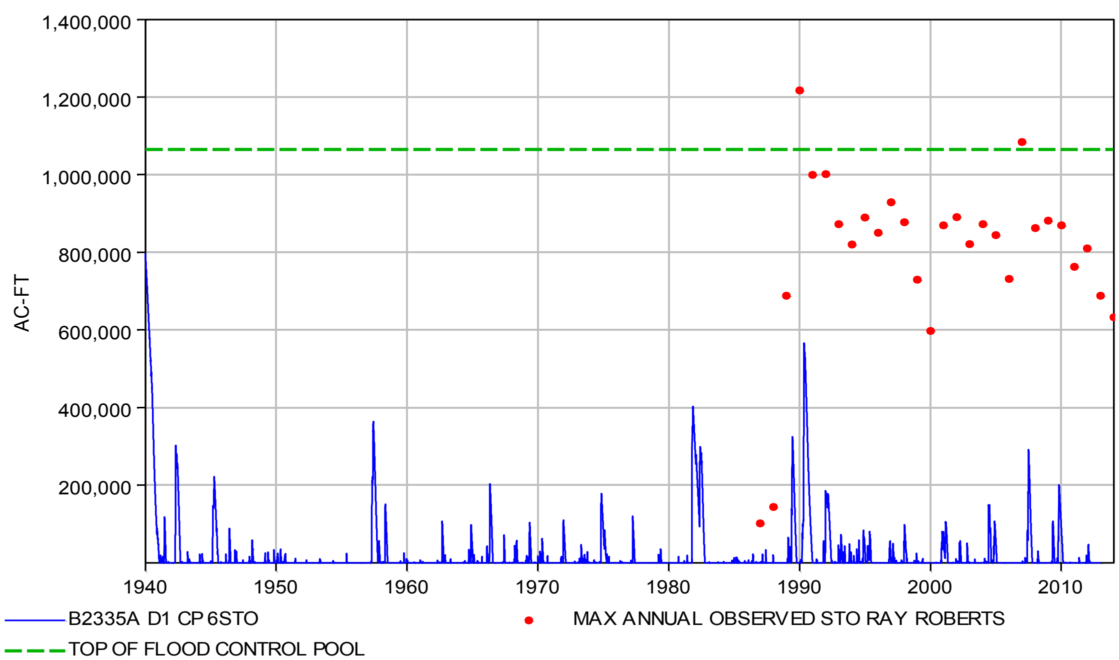

Figure 43. Ray Roberts Reservoir simulation D1 versus max annual observed storage

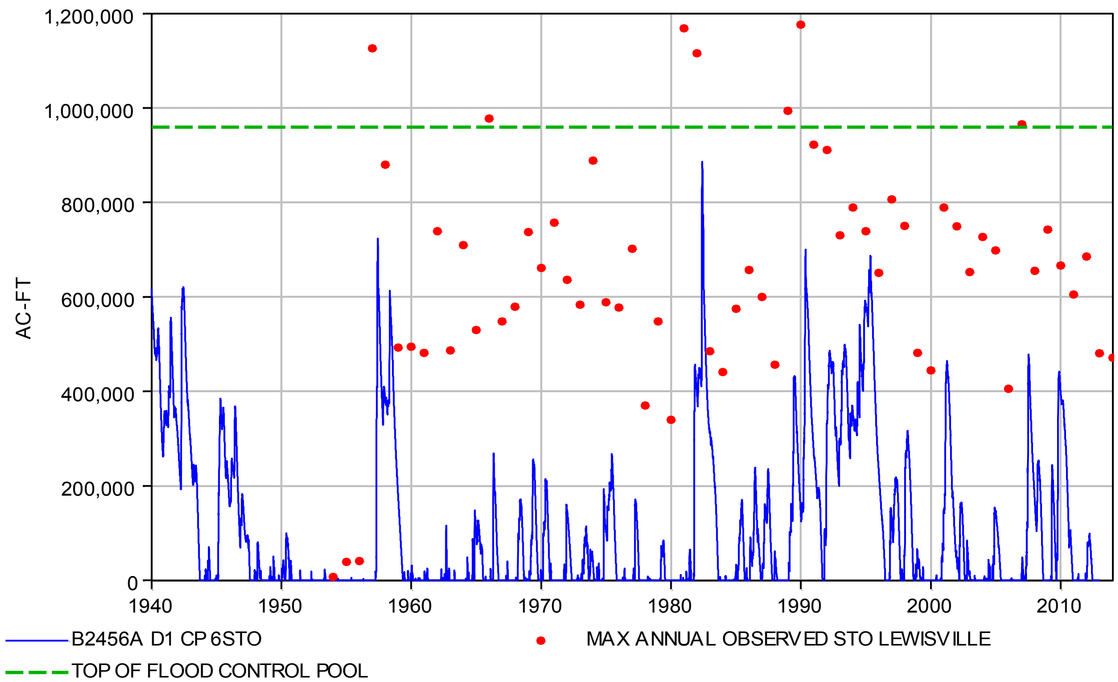

Figure 44. Lewisville Reservoir simulation D1 versus max annual observed storage

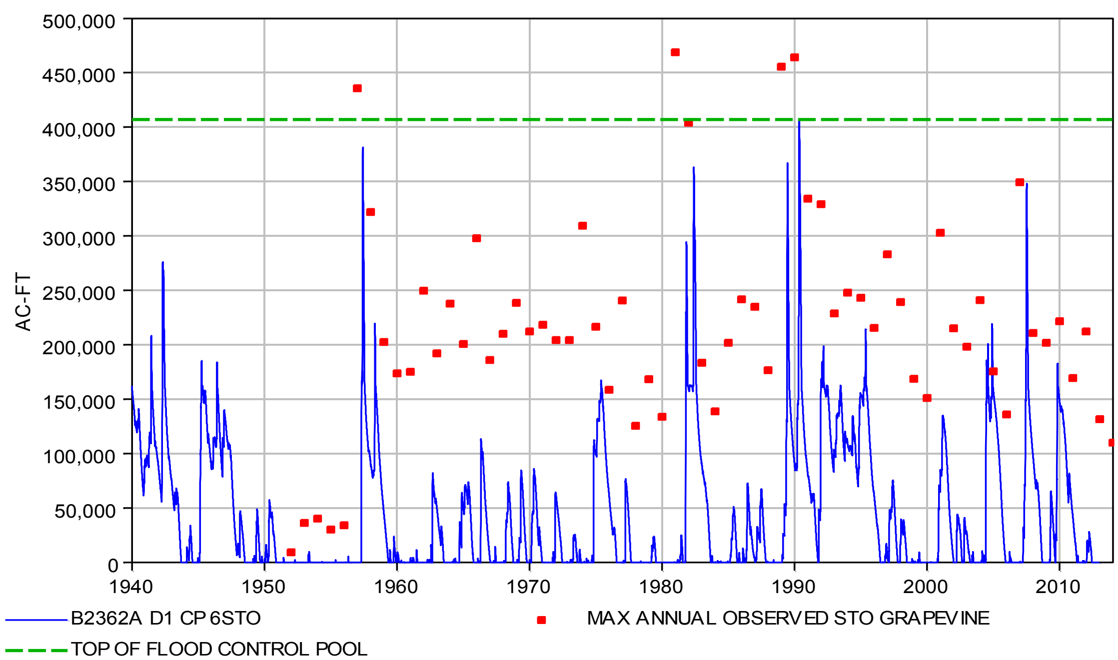

Figure 45. Grapevine Reservoir simulation D1 versus max annual observed storage

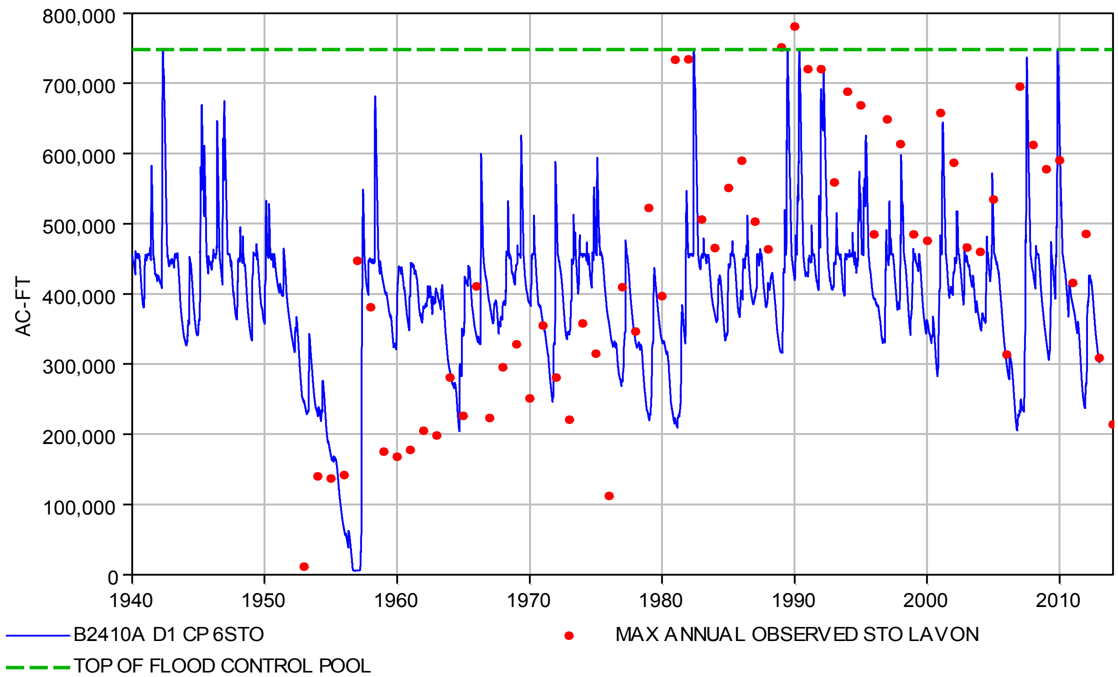

Figure 46. Lavon Reservoir simulation D1 versus max annual observed storage

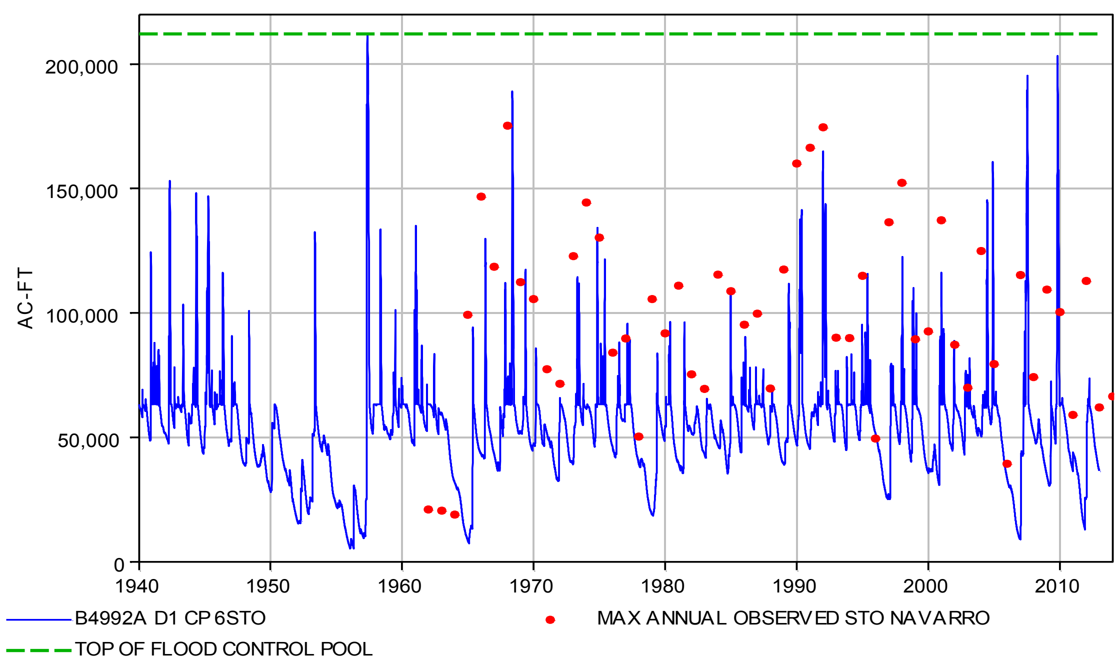

Figure 47. Navarro Mills Reservoir simulation D1 versus max annual observed storage

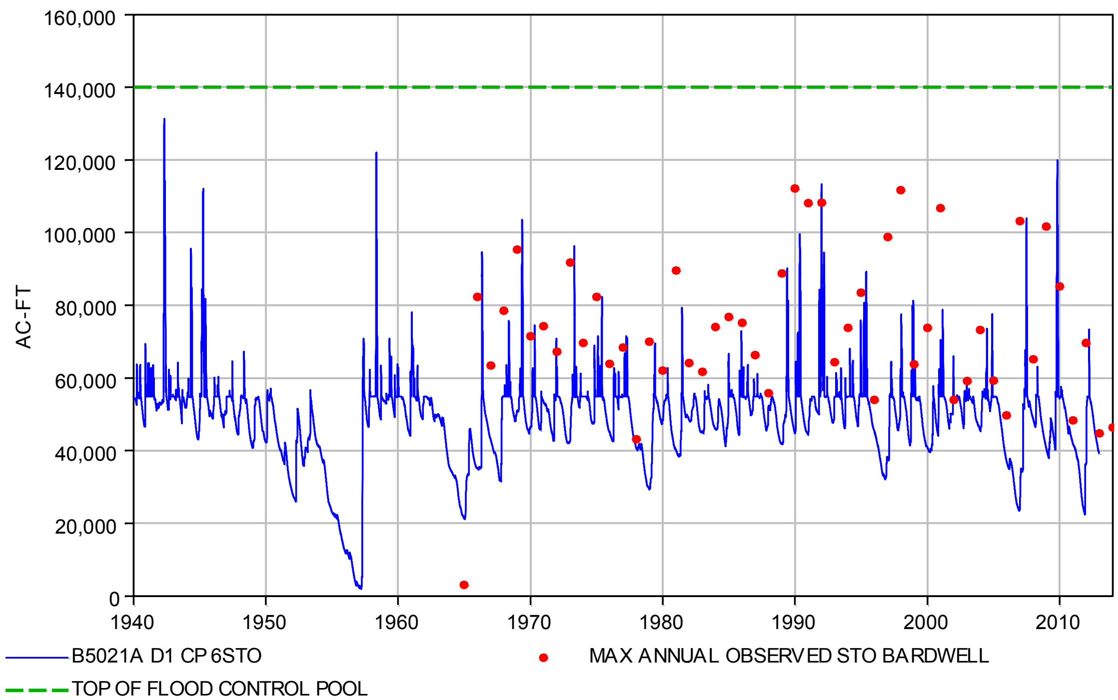

Figure 48. Bardwell Reservoir simulation D1 versus max annual observed storage

5.1.2 Comparison of Flood Frequency Analyses

Flood frequency analyses and return periods were performed with HEC-SSP and WRAP for observed data and simulation D1 respectively for the eight reservoirs. WRAP post simulation has capabilities to perform flood frequency analysis based on only for reservoir storage and summation of reservoir storage and excess flow. Excess flow represents maximum daily flow volume for each year whenever flows exceed the top of controlled flood control pool.

Flood frequency analyses were performed by employing both log-normal and log-Pearson type III probability distributions for simulation D1 and observed reservoir storage.

Tables 38-40 were created by using log-normal distribution and compared with observed data and only reservoir storage, and summation of reservoir and excess flow. Likewise, Tables 41-43 were created by using log-Pearson type III distribution and compared with observed data, only reservoir storage, and summation of reservoirs and excess flows.

Return period of observed storage for both log-normal and log-Pearson type III distribution were close to each other except Joe Pool and Navarro Mills. Return period of D1 simulation storage for both log-normal and log-Pearson type III distribution were far away from each other for only reservoir and summation of reservoir storage and excess flow. Log-normal distribution`s results for simulation D1 were closer to observed reservoir storage return period than log-Pearson type III distribution. However, specifically, Ray Roberts, Lewisville, and Grapevine Reservoirs' simulation D1 storage levels were lower than observed storage level. Although, for these reservoirs, simulation D1 storage levels were low, return period for flood event was very frequent for log-normal distribution. Log-normal probability distribution did not reflect storage level`s value for flood frequency analysis. Because of that, log-Pearson type III distribution exceedance probability of controlled flood control pool fit better than log-normal probability distribution.

Joe Pool and Ray Roberts Reservoirs were completed after 1980 and their periods-of-analysis are shorter than for the other reservoirs. Fewer years of record means a smaller sample size for the statistical analyses. Also, for Lewisville and Lavon Reservoirs, storage reallocations were made in 1989 and 1976 respectively. Because of reallocation, flood frequency analyses were performed by maximum storage level after reallocation was done, so sample size was low for these reservoirs. However, in the all simulation, hydrologic period was from 1940 to 2012. This difference affected return period. In addition to that as mentioned before, D1 was performed for full authorized water use scenario.

Table 38. Comparison of observed storage and simulation D1 exceedance probability of top of controlled flood control pool log-normal distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto.)		Sim D1 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	5.30	18.87	10.73	9.32	17.38	5.75
2	Joe Pool	B3404A	304000	0.10	1000.00	9.32	10.73	9.32	10.73
3	Ray Roberts	B2335A	1064600	6.89	14.51	7.84	12.76	7.84	12.76
4	Lewisville	B2456A	959177	9.60	10.42	8.04	12.44	8.04	12.44
5	Grapevine	B2362A	406900	3.63	27.55	11.46	8.73	11.55	8.66
6	Lavon	B2410A	748200	8.79	11.38	11.28	8.87	12.09	8.27
7	Navarro	B4992A	212200	1.02	98.04	3.38	29.59	3.44	29.07
8	Bardwell	B5021A	140000	0.43	232.56	1.90	52.63	1.90	52.63

Table 39. FFA for reservoir storage log-normal distribution for D1

FLOOD FREQUENCIES FOR RESERVOIR STORAGE

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	41330.	101581.	140638.	166709.	199856.	224696.	249665.	274942.	309026.	107340.
B3404A	55964.	163778.	241529.	295910.	367455.	422627.	479296.	537792.	618331.	179610.
B2335A	188.	35471.	236004.	635535.	1827780.	3616548.	6681544.	11717920.	23147640.	417461.
B2456A	4898.	124254.	400282.	737795.	1416245.	2158164.	3152412.	4459075.	6788134.	343645.
B2362A	848.	47848.	205840.	441325.	995360.	1683287.	2700239.	4161394.	7028580.	222147.
B2410A	211715.	483620.	652068.	762317.	900499.	1002810.	1104733.	1207064.	1343859.	504237.
B4992A	29695.	88820.	132024.	162418.	202577.	233657.	265666.	298788.	344510.	97907.
B5021A	27831.	65289.	88880.	104432.	124026.	138596.	153160.	167825.	187492.	68394.

Table 40. FFA for summation of reservoir storage and excess flow log-normal distribution for D1

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	36612.	106000.	155716.	190389.	235910.	270952.	306896.	343956.	394915.	115958.
B3404A	55964.	163778.	241529.	295910.	367455.	422626.	479295.	537792.	618330.	179609.
B2335A	188.	35471.	236004.	635535.	1827780.	3616548.	6681544.	11717920.	23147640.	417461.
B2456A	4898.	124254.	400281.	737794.	1416243.	2158162.	3152408.	4459070.	6788126.	343644.
B2362A	845.	47939.	206657.	443555.	1001540.	1694999.	2720845.	4195716.	7091802.	223460.
B2410A	209575.	485771.	658435.	771889.	914493.	1020332.	1125959.	1232183.	1374428.	507780.
B4992A	29582.	88915.	132401.	163033.	203545.	234923.	267259.	300738.	346979.	98127.
B5021A	27831.	65289.	88880.	104432.	124026.	138596.	153160.	167825.	187492.	68394.

Table 41. Comparison of observed storage and simulation D1 exceedance probability of top of controlled flood control pool log-Pearson type III distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto.)		Sim D1 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	7.22	13.85	0.10	1000.00	16.68	6.00
2	Joe Pool	B3404A	304000	0.71	140.85	0.10	1000.00	0.10	1000.00
3	Ray Roberts	B2335A	1064600	6.75	14.81	0.01	10000.00	0.01	10000.00
4	Lewisville	B2456A	959177	8.89	11.25	3.52	28.41	3.52	28.41
5	Grapevine	B2362A	406900	4.57	21.88	0.23	434.78	0.40	250.00
6	Lavon	B2410A	748200	7.08	14.12	0.10	1000.00	0.10	1000.00
7	Navarro	B4992A	212200	0.24	416.67	1.26	79.37	1.43	69.93
8	Bardwell	B5021A	140000	0.39	256.41	0.10	1000.00	0.10	1000.00

Table 42. FFA for reservoir storage log-Pearson type III distribution for D1

FLOOD FREQUENCIES FOR RESERVOIR STORAGE

CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
B5157P	25123.	114466.	137044.	143300.	146816.	147946.	148502.	148777.	148941.	100690.
B3404A	25241.	196574.	219628.	222130.	222707.	222773.	222787.	222790.	222791.	161245.
B2335A	4.	84618.	156595.	168888.	172421.	172931.	173059.	173092.	173102.	90342.
B2456A	2151.	150660.	407878.	621221.	908192.	1120745.	1324922.	1518268.	1755002.	266613.
B2362A	135.	74225.	197477.	268885.	332592.	363265.	383673.	397091.	407967.	115005.
B2410A	116887.	554964.	610446.	617466.	619366.	619633.	619698.	619715.	619720.	463284.
B4992A	24365.	92989.	132986.	156461.	182849.	200368.	216273.	230835.	248349.	95670.
B5021A	19901.	70718.	88667.	96020.	102069.	105020.	107102.	108588.	109936.	65604.

Table 43. FFA for summation of reservoir storage and excess flow log-Pearson type III distribution for D1

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
B5157P	28552.	112337.	156760.	181008.	206590.	222574.	236381.	248428.	262150.	112630.
B3404A	25241.	196574.	219628.	222130.	222707.	222773.	222787.	222790.	222791.	161245.
B2335A	4.	84618.	156595.	168888.	172421.	172931.	173059.	173092.	173102.	90342.
B2456A	2151.	150660.	407877.	621221.	908192.	1120746.	1324924.	1518271.	1755007.	266613.
B2362A	136.	74247.	198480.	271043.	336285.	367952.	389171.	403225.	414719.	115695.
B2410A	117647.	556221.	621874.	632027.	635332.	635909.	636078.	636129.	636147.	468550.
B4992A	24469.	92911.	133353.	157339.	184555.	202787.	219463.	234843.	253494.	95971.
B5021A	19901.	70718.	88667.	96020.	102069.	105020.	107102.	108588.	109936.	65604.

5.1.3 Water Supply Reliability for D1

The water supply reliability table was developed for control points located at dams for simulation D1 as shown in Table 44. Benbrook, Lavon, Navarro Mills, and Bardwell Reservoirs water diversion target 100% met in terms of simulation duration and diversion amount. On the other hand, Joe Pool, Ray Roberts, Lewisville, Grapevine Reservoirs have water shortage. Joe Pool water reliability was almost 100%. However, Ray Roberts Reservoir had very low water reliability in terms of period and volume. One of the research objectives is how reallocation affects water reliability. Simulation D4, D5, and D6 were compared in the following pages to show differences for water reliability.

Table 44. Water supply reliability for D1

Daily Data from January 1940 through December 2012

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF DAYS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%
B5157P	125768.6	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
B3404A	400242.1	170.20	98.95	99.96	99.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9	100.0	100.0	100.0	100.0	100.0	100.0
B2335A	799601.8	634935.06	20.38	20.59	20.4	20.5	20.5	20.8	21.2	21.6	22.8	11.3	11.4	11.9	14.5	18.7	26.1	42.8
B2456A	921060.9	534674.75	53.56	41.95	53.6	53.6	53.7	54.1	55.1	57.0	74.5	45.0	45.9	46.8	48.9	54.8	61.6	81.6
B2362A	171537.5	72116.69	58.34	57.96	58.3	58.4	58.4	58.8	59.5	61.5	70.1	51.0	51.8	52.3	53.9	59.0	65.4	81.2
B2410A	128754.7	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
B4992A	176698.6	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
B5021A	151885.5	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
Total	2875550.0	1241896.75		56.81														

5.2 Simulations D1 versus D2

The simulation D2 represents existing reservoir storage, full authorized water use, daily time step, has flood control operation, and was developed as component reservoir system. Component (multiple-owner) reservoir system means, for same reservoir, different agencies have water right contracts. To protect their water rights from other contractor, reservoirs were split up as components. Thus, contractor cannot withdraw much water that they were authorized. Because of that, conservation and flood control pools were divided based on contract proportion for Benbrook, Ray Roberts, Lewisville, Grapevine, and Lavon Reservoirs. However, flood control operation for component reservoirs did not work out. Component reservoir system for some years, even if water level in reservoir was lower than top of controlled flood control pool (FCGATE), in AFF file, there was excess flow. That was not supposed to be occurred. Excess flow was supposed to be only occurred when water level exceeded the top of controlled flood control pool. The reason for excess flow for component reservoir might be that one of the components in the same reservoir might overtop to top of flood control pool while others had low water level. Even if one of components was exceed flood control pool, it would cause excess flow.

Originally, Trinity WAM was designed as component reservoir for water allocation. However, the research focused on flood control operation, because of that, reservoirs were converted to single owner reservoir and base simulation (D1) was single owner reservoir. Simulation D1 and D2 were compared for water storages and water reliabilities to check how single-owner simulation make changes.

5.2.1 Comparison of Reservoirs Storage

Simulation D1 storage capacities were compared with simulation D2 storage capacities. As shown in Figures 49-56, straight blue line represents D1 likewise, dark red straight line represents D2 and green line represents top of controlled flood control pool level. As a result of this comparison, Joe Pool, Navarro Mills and Bardwell Reservoirs storage levels were almost same for D1 and D2, However, for rest of them, storage capacities had differences for D1 and D2.

The difference between simulation D1 and D2 caused by in a same reservoir, contractors used other contractor`s water when they had no water that they were authorized. Because of that usage of water storage levels and water reliabilities have changed. Joe Pool, Navarro Mills and Bardwell Reservoirs had same water storage levels because in both D1 and D2 simulation they were single reservoir.

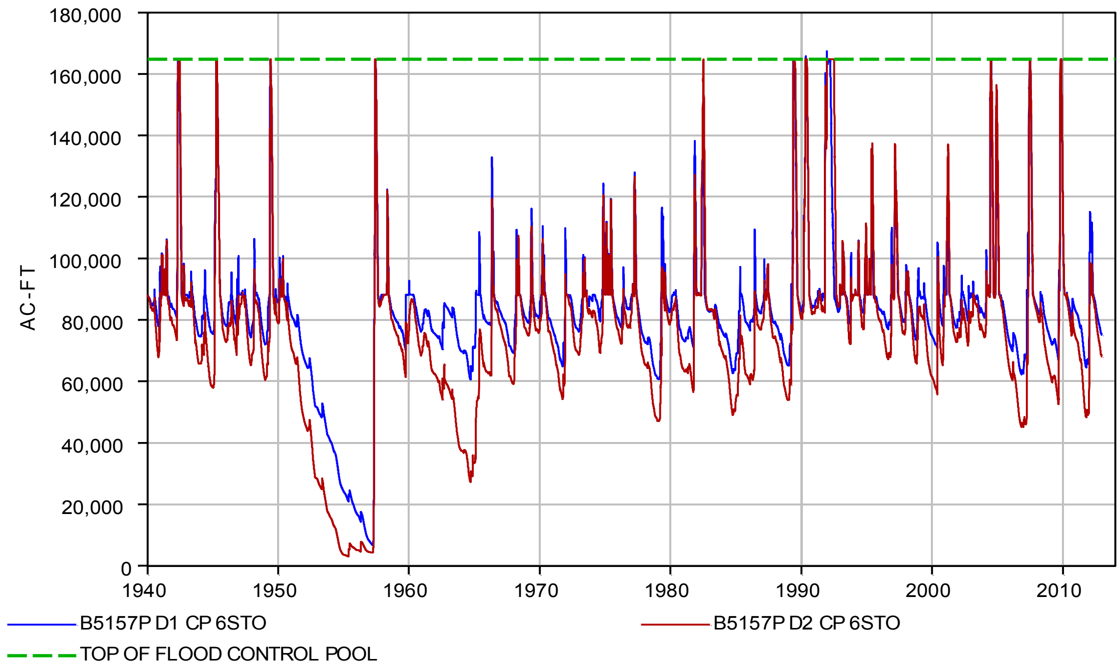

Figure 49. Benbrook Reservoir simulations D1 versus D2

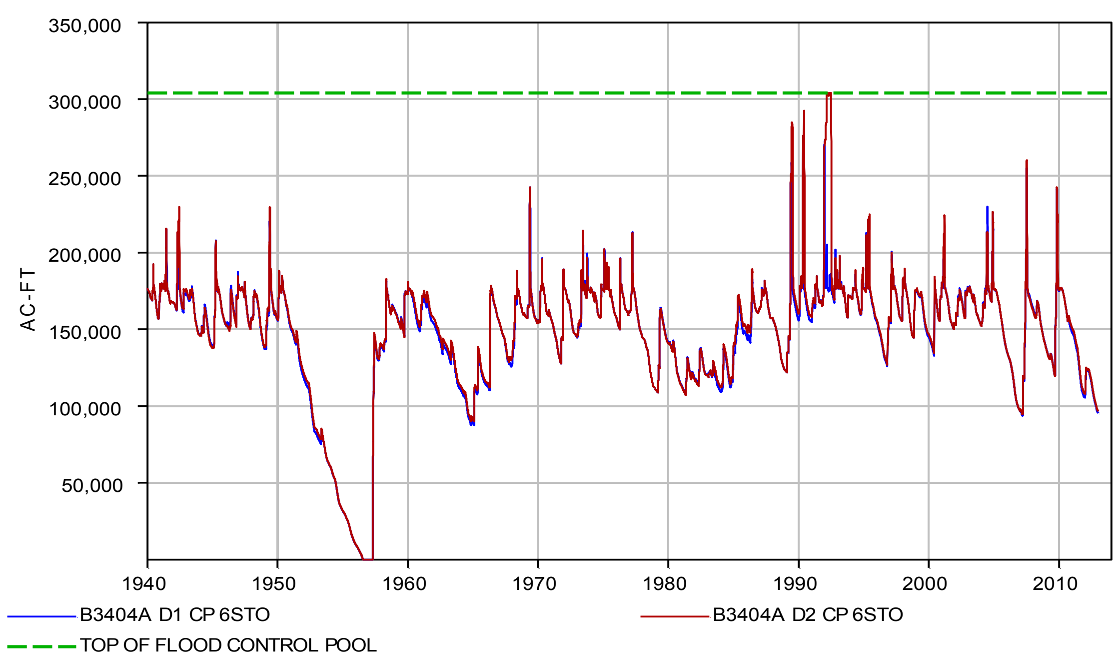

Figure 50. Joe Pool Reservoir simulations D1 versus D2

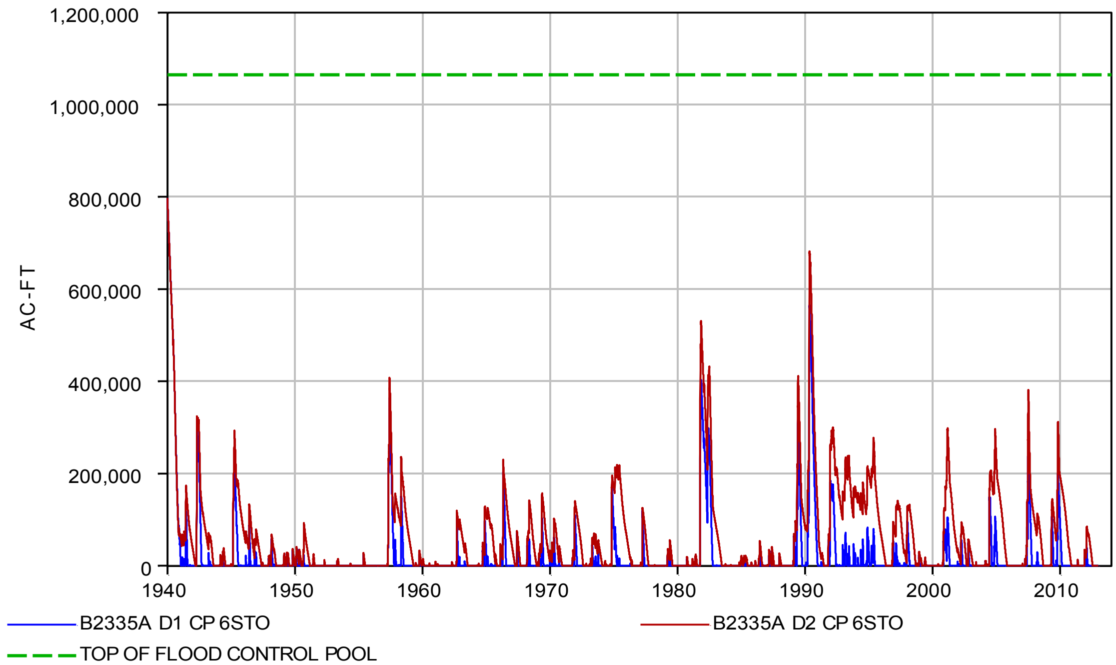

Figure 51. Ray Roberts Reservoir simulations D1 versus D2

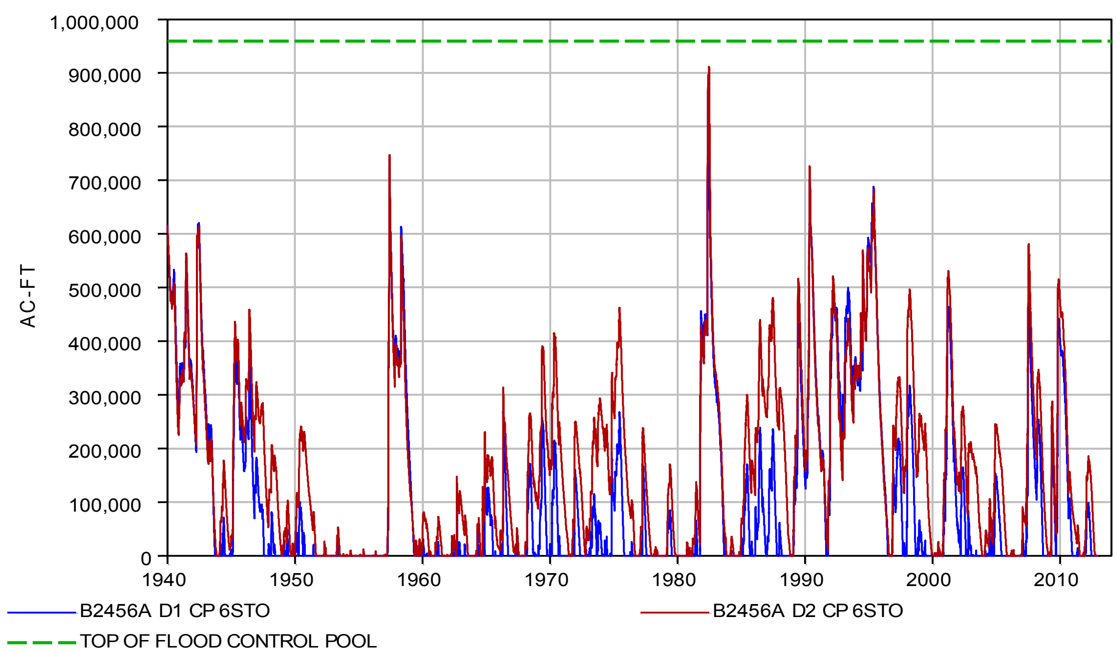

Figure 52. Lewisville Reservoir simulations D1 versus D2

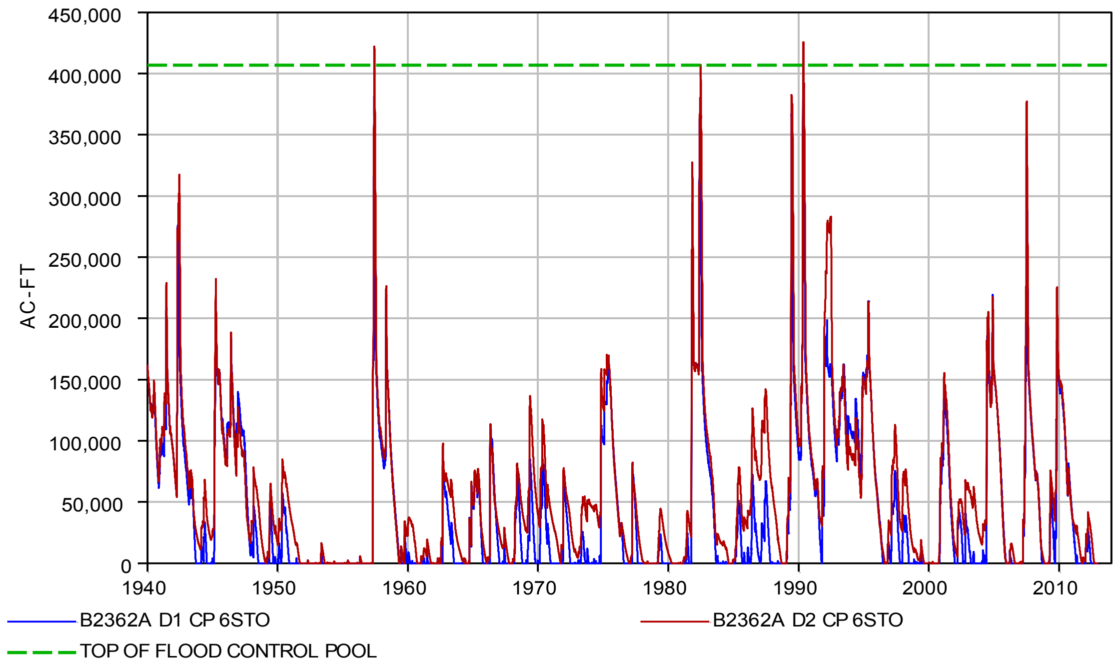

Figure 53. Grapevine Reservoir simulations D1 versus D2

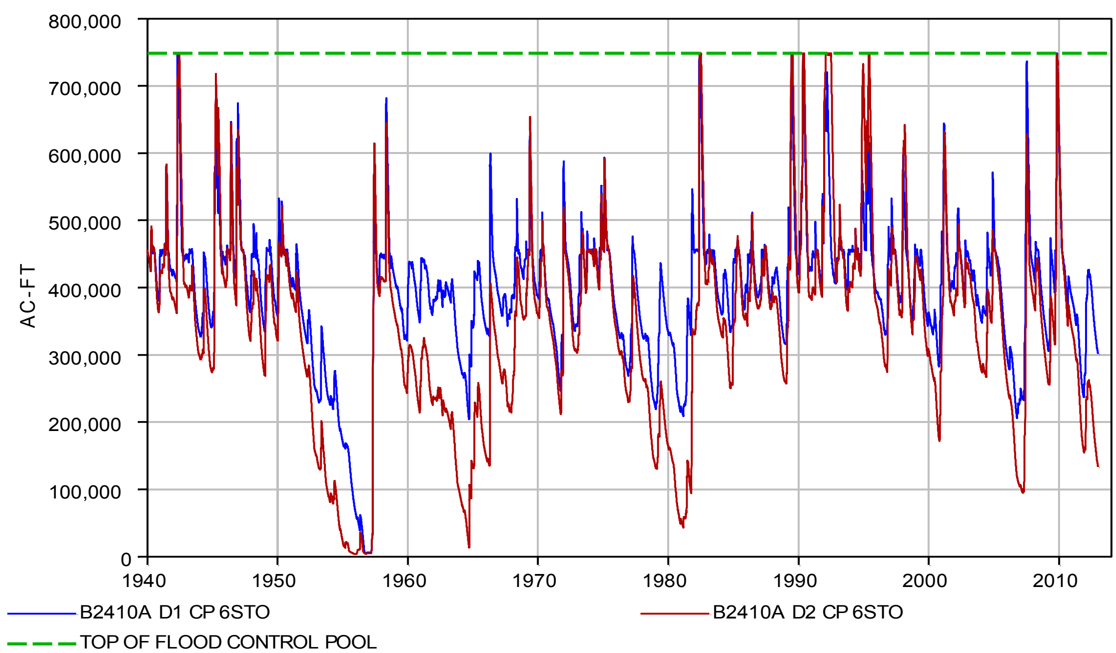

Figure 54. Lavon Reservoir simulations D1 versus D2

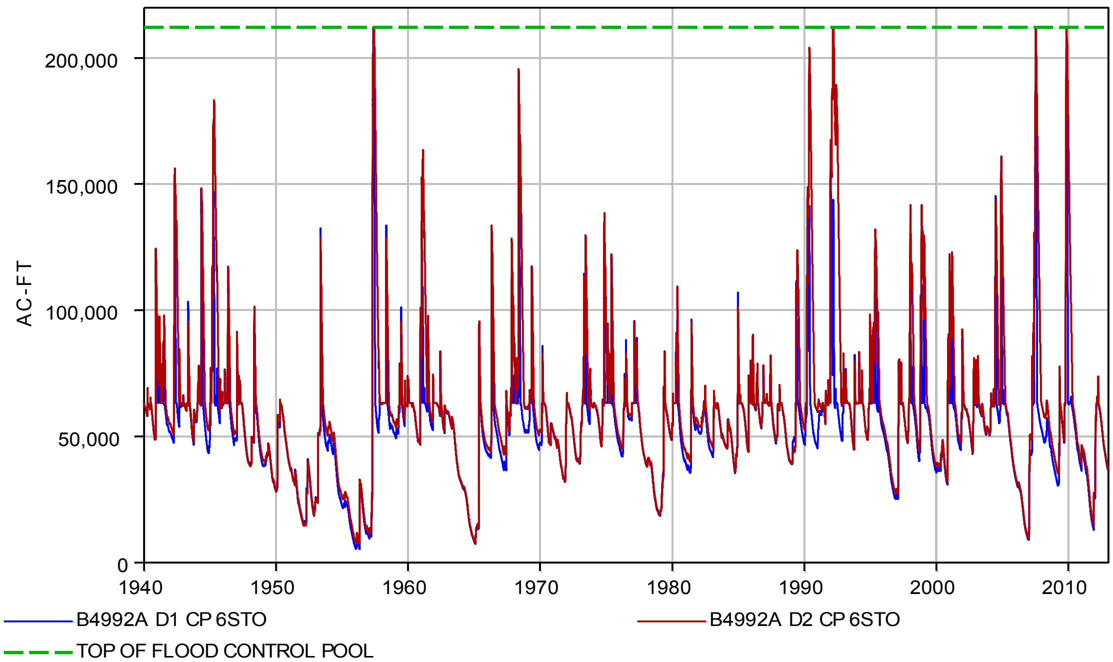

Figure 55. Navarro Mills Reservoir simulations D1 versus D2

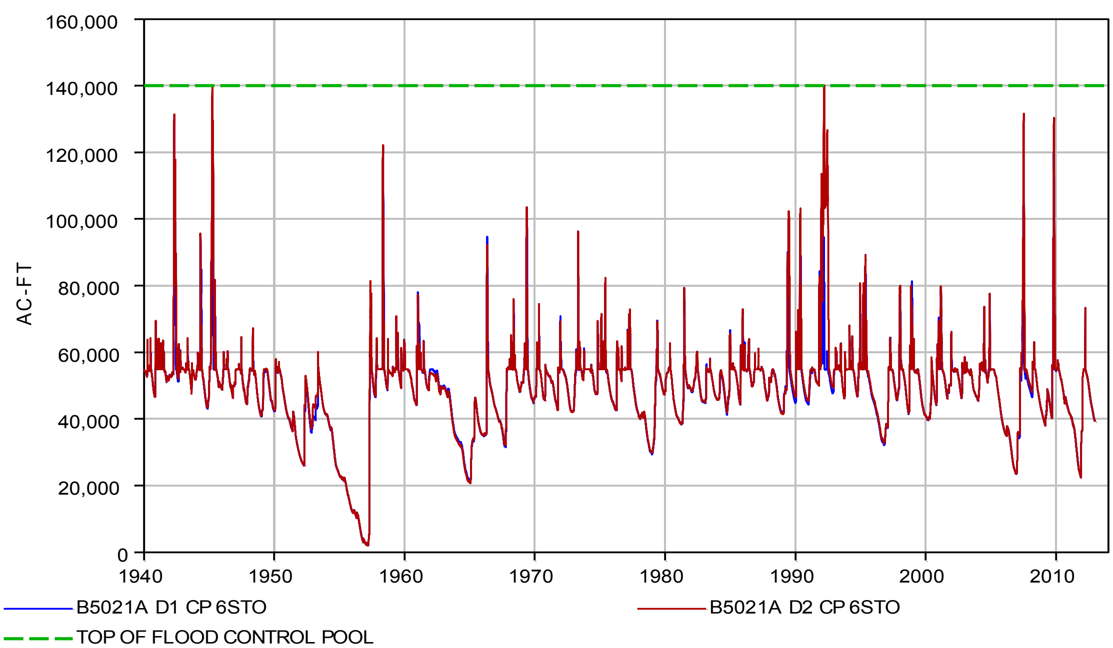

Figure 56. Bardwell Reservoir simulations D1 versus D2

5.2.2 Water Supply Reliabilities for D2

The water supply reliability table was developed for control points located at dams for simulation D2 as shown in Table 45. Navarro Mills and Bardwell Reservoirs water diversion target is 100% met in terms of simulation duration and diversion amount. On the other hand, Benbrook, Joe Pool, Ray Roberts, Lewisville, Grapevine Reservoirs had water shortage. Joe Pool water reliability was almost 100% and simulation D1 and D2 were almost same. However, Ray Roberts Reservoir had very low water reliability in terms of period and volume.

Table 45. Water supply reliability for D2

Daily Data from January 1940 through December 2012

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF DAYS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF MONTHS 100%	95%	90%	75%	50%	25%	1%
B5157P	47698.1	270.16	95.68	99.43	95.7	99.3	100.0	100.0	100.0	100.0	100.0	95.5	99.3	100.0	100.0	100.0	100.0	100.0
B3404A	391751.4	168.57	98.96	99.96	99.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9	100.0	100.0	100.0	100.0	100.0	100.0
B2335A	799601.8	630218.44	7.83	21.18	7.8	7.8	7.9	7.9	8.0	58.5	59.2	5.7	6.1	6.2	6.5	8.7	51.8	67.5
B2456A	821382.1	465421.44	17.24	43.34	17.2	17.3	17.6	27.9	52.0	77.5	86.9	15.2	16.3	17.4	27.6	51.4	76.1	90.6
B2362A	172852.2	78966.63	34.93	54.32	34.9	35.9	36.1	37.9	45.4	83.9	86.7	30.8	33.4	34.5	38.1	46.5	81.4	91.1
B2410A	136504.8	9598.97	42.25	92.97	42.3	48.8	71.6	94.0	99.5	100.0	100.0	34.1	46.7	79.5	93.8	99.9	100.0	100.0
B4992A	157847.4	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
B5021A	151294.8	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
Total	2678932.5	1184644.25		55.78														

5.3 Simulations D1, D3 versus Observed Annual Maximum Reservoirs Storage

The simulation D3 represents existing reservoir storage, no water withdrawn from the eight reservoirs, daily time step, has flood control operation, and was developed as single-owner reservoir system. Simulation D3 was executed in order to show how conservation pool affected flood frequency analysis. After a severe drought conservation, pool becomes empty and after drought season ends, at first conservation pool becomes full then starts to fill flood control pool. In other words, at the beginning of flood event, conservation pool behaves as flood control pool and stores water. In order to see how conservation pool affect flood control operation, simulation D3 was developed by changing water rights values as zero thus conservation pool remain full for the eight reservoirs.

5.3.1 Comparison of Reservoirs Storage

Simulation D1 storage capacities were compared with simulation D3 storage capacities. As shown in Figure 57-64, straight blue line represents D1 likewise, dark red straight line represents D3, red points represent observed annual maximum storage and green line represents top of controlled flood control pool level. As a result of simulation D3, all of the reservoirs storage levels increased as expected. Especially, Ray Roberts, Lewisville, Grapevine, Lavon Reservoirs` storage level increased dramatically.

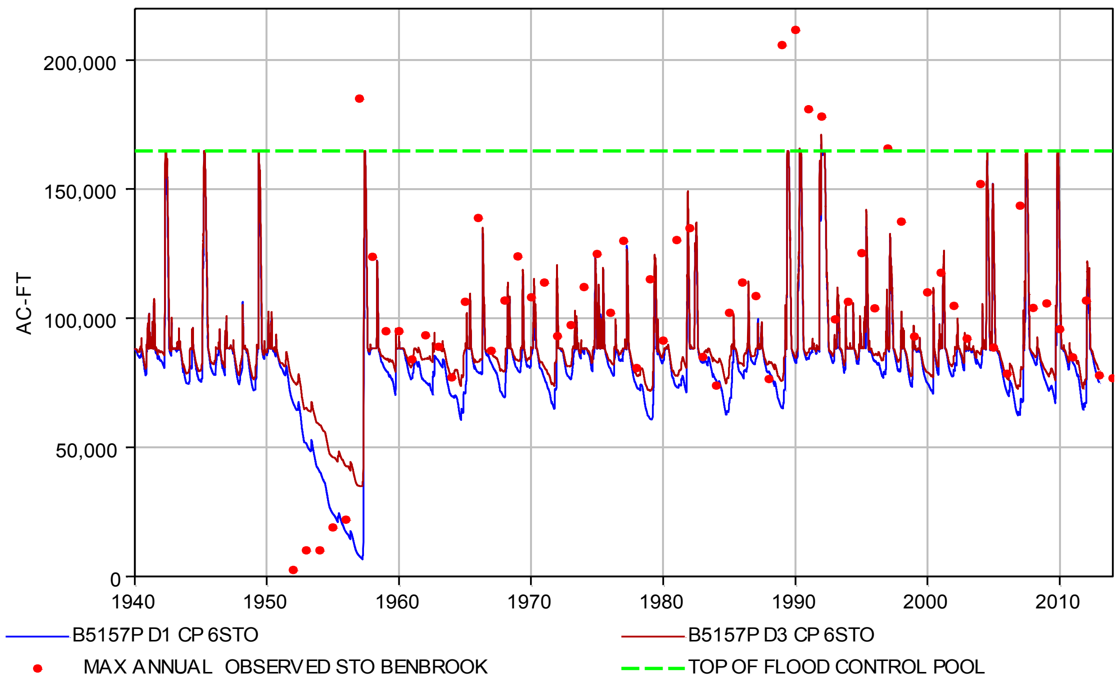

Figure 57. Benbrook Reservoir simulations D1, D3 versus max annual observed storage

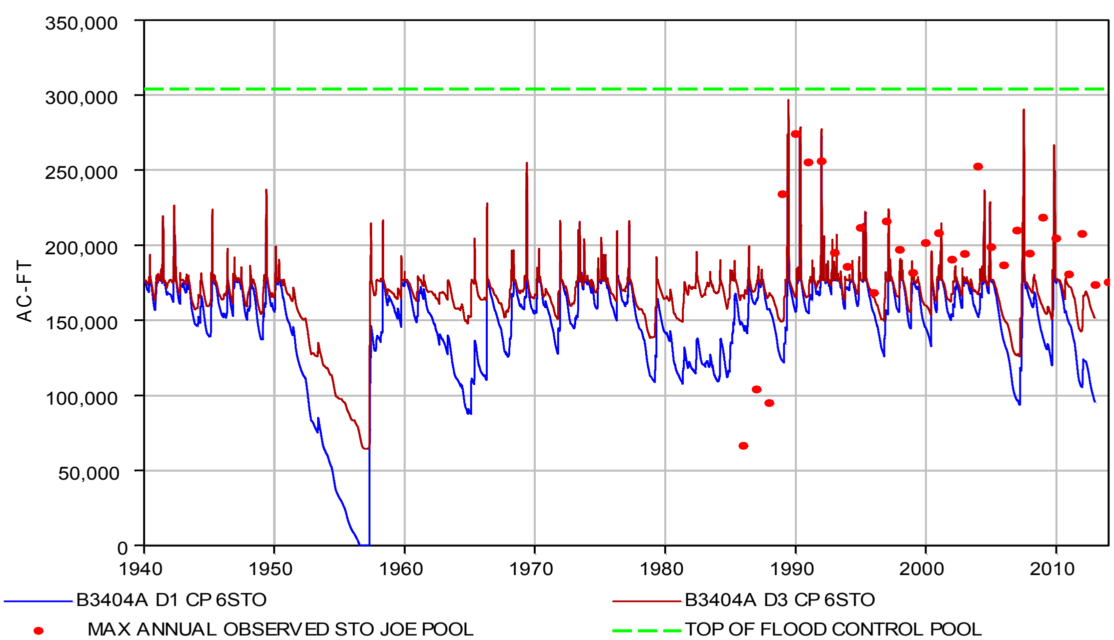

Figure 58. Joe Pool Reservoir simulations D1, D3 versus max annual observed storage

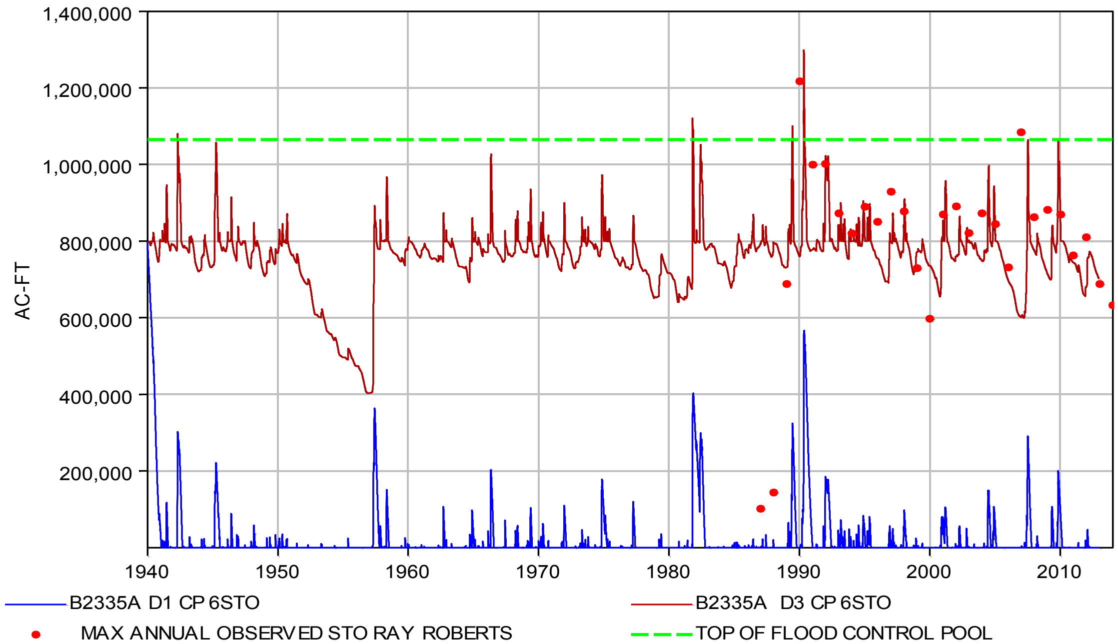

Figure 59. Ray Roberts Reservoir simulations D1, D3 versus max annual observed storage

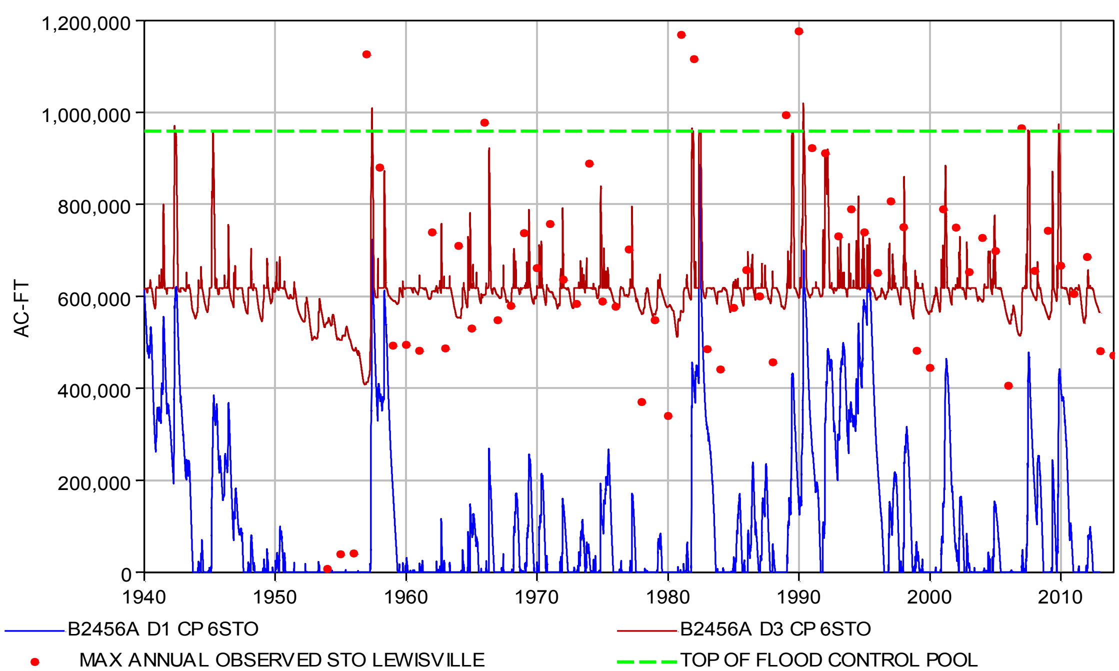

Figure 60. Lewisville Reservoir simulations D1, D3 versus max annual observed storage

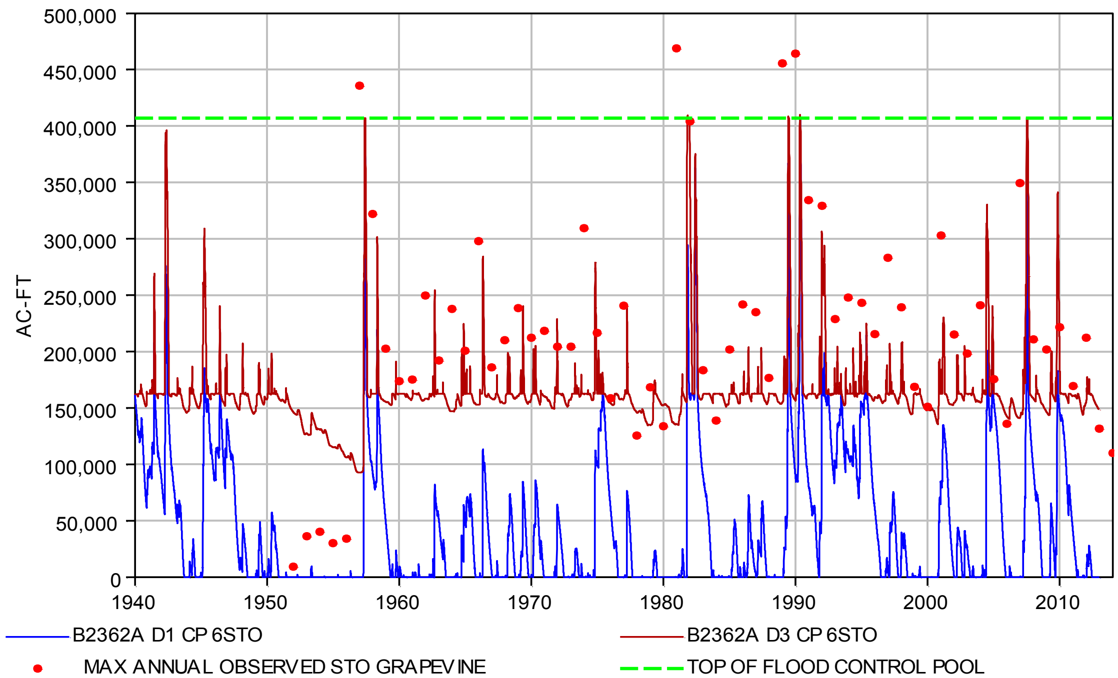

Figure 61. Grapevine Reservoir simulations D1, D3 versus max annual observed storage

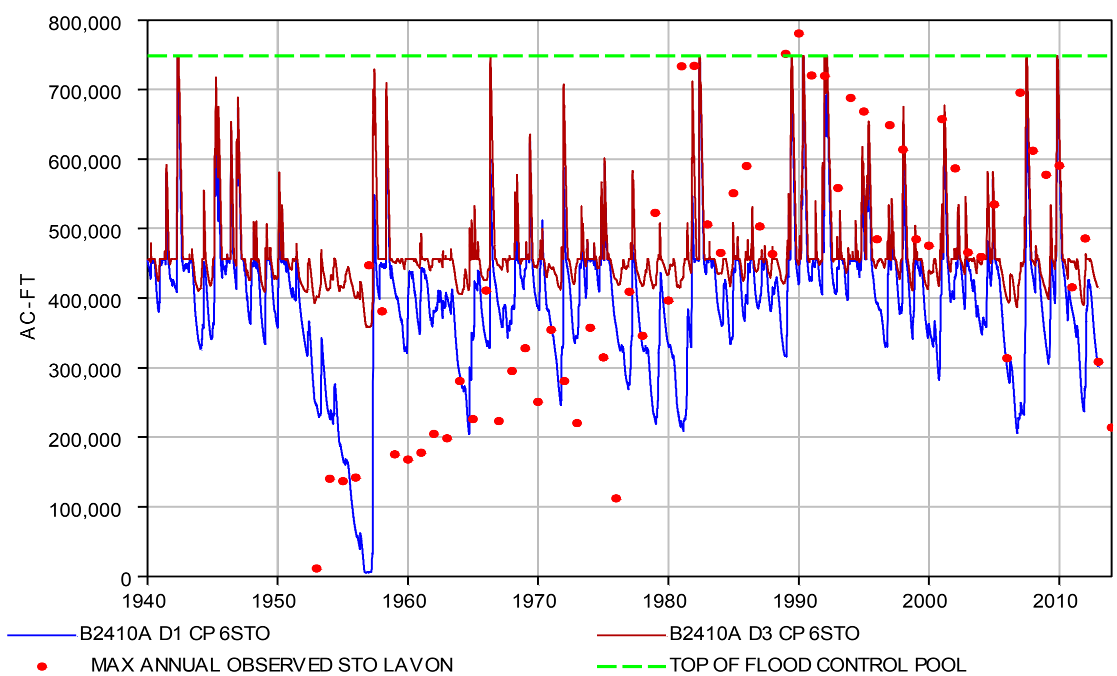

Figure 62. Lavon Reservoir simulations D1, D3 versus max annual observed storage

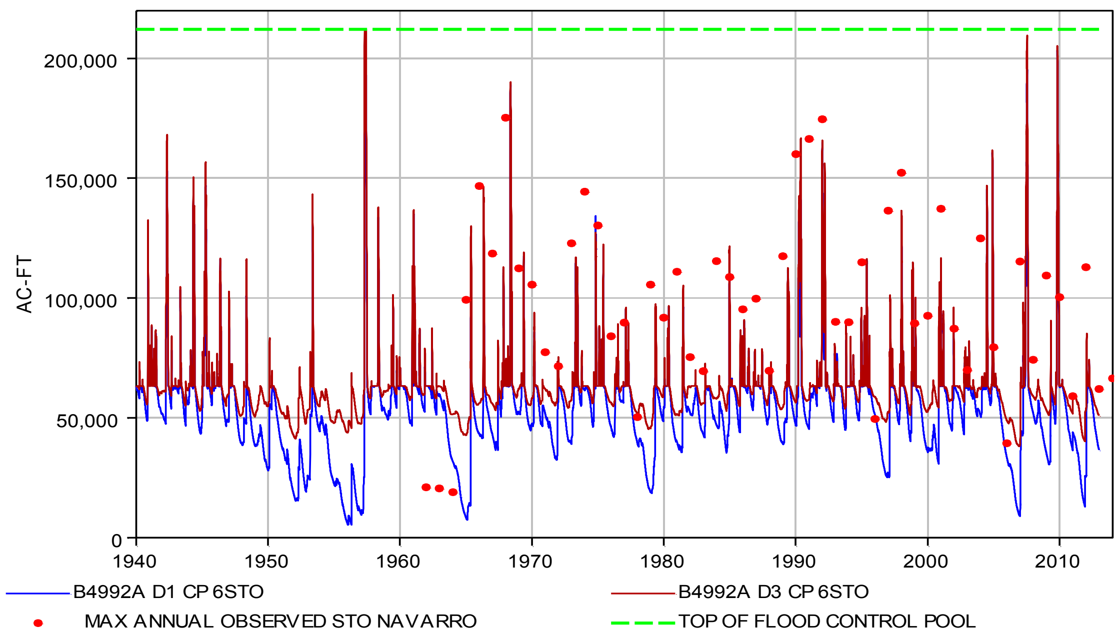

Figure 63. Navarro Mills Reservoir simulations D1, D3 versus max annual observed storage

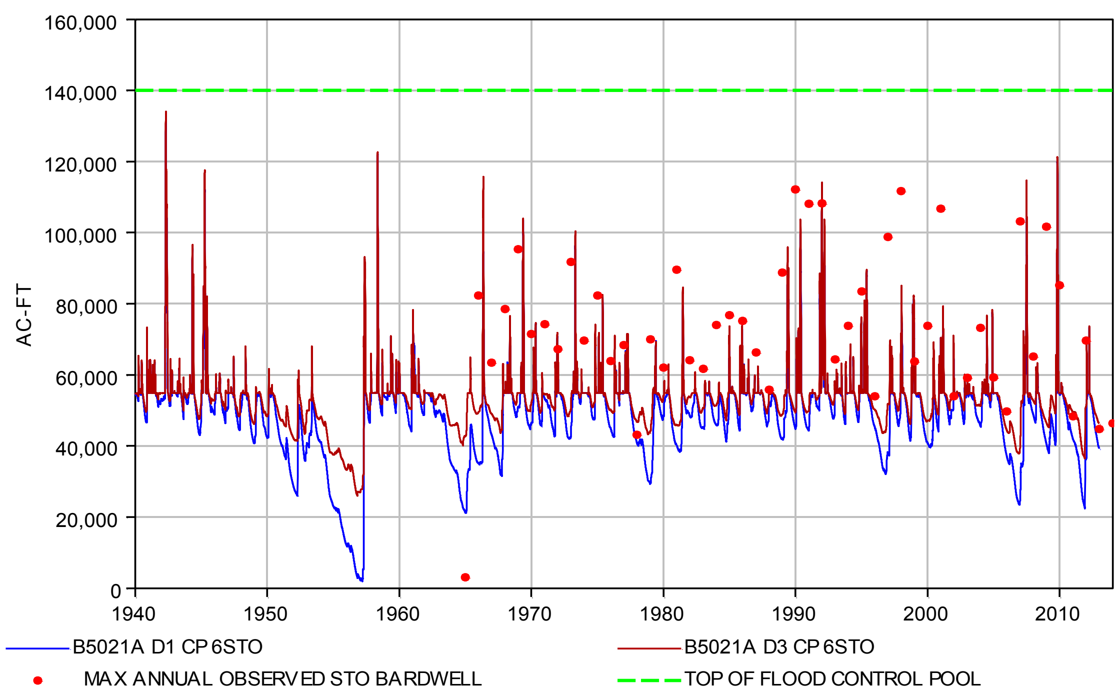

Figure 64. Bardwell Reservoir simulations D1, D3 versus max annual observed storage

5.3.2 Comparison of Flood Frequency Analyses

Exceedance probability of top of controlled flood control for simulation D3 was performed for log-normal and log-Pearson type III distribution, compared with simulation D1 and observed flood frequency analysis. For both distributions, simulation D3 return period values were expected lower than simulation D1 because there was not withdrawn for simulation D3 and water levels were higher than simulation D1.

Return period and statistical tables were developed for log-normal distribution as shown in Tables 46 and 47. However, return period values for simulation D3 was higher than simulation D1 except for Ray Roberts and Lewisville Reservoirs. The result for log-normal distribution was not expected since D3 simulation return period should have been lower than D1. Log-normal distribution did not work well.

Return period and statistical tables were developed for log-Pearson type III distribution as shown in Tables 48 and 49. Return period for simulation D3 values were lower than Simulation D1 and observed flood frequency analysis as expected. Simulation D1 flood return periods were significantly higher than simulation D3. For this study, log-Pearson Type III distribution fit better. Because of that, rest of the simulation was evaluated only with log-Pearson type III distribution.

These results show that conservation pools have great impact on flood control operation and flood frequency analysis. Especially after a severe drought like 1950-1957 drought, there was a flood event. The simulation D3 showed that in 1957 controlled flood control pools were overtopped for most of reservoirs. Consequently, conservation pools reduce flood events when they have water storage place.

Table 46. Comparison of observed storage, D1 and D3 exceedance probability of top of flood control pool log-normal distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto. +Excess Flow)		Sim D3 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	5.30	18.87	17.38	5.75	16.83	5.94
2	Joe Pool	B3404A	304000	0.10	1000.00	9.32	10.73	1.49	67.11
3	Ray Roberts	B2335A	1064600	6.89	14.51	7.84	12.76	12.13	8.24
4	Lewisville	B2456A	959177	9.60	10.42	8.04	12.44	9.07	11.03
5	Grapevine	B2362A	406900	3.63	27.55	11.55	8.66	3.17	31.55
6	Lavon	B2410A	748200	8.79	11.38	12.09	8.27	8.81	11.35
7	Navarro	B4992A	212200	1.02	98.04	3.44	29.07	2.31	43.29
8	Bardwell	B5021A	140000	0.43	232.56	1.90	52.63	0.70	142.86

Table 47. FFA for summation of reservoir storage and excess flow log-normal distribution for D3

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	47317.	113581.	155913.	183991.	219526.	246052.	272639.	299481.	335576.	119485.
B3404A	117951.	192013.	229031.	251139.	277072.	295231.	312579.	329349.	350880.	191631.
B2335A	558582.	855750.	998550.	1082440.	1179679.	1247091.	1311012.	1372379.	1450610.	850265.
B2456A	456230.	729470.	864463.	944694.	1038473.	1103946.	1166357.	1226564.	1303704.	726981.
B2362A	95174.	212595.	284332.	331002.	389240.	432203.	474884.	517628.	574616.	220811.
B2410A	348797.	563287.	669941.	733500.	807938.	859994.	909677.	957658.	1019205.	561804.
B4992A	41998.	100198.	137239.	161767.	192772.	215893.	239050.	262414.	293808.	105287.
B5021A	37288.	70724.	89154.	100627.	114492.	124449.	134143.	143675.	156138.	71713.

Table 48. Comparison of observed storage, D1 and D3 exceedance probability of top of flood control pool log-Pearson type III distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto. +Excess Flow)		Sim D3 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	7.22	13.85	16.68	6.00	16.53	6.05
2	Joe Pool	B3404A	304000	0.71	140.85	0.10	1000.00	0.10	1000.00
3	Ray Roberts	B2335A	1064600	6.75	14.81	0.01	10000.00	12.28	8.14
4	Lewisville	B2456A	959177	8.89	11.25	3.52	28.41	9.87	10.13
5	Grapevine	B2362A	406900	4.57	21.88	0.40	250.00	5.66	17.67
6	Lavon	B2410A	748200	7.08	14.12	0.10	1000.00	9.62	10.40
7	Navarro	B4992A	212200	0.24	416.67	1.43	69.93	3.13	31.95
8	Bardwell	B5021A	140000	0.39	256.41	0.10	1000.00	1.14	87.72

Table 49. FFA for summation of reservoir storage and excess flow log-Pearson type III distribution for D3

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	58258.	108444.	152644.	187673.	239139.	283158.	332441.	387786.	471698.	122451.
B3404A	101062.	199148.	229386.	242478.	254156.	260432.	265269.	269059.	272899.	187298.
B2335A	566829.	852936.	997444.	1084532.	1187520.	1260206.	1330100.	1398093.	1486032.	852042.
B2456A	529171.	705822.	849994.	955960.	1101273.	1217812.	1341553.	1473589.	1662561.	741661.
B2362A	125293.	199986.	275199.	337803.	433345.	517866.	615141.	727341.	902747.	228166.
B2410A	392311.	548750.	661888.	741649.	847840.	930915.	1017456.	1108168.	1235488.	570808.
B4992A	45535.	98398.	136338.	163389.	199792.	228547.	258723.	290564.	335556.	106287.
B5021A	39425.	69845.	88754.	101328.	117359.	129442.	141667.	154136.	171115.	72216.

5.4 Simulations D1, D4 versus Observed Annual Maximum Reservoirs Storage

The simulation D4 represents 10% flood control reservoir storage converted to conservation pool capacity, full authorized water use, daily time step, has flood control operation, and was developed as single-owner reservoir system. Simulation D4 was executed in order to show how 10% storage reallocation from flood control pool to conservation pool affects flood frequency analysis and water reliability.

5.4.1 Comparison of Reservoirs Storage

Simulation D1 storage capacities were compared with simulation D4 storage capacities. As shown in Figures 65-72, straight blue line represents D1 likewise, dark red straight line represents D4 and green line represents top of controlled flood control pool level. As a result of this comparison, all of reservoirs storage level increased in simulation D4 except Ray Roberts and Lewisville Reservoirs. Also, Grapevine Reservoir increased little for some days. Increase of reservoir storage was expected and aimed for all reservoirs. Ray Roberts, Lewisville, and Grapevine water level did not increase because they already had empty conservation place to store water in simulation D4.

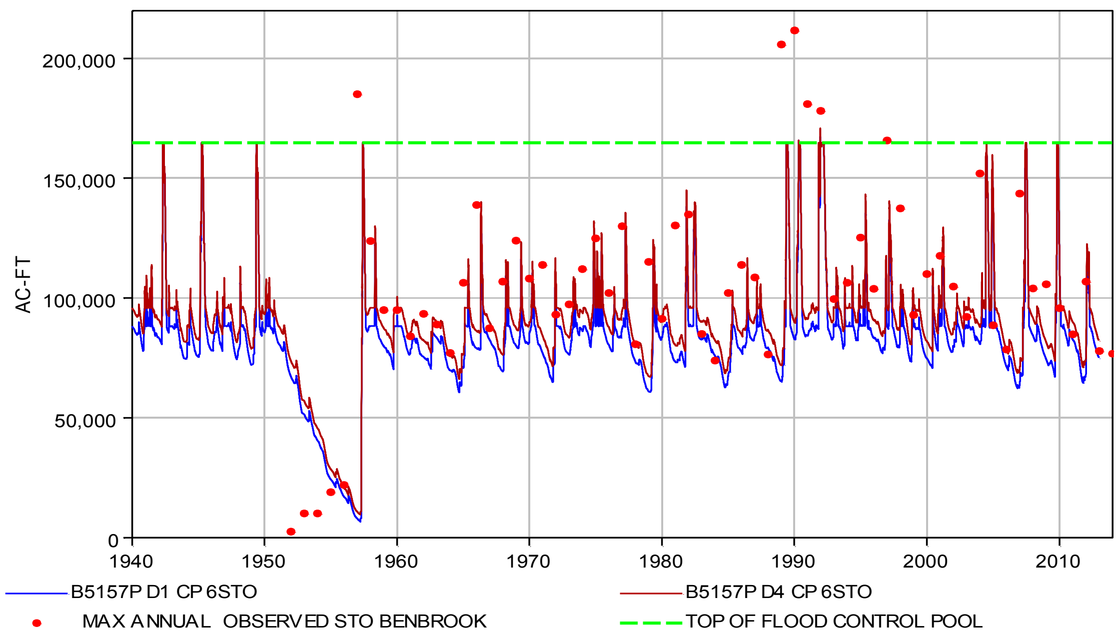

Figure 65. Benbrook Reservoir simulations D1, D4 versus max annual observed storage

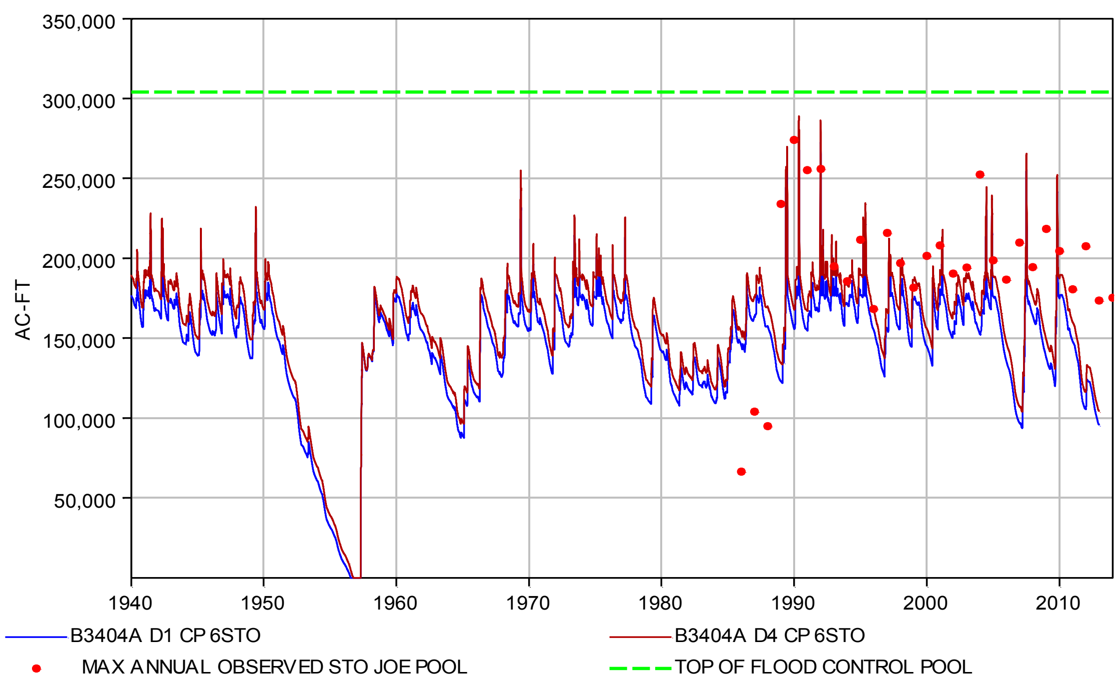

Figure 66. Joe Pool Reservoir simulations D1, D4 versus max annual observed storage

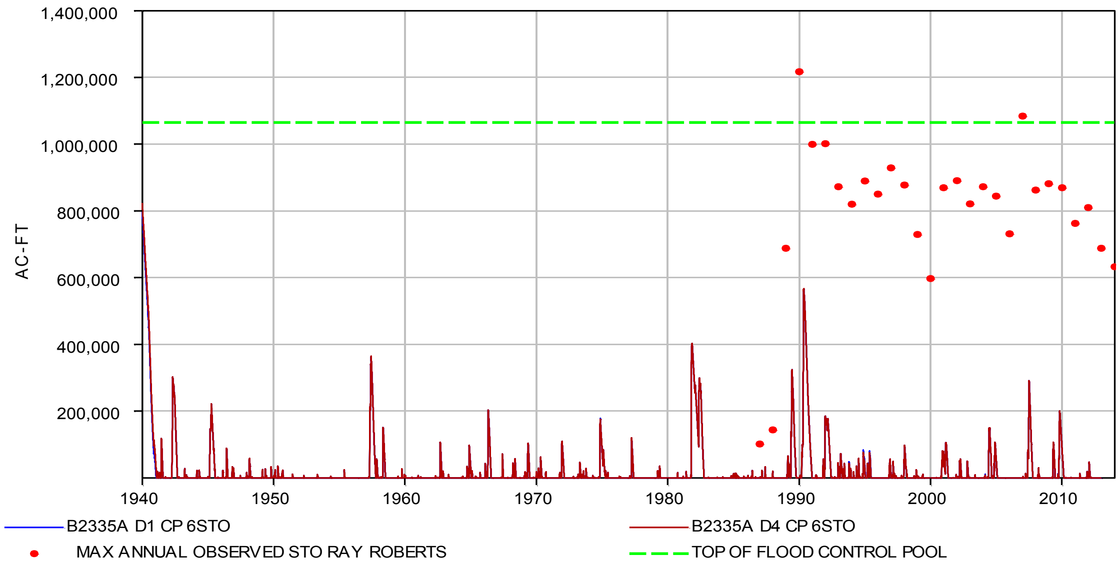

Figure 67. Ray Roberts Reservoir simulations D1, D4 versus max annual observed storage

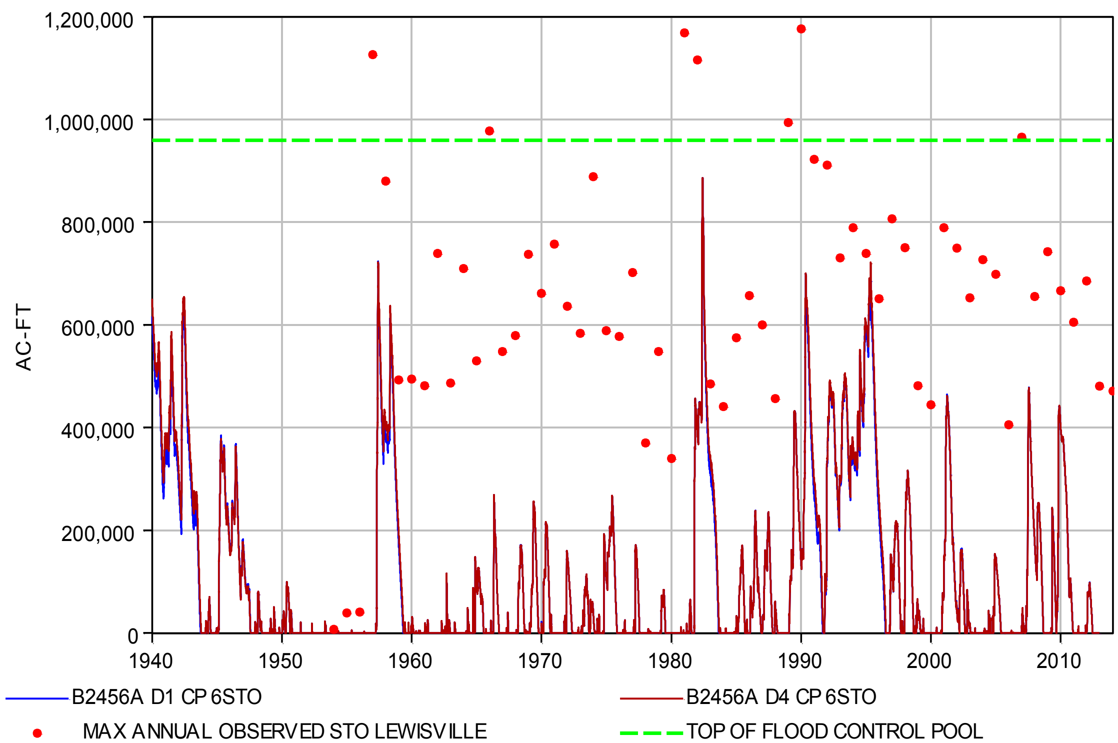

Figure 68. Lewisville Reservoir simulations D1, D4 versus max annual observed storage

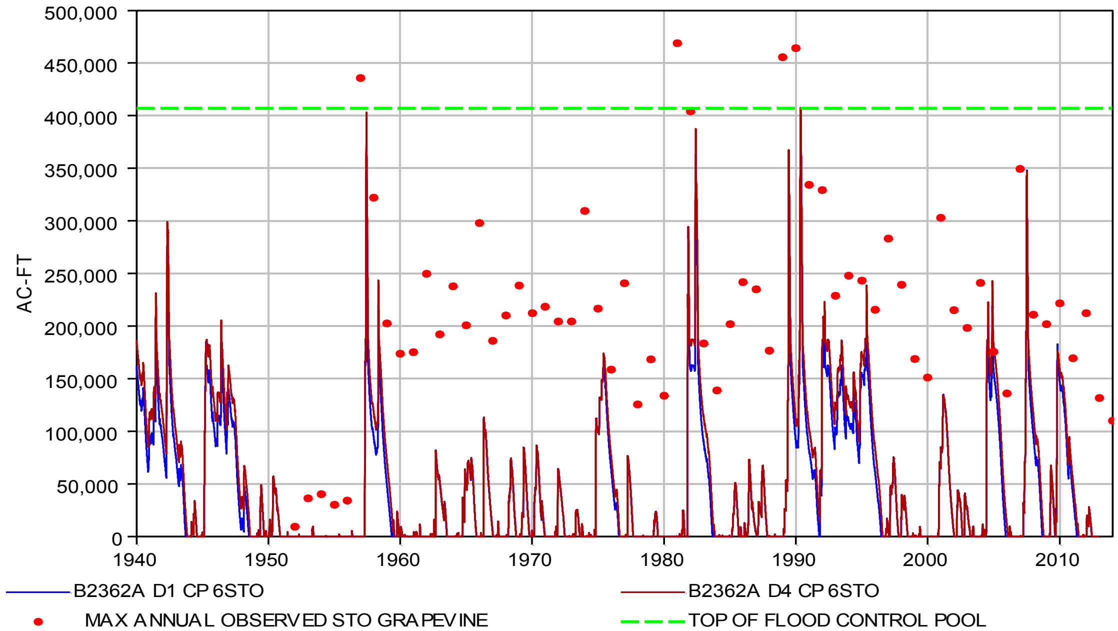

Figure 69. Grapevine Reservoir simulations D1, D4 versus max annual observed storage

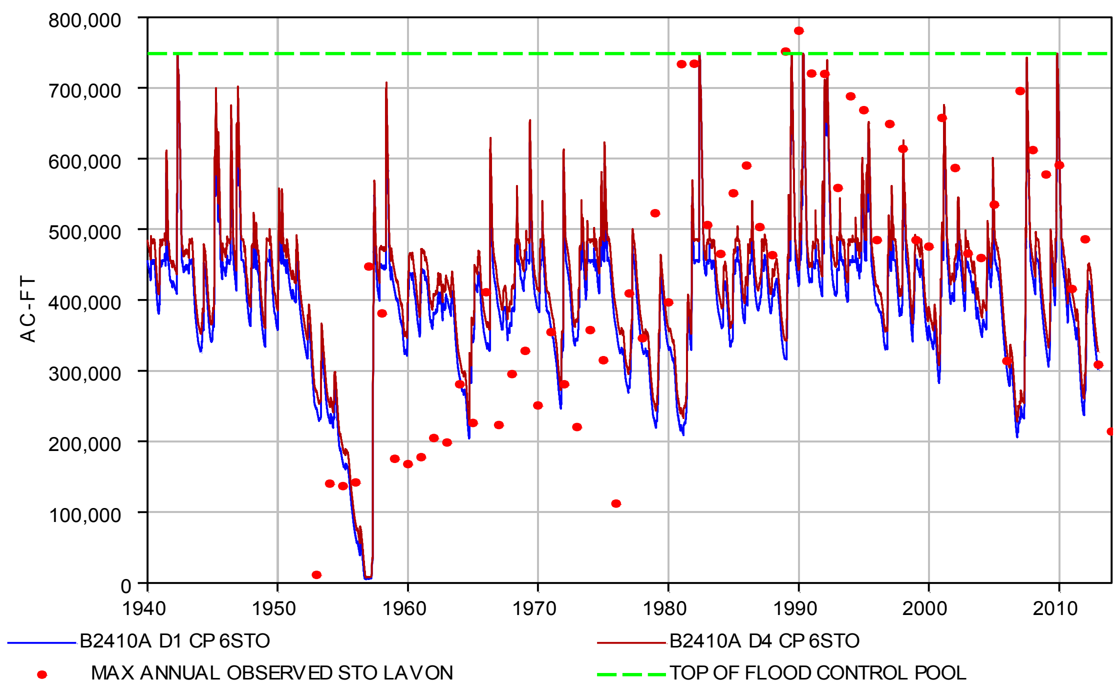

Figure 70. Lavon Reservoir simulations D1, D4 versus max annual observed storage

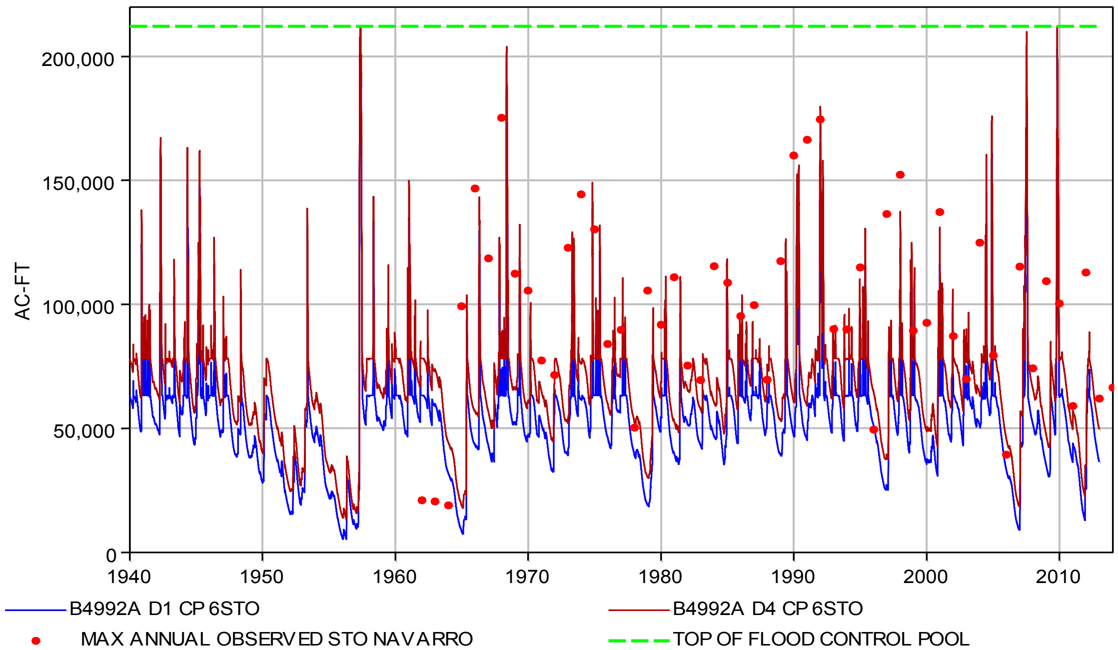

Figure 71. Navarro Mills Reservoir simulations D1, D4 versus max annual observed storage

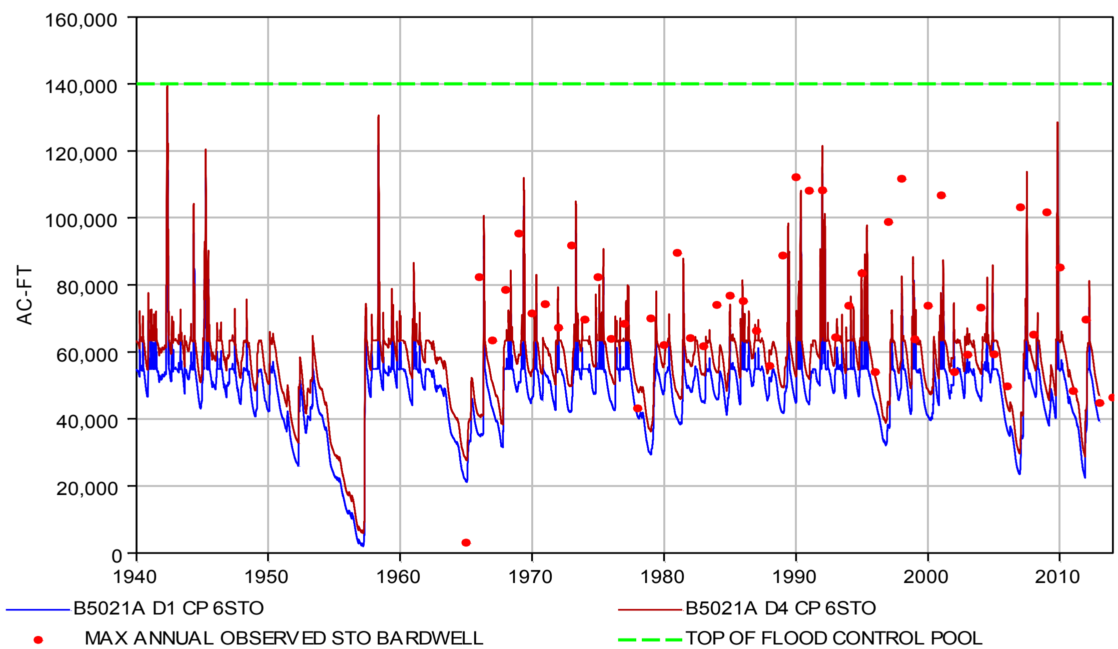

Figure 72. Bardwell Reservoir simulation D1, D4 vs max annual observed storage

5.4.2 Comparison of Flood Frequency Analyses

Exceedance probability of top of controlled flood control for simulation D4 was performed for log-Pearson type III distribution for summation of reservoir storage and excess flow, then compared with simulation D1 and observed flood frequency analysis. The simulation D4 return period values were expected lower than simulation D1 return period because conservation storage capacity increased and flood control storage capacity decreased in simulation D4 and water levels were higher than simulation D1.

Return period table was developed for log-Pearson type III distribution as shown in Table 50. Return period for simulation D4 for values were lower than simulation D1 as expected. Joe pool, Lavon and Bardwell Reservoirs, return periods look like same but when Table 43 and Table 51 (frequency tables) were compared, decrease of return period can be seen. These results show that storage reallocation from flood control pool to conservation pool have impact on flood control operation and flood frequency analysis.

Table 50. Comparison of observed storage, D1 and D4 exceedance probability of top of flood control pool log-Pearson type III distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto. +Excess Flow)		Sim D4 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	7.22	13.85	16.68	6.00	19.68	5.08
2	Joe Pool	B3404A	304000	0.71	140.85	0.10	1000.00	0.10	1000.00
3	Ray Roberts	B2335A	1064600	6.75	14.81	0.01	10000.00	0.01	10000.00
4	Lewisville	B2456A	959177	8.89	11.25	3.52	28.41	3.75	26.67
5	Grapevine	B2362A	406900	4.57	21.88	0.40	250.00	1.79	55.87
6	Lavon	B2410A	748200	7.08	14.12	0.10	1000.00	0.10	1000.00
7	Navarro	B4992A	212200	0.24	416.67	1.43	69.93	2.50	40.00
8	Bardwell	B5021A	140000	0.39	256.41	0.10	1000.00	0.10	1000.00

Table 51. FFA for summation of reservoir storage and excess flow log-Pearson type III distribution for D4

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

CONTROL POINT	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%) 1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	33248.	119419.	164025.	188410.	214280.	230563.	244732.	257192.	271525.	119205.
B3404A	32920.	206760.	228340.	230667.	231203.	231264.	231277.	231280.	231281.	170208.
B2335A	4.	84587.	156541.	168835.	172367.	172878.	173006.	173039.	173049.	90311.
B2456A	2140.	151953.	414574.	634196.	931624.	1153245.	1367127.	1570537.	1820743.	271679.
B2362A	133.	78975.	214349.	294264.	366555.	401810.	425509.	441253.	454171.	124874.
B2410A	141119.	580075.	651919.	665016.	670000.	671041.	671400.	671525.	671575.	494932.
B4992A	34683.	106913.	147239.	171097.	198339.	216771.	233807.	249704.	269262.	108917.
B5021A	26607.	78413.	96976.	105074.	112199.	115925.	118729.	120861.	122944.	73457.

5.4.3 Water Supply Reliability for D4

Water supply reliability table was developed for control points that located at dams for simulation D4 as shown in Table 52. Benbrook, Lavon, Navarro Mills, and Bardwell Reservoirs water diversion target is 100% met in terms of simulation duration and diversion amount. There were little increase of water reliabilities for Joe Pool, Ray Roberts, Lewisville, and Grapevine Reservoirs in simulation D4 than simulation D1. Joe Pool water reliability was almost 100%. However, like simulation D1, Ray Roberts Reservoir had very low water reliability in terms of period and volume.

Table 52. Water supply reliability for D4

Daily Data from January 1940 through December 2012

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF DAYS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%
B5157P	132812.9	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
B3404A	422737.6	110.80	99.22	99.97	99.2	100.0	100.0	100.0	100.0	100.0	100.0	99.2	100.0	100.0	100.0	100.0	100.0	100.0
B2335A	799601.8	634899.62	20.39	20.60	20.4	20.5	20.6	20.8	21.2	21.6	22.8	11.3	11.5	12.1	14.4	18.6	26.3	42.8
B2456A	918848.8	530853.25	53.84	42.23	53.8	53.9	54.0	54.4	55.4	57.3	74.6	45.1	46.0	46.8	49.0	54.9	62.2	82.0
B2362A	171130.4	69271.57	59.86	59.52	59.9	59.9	60.0	60.3	61.0	62.9	71.3	52.7	53.4	53.8	55.4	60.5	66.7	82.0
B2410A	128420.6	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
B4992A	192768.9	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
B5021A	158580.2	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
Total	2924901.2	1235135.38		57.77														

5.5 Simulations D1, D5 versus Observed Annual Maximum Reservoirs Storage

The simulation D5 represents 20% flood control reservoir storage allocated to conservation pool capacity, full authorized water use, daily time step, has flood control operation, and was developed as single-owner reservoir system. Simulation D5 was executed in order to show how 20% storage reallocation from flood control pool to conservation pool affects flood frequency analysis and water reliability.

5.5.1 Comparison of Reservoirs Storage

Simulation D1 storage capacities were compared with simulation D5 storage capacities. As shown in Figures 73-80, straight blue line represents D1 likewise, dark red straight line represents D5 and green line represents top of controlled flood control pool level. As a result of this comparison, all of reservoirs storage level increased in simulation D5 except Ray Roberts Reservoir. Also, Lewisville Reservoir increased little for some days. Increase of reservoir storage was expected and aimed for all reservoirs.

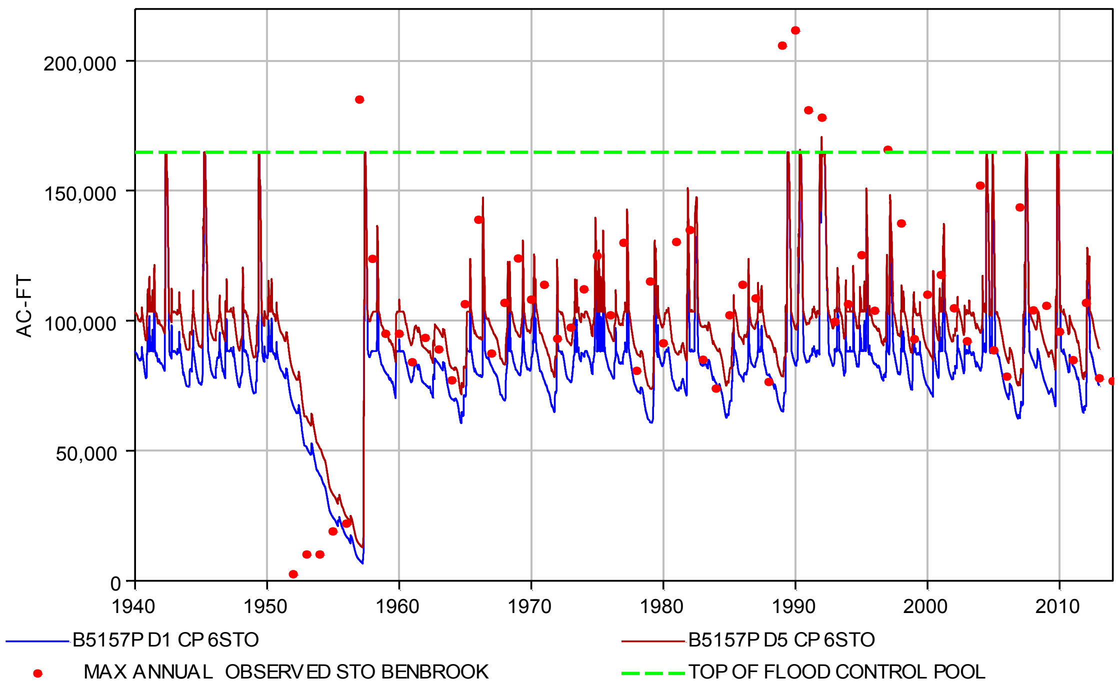

Figure 73. Benbrook Reservoir simulations D1, D5 versus max annual observed storage

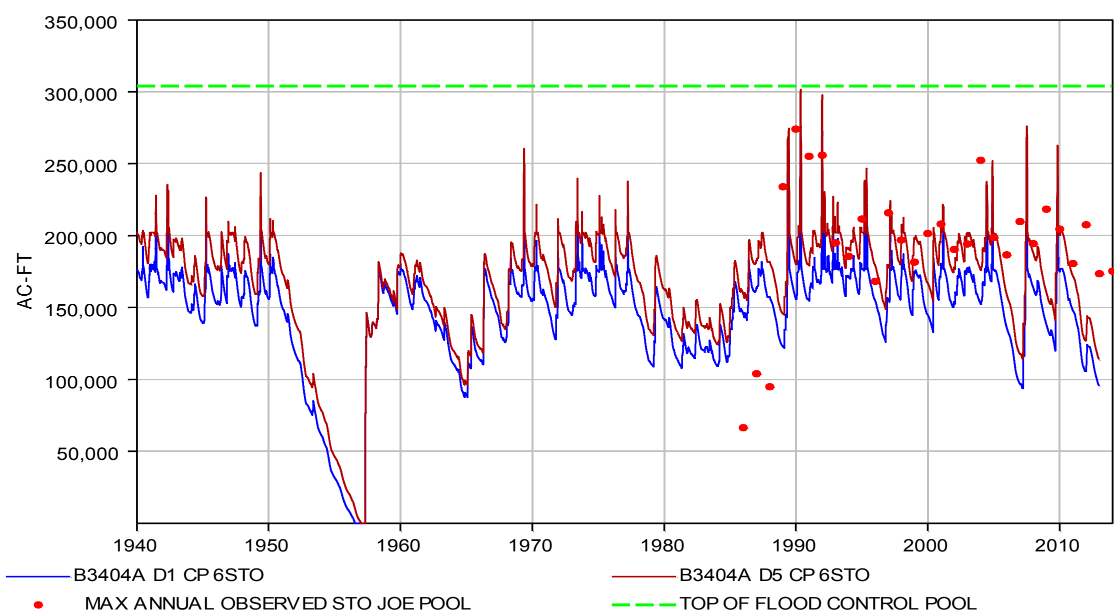

Figure 74. Joe Pool Reservoir simulations D1, D5 versus max annual observed storage

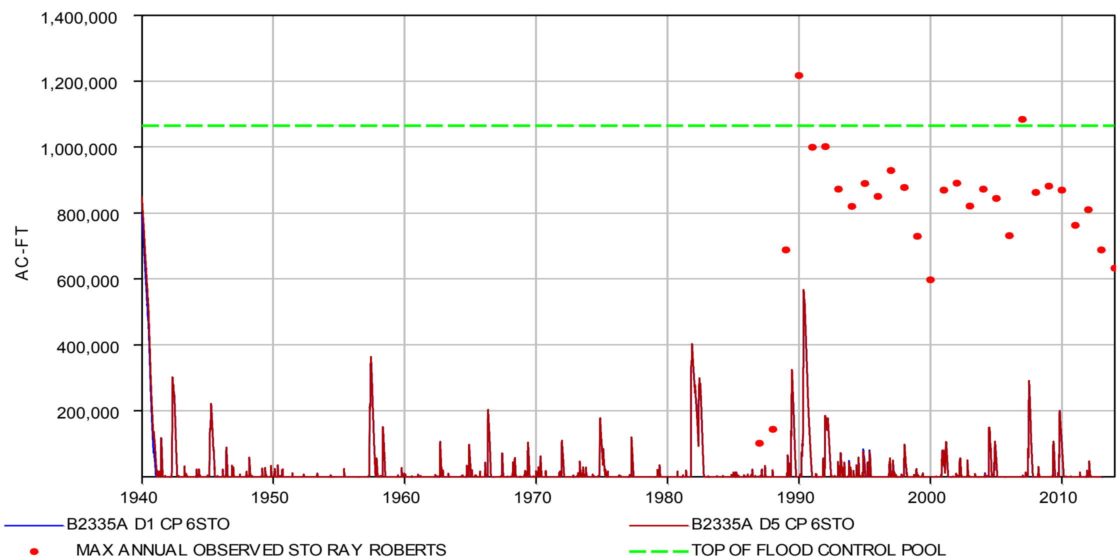

Figure 75. Ray Roberts Reservoir simulations D1, D5 versus max annual observed storage

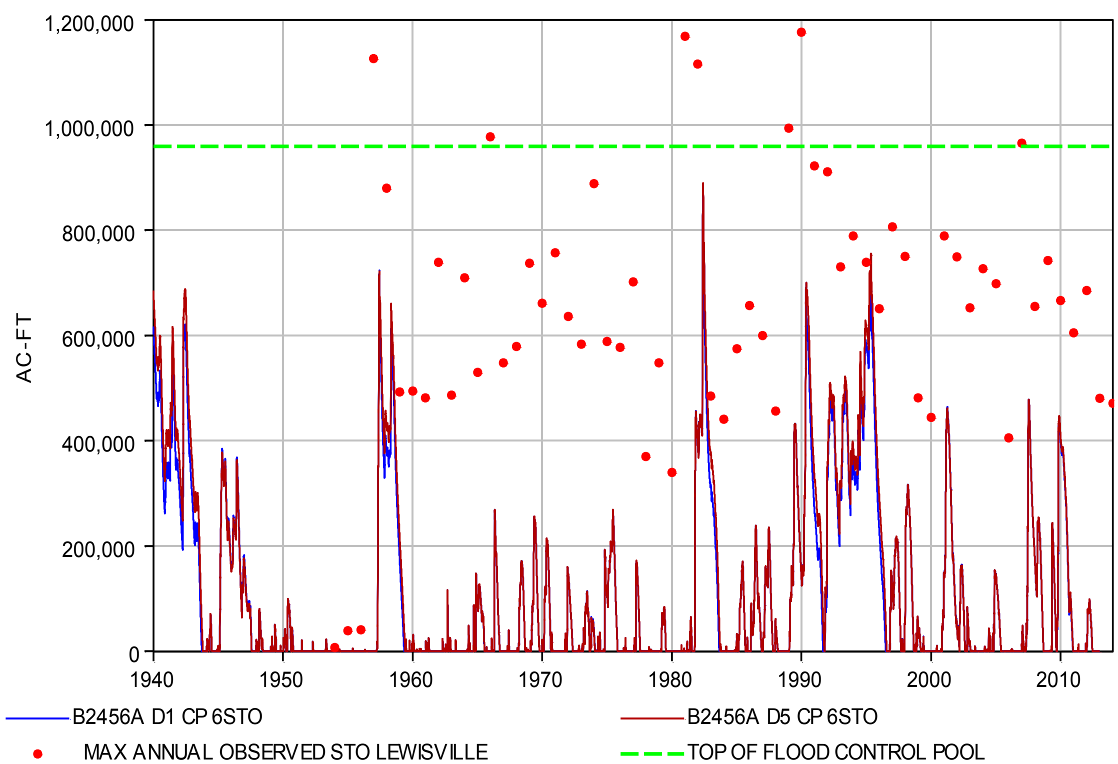

Figure 76. Lewisville Reservoir simulations D1, D5 versus max annual observed storage

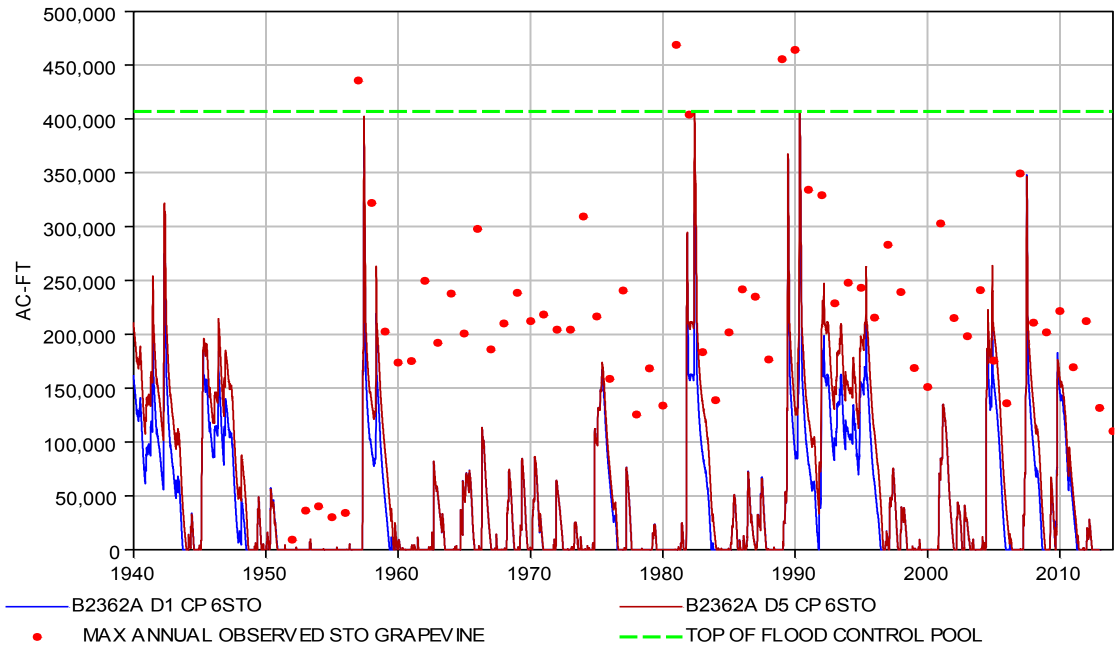

Figure 77. Grapevine Reservoir simulations D1, D5 versus max annual observed storage

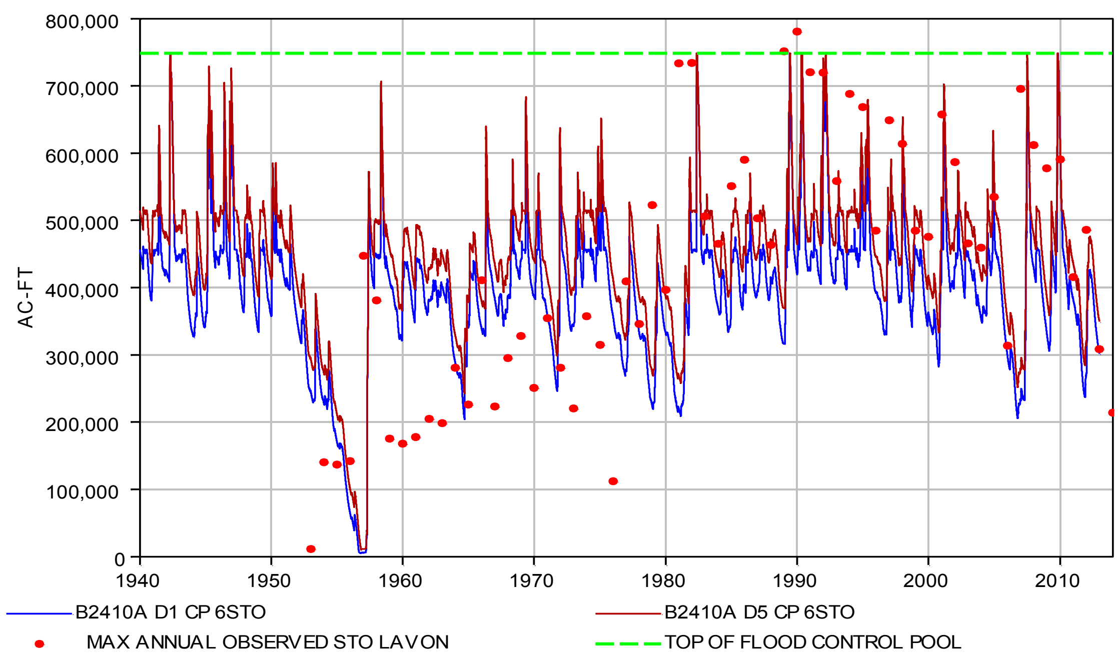

Figure 78. Lavon Reservoir simulations D1, D5 versus max annual observed storage

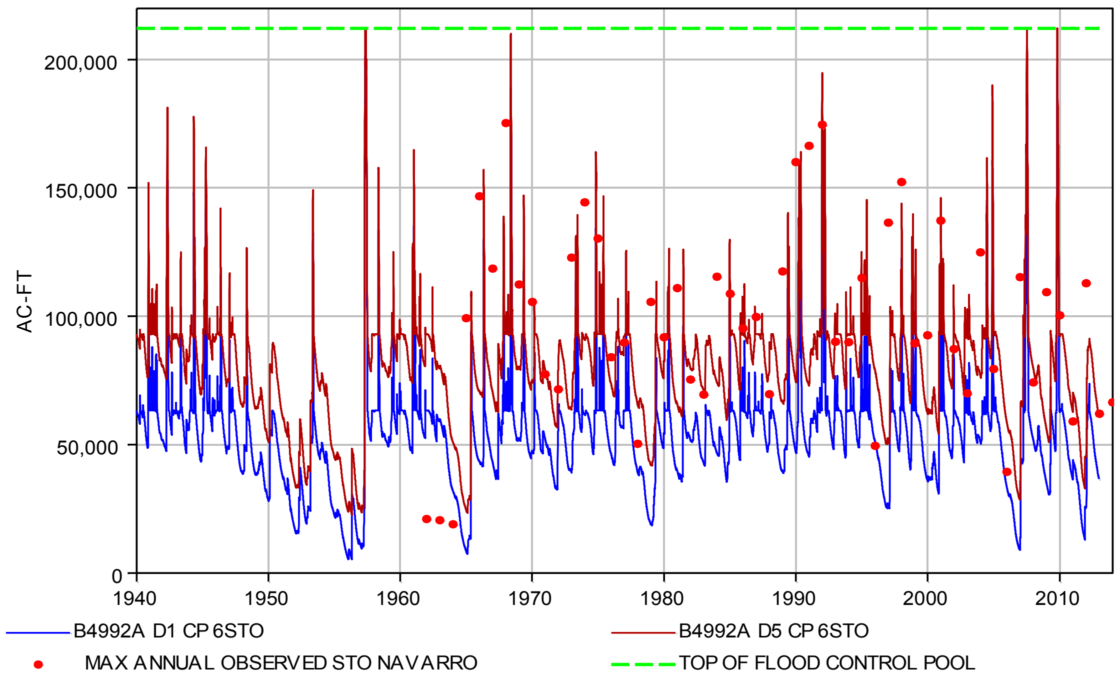

Figure 79. Navarro Mills Reservoir simulations D1, D5 versus max annual observed storage

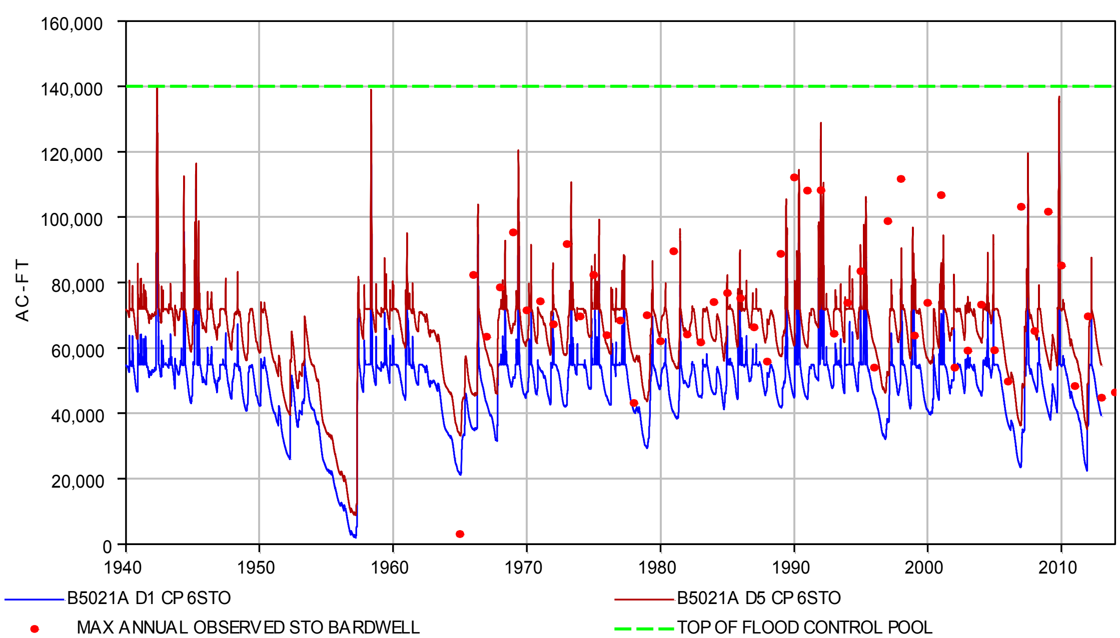

Figure 80. Bardwell Reservoir simulations D1, D5 versus max annual observed storage

5.5.2 Comparison of Flood Frequency Analyses

Exceedance probability of top of controlled flood control for simulation D5 was performed for log-Pearson type III distribution for summation of reservoir storage and excess flow, then compared with simulation D1 and observed flood frequency analysis. The simulation D5 return period values were expected lower than simulation D1 and D4 return period because conservation storage capacity increased and flood control storage capacity decreased in simulation D5 and water levels were higher than simulations D1 and D4.

Return period and statistical tables were developed for log-Pearson type III distribution as shown in Table 53 and 54. Return period for simulation D5 for values were lower than simulation D1 as expected. Joe pool, Ray Roberts, Lavon and Bardwell Reservoirs, return periods look like same but when Table 43 and Table 53 (frequency tables) were compared, decrease of return period can be seen. Benbrook Reservoir had very low return period as low as 4 years. Benbrook, Lewisville, Grapevine, and Navarro Mills Reservoirs` return flood control return period lower than 50 years in simulation D5. These results show that storage reallocation from flood control pool to conservation pool have impact on flood control operation and flood frequency analysis.

Table 53. Comparison of observed storage, D1 and D5 exceedance probability of top of flood control pool log-Pearson type III distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto. +Excess Flow)		Sim D5 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	7.22	13.85	16.68	6.00	24.26	4.12
2	Joe Pool	B3404A	304000	0.71	140.85	0.10	1000.00	0.10	1000.00
3	Ray Roberts	B2335A	1064600	6.75	14.81	0.01	10000.00	0.01	10000.00
4	Lewisville	B2456A	959177	8.89	11.25	3.52	28.41	4.03	24.81
5	Grapevine	B2362A	406900	4.57	21.88	0.40	250.00	2.13	46.95
6	Lavon	B2410A	748200	7.08	14.12	0.10	1000.00	0.10	1000.00
7	Navarro	B4992A	212200	0.24	416.67	1.43	69.93	3.73	26.81
8	Bardwell	B5021A	140000	0.39	256.41	0.10	1000.00	0.10	1000.00

Table 54. FFA for summation of reservoir storage and excess flow log-Pearson type III distribution for D5

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	38144.	126628.	171122.	195330.	220999.	237175.	251278.	263711.	278061.	125715.
B3404A	39393.	214314.	234852.	237058.	237566.	237624.	237636.	237639.	237640.	177069.
B2335A	4.	84761.	156936.	169277.	172825.	173338.	173467.	173500.	173510.	90527.
B2456A	2129.	153516.	422805.	650283.	960935.	1194124.	1420465.	1636864.	1904560.	277971.
B2362A	145.	85075.	225434.	305475.	375742.	409028.	430886.	445078.	456423.	130940.
B2410A	163572.	602987.	681044.	697353.	704419.	706130.	706796.	707057.	707177.	520443.
B4992A	44187.	118927.	159048.	182681.	209699.	228044.	245070.	261034.	280796.	120120.
B5021A	31446.	86547.	104641.	112156.	118505.	121699.	124026.	125742.	127360.	80393.

5.5.3 Water Supply Reliability for D5

Water supply reliability table was developed for control point that located at dams for simulation D5 as shown in Table 55. Benbrook, Lavon, Navarro Mills, and Bardwell Reservoirs water diversion target 100% met in terms of simulation duration and diversion amount. There were little increase of water reliability for Joe Pool, Ray Roberts, Lewisville, and Grapevine Reservoirs in simulation D5 than simulation D1. Joe Pool water reliability was almost 100%. However, like simulation D1, Ray Roberts Reservoir had very low water reliability in terms of period and volume.

Table 55. Water supply reliability for D5

Daily Data from January 1940 through December 2012

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF DAYS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%
B5157P	139237.4	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
B3404A	467670.6	54.27	99.61	99.99	99.6	100.0	100.0	100.0	100.0	100.0	100.0	99.5	100.0	100.0	100.0	100.0	100.0	100.0
B2335A	799601.8	634597.25	20.44	20.64	20.4	20.5	20.6	20.8	21.2	21.7	22.8	11.3	11.6	12.0	14.5	18.7	26.4	42.8
B2456A	916337.8	526631.56	54.16	42.53	54.2	54.2	54.3	54.7	55.7	57.7	74.8	45.1	46.2	47.1	49.4	55.5	62.2	81.7
B2362A	170838.0	67141.30	61.00	60.70	61.0	61.1	61.1	61.4	62.2	64.1	72.2	53.8	54.5	55.3	56.6	62.1	67.5	82.4
B2410A	128827.1	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
B4992A	212999.6	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
B5021A	166852.0	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
Total	3002364.2	1228424.25		59.08														

5.6 Simulations D1, D6 versus Observed Annual Maximum Reservoirs Storage

The simulation D6 represents 50% flood control reservoir storage allocated to conservation pool capacity, full authorized water use, daily time step, has flood control operation, and was developed as single-owner reservoir system. Simulation D5 was executed in order to show how 50% storage reallocation from flood control pool to conservation pool affects flood frequency analysis and water reliability.

5.6.1 Comparison of Reservoirs Storage

Simulation D1 storage capacities were compared with simulation D6 storage capacities. As shown in Figures 81-88, straight blue line represents D1 likewise, dark red straight line represents D5 and green line represents top of controlled flood control pool level. As a result of this comparison, all of reservoirs storage level increased in simulation D6 except Ray Roberts Reservoir. Also, Lewisville Reservoir increased little for some days. Increase of reservoir storage was expected and aimed for all reservoirs. Ray Roberts's storage level did not increase because it already had empty conservation place to store water in simulation D6.

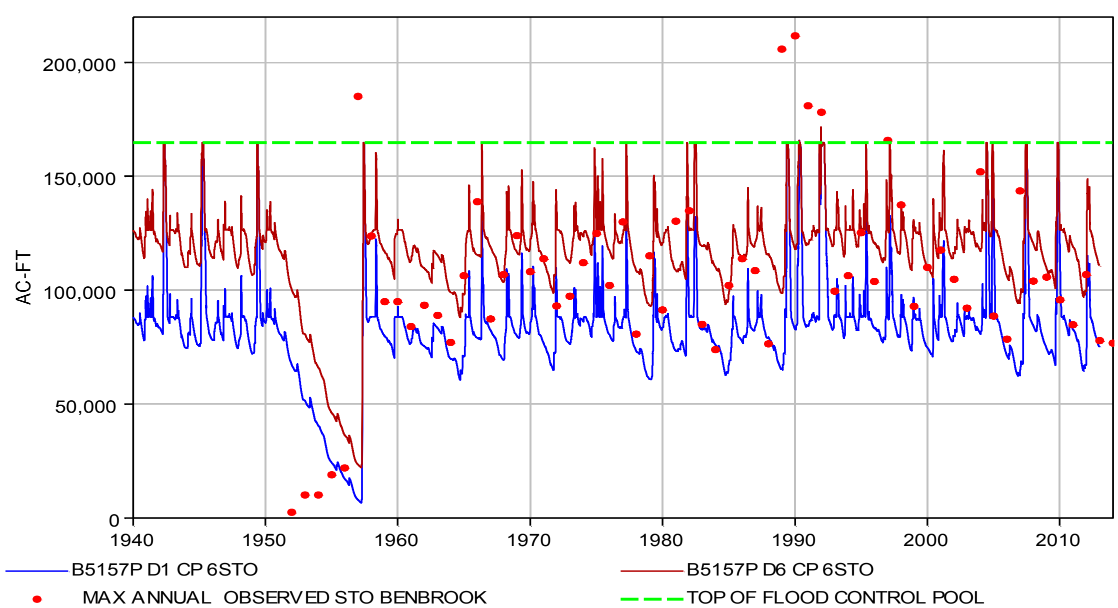

Figure 81. Benbrook Reservoir simulations D1, D6 versus max annual observed storage

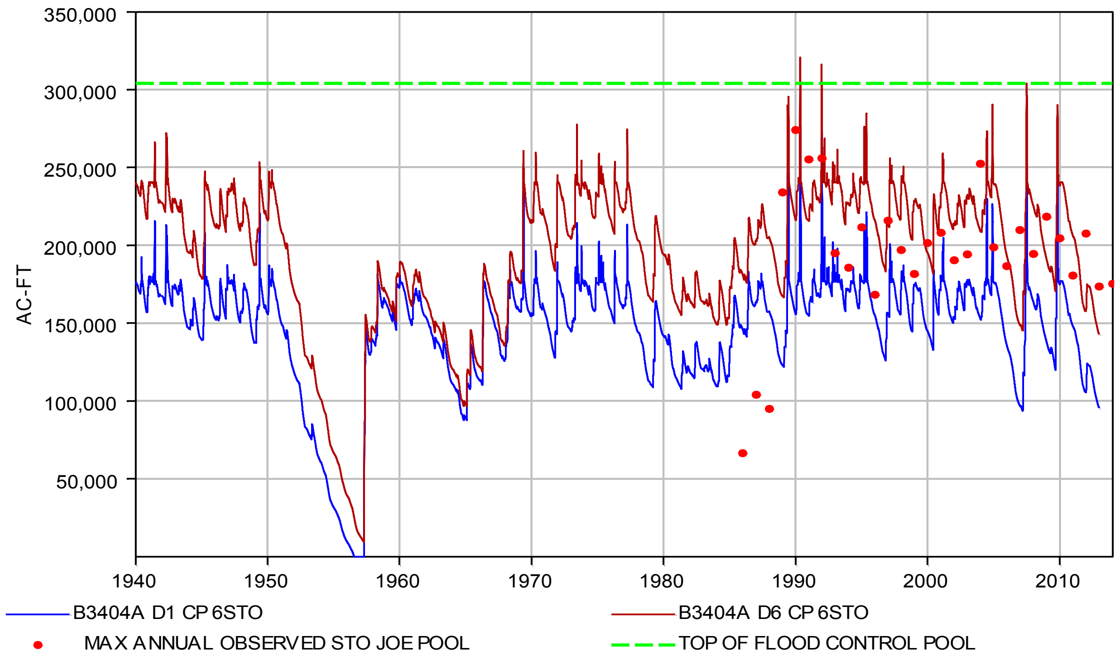

Figure 82. Joe Pool Reservoir simulations D1, D6 versus max annual observed storage

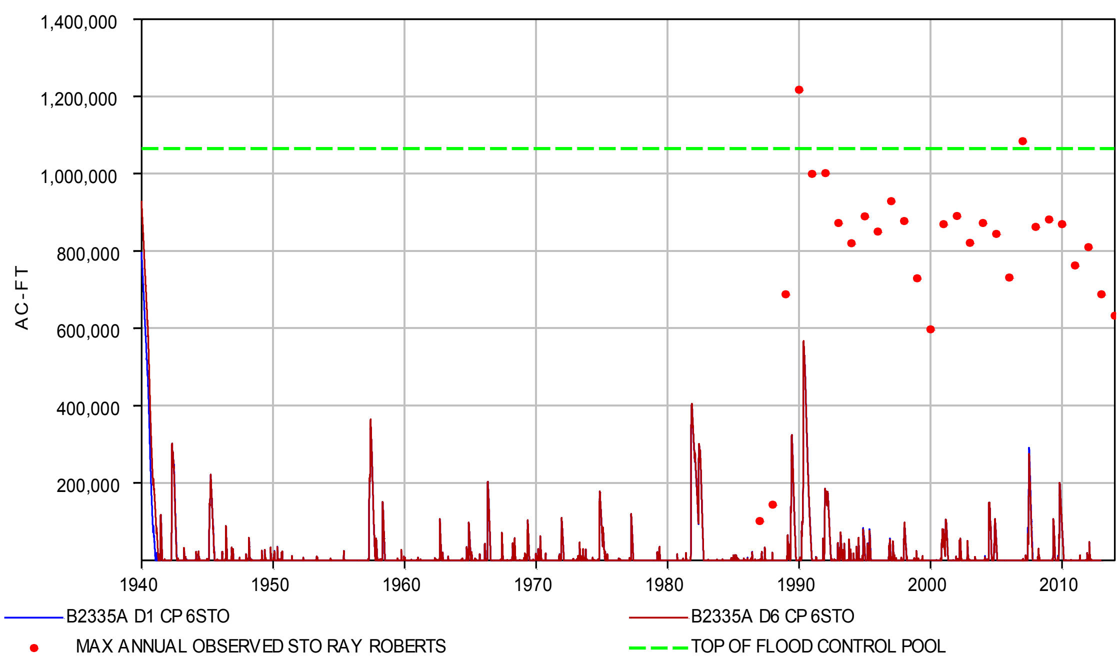

Figure 83. Ray Roberts Reservoir simulations D1, D6 versus max annual observed storage

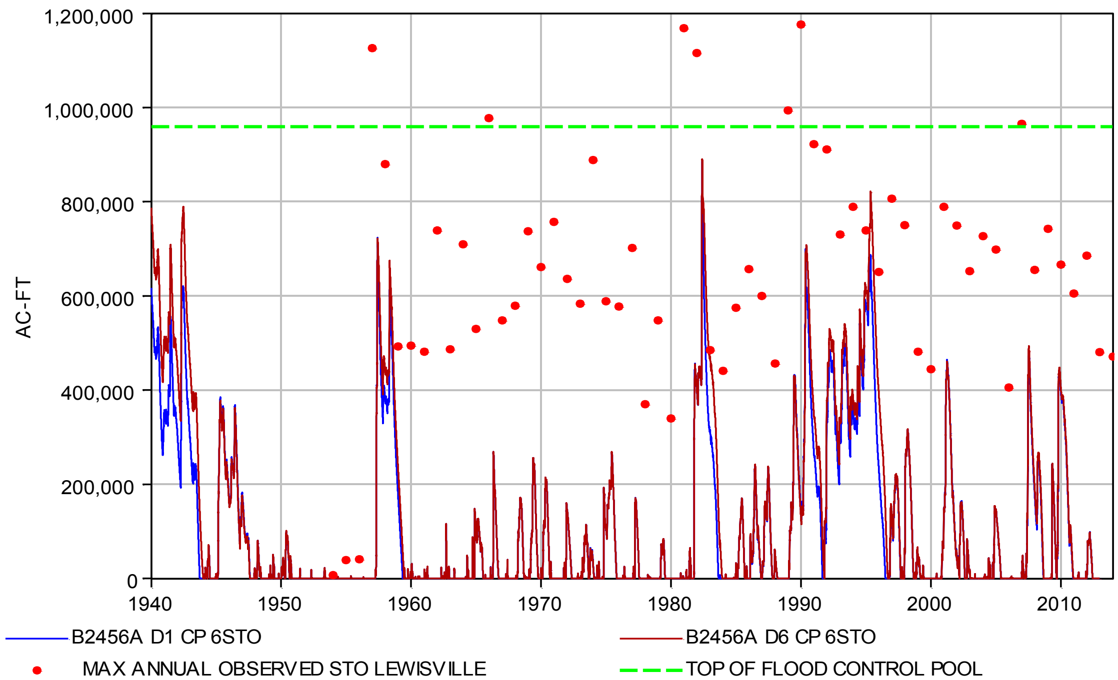

Figure 84. Lewisville Reservoir simulations D1, D6 versus max annual observed storage

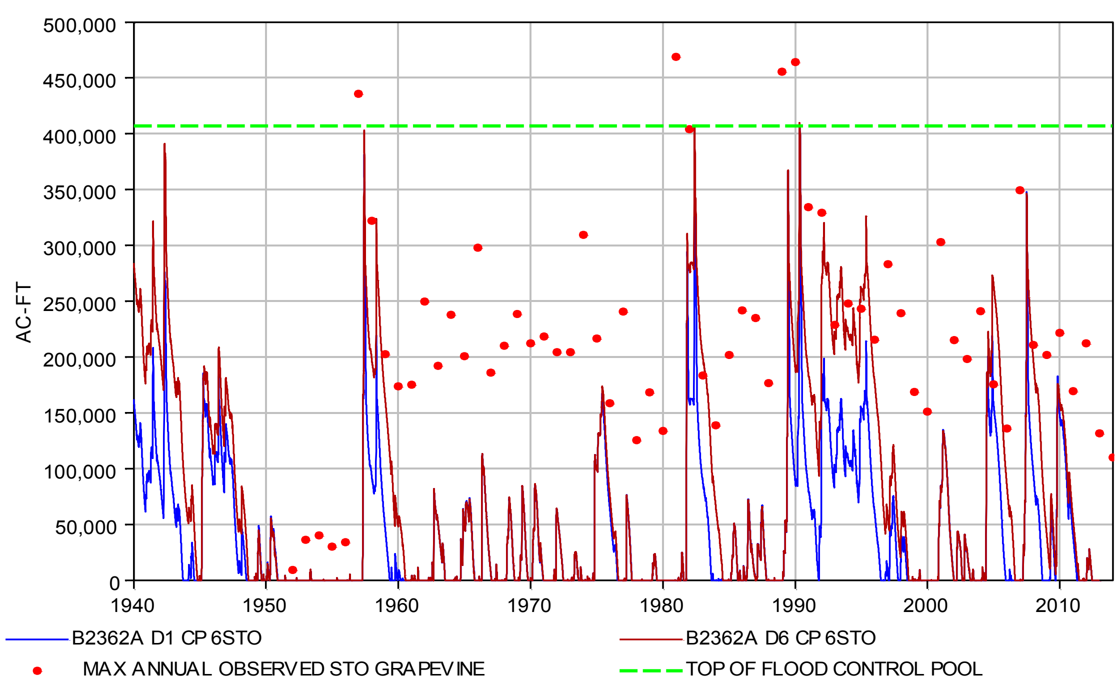

Figure 85. Grapevine Reservoir simulations D1, D6 versus max annual observed storage

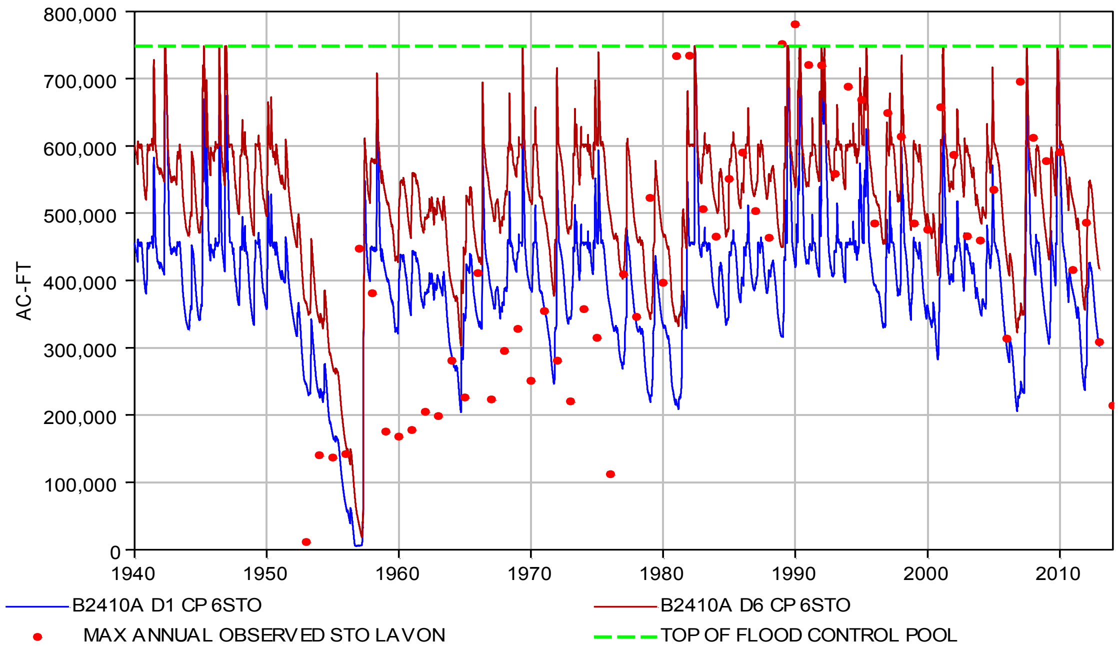

Figure 86. Lavon Reservoir simulations D1, D6 versus max annual observed storage

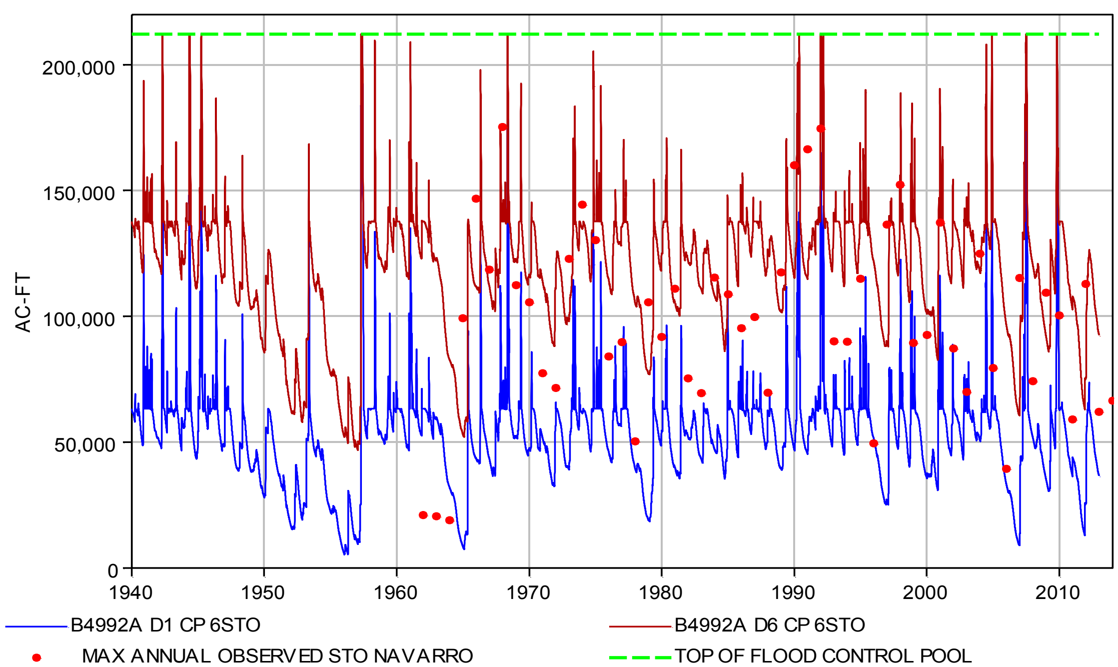

Figure 87. Navarro Mills Reservoir simulations D1, D6 versus max annual observed storage

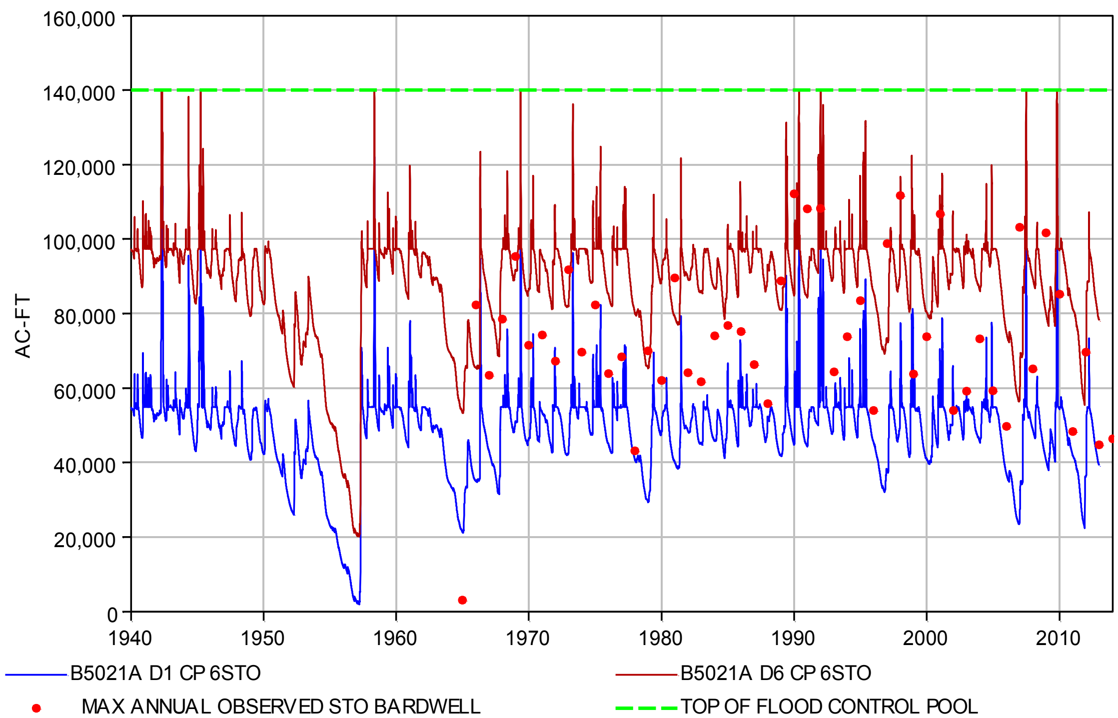

Figure 88. Bardwell Reservoir simulations D1, D6 versus max annual observed storage

5.6.2 Comparison of Flood Frequency Analyses

Exceedance probability of top of controlled flood control for simulation D6 was performed for log-Pearson type III distribution for summation of reservoir storage and excess flow, then compared with simulation D1 and was observed flood frequency analysis. The simulation D6 return period values were expected lower than simulations D1, D4 and D5 return period because conservation storage capacity increased and flood control storage capacity decreased in simulation D6 and water levels were higher than simulations D1, D4 and D5.

Return period table was developed for log-Pearson type III distribution as shown in Table 56. Return period for simulation D6 for values were lower than simulation D1 as expected. Joe pool and Ray Roberts Reservoirs, return periods look like same but when Table 43 and Table 57 (frequency tables) were compared, decrease of return period can be seen. Benbrook and Lavon Reservoir had very low return period as low as 2 and 4 year respectively. All of reservoirs` return flood control return period were lower than 50 years except Joe Pool and Ray Roberts in simulation D6. These results show that storage reallocation from flood control pool to conservation pool have great impact on flood control operation and flood frequency analysis.

Table 56. Comparison of observed storage, D1, and D6 exceedance probability of top of flood control pool log-Pearson type III distribution

No	Reservoir	Control Point	Top of Flood Control (ac-ft)	Observed		Sim D1 (Res. Sto. +Excess Flow)		Sim D6 (Res. Sto. +Excess Flow)	
				Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
1	Benbrook	B5157P	164800	7.22	13.85	16.68	6.00	38.63	2.59
2	Joe Pool	B3404A	304000	0.71	140.85	0.10	1000.00	0.10	1000.00
3	Ray Roberts	B2335A	1064600	6.75	14.81	0.01	10000.00	0.01	10000.00
4	Lewisville	B2456A	959177	8.89	11.25	3.52	28.41	5.19	19.27
5	Grapevine	B2362A	406900	4.57	21.88	0.40	250.00	4.38	22.83
6	Lavon	B2410A	748200	7.08	14.12	0.10	1000.00	24.50	4.08
7	Navarro	B4992A	212200	0.24	416.67	1.43	69.93	15.88	6.30
8	Bardwell	B5021A	140000	0.39	256.41	0.10	1000.00	7.86	12.72

Table 57. FFA for summation of reservoir storage and excess flow log-Pearson type III distribution for D6

FLOOD FREQUENCIES FOR SUMMATION OF RESERVOIR STORAGE AND EXCESS FLOW

	ANNUAL RECURRENCE INTERVAL (YEARS) AND EXCEEDANCE FREQUENCY (%)									
CONTROL POINT	1.01 99%	2 50%	5 20%	10 10%	25 4%	50 2%	100 1%	200 0.5%	500 0.2%	EXPECTED VALUE
B5157P	51904.	148384.	191706.	214152.	237126.	251164.	263119.	273432.	285056.	144378.
B3404A	58652.	237451.	268123.	274050.	276424.	276948.	277137.	277205.	277233.	203374.
B2335A	4.	85113.	158828.	171657.	175389.	175935.	176072.	176108.	176119.	91415.
B2456A	2108.	156277.	439750.	685056.	1027008.	1288458.	1545940.	1795479.	2108743.	291575.
B2362A	146.	104122.	263623.	345661.	410991.	439087.	456177.	466498.	474141.	151515.
B2410A	229305.	674678.	761162.	782972.	794436.	797894.	799514.	800280.	800716.	594440.
B4992A	73800.	160492.	202416.	226301.	253068.	270981.	287451.	302781.	321630.	159112.
B5021A	48747.	111637.	130258.	137770.	144013.	147114.	149354.	150993.	152528.	103582.

5.6.3 Water Supply Reliability for D6

Water supply reliability table was developed for control points that located at dams for simulation D6 as shown in Table 58. Benbrook, Joe Pool, Lavon, Navarro Mills, and Bardwell Reservoirs water diversion target 100% met in terms of simulation duration and diversion amount. There were little increase of water reliability for Ray Roberts, Lewisville, and Grapevine Reservoirs from in simulation D6 than simulation D1. However, like simulation D1, Ray Roberts Reservoir had very low water reliability in terms of period and volume. Storage reallocations increased water reliability but it was not much. However, return period of flood event increased especially simulation D6 was much than water reliability increase.

Table 58. Water supply reliability for D6

Daily Data from January 1940 through December 2012

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF DAYS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%
B5157P	160831.0	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
B3404A	601974.6	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
B2335A	799601.8	634122.00	20.52	20.70	20.5	20.6	20.7	20.9	21.3	21.8	22.9	11.3	11.6	12.1	14.6	19.3	26.3	42.7
B2456A	910953.8	517188.50	54.97	43.23	55.0	55.1	55.1	55.5	56.5	58.4	75.2	46.1	47.3	48.1	50.5	56.2	63.1	82.2
B2362A	170052.3	61839.68	64.17	63.63	64.2	64.2	64.2	64.5	65.2	66.9	74.2	57.8	58.2	59.0	60.4	65.4	70.1	83.7
B2410A	129264.4	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
B4992A	271708.2	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
B5021A	185777.6	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
Total	3230163.8	1213150.12		62.44														

5.7 Simulations D1 versus M1

The simulation M1 represents existing reservoir storage, full authorized water use, monthly time step, component reservoir system, and there is not flood control operation. The simulation M1 was considered as base simulation for monthly basis and compared with other alternative monthly simulation runs and simulation D1. In order to show differences between monthly and daily time step, simulation M1 was compared with simulation D1. In addition to that, water reliability summary table was developed to compare with other simulations results in order to show differences.

5.7.1 Comparison of Reservoirs Storage

The system of eight Trinity River Basin reservoirs storage capacities for simulation D1 were compared with simulation M1 storage capacities. As shown in Figures 89-96, straight blue line represents D1 likewise, dark red straight and green line represent simulation M1 and top of controlled flood control pool level respectively. As a result of this comparison, daily and monthly simulation matched very good. There were some differences on storage level for some reservoirs because D1 was designed as single owner and M1 was component reservoir. Also, daily time step showed storage value that was at the end of day. Likewise, monthly simulation showed storage value that was at the end of month. Because of that, daily simulation is more sensitive than daily. In a month, reservoir storage value might be higher than last day in a month, so simulation D1 storage level was going up and down more in the graphs.

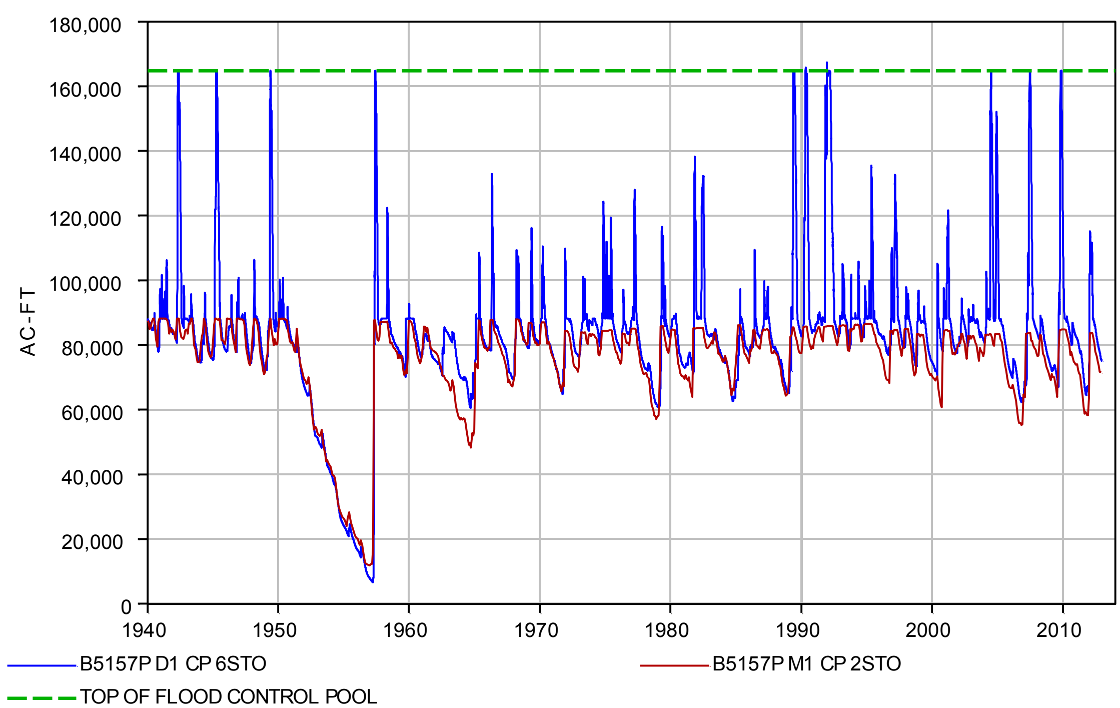

Figure 89. Benbrook Reservoir storage simulations D1 versus M1

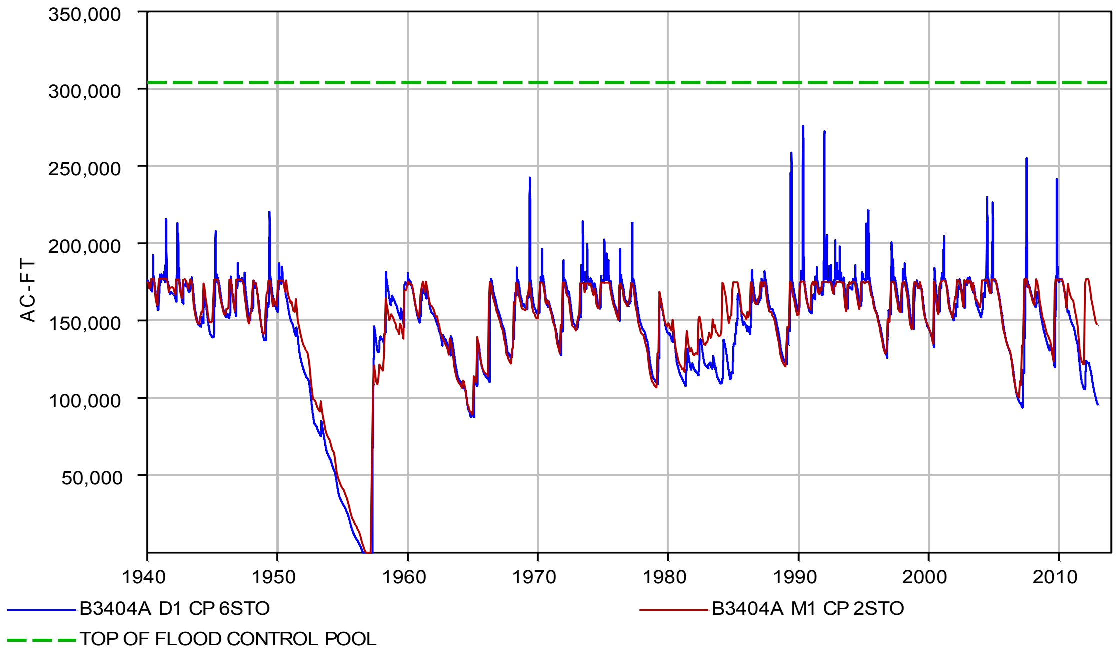

Figure 90. Joe Pool Reservoir storage simulations D1 versus M1

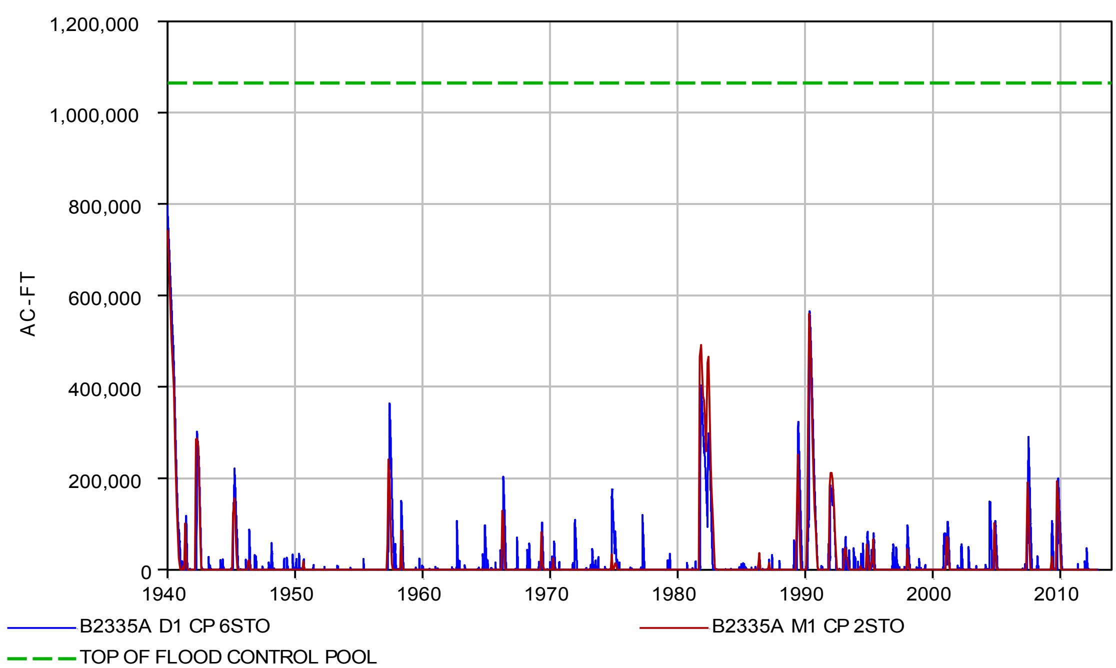

Figure 91. Ray Roberts Reservoir storage simulations D1 versus M1

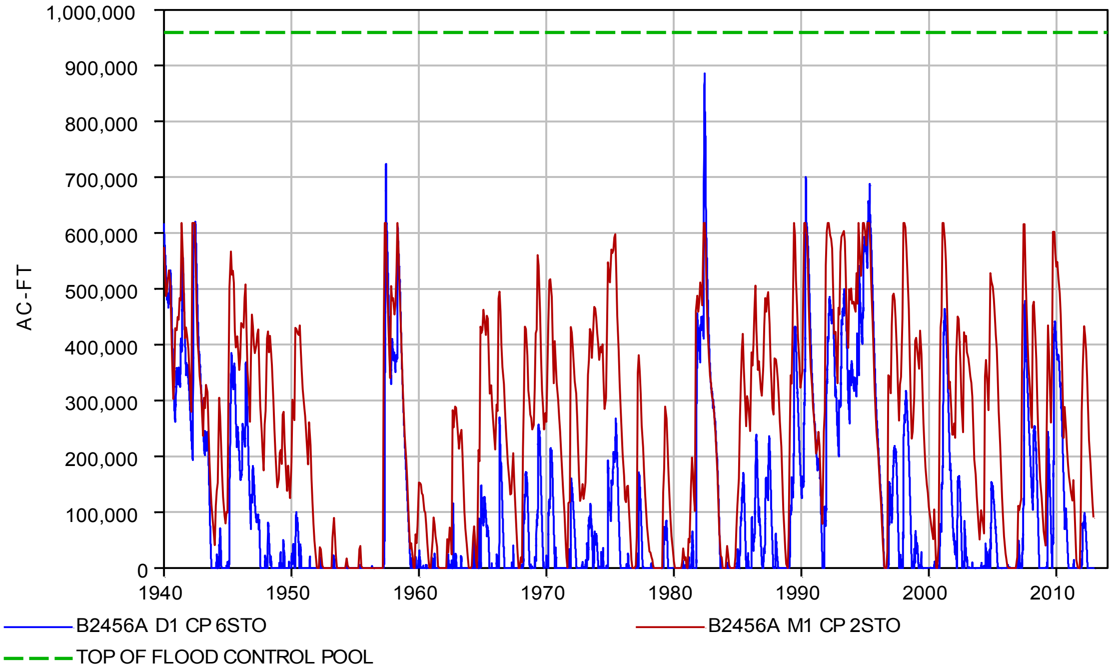

Figure 92. Lewisville Reservoir storage simulations D1 versus M1

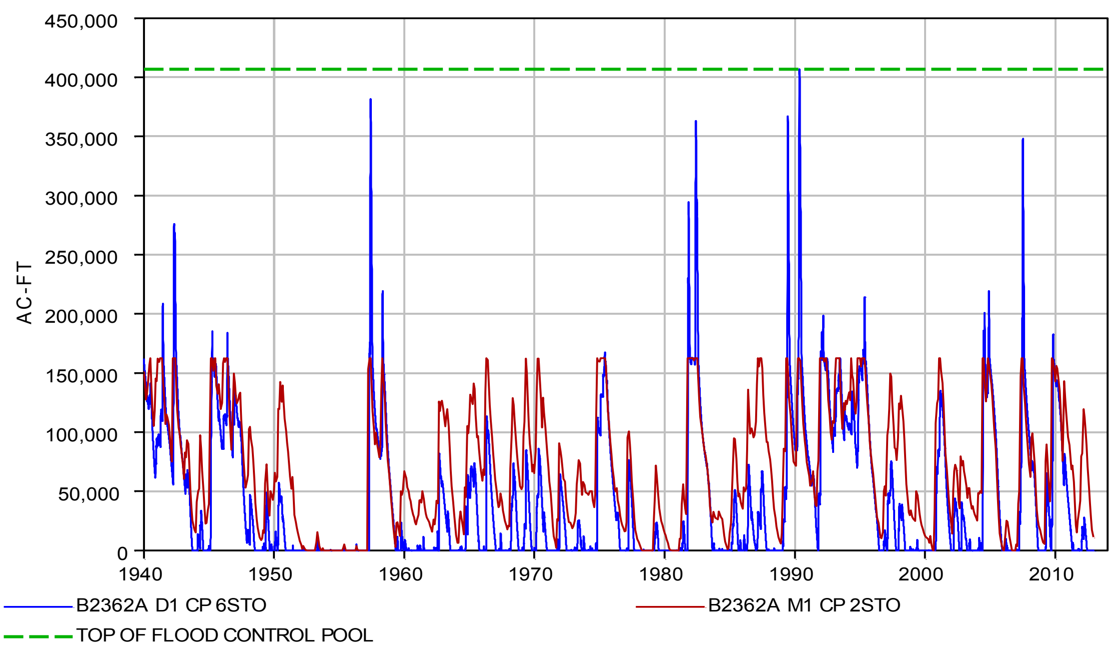

Figure 93. Grapevine Reservoir storage simulations D1 versus M1

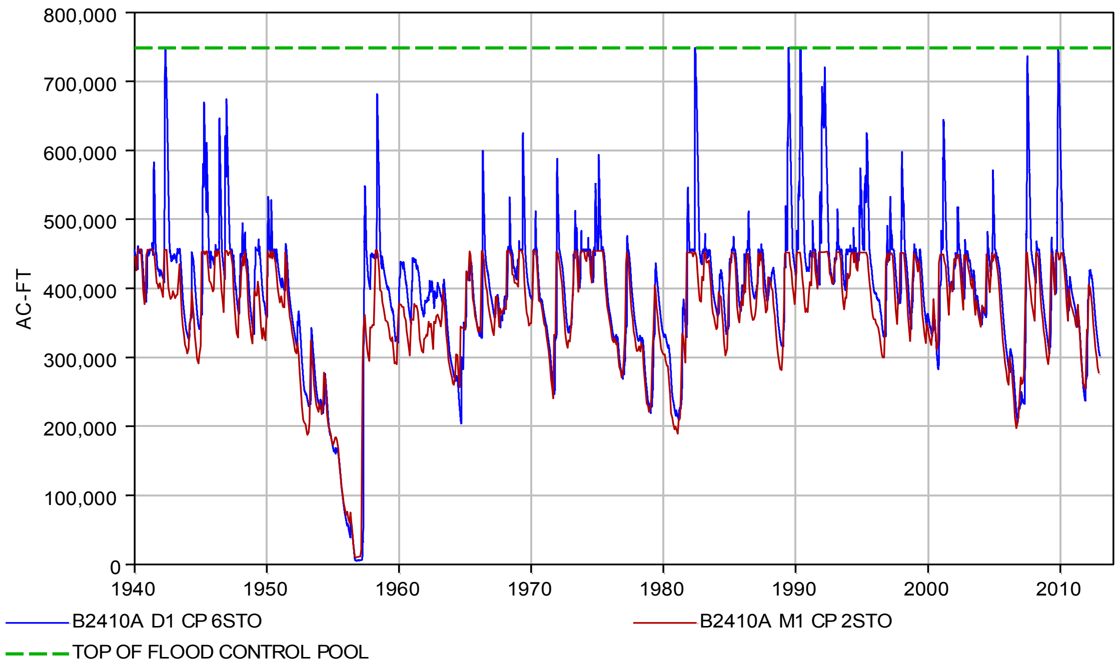

Figure 94. Lavon Reservoir storage simulations D1 versus M1

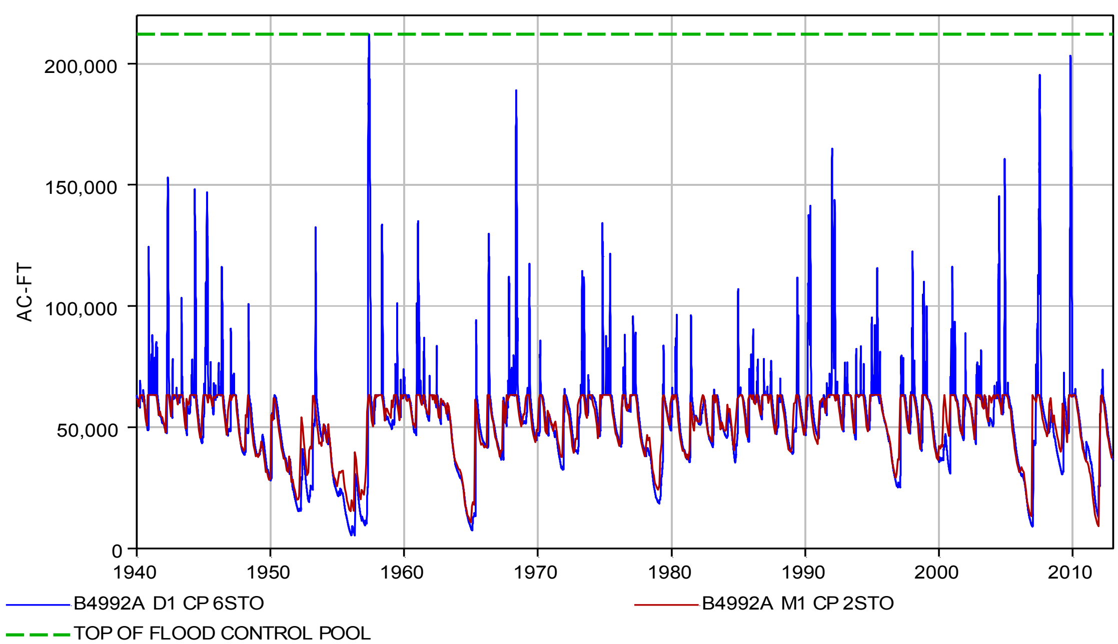

Figure 95. Navarro Mills Reservoir storage simulations D1 versus M1

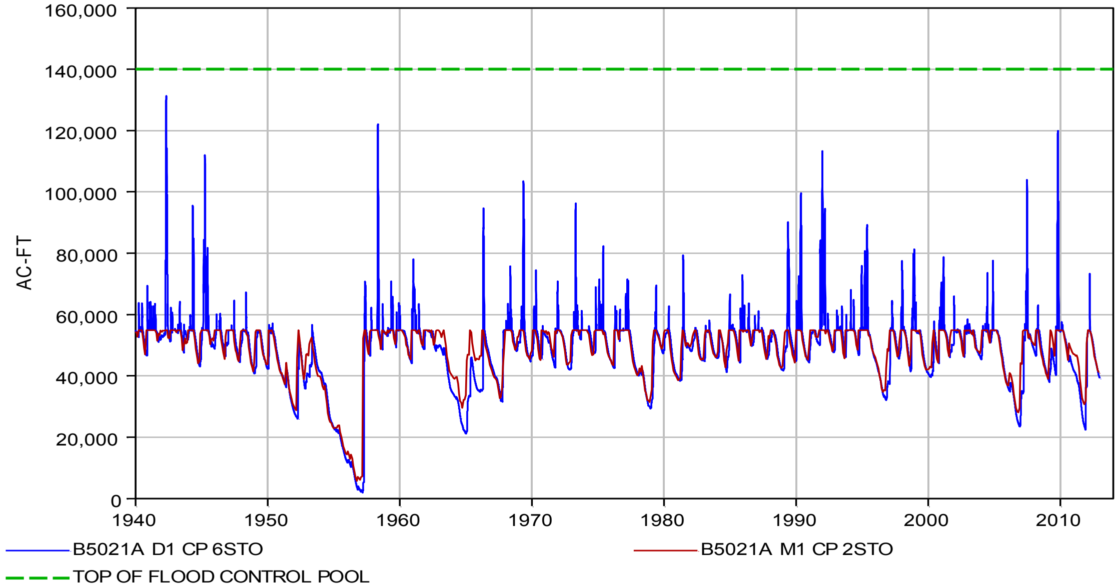

Figure 96. Bardwell Reservoir storage simulations D1 versus M1

5.7.2 Water Supply Reliability for M1

Water supply reliability table was developed for control points that located at dams for simulation M1 as shown in Table 59. In monthly time step, water reliability values were lower than daily time step in terms of volume and period for eight reservoirs.

Table 59. Water supply reliability for M1

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 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF YEARS 100%	98%	95%	90%	75%	50%	1%
B5157P	59868.8	43609.26	1.26	27.16	1.3	7.2	9.2	12.7	22.8	50.1	99.4	0.0	0.0	0.0	0.0	1.4	19.2	100.0
B3404A	371626.6	322916.19	1.48	13.11	1.5	4.6	7.1	13.9	24.7	37.4	97.4	0.0	0.0	0.0	0.0	0.0	9.6	98.6
B2335A	799599.9	671407.12	12.33	16.03	12.3	12.7	12.9	14.2	15.6	18.6	20.9	1.4	2.7	2.7	2.7	4.1	5.5	53.4
B2456A	941445.9	303688.00	23.63	67.74	23.6	28.7	30.5	45.0	75.3	88.2	94.7	4.1	16.4	19.2	26.0	46.6	76.7	100.0
B2362A	228361.6	65813.86	30.94	71.18	30.9	33.9	38.5	39.8	65.5	90.8	95.0	6.8	19.2	23.3	30.1	42.5	72.6	100.0
B2410A	491060.2	9458.60	39.89	98.07	39.9	59.5	71.1	98.3	99.9	100.0	100.0	5.5	57.5	82.2	94.5	98.6	100.0	100.0
B4992A	177210.8	125471.64	34.82	29.20	34.8	35.7	36.0	39.2	45.2	56.4	100.0	0.0	0.0	1.4	1.4	8.2	35.6	100.0
B5021A	90205.2	65253.16	44.86	27.66	44.9	45.8	46.5	48.9	54.6	63.5	100.0	2.7	2.7	2.7	4.1	11.0	35.6	100.0
Total	3159379.0	1607617.75		49.12														

5.8 Simulations M1 versus M2

The simulation M2 represents existing reservoir storage, full authorized water use, monthly time step, there is not flood control operation, and was developed as single-owner reservoir system. Simulation M1 and M2 were compared in order to show how component reservoir affects water storages and water reliability for dams in the Trinity River Basin.

5.8.1 Comparison of Reservoirs Storage

Simulation M1 storage capacities were compared with simulation M2 storage capacities. As shown in Figures 97-104, straight blue line represents M1 likewise, dark red straight line represents M2 and green line represents top of controlled flood control pool level. As a result of this comparison, Joe Pool, Navarro Mills and Bardwell Reservoirs storage levels were almost same for M1 and M2. However, rest of storage capacities had differences between simulations M1 and M2.

The difference between simulations M1 and M2 caused by in a same reservoir, contractors used other contractor`s water when they had no water that they were authorized. Because of that, usage of water storage levels and water reliabilities have changed. Joe Pool, Navarro Mills and Bardwell Reservoirs had same water storage levels because in both simulations M1 and M2, they were single reservoir.

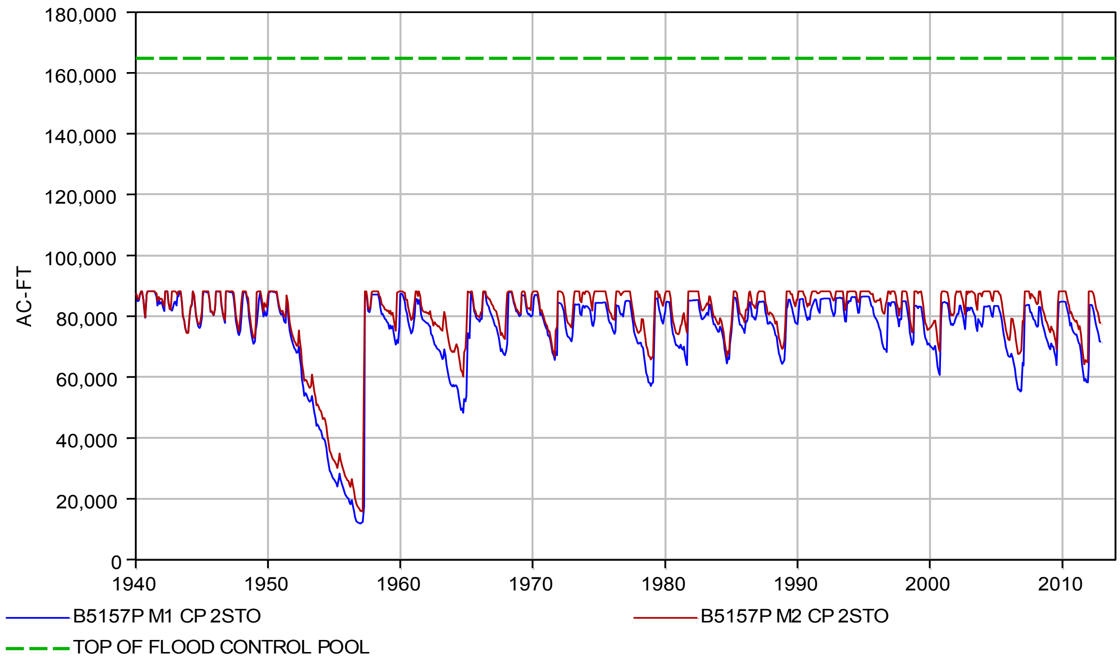

Figure 97. Benbrook Reservoir storage simulations M1 versus M2

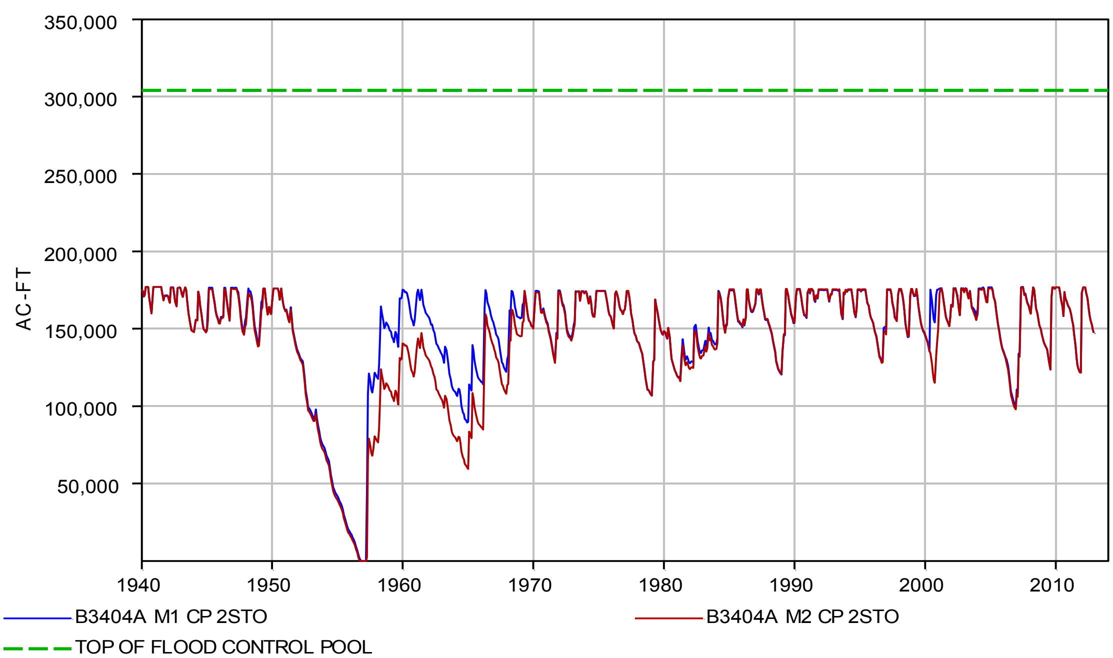

Figure 98. Joe Pool Reservoir storage simulations M1 versus M2

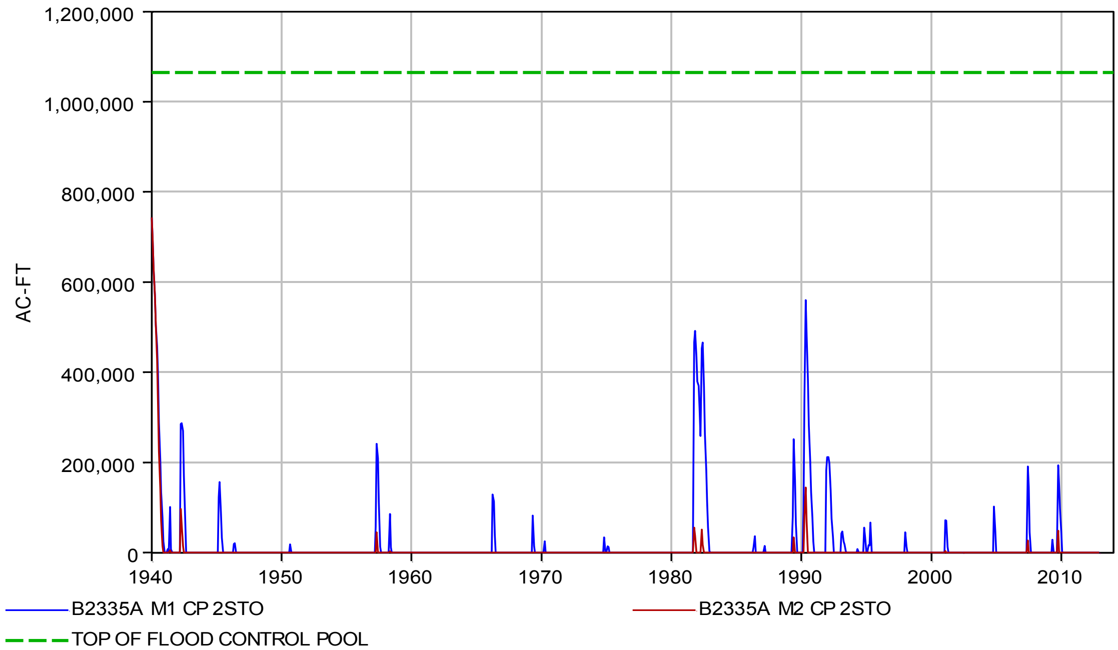

Figure 99. Ray Roberts Reservoir storage simulations M1 versus M2

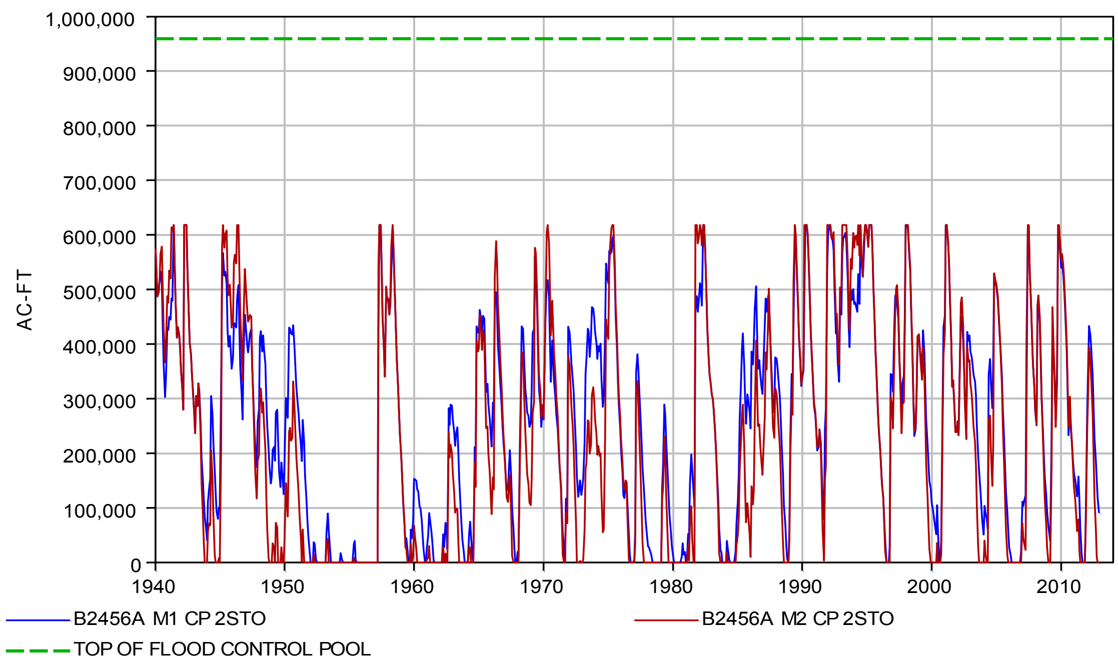

Figure 100. Lewisville Reservoir storage simulations M1 versus M2

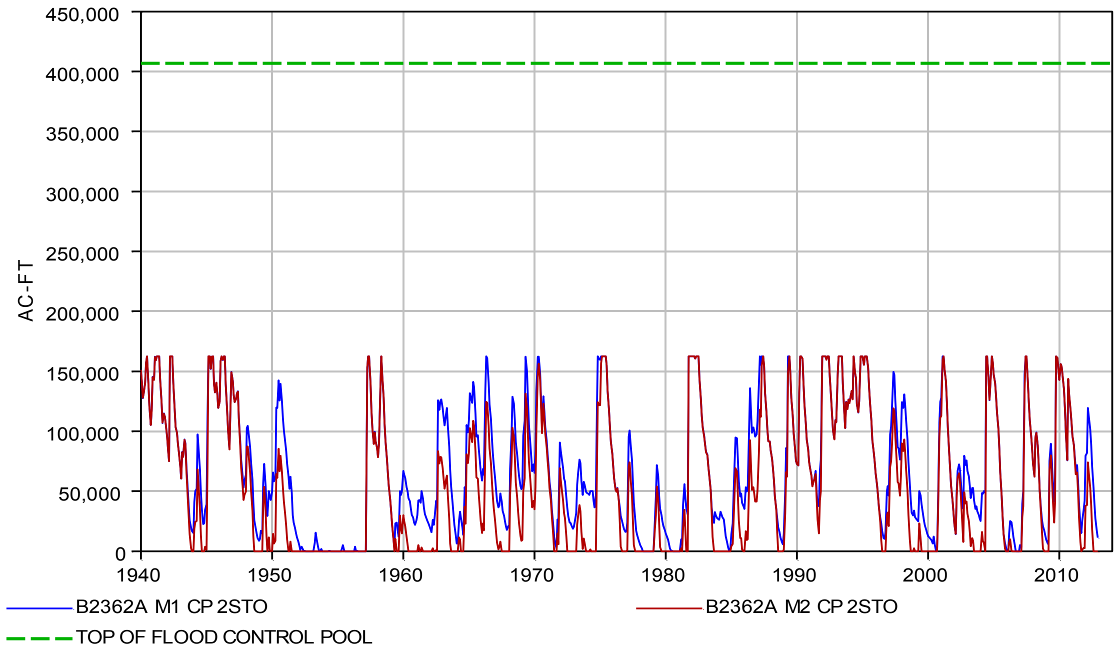

Figure 101. Grapevine Reservoir storage simulations M1 versus M2

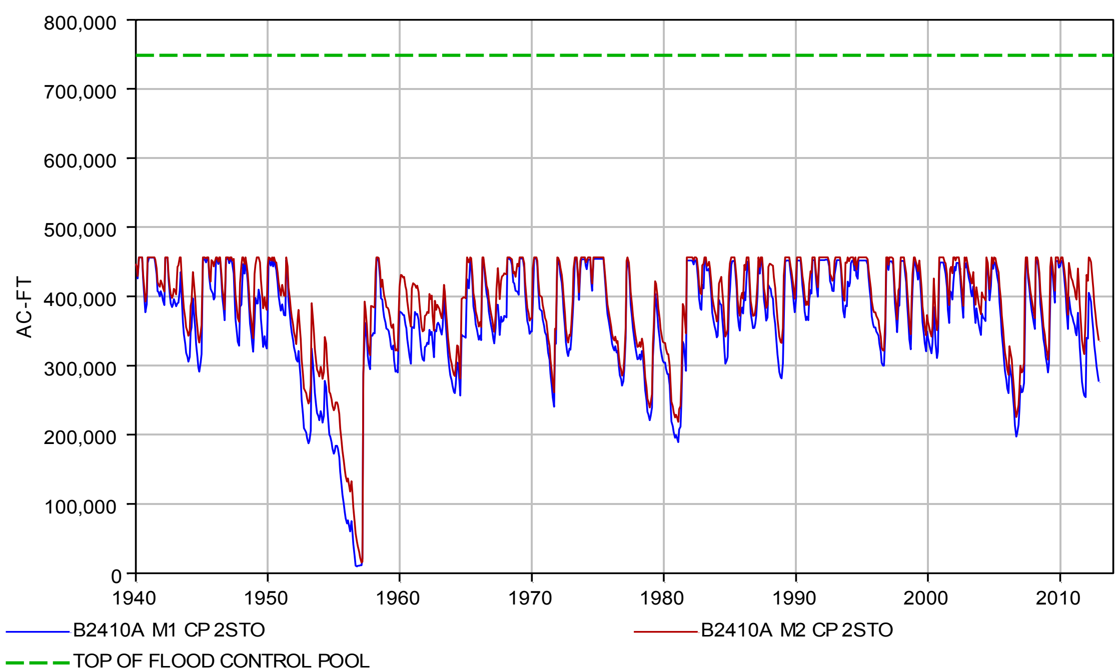

Figure 102. Lavon Reservoir storage simulations M1 versus M2

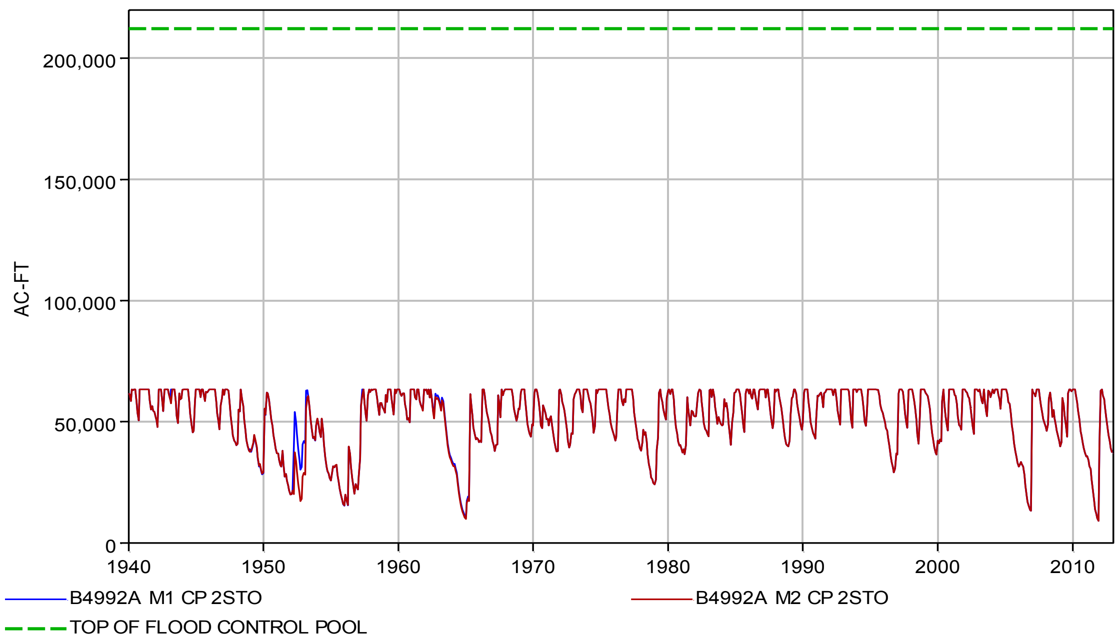

Figure 103. Navarro Mills Reservoir storage simulations M1 versus M2

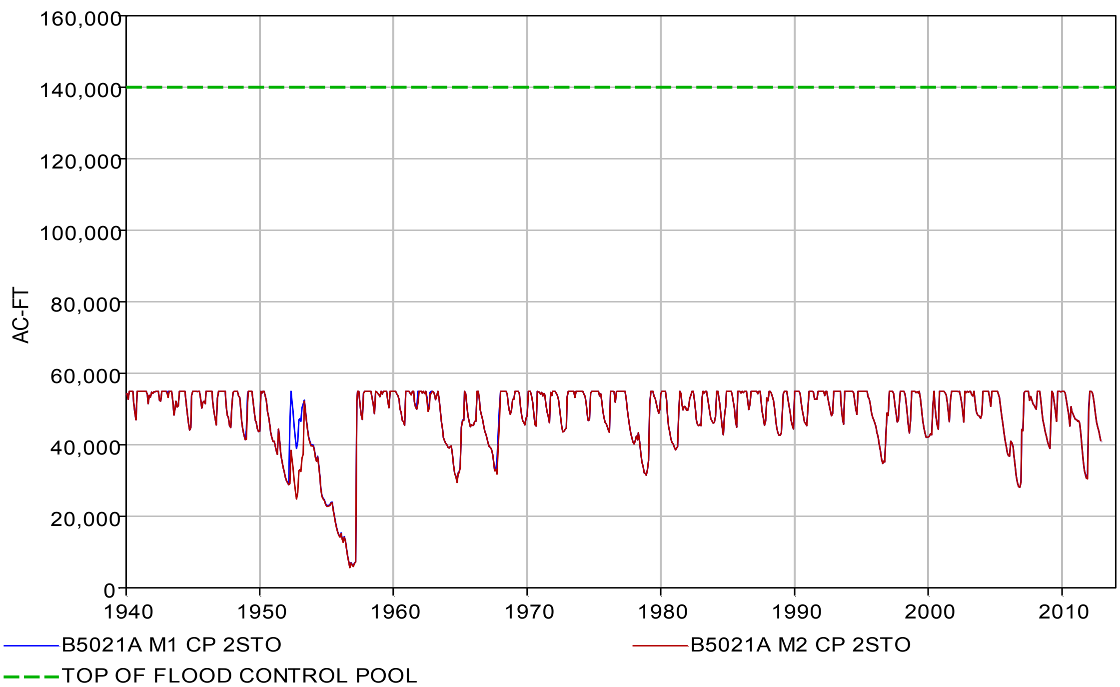

Figure 104. Bardwell Reservoir storage simulations M1 versus M2

5.8.2 Water Supply Reliability for M2

Water supply reliability table was developed for control points that located at dams for simulation M2 as shown in Table 60. Benbrook, Joe Pool, Ray Roberts Navarro Mills, and Bardwell Reservoirs` mean shortage values for water reliability in simulation M2 were higher than simulation M1. On the other hand, Lewisville, Grapevine, and Lavon Reservoirs` mean shortage values for water reliability in simulation M2 were lower than simulation M1.

Table 60. Water supply reliability for M2

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	98%	95%	90%	75%	50%	1%
B5157P	113693.3	102176.08	20.78	10.13	20.8	21.3	23.6	27.1	35.2	41.9	97.3	0.0	0.0	0.0	0.0	0.0	11.0	97.3
B3404A	438210.2	388911.84	1.37	11.25	1.4	3.7	6.1	10.6	21.7	34.2	97.1	0.0	0.0	0.0	0.0	0.0	8.2	98.6
B2335A	799599.9	757818.88	3.20	5.23	3.2	3.3	3.3	3.9	4.9	6.8	8.4	0.0	0.0	1.4	1.4	1.4	1.4	30.1
B2456A	869876.5	278832.47	67.92	67.95	67.9	73.4	74.0	75.0	76.9	79.2	90.3	21.9	45.2	46.6	50.7	57.5	74.0	100.0
B2362A	207458.2	51287.29	54.79	75.28	54.8	60.2	66.8	69.5	72.5	75.6	87.2	6.8	31.5	34.2	46.6	56.2	78.1	100.0
B2410A	388132.5	1046.43	98.17	99.73	98.2	98.6	99.1	99.8	99.9	99.9	100.0	80.8	95.9	98.6	98.6	100.0	100.0	100.0
B4992A	180010.5	127970.69	34.47	28.91	34.5	35.4	35.6	38.8	45.1	56.2	100.0	0.0	0.0	1.4	1.4	8.2	35.6	100.0
B5021A	93418.3	67989.65	44.52	27.22	44.5	45.5	46.2	48.6	53.8	63.0	100.0	2.7	2.7	2.7	4.1	11.0	35.6	100.0
Total	3090399.5	1776033.12		42.53														

5.9 Simulations M1, M3 versus Observed Annual Maximum Reservoir Storage

The simulation M3 represents existing reservoir storage, current water use, monthly time step, there is not flood control operation, and was developed as component reservoir system. Simulation M1 and M3 were compared in order to show how current use and full authorized water use affects water storage level and water reliability.

5.9.1 Comparison of Reservoirs Storage

The reservoirs storage capacities for simulation M1 were compared with simulation M3 and observed maximum storage level. As shown in Figures 105-112, straight blue line represents M1, red points represent observed maximum annual water level, and dark red straight and green line represent simulation M3 and top of controlled flood control pool level respectively. As a result of this comparison, for all reservoir water level in simulation M3 were higher than M1 because contractors didn't use all water that they were authorized. Especially, Ray Roberts Reservoirs water level was higher than before.

Simulation M1 and M3 also were compared with observed annual maximum water storage level. For some years, they matched well for some years. However, some of them were far away than each other because M1 and M3 were monthly simulation and red points were annual maximum storage values.

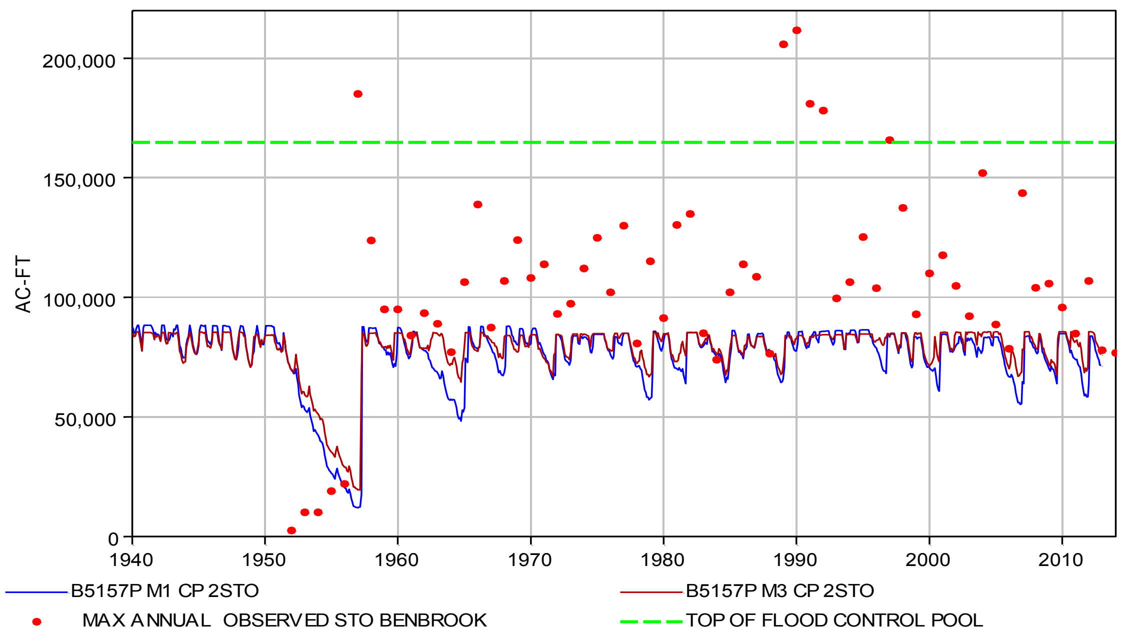

Figure 105. Benbrook Reservoir simulations M1, M3 versus max annual observed storage

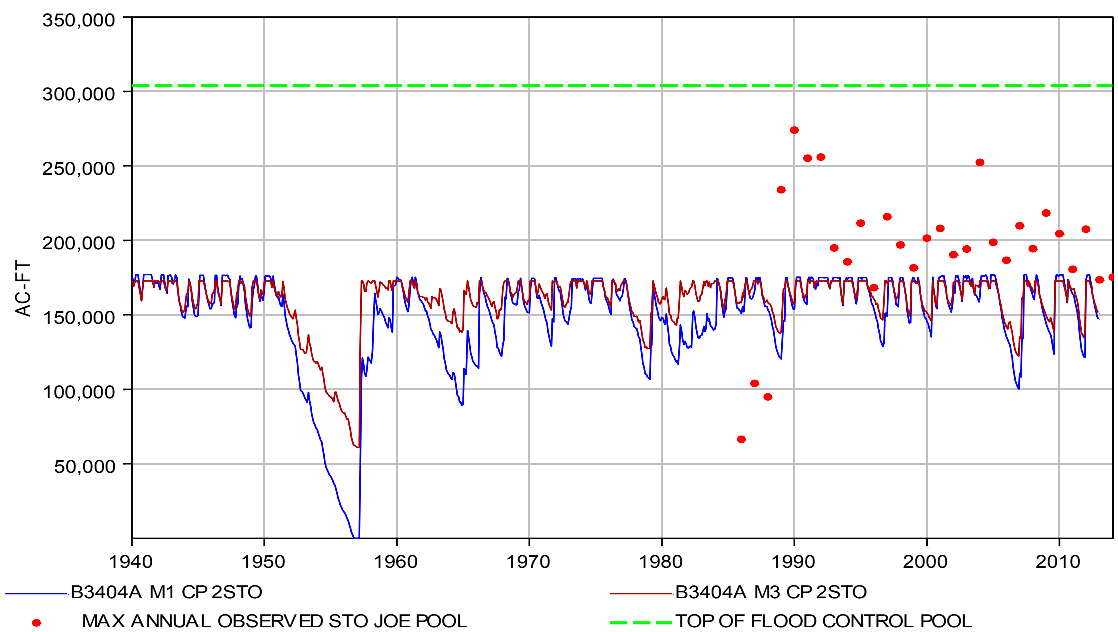

Figure 106. Joe Pool Reservoir simulations M1, M3 versus max annual observed storage

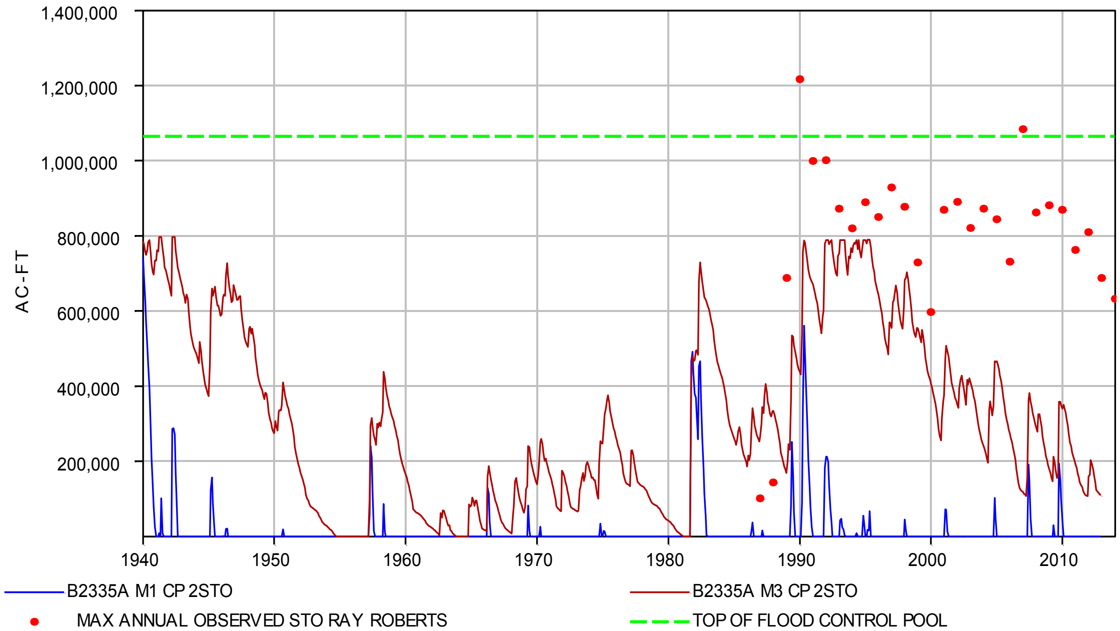

Figure 107. Ray Roberts Reservoir simulations M1, M3 versus max annual observed storage

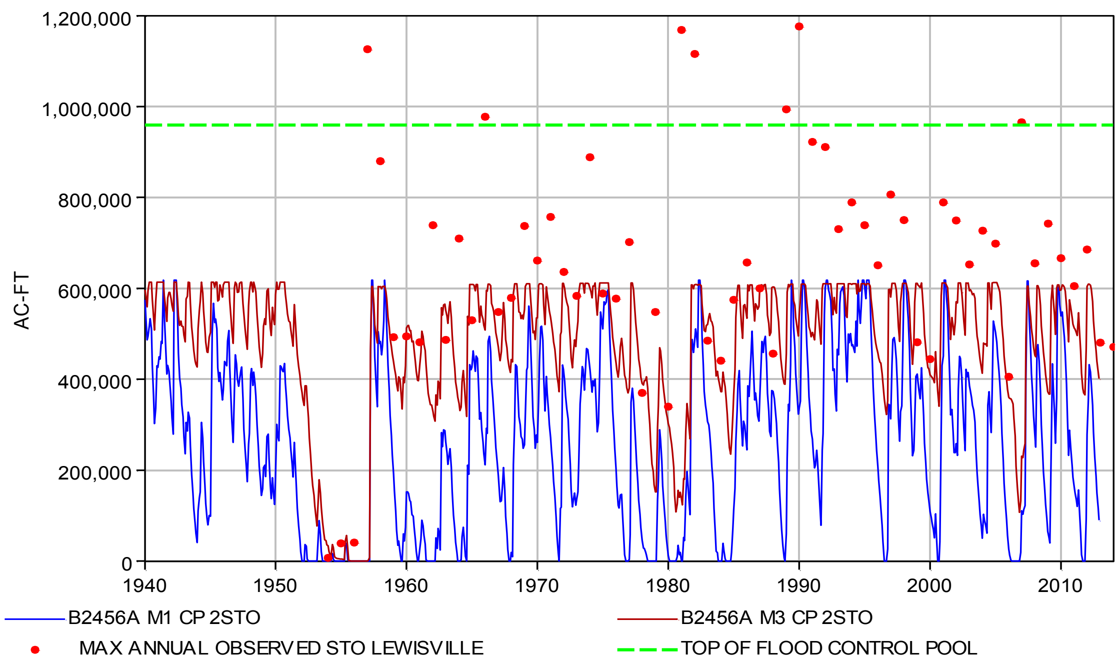

Figure 108. Lewisville Reservoir simulations M1, M3 versus max annual observed storage

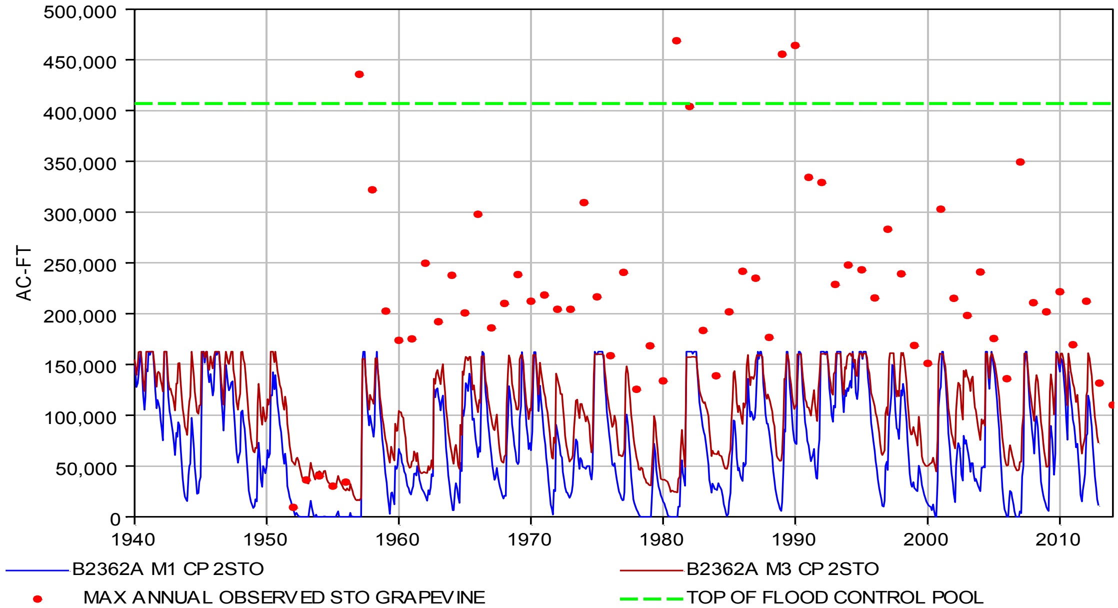

Figure 109. Grapevine Reservoir simulations M1, M3 versus max annual observed storage

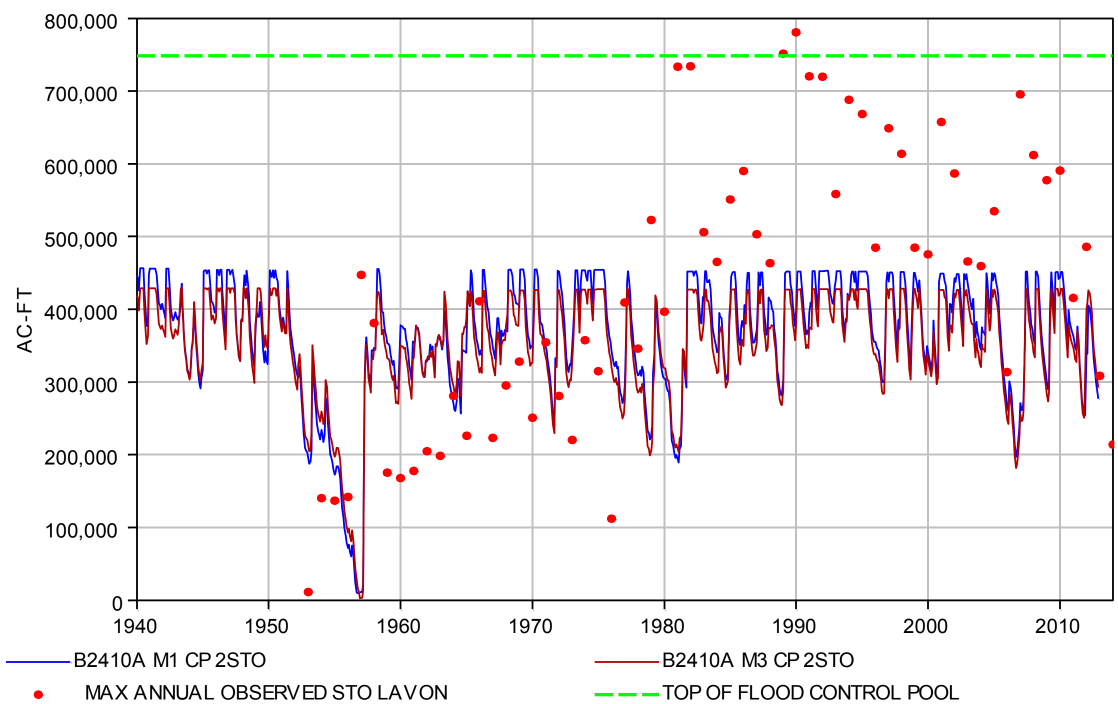

Figure 110. Lavon Reservoir simulations M1, M3 versus max annual observed storage

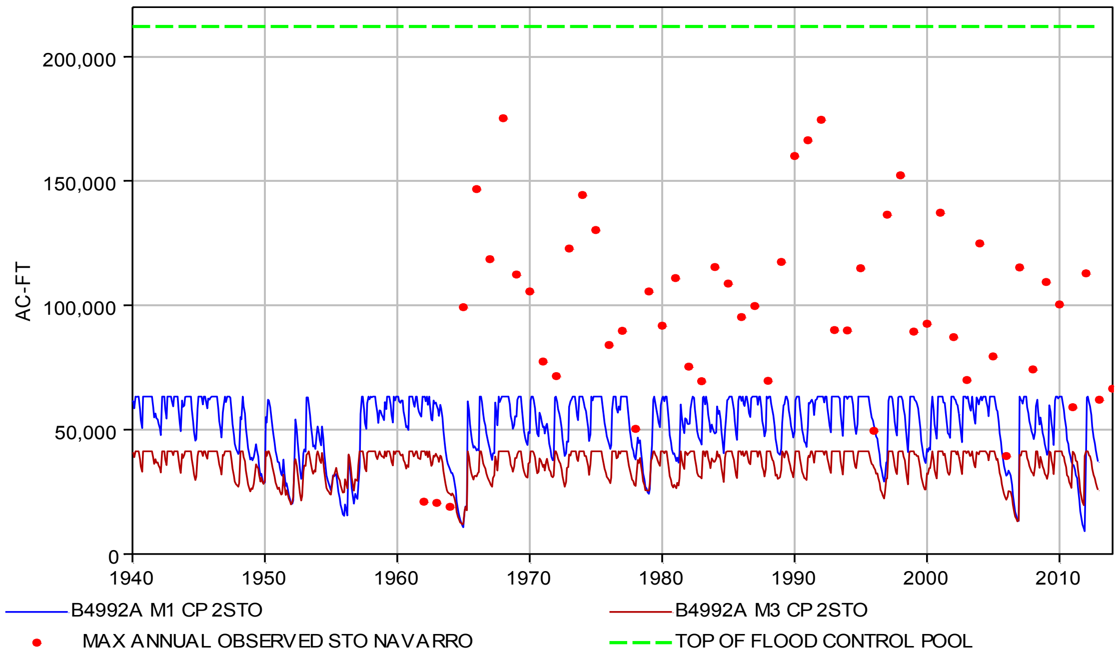

Figure 111. Navarro Mills Reservoir simulations M1, M3 versus max annual observed storage

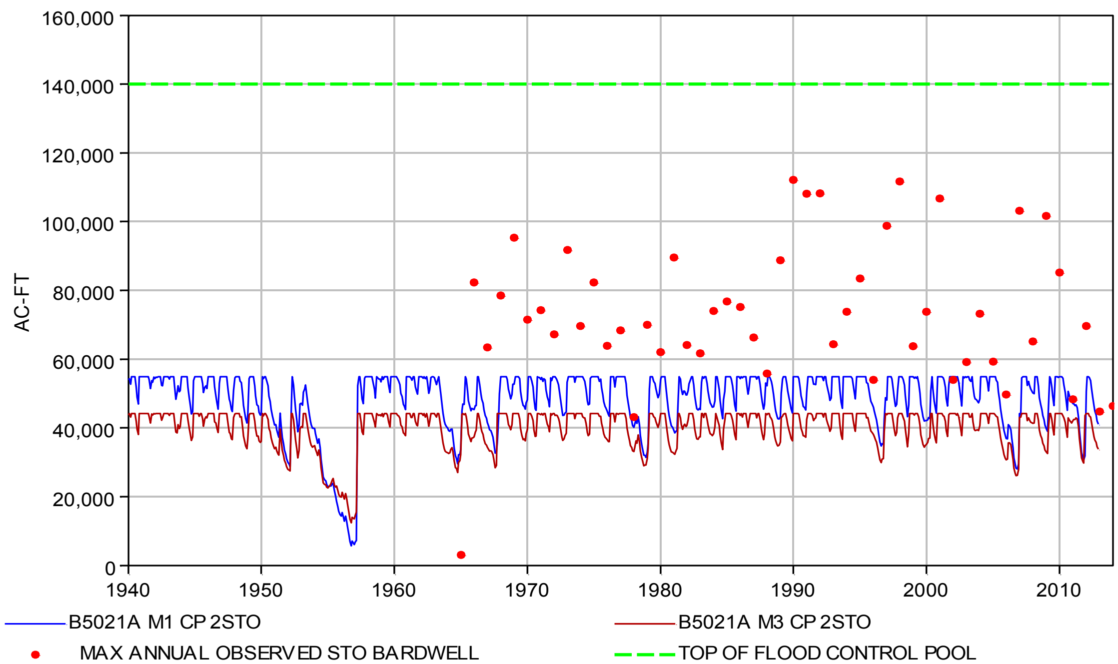

Figure 112. Bardwell Reservoir simulations M1, M3 versus max annual observed storage

5.9.2 Water Supply Reliability for M3

Water supply reliability table was developed for control points that located at dams for simulation M3 as shown in Table 61. All of the reservoirs` mean shortage were in simulation M3 lower simulation M1 except for Lavon Reservoir as expected. Water reliability was higher in simulation M3 than M1 in terms of period and volume.

Table 61. Water supply reliability for M3

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	*RELIABILITY* PERIOD (%)	*RELIABILITY* VOLUME (%)	+++++++++ PERCENTAGE OF MONTHS +++++++++ WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	1%	---------- PERCENTAGE OF YEARS ---------- 100%	98%	95%	90%	75%	50%	1%
B5157P	35395.0	21404.99	1.26	39.53	1.3	5.1	10.3	23.5	42.7	70.0	100.0	0.0	0.0	0.0	0.0	2.7	42.5	100.0
B3404A	166476.0	141686.59	31.96	14.89	32.0	32.5	32.9	34.6	42.5	48.5	95.1	0.0	0.0	2.7	2.7	4.1	19.2	98.6
B2335A	136028.0	24330.41	77.85	82.11	77.9	78.0	78.0	78.2	78.5	79.1	94.9	61.6	61.6	61.6	64.4	75.3	83.6	97.3
B2456A	617957.9	26190.85	68.04	95.76	68.0	90.2	92.9	94.2	96.5	97.3	99.9	24.7	82.2	83.6	89.0	94.5	95.9	100.0
B2362A	177984.0	18836.30	33.11	89.42	33.1	67.4	76.5	80.9	81.5	83.6	100.0	0.0	28.8	58.9	69.9	83.6	87.7	100.0
B2410A	528659.3	10201.41	36.07	98.07	36.1	56.7	97.5	98.2	100.0	100.0	100.0	2.7	56.2	80.8	97.3	98.6	100.0	100.0
B4992A	79453.3	53159.71	44.18	33.09	44.2	44.4	44.5	47.8	53.4	63.2	100.0	0.0	0.0	1.4	1.4	9.6	41.1	100.0
B5021A	64668.4	41193.45	51.26	36.30	51.3	52.2	53.0	55.7	59.6	71.7	100.0	2.7	2.7	4.1	6.8	19.2	50.7	100.0
Total	1806621.9	337003.69		81.35														

CHAPTER VI

SUMMARY AND CONCLUSIONS

The system of eight multiple-purpose reservoirs in the Trinity River Basin is representative of USACE reservoir systems throughout the United States. The USACE owns these federal reservoirs and is responsible for flood control operations. Non-federal water supply entities contract for the conservation storage capacity. Storage is allocated between flood control and conservation purposes in each reservoir by a designated top of conservation pool elevation. Flood control pools are maintained empty except during and immediately following flood events. Operations are based on empting flood control pools as expediently as feasible without contributing to stream flows exceeding specified non-damaging flooding levels at downstream gaging stations. Multiple reservoirs are operated for the same multiple downstream sites. Surcharge storage above the top of flood control pool is spilled through emergency spillways.

This thesis investigates issues in estimating the flood control capacities of these reservoirs. The analyses presented in the thesis are based on historical observed storage and storage sequences computed in WRAP simulations with alternative modeling premises and storage allocations. Storage frequency analyses are performed with HEC-SSP alternatively based on the log-Pearson type III and log-normal probability distributions. The log-Pearson III is concluded to be the more appropriate distribution, but the log-normal results are also included in the thesis for comparison. The frequency analyses are performed for data series consisting of the maximum peak storage volume in each year of the period-of-analysis, which is 1940-2012 for the simulated storage and the period extending from filling of currently designated conservation pool capacity to 2013 for actual observed storage.

Nonhomogeneities occur due to the datasets used the frequency analyses reflecting conservation pool operations, flood control pool operations, and spills from surcharge storage above the top of flood control pool. The WRAP modeling system includes an option that combines relevant surcharge spills, called excess flows, from storage above the top of flood control pool to the peak storage volume.

The probability of storage exceeding the top of flood control pool provides a concise metric for quantifying flood control capabilities. The recurrence interval computed as the reciprocal of this exceedance probability also provides a convenient storage capacity metric. Recurrence intervals associated with filling flood control pools are tabulated in Table 62. The recurrence interval estimates in Table 62 are based on the frequency analyses of observed storage covered in Chapter 3 and the base simulation D1 presented in Chapters 4 and 5.

Table 62. Comparison of recurrence intervals for overtopping flood control pools based on applying the log-Pearson type III (LP) and log-normal (LN) distributions to observed storage, simulated storage, and simulated storage plus excess flow

Reservoir	Storage (ac-ft) at Top of		Observed		Simulation		Excess Flow	
	Conservation	Fld Control	LP	LN	LP	LN	LP	LN
Benbrook	88,250	164,800	13.9	18.9	1,000	9.32	6.00	5.75
Joe Pool	176,900	304,000	141	1,000	1,000	10.7	1,000	10.7
Ray Roberts	799,600	1,064,600	14.8	14.5	10000	12.8	10000	12.7
Lewisville	618,400	959,177	11.3	10.4	28.4	12.4	28.4	12.4
Grapevine	162,500	406,900	21.9	27.6	435	8.73	250	8.66
Lavon	456,500	748,200	14.1	11.4	1,000	8.87	1,000	8.27
Navarro	63,300	212,200	417	98.0	79.4	29.6	69.9	29.1
Bardwell	54,900	140,000	256	233	1,000	52.6	1,000	52.6

The recurrence intervals shown in Table 62 vary greatly between reservoirs, vary greatly between observed and simulated storage, and vary significantly between the log-Pearson III (LP) and log-normal (LN) distributions. The recurrence interval estimates are unrealistically high is some cases and too low in other cases.

In addition to the base daily simulation (D1) included in Table 62, eight other simulations are presented in the preceding Chapters 4 and 5 to explore the effects of various factors on storage levels. Various issues affecting storage contents are addressed in the preceding chapters. Key issues are highlighted as follows.

Analyses based on observed flows are appealing but reflect significant shortcomings. The sample size of the annual frequency analyses is limited by the number of years in the period-of-record of observed storage. Impoundment of flows in Benbrook, Joe Pool, Ray Roberts, Lewisville, Grapevine, Lavon, Navarro Mills, and Bardwell Reservoirs began in 1952, 1985, 1987, 1952 (1989), 1952, 1952, 1953 (1975), 1963, and

1965. Several years were required to initially fill the conservation pools. Storage reallocations raising the top of conservation pools of Lewisville and Lavon Reservoirs occurred in November 1989 and December 1975, respectively. The years required to initially fill the conservation pools and the years before the storage reallocations at Lewisville and Lavon were not included in the frequency analyses. The simulation model has a consistent 73-year 1940-2012 period-of-analysis. The simulation model also applies a constant specified water management scenario and reservoir operating rules throughout the 1940-2012 hydrologic period-of-analysis.

Storage draw-downs in conservation pools provide additional storage of flood waters reducing the storage contents of flood control pools. For example, the 1950-1957 most severe drought on record ended with a major flood in April-May 1957, with much of the flood waters captured in conservation pools. The WAM dataset adopted for this research incorporates the authorized use scenario which is based on the premise that all water users use the full amounts authorized in their water right permits. Simulations presented in the preceding chapters show the significant increases in storage contents of flood control pools that result from adopting the current water use scenario or no water use in the simulations.

Simulation results are presented in Chapter 5 for alternative hypothetical storage relocation plans consisting of converting 10%, 20%, and 50% of the flood control pool storage capacity in each of the eight reservoirs to water supply by raising the designated top of conservation pool. Simulations D4, D5, and D6 described in Chapter 4 are identical to simulation D1 except for the reallocation of storage capacity. The volume reliability for the aggregated totals of all water supply diversions from the eight reservoirs for the alternative storage allocations are tabulated in Table 63 along with the recurrence intervals for overtopping the flood control pools.

Table 63. Water supply reliabilities and flood control pool recurrence intervals for alternative storage allocations

	D1	D4	D5	D6
	0%	10%	20%	50%
Reliability	56.81%	57.77%	59.08	62.44%
Recurrence Interval (years) for Overtopping FC Pool				
Benbrook	6.00	5.08	4.12	2.59
Joe Pool	1,000	1,000	1,000	1,000
Ray Roberts	10,000	10,000	10,000	10,000
Lewisville	28.4	26.7	24.8	19.3
Grapevine	250	55.9	48.0	22.8
Lavon	1,000	1,000	1,000	4.08
Navarro	69.9	40.0	26.8	6.30
Bardwell	1,000	1,000	1,000	12.7

REFERENCES

Booy, C., and Lye, L. M. (1989). "A New Look at Flood Risk Determination." *Water Resources Bulletin*, 25, 933–943.

Burn, D. H., and Goel, N. K. (2001). "Flood Frequency Analysis for the Red River at Winnipeg." *Canadian Journal of Civil Engineering*, 28(3), 355-362.

Dowel, C. L., and Petty, R. G. (1973). "Dams and Reservoirs in Texas." *Report 126*, Texas Water Development Board, Austin, Texas.

HEC (2010). "HEC-SSP Statistical Software Package User`s Manual." US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center, Davis, California

Hsu, Y. C., Tung, Y. K., and Kuo, J. T. (2010). "Evaluation of Dam Overtopping Probability Induced by Flood and Wind." *Stochastic Environmental Research and Risk Assessment*, 25(1), 35-49.

Hui, R., and Lund, J. (2014). "Flood Storage Allocation Rules for Parallel Reservoirs." *Journal of Water Resources Planning and Management*, 0(0), 04014075.

ICOLD (1973). *Lessons from Dam Incidents (Reduced edition)*, International Commission on Large Dams (ICOLD), Paris.

Kim, T. J. (2009). "Modelling Reallocation of Reservoir Storage Capacity Between Flood Control and Conservation Purposes."Ph.D. dissertation, Texas A&M University, College Station Texas.

Kuo, J. T., Yen, B. C., Hsu, Y. C., and Lin, H. F. (2007). "Risk Analysis for Dam Overtopping Feitsui Reservoir as a Case Study." *Journal of Hydraulic Engineering*, 133(8), 955-963.

Lee, B. S., and You, G. J. (2013). "An Assessment of Long-term Overtopping Risk and Optimal Termination Time of Dam Under Climate Change." *Journal of Environmental Management*, 121, 57-71.

Miller, J. F., Cronshey, R., Huffman, R. G., Kirby, W. H., Thomas, W. O., Bertle, F. A., and Newton, D. W. (1981). "Guidelines for Determining Flood Flow Frequency ", United States Water Resources Council, Washington, D.C.

USACE (2015). "United States Army Corps of Engineers Fort Worth District Website Flood Control Pertinent Datasheet." www.swf.usace.army.mil.

USBR (2014). " United States Bureau of Reclamation Regions Webpage.", www.usbr.gov.

Vaughan, E. G., Crutcher, J. M., Labatt, T. W., McMahan, L. H., Bradford Jr., B. R., Cluck, M., and Callahan, M. (2012). "Water for Texas 2012 State Water Plan." Texas Water Development Board, Austin Texas.

Wurbs, R. (1987). "Reservoir Management in Texas." *Journal of Water Resources Planning and Management*, 113(1), 130-148.

Wurbs, R. (2005). "Texas Water Availability Modeling System." *Journal of Water Resources Planning and Management*, 131(4), 270-279.

Wurbs, R., and Carriere, P. E. (1988). "Evaluation of Storage Reallocation and Related Strategies for Optimizing Reservoir System Operations." *TR-145*, Texas Water Resources Institute Texas A&M University, College Station Texas.

Wurbs, R. A. (1996). *Modeling and Analysis of Reservoir System Operations*, Prentice Hall PTR, Upper Saddle River, NJ.

Wurbs, R. A. (2013a). "Fundamentals of Water Availability Modeling with WRAP." *TR-283*, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. (2013b). "Water Rights Analysis Package (WRAP) Modeling System Reference Manual." *TR-255*, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. (2013c). "Water Rights Analysis Package (WRAP) Modeling System Users Manual." *TR-256*, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A., and Hoffpauir, R. J. (2013). "Water Rights Analysis Package (WRAP) Daily Modeling System." *TR-430*, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A., and James, W. P. (2002). *Water Resources Engineering*, Prentice Hall, Upper Saddle River, New Jersey.