INTEGRATED MULTIPLE PURPOSE RESERVOIR SYSTEM OPERATIONS

A Thesis

by

CEMIL ARSLAN

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Chair of Committee,	Ralph Wurbs
Committee Members,	James Brumbelow
	Vijay Singh
Head of Department,	Robin Autenrieth

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ABSTRACT

Water resources management, development, allocation, and protection in system engineering has become increasingly essential to ensure sustainability, protect the ecosystem, and raise water availability. Depending on the reservoirs built over time and the streamflow conditions identified for environmental protection, river basin management strategies are designated in multi-objective gains by subjecting river system rules. Increased complexities caused by drought and flooding and constantly varying water demands result in the change among reliability of water supply on river basin areas. Due to these changes, interactions and tradeoffs between integrated water operations are observed depending on the priority of storage and allocation. The proposed research analyzes the interactions between hydropower generation, flood control operations, and environmental flow standards on the case study area of Brazos River Basin by simulating Brazos Water Availability Modeling (WAM) dataset with the daily and monthly versions of the Water Rights Analysis Package (WRAP) modeling system.

Real-world reservoir system operations, river system rules, and water management strategies are investigated and WRAP capabilities for simulating hydropower generation, flood control operations, and environmental flows are explored. The case study area is analyzed and depending on the structure of the river/reservoir system, different water allocation scenarios are formulated to define the degree to interactions between water resources operations in the basin area. Simulations are performed in daily and monthly computational time steps in a period between 1940 and 2017 by modeling operational

procedures applied in river and reservoir systems to increase the accuracy of the system. Additionally, comparative analysis between daily versus monthly river/reservoir modeling systems are performed for hydropower generation and instream flows by comparing energy output and streamflow metrics.

The Hydrologic Engineering Center (HEC) Statistical Software Package (SSP) and Data Storage System (DSS) are used to monitor reservoir storage and develop frequency analyses based on log-normal and log-Pearson Type III probability distribution methods. TABLES program of the WRAP modeling system is applied to develop reliability and yield analyses for water and flow rights, define streamflow metrics at pertinent control points, and develop flood frequency analyses at reservoirs and stream gages.

DEDICATION

To my family.

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Contributors

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NOMENCLATURE

BBASC	Basin and Bay Area Stakeholder Committee
BBEST	Basin and Bay Expert Science Team
BRA	Brazos River Authority
DSS	Data Storage System
FFA	Flood Frequency Analysis
HEC	Hydrologic Engineering Center
SB1	Senate Bill 1
SB2	Senate Bill 2
SB3	Senate Bill 3
SSP	Statistical Software Package
TAMU	Texas A&M University
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAM	Water Availability Modeling
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

1.1 Background

River basin management strategies are specialized to satisfy water demand for human use, energy generation, and environmental protection for each basin by mitigating flooding, protecting existing water diversion rights, and ensuring future water availability. Reservoir operations for storing and regulating stream flows and environmental policies for protecting the biological and ecological system are the main aspects of river basin development and management. Additionally, water operations including reliable water supply, storing excess flows, maintaining instream flows, and energy generation can play a crucial role in management strategies. Various river basin strategies are applied to allocate water considering maximization gains. Similarly, reservoirs are divided into different volumes as multipurpose functions, such as water supply, flood control, energy generation, moreover; instream flow requirements for the preservation of the ecosystem are established based on flow conditions defined by decision-makers and scientists.

Reservoirs are typically kept at specified water level to store as much water as for energy potential and water availability for diversions as well as to prevent overtopping the dam during flooding. Releases from the dams are made by considering minimum instream flow requirements and maximum allowable flood flow limits through downstream points in the purpose of the higher reliability of water diversions. It is widely observed that the implementation of reservoir operations and river system rules that differ based on regions results in tradeoffs between water resources purposes. Energy demand and environmental flow needs on the basin area can be met with releases from reservoirs simultaneously or differently. Moreover, depending on the season and hydrologic conditions of the watershed area, flood flow limits and environmental flow standards can vary in each stream gage of the river. Furthermore, water can be released from conservation pools to make space available for estimated flood. When everything is taken into consideration, it is obvious that there are always changing interactions between reservoir operations and river system rules in basin areas. This study aims to develop methodologies and formulates different water allocation scenarios to observe interactions and tradeoffs between hydropower output, environmental flows, and flood control operations.

The WAM system has been applied in the state of Texas over several years for supporting regional and statewide planning, implementation of water right permits system, and other water management activities to meet the water supply for hydropower, municipal, industrial, agricultural, and environmental needs (Wurbs, 2005). The WAM system maintained by Texas Commission on Environmental Quality (TCEQ) consists of WRAP modeling system and sets of databases that contain hydrology, water right input files, and operation rules for 23 river basins in Texas (Wurbs, 2005). The WRAP modeling system developed by Texas A&M University includes daily and monthly versions. The modeling system provides reliability and frequency analyses for hydropower generation and flood control and statistical and probabilistic metrics for naturalized, regulated, and unappropriated flows. The Brazos River Basin serves as a case area for this study. The Brazos WAM authorized dataset with current priority-based water allocation rules, flood control operations, and Senate Bill 3 environmental flow standards that consist of metrics and rules depending on location, season, and hydrologic condition are applied in this study. Also, hydropower plants in the reservoirs of Whitney and Possum Kingdom are hypothetically assigned in the dataset by protecting existing water rights.

1.2 Literature Review

Several studies thus far have described the interactions between integrated water operations of hydropower, flood control, and environmental flows on different river basin modeling systems. Any study is not be conducted to define the interactions between reservoir operations for hydropower generation and flood control and Senate Bill 3 environmental flow standards on the WRAP modeling system. Several academic studies were reviewed in this research to comprehend the river/reservoir modeling systems, water resources planning and management, climate change, river system hydrology, reservoir operations, environmental flow standards, and the impacts of hydropower generation, flood control, and environmental flows on each other. WRAP manuals and reports for authorities were analyzed to create a methodology for the assessment of different water allocation scenarios.

Wurbs et al. (2005) studied the potential impacts of climate change on water supply capabilities and the way to incorporate climate change in the WAM system. The impacts of climate change on water availability and reliability were examined by analyzing changes in the twentieth century and future changes during the twenty-first century. They pointed out that the impacts on water supply capabilities are mainly dependent on reservoir storage capacity and statewide water management is affected by the need for reservoir storage and demand management strategies to address severe droughts. They highlighted that climate change has impacts on regulated and unappropriated flows differently in comparison with naturalized flows because of the reservoir releases for human use and regulating streamflow.

Wurbs (2011) evaluated different river system modeling systems for water resources management, simulation, and allocation that are used in the United States and applicable in all countries. His study analyzed the capacities and methodologies of four selected generalized modeling systems, ResSim, MODSIM, WRAP, and RiverWare by comparing applications, model development, and computation methods. He highlighted that generalized river/reservoir modeling systems are categorized as prescriptive and descriptive based on input datasets, computational algorithms, and terminology in a broad-based general capacity. In this study, it was outlined that conservation purposes are commonly modeled in weekly and monthly intervals while flood control operations are modeled in daily or smaller time intervals.

Wurbs (2014) summarized the process of water resources management and the efforts of the development process for regional planning in the state of Texas. He detailed the climate, geography, water use and hydrology of Texas, prior appropriation doctrine, development process of WRAP/WAM system, regional and statewide planning for surface water and groundwater, and water management community. According to Wurbs (2014), sustainable management of groundwater and surface water is a significant challenge for Texas, as in other states in the U.S. and regions in the world due to increasing water demand and future predictions of water availability in the state. In this way, Senate Bill 1

(SB1), Senate Bill 2 (SB2), and Senate Bill 3 (SB3) were processed to set up long-term water resources implementation plans by the water community. By considering flow regimes that are described in terms of the magnitude, frequency, duration, timing, and change, instream flow standards that vary with location, season and hydrologic condition were established in some control points over the state and incorporated in the WRAP/WAM system. The study reveals that flow regimes are divided into the following categories: subsistence flows, base flows, within-bank high flow pulses, and overbank high-flow pulses.

Pauls and Wurbs (2016) studied on the attainment of the environmental flow standards and simulated stream flows to evaluate the metrics of these standards. They demonstrated that instream flows should be maintained at allowable limits when the water supply is provided in reliable conditions. It was determined that SB3 environmental flow standards that are implemented at Colorado River Basin do not have any impacts on water rights for existing diversions and storage but decrease the unappropriated flows.

Zhang and Wurbs (2018) conducted a study to evaluate the relative effects of climate change, water resources management, and other factors on long-term changes in reservoir storage, streamflow, evaporation, and other components of water budget on the state of Texas by applying the WRAP modeling system. They observed that the changes in precipitation depths in the long-term period are minimal, while evaporation rates vary significantly seasonally with an upward trend. Furthermore, it was determined that the water budget in the river/reservoir system and flow characteristics have experienced the changes during the long-term period depending on the water resources planning and management strategies.

Wurbs (2019) studied statistical regression trend analysis to detect and analyze long-term changes (non-stationary) and lack thereof (stationary) on the state of Texas for the historical hydrology. He pointed out that population growth, land use change, increased water use, climate change, and water resources development facilities can result in long-term changes in the characteristics of precipitation, evaporation, streamflow, and other hydrologic variables. His linear regression analysis results for the 79 years period illustrated that no long-term trends or permanent modifications in precipitation and evaporation characteristics for the state of Texas.

Jager and Smith (2008) suggested an optimization strategy in their study to maximize the energy generation in terms of benefit-cost analysis and meet ecosystem values by constraining reservoir releases and elevations. They summarized different ways to address environmental objectives and the methods implemented for optimal reservoir releases. Renofalt et al. (2010) studied the effects of hydroelectricity generation and opportunities for environmental flows in Sweden. They observed that flow releases for the environment increased slightly while the hydropower is generated through the river/reservoir system. Pittock and Hartmann (2011) conducted another study to evaluate the impacts of dams and reservoir operations on the ecosystem. They pointed out that the master plan that is integrated into river-basin management provides opportunities to the river/reservoir system. They suggested that hydropower generation may be optimized in pursuant of peak hours thanks to reoperation of upstream dams, and downstream dams may be operated to meet environmental flows by reregulating of the operations.

Another study about the impacts of hydropower generation on instream flows completed by Viers (2011) and illustrated that the effects of hydroelectricity generation from dams vary across time. He pointed out that this change includes a rapid change at downstream flow conditions due to peak-hour operations and long-term hydrologic regime change at downstream points due to long-term impoundments. Rheinheimer et al. (2012) studied hydropower generation under the constraints of instream flow requirements in the Yupa River Basin, California. In their study, they developed a multi-reservoir optimization model in linear programming to evaluate the impacts of hydropower generation and minimum instream flows on each other. The results revealed that the mean annual hydropower generation and mean revenue experienced a decline in historical hydrology. Nguyen et.al (2018) studied ecological models used in the evaluation of hydropower effects on ecosystem by applying different scenarios in varying parameters.

Zsuffa (1999) argued the impacts of hydropower operations on flood control safety in Hungary. His findings illustrated that hydropower plants do not have any negative effects on flood control safety except fluctuations on daily water level across the stream. He also suggested that if forecasting and alarm methods are applied well, not only flood safety but also energy generation may be improved. Luis et al. (2013) questioned the impacts of releases from dams on hydropower generation and flood control. They evaluated various scenarios for discharge released from gated spillway dams to monitor the impacts towards the hydropower generation and flood control. Their findings show that the controlled release of floodwater from the dams is the real situation for hydropower generation and floodplain management. Keophila et al. (2019) presented the effectiveness of reservoirs for energy production and flood control concurrently by modeling the system in HEC-ResSim. They measured two hydropower plants in 34 years including flood period, and the results illustrated that efficient operation rules for controlling the water decreased the flood days and increased the energy production at considerable rates.

1.3 Overview of the WRAP/WAM System

The WAM system was implemented in the state of Texas over the past several years for supporting regional and statewide planning, implementation of water right permits system, and other water management activities to meet the water supply for hydropower, municipal, industrial, agricultural, and environmental needs. Prior appropriation-based water rights permitting system is implemented through the state to use of water in the system by TCEQ. In 1967, The Water Rights Adjudication Act launched water right permitting system based on the concept of firm yield to use water efficiently. The priorities of water rights are defined based on the acceptance date of their applications. In 1997, Senate Bill 1 was passed at 75th Texas legislature to develop the WAM system for regional and statewide water resources management in all river basins to support water rights permit system. The WAM system underlines the significance of modeling institutional aspects of water resources management and effectiveness of the modeling system implementations. Under the leadership of TCEQ, the WAM System was implemented by the TCEQ, Texas Water Development Board (TWDB), Texas Parks and

Wildlife Department (TPWD), river authorities, universities, water management agencies, and consulting engineering firms to conduct different studies.

The WAM system consists of modeling tools and sets of databases to use in planning, management, and allocation studies and make analyses. The Texas WAM system contains WRAP modeling system, WRAP input files that contain hydrology, water rights, operation rules for 23 river basins, geographic information system (GIS), and other databases. WRAP simulates the water allocation for river basin areas under a priority sequenced based system by applying historical hydrologic data to obtain a representation of future hydrologic conditions in river and reservoir systems. This generalized model is used for assessment of water availability for water supply diversions, reliability of water rights, frequency of reservoir storage, metrics of environmental flow standards, and hydropower generation. The TWDB, TCEQ, river authorities, water management agencies, and engineering firms use the WRAP modeling to make studies about the WAM System.

The original WRAP/WAM system works at monthly computation time scale, and in order to make analyses for flood control operations and pursue reliability of environmental flow standards well, a daily version of the modeling system was developed. The WRAP modeling system is documented in detail by several manuals. The river basin hydrology contains daily and naturalized monthly stream flows and reservoir net evaporation less precipitation. The input dataset consists of naturalized stream flows, watershed parameters, and net evaporation rates (Wurbs,2005). Different scenarios for water resources management and allocation in river basin areas are modeled and simulated in WRAP modeling system by modifying parameters in input datasets. Authorized use (Run 3) and current use (Run 8) are two river basin management scenarios most commonly used for evaluations and analyses. The authorized scenario use contains diversions being made without any return flow and reservoir storage without sedimentation. However, the current use considers return flow in diversions and sedimentation in reservoir storage.

WRAP modeling system is continuously being modified and developed by adding new capabilities to meet the needs formed over time. Modeling reservoir flood control operations and environmental flow standards required a sub-monthly computational time scale. Upon this necessity, daily version of the WRAP modeling system was developed, and input parameters for reservoir flood control operations and environmental flow standards were incorporated to river basin management databases. To extend capabilities to determine water availability and flood flow capacity, flow forecasting has been defined in the modeling system. Also, flow routing was included in the simulation model to propagate flow changes through the river.

Reservoir operations for flood control and hydropower were included in the simulation model by defining capacities in accordance with reservoir operation rules. The WRAP simulation model has capabilities for multiple-purpose and multiple-reservoir system operations. Storage and release rules are defined in the model with the purpose of minimizing the risk of flooding and meeting diversion targets. The WRAP modeling system has features for frequency analyses of naturalized stream flows, excess flows, and reservoir storages based on different probability distribution methods. Output files from the simulation model can be opened on HEC-DSS and HEC-SSP package programs to develop storage and streamflow graphs, determine frequency analyses, and calculate statistics for flow.

1.4 Research Objectives

The overall goal of this research is to evaluate the interactions between hydropower generation, flood control, and environmental flows by developing different water allocation scenarios. Also, reservoir operation rules for hydropower generation and flood control are studied in this research within the framework of reservoir/river system management. Monthly and daily versions of the Brazos WAM dataset are the central focus of this research. The objectives of this research are:

- Investigation of WRAP/WAM capabilities for simulation of reservoir system operations for hydropower generation and flood control and river system rules for environmental needs.
- Review of the published literature and reports available about hydropower, flood control, and environmental needs, and research studies about the WRAP/WAM modeling system.
- Investigation of hydroelectric systems, hydropower generation rules, and reservoir operations for energy generation.
- Investigation of flood frequency analysis capabilities for evaluating the risk of overtopping the dam based on the observed reservoir storage of flood control reservoirs in the Brazos River Basin.
- Investigation of the Senate Bill 3 environmental flow standards and the methods to incorporate instream flow targets in the WRAP/WAM system.

- Modeling hydropower generation rules for the reservoirs in the Brazos WAM dataset for comparative analysis between energy generation in daily and monthly modeling systems, and evaluating the impacts of flood control operations and environmental flow standards on hydropower generation by formulating different scenarios.
- Formulation of different water allocation scenarios and assessing the impacts of energy generation and environmental flow standards on flood control by quantifying the risk of exceeding the top of flood control pools and maximum allowable flow limits through river at stream gages.
- Formulation of different river basin management scenarios to assess the effects of reservoir operations for hydropower generation and flood control on environmental flow standards by performing frequency analyses and calculating streamflow metrics.

1.5 Thesis Organization

This thesis is divided into five chapters and two appendixes. Chapter I includes background information, general information about the WRAP/WAM system, and research objectives of the thesis. Literature review in this chapter describes historical background of generalized river and reservoir modeling systems and sustainable water management issues in Texas. The effects of water operations on each other are also included in the literature review. Chapter II gives a general information about reservoir system operations, hydroelectric systems, hydropower operations rules, flood control operations, and incorporation of reservoir operations in the WRAP modeling system.

Chapter III describes the case study area of the Brazos River Basin. It includes overview of reservoirs, hydropower and flood control operations in reservoirs, details about SB3 environmental flow standards, and water supply operations.

Chapter IV focuses on the methodology followed in this research. The probabilistic distribution methods for flood frequency analyses and reliability analyses for hydropower and instream flow rights are explained in this chapter. It also illustrates general information about the auxiliary software used in this study and water allocation scenarios formulated and performed in the modeling system. Chapter V presents the results of the alternative scenarios as well as the evaluations of the outcomes. Comparative analysis of the daily versus monthly modeling systems for hydropower generation and instream flow requirements is also presented in this chapter. Chapter VI summarizes and integrates topics covered in the previous chapters. Finally, conclusion and recommendations on different topics of the research are presented in Chapter VI. Appendixes A and B have tables and figures about hydropower generation and flood frequency analyses respectively.

CHAPTER II

RESERVOIR SYSTEM OPERATIONS

2.1 Overview of Reservoir System Operations

Typical reservoirs are designed to separate total capacity into one or more designated pools, inactive pool, conservation pool, flood control pool, and surcharge zone (Wurbs,1991). The inactive pool is sometimes called dead storage not used for any withdrawals or releases except for seepage and evaporation processes. This zone is used for sedimentation reserve, head for hydroelectric power, recreational facilities, and ecosystem. Water demands for conservation purposes, such as hydropower generation, municipal and industrial water supply, agricultural irrigation, and environmental flows are satisfied by releases and withdrawals from conservation pools. Flood control pools remain empty except for the period of flood events. When the water level in reservoirs exceeds the top of conservation pool, flood control operations are activated to release water by maintaining water level at allowable limits in downstream points.

Releases are made through gated spillways to empty water storage in flood control pools expeditiously. The surcharge zone is used for uncontrolled water storage at the period of flood events exceeding the flood control pool or conservation pool (for the reservoirs that has no flood control pool). The maximum design water surface is the elevation for the dam safety. There is a freeboard between the maximum design water surface and the top of the dam. Reservoir operations are made based on the rule that water level will never pass the maximum design water surface. Reservoir pools are designed in Figure 1.

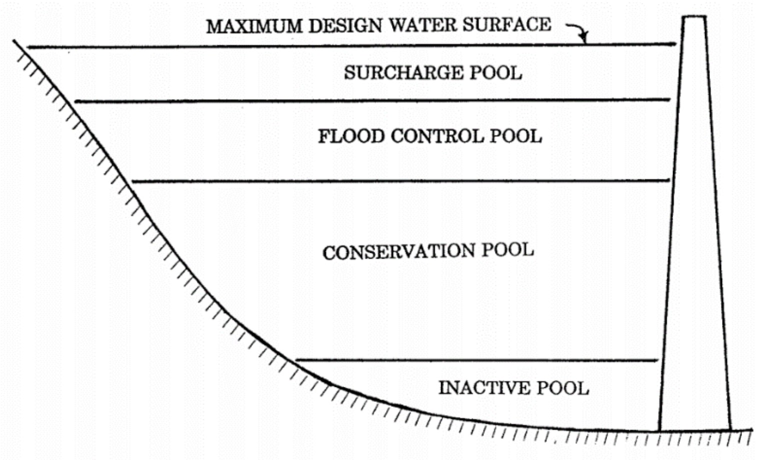


Figure 1: Reservoir Pools (Wurbs, 1991)

Reservoirs are operated to generate electricity by making releases for just hydropower generation or other purposes, such as municipal, industrial, irrigational, and environmental water supply. While meeting the water demand for conservation purposes, hydroelectricity is produced through the turbines. In many reservoirs, dead or inactive storage area that is below the power pool is reserved to provide power system with an additional head for a generation. When the water level passes the top of power pool or conservation pool, net inflows are released through the reservoir intake system to generate electricity with flows up to capacity, and the remainder of the flow is spilled. If the water level below the top of the power pool, hydropower generation is stopped till enough water is stored.

Environmental flow standards are one of the main objectives in reservoir/river systems. River inflow and reservoir releases meet the minimum instream flow requirements for the ecosystem. To prevent negative impacts of reservoir releases, seasonal upper limits are also set through the river system. Releases for hydropower generation and flood control operations are made by considering lower and upper limits of environmental flow standards, flood flow limits, and water availability. Figure 2 shows the general outline of the river/reservoir system.

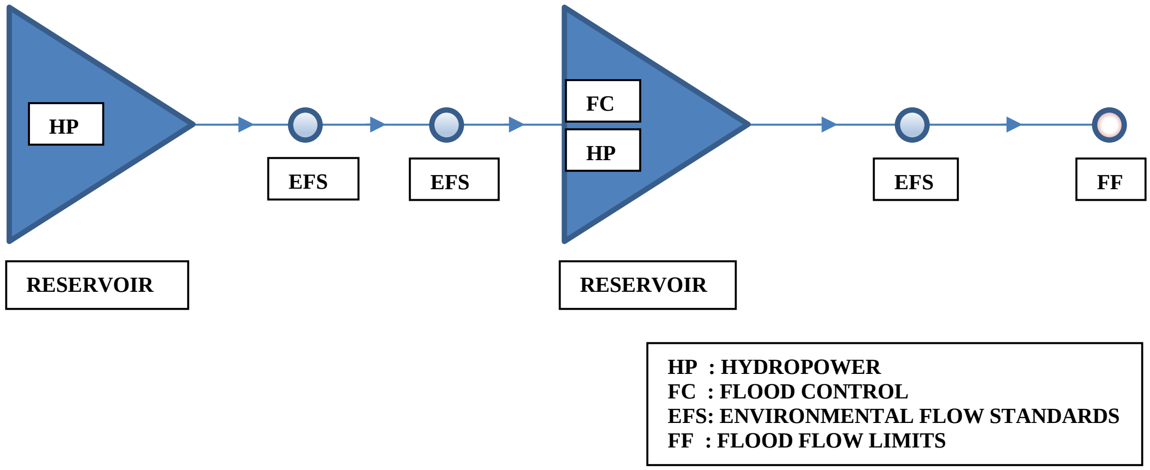


Figure 2: The Systematic Overview of River/Reservoir System

Three types of energy that are average, firm, and secondary are the main purposes of hydropower generation. The average energy is mean annual energy generated at power plants. Firm energy is the maximum energy produced continuously. Secondary energy is the surplus energy of primary energy or difference between average energy and firm energy.

Reservoir operations for other purposes are a key aspect that should be considered as a part of hydropower generation. If the reservoirs have zones for flood control, the water level can vary seasonally based on flood control operations, which affects the hydroelectricity generation. Power rule curve in these reservoirs is established in view of the reservoir pools and flood seasons. In the same way, water supply decisions for irrigation, municipal, industrial, and environmental flows may be based on optimizing hydropower generation and providing higher reliable supplies (Wurbs,1996).

During flooding, the gates of spillway and outlet works are closed until the observation is made that flood has reached the peak and flows at downstream points are at allowable flow limits. Allowable flow rates depend on the historical hydrology, overbank flow capacities, environmental flows, road crossings, and stages at which flood damages occurred before. The regulation schedule is also developed by considering allowable flow rates at downstream points of the flood control reservoirs. During normal period conditions when the level is at below the top of conservation pool, any operation schedules and releases are not applied. However; if flood forecast reports illustrate that inflow will exceed the current conservation storage, flood control operations are made to release water from conservation pools by ensuring maximum allowable limits at downstream points. This case is applied to maximize the storage capacity available for the incoming flood (Wurbs,1996).

2.2 Hydropower Generation

Hydropower is the form of energy that is generated when the water falls or streams flows. Hydropower is a type of renewable energy, and it provides an efficient, clean, cheap, reliable, and flexible power source for countries. It has advantages over alternative energy sources:

- A continual supply of water from the rainfall and snowmelt
- Converting the energy in falling water into electricity

- Not emitting waste heat and gases
- Simple, reliable and durable machinery
- Starting quickly and adjusting rapidly to changes in demand

Hydroelectricity generation has an essential role in the economy by offering affordable electricity source that keeps the energy prices down and increasing availability of energy that helps to reduce independence on other nations for energy.

2.2.1 Historical Background

The old grist mill has accepted as an ancient power plant that is primarily used for irrigational purposes in Europe and Asia. After starting the construction of the dams in the 19th century with the integration of technology, hydropower had become an essential way to generate power and transport many hundreds of miles as electricity. Around the 20th century that was the golden age of hydropower, North America and Europe built numerous dams and hydropower plants at a rapid rate. In this century, hydropower plants generate 15.9% of all world electricity power and 62.1% of all renewable electricity (Hydropower Status Report, 2019). These numbers are expected to increase over the next decades with an increase of over 3%. Hydropower is generated in 159 countries in the world, and China, the United States, Brazil, and China are making up almost half of the whole world's hydropower production. However; these countries are not utilizing the total of their hydroelectricity capacity. Table 1 obtained from Hydropower Status Report shows the percent of world hydropower capacity and hydropower generation in these countries.

Table 1: Hydropower Generation in the World (Hydropower Status Report, 2019)

Country	Installed Capacity (GW)	Percentage (%)	Generation (TWh/year)
China	352.26	27.26	1,232.90
Brazil	104.14	8.06	417.91
United States	102.75	7.95	291.72
Canada	81.39	6.30	381.18
Japan	49.91	3.86	88.47
India	49.92	3.86	129.96
Russia	48.51	3.75	183.76
Norway	32.26	2.50	139.51
Turkey	28.36	2.19	59.70
France	25.52	1.98	63.10

2.2.2 Hydroelectric Systems

Hydropower plants are usually used to meet the demands of the overall electric utility system. Demands for electricity varies seasonally, and in order to define the demand in a period, the terms of base load and peak load are generally used to refer to minimum power demand and additional power demand respectively (Wurbs, 1996). Thermal plants are usually used to meet the demands of base load and hydropower plants are operated to generate electricity to supply the peak load.

The general concept of hydropower plants is electricity generation by dams built on flow rivers. The height of water in a reservoir is greater than the river, that is defined as potential energy on storage. The potential energy is converted into kinetic energy, by allowing water in storage flows through the penstocks and intaking the turbines. In order to generate hydroelectricity, water must be in motion, which is kinetic energy. With this kinetic energy, water runs through the blades of the turbine and causes blades to spin, which results in the conversion of kinetic energy into mechanical energy. The turbine turns the generator rotor by a shaft and spinning of the generator uses electromagnetic fields to convert mechanical energy to electricity. Transformer inside the powerhouse takes the electricity to convert higher voltage. Power lines are connected to powerhouse transmit electricity to power users. Used water is carried through pipelines re-enter the downstream of rivers.

Power plants are located on rivers, streams, and canals for energy generation; however, to supply water for industrial, municipal, and agricultural needs and generate hydropower, dams are a necessity. Dams store water for conservation purposes and act like a battery. Figure 3 shows the basic components of hydropower plants.

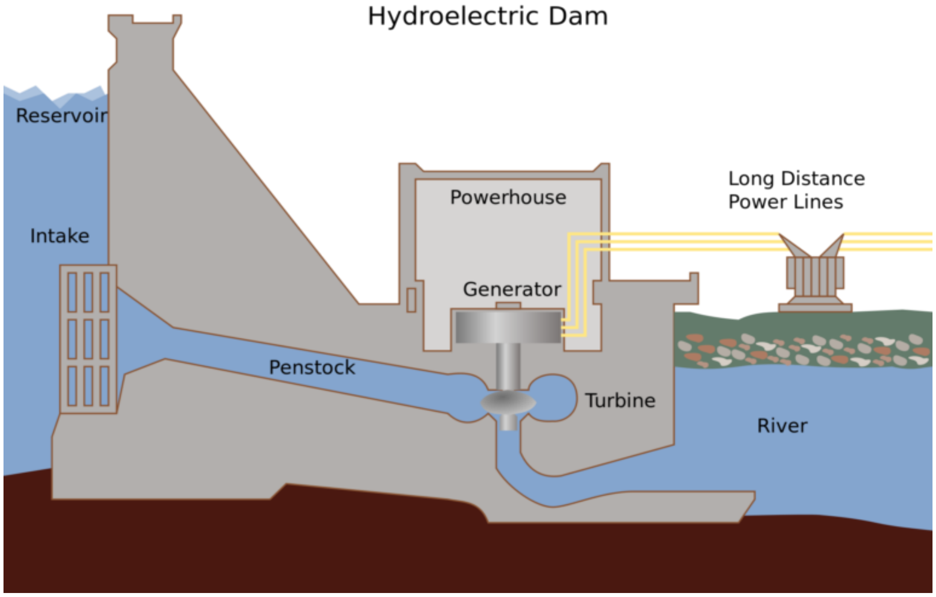


Figure 3: Components of Hydropower Plants

A turbine is a rotary mechanical device that extracts energy from fluid and converts it into different forms. The turbine is combined with a generator in hydropower plants to generate electricity. Two basic types of turbines that are impulse and reaction are used to generate power in different variations. Turbines are selected depends on cost estimates and site conditions. Reaction turbine that can be horizontal or vertical works with wheel completely submerged and has a feature to reduce the turbulence. The reaction turbine rotates at a central point where water is under pressure and escapes from the ends of the blades that cause rotation. This type of turbine is most commonly used.

Impulse turbine that can be horizontal or vertical works uses the kinetic energy of water striking its blades to make a rotation. The blades are shaped and the wheel is covered by housing so they turn the flow around 170 degrees, which results in water falling to the bottom of the wheel and flowing out. Characteristics of these two types of turbines can also be classified by considering the head. Table 2 shows the head classification of the turbine types.

Table 2: Turbine Classification

Head Classification	**Turbine Type**	
	Reaction	**Impulse**
High (>50 m)	Pelton Turgo	
Medium (10-50 m)	Crossflow Turgo Multijet Pelton	Francis
Low (<10m)	Crossflow	Propeller Kaplan Francis

2.2.3 Types of Hydropower Plants

Hydropower plants are classified depending on their sizes and usage types.

2.2.3.1 Classification by Size

Hydropower facilities may be classified from large power plants that supply many customers with electricity to small, micro, pico, and underground plants.

2.2.3.1.1 Large Hydropower Plants

Large hydropower plants (LHP) are commonly seen as the largest power generation facilities in the world. The hydropower plants that have a capacity of more than 30 MW (megawatts) are classified as LHP.

2.2.3.1.2 Small Hydropower Plants

Small hydropower plants (SHP) serves small communities and industrial plants. The hydropower plants that generate 10 MW (megawatts) or less are classified as SHP.

2.2.3.1.3 Micro Hydropower Plants

Micro hydropower plants generate electricity for home, ranch, farm, or village to meet the demand. Micro hydropower plants have capacity up to 100 kW (kilowatts)

2.2.3.1.4 Pico Hydropower Plants

Hydroelectricity generation under 5 kW (kilowatts) is classified as Pico hydropower. It is useful for small communities to produce a small amount of electricity.

2.2.3.1.5 Underground Hydropower Plants

The underground hydropower plants are used to generate electricity between two facilities by utilizing natural height differences. Underground tunnel is built to take water from the high reservoir to the low reservoir at which generator located, and electricity is produced by taking water away.

2.2.3.2 Classification by Type

Hydroelectric plants can be classified into three main categories depending on operation and type of flow. Run-of-river, storage, and pumped storage vary from the very small to the very large plants depends on the hydrology and watershed topography.

2.2.3.2.1 Run-of-the-River Facilities

Run-of-the-River (RoR) hydropower plants that have small or no reservoir capacity generates electricity from water coming from upstream available at that moment or surplus water must pass unused. Generation profiles of RoR facilities vary depends on river flow conditions, precipitation, run-off, and seasonal variations. RoR facilities are cheap, more reliable, and environmentally-friendly in comparison with similar-sized storage hydropower plants. In some rivers, water may be diverted to channel or pipeline to convey the water to turbines for hydroelectricity generation. Constant water supply from the upstream reservoir has an important advantage for RoR hydropower plants. Figure 4 shows the general plan of run-of-the-river power plants.

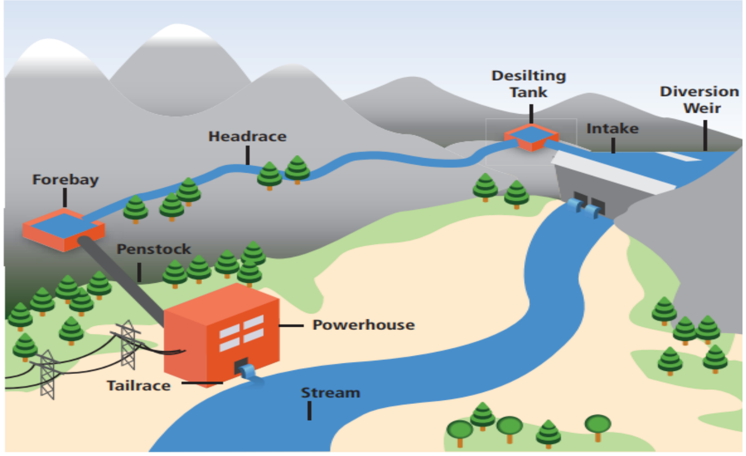


Figure 4: Run-of-river Hydropower Plants (Edenhofer et al., 2012)

2.2.3.2.2 Storage (Reservoir) Hydropower Plants

Hydroelectricity plants with a reservoir that has sufficient capacity to store water for later consumption are called storage hydropower. Storage of water provides flexibility for power generation depends on demand and water availability for next days. Generators and turbines are located at the further downstream points of the dam to where water is conveyed through tunnels and pipelines that are called the penstock. Type and size of the dams are determined by the topography of the region and river valleys. The power generated at storage hydropower plants depends on the height difference of the dam and outflow of water. Storage hydropower plants can be operated to meet the demand of base load, as well as peak load thanks to the capability of starting and shutting down in a short time. Figure 5 shows the general plan of storage (reservoir) hydropower plants.

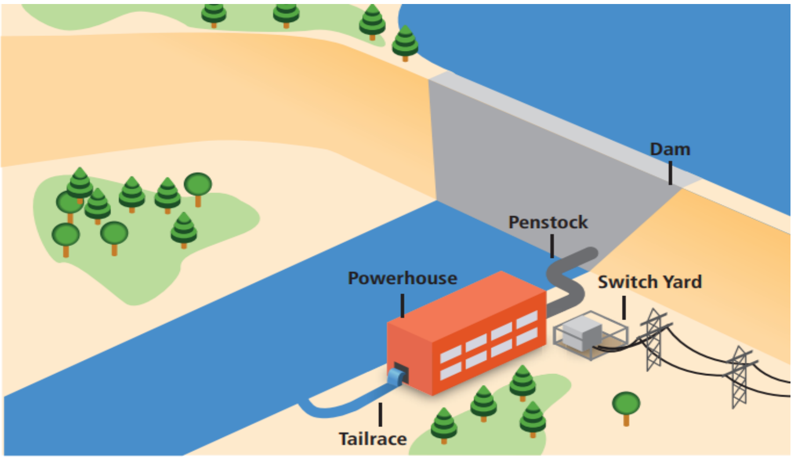


Figure 5: Storage Hydropower Plants (Edenhofer et al., 2012)

2.2.3.2.3 Pumped Storage Hydropower Plants

Pumped storage hydropower plants generate electricity for peak load by allowing water flows through pipelines from the upper reservoir to lower reservoir. During periods of low demand, water is pumped from the lower reservoir to the upper reservoir through pipelines by powering pumps with secondary energy from other plant systems in the region. Even if there are energy losses through the pumping process, pumped storage hydropower plants provide the most commercial energy storage systems in large-scale. It also provides the electrical system with safety, sustainability, and stability without losing any water due to evaporation whilst generating huge amounts of hydroelectricity. Pumped-storage hydroelectricity plants are constructed to help to balance of frequent changes between oversupplies and power shortages. Figure 6 shows the general plan of pumped storage hydropower plants.

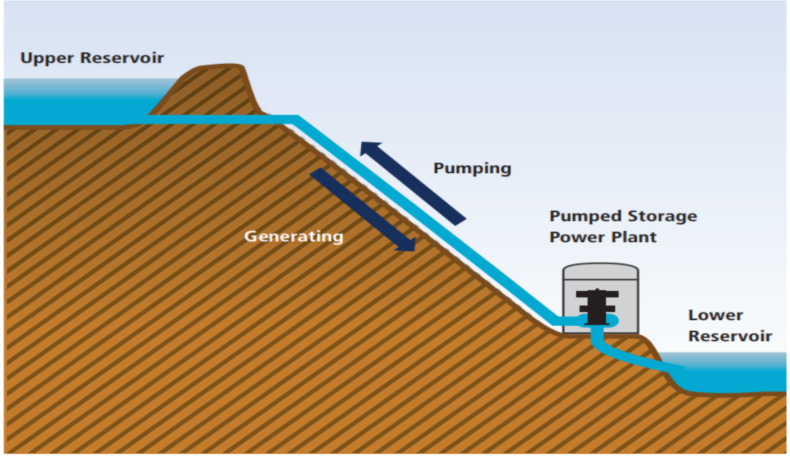


Figure 6: Pumped Storage Hydropower Plants (Edenhofer et al., 2012)

2.2.4 Hydropower Operations

Reservoirs are operated to generate electricity by releasing water for just hydropower generation or other purposes, such as municipal, industrial, and irrigational water supply. While meeting the water demand for conservation purposes at downstream points, hydroelectricity is produced through the turbines. Reservoir operation rules for hydropower generation are defined by using different methods and algorithms depending on the characteristics of the utility system, reservoir system, hydrology of river basin, and other constraints (Wurbs, 1996). Figure 7 illustrates the key aspect of hydropower generation monthly operations.

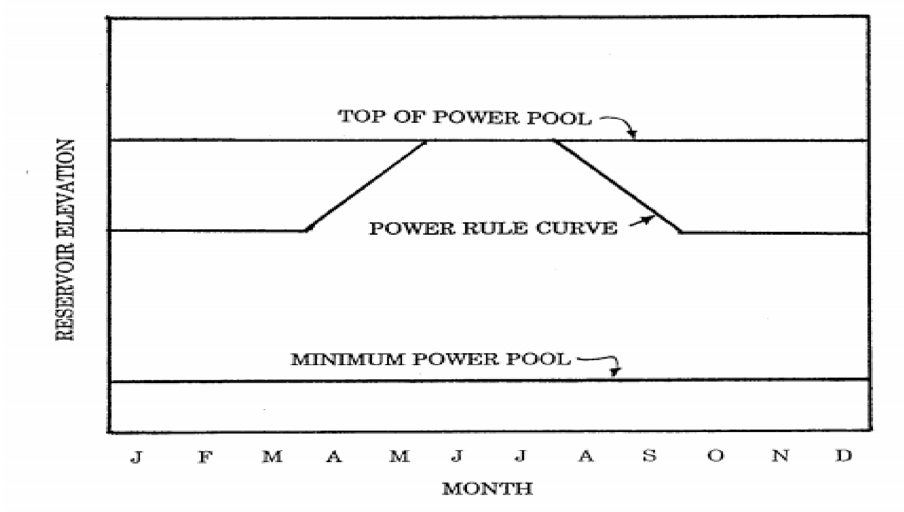


Figure 7: Rule-Curve for Hydroelectric Power Operations (Wurbs, 1991)

In many reservoirs, dead or inactive storage area that is below the power pool is reserved to provide power system with an additional head for generation. When the water level passes the top of power pool or conservation pool, net inflows are released through the reservoir intake system to generate electricity with flows up to capacity, and the remainder of the flow is spilled. If the water level below the top of the power pool, hydropower generation is stopped till enough water is stored (Wurbs, 1996).

Three types of energy that are average, primary, and secondary are the main purposes of hydropower generations. The average energy is mean annual energy generated at power plants. Primary energy is the electrical energy produced to meet the specific demands. Secondary energy is the surplus energy of primary energy or difference between average energy and firm energy.

Hydropower operations are typically made on two objectives: providing the demand for primary energy and meeting total system electricity demands cost-effectively (Wurbs, 1996). Hydropower operations are modeled to ensure the primary energy supply continuously in accordance with the power rule curve that is specifically developed depending on historical streamflow and power demand. Based on the storage level in reservoirs and power rule curve, primary and secondary energy generation can vary. When the storage is below the rule curve, only primary energy can be generated. However, secondary energy can be produced in the case of water level above rule curve. Due to difference in electricity unit price of primary and secondary energy, different approaches and optimization techniques are applied to obtain maximum benefit.

Reservoir operations for other purposes are also a key aspect that should be considered of hydropower generation. If the reservoirs have zones for flood control operations, the water level can vary seasonally that causes tradeoffs between primary energy and secondary energy. Power rule curve in these reservoirs is established by considering the reservoir pools and seasons. In the same way, water supply decisions for irrigation, municipal, industrial, and environmental flows may be based on optimizing hydropower generation and providing higher reliable supplies.

Hydropower is basically calculated based on the following equation:

$$P = \eta \times \rho \times Q \times g \times h$$

P : power generated [watt (W)]

η : efficiency of turbine [lb/ft^3, kN/m^3]

ρ : density of water [lb/ft^3, kg/m^3]

Q : discharge flow through turbines during time period [cfs, m^3]

g : the acceleration due to gravity [ft/sec^2, m/sec^2]

h : head [ft, m]

2.3 Flood Control Operations

The main concept of reservoir flood control operations is the minimization of the risk and results of making releases through outlets of the dam without contribution to flooding at downstream points by considering that water level does not exceed the maximum design surface level of dams. Flood control pools are emptied as expeditiously as to reduce the risk of filling the capacity and possibility of overtopping the dam (Wurbs, 1996).

In reservoir system operations, in order to intake the water in the flood control pools, the regulation schedule is developed to make releases from the reservoirs for mitigating the uncertainties. Real-time flood control operations are pursued in a framework of the regulation schedule, that help operators to do reliable releases. Real-time operations consist of current storage, hydrologic data, and forecasted flows at specific points for next hours and days.

During flooding, the gates of spillway and outlet works are closed until the observation is made that flood has reached the peak and flows at downstream points are allowable flow limits. Allowable flow rates depend on the historical hydrology, overbank flow capacities, environmental flows, road crossings, and stages flood damages occurred before. The regulation schedule is also developed by taking into consideration of allowable flow rates at downstream points of the flood control reservoirs.

During normal period conditions when the level is at below the top of conservation pool, any operation schedules and releases are not applied. However; if flood forecast reports illustrate that inflow will exceed the current conservation storage, flood control operations are made to release water from conservation pools by ensuring maximum allowable limits at downstream points. This case is applied to maximize the storage capacity available for an incoming flood. When ensuring the allowable flow rates at downstream points, flood attenuation and travel time from the dam to downstream points and inflow coming from watershed areas below the dam may be estimated in the reservoir operation process. Also, rapid changes in flow stage because of the gate openings are considered for the public safety and variations of streambank sedimentation. (Wurbs, 1996).

In many regions, flood control reservoirs are operated in multiple reservoir system, and regulation schedule for flood control operations is applied together. Flood control reservoirs may share the same downstream points that have allowable flood limits. In this issue, multiple-reservoir release decisions are implemented based on the relative balance between the reservoir storage capacity utilized. Different operation rules for balancing are developed for multiple reservoir systems by taking into account of runoff from watershed areas and releases from all reservoirs (Wurbs, 1996).

2.4 Reservoir System Operations in the WRAP Modeling System

Reservoirs are mainly constructed in the WRAP modeling system in two purposes: maintaining the storage and meeting water needs by releasing from storage. Depending on the purpose of reservoirs, input parameters are assigned to define operation rules. The water right WR, reservoir storage WS, operation rules OR, flood control reservoir operation FR, and pairs of SV/SA, PV/PE, and FV/FQ records are mainly used to construct reservoir system operations.

Reservoir storage parameters are inputted on the storage WS record associated with water right WR record. WS record includes details about the total storage capacity of conservation pool and inactive pool, storage-area relationship, optional storage specifications, and evaporation parameters. Hydropower generation is defined on HP record associated with WR, WS, and PV/PE records. HP record includes details of efficiency of hydropower plants, tailwater discharge-elevation relationship, turbine inlet elevation, turbine discharge capacity, and maximum limit of energy production. Flood control operations in the daily modeling system are controlled by the records of FR, FF, FV, and FQ. Flood control records define the total storage capacity of flood control pool, maximum allowable flood flow limits, the priority of storage and release, multiple-reservoir system balancing index, and storage-outflow relationship.

Reservoirs are modeled range from very simple to very complex and operated in the WRAP as an individual reservoir or multiple-reservoir system depending on the purposes. Conservation pools in reservoirs that include active storage and dead storage are modeled in WS record. Releases to meet water needs for water rights are made from the active storage while there is no withdrawal in inactive storage area except for evaporation. Maximum release capacity of the reservoirs can be specified on the OR record. Each reservoir is assigned a control point. Any number of water rights can be assigned to the same reservoir. Releases from dams and refilling storage are made based on target and priorities assigned in WR records. Storage volume versus surface area relationships is inputted with either SV/SA records or coefficients on WS record.

2.4.1 Hydropower Generation

The WRAP modeling system has the capability of hydropower generation in the daily and monthly version depending on characteristics of hydropower plants and energy demand curve. Energy production is treated similar to water supply, and hydropower target entered on the WR record. Reservoir storage and hydropower generation details are specified on WS and HP records. Reservoir head for energy generation is interpolated from reservoir PV/PE records that are storage volume versus water surface elevation table. Tailwater elevation is specified as constant elevation in HP records or TE/TQ records that are tailwater elevation versus discharge table. The energy demand curve is defined for twelve months with UC distribution coefficients record that is incorporated in WR record.

WRAP generates hydropower with all water that is available to the turbines in the priority-based system by considering turbine discharge capacity, secondary energy capacity, and energy demand curve. In each period, the energy production target is met in case enough water and the head is available in reservoir storage. If there is not enough water in the dam, energy shortage occurs based on energy target for the period. Depending on releases for downstream points, secondary energy that is the energy above specified energy target is generated. When the water level in reservoir decrease to minimum reservoir storage or dead storage, hydropower generation is curtailed. WRAP enables flows through power turbines to return with the default

Hydropower computations are made in the WRAP modeling system based on following equations:

$$E = P \times t$$

$$P = \gamma \times Q \times H \times e$$

$$E = P \times \gamma \times Q \times H \times e \times t$$

E : energy generated [watt-hour (W-hour)]

P : power generated [watt (W)]

γ : unit weight of water [lb/ft^3, kN/m^3]

Q : discharge flow through turbines during time period [cfs, m^3]

H : head [ft, m]

e : plant efficiency [dimensionless]

t : time period

Energy generation results in the simulation are written to HRR file and tabulated with TABLES. WRAP-SIM OUT file also includes reservoir releases for energy generation and reliability details of hydropower rights.

2.4.2 Flood Control Operations

Flood control operations are modeled in the daily version of the WRAP modeling system with records of FR, FF, FV, and FQ. Flood control pools in reservoirs are defined in FR records by inputting storage capacity details, discharge limits, and storage and release priorities. Releases are made based on allowable flood flow limits at downstream points that are identified in FF records. FV/FQ records that are storage versus outflow tables can be used to simulate surcharge storage and spills for reservoirs.

In the WRAP modeling system, flood control operations are made depending on the purpose of minimizing the risk of flooding at downstream points caused by releases from reservoirs. The terms of controlled and uncontrolled are used to describe flood control structures. Controlled flood control operations that defined with FR and FF records state opening and closing gates to empty operated by people. Ungated outlet structures that are modeled with FR and FV/FQ records refer to uncontrolled flood control operations where flows discharge depending on the storage of the reservoirs.

Reservoir flood control operations are made in the priority system junior to all water rights. Different priorities are assigned for reservoir storage and release depending on the judgment of the operators. Flow routing and flow forecasting methods can be applied to increase the accuracy of the simulations. In the reservoir system, the same priorities of storage and release are assigned to each reservoir to make operations in multiple reservoir system. In this system, the rank index is calculated to make a decision for storage and release. The reservoir that has a smaller rank index is considered first to store water. However, in releases of flood control pools, the reservoir that has the largest index is treated first. The following equation is used to calculate the rank index for the reservoirs:

$$\text{rank index} = (\text{multiplier factor})\left[\frac{\text{storage content in FC pool}}{\text{storage capacity of FC pool}}\right] + \text{addition factor}$$

Addition factor is used when the conservation pool of the reservoir is considered to use for storage of flood flows. Also, the multiplier factor is assigned to make changes on the order of flood control operations in multiple reservoir system.

CHAPTER III

BRAZOS RIVER BASIN

3.1 Overview of the Brazos River Basin

The Brazos River Basin extends from the Salt Fork and Double Mountain Fork in New Mexico to the city of Freeport at the Gulf of Mexico about 920 miles across Texas. The climate in the region varies from arid flat area in the upper basin with an average annual precipitation of 19 inches to gypsum-salty intermittent in the lower basin with a mean annual precipitation of 45 inches. The total drainage area of the basin accounts for 45,870 square miles, of which 43,160 square miles are in Texas. The Brazos River Basin has borders with Colorado River Basin on the west, Trinity River Basin on the east and Buffalo Bayou watershed on the south. The Brazos River flows into Galveston Bay and the Gulf of Mexico.

Figure 8: Major Tributaries and 16 Largest Reservoirs in the Brazos River Basin

The Brazos River Basin has 675 reservoirs of which 43 have storage capacities of 5,000 acre-feet or greater. 16 reservoirs in the basin area have a storage capacity of greater than 75,000 acre-feet. Nine of these reservoirs have portions for flood control operations. Possum Kingdom Lake is the largest reservoir for conservation purposes with a capacity of 724,739 acre-feet. When conservation pool and flood control pool are considered together, Lake Whitney is the largest reservoir in the basin area and the seventh-largest reservoir in the state of Texas. Table 3 shows the details of the largest reservoirs in the Brazos River Basin.

Table 3: Largest Reservoirs in the Brazos River Basin (Wurbs, 2019)

Reservoir	Initial Impoundment	Conservation Pool (acre-feet)	Flood Control Pool (acre-feet)	Total Capacity (acre-feet)
		USACE and Brazos River Authority (BRA)		
Whitney	1951	636,100	1,363,400	1,999,500
Aquilla	1983	52,400	93,600	146,000
Waco	1965	206,562	519,840	726,402
Proctor	1963	59,400	314,800	374,200
Belton	1954	457,600	640,000	1,097,600
Stillhouse Hollow	1968	235,700	394,700	630,400
Georgetown	1980	37,100	93,700	130,800
Granger	1980	65,500	178,500	244,000
Somerville	1967	160,110	347,290	507,400
		Brazos River Authority (BRA)		
Possum Kingdom	1941	724,739	-	724,739
Granbury	1969	155,000	-	155,000
Limestone	1978	225,400	-	225,400
Allen's Creek	proposed	145,533	-	145,533
		City of Lubbock		
Alan Henry	1993	115,937	-	115,937
		West Central Texas Municipal Water District		
Hubbard Creek	1962	317,750	-	317,750
		Texas Utilities Services		
Squaw Creek	1977	151,500	-	151,500

The Brazos River Authority, City of Waco, City of Lubbock, West Central Texas Municipal Water District, and Texas Utilities Services have contracted with the U.S. Army Corps of Engineers (USACE) for the conservation capacity of the reservoirs in the basin area. The Brazos River Basin Authority (BRA) has dealt with USACE for the conservation capacity of nine federal reservoirs and three other reservoirs. City of Waco and City of Lubbock have also contract for the storage capacities in Lake Waco and Alan Henry respectively. The conservation pools in these reservoirs are used mainly for municipal and industrial water supply, irrigation, hydropower, and recreation.

3.2 Flood Control Reservoirs in the Brazos River Basin

The flood control pools in nine reservoirs that are operated by USACE are used to mitigate the effects of pulse flow on downstream points by maintaining water levels at allowable levels. In general, flood control pools are maintained empty and flood control operations occur whenever water levels pass the top of conservation pool. Table 4 shows the technical features of flood control reservoirs in the Brazos River Basin area. Flood control reservoirs are also mapped in Figure 9.

Table 4: Elevation Details of Reservoir Pools

Reservoir	Top of Conservation (ft)	Top of Flood Control (ft)	Top of Dam (ft)	Max Flow Limit at Dam (cfs)
Whitney	533.0	571.0	584.0	25,000
Aquilla	537.5	556.0	582.5	3,000
Waco	462.0	500.0	510.0	30,000
Proctor	1,162.0	1,197.0	1,205.0	2,000
Belton	594.0	631.0	662.0	10,000
Stillhouse Hollow	622.0	666.0	698.0	10,000
Georgetown	791.0	834.0	861.0	3,000
Granger	504.0	528.0	555.0	6,000
Somerville	238.0	258.0	280.0	2,500

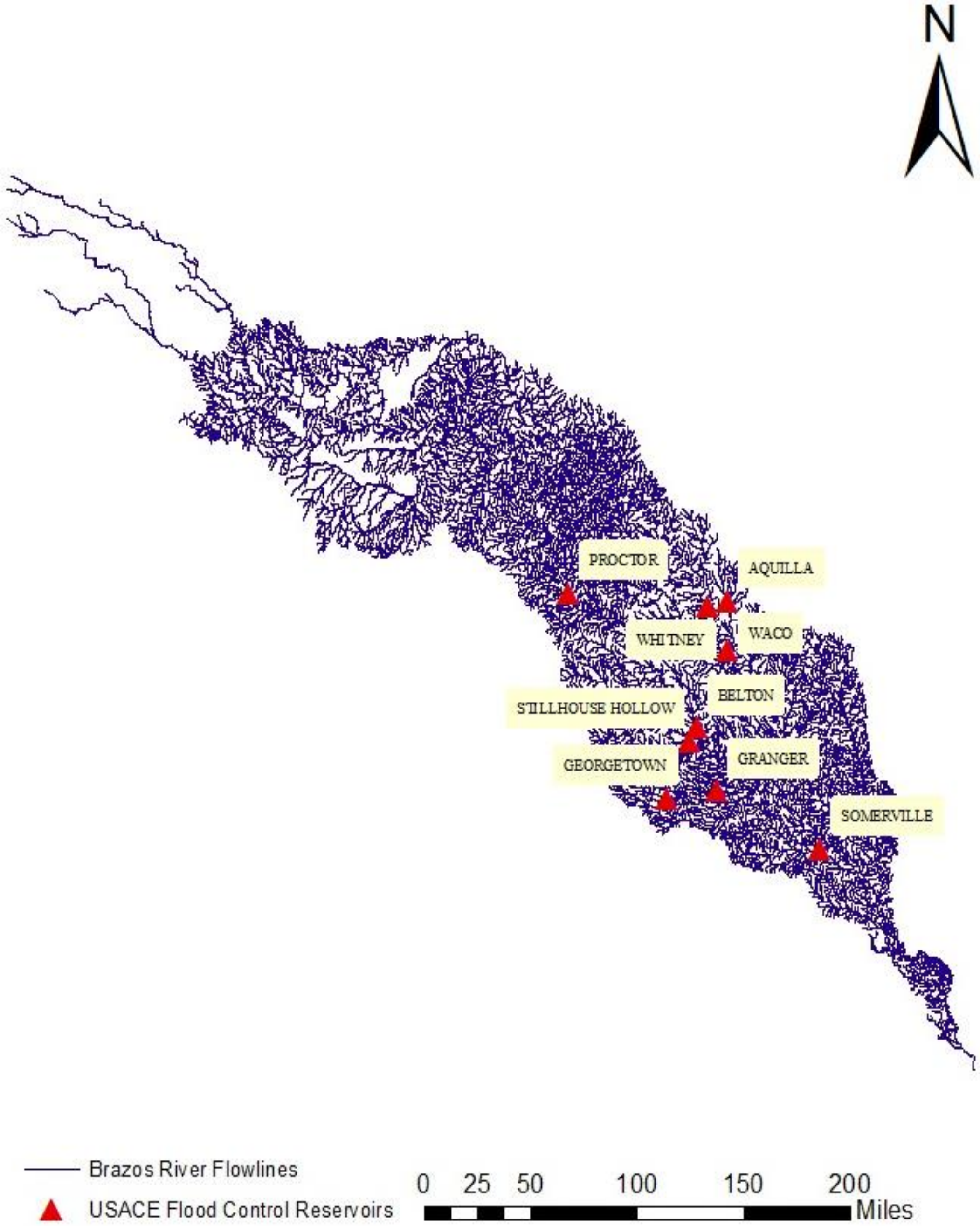


Figure 9: USACE Flood Control Reservoirs in the Brazos River Basin

3.2.1 Whitney Reservoir

Lake Whitney is located in Bosque and Hill Counties on the main tributaries of the Brazos River in Central Texas. The main purpose of this reservoir is flood control operations. Secondarily, Lake Whitney is used for hydropower generation and recreation as conservation purposes. The drainage area of this reservoir is approximately 27,189 square miles. The type of the dam is concrete gravity and earth fill. The dam has a length of 17,695 feet, a maximum height of 159 feet, embankment width of 34 feet, and 28 feet of spillway width. The construction of the dam was begun on May 12, 1947, and powerhouse that consists of two turbines of 15,000 kilowatts capacity was completed between the period of 1951 and 1953. Average annual hydropower generation in Whitney Reservoir is 73,100 megawatts. Lake Whitney is owned by the U.S. Government and operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 5 illustrates the technical details of Whitney Dam, and Figure 10 shows the daily observed reservoir storage in Whitney Dam.

Table 5: Technical Details of Whitney Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	584.0	--	--
Maximum Design Water Surface	573.0	2,100,400	51,190
Top of Flood Control	571.0	1,999,500	49,820
Top of Conservation Pool	533.0	636,100	23,220
Sediment reserve and power-head	520.0	387,024	14,301
Streambed	425.0	0	0

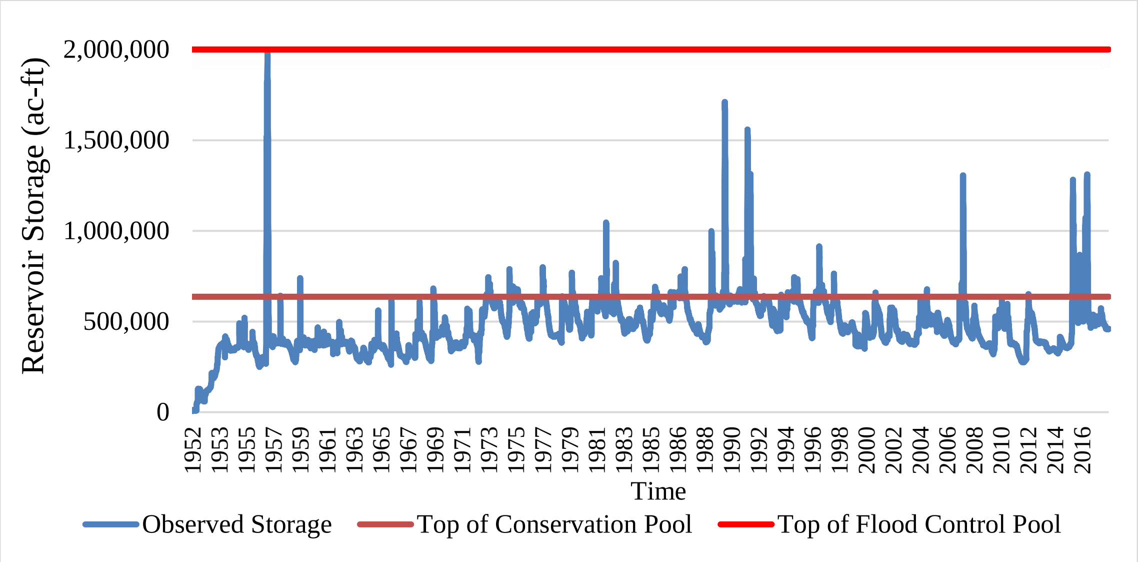


Figure 10: Whitney Reservoir Daily Observed Storage

3.2.2 Waco Reservoir

Waco Dam and Lake Waco are located on the Bosque River in McLennon County, within the city of Waco. Waco Reservoir is used for conservation purposes for water supply in the city of Waco and flood control operations. The drainage area of this reservoir is approximately 1,670 square miles. The type of the dam is Earth fill with concrete spillway left bank. The dam has a length of 24,616 feet that includes spillway, a maximum height of 140 feet, embankment width of 20 feet, and 16 feet of non-overflow width. The construction of the dam was completed on June 24, 1965. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the city of Waco and the Brazos River Authority. Table 6 illustrates the technical details of Waco Dam, and Figure 11 shows the daily observed reservoir storage in Waco Reservoir.

Table 6: Technical Details of Waco Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	510.0	--	--
Maximum Design Water Surface	505.0	828,300	21,390
Top of Flood Control	500.0	726,400	19,440
Spillway Crest	465.0	233,500	9,220
Top of Conservation Pool	462.0	206,562	7,260
Streambed	370.0	0	0

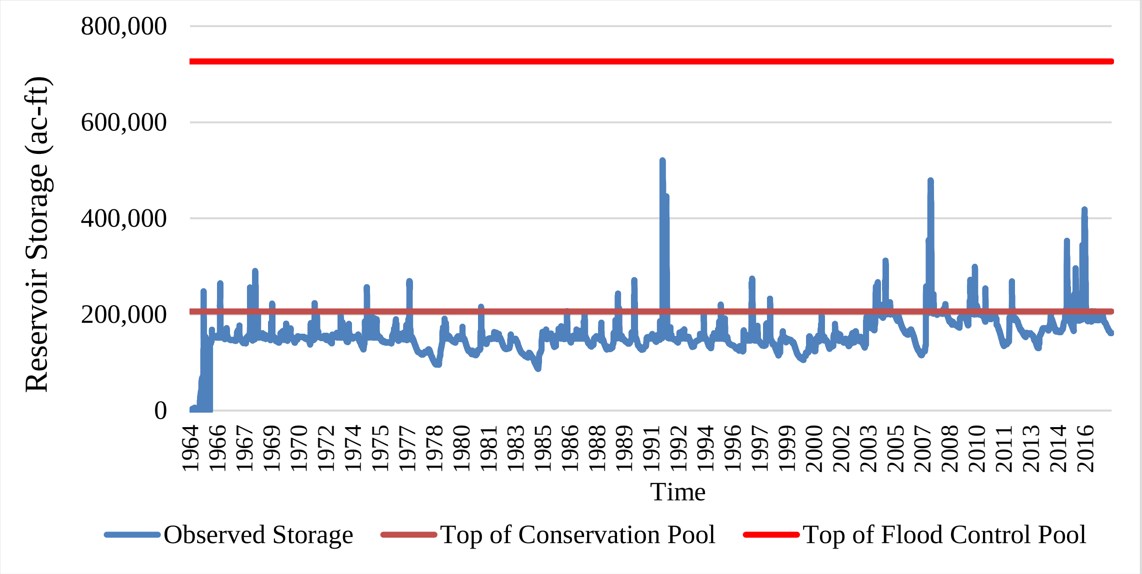


Figure 11: Waco Reservoir Daily Observed Storage

3.2.3 Aquilla Reservoir

Aquilla Dam and Aquilla Lake are located on Aquilla and Hackberry Creeks that are the tributaries of the Brazos River. This reservoir is primarily used for flood control operations and water supply storage. The drainage area of this reservoir is approximately 252 square miles. The type of the dam is rolled earth fill. The dam has a length of 11,890 feet, a maximum height of 104.55 feet, and a top width of 38 feet. The construction of the dam was completed on May 16, 1983. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 7 illustrates the technical details of Aquilla Dam, and Figure 12 shows the daily observed reservoir storage in Aquila Reservoir.

Table 7: Technical Details of Aquilla Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	582.5	--	--
Maximum Design Water Surface	577.5	359,900	14,495
Spillway Crest	564.5	213,800	8,980
Top of Flood Control	556.0	146,000	7,000
Top of Conservation Pool	537.5	52,400	3,266
Streambed	478.0	0	0

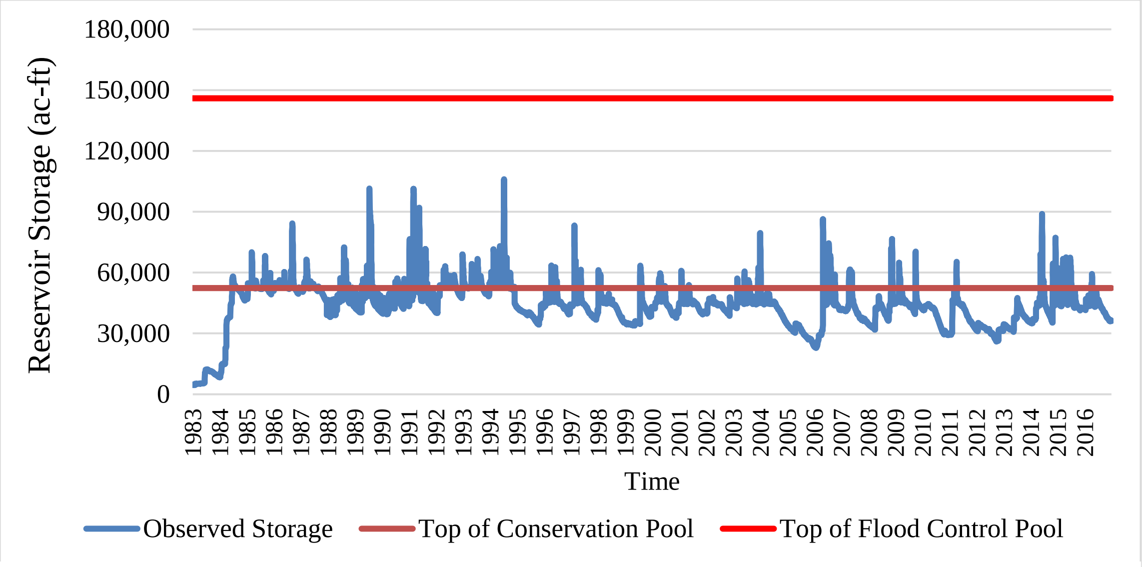


Figure 12: Aquilla Reservoir Daily Observed Storage

3.2.4 Proctor Reservoir

Proctor Dam and Proctor Lake are located on the Leon River in Comanche County. This reservoir is primarily used for flood control operations and water supply diversions for communities in Comanche, Erath, and Hamilton Counties. The drainage area of this reservoir is approximately 1,265 square miles. The type of the dam is rolled earth fill with concrete spillway in right abutment ridge. The dam has a length of 13,460 feet, a maximum height of 86 feet, and a top width of 30 feet. The construction of the dam was completed on January 2, 1964. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 8 illustrates the technical details of Proctor Dam, and Figure 13 shows the daily observed reservoir storage in Proctor Reservoir.

Table 8: Technical Details of Proctor Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	1,205.0	--	--
Maximum Design Water Surface	1,201.0	433,000	15,410
Top of Flood Control	1,197.0	374,200	14,010
Top of Conservation Pool (spillway crest)	1,162.0	59,400	4,610
Streambed	1,128.0	0	0

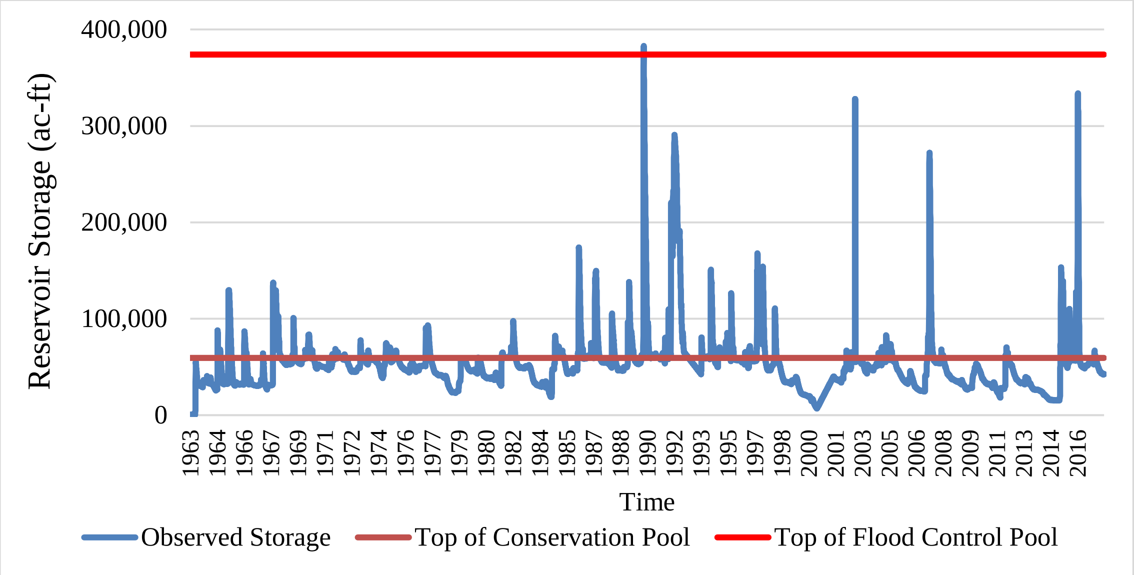


Figure 13: Proctor Reservoir Daily Observed Storage

3.2.5 Belton Reservoir

Belton Dam and Belton Lake are located on the Leon River that is a tributary of Brazos River. This reservoir is used for flood control, conservation purposes, and other multi-objective uses. The drainage area of this reservoir is approximately 3,560 square miles. The type of the dam is rolled earth fill. The dam has a length of 5,524 feet that includes spillway, a maximum height of 192 feet, and a top width of 30 feet. The construction of the dam was completed on December 15, 1954. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 9 illustrates the technical details of Belton Dam, and Figure 14 shows the daily observed reservoir storage in Belton Reservoir.

Table 9: Technical Details of Belton Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	662.0	--	--
Maximum Design Water Surface	656.9	1,876,700	37,340
Top of Flood Control (spillway crest)	631.0	1,097,600	23,620
Top of Conservation Pool	594.0	457,600	12,445
Streambed	470.0	0	0

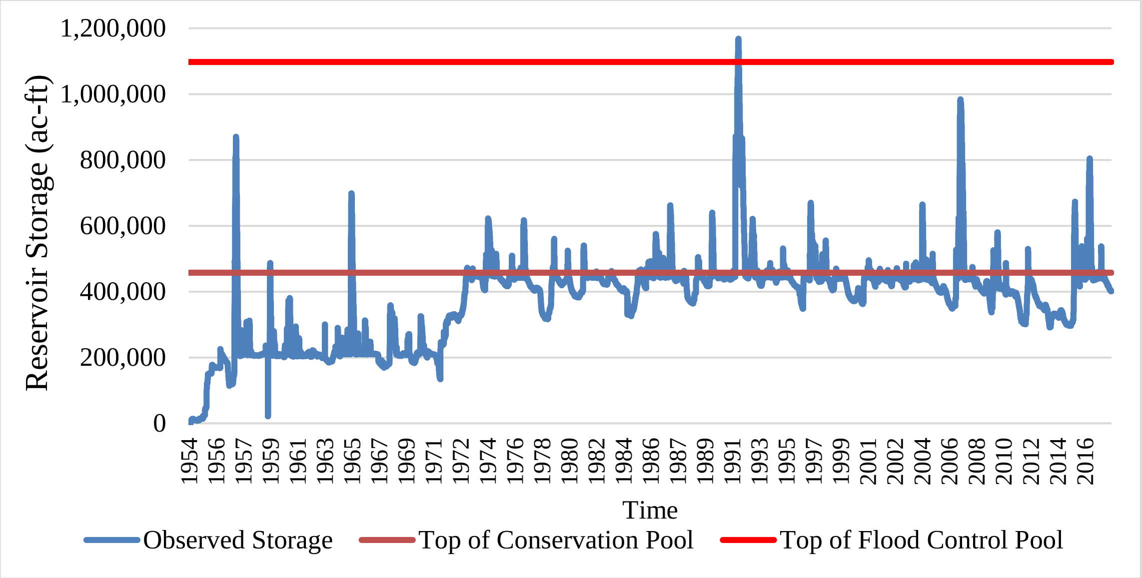


Figure 14: Belton Reservoir Daily Observed Storage

3.2.6 Stillhouse Hollow Reservoir

Stillhouse Dam and Stillhouse Lake are located on Lampasas River that is a tributary of Little River. This reservoir is used for flood control, conservation purposes, and other multi-objective uses. The drainage area of this reservoir is approximately 1,318 square miles. The type of the dam is rolled earth fill. The dam has a length of 15,624 feet that includes spillway, a maximum height of 200 feet, and a top width of 42 feet. The construction of the dam was completed on May 10, 1968. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 10 illustrates the technical details of Stillhouse Hollow Dam, and Figure 15 shows the daily observed reservoir storage in Stillhouse Hollow Reservoir.

Table 10: Technical Details of Stillhouse Hollow Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	698.0	--	--
Maximum Design Water Surface	693.2	1,013,300	16,370
Top of Flood Control (spillway crest)	666.0	630,400	11,830
Top of Conservation Pool	622.0	235,700	6,430
Streambed	498.0	0	0

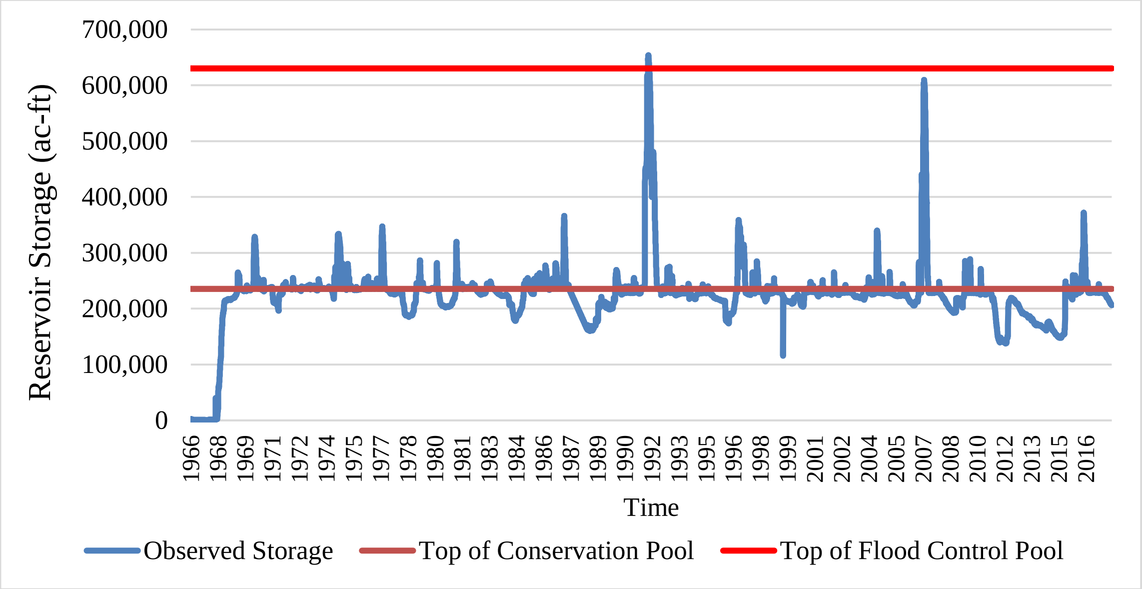


Figure 15: Stillhouse Hollow Reservoir Daily Observed Storage

3.2.7 Georgetown Reservoir

North San Gabriel Dam and Lake Georgetown are located on the North Fork of the San Gabriel River that is a tributary of the Brazos River. This reservoir is used for flood control, conservation purposes, and other multi-objective uses. The drainage area of this reservoir is approximately 246 square miles. The type of the dam is rock fill. The dam has a length of 6,700 feet that includes spillway, a maximum height of 164 feet, and a top width of 30 feet. The construction of the dam was completed on 1982. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 11 illustrates the technical details of North San Gabriel Dam, and Figure 16 shows the daily observed reservoir storage in the Georgetown Reservoir.

Table 11: Technical Details of Georgetown Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	861.0	--	--
Maximum Design Water Surface			
Top of Flood Control (spillway crest)	834.0	130,800	3,260
Top of Conservation Pool	791.0	37,100	1,310
Streambed	720.0	0	0

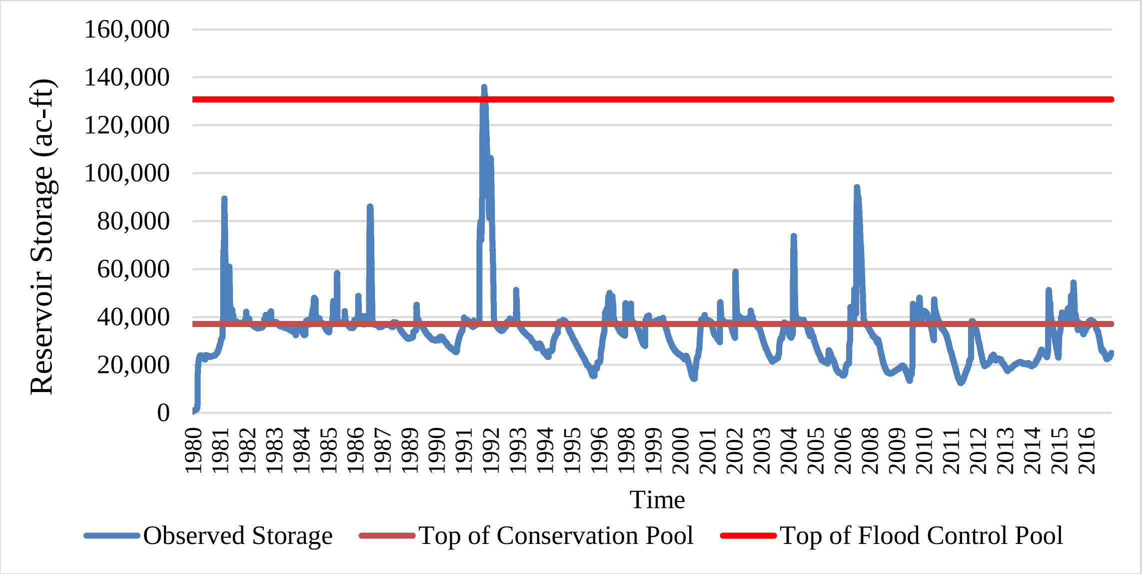


Figure 16: Georgetown Reservoir Daily Observed Storage

3.2.8 Granger Reservoir

Granger Dam and Granger Lake are located on the San Gabriel River in the Brazos River Basin. This reservoir is used for flood control, conservation purposes water conservation, fish and wildlife habitat, and recreation. The drainage area of this reservoir is approximately 709 square miles. The type of the dam is earth fill. The dam has a length of 16,320 feet that includes spillway, a maximum height of 115 feet, and a top width of 30 feet. The construction of the dam began on January 21, 1980. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 12 illustrates the technical details of Granger Dam, and Figure 17 shows the daily observed reservoir storage in Granger Reservoir.

Table 12: Technical Details of Granger Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	555.0	--	--
Maximum Design Water Surface	549.3	579,900	19,220
Top of Flood Control (spillway crest)	528.0	244,000	11,250
Top of Conservation Pool	504.0	65,500	4,400
Streambed	457.0	0	0

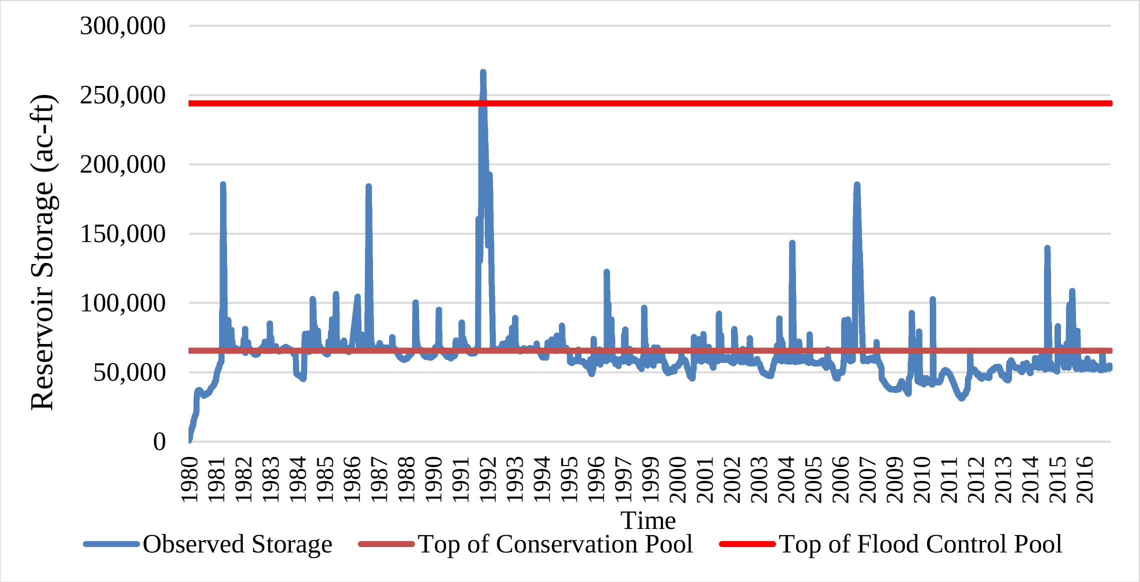


Figure 17: Granger Reservoir Daily Observed Storage

3.2.9 Somerville Reservoir

The Somerville Dam and Somerville Lake are located on Yegua Creek in Burleson, Lee, and Washington Counties. This reservoir is used for flood control, conservation purposes, and other multi-objective uses. The drainage area of this reservoir is approximately 1,006 square miles. The type of the dam is earth fill. The dam has a length of 20,210 feet that includes spillway, a maximum height of 80 feet, embankment width of 34 feet, and spillway width of 20 feet. The construction of the dam was completed on October 27, 1967. Flood control pool is operated by the U.S. Army Corps of Engineers, and water rights for diversion and refilling in this reservoir are appropriated to the Brazos River Authority. Table 13 illustrates the technical details of the Somerville Dam, and Figure 18 shows the daily observed reservoir storage in Somerville Reservoir.

Table 13: Technical Details of Somerville Dam

Feature	Elevation (ft)	Capacity (acre-feet)	Area (acres)
Top of Dam	280.0	--	--
Maximum Design Water Surface	274.5	1,028,800	39,800
Top of Flood Control (spillway crest)	258.0	507,500	24,400
Top of Conservation Pool	238.0	160,100	11,460
Streambed	200.0	0	0

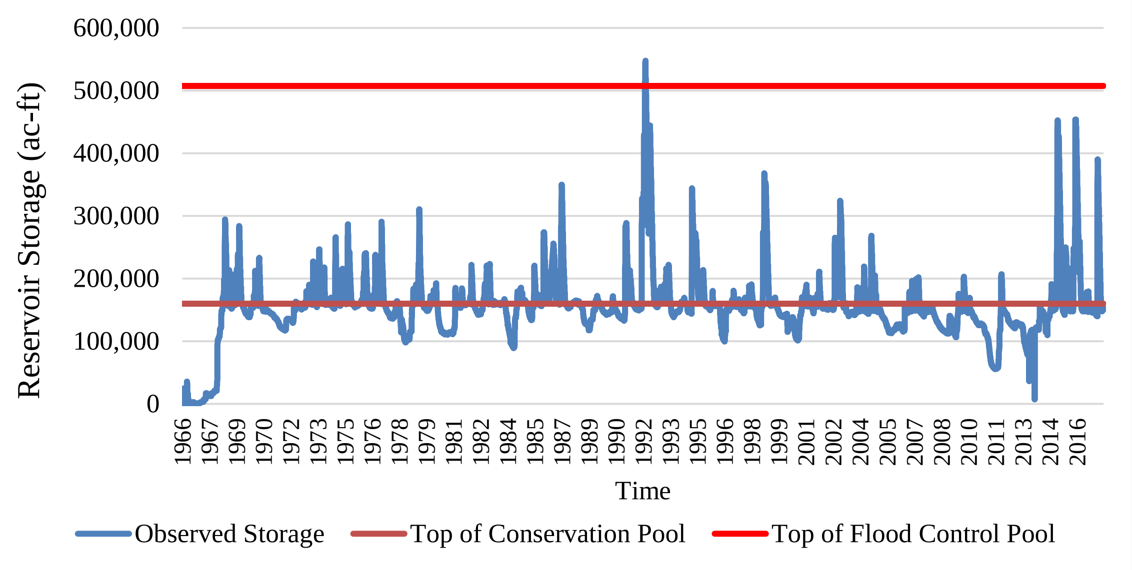


Figure 18: Somerville Reservoir Daily Observed Storage

3.3 Hydropower Generation in the Brazos River Basin

There are two hydropower plants at Lake Whitney and Possum Kingdom Reservoir that have turbines with a capacity of 30 MW and 22.5 MW respectively. Hydropower is generated at Lake Whitney by releases for diversions at downstream points under the control of USACE. Marketing is processed by The Southwest Power Administration that sells power to the Brazos Electric Power Cooperative. However, the hydropower plant at Possum Kingdom Reservoir was stopped several years ago. In the Brazos WAM, there are no water rights for hydropower generation. For this study, water rights, elevation-volume tables, and power curve for hydropower generation at both reservoirs are modeled in the daily and monthly dataset. Table 14 shows the details of the hydropower plant and turbines at Brazos River Basin. Also, historical hydropower generation in these reservoirs are tabulated in Appendix A.

Table 14: Hydropower Plants in the Brazos River Basin (Godfrey and Dowell, 1968)

Reservoir	Turbine		Generator	
	Type	Capacity (hp)	Volt	Capacity (MW)
Whitney	Francis	24,000	13,800	30.0
Possum Kingdom	Francis	17,000	6,900	22.5

Reservoir hydropower operation rules discussed in Chapter II and power rule-curve presented in Figure 7 are applied in this research for the hydropower plants is the Brazos River Basin. Operation rules and monthly energy targets are tabulated in Table 15 and Table 16 respectively.

Table 15: Reservoir Operation Rules for Hydropower Generation

	Whitney	Possum Kingdom
Annual Energy Target (MWh)	36,000	24,000
Maximum Daily Generation (MWh)	300	225
Minimum Water Level (msl)(feet)	520.0	960.0
Maximum Water Level (msl)(feet)	533.0	1,000.0
Tailwater Elevation (msl)(feet)	448.8	874.8
Turbine Discharge Capacity (cfs)	6,000	2,400

Table 16: Monthly Energy Generation Targets in Hydropower Plants

Month	Whitney (MWh)	Possum Kingdom (MWh)
JAN	2,250	1,500
FEB	2,250	1,500
MAR	2,250	1,500
APR	2,250	1,500
MAY	2,250	1,500
JUN	3,000	2,000
JUL	6,000	4,000
AUG	6,000	4,000
SEP	3,000	2,000
OCT	2,250	1,500
NOV	2,250	1,500
DEC	2,250	1,500
TOTAL	36,000	24,000

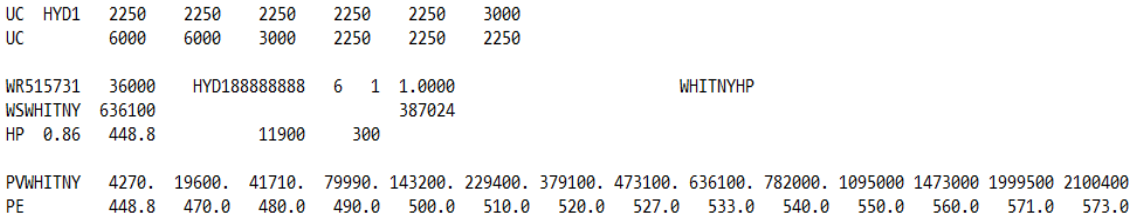
3.3.1 Whitney Hydropower Plant

The Whitney Powerplant is at Whitney Dam on the Brazos River, 7 miles southwest of Whitney and 38 miles upstream from Waco. The two generators that have 30,000 kw total capacity were placed in operation on June 25, 1953. Marketing of hydropower generated is at the responsibility of the Southwest Power Administration that sells to the Brazos Electric Power Cooperative. Hydropower in Brazos River Basin is generated by excess flows and releases for water supply diversions in downstream points. The inactive pool at Whitney Reservoir provides dead storage as the capacity of 387,024 acre-feet to generate hydroelectricity. The power distribution to the service area is controlled from the operation center in Waco. Electricity is generated during peak hours in accordance with the power requirement system. Table 86 in Appendix A illustrates the monthly hydropower generation in this power plant.

16-foot diameter penstocks carry water from the Whitney Reservoir to two 20,700 hp turbines that are connected to generators through 16 gate-controlled conduits, 5 feet wide by 9 feet high, with invert at elevation 448.83 feet above msl for floodwater release. The generators that were manufactured by Allis-Chalmers Manufacturing Company are 15,000 kw, 3 phase, 60 cycle, 13,800-volt, 128.6 rpm unit. The vertical turbines that were manufactured by Woodward Governor Company are Francis type 128.6 rpm unit, with a capacity of 24,000 hp.

The energy target in this study for the Whitney Reservoir is 36,000 MWh/year. The monthly energy demands in this case study model are modeled in power curve that is 6,000 megawatt-hours in July and August, 3,000 megawatt-hours in June and September, and 2,250 kilowatt-hours in each of the other eight months. This approximation of the monthly distribution of the annual energy are decided in accordance with hydroelectric power rule curve as shown in Figure 7. The hydropower input data for Whitney Reservoir in this study is an efficiency factor of 0.86 and constant tailwater elevation of 448.8 feet above msl. In this research, Whitney Reservoir that has multiple owners in Brazos WAM is converted to a single reservoir system to operate hydropower operations well. Hydropower generation at Whitney Reservoir is initiated in Table 17 by applying UC, WR, WS, HP and PV/PE records in the WRAP system.

Table 17: Modeling Operation Rules in the WRAP System for Whitney Reservoir



```
UC  HYD1    2250    2250    2250    2250    2250    3000
UC          6000    6000    3000    2250    2250    2250

WR515731   36000    HYD188888888   6   1  1.0000                        WHITNYHP
WSWHITNY  636100                          387024
HP  0.86   448.8           11900     300

PVWHITNY   4270.  19600.  41710.  79990. 143200. 229400. 379100. 473100. 636100. 782000. 1095000 1473000 1999500 2100400
PE         448.8   470.0   480.0   490.0   500.0   510.0   520.0   527.0   533.0   540.0   550.0   560.0   571.0   573.0
```

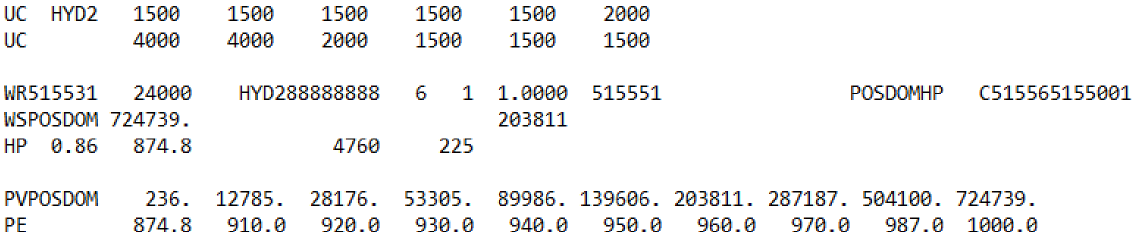
3.3.2 Possum Kingdom Hydropower Plant

The Possum Kingdom Hydroelectric Powerplant that is also known as Morris Sheppard Hydroelectric Powerplant is at Possum Kingdom Reservoir on the Brazos River, 11 miles southwest of Graford and 18 miles northeast from Mineral Wells. The Possum Kingdom Reservoir was built in March 1941, and power generation was started in April 1941. The powerhouse that is a concrete structure has a total capacity of 22,500 kw with two generators. The electricity was sold to the Brazos River Transmission Electric Cooperative for use in its service area. Table 87 in Appendix A illustrates the monthly hydropower generation in this power plant.

12-foot diameter penstocks carry water from Possum Kingdom Dam to two turbines. The generators that were furnished by General Electric Company are 11,250 KW, 3 phase, 60 cycle, 6,900-volt, and 171.4 rpm unit. The vertical turbines that were manufactured by Allis-Chalmers Company are Francis type 171.4 rpm unit, with a capacity of 17,000 hp. When turbines are not operating, water is controlled by a 54-inch valve that discharges water into the outlet conduit.

The energy target in this study for the Possum Kingdom Reservoir is 24,000 MWh/year. The monthly energy demands in this case study model are modeled in power curve that is 4,000 megawatt-hours in July and August, 2,000 megawatt-hours in June and September, and 1,500 megawatt-hours in each of the other eight months. This approximation of the monthly distribution of the annual energy are decided in accordance with hydroelectric power rule curve as shown in Figure 7. The hydropower input data for Possum Kingdom Reservoir in this study is an efficiency factor of 0.86 and constant tailwater elevation of 874.8 feet above msl. In this research, Possum Kingdom Reservoir is initiated into the Brazos WAM by applying previous generation records from the earlier study reported by TWDB (1968). Hydropower generation at Possum Kingdom Reservoir is initiated in Table 18 by applying UC, WR, WS, HP and PV/PE records in the WRAP system.

Table 18: Modeling Operation Rules in the WRAP System for Possum Kingdom



```
UC  HYD2   1500    1500    1500    1500    1500    2000
UC         4000    4000    2000    1500    1500    1500

WR515531   24000    HYD288888888   6   1  1.0000  515551                POSDOMHP   C515565155001
WSPOSDOM 724739.                          203811
HP  0.86   874.8            4760     225

PVPOSDOM    236.  12785.  28176.  53305.  89986. 139606. 203811. 287187. 504100. 724739.
PE         874.8   910.0   920.0   930.0   940.0   950.0   960.0   970.0   987.0  1000.0
```

3.4 Senate Bill 3 Environmental Flow Standards

In 2007, Senate Bill 3 (SB3) legalized by 80th Texas Legislature launched to the establishment of a new approach called to meet the needs of environment for sustainable flow conditions through the standards developed by Texas Commission on Environmental Quality (TCEQ). These standards are applied in prior-based water rights permit system in the WRAP modeling system without affecting the water rights prior to data of September 1, 2007. New water rights and water right amendments that are approved after the process of the establishment of environmental flow standards are impacted (Wurbs, 2019).

The process of the establishment of the environmental flow standards is the determination and satisfaction of the environmental needs for support of ecosystem, sustainable water availability, and productivity on habitat. Environmental flow standards for specific locations or regions are determined and defined in terms of the flow regime observed. The environmental flow standards were modeled in terms of flow regime that includes subsistence flows, base flows, within-bank high pulse flows, and overbank high pulse flows.

The Brazos River Basin and Bay Expert Science Team (BBEST) submitted its Environmental Flow Regime Recommendation Report to the Basin and Bay Area Stakeholders Committee (BBASC), Texas Commission on Environmental Quality (TCEQ), and Environmental Flow Advisory Group in March 2012. The BBASC submitted its Environmental Flow Standards and Strategies Recommendation Report to TCEQ in 2012. The BBASC proposed instream flow requirements in accordance with the views from the BBEST recommended flow regimes. The final environmental flow standards were adopted on February 2014 and published at Subchapter G of Chapter 298 of Title 30 of the Texas Administrative Code (Texas Water Code,2012).

The SB3 Environmental Flow Standards are developed at 19 stream gaging stations on the Brazos River and its tributaries. Figure 19 shows the locations of these gage stations on the map. Table 19 shows the WAM control point ID, stream, nearest city, and watershed area of these points in an order of upstream to downstream of the river.

Table 19: Brazos River Basin Control Point Locations for Senate Bill 3 Environmental Flow Standards

WAM CP ID	Stream	Nearest City	Watershed Area
SFAS06	Salt Fork Brazos River	Aspermont	2,504
DMAS09	Double Mountain Fork	Aspermont	1,891
BRSE11	Brazos River	Seymour	5,996
CFNU16	Clear Fork Brazos	Nugent	2,236
CFFG18	Clear Fork Brazos	Fort Griffin	4,031
BRSB23	Brazos River	South Bend	13,171
BRPP27	Brazos River	Palo Pinto	14,309
BRGR30	Brazos River	Glen Rose	16,320
NBCL36	North Bosque River	Clifton	977
BRWA41	Brazos River	Waco	20,065
LEGT47	Leon River	Gatesville	2,379
LAKE50	Lampasas River	Kempner	817
LRLR53	Little River	Little River	5,266
LRCA58	Little River	Cameron	7,100
BRBR59	Brazos River	Bryan	30,016
NAEA66	Navasota River	Easterly	936
BRHE68	Brazos River	Hempstead	34,374
BRRI70	Brazos River	Richmond	35,454
BRRO72	Brazos River	Rosharon	35,775

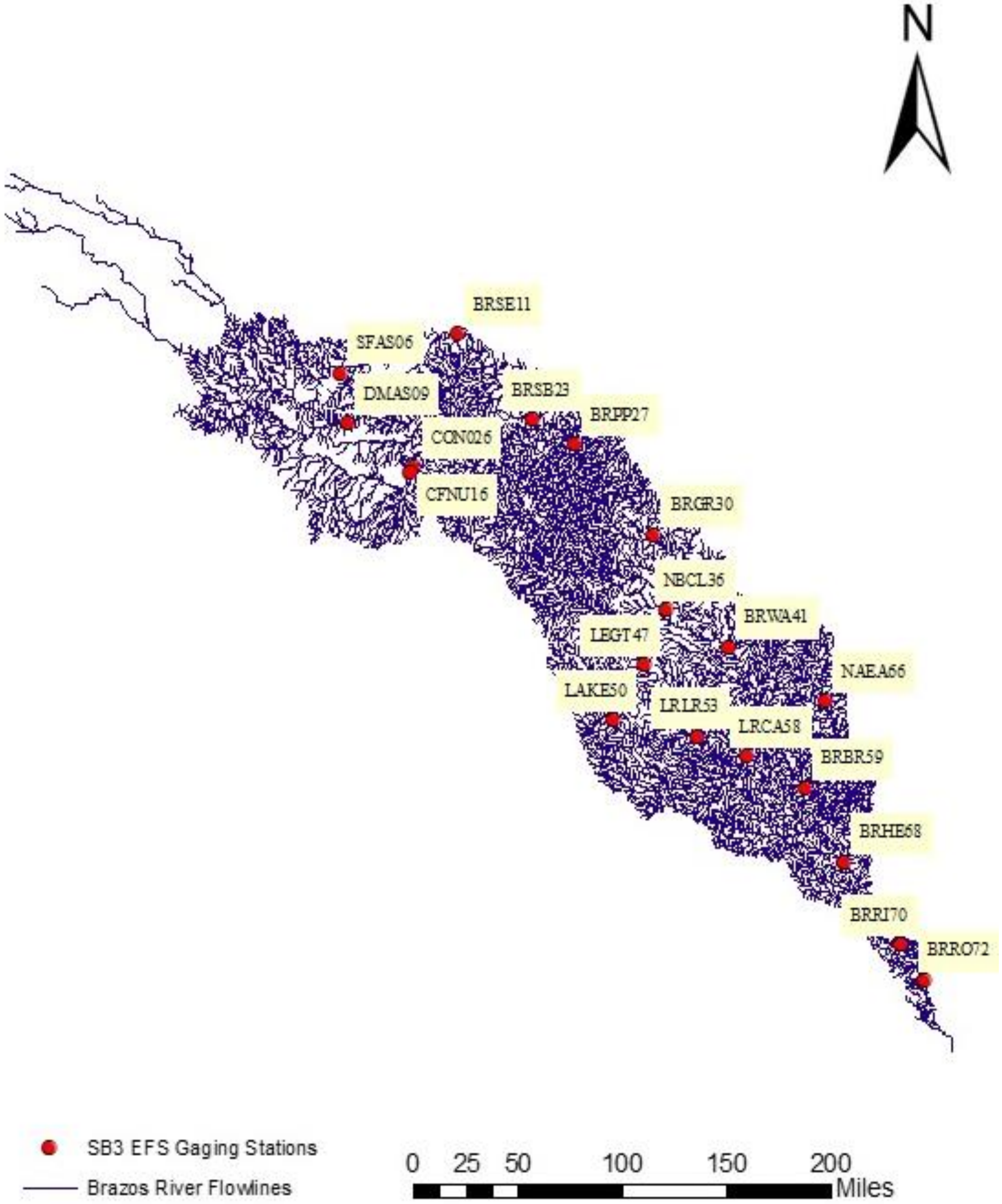


Figure 19: SB3 Environmental Flow Standards Gaging Stations

The environmental flow standards for the various river basin areas were published as Subchapters B through F of Chapter 298 of Title 30 of the Texas Administrative Code. The Senate Bill 3 Environmental Flow Standards for Brazos WAM are reached in *"Subsection G: Brazos River and its Associated Bay and Estuary System"* that became effective on March 2014. The environmental flow standards for the Brazos WAM were modeled in water availability modeling system in a priority date of March 1, 2012 (Wurbs, 2019).

The Texas Instream Flow Program (TIFP) focuses on environmental variables such as habitat, hydrology, biology, geomorphology, water quality, and stream system connectivity (Wurbs, 2014). The TIFP determines the environmental needs and necessary refinements in multidisciplinary collaboration, that is the main framework for flow standards. The environmental flow standards include metrics and rules that change depending on location, season, and hydrologic condition.

The standards are determined in terms of flow regimes that represent the magnitude, frequency, duration, timing, and rate of flow change. The framework of flow regime components is subsistence flows, base flows, within-bank flow pulses, and high-flow pulses. However; the WAM does not differentiate within-bank versus overbank high pulse flows, and there are no overbank pulse flows for the Brazos WAM. Seasons and hydrologic conditions for the Senate Bill 3 Environmental Flow Standards in the Brazos River Basin are defined in Table 20 and Table 21. The year is divided into three seasons, and hydrologic conditions are divided based on Palmer hydrologic drought index (PHDI).

Table 20: Months Included in Each Season

Season	Months
Winter	November, December, January, February
Spring	March, April, May, June
Summer	July, August, September, October

Table 21: Hydrologic Conditions Based on the Palmer Hydrologic Drought Index (PHDI)

Condition	Palmer Hydrologic Drought Index (PHDI)
Low (Dry)	PHDI within lowest 25% PHDI quartile
Medium (Average)	PHDI between 25th and 75th percentiles
High (Wet)	PHDI within highest 75% PHDI quartile

Flow limits for subsistence and base flow are illustrated in Table 22. Subsistence flow is listed in the second column while base flow limits are tabulated in functions of the season and hydrologic condition at next columns. The target of subsistence and base flows for a particular day is met depending on the framework as follows:

- Under average or wet conditions, the minimum environmental flow target is set as equal to the base flow for each gage station.
- Under dry conditions
    - If the flow is less than the subsistence flow, flow target is set equal to subsistence flow limit.
    - If the flow is at between subsistence flow limit and base flow limit, flow target is equal to the subsistence flow limit plus 50 percent of the difference between the actual flow and the subsistence flow limit.

Table 22: Subsistence and Base Flow Limits at 19 Control Points

Control Point	Subsist Flow (cfs)	Base Flows (cfs)								
		Winter			Spring			Summer		
		Dry	Avg	Wet	Dry	Avg	Wet	Dry	Avg	Wet
SFAS06	1	1	4	9	1	2	5	1	1	3
DMAS09	1	1	4	15	1	3	8	1	2	7
BRSE11	1	10	25	46	7	19	35	4	13	32
CFNU16	1	5	8	13	3	6	12	1	4	9
CFFG18	1	7	10	16	4	7	15	1	5	11
BRSB23	1	36	73	120	29	60	100	16	46	95
BRPP27	17	40	61	100	39	75	120	40	72	120
BRGR30	16	42	77	160	47	92	170	37	70	160
NBCL36	1	5	12	25	7	16	33	3	8	17
BRWA41	56	120	210	480	150	270	690	140	250	590
LEGT47	1	9	20	52	10	24	54	4	12	27
LAKE50	10	18	27	39	21	29	43	16	23	32
LRLR53	55	82	110	190	95	150	340	84	120	200
LRCA58	32	110	190	460	140	310	760	97	160	330
BRBR59	300	540	860	1,760	710	1,260	2,460	630	920	1,470
NAEA66	1	9	14	23	10	19	29	3	8	16
BRHE68	510	920	1,440	2,890	1,130	1,900	3,440	950	1,330	2,050
BRRI70	550	990	1,650	3,310	1,190	2,140	3,980	930	1,330	2,190
BRRO72	430	1,140	2,090	4,700	1,250	2,570	4,740	930	1,420	2,630

Flow limits for high flow pulse targets are tabulated in Tables 23-41. Following metrics are used to describe high flow pulse events:

- The trigger flow rates for high pulse events were defined in accordance with annual exceedance frequencies. In flow pulse events, the instream flow target for each day is the minimum of Q_p, the actual flow rate, or the remaining volume required for volume criterion.
- The frequency is the target number of pulse events with specified metrics.

- The volume that is the summation of the daily flow from the day event starts is criteria for termination of the tracking of high pulse event.
- The duration in days is criteria for termination of the tracking of high pulse event.

If the flow exceeds the peak trigger flow (Q_p), pulse event is initiated, and the event is terminated when the volume limit (Vol) or the duration limit (Dur) is reached. Pulse flow events are applied in specified season or year until meeting the volume or the duration criteria. The daily pulse flow target is computed as the minimum of the peak trigger volume, daily regulated flow or remaining volume that satisfy the volume criterion. In the Brazos River Basin, environmental flow standards have just in-bank pulse flow standards that are the same target-setting procedures for within-bank and overbank flows.

Table 23: High Flow Pulse Standards on the Control Point of SFAS06

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	-	-	-	-
Spring	dry	160	1	720	10
	average	160	2	720	10
	wet	300	1	1,350	11
Summer	dry	140	1	560	8
	average	140	2	560	8
	wet	260	1	1,090	10

Table 24: High Flow Pulse Standards on the Control Point of DMAS09

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	-	-	-	-
Spring	dry	280	1	1,270	10
	average	280	2	1,270	10
	wet	570	1	2,600	12
Summer	dry	230	1	990	9
	average	230	2	990	9
	wet	480	1	2,160	12

Table 25: High Flow Pulse Standards on the Control Point of BRSE11

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	-	-	-	-
Spring	dry	560	1	2,960	10
	average	560	2	2,960	10
	wet	1,040	1	5,870	12
Summer	dry	370	1	1,870	8
	average	370	2	1,870	8
	wet	800	1	4,290	11

Table 26: High Flow Pulse Standards on the Control Point of CFNU16

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	26	1	160	9
Spring	dry	180	1	860	9
	average	180	2	860	9
	wet	590	1	2,800	12
Summer	dry	100	1	460	8
	average	100	2	460	8
	wet	390	1	1,890	12

Table 27: High Flow Pulse Standards on the Control Point of BRSB23

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	-	-	-	-
Spring	dry	1,260	1	7,280	10
	average	1,260	2	7,280	10
	wet	2,480	1	15,700	13
Summer	dry	580	1	3,140	8
	average	580	2	3,140	8
	wet	1,180	1	7,050	11

Table 28: High Flow Pulse Standards on the Control Point of CON026

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	26	1	158	9
Spring	dry	18	1	74	2
	average	37	2	148	2
	wet	355	1	2,054	9
Summer	dry	18	1	74	2
	average	37	2	148	2
	wet	170	1	779	5

Table 29: High Flow Pulse Standards on the Control Point of BRPP27

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	930	2	3,690	5
	average	930	4	3,690	5
	average	1,390	2	7,180	7
	wet	850	2	3,690	5
	wet	1,390	3	7,180	7
Spring	dry	1,400	2	6,600	6
	average	1,400	4	6,600	6
	average	3,370	2	20,200	10
	wet	1,400	4	6,600	6
	wet	3,370	3	20,200	10
Summer	dry	1,230	2	5,920	6
	average	1,230	4	5,920	6
	average	2,260	2	13,000	9
	wet	1,230	4	5,920	6
	wet	2,260	3	13,000	9

Table 30: High Flow Pulse Standards on the Control Point of BRGR30

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	930	2	5,400	8
	average	930	4	5,400	8
	average	1,700	2	10,800	10
	wet	930	4	5,400	8
	wet	1,700	3	10,800	10
Spring	dry	2,350	2	14,300	10
	average	2,350	4	14,300	10
	average	6,480	2	46,700	14
	wet	2,350	4	14,300	10
	wet	6,480	3	46,700	14
Summer	dry	1,320	2	7,830	8
	average	1,320	4	5,920	6
	average	3,090	2	21,200	12
	wet	1,230	4	7,830	6
	wet	3,090	2	21,200	12

Table 31: High Flow Pulse Standards on the Control Point of NBCL36

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	120	2	750	10
Spring	dry	710	1	3,490	12
	average	710	3	3,490	12
	wet	710	3	3,490	12
Summer	dry	-	-	-	-
	average	-	-	-	-
	wet	130	2	500	6

Table 32: High Flow Pulse Standards on the Control Point of BRWA41

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	2,320	1	12,400	7
	average	2,320	3	12,400	7
	wet	2,320	2	12,400	9
Spring	dry	5,330	1	32,700	10
	average	5,330	3	32,700	10
	wet	13,600	2	102,000	14
Summer	dry	1,980	1	10,500	7
	average	1,980	3	10,500	7
	wet	4,160	2	26,400	10

Table 33: High Flow Pulse Standards on the Control Point of LEGT47

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	-	-	-	-
	average	-	-	-	-
	wet	100	2	540	6
Spring	dry	340	1	1,910	10
	average	340	3	1,910	10
	wet	630	2	4,050	13
Summer	dry	58	1	220	4
	average	58	3	220	4
	wet	140	2	600	6

Table 34: High Flow Pulse Standards on the Control Point of LAKE50

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	78	1	430	8
	average	78	3	430	8
	wet	190	2	1,150	11
Spring	dry	780	1	4,020	13
	average	780	3	4,020	13
	wet	1,310	2	6,860	16
Summer	dry	77	1	270	4
	average	77	3	270	4
	wet	190	2	680	6

Table 35: High Flow Pulse Standards on the Control Point of LRLR53

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	520	1	2,350	5
	average	520	3	2,350	5
	wet	1,600	2	11,800	11
Spring	dry	1,420	1	9,760	10
	average	1,420	3	9,760	10
	wet	3,290	2	32,200	17
Summer	dry	430	1	1,560	4
	average	430	3	1,560	4
	wet	1,060	2	5,890	8

Table 36: High Flow Pulse Standards on the Control Point of LRCA58

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	1,080	1	6,680	8
	average	1,080	3	6,680	8
	wet	2,140	2	14,900	10
Spring	dry	3,200	1	23,900	12
	average	3,200	3	23,900	12
	wet	4,790	2	38,400	14
Summer	dry	560	1	2,860	6
	average	560	3	2,860	6
	wet	990	2	5,550	8

Table 37: High Flow Pulse Standards on the Control Point of BRBR59

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	3,230	1	21,100	7
	average	3,230	3	21,100	7
	wet	5,570	2	41,900	10
Spring	dry	6,050	1	49,000	11
	average	6,050	3	49,000	11
	wet	10,400	2	97,000	14
Summer	dry	2,060	1	12,700	7
	average	2,060	3	12,700	7
	wet	2,990	2	20,100	8

Table 38: High Flow Pulse Standards on the Control Point of NAEA66

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	260	1	1,610	9
	average	260	3	1,610	9
	wet	800	2	5,440	12
Spring	dry	720	1	4,590	11
	average	720	3	4,590	11
	wet	1,340	2	8,990	13
Summer	dry	-	-	-	-
	average	-	-	-	-
	wet	49	2	220	5

Table 39: High Flow Pulse Standards on the Control Point of BRHE68

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	5,720	1	49,800	10
	average	5,720	3	49,800	10
	wet	11,200	2	125,000	15
Spring	dry	8,530	1	85,000	13
	average	8,530	3	85,000	13
	wet	16,800	2	219,000	19
Summer	dry	2,620	1	17,000	7
	average	2,620	3	17,000	7
	wet	5,090	2	40,900	9

Table 40: High Flow Pulse Standards on the Control Point of BRRI70

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	6,410	1	60,600	11
	average	6,410	3	60,600	11
	wet	12,400	2	150,000	16
Spring	dry	8,930	1	94,000	13
	average	8,930	3	94,000	13
	wet	16,300	2	215,000	19
Summer	dry	2,460	1	16,400	6
	average	2,460	3	16,400	6
	wet	5,430	2	46,300	10

Table 41: High Flow Pulse Standards on the Control Point of BRRO72

Season	Hydrologic Condition	Trigger (cfs)	Frequency	Volume (ac-ft)	Duration (days)
Winter	dry	9,090	1	94,700	12
	average	9,090	3	94,700	12
	wet	13,600	2	168,000	16
Spring	dry	6,580	1	58,500	10
	average	6,580	3	58,500	10
	wet	14,200	2	184,000	18
Summer	dry	2,490	1	14,900	6
	average	2,490	3	14,900	6
	wet	4,980	2	39,100	9

SB3 environmental flow standards are modeled in the WRAP modeling system by applying different records. WRAP User's Manual, Reference Manual, and Daily Manual explain the records to model instream flow requirements in the daily modeling and monthly modeling technically. In Brazos WAM, environmental flow standards were established in a priority date of March 1, 2012 by using IF, HC, ES, PF and PO records in daily time interval and IF and TS records in monthly time interval.

3.5 Water Supply Operations

The Brazos River Authority (BRA) operates its system reservoirs based on legal requirements, terms, and conditions of the water rights permit system. Reservoir releases are made from the reservoirs for water supply depending on the following constraints:

- drawdown limits defined in water right contracts
- terms and conditions of reservoir water rights and system operation permit
- provisions of system order
- provisions of excess flows permit
- interbasin transfers authorized under water rights and contractual arrangements

Minimum flow releases, excess water supply releases, reservoir leakage, flood releases, and hydropower generation results in undedicated releases in the BRA system. These releases are used to first to meet the downstream water demand. The BRA makes reservoir release decisions to provide for beneficial use of the water by considering environmental needs, local water supply needs, and recreational needs. The BRA determines the timing and amount of release depending on the location of the reservoir and the location of the customer. The BRA may make releases from one or more system reservoirs to meet water supply needs at downstream points. Municipal, industrial, and agricultural water supply rights in the BRA system are treated senior to hydropower and environmental flows rights.

The bed and banks of the Brazos River and its tributaries are used to deliver stored water to downstream customers. The BRA's releases to meet demands include sufficient water for the requested downstream diversion, plus the amount needed to cover estimated channel losses from the reservoir location to diversion location. Channel losses are calculated based on travel time and loss values for each stream segment in the basin.

CHAPTER IV

METHODOLOGY

4.1 General Concepts

The research applies the WRAP modeling system to evaluate impacts of hydropower, flood control, and environmental flows on each other that will be relevant to similar multiple-reservoir system operations in other river basin areas in Texas and elsewhere. This research also addresses the following issues: simulation of reservoir system operations, hydroelectric systems and operations, flood control operations, statistical and probability flood risk analysis methods, environmental flow standards, and implementation of instream flow requirements in modeling system. The flowchart of the study is presented in Figure 20.

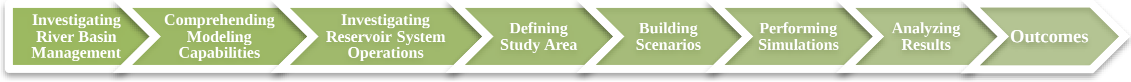


Figure 20: Flowchart of the Study

In this study, the river/reservoir system was operated to address following objectives:

- meeting minimum instream flow requirements,
- not exceeding flood flow limits at downstream points,
- generating hydropower to meet the energy demand,
- storing excess flows to mitigate flooding at downstream points.

While applying these objectives, interactions between hydropower, flood control, and environmental flows were observed in the river basin.

The simulation study is based on 1940-2017 hydrologic period of analysis by applying different water allocation scenarios. The daily and monthly Brazos WAM dataset developed from TCEQ recently was applied to simulate river and reservoir operations in the river basin area. This dataset was improved to make the river basin area compatible with real-time reservoir operations. Hydropower plants at two reservoirs were hypothetically assigned in the daily and monthly Brazos WAM dataset. Flood control operation rules in the daily dataset were modified to create scenarios in multiple-reservoir system operations. Senate Bill 3 environmental flow standards implemented in nineteen primary control points in original daily and monthly Brazos WAM dataset was used for this research.

General information about the hydropower generation at Whitney Reservoir and Possum Kingdom Reservoir was reviewed, and technical information about the turbines and generators was researched. Historically observed storage levels obtained from USGS in nine flood control pools were analyzed, and statistical and probability analyses for reservoir storage in these dams were developed. Observed storage levels in reservoirs were used in the scenarios to show the differences between real-time reservoir operations and river/reservoir modeling simulations by applying historical hydrology.

Reliability of hydropower water rights, firm energy generation, average energy generation, and mean energy shortage were compared to make quantitative analysis on different water allocation scenarios. Environmental flow standards were analyzed by developing statistical analyses for instream flow rights and pulse flow events, evaluating mean shortages and comparing results from daily and monthly modeling systems. For the flood control analyses, water storage levels in nine reservoirs, the number of days water existence in flood control pools, and the annual exceedance probabilities for flood control pools and stream gages were assessed. Differences between daily and monthly modeling systems for energy production and environmental flows were evaluated and discussed.

4.2 Flood Frequency Analyses

Flood frequency analysis is the method used by hydrologists to predict streamflow values and overtopping of the dam in terms of return periods and probabilities of the river and reservoir systems. Frequency analysis is applied to estimate probabilities of flood flows for planning, management, and modeling process in reservoir system management applications (Wurbs, 1996). Different types of flood frequency analysis methods are developed in hydrology to determine the operation rules for reservoir management and floodplain management issues. The available annual peak data for the past several years is used to calculate statistical information, such as mean, standard deviation, and skewness factor. After the results getting from statistical distribution methods, such as log-normal, log-Pearson III, Exponential, Weibull, and Gumbel, are analyzed, and the most appropriate one is selected to make necessary evaluations and develop the flood frequency curves.

Flood frequency analysis has a vital role in the estimation of recurrence of floods that are used for designing and planning of dams, bridges, culverts, levees, highways, sewages, industrial building, energy plants, and other hydraulics structures. Applying flood frequency analysis of river and reservoir systems enables to define optimum design parameters for hydraulic structures. Flood frequency curves help engineers and practitioners to design structures in safe conditions and develop a protection system against economic losses due to maintenance.

4.2.1 Basic Definitions

Annual exceedance probability and return period have a vital role to comprehend how flood frequency analysis works. The annual exceedance probability (P) is the probability that an event or a specified storage magnitude will be equaled or exceeded in any year. The recurrence interval or return period (T) is the mean interval, in years, between the flood occurrence that equals or exceeds a specified storage magnitude or an event. The recurrence interval (T) and exceedance probability (P) are reciprocals each other.

$$T = \frac{1}{P} \quad \text{or} \quad P = \frac{1}{T}$$

The risk (R) is the probability that an event or specified storage magnitude will be exceeded or exceeded in a series of N years.

$$R = 1 - (1 - P)^{N}$$

4.2.2 Probability Distribution Functions

4.2.2.1 Log-Normal Distributions

The normal distribution, that is also called the Gaussian distribution, express the distribution in terms of mean and standard deviation that are the parameters estimated from observed data. The normal distribution has a bell-shaped density curve that is symmetrical to the mean. The general formulation of the normal distribution is expressed as;

$$X = \mu + K\,\sigma$$

where μ and σ are the mean and standard deviation of random variable X, and K is the standard variant from the normal distribution table.

The log-Normal probability distribution is a logarithmic transformation of normal distribution. The random variable of X is transferred logarithm, and normal distribution is applied to eliminate the outlier effects on the calculations. Also, standard deviation (σ) and mean (μ) are also transferred to the logarithm, and K is defined from the normal distribution table again. The general formulation of the log-normal distribution is expressed as;

$$\log X = \mu_{\log X} + K\,\sigma_{\log X}$$

4.2.2.2 Log-Pearson Type III Distributions

The log-Pearson type III distribution, that is also called as Pearson type III distribution, express the distribution in terms of skew coefficient in addition to the mean and standard deviation. The frequency factor of K is obtained from the Pearson type III distribution table. The mean, standard deviation and skew coefficient (G) are calculated from observed annual peak flow or reservoir storage. Due to the sensitiveness of the skew coefficient to sample size, the adequate sample size should be used to perform accurate probability results. When skew coefficient (G) is equal to zero, the log-Pearson type III distribution become the log-normal distribution. The log-Pearson type III is applied by the federal water agencies for flood frequency analyses.

4.2.2.3 Expected Probabilities and Confidence Limits

The guidelines to use these distribution methods developed by the Hydrology Committee of the former U.S. Water Resources Council are provided in Bulletin 17B that provides more accurate and complete K table (Wurbs, 1996). Bulletin 17B techniques were developed for annual maximum flows and integrated with log-Pearson type III distribution. HEC-SSP that was developed by U.S. Corps of Engineers is used to compute expected probability and confidence limits for flood frequency analyses. The expected probability is calculated by averaging of all magnitude estimations for any flood frequency analyses from true samples. In other words, the expected probability is the value at the center of the confidence limits.

HEC-SSP has also capabilities to define confidence limits for any level or percentage. Default lower and upper levels for confidence limits are 5% and 95% respectively. In accordance with the size of samples, the magnitude of confidence limits can vary. Small sample size provides higher confidence limits while large sample size provides lower confidence limits. Confidence limits are calculated by applying the following equations in Bulletin 17B.

4.3 Reliability Analyses

Reliability is the percentage of total target demand that is supplied. It is useful to analyze and display the results of the water availability. Program TABLES allows organizing simulation results by inputting different records. Water supply diversion rights, hydropower generation rights, and the aggregation of reservoir storage and control points can be analyzed in terms of reliability. TABLES computes period and volume reliabilities for pertinent water rights.

4.3.1 Volume Reliabilities

Volume reliability is the percentage of the total target amount that is actually supplied. The target amount is a volume for water supply diversions while kilowatt-hours of energy generated is the target amount for hydropower. Volume reliability (R_V) is the ratio of the volume of water supplied or the energy produced (v) to the target (V), converted to a percentage.

$$\mathrm{Rv} = \frac{\mathrm{v}}{\mathrm{V}}\ (100\%)$$

R_V is also the mean actual diversion rate as a percentage of the mean target diversion rate and mean actual rate of energy production for water supply and hydropower respectively.

4.3.2 Period Reliabilities

Period reliability is based on counting the number of periods of the simulation during which the specified demand target is either fully supplied or a specified percentage of the target is equaled or exceeded. A reliability summary is tabulated in terms of the percentage of months and the percentage of years during the simulation which either water supply diversions or hydroelectric energy produced equaled or exceeded specified magnitudes expressed as a percentage of the target demand.

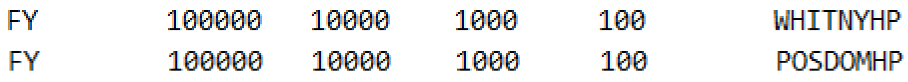
$$\mathrm{Rp} = \frac{\mathrm{n}}{\mathrm{N}}\ (100\%)$$

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

4.4 Firm Yield

The firm yield is the maximum water supply diversion or hydroelectricity generation that can be provided with 100 percent of the volume and period reliability. The firm yield activated by the FY record is determined by iteratively adjusting a target amount until the diversion or energy target meeting the 100 percent reliability. The reliabilities calculated by FY record are based on the volume and period reliability equation. The yield-reliability table for diversion and hydropower rights is written to YRO table.

The firm energy generation for Whitney Reservoir and Possum Kingdom Reservoir is computed on the WRAP modeling system by inputting FY records separately in each simulation as following:



```
FY        100000   10000    1000     100          WHITNYHP
FY        100000   10000    1000     100          POSDOMHP
```

The iterative simulation starts with target amount in field 2. It is decreased by field 3 in each subsequent level iteration until either no shortages occur or the target amount is decreased to zero. The computations proceed to next level by decreasing target in each iteration based on the value in field 4 until no shortages occur. Same processes are applied by the modeling system to reach the final value. The final value is written to YRO file as firm yield. Depending on the target amount of water supply diversion and hydropower different values are inputted to get firm yield quickly. Firm yield is computed for just one water right in one simulation.

4.5 WRAP Modeling System

The general information about the WRAP modeling system was explained in Chapter I. The progress followed and modeling functions used in this thesis are explained in this section. The scenarios of daily and monthly time interval are performed with Brazos WAM dataset and historical hydrology file for the basin area. The Texas WAM system is efficiently modelled based on monthly computational time interval. However; the needs of daily time interval in computations emerged to model environmental flows standards accurately and make reservoir operations for flood control effectively. Daily modeling system enables environmental flow standards that vary by location, season, and hydrologic condition to be modeled appropriately and reservoirs to operate for storing and releasing excess flows systematically. It also provides to deal with continuously changing variables and track high pulse flow events.

Streamflow depletions for water supply and refilling reservoirs storage, reservoir releases, and return flows propagate stream flow at downstream points. The flow changes occur through river are not modeled in the monthly version of WRAP modeling system, and it is assumed to propagate river system at outlet point. The daily simulation model includes flow routing option to make lag and attenuation adjustments to the flow changes in simulation in order to reflect real-time water variations well. Also, flow forecasting option is designed to mitigate the effects of flow routing on the modeling system and flood control operations.

Flow routing parameters are defined on RT records in the DIF file. This file is inputted to the daily SIMD simulation. The routing parameters are applied in each time step of simulation. Routing parameters are determined for river reaches defined by stream gages in terms of travel time and effects of attenuation. Routing occurs between two control points. Routing is not a major concern in simulations since reasonable results can also be obtained without applying routing. Flow routing improves the accuracy of the system even if it has minimal effects on the simulation results.

Flow forecasting option in the daily modeling system is applied only if routing option is activated. Forecasting is applied in the simulations to deal with effects of water and instream rights on downstream flows in future time steps. Flow is mainly used for two purposes: (1) protecting water rights from the flow routing effects associated with stream flow depletions, (2) facilitating reservoir flood control operations to prevent flooding in future time steps. The process SIMD follows for flow forecasting is shown in Figure 21. Forecasting is opened in simulation model inputting parameters in JU record. The activation field and forecast period is inputted in necessary fields. In this research, 10-day forecasting is applied in the simulations.

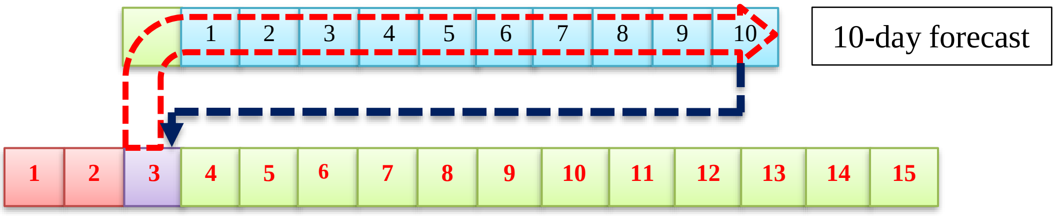


Figure 21: Conceptual Demonstration of Flow Forecasting

Figure 22 illustrates the three steps of the daily simulation. The file formats are explained in Table 42.

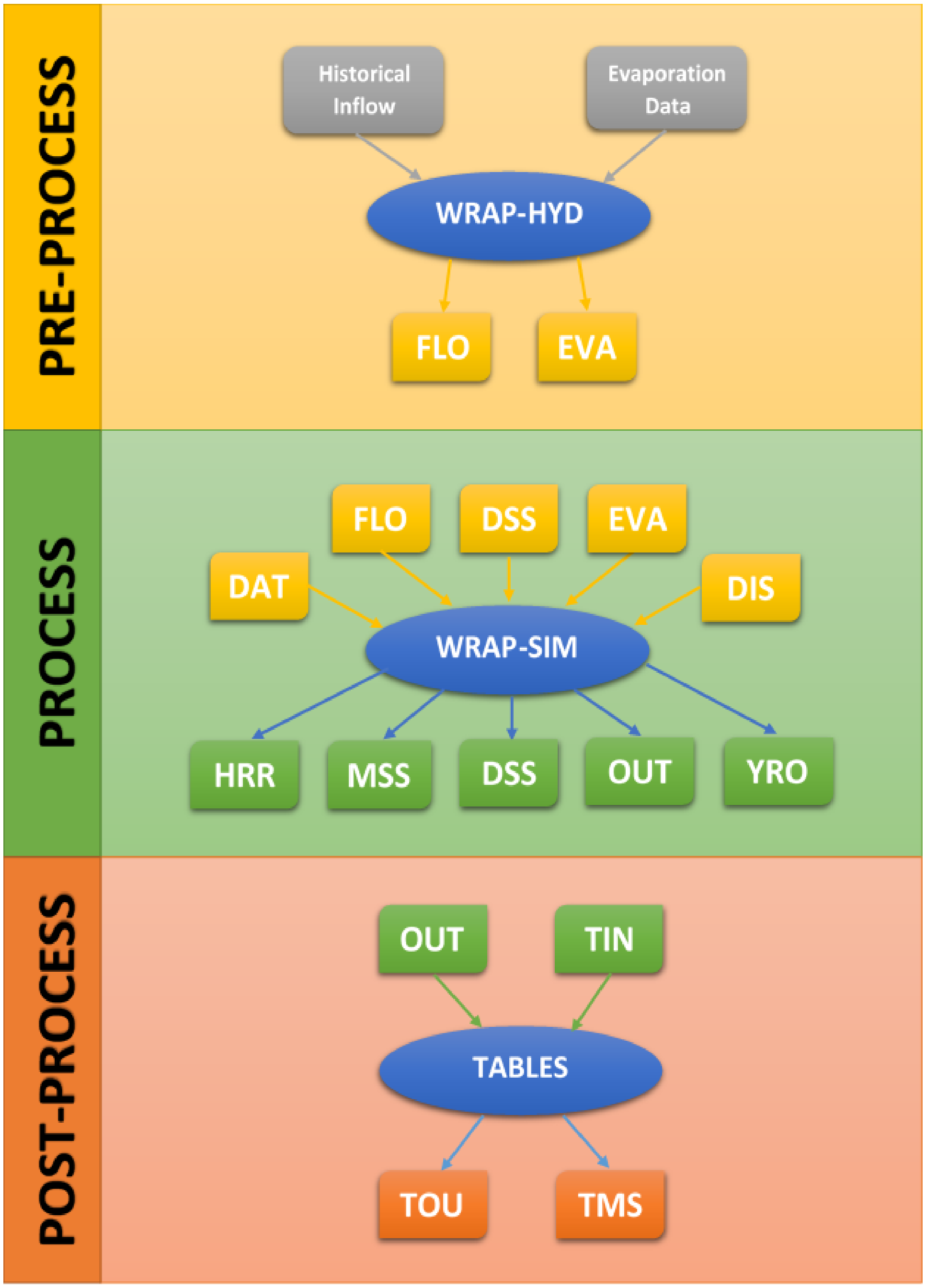


Figure 22: The Monthly Simulation Process in the WRAP Modeling System

Figure 23 illustrates the three steps of the monthly simulation. The file formats are explained in Table 42.

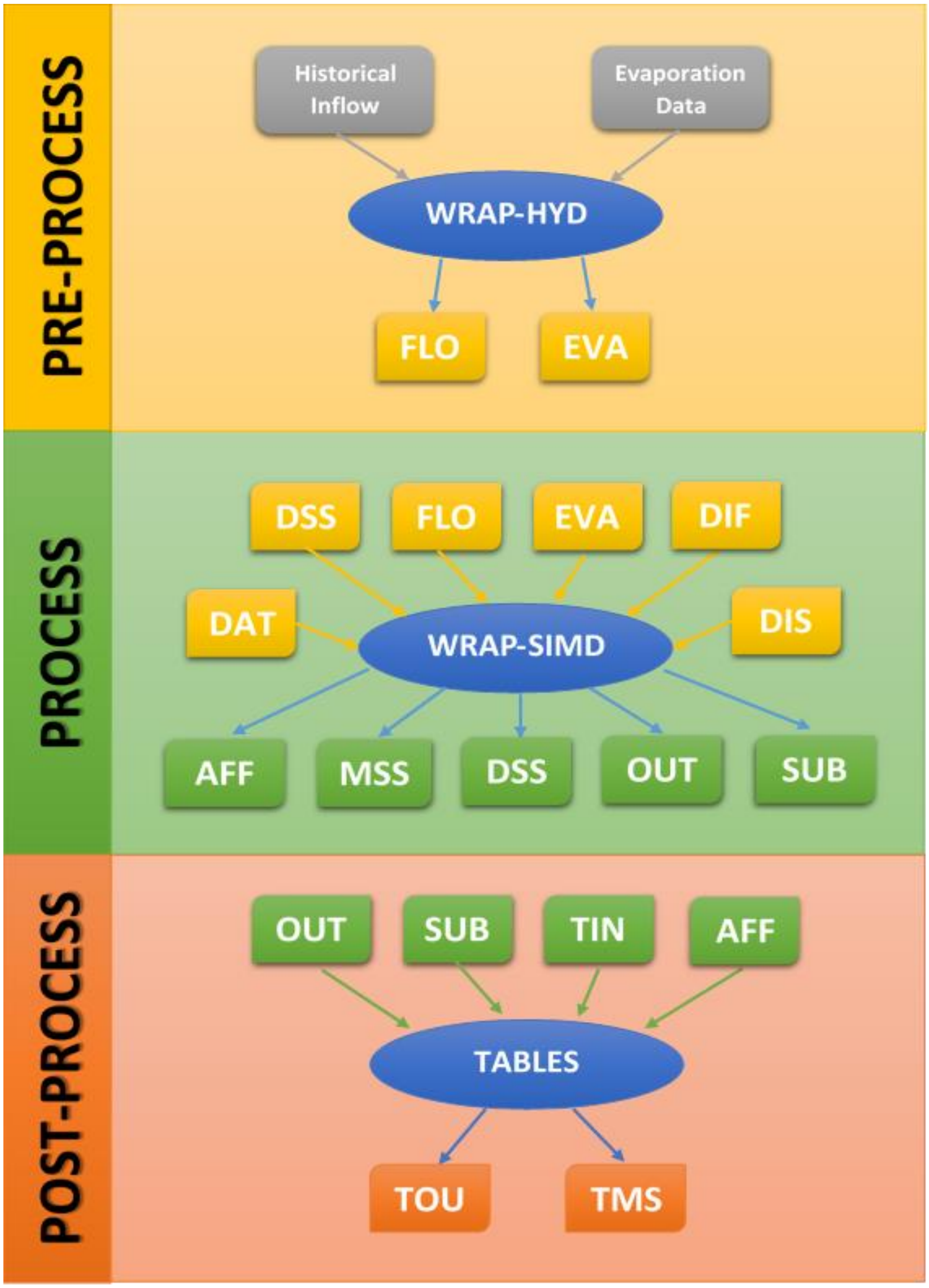


Figure 23: The Daily Simulation Process in the WRAP Modeling System

Table 42: Details of Input and Output Files of the WRAP Modeling System

File Name	File Function	WRAP Programs			
		HYD	SIM	SIMD	TABLES
AFF	Annual Flood Frequency	-	-	output	input
DAT	Main Input File	-	input	input	-
DIF	Daily Input File (Flow Routing)	-	-	input	-
DIS	Flow Distribution Parameters	input	input	input	-
DSS	Flow and Evaporation Data	in & out	input	input	-
EVA	Net Evaporation Data	in & out	input	input	-
FLO	Naturalized Flows	in & out	input	input	-
HRR	Hydropower and Reservoir Releases	-	output	output	input
MSS	Message File	-	output	output	-
OUT	Main Output File	input	output	output	input
SUB	Sub-Monthly Time Step Output File	-	-	output	input
TIN	TABLES Input File	-	-	-	input
TMS	TABLES Message File	-	-	-	output
TOU	TABLES Main Output File	-	-	-	output
YRO	Yield Reliability Output	-	output	output	-

4.6 Auxiliary Software

The HEC-DSS Visual Utility Engine (HEC,2009) and the HEC-SSP Statistical Software Package (HEC, 2009) available from Hydrologic Engineering Center (HEC) of U.S. Army Corps of Engineering were used to monitor the results from different water allocation scenarios. The HEC-DSS was used to display water storage levels at reservoirs and naturalized, regulated, and unappropriated flows at control points obtained from WRAP simulations. To perform frequency analyses for overtopping flood control pool, log-Normal and log-Pearson type III probability distributions were performed in HEC-SSP and TABLES in WRAP Software.

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

USACE Hydrologic Engineering Center developed the Statistical Software Package (HEC-SSP) to perform statistical analyses of hydrologic data. It can perform flood flow frequency analyses based on Bulletin 17B, generalized frequency analysis on flow data, volume frequency analysis, duration analysis, coincident frequency analysis, and curve combination analysis (HEC, 2010).

HEC-SSP is an integrated system that consists of a graphical user interface, separate statistical analysis components, data storage, and management capabilities, mapping, graphics, and reporting tools. The objective of HEC-SSP unifies all of the statistical analysis capabilities of other analysis software that were developed before, such as HEC-FFA, STATS, REGFRQ and MLRP. In accordance with necessity on statistical analyses, new features and capabilities are added to the HEC-SSP.

The HEC-SSP software package provides engineers and hydrologists with a lot of ways 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 HEC-SSP from HEC-DSS by converting regular reservoir storage data to irregular data. Available data for frequency analysis is performed in different probability distribution methods. In this research, log-normal distribution and log-Pearson type III distribution were used in analyses. By applying HEC-SSP, flood frequency curve for observed reservoir storage were plotted with confidence limits of 5% and 95%, computed curves and expected probability curves in these two distributions.

4.6.2 Hydrologic Engineering Center Data Storage System (HEC-DSS)

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) has developed a suite of generalized hydrologic, hydraulic, and water management simulation models that are applied extensively by numerous agencies and consulting firms throughout the United States and abroad. The HEC-DSS (Data Storage System) is used routinely with HEC simulation models and with other non-HEC modeling systems as well. Multiple simulation models share the same graphics and data management software as well as a set of basic statistical and arithmetic routines. Data can be conveniently transported between Microsoft Excel and HEC-DSS.

4.6.3 TABLES Organization of Simulation Results

TABLES that is a program of WRAP modeling system develops frequency and reliability analyses and various user-defined tables to summarize and display simulation results. It provides a comprehensive array of tables and tabulations to summarize the output from SIM and SIMD. TIN file is created by the user to define computational options for developing tables of water supply, flow, and storage indices. The results in TOU file consists of tabulations user identified is an output of simulation results and TIN file. These tables can be exported to Microsoft Excel and HEC-DSSVue.

4.7 Water Allocation Scenarios

The main objective of this study to assess the impacts of hydropower generation, flood control operations, and environmental flow standards on each other in a reservoir system rules. Brazos WAM dataset was modeled in the WRAP modeling system and performed in daily and monthly computational time interval. Fourteen alternative water allocation scenarios were formulated to enhance understanding on tradeoffs between water operations. The hydrologic period-of-analysis was made from 1940 to 2017 in daily and monthly time step simulations. Water supply operations are treated senior to hydropower rights, flood control rights, and environmental flow rights in all scenarios. Any modifications are not made for municipal, industrial, and agricultural water supply on the original Brazos WAM dataset. Alternative simulation runs, as shown in Table 43, include ten daily time interval scenarios and four monthly time interval scenarios.

Table 43: Formulated Scenarios

Scenario Code	PRIORITY		Flood Control Operations	Energy Target (MW/year)	Time Step	Lag Routing	Flow Forecasting
	Hydropower	SB3 EFS					
M1	88888888	NO	--	60,000	Monthly	NO	NO
M2	88888888	20120301	--	60,000	Monthly	NO	NO
M3	NO	20120301	--	--	Monthly	NO	NO
M4	88888888	20120301	--	90,000	Monthly	NO	NO
D1	88888888	NO	--	60,000	Daily	YES	NO
D2	88888888	20120301	--	60,000	Daily	YES	NO
D3	NO	20120301	--	--	Daily	YES	NO
D4	88888888	20120301	--	90,000	Daily	YES	NO
D5	NO	20120301	RANK	--	Daily	YES	10
D6	88888888	20120301	RANK	60,000	Daily	YES	10
D7	88888888	20120301	PRIORITY	60,000	Daily	YES	10
D8	88888888	20120301	PRI+RANK	60,000	Daily	YES	10
D9	88888888	20120301	RANK	90,000	Daily	YES	10
D10	88888888	NO	RANK	60,000	Daily	YES	10

Scenario M1: Simulation M1 was performed in monthly time step by performing hypothetically assigned hydropower operations in a priority of 88888888 as total energy target is 60,000 MWh/year. Flood control operations and environmental flow standards were not implemented. Lag routing and flow forecasting options were not applied. This scenario was performed in two cases: (A) permitting diversions for existence water rights from the reservoirs in which energy generated, (B) disallowing diversions except for hydropower in the reservoirs in which energy generated. These scenarios were named M1A and M1B in the results.

Scenario M2: Simulation M2 was performed in monthly time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 60,000 MWh/year. Flood control operations were not implemented. Lag routing and flow forecasting options were not applied. This scenario was performed in two cases: (A) permitting diversions for existence water rights from the reservoirs in which energy generated, (A) disallowing diversions except for hydropower in the reservoirs in which energy generated. These scenarios were named M2A and M2B in the results.

Scenario M3: Simulation M3 was performed in monthly time step by performing environmental flow standards in a priority of 20120301. Hydropower operations and flood control operations were not implemented. Lag routing and flow forecasting options were not applied.

Scenario M4: Simulation M4 was performed in monthly time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 90,000 MWh/year. Flood control operations were not implemented. Lag routing and flow forecasting options were not applied.

Scenario D1: Simulation D1 was performed in daily time step by performing hypothetically assigned hydropower operations in a priority of 88888888 as total energy target is 60,000 MWh/year. Flood control operations and environmental flow standards were not implemented. Whilst lag routing option was used, flow forecasting was not applied.

Scenario D2: Simulation D2 was performed in daily time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 60,000 MWh/year. Flood control operations were not implemented. Whilst lag routing option was used, flow forecasting was not applied.

Scenario D3: Simulation D3 was performed in daily time step by performing environmental flow standards in a priority of 20120301. Hydropower operations and flood control operations were not implemented. Whilst lag routing option was used, flow forecasting was not applied.

Scenario D4: Simulation D4 was performed in monthly time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 90,000 MWh/year. Flood control operations were not implemented. Whilst lag routing option was used, flow forecasting was not applied.

Scenario D5: Simulation D5 was performed in daily time step by performing environmental flow standards in a priority of 20120301 without any hydropower operations. Multiple reservoir system operations were applied by assigning storage priority of 91000000 and release priority of 9200000000 for nine flood control reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

Scenario D6: Simulation D6 was performed in daily time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 60,000 MWh/year. Multiple reservoir system operations were applied by assigning storage priority of 91000000 and release priority of 9200000000 for nine flood control reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

Scenario D7: Simulation D7 was performed in daily time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 60,000 MWh/year. Flood control operations were implemented by assigning different priorities for gage closure and releases depending on the capacity of the reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

Scenario D8: Simulation D8 was performed in daily time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 60,000 MWh/year. Flood control operations in Whitney Reservoir were implemented by assigning storage priority of 70000000 and release priority of 99999999. Multiple reservoir system operations were applied by assigning storage priority of 91000000 and release priority of 9200000000 for rest of flood control reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

Scenario D9: Simulation D9 was performed in daily time step by performing environmental flow standards in a priority of 20120301 and hypothetically assigned hydropower operations in a priority of 88888888. Total energy target is 90,000 MWh/year. Multiple reservoir system operations were applied by assigning storage priority of 91000000 and release priority of 9200000000 for nine flood control reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

Scenario D10: Simulation D10 was performed in daily time step by performing hypothetically assigned hydropower operations in a priority of 88888888. SBS environmental flow standards were not implemented. Total energy target is 60,000 MWh/year. Multiple reservoir system operations were applied by assigning storage priority of 91000000 and release priority of 9200000000 for nine flood control reservoirs. Lag routing option and 10-day flow forecasting were applied in this scenario.

CHAPTER V

RESULTS AND EVALUATIONS

The fourteen alternative scenarios were performed on the daily and monthly versions of the WRAP modeling system to evaluate the interactions between hydropower generation, flood control operations, and environmental flow standards for the case study area of Brazos River Basin. In chapter IV, the details of the scenarios were described. This chapter assesses the simulation results in four sections. Hydropower generation, environmental flow standards, and flood control were examined in a framework respectively. While simulations for hydropower operations and environmental flow standards were performed at monthly and daily versions of the modeling system, flood control operations were analyzed at only daily modeling system due to capability of the WRAP modeling system.

Hydropower generation was analyzed to quantify the impacts of environmental flow standards and flood control operations on electricity generation. Environmental flow standards were evaluated to explain the effects of reservoir operations for hydropower generation and flood control on base flow targets and pulse flow events at pertinent control points. Performance of flood control operations was examined to illustrate the impacts of hydropower generation and instream flow requirements on the risk of overtopping the dam, the number of days water in flood control pools, the risk of exceeding maximum allowable flow limits at downstream points, and the number of days flow exceeds or equals maximum allowable flow limits. Finally, comparative analysis between the daily and monthly versions of the WRAP modeling system was made to reveal the differences between river and reservoir system operations on different time intervals. This section compares the results of daily and monthly modeling systems for modeling of hydropower generation and environmental flow standards in the river system.

Observed reservoir storages at flood control reservoirs and observed stream flow at interested stream gages obtained from USGS were used in the simulations to compare real-world river/reservoir system operations and simulated river/reservoir system operations. Scenarios were compared based on reliability analyses, storage level of reservoirs, frequency metrics of regulated flows, and return period of flood events. HEC-DSS and HEC-SSP software were used to calculate statistics for flood events.

5.1 Evaluations of Hydropower Generation on River/Reservoir System

Hypothetically assigned hydropower generation was simulated on the daily and monthly versions of the WRAP modeling system to evaluate impacts of flood control operations and river system environmental policies. Simulation results revealed insights of impacts of multiple purpose river basin management and modeling strategies on hydropower productivity. Outline of hydropower analyses is:

- impacts of environmental flows on hydropower generation,
- impacts of flood control operations on hydropower generation,

Analyses to illustrate the variations on hydropower reliability in the multiple purpose river system were made to define optimal modeling strategies for energy generation by formulating different scenarios. In this section, M1, M2, D1, D2, D6, D7, and D8 scenarios that focus on analyzing tradeoffs between water for hydropower, water for the environment in regulated rivers, and flood control operations were performed. Likelihood examination of the water tradeoffs between selected scenarios, reliability metric of energy generation, firm energy yield, and total electricity generation through stream river were discussed.

5.1.1 Impacts of Environmental Flow Standards on Hydropower Generation

Senate Bill 3 Environmental Flow Standards are treated in the water allocation system as being junior to other water rights that were permitted with earlier priority dates. Therefore, water rights in the river system modeling system affect instream flow rights to curtail degree to water availability. However, hydropower rights in modeling system were defined as being junior to all water rights and instream flow rights with a priority of 88888888, which enables river/reservoir system to generate power by releasing water through penstock of the dam to meet diversion and environmental needs. Energy generation is made by releases from the dams to meet the demand for water rights and environmental flow rights first in priority-system, and then rest of the energy target is generated when hydropower right is processed. Depending on senior water diversions and available water storage in the dams, energy target can be met or curtailed. As expected, daily and monthly unappropriated flows frequency decrease once environmental flow standards are incorporated in the modeling system, which means that water availability through river system decreases. Besides the reduction of water availability, one of the main conclusions drawn from reliability analyses is that water diversion for hydroelectricity is also curtailed.

The impacts of environmental flow standards on hypothetically assigned hydropower generation in the case study area were required to evaluate in two different scenarios: (I) simulation that does not include environmental flow standards and (II) simulations including environmental flow standards. In addition to that, for the scenarios in monthly modeling system, two cases were identified to assess tradeoffs between water usages well: (A) permitting all water diversions from hydropower reservoirs and (B) disallowing water diversions from the dams except for hydropower and environmental flow standards. These cases were applied for the scenarios of M1 and M2 in scenario codes of M1A, M1B, M2A, and M2B.

5.1.1.1 Comparison of Monthly Scenarios – Case A

The scenario of M1A in which environmental flow standards are not included was compared with the scenario of M2A that includes environmental flow standards with a priority of 20120301. The main concern of this comparison was determining the relative change on hydropower generation due to environmental flow standards that have senior priority. These scenarios were performed by applying historically hydrologic data at the period between 1940 and 2017. The simulations based on each scenario begin with all reservoir storages equal to full capacities. Energy shortages, firm energy generations, mean energy generations, reliability of hydropower rights, reservoir releases, inflow taken by streamflow, and frequency of reservoir storages were examined with both scenarios. Table 44 shows the hydropower generation in reservoirs for the scenarios of M1 and M2.

Table 44: Comparison of Reliability of Hydropower for the Scenarios M1A and M2A

Reservoir ID	Energy Target (MWh-year)	Scenario M1A Mean Shortage (MWh-year)	Scenario M1A Reliability Period (%)	Scenario M1A Reliability Volume (%)	Scenario M2A Mean Shortage (MWh-year)	Scenario M2A Reliability Period (%)	Scenario M2A Reliability Volume (%)
POSDOM	24,000	594	96.69	97.53	594	96.69	97.53
WHITNY	36,000	6,871	73.40	80.92	7,349	70.94	79.59
TOTAL	60,000	7,464		87.56	7,943		86.76

As the results of scenario M1A and M2A, total reliability for energy generation in the Brazos River Basin declined from 87.56% to 86.76%. Energy generation shortage increased from 7,464 MWh/year to 7,943 MWh/year during the period of 1940-2017 in Whitney Reservoir due to environmental flow needs. However, hydroelectricity shortage remained the same shortage as 594 MWh/year in Possum Kingdom Reservoir once environmental flow standards were implemented in the priority system. This is possible that hydropower generation at reservoir and water supply for environmental flow standards were processed concurrently by the same releases. Firm and total energy generation in reservoirs for both reservoirs were also tabulated in Table 45.

Table 45: Comparison of Hydropower Generation for the Scenarios M1A and M2A

Scenario	Whitney Firm Energy (MWh-year)	Whitney Total Energy (MWh-year)	Possum Kingdom Firm Energy (MWh-year)	Possum Kingdom Total Energy (MWh-year)
M1A	8,890	40,883	0	34,979
M2A	8,730	40,017	0	34,979

Concerning comparisons between hydropower plants, the change on water availability through river basin area caused mean hydropower production and the firm energy through the 78 years period to decrease slightly on Whitney Reservoir. Similar to the reliability of hydropower right, total energy generation in the Possum Kingdom was not affected by environmental flow standards while the firm energy for Possum Kingdom Reservoir was not computed due to drawn downs on the reservoir storage. This is possible in this reservoir that water supply releases for the existence of water rights are enough to meet instream flow requirements at downstream points.

Annual hydroelectricity generation through the 78 years period and mean monthly generation in hydropower plants were illustrated. As shown in Figures 24-27, straight blue line and dashed red line represent the scenarios M1A and M2A respectively while the green line shows the monthly energy target in plants. Even if there were fluctuations over the period in meeting energy demand for Whitney Reservoir, hydropower target was always provided in Possum Kingdom Reservoir except for last five years at which reservoir storage has stayed minimum water level and electricity was not generated based on operation rules.

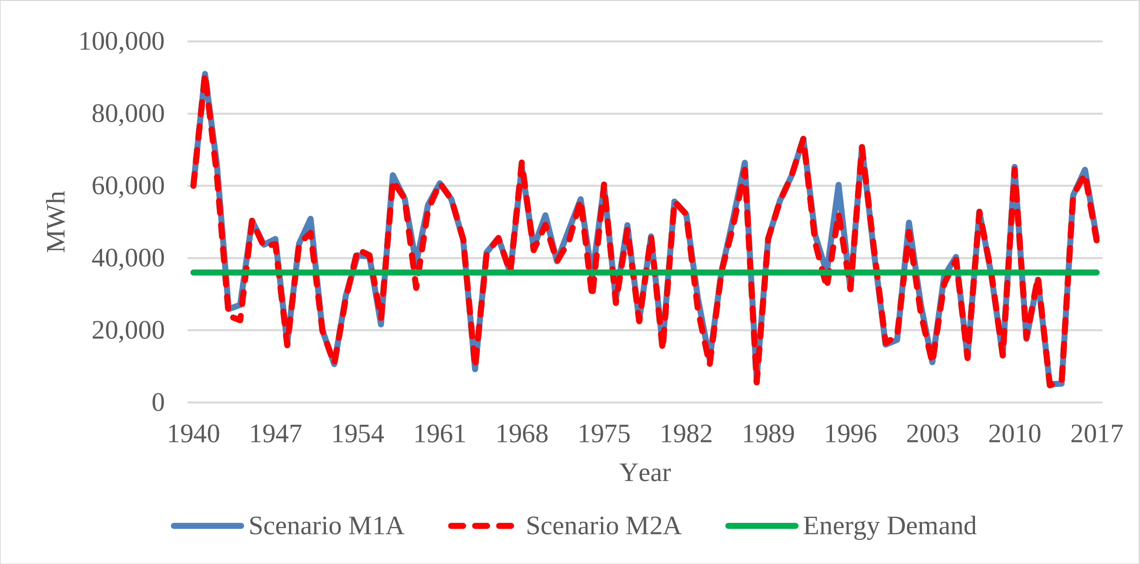


Figure 24: Comparison of Hydropower Generation over the period between 1940 and 2017 in Whitney Hydropower Plant for the Scenarios M1A and M2A

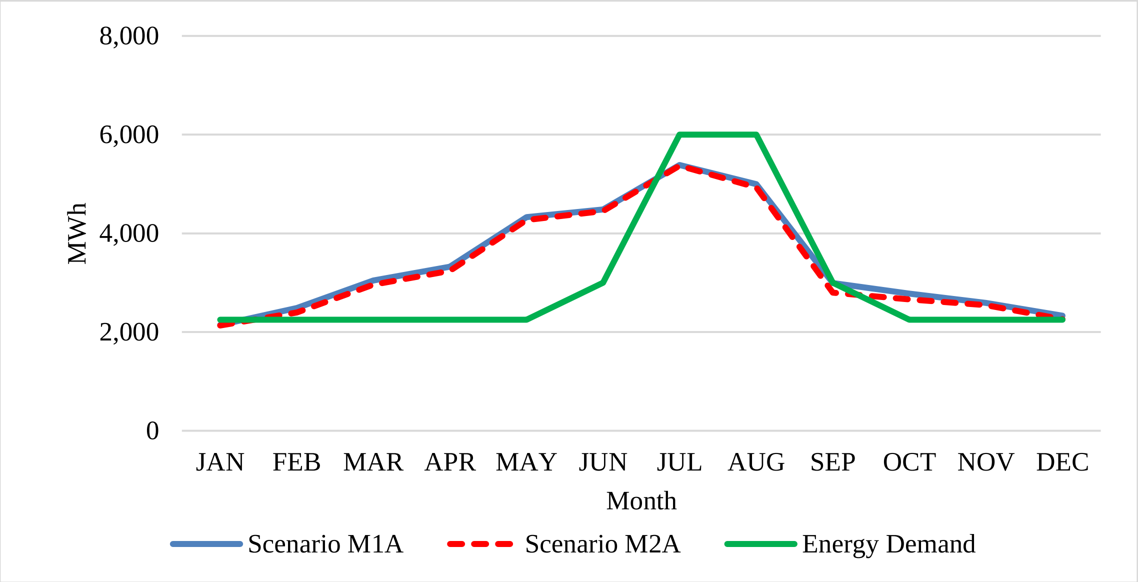


Figure 25: Comparison of Mean Monthly Hydropower Generation in Whitney Hydropower Plant for the Scenarios M1A and M2A

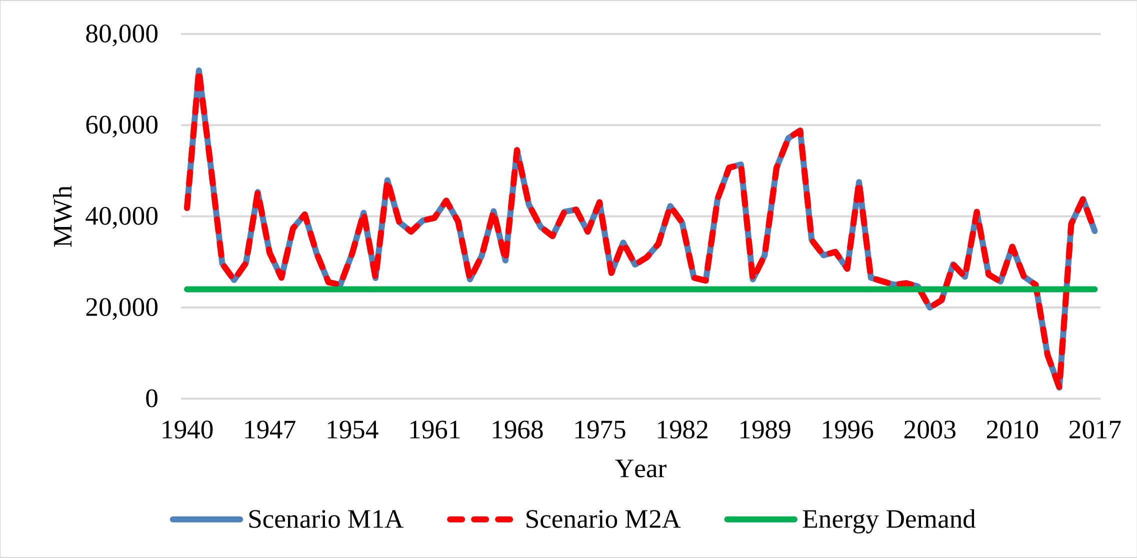


Figure 26: Comparison of Hydropower Generation over the period between 1940 and 2017 in Possum Kingdom Hydropower Plant for the Scenarios M1A and M2A

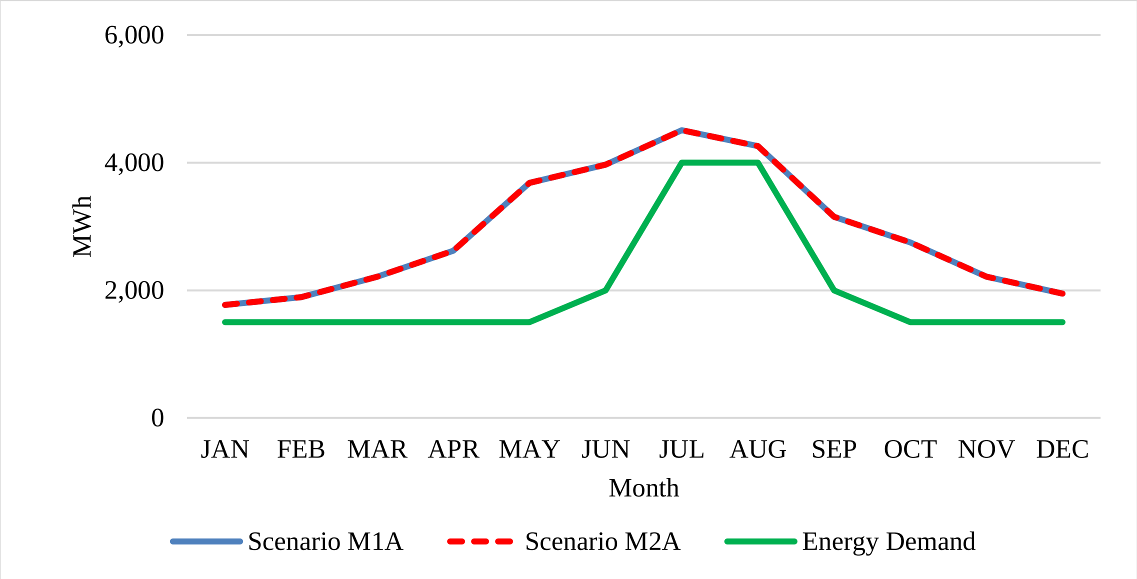


Figure 27: Comparison of Mean Monthly Hydropower Generation in Possum Kingdom Hydropower Plant for the Scenarios M1A and M2A

In addition to annual generation graphs, considering the mean monthly generation curve, it is seen that Whitney Dam does not produce enough electricity in the summer season, while Possum Kingdom Dam does not have any seasonal problems in meeting the energy demand. The graphs for Whitney Reservoir illustrate the slight decrease in energy generation because of the implementation of environmental flow standards.

The main concern of these simulations in hydrology is streamflow depletions to reservoirs and releases from dams to generate hydroelectricity. The quantity of inflows taken from streamflow to meet water supply at the reservoirs and releases for energy generation for the Whitney Reservoir and Possum Kingdom Reservoir, as shown in Table 46, indicate the same trend with changes of shortage and hydroelectricity.

Table 46: Comparison of Inflows and Releases in Hydropower Reservoirs for the Scenarios M1A and M2A

Reservoir	Scenario	Inflows from Streamflow (ac-ft/year)	Hydropower Releases (ac-ft/year)
Whitney	M1A	280,947.3	234,996.7
	M2A	278,441.7	233,083.2
Possum Kingdom	M1A	293,219.8	242,757.4
	M2A	293,219.6	242,757.3

Figures 28-31 illustrate the annual inflows from stream river to hydropower reservoirs and annual releases to generate hydropower over the 78 years period. As shown in figures, straight blue line and dashed red line represent the scenarios M1A and M2A respectively.

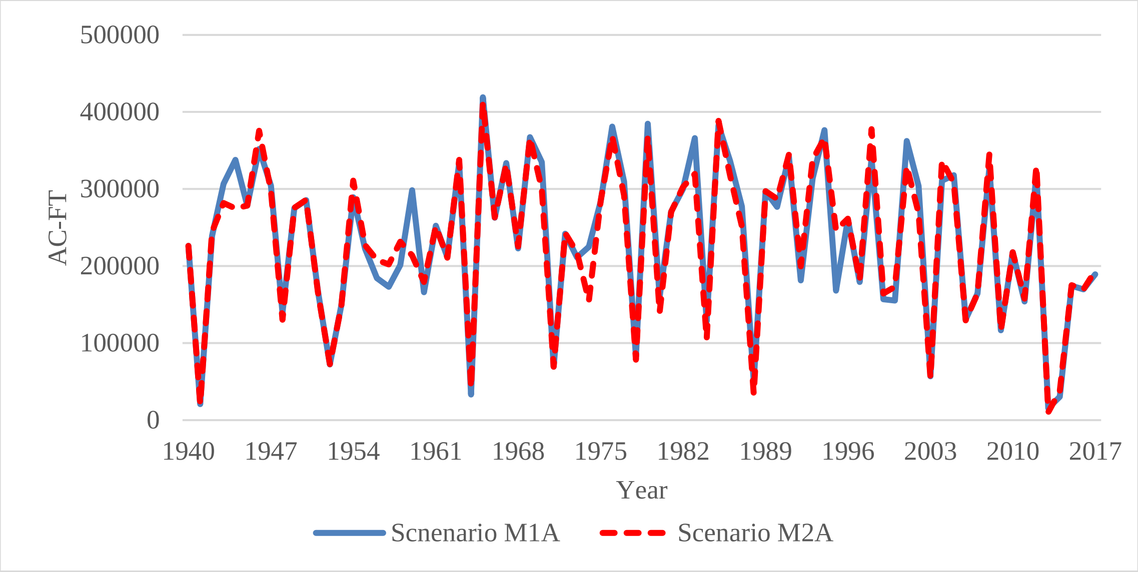


Figure 28: Comparison of Releases in Whitney Reservoir for the Scenarios M1A and M2A

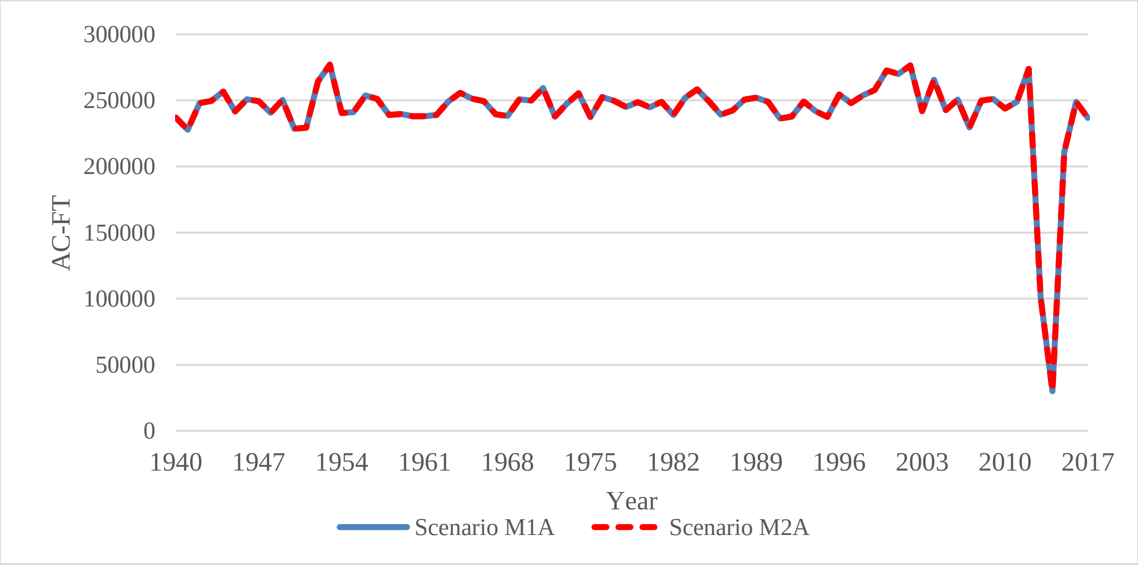


Figure 29: Comparison of Releases in Possum Kingdom Reservoir for the Scenarios M1A and M2A

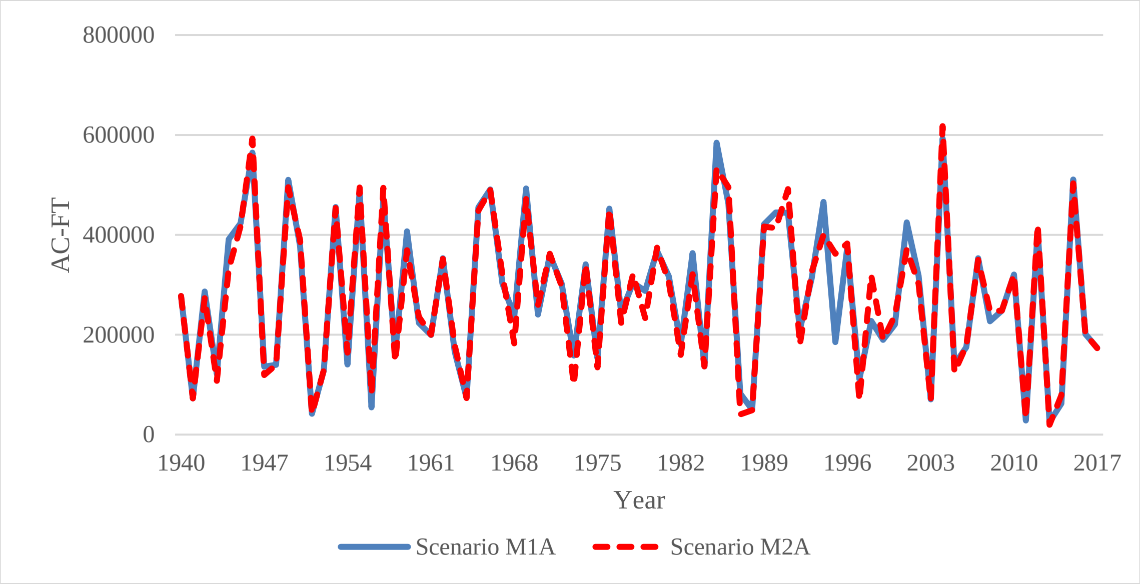


Figure 30: Comparison of Inflows from Streamflow in Whitney Reservoir for the Scenarios M1A and M2A

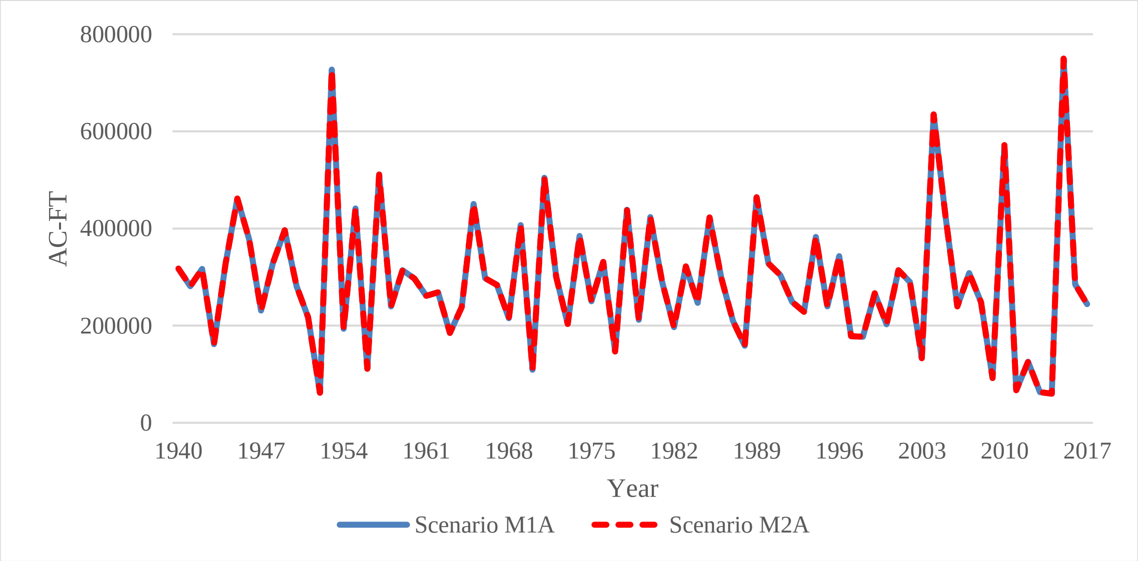


Figure 31: Comparison of Inflows from Streamflow in Possum Kingdom Reservoir for the Scenarios M1A and M2A

Hydropower is generated with water that is available to turbines in modeling system computations and reservoir releases for water supply are specifically used to meet hydropower generation target. Because of the change on water availability in Whitney Reservoir, inflows to reservoirs and releases from the dams may have variations through the simulation scenarios regarding the implementation of environmental flow standards. However, the metrics of inflows and releases for the Possum Kingdom Reservoir has not experienced any reduction. Existing water diversion rights from this reservoir are indeed enough to meet environmental flow standards at downstream points. Consequently, any change on the Possum Kingdom reservoir for the inflows and releases were not observed.

Releases from the dams to supply water for human uses and environmental flows also affects the water availability on the reservoirs. The scenario M1A storage capacities were compared with scenario M2A storage levels for two hydropower reservoirs. As shown in Figures 32 and 33, dashed blue line and straight red line represent the scenarios M1A and M2A respectively. Based on the metrics of reservoir storage, frequency analyses were developed for hydropower plants by comparing M1A and M2A scenarios in Table 47. As expected, water availability was declined once the environmental flow standards were included in river/reservoir system. The results illustrate the effects of the environmental flow standards on Whitney Reservoir and Possum Kingdom Reservoir.

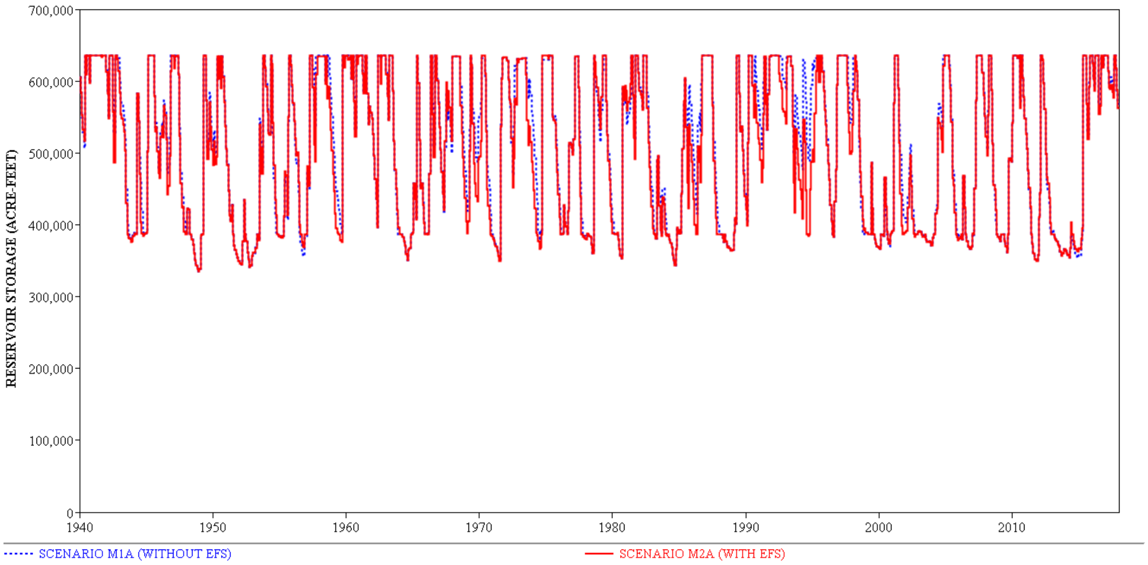


Figure 32: Comparison of Reservoir Storage in Whitney Reservoir for the Scenarios M1A and M2A

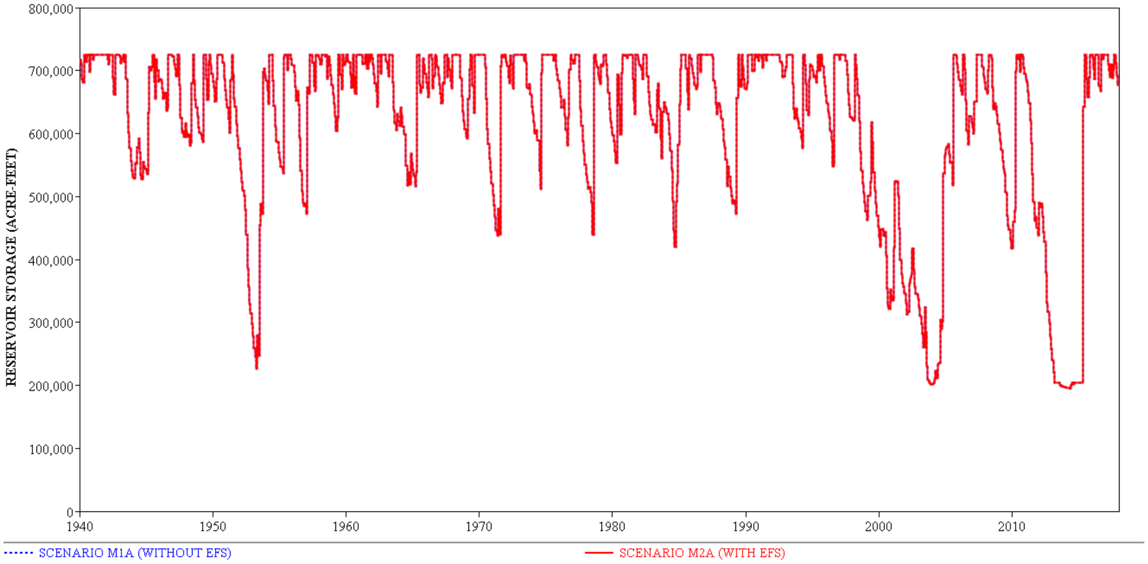


Figure 33: Comparison of Reservoir Storage in Possum Kingdom Reservoir for the Scenarios M1A and M2A

Table 47: Comparison of Storage Frequency Statistics in Hydropower Reservoirs for the Scenarios M1A and M2A

Reservoir	Whitney		Possum Kingdom	
Scenario	M1A	M2A	M1A	M2A
Mean	508,483	500,336	617,651	617,651
Std Dev	103,729	103,371	138,307	138,307
Minimum	334,978	334,978	193,872	193,872
99.5%	343,158	343,215	196,801	196,801
99%	347,274	347,274	200,400	200,400
98%	353,013	353,013	203,811	203,811
95%	361,264	364,183	278,193	278,193
90%	375,148	375,674	419,317	419,317
85%	384,391	383,071	489,570	489,570
80%	387,024	387,024	535,976	535,976
75%	388,891	387,024	571,363	571,363
70%	409,881	396,578	600,351	600,351
60%	470,592	450,578	641,876	641,876
50%	521,553	502,874	675,747	675,747
40%	561,114	543,548	696,336	696,336
30%	597,617	586,872	715,718	715,718
25%	619,996	609,752	724,739	724,739
20%	633,418	632,737	724,739	724,739
15%	635,632	635,639	724,739	724,739
10%	636,036	635,943	724,739	724,739
5%	636,100	636,100	724,739	724,739
2%	636,100	636,100	724,739	724,739
1%	636,100	636,100	724,739	724,739
0.5%	636,100	636,100	724,739	724,739
Maximum	636,100	636,100	724,739	724,739

5.1.1.2 Comparison of Monthly Scenarios – Case B

The scenarios M1B in which environmental flow standards are not included was compared with the scenario M2B that includes environmental flow standards with a priority of 20120301. Both scenarios are different from M1A and M2A because of the reason that diversion rights for other uses from the hydropower reservoirs were terminated. In the scenarios of case A, firm energy analysis for Possum Kingdom Reservoir were not able to be made due to water availability through the 78 years period in the dam. After exclusion of water diversion rights for not only from Possum Kingdom Reservoir but also from Whitney Dam, firm energy alteration occurred by the implementation of instream flow requirements was observed well. Total diversion of 18,338 acre-feet from Whitney Reservoir and 227,150 acre-feet from Possum Kingdom Reservoir was deactivated in the simulations. These scenarios were performed by applying hydrological data over the period of 1940-2017. The simulations based on each scenario begin with all reservoir storages equal to full capacities. Energy shortages, firm energy generations, mean energy generations, reliability of hydropower rights, reservoir releases, and frequency of reservoir storages were examined with both scenarios. Table 48 shows the hydropower generation in the scenarios of M1B and M2B.

Table 48: Comparison of Reliability of Hydropower for the Scenarios M1B and M2B

		Scenario M1B			Scenario M2B		
		Mean	Reliability		Mean	Reliability	
Reservoir ID	Energy Target (MWh-year)	Shortage (MWh-year)	Period (%)	Volume (%)	Shortage (MWh-year)	Period (%)	Volume (%)
POSDOM	24,000	695	96.05	97.11	888	94.87	96.30
WHITNY	36,000	1,985	90.28	94.49	2,281	88.57	93.66
TOTAL	60,000	2,680		95.53	3,169		94.72

As the results of scenario M1B and M2B, total reliability for energy generation in the Brazos River Basin declined from 95.53% to 94.72% in terms of volume. Energy generation shortage increased from 2,680 MWh/year to 3,169 MWh/year during the 1940-

2017 period of simulations to environmental flow needs. Firm and total energy generation were also tabulated in Table 49 for the interested scenarios.

Table 49: Comparison of Hydropower Generation for the Scenarios M1B and M2B

Scenario	Whitney		Possum Kingdom	
	Firm Energy (MWh-year)	Total Energy (MWh-year)	Firm Energy (MWh-year)	Total Energy (MWh-year)
M1B	9,290	55,533	13,020	38,686
M2B	10,040	55,068	12,170	38,269

The change on water availability because of the environmental flow standards through river basin area caused mean hydropower generation, firm energy production, and energy shortage to decline. However, there is an increase in firm energy generation for the Whitney Reservoir when environmental flows are included. A possible explanation for this might be that making releases for environmental needs through the turbines increases firm energy even if causing the decrease on total energy generation.

The quantity of inflows taken from streamflow and hydropower releases for the Whitney Reservoir and Possum Kingdom Reservoir, as tabulated in Table 50, experienced a slight decline. The reasons identified for M1A vs M2A comparisons are also valid for this comparison.

Table 50: Comparison of Inflows and Releases in Hydropower Reservoirs for the Scenarios M1B and M2B

Reservoir	Scenario	Inflows from Streamflow (ac-ft/year)	Hydropower Releases (ac-ft/year)
Whitney	M1B	165,417.9	115,009.7
	M2B	161,904.5	113,220.3
Possum Kingdom	M1B	139,497.9	89,239.2
	M2B	137,651.9	89,840.3

Releases from the dams to supply water for human uses and environmental flows also affects the water availability on the reservoirs. The scenario M1B storage capacities were compared with scenario M2B storage capacities for two hydropower reservoirs. As shown in Figures 34 and 35, dashed blue line and straight red line represent the scenarios M1B and M2B respectively. Based on the metrics of reservoir storage, frequency analyses were developed for hydropower plants by comparing M1B and M2B scenarios in Table 51. As expected, water availability was declined once the environmental flow standards were included in the river/reservoir system. The results illustrate the effects of the environmental flow standards on Whitney Reservoir and Possum Kingdom Reservoir.

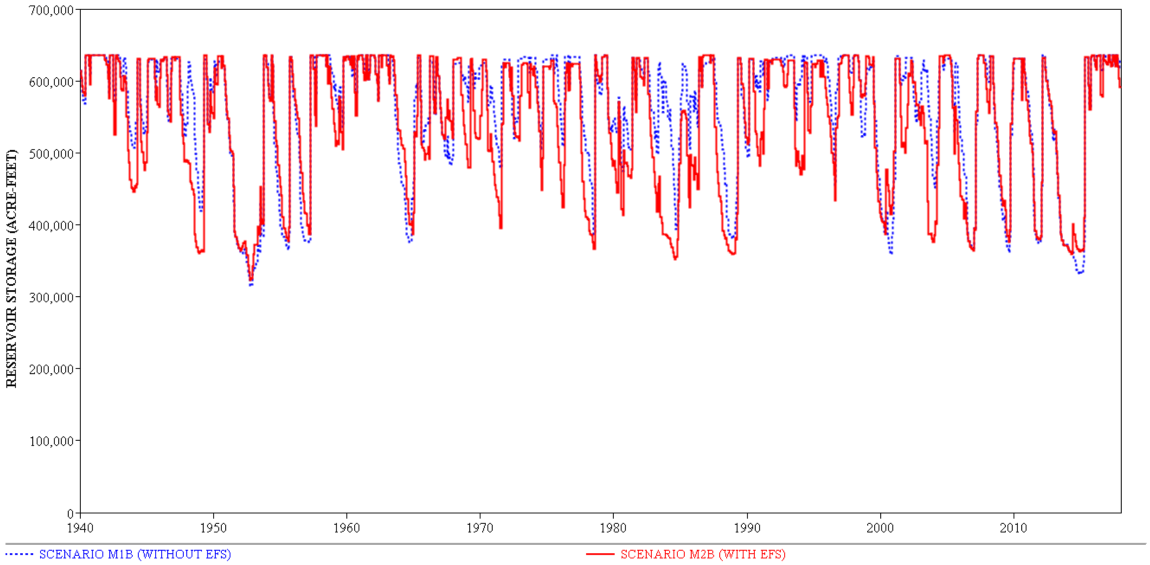


Figure 34: Comparison of Reservoir Storage in Whitney Reservoir for the Scenarios M1B and M2B

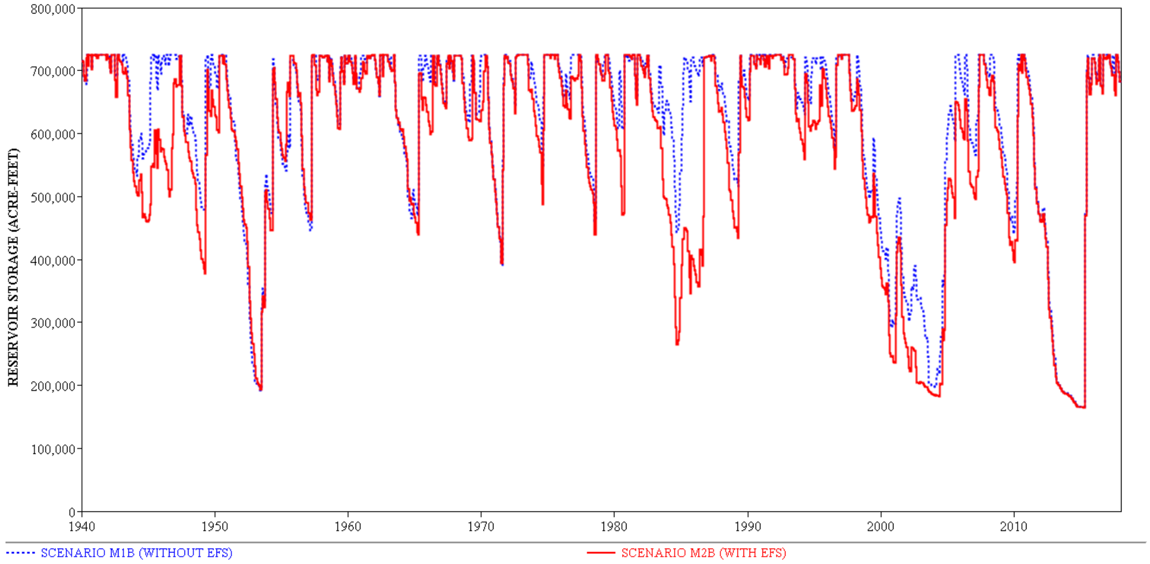


Figure 35: Comparison of Reservoir Storage in Possum Kingdom Reservoir for the Scenarios M1B and M2B

Table 51: Comparison of Storage Frequency Statistics in Hydropower Reservoirs for the Scenarios M1B and M2B

Reservoir	Whitney		Possum Kingdom	
Scenario	M1B	M2B	M1B	M2B
Mean	560,175	539,795	615,093	579,287
Std Dev	87,090	91,282	145,535	156,078
Minimum	314,044	323,184	165,495	164,317
99.5%	331,988	349,564	166,549	165,365
99%	335,188	358,527	175,303	174,072
98%	356,319	362,405	189,249	184,245
95%	372,747	371,000	249,604	203,787
90%	389,689	387,024	379,429	322,618
85%	453,777	412,034	474,856	422,401
80%	496,757	446,163	517,831	463,441
75%	520,460	473,640	564,110	495,153
70%	538,932	493,327	597,182	525,640
60%	572,303	528,972	646,211	595,287
50%	596,825	564,774	682,705	632,079
40%	616,410	595,294	701,675	671,210
30%	626,807	621,179	717,670	695,607
25%	629,921	625,740	721,391	707,232
20%	631,726	629,965	724,039	716,825
15%	633,284	632,412	724,739	723,516
10%	635,707	634,690	724,739	724,293
5%	636,100	636,100	724,739	724,739
2%	636,100	636,100	724,739	724,739
1%	636,100	636,100	724,739	724,739
0.5%	636,100	636,100	724,739	724,739
Maximum	636,100	636,100	724,739	724,739

5.1.1.3 Comparison of Daily Scenarios

The scenarios of D1 an D2 that are the daily versions of M1 and M2 monthly scenarios were performed in the daily modeling system to evaluate the effects of environmental standards well. Reservoir storage is treated in monthly modeling system as cumulative storage for a month and the head accounts for specified storage is used in calculations. However, decreases and increases in reservoir storage cause water level change gradually in daily modeling and instead of using the maximum head for monthly cumulative volume, the head corresponding to the daily storage is considered.

Moreover, the minimum instream flow requirements are applied with TS records as the same metric for each season and hydrologic condition. Changing minimum instream flows and maximum allowable limits are not accounted in monthly modeling, which does not allow to observe the effects of Senate Bill 3 environmental flow standards on energy generation well. When everything is considered, it is obvious that hydropower generation in daily time scale differs with a monthly time scale. Table 52 shows the hydropower generation for the scenarios of D1 and D2 in which environmental flow standards are applied and not applied respectively.

Table 52: Comparison of Reliability of Hydropower for the Scenarios D1 and D2

Name	Energy Target (MWh-year)	Scenario D1 Mean Shortage (MWh-year)	Scenario D1 Reliability Period (%)	Scenario D1 Reliability Volume (%)	Scenario D2 Mean Shortage (MWh-year)	Scenario D2 Reliability Period (%)	Scenario D2 Reliability Volume (%)
POSDOM	24,000	5,237	74.55	78.18	5,046	75.64	78.98
WHITNY	36,000	12,772	55.61	64.52	13,953	51.34	61.24
TOTAL	60,000	18,010		69.98	18,999		68.33

Implementation of environmental flow standards increased hydropower shortage at Whitney Reservoir while decreasing shortage at Possum Kingdom slightly. Total reliability for hydropower generation decreased from 69.98 % to 68.33% due to environmental flow standards. Table 53 illustrates mean annual energy generation in power plants for the scenarios D1 and D2. Environmental flow standards in basin area caused to decrease on mean annual energy generation. Even if there is a decrease on energy target for Possum Kingdom Reservoir, mean annual energy generation experienced reduction due to instream flow rights. This can be explained curtailment of the electricity generation occurred on secondary energy generation.

Table 53: Comparison of Total Hydropower Generation for the Scenarios D1 and D2

Scenario	Whitney (MWh)	Possum Kingdom (MWh)
D1	35,664	30,572
D2	34,094	30,318

Figure 36 illustrates hydropower plants and downstream control points at which environmental flow standards incorporated. Water supply for instream flow rights at downstream gages and decrease in water availability in basin area are the main reasons for reduction in energy production.

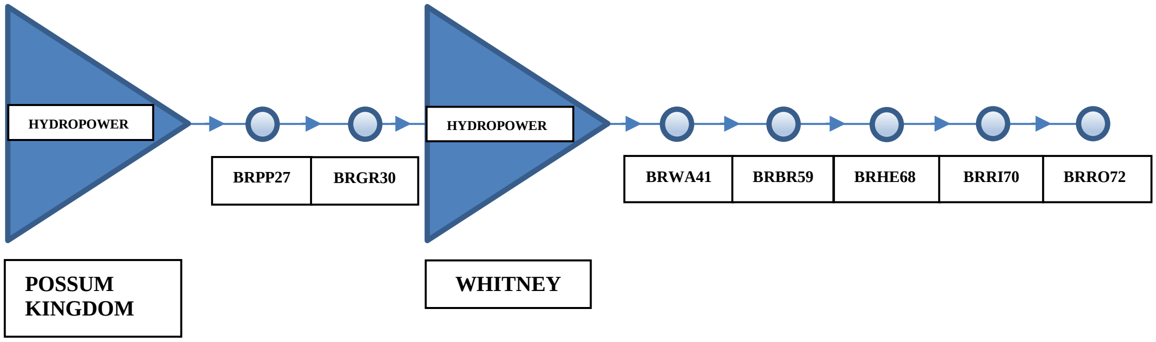


Figure 36: Systematic Overview of Hydropower Reservoirs and Stream Gages

Hydropower generation through the period and mean monthly energy output are illustrated for two reservoirs. As shown in Figures 37-40, straight blue line and dashed red line represent the scenarios D1 and D2 respectively.

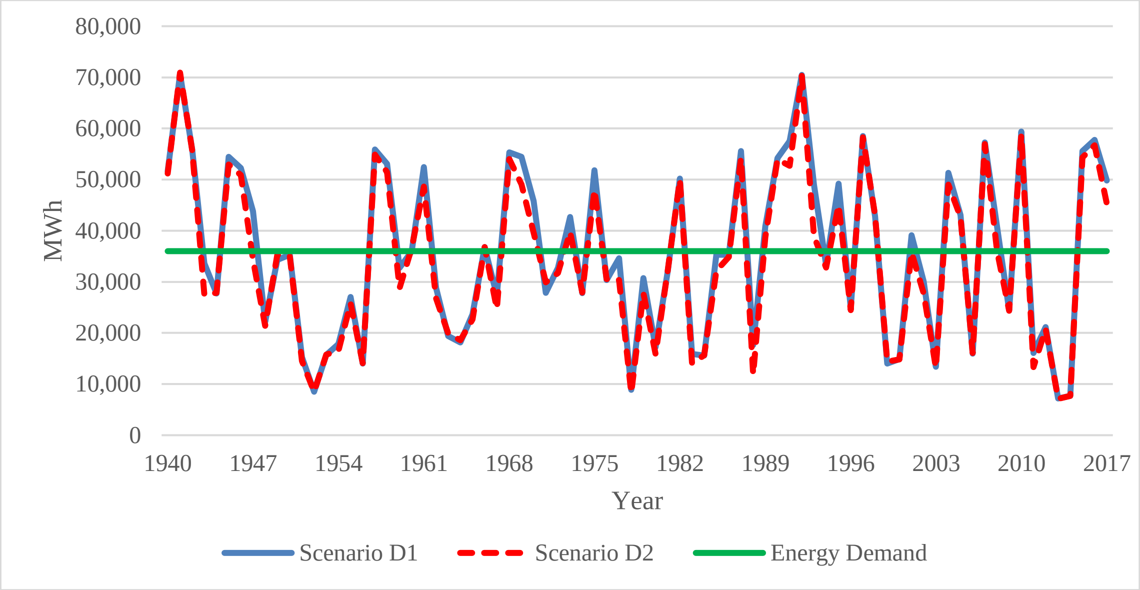


Figure 37: Comparison of Hydropower Generation over the period between 1940 and 2017 in Whitney Hydropower Plant for the Scenarios D1 and D2

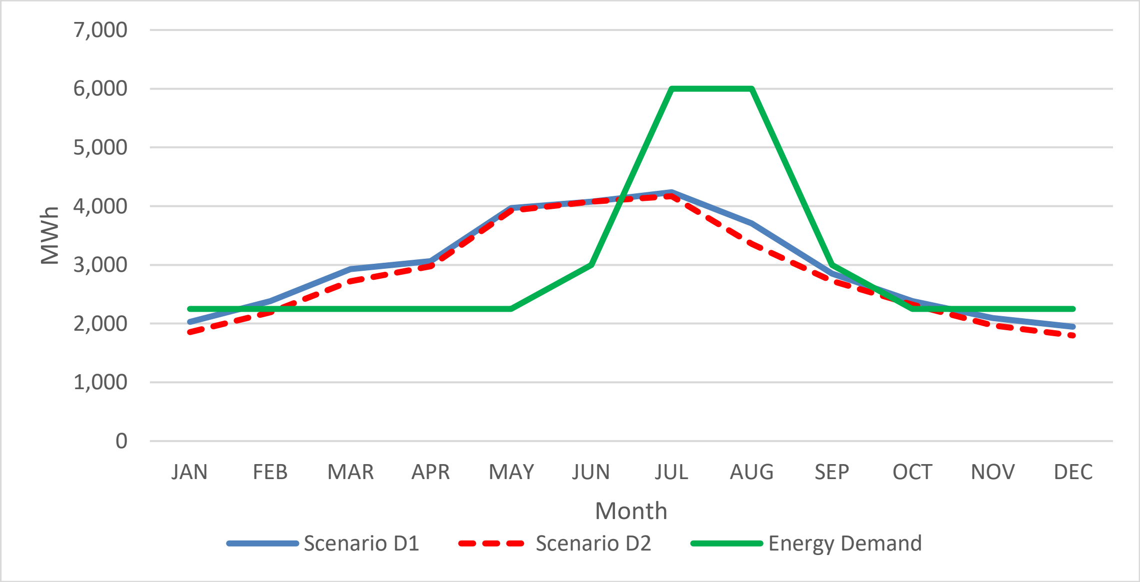


Figure 38: Comparison of Mean Monthly Hydropower Generation in Whitney Hydropower Plant for the Scenarios D1 and D2

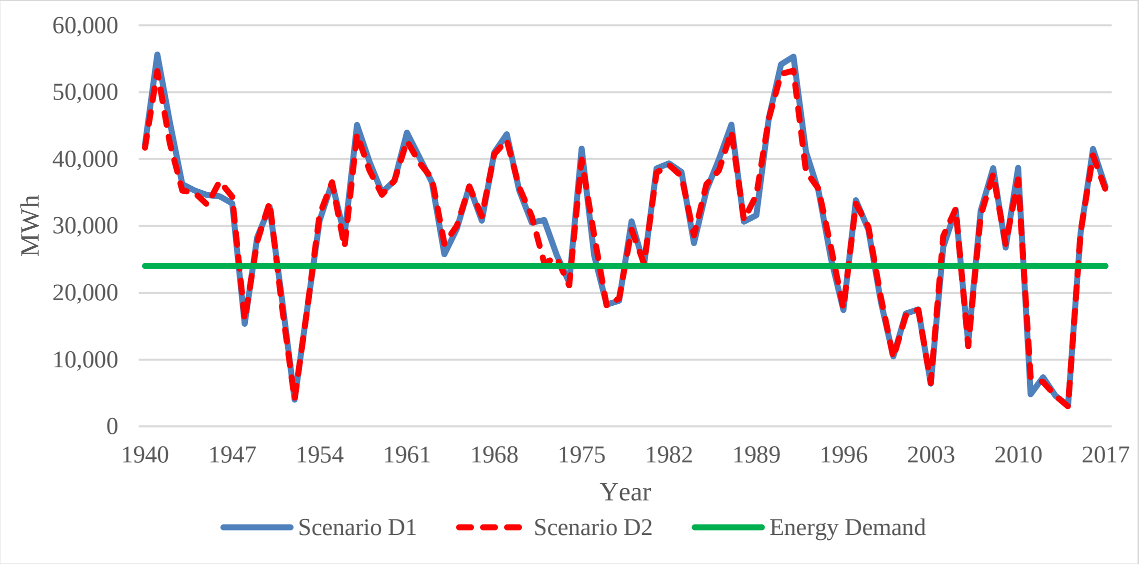


Figure 39: Comparison of Hydropower Generation over the period between 1940 and 2017 in Possum Kingdom Hydropower Plant for the Scenarios D1 and D2

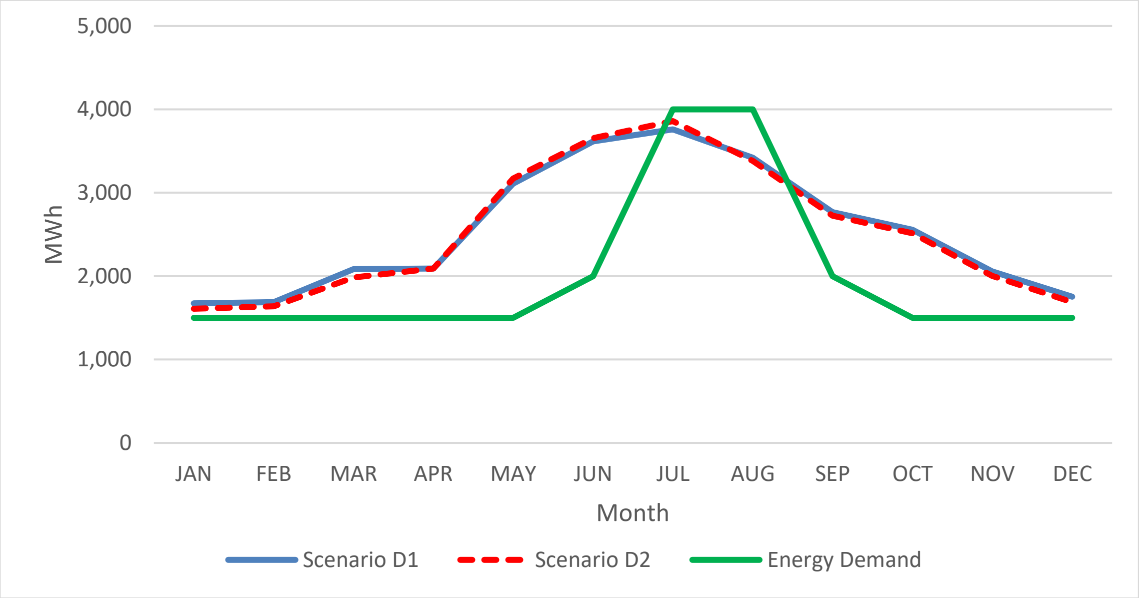


Figure 40: Comparison of Mean Monthly Hydropower Generation in Possum Kingdom Hydropower Plant for the Scenarios D1 and D2

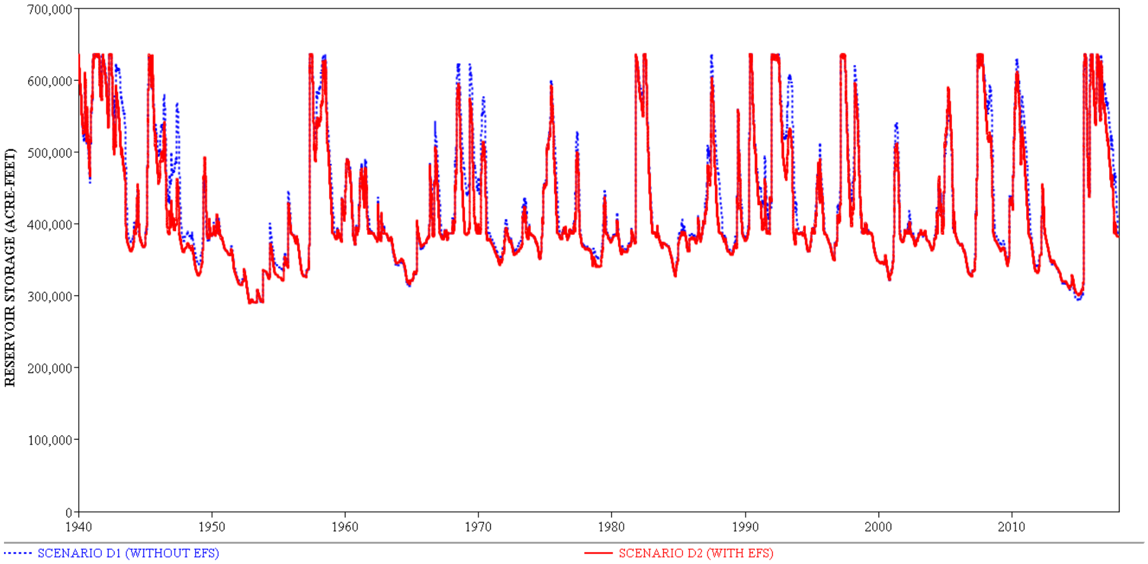


Figure 41: Comparison of Reservoir Storage in Whitney Reservoir for the Scenarios D1 and D2

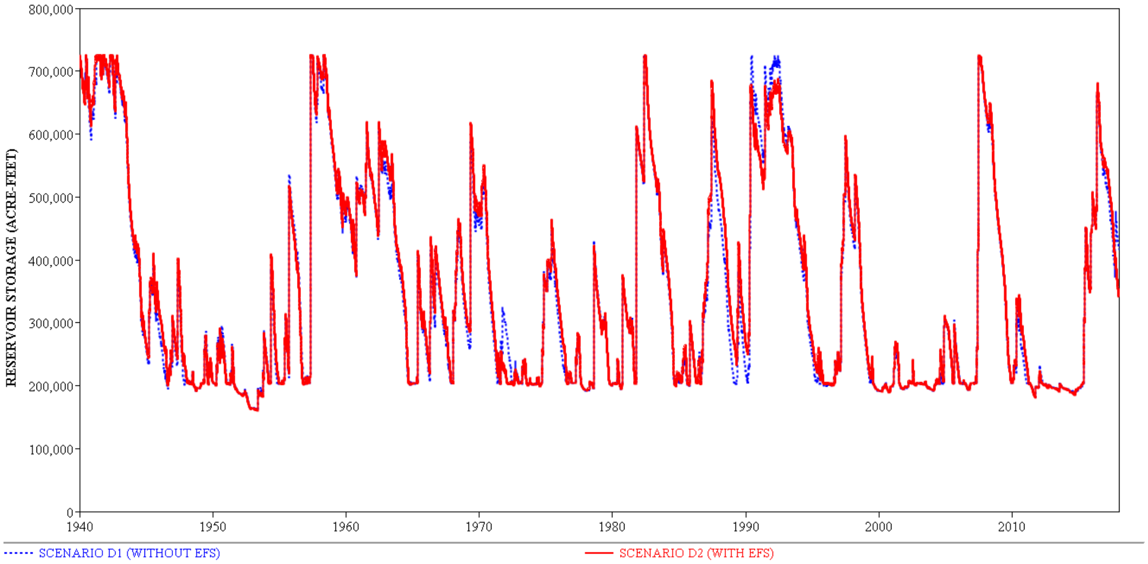


Figure 42: Comparison of Reservoir Storage in Possum Kingdom Reservoir for the Scenarios D1 and D2

In similar to monthly simulations, water availability in two reservoirs varies depending on the implementation of Senate Bill 3 environmental flow standards. The daily time series of reservoir storages are plotted in Figures 41 and 42. The frequency statistics of reservoir storage are tabulated in Table 54.

Table 54: Comparison of Storage Frequency Statistics in Hydropower Reservoirs for the Scenarios D1 and D2

Reservoir	Whitney		Possum Kingdom	
Scenario	D1	D2	D1	D2
Mean	428,656	417,108	348,827	354,614
Std Dev	91,492	85,266	164,761	164,930
Minimum	289,401	288,900	162,374	160,552
99.5%	291,270	291,436	164,910	163,606
99%	293,749	295,397	180,371	179,794
98%	302,214	306,770	187,865	186,934
95%	322,870	322,802	193,223	193,275
90%	339,731	334,762	197,291	197,648
85%	351,051	346,774	201,367	202,061
80%	361,655	357,910	203,285	203,468
75%	368,034	364,402	203,806	203,811
70%	373,832	369,621	207,340	211,899
60%	382,161	378,824	236,361	245,411
50%	386,963	385,543	283,146	293,549
40%	408,529	391,250	349,222	359,781
30%	456,151	428,097	429,570	439,553
25%	485,141	459,031	468,207	483,048
20%	520,212	488,734	510,042	523,231
15%	553,818	521,423	561,153	568,511
10%	586,633	564,440	624,521	625,193
5%	621,797	612,896	685,558	679,099
2%	635,948	634,798	715,390	716,645
1%	636,100	636,100	723,320	723,237
0.5%	636,100	636,100	724,739	724,739
Maximum	636,100	636,100	724,739	724,739

5.1.2 Impacts of Flood Control Operations on Hydropower Generation

Flood control operations are activated in nine reservoirs at the scenarios of D5, D6, D7, D8, D9, and D10. In order to observe the effects of flood control operations on hydropower generation in multiple reservoir system, the scenario D2 in which any reservoir flood control pools are closed and the scenarios of D6, D7, and D8 in which reservoirs operations for flood control were assigned differently were compared. Without flood control pools and flood control operations, environmental flow standards and water supply are considered to allocate water and excess flows are stored in conservation pools of the reservoirs. The scenario D2 and the scenario D6 that represents the multiple-system reservoir flood control operations were compared in Table 54 about hydropower generation.

Table 55: Comparison of Reliability of Hydropower for the Scenarios D2 and D6

Name	Energy Target (MWh-year)	Scenario D2			Scenario D6		
		Mean Shortage (MWh/year)	Reliability		Mean Shortage (MWh/year)	Reliability	
			Period (%)	Volume (%)		Period (%)	Volume (%)
POSDOM	24,000	5,046	75.64	78.98	5,640	73.35	76.50
WHITNY	36,000	13,953	51.34	61.24	11,579	60.03	67.84
TOTAL	60,000	18,999		68.33	17,219		71.30

The results indicate that reservoir flood control operations decrease hydropower shortage in Whitney Reservoir while curtailing energy generation in Possum Kingdom Reservoir. Water availability in Whitney Reservoir that is mainly used for hydropower generation and flood control increased in the scenario D6, which affects energy output in the dam positively. However; since excess flows were stored in USACE flood control reservoirs instead of other reservoirs, water availability and energy generation in Possum Kingdom Reservoir decreased. In addition to multiple system reservoir operations, priority-based flood control operations were applied in the scenarios of D7 and D8 as illustrated in Table 43. Priorities for storage and releases were assigned depending on the capacity of the dam for the scenario of D7. In the scenario D8, multiple system reservoir operations were applied in eight flood control dams while the most senior priority for storage and the most junior priority for release were assigned for the Whitney Dam. The generation of hydroelectricity in the reservoir was analyzed by keeping the flood water in the dam for a long time compared to normal operations. Tables 55 and 56 illustrate the reliability analyses of hydropower generation and total energy output for the reservoirs of Whitney and Possum Kingdom.

Table 56: Comparison of Reliability of Hydropower for the Scenarios D6, D7, and D8

	Scenario D6			Scenario D7			Scenario D8		
		Reliability			Reliability			Reliability	
Name	Mean Shortage (MWh/year)	Period (%)	Volume (%)	Mean Shortage (MWh/year)	Period (%)	Volume (%)	Mean Shortage (MWh/year)	Period (%)	Volume (%)
POSDOM	5,640	73.35	76.50	5,608	73.71	76.63	5,643	73.40	76.49
WHITNY	11,579	60.03	67.84	11,632	59.80	67.69	12,066	58.49	66.48
TOTAL	17,219		71.30	17,240		71.27	17709.5		70.48

Table 57: Comparison of Hydropower Generation for the Scenarios D2, D6, D7, and D8

Reservoir ID	D2	D6	D7	D8
POSDOM	30,318	28,202	28,260	28,218
WHITNY	34,094	35,341	35,266	34,035
TOTAL	64,412	63,543	63,526	62,253

The results obtained from this comparative analysis illustrates that energy generation along the river basin varies by reservoir flood control operations. The scenario D6 in which multiple system reservoir operation system was used gives the higher reliability and maximum energy generation in comparison with other scenarios. Depending on rank assigned for flood control reservoirs, floodwater is usually stored in Whitney Dam due to its capacity, which enabled water availability to increase in this reservoir.

The flood control operation rules that are currently applied in original Brazos WAM dataset by giving priorities based on the capacity of the reservoirs, were used in the scenario D7. Closest reliability and energy generation results to the scenario D6 were obtained in the scenario D7. However, hydropower output decreased in the scenario D8 in which priority of the reservoir operations was applied in order of floodwater storage, hydropower generation, and flood flow releases respectively at Whitney Reservoir. Other flood control pools were operated in multiple reservoir system. The reservoir storages in two hydropower reservoirs were plotted for the scenarios of D2, D6, D7, and D8 in Figures 43 and 44.

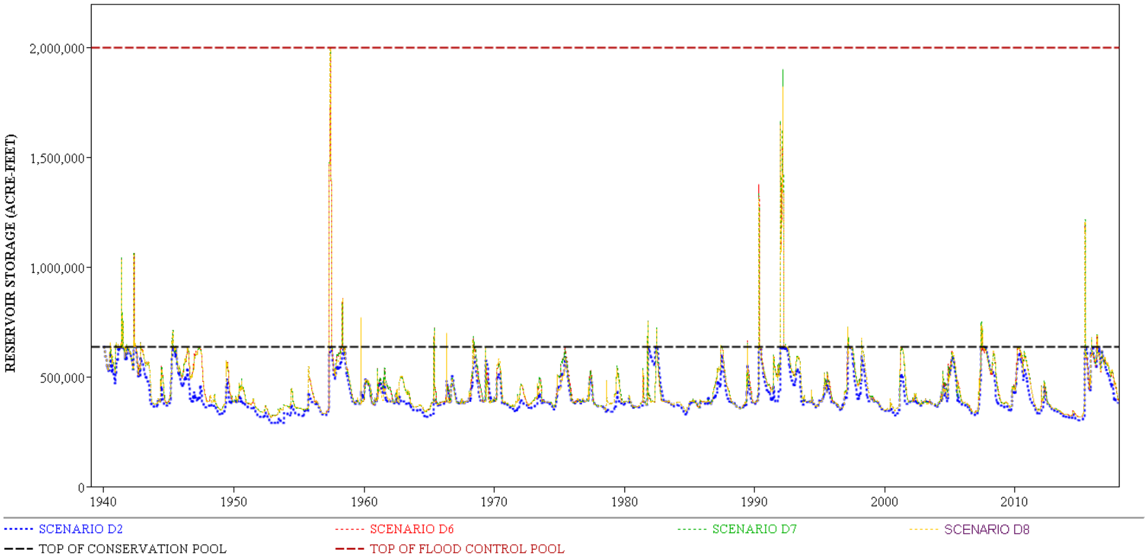


Figure 43: Comparison of Reservoir Storage in Whitney Reservoir for the Scenarios D2, D6, D7, and D8

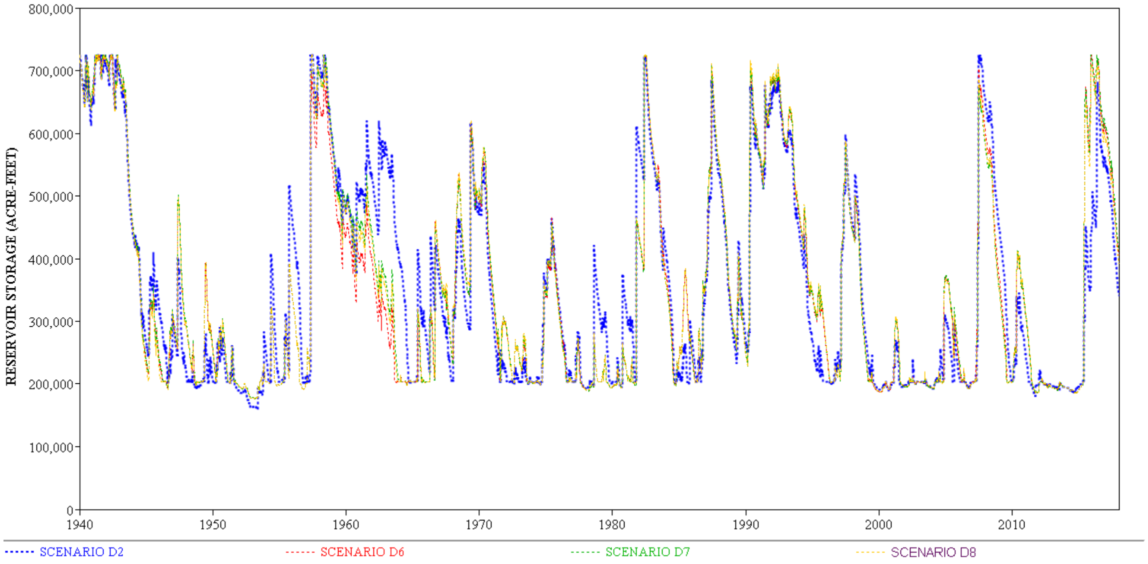


Figure 44: Comparison of Reservoir Storage in Possum Kingdom Reservoir for the Scenarios D2, D6, D7, and D8

5.2 Evaluations of Environmental Flow Standards on River/Reservoir System

Time series plots and statistical frequency metrics for regulated and unappropriated flows and instream flow targets and shortages at pertinent control points were evaluated to define changes caused by reservoir operations for hydropower generation and flood control. Similarly, pulse flows that were established by the SB3 environmental flow standards were analyzed by comparing the total number of events. Chapter III provides descriptive information about the SB3 environmental flow standards in 19 primary control points as well as the incorporation of instream flow rights in the daily and monthly modeling system. The outline of environmental flows analyses:

- analyzing the impacts of hydropower generation on environmental flow standards in the daily and monthly versions of the WRAP modeling system,
- analyzing the impacts of flood control operations on environmental flow standards,

Statistical analyses for regulated, unappropriated, and instream flows to observe impacts of hydropower generation were conducted by simulating D2, D3, and D4 scenarios and M2, M3, and M4 scenarios in the daily and monthly versions of the WRAP modeling system respectively because of the differences in incorporation of environmental flow standards in the daily and modeling system. The effects of flood control operations on environmental flows were quantified by applying the daily modeling system. Furthermore, the analyses of pulse flow events were computed in daily modeling system by using the tracking option to get an output for total quantities of initiated, terminated, and completed pulse flow events for all control points at which instream flow rights established. The metrics of annual volumes of regulated and unappropriated stream flows and SB3 EFS instream flow targets and shortages for each scenario were developed in TABLES to illustrate the variations.

5.2.1 Impacts of Hydropower Generation on Environmental Flow Standards

Releases from reservoirs for energy production contribute to regulated and unappropriated flows at downstream points. The algorithms in modeling systems do not allow hydropower rights being curtailed because of instream flow rights. However, depending on energy target in power plants, instream flow targets and shortages at downstream points are affected even if all flow returned to stream in the same month. Similarly, regulated and unappropriated flow through river system can vary depending on location, season, and hydrologic condition once taking inflow to reservoirs for maintaining optimal head required for energy generation. Also, hydropower plants in river basin areas cause tradeoffs between stream flows and reservoir storage to occur.

The priority date of the SB3 environmental flow standards is treated in the modeling system as being junior to hydropower rights, which means that environmental needs in the basin area are met before than hydropower rights. As discussed on Chapter III, environmental flow standards were incorporated in daily and monthly modeling systems by inputting different metrics, which causes uncertainties between simulation results. Incorporating monthly targets in modeling system as an aggregation of daily targets cannot provide to track base flows, subsistence flows, and pulse flows well. Therefore, regulated flows, unappropriated flows, instream flow targets, and shortages were computed in daily and monthly time intervals to make more accurate evaluations. The metrics for 19 primary control points were computed in SIM and SIMD, and the control points at downstream of hydropower plants were compared to quantify the hydropower effects on stream flows.

5.2.1.1 Comparison of Monthly Simulation Results

The simulation M3 that represents authorized scenario use without any hydropower rights at two reservoirs were compared with M2 and M4 scenarios in which hydropower generation was included in the dataset with energy target of 60,000 MWh/year and 90,000 MWh/year respectively. Naturalized flows and instream flow targets that were incorporated in SIM hydrology input DSS file are the same for scenarios. Table 58 shows the naturalized, regulated, and unappropriated flows in 19 primary control points in the Brazos WAM system for the interested scenarios. As a result of this comparison, energy generation increased regulated flows at just downstream of hydropower plants considerably due to releases for power generation while unappropriated flows showed slight change.

Table 58: Mean Naturalized and Simulated Regulated and Unappropriated Stream Flows at 19 Control Points for the Scenarios M2, M3, and M4

Control Point	Naturalized Flow (cfs)	Regulated Flows (cfs)			Unappropriated Flows (cfs)		
		M3	M2	M4	M3	M2	M4
SFAS06	89.30	83.10	83.20	84.30	38.40	35.40	31.40
DMAS09	135.40	112.10	113.20	118.40	40.80	37.30	33.60
BRSE11	303.80	284.70	285.50	289.40	119.60	110.50	95.20
CFNU16	111.70	50.60	50.90	54.00	23.70	22.80	20.80
BRSB23	805.50	681.70	685.80	704.10	257.20	240.90	206.20
CON026	130.20	69.10	69.50	72.90	36.10	34.10	30.00
BRPP27	990.90	471.10	479.60	520.60	297.40	276.30	236.70
BRGR30	1,398.20	747.10	756.30	798.70	491.80	450.70	405.80
NBCL36	224.80	213.80	213.80	213.80	156.30	154.90	154.80
BRWA41	2,569.80	1,769.50	1808.50	1876.10	1,220.30	1,113.10	1110.8
LEGT47	347.40	302.50	302.50	302.50	205.10	205.30	204.90
LAKE50	165.80	160.60	160.60	160.60	97.40	97.80	97.80
LRLR53	1,167.40	801.50	801.50	801.50	604.80	605.10	605.30
LRCA58	1,844.50	1,400.90	1,401.00	1,401.00	1,013.10	1,017.30	1,017.30
BRBR59	5,479.50	4,172.40	4,211.80	4,277.80	2,692.70	2,611.50	2,612.60
NAEA66	465.80	331.40	331.40	331.40	262.90	263.50	264.40
BRHE68	7,389.50	5,849.50	5,888.20	5952.50	3,388.80	3,317.60	3,322.60
BRRI70	8,073.50	6,364.10	6,401.80	6,464.50	4,012.80	3,922.60	3,928.80
BRRO72	8,457.40	6,262.80	6,300.70	6,363.00	4,123.80	4,036.30	4,044.50

Additionally, Table 59 represents the instream flow rights incorporated with TS records and shortages at control points for three scenarios. Shortages are computed in the modeling system by calculating deficits between minimum flow limits and regulated flow limits at the end of each sequence of simulation for the day.

Table 59: Means of SB3 EFS Instream Flow Targets and Shortages at 19 Control Points for the Scenarios M2, M3, and M4

Control Point	Target (cfs)	Shortages (cfs)		
		M3	M2	M4
SFAS06	5.54	0.32	0.32	0.32
DMAS09	9.37	0.84	0.84	0.84
BRSE11	30.18	2.20	2.20	2.20
CFNU16	9.11	0.93	0.93	0.90
BRSB23	82.48	6.31	6.31	6.32
CON026	9.01	1.15	1.15	1.15
BRPP27	181.19	96.40	84.24	57.21
BRGR30	299.30	124.92	114.53	87.45
NBCL36	22.91	1.13	1.13	1.13
BRWA41	508.93	157.00	74.68	58.53
LEGT47	29.28	3.38	3.38	3.38
LAKE50	36.80	2.97	2.97	2.97
LRLR53	204.72	49.96	49.92	49.91
LRCA58	408.78	94.18	94.16	94.15
BRBR59	1,327.95	268.62	161.76	125.07
NAEA66	34.15	3.06	3.06	3.06
BRHE68	2,155.10	380.25	270.08	228.61
BRRI70	2,372.17	376.52	287.56	248.74
BRRO72	2,670.43	624.10	498.63	441.58

Instream flow rights established at downstream of reservoirs experienced a decrease in shortage depending on the rate of increase in regulated flows. Figure 36 outlines the order of instream flow rights gaging stations and hydropower reservoirs. Seven of nineteen control points are interested in this section to define the curtailment of instream flow targets.

The stream gages that were affected by releases from the hydropower reservoirs were tabulated in Table 60 in order to illustrate the decreases in shortages when the electricity generation was applied and the target was increased.

Table 60: Means of SB3 EFS Shortage at the Downstream Points of Hydropower Reservoirs for the Scenarios M2, M3, and M4

Control Point	Shortages (cfs)		
	M3	M2	M4
BRPP27	96.40	84.24	57.21
BRGR30	124.92	114.53	87.45
BRWA41	157.00	74.68	58.53
BRBR59	268.62	161.76	125.07
BRHE68	380.25	270.08	228.61
BRRI70	376.52	287.56	248.74
BRRO72	624.10	498.63	441.58

The monthly scenarios to observe the interactions between hydropower generation and environmental flows reflect significant results. It is possible to conclude from the comparisons that releases from the reservoirs to generate power is not only for meeting energy demand for the region but also reducing the water shortage for environmental needs. Analyses based on monthly historical data and firm instream flow targets also reflects shortcomings. Instream flow rights are established by TCEQ based on magnitude, hydrologic condition, season, and location of the stream gages. Therefore, this analysis should be applied in the daily modeling system with the same methodology to observe not only instream flow targets and shortages but also pulse flow events.

5.2.1.2 Comparison of Daily Simulation Results

SB3 environmental flow standards were defined in terms of flow regimes that describes the magnitude, frequency, duration, timing, and rate of change of flows depending on the location, season and hydrologic condition, which means that minimum environmental flows vary day to day. Because of the capability of the monthly modeling system, targets were defined in input data by aggregating daily targets, which indicate uncertainties. In order to observe how hydropower generation affects environmental flow standards in terms of streamflow targets and pulse flow events, scenarios in daily time interval were formulated. In this section, the first part evaluates the metrics of naturalized, regulated, and unappropriated and instream flow targets and shortages for control points. The second part assesses the pulse flow events in terms of total quantities of initiated, terminated, and completed pulse flows.

5.2.1.2.1 Comparisons of D2, D3 and D4 Scenarios

Daily versions of the scenarios of D2, D3, and D4 were performed by using original SB3 environmental flow standards that were summarized in Chapter III instead of instream flow rights that were assigned with TS records. D2, D3, and D4 scenarios are the monthly analysis of scenarios performed in the previous section. Except for naturalized flows that were inputted into the modeling system, results for stream flow of regulated and unappropriated and instream flows targets and shortages vary in each scenario. Simulation results indicate that hydropower generation in the basin area enables to decline the shortages of instream flows at downstream points of hydropower dams. Similarly, mean regulated flows show a possible upward trend due to hydropower releases. Table 61 shows the regulated and unappropriated stream flows at 19 primary control points for the scenarios of D3, D2, and D4 respectively.

Table 61: Means of SB3 EFS Instream Flow Targets and Shortages at 19 Control Points for the Scenarios D2, D3, and D4

Control Point	Naturalized Flow (cfs)	Regulated Flows (cfs)			Unappropriated Flows (cfs)		
		D3	D2	D4	D3	D2	D4
SFAS06	89.59	88.45	88.46	88.51	5.59	6.06	7.23
DMAS09	135.84	132.70	132.81	133.15	3.49	3.83	6.02
BRSE11	304.74	301.63	301.74	302.07	15.63	15.75	18.80
CFNU16	111.96	80.67	82.89	85.26	4.66	4.78	6.27
BRSB23	806.85	767.81	772.16	776.32	35.06	30.07	31.11
CON026	130.46	99.47	101.66	104.05	6.93	7.20	9.54
BRPP27	992.28	634.02	675.51	768.74	56.74	47.55	57.23
BRGR30	1,399.72	928.46	970.58	1,063.08	133.06	106.99	119.87
NBCL36	224.36	213.54	213.69	213.92	69.87	71.21	73.40
BRWA41	2,569.08	1,826.37	1,902.21	1,998.45	659.12	622.79	669.67
LEGT47	347.13	316.23	316.37	316.61	39.26	39.04	40.43
LAKE50	165.31	161.07	161.12	161.20	46.97	46.76	46.83
LRLR53	1,164.95	852.64	854.16	856.35	353.76	353.39	356.93
LRCA58	1,840.85	1,453.42	1,455.13	1,457.63	646.12	648.42	657.46
BRBR59	5,473.76	4,292.09	4,370.67	4,470.74	1,838.23	1,807.90	1,857.92
NAEA66	464.73	332.85	332.86	333.24	124.52	125.75	126.46
BRHE68	7,378.07	5,957.58	6,034.76	6,133.45	2,831.31	2,808.92	2,861.84
BRRI70	8,061.21	6,477.48	6,553.61	6,651.43	3,327.95	3,325.56	3,395.14
BRRO72	8,444.70	6,436.19	6,516.59	6,620.26	4,261.52	4,259.61	4,333.07

It is noted that mean instream flow targets that were computed in the monthly version are quite different from the daily version because of the way environmental flow standards incorporated in the modeling system. The modeling of instream flows in a mean value for each month instead of incorporating minimum flow value for each season and hydrologic condition differently depending on different flow types causes results from scenarios to be different. Shortages in meeting targets are computed in each day with the formulation of regulated streamflow less instream flow target. The reason mentioned for the difference between daily and monthly analysis shows its effects on shortages. As a result of simulations, the mean shortage of instream flows shows the decreasing trend with monthly simulations but lower values were obtained. Table shows 62 the mean instream flow targets and shortages of the relevant scenarios.

Table 62: Means of SB3 EFS Instream Flow Targets and Shortages at 19 Control Points for the Scenarios D2, D3, and D4

Control Point	Instream Flow Targets (cfs)			Instream Flow Shortages (cfs)		
	D3	D2	D4	D3	D2	D4
SFAS06	5.49	5.49	5.49	0.61	0.61	0.61
DMAS09	9.20	9.20	9.20	1.08	1.08	1.08
BRSE11	30.28	30.28	30.28	2.86	2.86	2.86
CFNU16	9.54	9.59	9.57	1.02	1.01	0.99
BRSB23	81.87	81.85	81.87	8.62	8.49	8.40
CON026	9.02	9.02	9.02	1.56	1.54	1.49
BRPP27	161.14	162.33	162.27	37.40	28.36	18.92
BRGR30	266.14	265.43	265.21	35.27	26.69	16.99
NBCL36	22.99	23.00	22.93	1.69	1.67	1.65
BRWA41	447.15	444.09	443.55	77.77	31.02	33.61
LEGT47	29.05	29.06	29.06	3.24	3.22	3.20
LAKE50	36.84	36.84	36.84	3.93	3.93	3.90
LRLR53	200.99	201.10	201.04	34.80	34.49	33.77
LRCA58	377.38	377.18	378.55	43.80	43.39	43.04
BRBR59	1,294.04	1,290.19	1,288.80	237.70	165.92	153.82
NAEA66	33.69	33.73	33.94	4.62	4.59	4.55
BRHE68	2,082.69	2,076.47	2,072.27	329.38	256.02	237.62
BRRI70	2,297.34	2,290.80	2,288.52	379.79	310.56	285.97
BRRO72	2,598.93	2,595.29	2,590.25	573.75	490.62	458.13

The stream gages as shown in Figure 36 that are just downstream points of reservoirs showed a cumulative decrease on mean instream flow shortages from upstream to downstream. Table 63 outlines the curtailment of the environmental flow rights at the downstream points of the dams for three scenarios.

Table 63: Means of SB3 EFS Shortage at the Downstream Points of Hydropower Reservoirs for the Scenarios D2, D3, and D4

Control Point	Instream Flow Shortages (cfs)		
	D3	D2	D4
BRPP27	37.40	28.36	18.92
BRGR30	35.27	26.69	16.99
BRWA41	77.77	31.02	33.61
BRBR59	237.70	165.92	153.82
BRHE68	329.38	256.02	237.62
BRRI70	379.79	310.56	285.97
BRRO72	573.75	490.62	458.13

5.2.1.2.2 Comparisons of D5, D6 and D9 Scenarios

Reservoir releases for hydroelectric power result in short-term fluctuations in flow rates at downstream control points. Pulse flow events are the consecutive days between the days in which regulated flows meet the initiation and termination criteria that are defined in environmental flow standards. The comparison between the scenarios of D5, D6, and D9 was made to observe the impacts of hydropower generation on pulse flow events. The D5 scenario represents the authorized scenario use without any hydropower rights at two reservoirs were compared with D6 and D9 scenarios in which hydropower generation was included in the dataset with energy target of 60,000 MWh/year and 90,000 MWh/year respectively. The simulations were performed using daily time interval with routing and forecasting to increase the accuracy of the modeling process and high pulse flow event properly.

Pulse flow events in each scenario were evaluated by comparing the total number of events that were initiated, terminated, and completed. Tracking option in all PF records was activated to get an output of the total quantities of initiated, terminated, and completed pulse flows. Table 64 shows the simulation results for pulse flow events. The results illustrated that hydropower generation increased the number of days of pulse flow events at just downstream points of the reservoirs while the effects of hydropower releases at further downstream points normalized.

Table 64: Comparison of Pulse Flow Events in 19 Control Points for the Scenarios D5, D6, and D9

Control Point	D5 SCENARIO			D6 SCENARIO			D9 SCENARIO		
	Initiated	Terminated	Completed	Initiated	Terminated	Completed	Initiated	Terminated	Completed
SFAS06	208	11	197	208	11	197	208	11	197
DMAS09	205	10	195	205	10	195	204	10	194
BRSE11	212	7	205	212	7	205	212	7	205
CFNU16	224	24	200	224	24	200	224	23	201
BRSB23	212	7	205	212	7	205	212	7	205
CON026	239	18	221	239	18	221	239	18	221
BRPP27	1,015	116	899	1,030	97	933	1,046	85	961
BRGR30	890	66	824	901	46	855	901	39	862
NBCL36	229	2	227	229	2	227	229	3	226
BRWA41	382	22	360	390	23	367	394	17	377
LEGT47	363	5	358	363	5	358	363	5	358
LAKE50	359	12	347	359	12	347	358	12	346
LRLR53	438	27	411	434	24	410	435	26	409
LRCA58	441	128	313	440	128	312	442	129	313
BRBR59	458	11	447	456	5	451	454	4	450
NAEA66	326	21	305	326	22	304	326	23	303
BRHE68	454	11	443	454	10	444	454	9	445
BRRI70	462	21	441	463	20	443	463	18	445
BRRO72	457	16	441	455	14	441	458	14	444
TOTAL	7,574	535	7,039	7,600	485	7,115	7,622	460	7,162

5.2.2 Impacts of Flood Control Operations on Environmental Flow Standards

Reservoir operation rules that are followed to store and release water during flooding may vary water availability through stream rivers. Storing and releasing excess flows depending on maximum allowable flood limits and discharge capacity of the reservoirs affect not only regulated and unappropriated flows but also pulse flow events. In this part of the section, impacts of flood control operations on streamflow of regulated and unappropriated, instream flow targets and shortages, and pulse flow events were assessed. The scenarios of D6, D7, and D8 were performed by applying flow routing and 10-day forecasting. Table 65 and 66 show the regulated flows and unappropriated flows at the 19 control points environmental flow standards identified respectively.

Table 65: Mean Naturalized and Mean Simulated Regulated Stream Flows at 19 Control Points for the Scenarios D2, D6, D7, and D8

Control Point	Naturalized Flow (cfs)	Regulated Flows (cfs) D2	D6	D7	D8
SFAS06	89.59	88.46	80.57	80.57	80.57
DMAS09	135.84	132.81	100.96	100.96	100.96
BRSE11	304.74	301.74	280.04	280.04	280.04
CFNU16	111.96	82.89	66.31	66.34	66.31
CON026	130.46	101.66	84.63	84.65	84.63
BRSB23	806.85	772.16	751.32	751.30	751.43
BRPP27	992.28	675.51	657.55	656.25	657.27
BRGR30	1,399.72	970.58	956.20	955.98	956.76
NBCL36	224.36	213.69	214.66	214.65	214.68
BRWA41	2,569.08	1,902.21	1,878.43	1,878.11	1,879.48
LEGT47	347.13	316.37	312.02	312.00	311.99
LAKE50	165.31	161.12	160.68	160.68	160.68
LRLR53	1,164.95	854.16	831.33	831.32	831.27
LRCA58	1,840.85	1,455.13	1,428.25	1,428.24	1,428.14
BRBR59	5,473.76	4,370.67	4,330.09	4,329.75	4,330.75
NAEA66	464.73	332.86	335.93	335.80	335.89
BRHE68	7,378.07	6,034.76	5,999.04	5,998.57	5,999.58
BRRI70	8,061.21	6,553.61	6,521.00	6,520.48	6,521.38
BRRO72	8,444.70	6,516.59	6,496.08	6,495.61	6,496.15

Table 66: Mean Naturalized and Mean Simulated Unappropriated Stream Flows at 19 Control Points for the Scenarios D2, D6, D7, and D8

Control Point	Naturalized Flow (cfs)	Unappropriated Flows (cfs) D2	D6	D7	D8
SFAS06	89.59	6.06	35.36	35.47	35.4
DMAS09	135.84	3.83	18.86	18.82	18.86
BRSE11	304.74	15.75	39.90	40.18	39.54
CFNU16	111.96	4.78	7.73	7.75	7.76
CON026	130.46	30.07	11.41	11.37	11.4
BRSB23	806.85	7.20	21.31	23.64	24.27
BRPP27	992.28	47.55	50.18	49.97	49.25
BRGR30	1,399.72	106.99	108.51	107.86	106.56
NBCL36	224.36	71.21	65.74	66.63	66.35
BRWA41	2,569.08	622.79	704.08	698.94	705.26
LEGT47	347.13	39.04	61.65	61.59	61.24
LAKE50	165.31	46.76	46.32	46.10	46.33
LRLR53	1,164.95	353.39	362.38	363.28	362.03
LRCA58	1,840.85	648.42	608.33	608.85	608.66
BRBR59	5,473.76	1,807.90	1,647.35	1,649.65	1,652.69
NAEA66	464.73	125.75	130.68	130.58	130.64
BRHE68	7,378.07	2,808.92	2,424.90	2,430.30	2,436.00
BRRI70	8,061.21	3,325.56	3,182.12	3,185.19	3,190.44
BRRO72	8,444.70	4,259.61	4,170.83	4,173.77	4,178.15

It is apparent from the tables that incorporation of flood control operations in the reservoir system decreases regulated flow at pertinent control points because water is stored in reservoirs based on operation rules. Also, unappropriated flows show varies depending on water availability due to flood control operations. In addition to regulated and unappropriated flows, instream flow targets and shortages change at control points for each scenario. Table 67 and 68 compare instream flow targets and shortages for the scenarios of D2, D6, D7, and D8.

Table 67: Means of SB3 EFS Flow Targets for the Scenarios D2, D6, D7, and D8

Control	SB3 EFS Instream Flow Targets			
Point	D2	D6	D7	D8
SFAS06	5.49	5.46	5.46	5.46
DMAS09	9.20	8.95	8.95	8.95
BRSE11	30.28	30.16	30.16	30.16
CFNU16	9.59	9.36	9.36	9.36
CON026	81.85	8.96	8.96	8.96
BRSB23	9.02	81.70	81.70	81.70
BRPP27	162.33	162.49	162.79	162.21
BRGR30	265.43	265.98	265.65	264.49
NBCL36	23.00	23.08	23.08	23.08
BRWA41	444.09	438.48	438.55	436.91
LEGT47	29.06	29.04	29.04	29.04
LAKE50	36.84	36.82	36.82	36.82
LRLR53	201.10	198.92	198.87	198.81
LRCA58	377.18	382.42	382.63	382.48
BRBR59	1,290.19	1,281.61	1,281.47	1,280.79
NAEA66	33.73	33.94	33.94	33.94
BRHE68	2,076.47	2,056.81	2,054.76	2,054.30
BRRI70	2,290.80	2,281.36	2,281.56	2,281.80
BRRO72	2,595.29	2,578.87	2,577.76	2,579.04

Table 68: Means of SB3 EFS Flow Shortages for the Scenarios D2, D6, D7, and D8

Control	SB3 EFS Instream Flow Shortages			
Point	D2	D6	D7	D8
SFAS06	0.61	1.08	1.08	1.08
DMAS09	1.08	1.57	1.57	1.57
BRSE11	2.86	3.77	3.77	3.77
CFNU16	1.01	1.24	1.24	1.24
CON026	8.49	2.18	2.18	2.19
BRSB23	1.54	9.51	9.51	9.51
BRPP27	28.36	29.34	29.54	29.40
BRGR30	26.69	25.75	25.82	25.57
NBCL36	1.67	1.72	1.71	1.72
BRWA41	31.02	26.15	26.70	28.06
LEGT47	3.22	3.23	3.23	3.23
LAKE50	3.93	4.02	4.02	4.02
LRLR53	34.49	39.60	39.59	39.65
LRCA58	43.39	52.96	53.01	52.88
BRBR59	165.92	159.11	159.65	162.25
NAEA66	4.59	5.08	5.09	5.08
BRHE68	256.02	242.71	243.25	246.06
BRRI70	310.56	301.99	302.63	305.33
BRRO72	490.62	488.44	489.96	492.59

Flood control operations in basin areas have also effects on pulse flow events. The scenarios of D2 and D6 were compared to evaluate the effectiveness of flood control operations on pulse flow events. Table 69 presents change in the days of pulse flow events due to flood control operations in the Brazos River Basin.

Table 69: Comparison of Pulse Flow Events in 19 Control Points for the Scenarios D2 and D6

Control Point	D2 SCENARIO			D6 SCENARIO		
	Initiated	Terminated	Completed	Initiated	Terminated	Completed
SFAS06	212	14	198	208	11	197
DMAS09	214	11	203	205	10	195
BRSE11	212	5	207	212	7	205
CFNU16	228	18	210	224	24	200
BRSB23	212	7	205	212	7	205
CON026	239	18	221	239	18	221
BRPP27	1,017	88	929	1,030	97	933
BRGR30	893	49	844	901	46	855
NBCL36	227	3	224	229	2	227
BRWA41	394	21	373	390	23	367
LEGT47	364	7	357	363	5	358
LAKE50	359	13	346	359	12	347
LRLR53	451	25	426	434	24	410
LRCA58	449	148	301	440	128	312
BRBR59	467	14	453	456	5	451
NAEA66	321	18	303	326	22	304
BRHE68	461	6	455	454	10	444
BRRI70	468	16	452	463	20	443
BRRO72	453	11	442	455	14	441
TOTAL	7,641	492	7,149	7,600	485	7,115

As Table 69 shows, there is a decrease in the number of days pulse flow events of initiated, terminated, and completed. Also, the scenarios of D6, D7, and D8 were compared to observe the number of days of high pulse flow events in different reservoir flood control operations. Table 70 compares high pulse flow events for the scenarios of D6, D7, and D8. Depending on the flood control operation rules, a different number of pulse flow events were observed in the Brazos River Basin.

Table 70: Comparison of Pulse Flow Events in 19 Control Points for the Scenarios D6, D7, and D8

Control Point	D6 SCENARIO			D7 SCENARIO			D8 SCENARIO		
	Initiated	Terminated	Completed	Initiated	Terminated	Completed	Initiated	Terminated	Completed
SFAS06	208	11	197	208	11	197	208	11	197
DMAS09	205	10	195	205	10	195	205	10	195
BRSE11	212	7	205	212	7	205	212	7	205
CFNU16	224	24	200	224	24	200	224	24	200
BRSB23	212	7	205	212	7	205	212	7	205
CON026	239	18	221	239	18	221	239	18	221
BRPP27	1,030	97	933	1,034	99	935	1,031	97	934
BRGR30	901	46	855	903	45	858	902	48	854
NBCL36	229	2	227	229	2	227	229	2	227
BRWA41	390	23	367	389	23	366	387	23	364
LEGT47	363	5	358	363	5	358	363	5	358
LAKE50	359	12	347	359	12	347	359	12	347
LRLR53	434	24	410	434	24	410	433	24	409
LRCA58	440	128	312	441	128	313	442	129	313
BRBR59	456	5	451	456	5	451	455	6	449
NAEA66	326	22	304	326	22	304	326	22	304
BRHE68	454	10	444	452	11	441	452	11	441
BRRI70	463	20	443	463	20	443	464	21	443
BRRO72	455	14	441	456	14	442	457	13	444
TOTAL	7,600	485	7,115	7,605	487	7,118	7,600	490	7,110

5.3 Evaluations of Flood Control on River/Reservoir System

Flood control capabilities of the WRAP modeling system and the methods for flood frequency analyses of the reservoirs and stream gages based on observed hydrology were studied in Chapter III and IV. The nine flood control reservoirs in the case study area is analyzed based on the methods studied in Chapter IV. In order to observe the changes on the risk of exceeding the allowable limits and recurrence period for the reservoirs and stream gages due to hydropower generation and environmental flow standards, different water allocation runs were evaluated. The main objectives of this section are assessing the following cases:

- assessment of the exceedance probability of nine flood control reservoirs
- impacts of hydropower generation on flood control,
- impacts of environmental flow standards on flood control.

The scenarios detailed in chapter IV were performed in this section. First of all, flood frequency analyses for nine USACE reservoirs were analyzed based on observed reservoir storage. This analysis was made to define the results from real-time reservoir system operations. Secondly, the impacts of hydropower generation on the risk of overtopping the reservoir at which energy generated and the flood frequency analyses of stream gages that have flood flow limits were assessed. Finally, impacts of implementation of SB3 environmental flow standards in the basin area on the risk of flooding at reservoirs and stream gages were evaluated.

The statistical and probability methods and package programs detailed in Chapter IV were applied for the simulation results. Reservoir storage in flood control reservoirs and regulated flows at stream gages were also assessed by developing frequency analyses. Statistical and probabilistic analysis methods and the programs of TABLES, HEC-DSS, and HEC-SSP explained in Chapter IV were used to calculate the exceedance risk and recurrence period for the reservoirs and stream gages. The flood frequency curves for reservoirs and stream gages based on the probability distribution methods of log-normal and log-Pearson type III are illustrated in Appendix B for interested scenarios. The results were compared with observed storage and observed stream flows that were derived from USGS.

5.3.1 Assessment of the Frequency Analysis Results in Nine USACE Flood Control Reservoirs

The data available on USGS for the daily observed storage volume in nine flood control reservoirs was analyzed to evaluate the risk of overtopping the dam. The maximum annual reservoir storage for nine dams was calculated on HEC-DSS, and the data file was imported to HEC-SSP to perform general frequency analyses. The probability distribution methods of log-normal and log-Pearson type III were used to develop flood frequency curves. After getting the results, linear interpolation was made to calculate the risk of exceedance the top of flood control pool. By using the equation recurrence time for exceeding the flood control pool was obtained for each dam. Tables 88-105 and Figures 65-82 show the flood frequency curves for reservoirs in log-normal and log-Pearson type III probability distribution methods. The probabilities of exceeding top of flood control pool for nine reservoirs were tabulated with return periods in Table 71.

Table 71: Recurrence Interval of Exceeding Top of Flood Control Pools

Reservoirs	Top of Flood Control Pool (ac-ft)	log-normal		log-Pearson type III	
		Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
Waco	726,400	1.60	62.57	0.33	307.61
Whitney	1,999,500	0.39	258.53	1.10	90.95
Aquilla	146,000	4.65	21.50	0.01	10000
Proctor	374,200	1.00	100.42	1.93	51.75
Belton	1,097,600	5.61	17.82	0.55	181.70
Stillhouse Hollow	630,400	16.64	6.01	1.01	99.21
Georgetown	130,800	0.40	249.00	1.32	75.56
Granger	244,000	0.68	146.58	1.79	55.94
Somerville	507,400	5.32	18.81	1.86	53.79

The results of frequency analyses for observed storage reveal that probability distribution methods may give different results for the risk of exceedance and return period with the same data. The log-Pearson type III is a recommended distribution method for not only flood volumes but also flood flows. Return periods calculated by log-Pearson type III distribution method for nine reservoirs are higher the 50-year recurrence interval that is the minimum design standard for federal dams.

5.3.2 Impacts of Hydropower Generation on Flood Control

The cumulative water storage in reservoirs makes flood control a crucial part of hydropower generation. Properly modeled and operated hydropower plants prevent flooding as well as produce energy simultaneously on river basin area. The simulation D6 that represents authorized scenario use without any hydropower rights at two reservoirs were compared with D7 and D8 scenarios in which hydropower generation was included in the dataset with energy target of 60,000 MWh/year and 90,000 MWh/year respectively. The simulations were performed in the daily modeling system by applying flow routing and 10-day forecasting. The effects of hydropower generation on flood control were examined for reservoirs and stream gages respectively. The number of days water level exceeds the conservation pool and flood control pool, the risk of overtopping the dam, and reservoir storage frequency statistics were computed to evaluate the flood control on the reservoirs. On the other hand, to assess the flooding at stream gages, the number of days water level passed the allowable flood flow limits at five control points were computed, and flood frequency analyses were performed.

Releases from the dams vary based on hydropower operations and energy target, which causes the storage in flood control reservoirs to vary. As expected, releases for energy production decreases storage, which makes a comparatively relative change on the risk of overtopping the dam. However, water demands at downstream of the hydropower reservoirs that are originally supplied from other reservoirs can be met from the releases for energy production, which increases water availability in other reservoirs. Consequently, hydropower operations may increase the risk of exceedance the top of flood control pool at other reservoirs while decreasing water availability in the flood control pool at the reservoir hydroelectricity generated.

Whitney Reservoir is mainly used for hydropower generation and flood control. Water diversions for other purposes are just for one water right and minimum instream flows at downstream control points. As illustrated in the previous section, hydropower generation affects environmental flows standards positively by decreasing instream flow shortages. Depending on water availability and minimum and maximum instream flow limits at downstream points, reservoir storages in the case study area varies. Figure 45 outlines the interested area including three reservoirs to analyze on hydropower impacts on flood control pool.

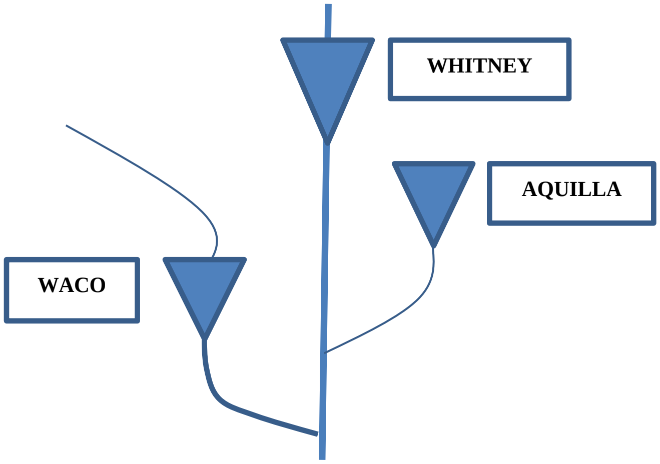


Figure 45: USACE Flood Control Reservoirs in the Hydropower Generation Area

Table 72 and 73 show the number of the days in the simulations when the storage content equals or exceeds the conservation capacity and flood control capacity respectively for nine reservoirs in the Brazos River Basin. Also, the return period and the percent chance exceedance the top of flood control pools were tabulated for three reservoirs by using log-Pearson Type III method in Table 74.

Table 72: The Number of Days Reservoir Storage Equals or Exceeds the Top of Conservation Pools in USACE Flood Control Reservoirs for the Scenarios D5, D6, and D9

	Waco	Whitney	Aquilla	Proctor	Belton	Stillhouse Hollow	Georgetown	Granger	Somerville
D5	753	967	965	1,706	1,813	1,787	225	3,458	4,405
D6	742	550	871	1,710	1,805	1,780	225	3,459	4,375
D9	772	504	843	1,703	1,792	1,779	225	3,460	4,376

Table 73: The Number of Days Reservoir Storage Equals or Exceeds the Top of Flood Control Pools in USACE Flood Control Reservoirs for the Scenarios D5, D6, and D9

	Waco	Whitney	Aquilla	Proctor	Belton	Stillhouse Hollow	Georgetown	Granger	Somerville
D5	0	0	1	21	43	73	0	0	0
D6	0	0	2	21	41	73	0	0	0
D9	0	0	0	21	39	72	0	0	0

Table 74: Recurrence Interval of Exceeding Top of Flood Control Pools based on log-Pearson Type III Distribution for the Scenarios D5, D6, and D9

	Waco		Whitney		Aquila	
	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
D5	0.01%	10,000	1.01%	99.08	0.06%	1,587.93
D6	0.01%	10,000	0.91%	110.29	0.32%	312.41
D9	0.01%	10,000	0.82%	121.99	0.18%	563.58

It can be seen from the results that the number of days water occurrence in flood control pools in Whitney and Aquilla decrease when the degree of hydropower generation in the river basin was increased. Notably, hydropower generation in dams results in reducing the risk of exceeding the top of flood control pool. Contrary to decreases in two reservoirs, the number of days water storage exceeded the top conservation pool in Waco rose slightly. A possible explanation for these results may be satisfying water demand and maintaining streamflow conditions at allowable levels at downstream points of the reservoirs. It seems possible that water releases for conservation purposes and minimum instream flows are met by hydropower releases instead of reservoir storage in Lake Waco, which results in the frequency of water occurrence in Lake Waco increases. Furthermore; floodwater is stored mostly in Lake Waco because of the multiple-system reservoir operations in scenarios. Another possible explanation for Aquilla Reservoir is that water needs at downstream points may be made from Aquilla Reservoir instead of Lake Whitney in some periods to maintain the optimum water level in Whitney Reservoir to generate hydroelectricity efficiently. Reservoirs are not operated to generate hydropower when the water level decrease below to minimum operational water level.

Overall, it is clear to say that hydropower generation in reservoir decreases the risk of overtopping the dam while affecting downstream reservoirs to rise the number of days water level exceeding the top of the conservation pools. However, more research on this topic needs to be undertaken before the association between hydropower generation and flood control is more clearly understood for reservoir management. This research analyzes just two hydropower plants and nine flood control pools in ten reservoirs. The effects of flood control operations on energy output changes depending on the basin area and operation policies. Figures 46-48 show the storage levels from three simulations for the reservoirs of Waco, Whitney, and Aquilla respectively.

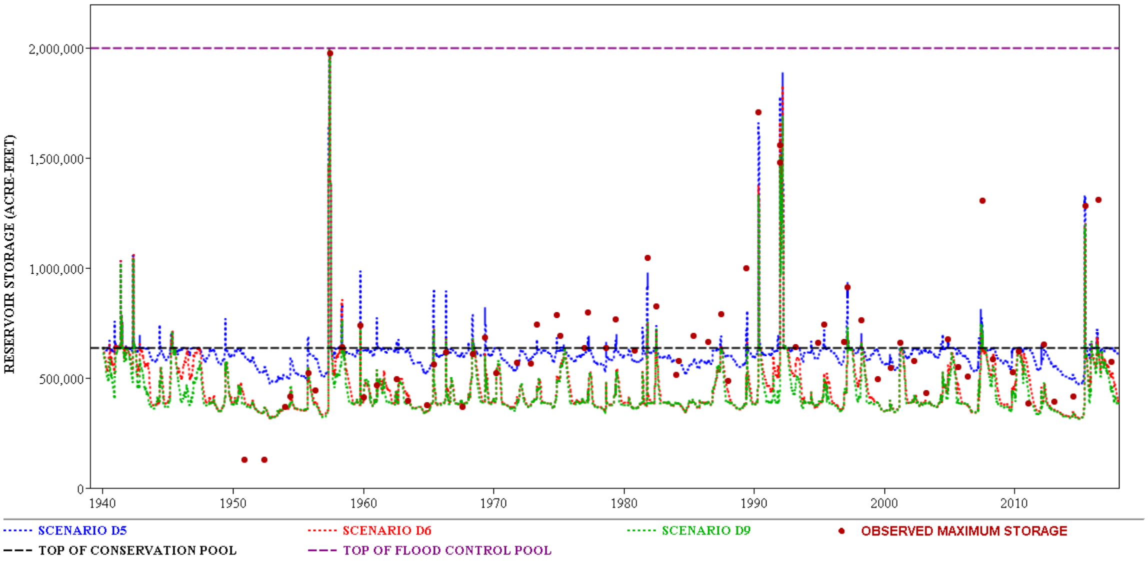


Figure 46: Comparison of Reservoir Storage in Whitney Reservoir for the Observed Values and the Scenarios D5, D6, and D9

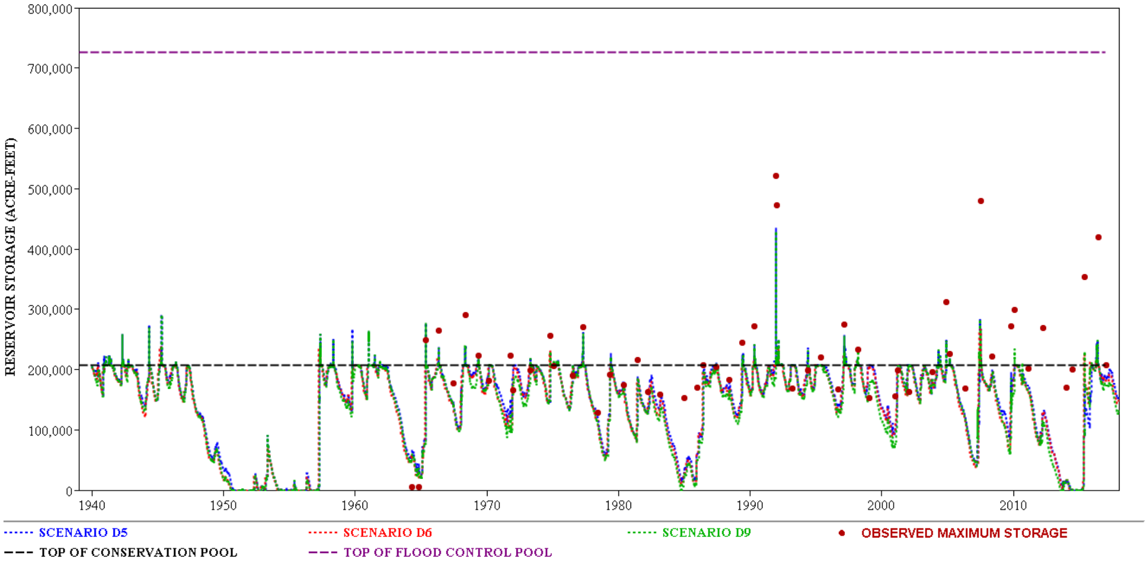


Figure 47: Comparison of Reservoir Storage in Waco Reservoir for the Observed Values and the Scenarios D5, D6, and D9

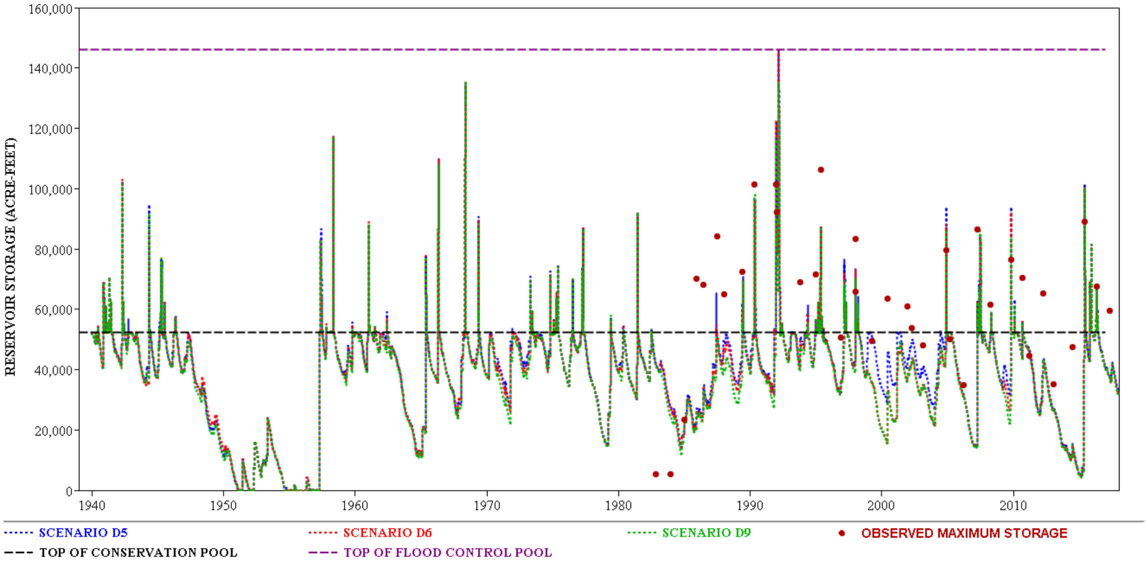


Figure 48: Comparison of Reservoir Storage in Aquilla Reservoir for the Observed Values and the Scenarios D5, D6, and D9

Releases from the dams are also made depending on maximum flow conditions at downstream points. USACE defined maximum allowable flow limits at several stream gages to prevent flooding. Flood control operations in reservoirs are implemented depending on these limits. Due to increases in regulated flows at downstream points of hydropower reservoirs, the percent of exceedance allowable flow limits increase through the river basin area. Figure 49 shows the two hydropower reservoirs and three stream gages where allowable flow limits are defined.

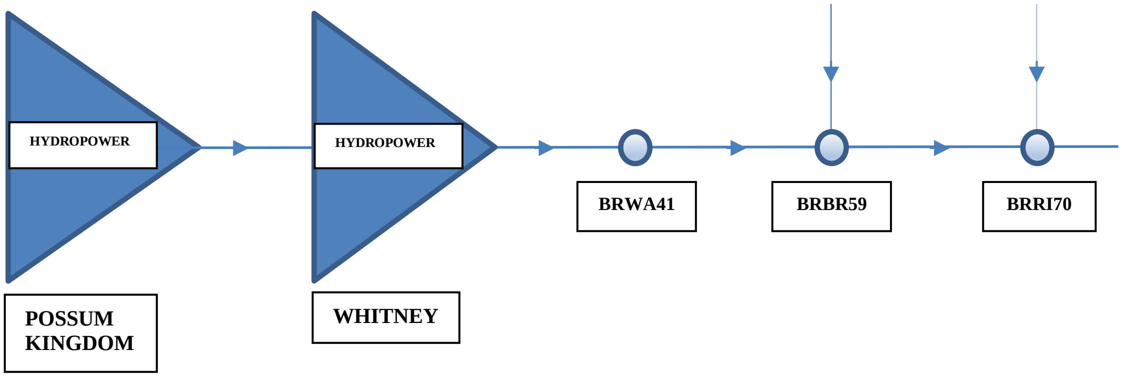


Figure 49: Systematic Overview of Hydropower Reservoirs and Stream Gages

Table 75 shows the number of days regulated flows at selected control points exceeds the maximum allowable flow limits for the scenarios of D5, D6 and D9.

Table 75: The Number of Days Regulated Flows at Control Points Equals or Exceeds the Maximum Allowable Flow Limits for the Scenarios D5, D6, and D9

	BRWA41	BRBR59	BRRI70
D5	51	826	1,324
D6	44	758	1,290
D9	44	760	1,276

The results illustrate that flooding at downstream points of hydropower reservoirs decrease slightly while hydropower is generated. These findings may be explained by the fact that reservoir storage decrease caused by hydropower generation results in emptying flood control pools more expeditiously during flooding. Consequently, the transition from flooding conditions to normal conditions at stream gages takes less time. Additionally, this slight change at downstream stream gages can be analyzed by performing statistical and probabilistic distribution methods of log-normal and log-Pearson type III. Tables 76 and 77 show the risk of exceeding maximum allowable flow limits at three stream gages that are located at downstream of hydropower reservoir for log-normal and log-Pearson type III methods respectively.

Table 76: Recurrence Interval of Exceeding Maximum Allowable Flow Limits based on log-Normal Distribution at for the Scenarios D5, D6, and D9

	BRWA41		BRBR59		BRRI70	
	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
D5	31.61%	3.16	72.92%	1.37	78.20%	1.28
D6	32.01%	3.12	73.02%	1.37	78.59%	1.27
D9	30.99%	3.23	72.86%	1.37	78.30%	1.28

Table 77: Recurrence Interval of Exceeding Maximum Allowable Flow Limits based on log-Pearson Type III Distribution for the Scenarios D5, D6, and D9

	BRWA41		BRBR59		BRRI70	
	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)	Percent Chance Exceedance	Return Period (year)
D5	32.31%	3.09	74.46%	1.34	80.87%	1.24
D6	32.83%	3.05	74.35%	1.35	81.02%	1.23
D9	31.88%	3.14	74.24%	1.35	80.63%	1.24

The findings observed in this analysis mirror those of the previous analysis for the just downstream of hydropower reservoir. However; there are ups and downs between the scenarios for the further downstream stream gages of the hydroelectricity dam. In general, there is a consistency that hydropower generation through river basin decrease flooding at not only reservoirs but also stream gages.

5.3.3 Impacts of Environmental Flow Standards on Flood Control

The scenarios of D6 and D10 were performed to assess the impacts of environmental flow standards on the flood control reservoirs and stream gages. The scenario D6 employs the version of the daily Brazos WAM adopted in this study by changing reservoir operations for flood control and hydropower. The scenario D10 is identical to scenario D6 except for the removal of SB3 environmental flow standards. The results of the simulations were compiled in tables showing the number of days of exceedance during the simulation. The simulations were analyzed for flood control reservoirs and stream gages separately. The number of days when the reservoir storage equals or exceeds the top of the conservation pools and flood controls are listed in Tables 78 and 79. The results show that environmental flow standards have minimal effects on reservoir flood control operations. The storage in nine flood control pools was plotted in Figures 51-58 for the scenarios of D6 and D10.

Table 78: The Number of Days Reservoir Storage Equals or Exceeds the Top of Conservation Pools in USACE Flood Control Reservoirs for the Scenarios D6 and D10

Scenario	Waco 509431	Whitney 515731	Aquila 515831	Proctor 515931	Belton 516031	Stillhouse 516131	Georgetown 516231	Granger 516331	Somerville 516431
D6	742	550	871	1,710	1,805	1,780	225	3,459	4,375
D10	754	548	840	1,709	1,804	1,778	225	3,459	4,375

Table 79: The Number of Days Reservoir Storage Equals or Exceeds the Top of Flood Control Pools in USACE Flood Control Reservoirs for the Scenarios D6 and D10

Scenario	Waco 509431	Whitney 515731	Aquila 515831	Proctor 515931	Belton 516031	Stillhouse 516131	Georgetown 516231	Granger 516331	Somerville 516431
D6	0	0	2	21	41	73	0	0	0
D10	0	0	1	21	41	72	0	0	0

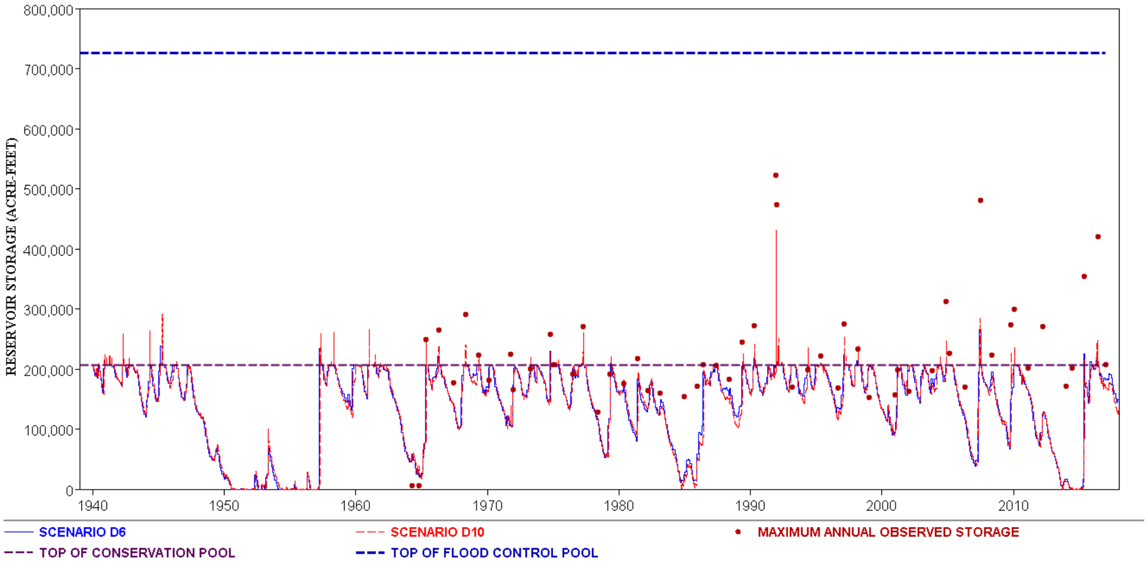


Figure 50: Comparison of Reservoir Storage in Waco Reservoir for the Observed Values and the Scenarios D6 and D10

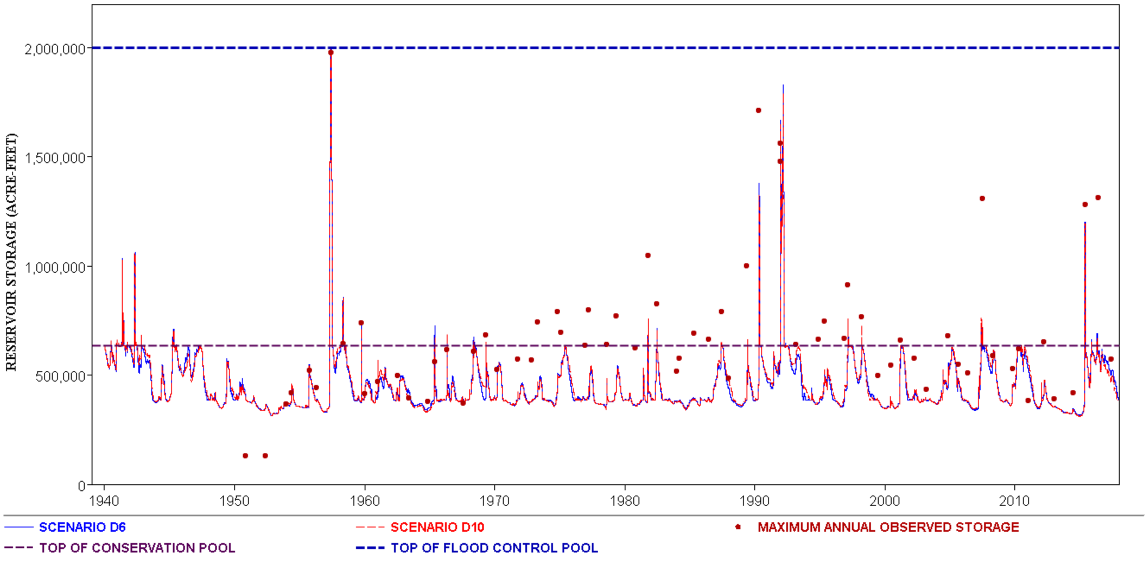


Figure 51: Comparison of Reservoir Storage in Whitney Reservoir for the Observed Values and the Scenarios D6 and D10

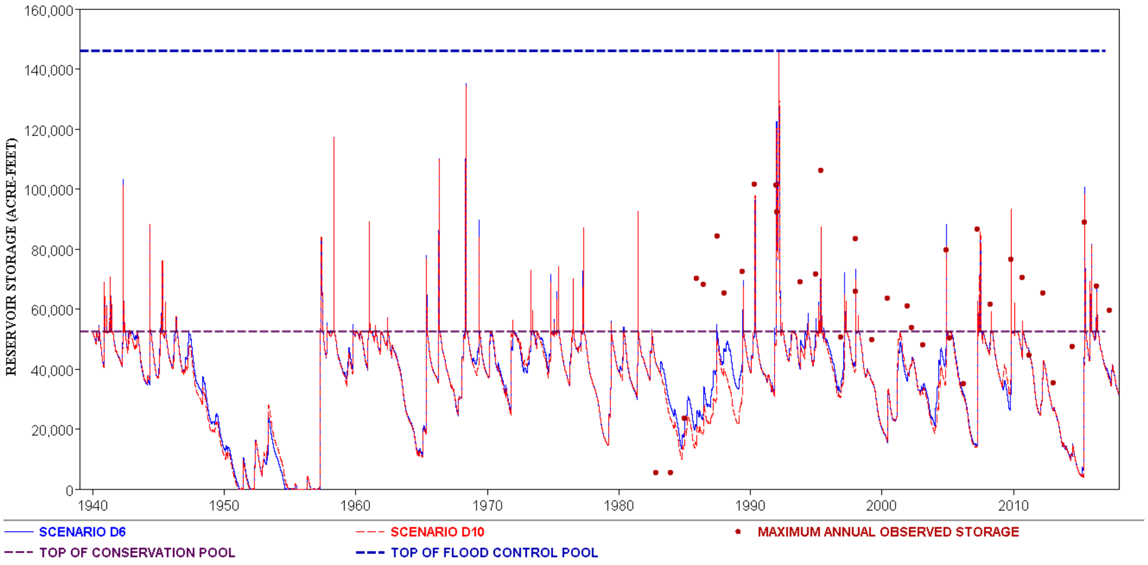


Figure 52: Comparison of Reservoir Storage in Aquilla Reservoir for the Observed Values and the Scenarios D6 and D10

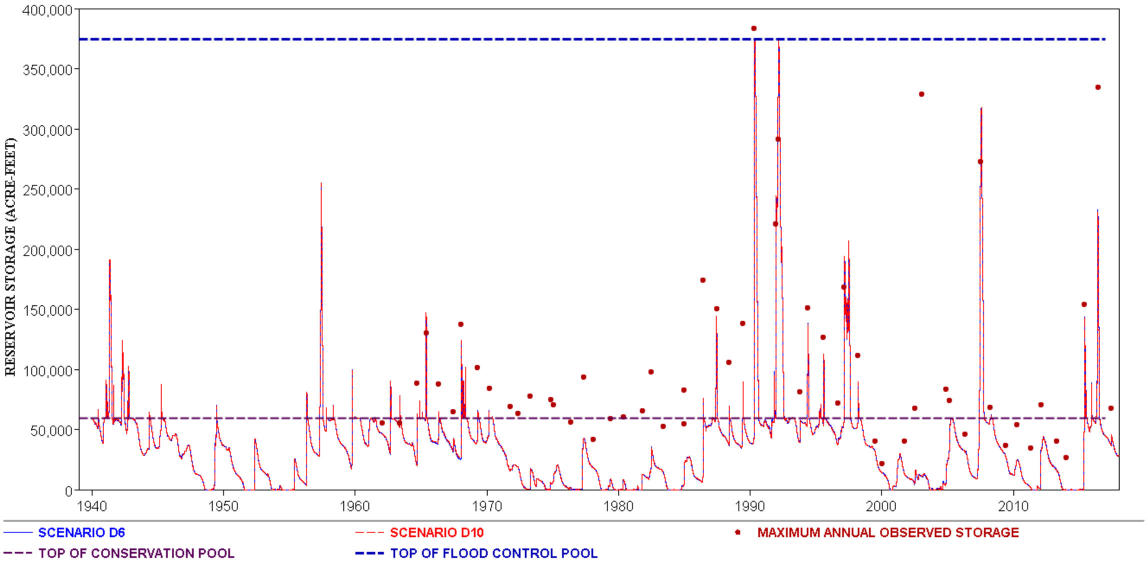


Figure 53: Comparison of Reservoir Storage in Proctor Reservoir for the Observed Values and the Scenarios D6 and D10

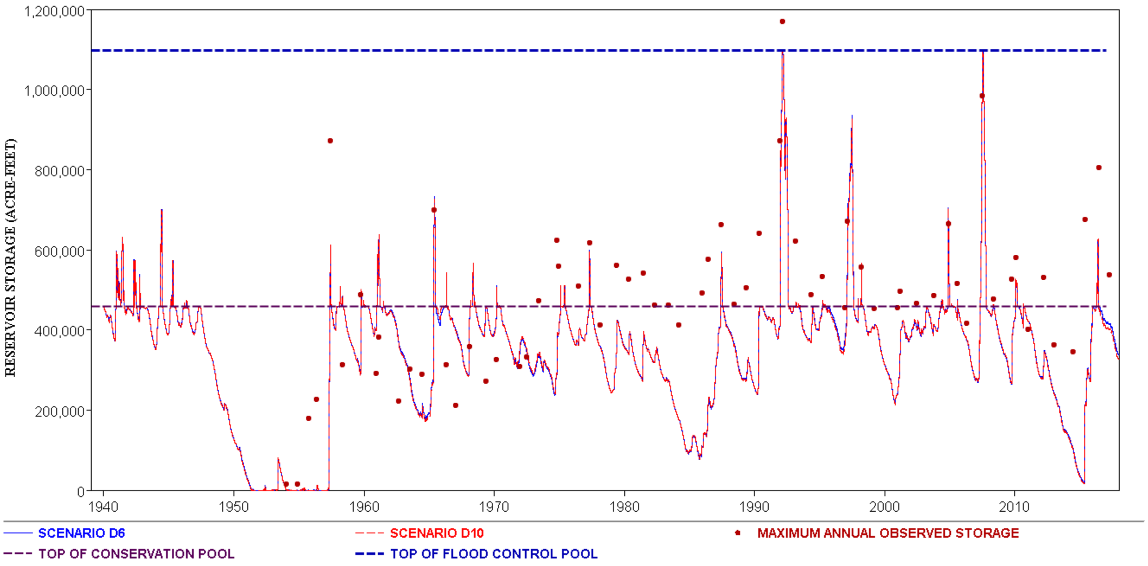


Figure 54: Comparison of Reservoir Storage in Belton Reservoir for the Observed Values and the Scenarios D6 and D10

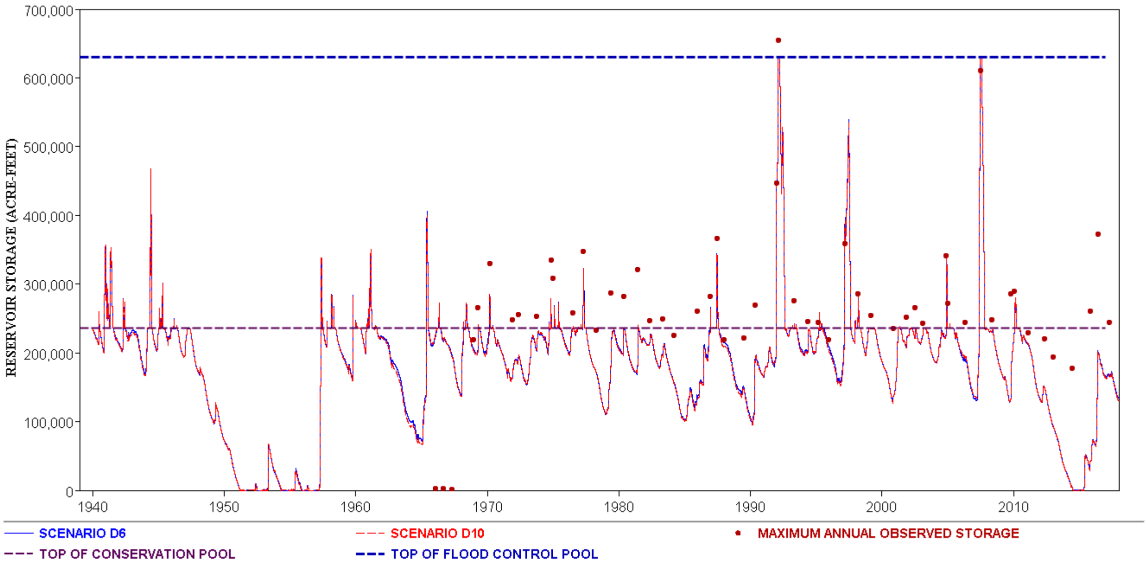


Figure 55: Comparison of Reservoir Storage in Stillhouse Hollow Reservoir for the Observed Values and the Scenarios D6 and D10

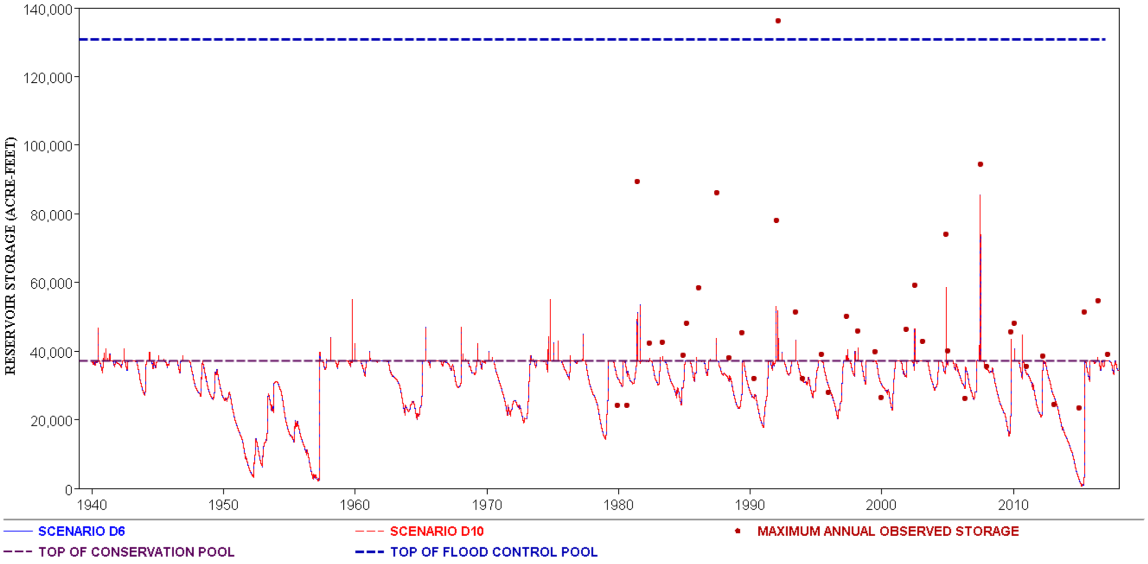


Figure 56: Comparison of Reservoir Storage in Georgetown Reservoir for the Observed Values and the Scenarios D6 and D10

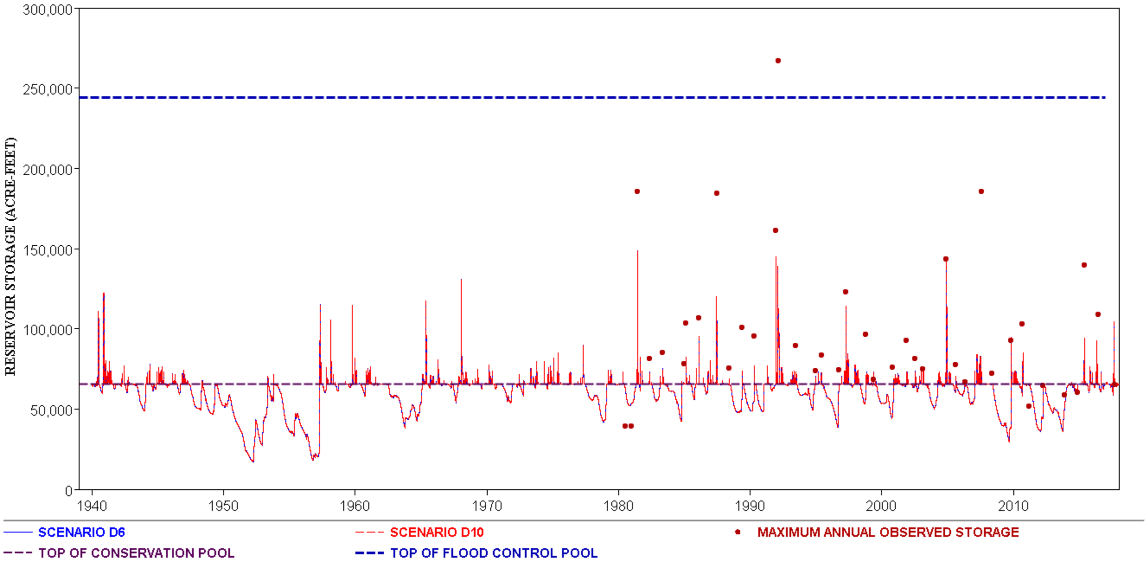


Figure 57: Comparison of Reservoir Storage in Granger Reservoir for the Observed Values and the Scenarios D6 and D10

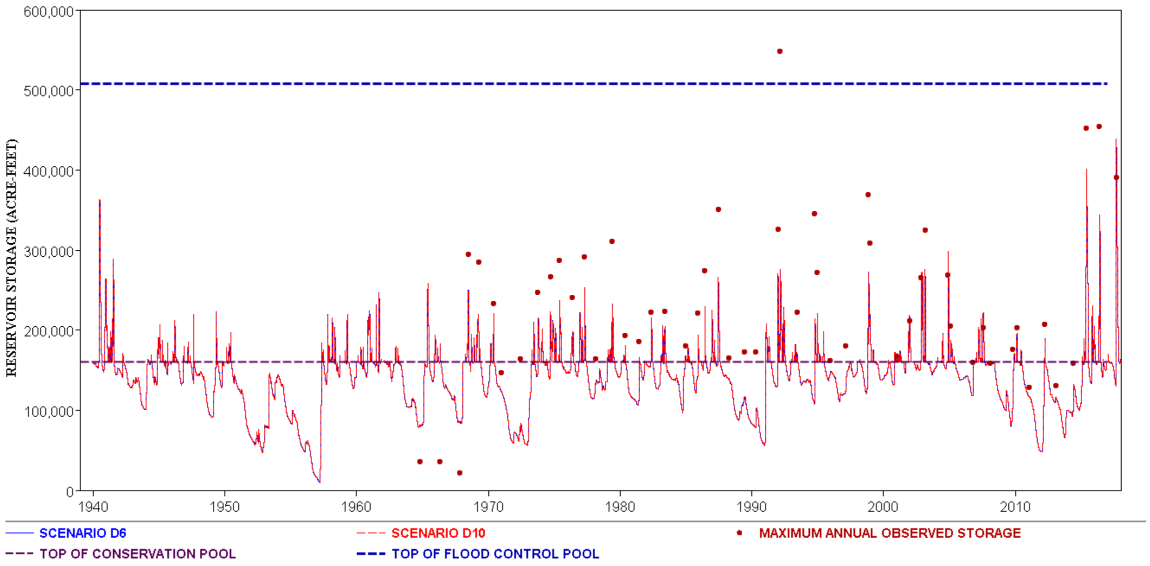


Figure 58: Comparison of Reservoir Storage in Somerville Reservoir for the Observed Values and the Scenarios D6 and D10

The scenarios of D6 and D10 were also compared with the maximum annual observed reservoir storage that is obtained from USGS. These comparisons for nine reservoirs show the differences between real-time flood control operations and reservoir system modeling simulations. Even if flow forecasting was applied in flood control simulations to increase the accuracy of the model, different water storage levels were computed for nine reservoirs. These differences can be explained by the capacity of the modeling systems to make historical analyses for river basin areas. As shown in Figures 50-58, maximum annual observed storages for nine flood control reservoirs are below the scenarios of D6 and D10.

The scenarios were also performed to analyze the risk of flooding at stream gages when the environmental flow standards were applied. Figure 59 presents the nine flood control reservoirs and six stream gages that have maximum allowable flow limits. The number of days water exceeds or equals the maximum allowable flow limits for these gages were tabulated in Table 80 for the scenarios of D6 and D10.

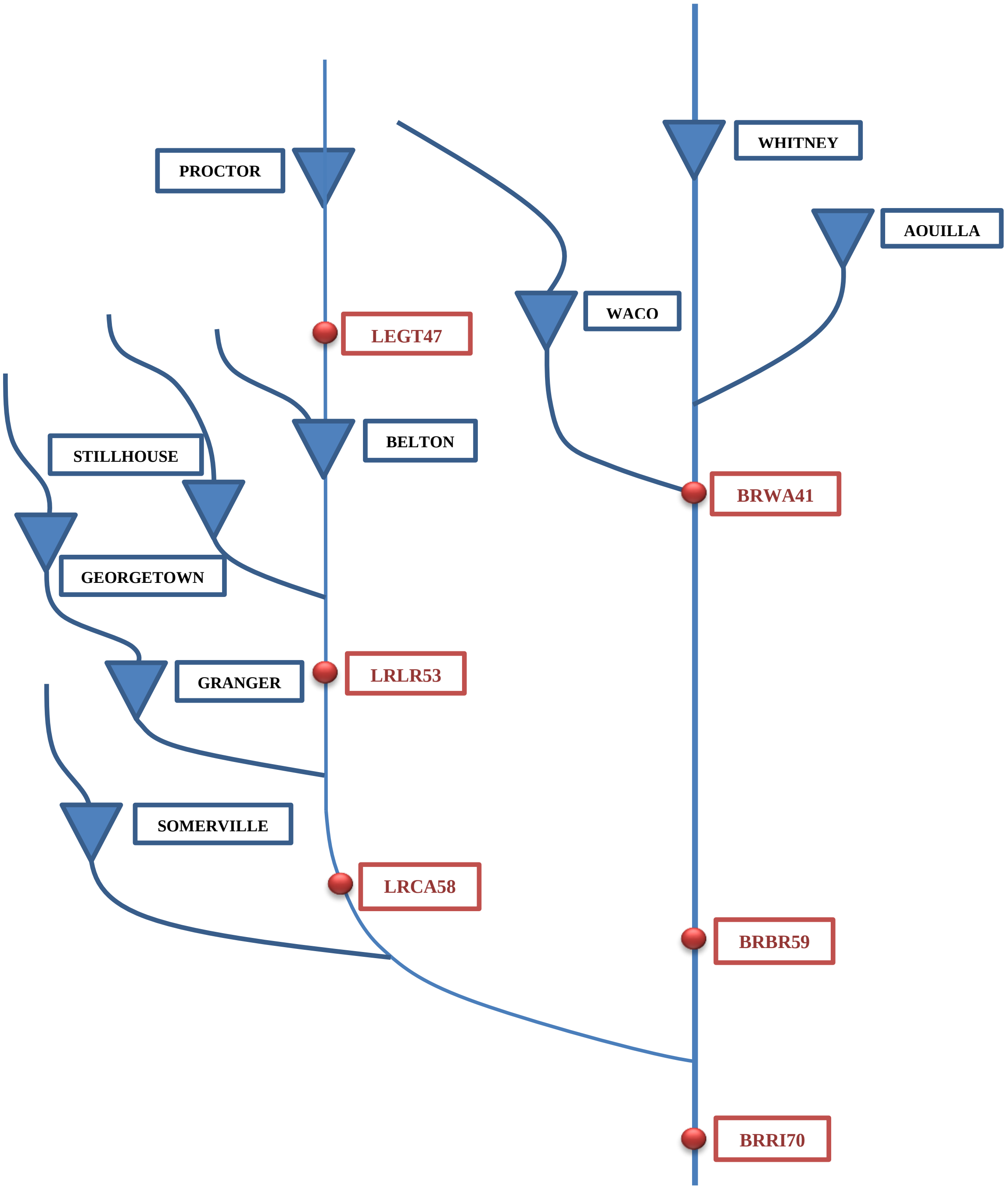


Figure 59: Systematic Overview of USACE Flood Control Reservoirs and Stream Gages

Table 80: The Number of Days Regulated Stream Flow Equals or Exceeds Maximum Allowable Flow Limits for the Scenarios D6 and D10

	BRWA41	LEGT47	LRLR53	LRCA58	BRBR59	BRRI70
D6	44	651	1,420	2,562	758	1,290
D10	45	648	1,420	2,556	757	1,283

As shown in Table 80, environmental flow standards have minimal effects on the number of days water level exceeds or equals the maximum allowable flow limits at selected stream gages. Also, the risk of exceedance flow limits at the gages was calculated on HEC-SSP, as shown in Table 81, by applying probability distribution methods of log-normal and log-Pearson Type III for both scenarios. The percent chance exceedance and return periods for the stream gages also show these smaller effects.

Table 81: Recurrence Interval of Exceeding Maximum Allowable Flow Limits based on log-Normal and log-Pearson Type III Distribution Methods for the Scenarios D6 and D10

Stream Gages		Log-Normal		Log-Pearson Type III	
		Scenario D6	Scenario D10	Scenario D6	Scenario D10
BRWA41	*Risk (%)*	32.01%	31.55%	32.83%	32.29%
	Period (year)	3.12	3.17	3.05	3.10
LEGT47	*Risk (%)*	77.60%	77.52%	82.21%	82.10%
	Period (year)	1.29	1.29	1.22	1.22
LRLR53	*Risk (%)*	78.07%	78.19%	78.05%	78.14%
	Period (year)	1.28	1.28	1.28	1.28
LRCA58	*Risk (%)*	93.66%	93.70%	92.72%	92.75%
	Period (year)	1.07	1.07	1.08	1.08
BRBR59	*Risk (%)*	73.02%	72.88%	74.35%	74.23%
	Period (year)	1.37	1.37	1.35	1.35
BRRI70	*Risk (%)*	78.59%	78.61%	81.02%	80.95%
	Period (year)	1.27	1.27	1.23	1.24

5.4 Comparative Analysis of Daily versus Monthly River/Reservoir System Modeling

River/reservoir simulation models are way to simplify real-world systems to analyze and develop water operations. Simulation models are routinely developed to increase the accuracy and ensure system to reflect real-world. Depending on the water management situations and applications, different computational time intervals are chosen to model components and deal with variables accurately. The modeling procedures followed in each system cause to get different outcomes of the reservoir and river systems. This section compares the results from the scenarios that employ the daily and monthly versions of the WRAP modeling system and reveal the factors that cause it. The main objectives of this section are assessing the following cases:

- comparative analysis of hydropower generation in daily and monthly modeling system
- comparative analysis of the incorporation of environmental flow standards in daily and monthly modeling system

The scenarios of D1, D2, M1, and M2 perform hydropower generation in two reservoirs and SB3 environmental flow standards at nineteen control points. First of all, this section analyzes the hydropower generation in different time interval by inputting Brazos WAM dataset and make comparisons between energy shortage, total hydroelectricity generation, and reservoir storage in a period between 1940 and 2017. Secondly, statistical frequency metrics for naturalized, regulated, and unappropriated flows and flow targets and shortages at nineteen control points that represent gaging stations the SB3 environmental flow standards incorporated were compared. Also, the reasons for these differences were conducted in this chapter to define the best way for the incorporation of instream flow rights in modeling systems.

5.4.1 Comparative Analysis of Hydropower Generation

Hydropower generation in daily and monthly timescale differs because of the implementation of river system rules and reservoir operations. Depending on each day, instream flow requirements at stream gages and optimal head in reservoirs change, which makes energy production different from monthly simulations. The height corresponding to the monthly storage at the beginning period is considered in a monthly time interval. However, the height corresponding the daily storage resulting from daily releases and smaller than in monthly modeling is used in computations. As a result of applying the same discharge but different height in calculations, different hydroelectricity output is obtained in different time interval approaches. Hydropower head differences in computations were shown in Figure 60 for monthly and daily time interval.

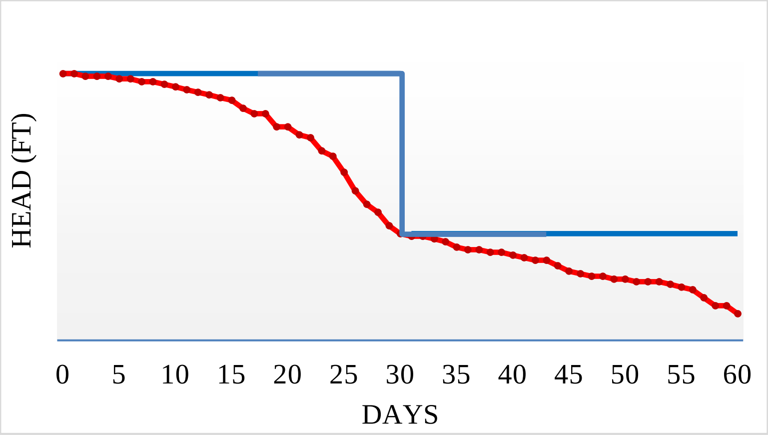


Figure 60: Comparison of Hydropower Generation in Daily and Monthly Modeling

Table 82 illustrates monthly and daily simulation results based on the same operations rules for hypothetically assigned hydropower generation in the basin area. As it can be seen from the results, hydropower generation in daily modeling is considerably lower than in monthly modeling.

Table 82: Comparison of Reliability of Hydropower for the Scenarios D1 and M1

Name	Energy Target (MWh-year)	Scenario D1 Mean Shortage (MWh-year)	Scenario D1 Reliability Period (%)	Scenario D1 Reliability Volume (%)	Scenario M1 Mean Shortage (MWh-year)	Scenario M1 Reliability Period (%)	Scenario M1 Reliability Volume (%)
POSDOM	24,000	5,237	74.55	78.18	594	96.69	97.53
WHITNY	36,000	12,772	55.61	64.52	6,871	73.40	80.92
TOTAL	60,000	18,010		69.98	7,464		87.56

Comparisons of the simulation results for the two scenarios in the daily and monthly version of the modeling system reveals the differences in terms of mean shortage and reliability of period and volume. It is also apparent from Table 83 which compares mean annual generation in the daily and monthly time interval that energy output in reservoir system varies depending on the computational time interval.

Table 83: Comparison of Hydropower Generation for the Scenarios D1 and M1

Scenario	Whitney (MWh/year)	Possum Kingdom (MWh/year)
D1	35,664	30,572
M1	40,883	34,979

Addition to issues explained flow routing is also another factor that effects on energy output in the reservoir system. Flow routing should be also considered detailly in river system to reflect real-time reservoir operations and increase the accuracy of the model. Lag and attenuation method that is applied in the daily version of the WRAP modeling system routes changes in flows that caused by reservoir releases, return flows, and streamflow depletion and adjusts the available flows at downstream points for reservoir operations and river system rules occurring upstream. Depending on this method, water availability through the reservoirs and streams differ from monthly modeling.

Following these differences, reservoir storage and energy generation for the interested reservoirs vary depending on the time scale. Comparing the two results, it can be seen that energy output may change when the sub-daily modeling system and hourly power demand are applied. Figures 61-64 show the annual energy generation and reservoir storage at the reservoirs of Whitney and Possum Kingdom respectively by comparing the scenarios 1 and 2.

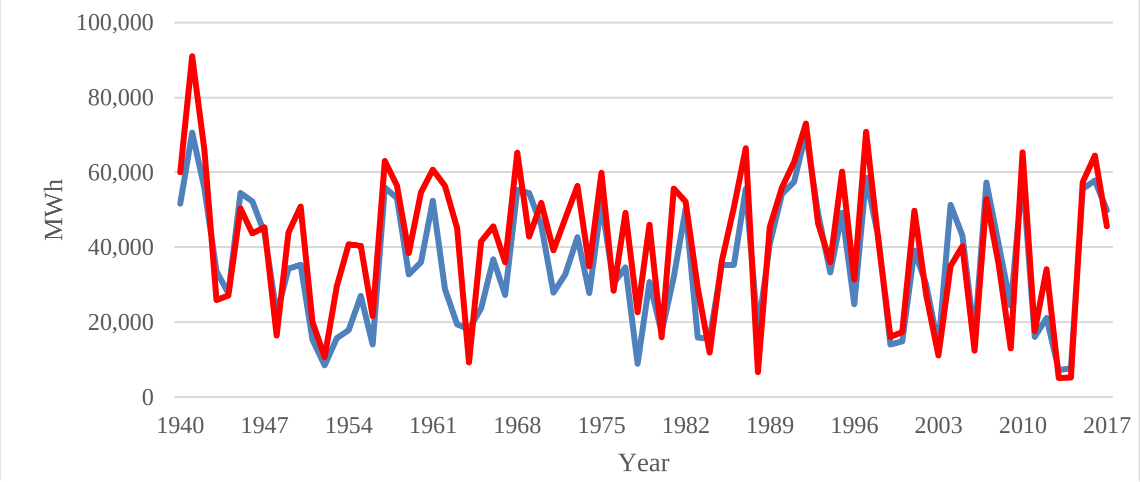


Figure 61: Comparison of Hydropower Generation over the period between 1940 and 2017 in Whitney Hydropower Plant for the Scenarios D1 and M1

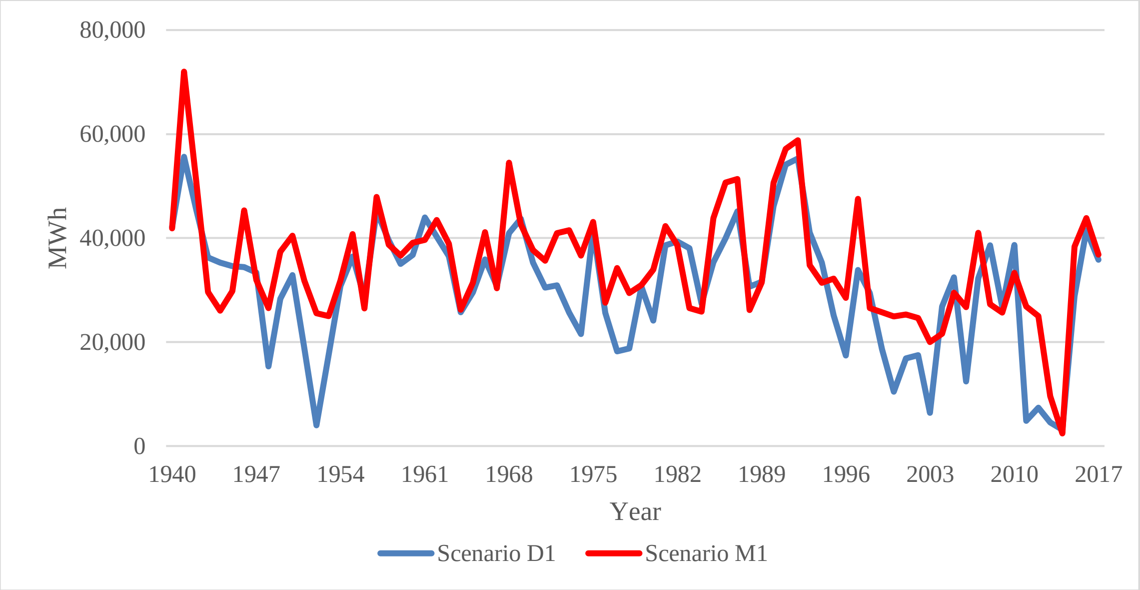


Figure 62: Comparison of Hydropower Generation over the period between 1940 and 2017 in Possum Kingdom Hydropower Plant for the Scenarios D1 and M1

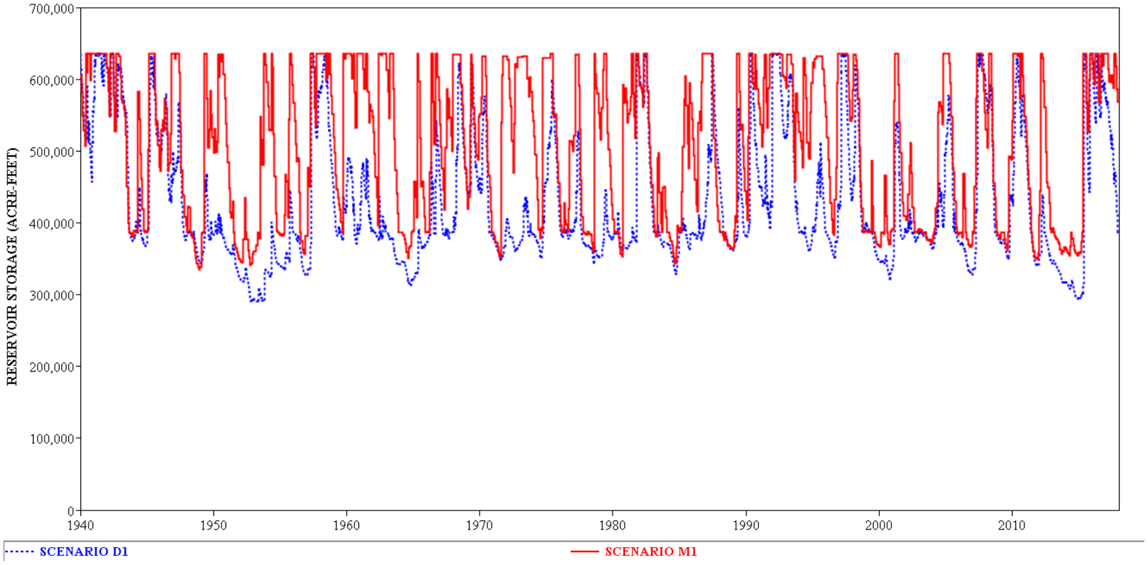


Figure 63: Comparison of Reservoir Storage in Whitney Reservoir for the Scenarios D1 and M1

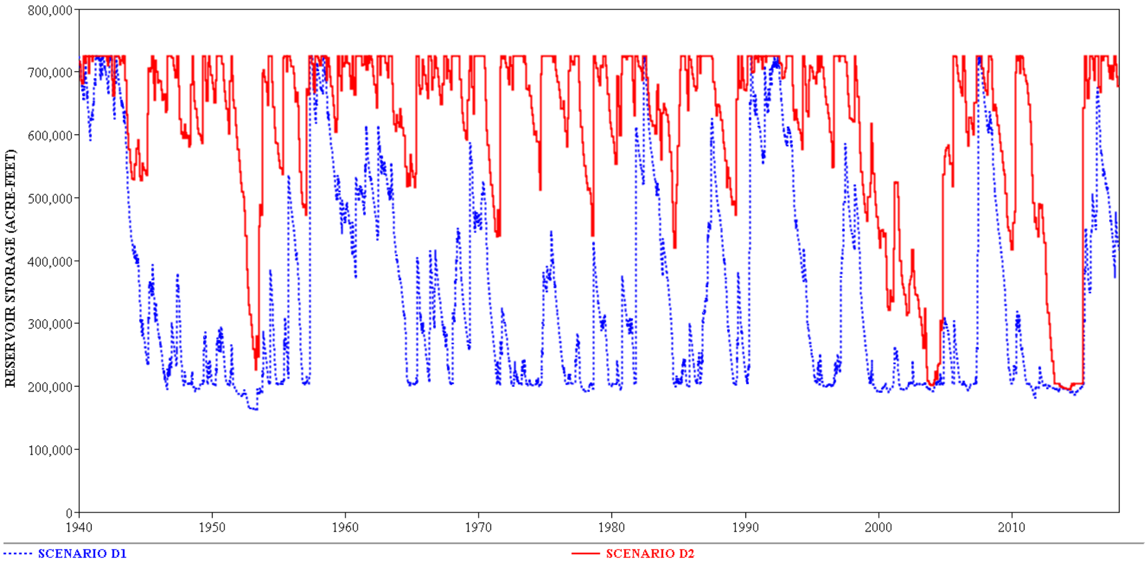


Figure 64: Comparison of Reservoir Storage in Possum Kingdom Reservoir for the Scenarios D1 and M1

5.4.2 Comparative Analysis of Environmental Flow Standards

SB3 environmental flow standards are modeled in terms of flow regimes that describes the magnitude, frequency, duration, timing, and rate of change of flows depending on the location, season, and hydrologic condition, which means that minimum environmental flows vary day to day. Hydrologic condition HC, environmental standard ES, pulse flow PF, and pulse flow supplemental options PO records are used to define instream flow rights for each control point specifically in the daily modeling system. However; instream flow targets are defined in a monthly time interval by aggregating daily targets, which decrease the accuracy of the model. A strategy is used here in which instream flow targets for each location are computed with daily time interval and inputted to the monthly version of the modeling system with target series TS records in DSS file. Table 84 shows the instream flow targets and shortage for the scenarios of D2 and M2.

Table 84: Comparison of Instream Flow Targets and Shortages for the Scenarios D2 and M2

Control Point	Targets (cfs)		Shortages (cfs)	
	D2	M2	D2	M2
SFAS06	5.49	5.54	0.61	0.32
DMAS09	9.20	9.37	1.08	0.84
BRSE11	30.28	30.18	2.86	2.20
CFNU16	9.59	9.11	1.01	0.93
BRSB23	81.85	82.48	8.49	6.31
CON026	9.02	9.01	1.54	1.15
BRPP27	162.33	181.19	28.36	84.24
BRGR30	265.43	299.30	26.69	114.53
NBCL36	23.00	22.91	1.67	1.13
BRWA41	444.09	508.93	31.02	74.68
LEGT47	29.06	29.28	3.22	3.38
LAKE50	36.84	36.80	3.93	2.97
LRLR53	201.10	204.72	34.49	49.92
LRCA58	377.18	408.78	43.39	94.16
BRBR59	1,290.19	1,327.95	165.92	161.76
NAEA66	33.73	34.15	4.59	3.06
BRHE68	2,076.47	2,155.10	256.02	270.08
BRRI70	2,290.80	2,372.17	310.56	287.56
BRRO72	2,595.29	2,670.43	490.62	498.63

Incorporation of environmental flow rights on monthly computational time step is used to compute regulated flows at pertinent control points and water availability for the monthly target volumes. The subsistence and base flow targets can be modeled accurately on the monthly computational time step than high pulse flows. On account of the approaches to incorporate instream flows on the modeling system, differences between daily and monthly computational time intervals are seen even if the same input dataset is inserted. In order to decrease uncertainties on the monthly version of the modeling system, different ways are applied to aggregate daily values to monthly values. However, the daily computational time step is a recommended way to make analysis on streamflow and greatly improve the accuracy of the model. Based on the methodology explained, mean naturalized, regulated, and unappropriated stream flows were compared at nineteen control points for the scenarios of D2 and M2 in Table 85.

Table 85: Comparison of Mean Naturalized, Regulated, and Unappropriated Stream Flow at 19 Control Points for the Scenarios D2 and M2

Control Point	Naturalized Flow (cfs)		Regulated Flows (cfs)		Unappropriated Flows (cfs)	
	D2	M2	D2	M2	D2	M2
SFAS06	89.59	89.30	88.46	83.20	6.06	35.40
DMAS09	135.84	135.40	132.81	113.20	3.83	37.30
BRSE11	304.74	303.80	301.74	285.50	15.75	110.50
CFNU16	111.96	111.70	82.89	50.90	4.78	22.80
BRSB23	806.85	805.50	772.16	685.80	30.07	240.90
CON026	130.46	130.20	101.66	69.50	7.20	34.10
BRPP27	992.28	990.90	675.51	479.60	47.55	276.30
BRGR30	1,399.72	1,398.20	970.58	756.30	106.99	450.70
NBCL36	224.36	224.80	213.69	213.80	71.21	154.90
BRWA41	2,569.08	2,569.80	1,902.21	1,808.50	622.79	1,113.10
LEGT47	347.13	347.40	316.37	302.50	39.04	205.30
LAKE50	165.31	165.80	161.12	160.60	46.76	97.80
LRLR53	1,164.95	1,167.40	854.16	801.50	353.39	605.10
LRCA58	1,840.85	1,844.50	1,455.13	1,401.00	648.42	1,017.30
BRBR59	5,473.76	5,479.50	4,370.67	4,211.80	1,807.90	2,611.50
NAEA66	464.73	465.80	332.86	331.40	125.75	263.50
BRHE68	7,378.07	7,389.50	6,034.76	5,888.20	2,808.92	3,317.60
BRRI70	8,061.21	8,073.50	6,553.61	6,401.80	3,325.56	3,922.60
BRRO72	8,444.70	8,457.40	6,516.59	6,300.70	4,259.61	4,036.30

As the simulation results indicate, the regulated and unappropriated stream flows at pertinent control points in a monthly time step is less than in daily time step. The change on daily targets and water availability through basin causes these variations.

CHAPTER VI

SUMMARY AND CONCLUSIONS

River basin management strategies and multiple-purpose reservoir system operations are modeled interconnectedly based on public and environmental needs. River system rules and reservoir operation policies determined according to beneficial use, sustainability, and higher reliability represent a great importance of water budget. Depending on the planning and management policies, tradeoffs between water operations through basin areas are observed and impacts on water availability are quantified to evaluate the effectiveness of strategies. Multiple-purpose reservoir system that is operated for flood control, hydropower, water supply, and instream flow standards for the environment, ecosystem, and vegetation are key factors in water resources systems and have effects on each other. These impacts through basin areas can be quantified based on observations and output from modeling systems.

The thesis research investigates the interactions between integrated water operations for hydropower, flood control, and environmental flows by applying the WRAP/WAM system in the case study area of the Brazos River Basin. The original Brazos WAM dataset modified assigning hypothetical hydropower plants and formulating flood control operation rules was performed on the daily and monthly time interval in the WRAP modeling system. The system of nine flood control reservoirs operated by USACE, two hydropower plants, and SB3 environmental flow standards were analyzed within alternative water allocation scenarios as much similar to real-time river basin management strategies. Comparisons between water allocation scenarios were made in a framework of reliability and frequency analyses of reservoirs and stream gages.

Two hydropower plants that are not incorporated in the original dataset were modeled on the WRAP system based on reservoir system operations as well as technical details about the dams and hydroelectric systems. Considering historical hydropower generation and capability of the power plants, energy target and power rule-curve were also defined in the dataset. Reliability metrics of hydropower rights, firm energy generation, energy shortages, and storage-frequency tables were developed to evaluate hydroelectricity output in the dams.

Nine flood control reservoirs in the case study area operated by USACE were evaluated in terms of the risk of exceedance top of flood control pools based on historically observed reservoir storage. Log-normal and log-Pearson type III probability distribution methods were applied to calculate the risk and recurrence interval. Different flood control operations were formulated and simulated on the daily time interval. The frequency analyses for reservoirs and stream gages were performed on HEC-SSP and TABLES.

Senate Bill 3 environmental flow standards in the original dataset were used as river system rules through the basin area. Instream flow rights representing SB3 environmental flow standards were evaluated comparing target and shortages through the simulation period. Mean regulated and unappropriated flows at pertinent control points were then comparatively analyzed to observe the changes. Additionally, high pulse flow events were computed on the daily time interval in terms of the termination, initiation, and completion of the events.

The alternative water allocation scenarios were analyzed comparatively to reveal tradeoffs between water operations for hydroelectric generation, flood control, and environmental flows on both daily and monthly time interval. The results presented in Chapter V illustrates the interactions between reservoir operations and river system rules. Hydropower generation in two reservoirs was evaluated in daily and monthly time interval to define the impacts of environmental flow standards and flood control. SB3 environmental flow standards curtail mean annual energy generation and firm energy production on reservoirs slightly since water availability on reservoirs decreases. On the other hand; incorporation of flood control pools in the basin area changes energy output considerably because excess flows are stored in pools instead of streams. Depending on the increase in water availability by storing excess flows, energy output increases on the reservoirs that have both flood control pool and conservation pool. However, the reservoir that has no flood control pool experienced a decrease in hydroelectricity output because of excess flows are stored in flood control reservoirs.

Environmental flows were evaluated at 19 stream gages in the basin area comparing the metrics of regulated and unappropriated stream flows, target and shortages of instream flow rights, and high pulse flows events. The results illustrate that hydropower generation decreases the shortages for instream flow rights at downstream points of the reservoirs while increasing the number of high pulse flow events at the same locations. However; instream flow targets and shortages at pertinent control points were not affected by different flood control operations even if different policies were applied as well. Including flood control operations in the dataset makes impacts on regulated and unappropriated stream flows because of the storing excess flows in reservoirs and maximum allowable flow limits.

The effectiveness of flood control operations was treated in the same way as other applications. It is observed that hydropower operations decrease the risk of overtopping the dam energy generated while increasing the number of days of water existence in flood control pools at downstream reservoirs. Decrease in reservoir storage caused by hydroelectricity production enabled a transition from flooding conditions to normal conditions more quickly during flooding. It resulted in decreases on the number of days water level exceeds maximum flood flow limits at downstream control points, the percent change exceedance as well. The simulation results also illustrate that environmental flow standards do not have any considerable impacts on flooding at reservoirs and stream gages.

Water resources operations were performed on daily and monthly computational time intervals in this research. Computer simulation models are just approximation of real-world systems and periodically varying parameters are performed based on the time intervals. The daily and monthly time intervals of the WRAP modeling system were compared in terms of methodology and computation. Methodology for the incorporation of environmental flows in daily and monthly modeling system was compared. The comparison results indicate that instream flow rights varying by location, season, and hydrologic condition were modeled more accurately in daily modeling. Also, computational differences were evaluated for hydroelectricity generation using the same dataset. The considerable differences between simulation results were observed because of the consideration of different height in calculations.

Simulation results for alternative scenarios were presented in Chapter V. Based on results and evaluations, the interactions between water operations studied in this research can be summarized for the case study area as following:

- Environmental flow standards decrease the hydroelectricity generation slightly.
- Hydropower operations decrease the shortages of instream flow rights at downstream of reservoirs while increasing the number of high pulse flow events.
- Incorporation of flood control operations in the modeling system increases water availability on reservoirs, which results in higher reliability of hydropower generation.
- Hydropower generation decreases water availability in reservoirs and the risk of exceedance in not only reservoirs but also stream gages.
- There are no considerable interactions between flood control operations and environmental flow standards in the long-term period.
- The daily time interval computations for hydropower generation and environmental flows is more accurate than the monthly time interval due to consideration of continuously varying variables in the river/reservoir system.

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APPENDIX A

A.1 HISTORICAL HYDROPOWER GENERATION IN BRAZOS RIVER BASIN

Table 86: Historical Hydropower Generation in Whitney Hydropower Plant

YEAR	JAN (MWh)	FEB (MWh)	MAR (MWh)	APR (MWh)	MAY (MWh)	JUN (MWh)	JUL (MWh)	AUG (MWh)	SEP (MWh)	OCT (MWh)	NOV (MWh)	DEC (MWh)	TOTAL (MWh)
1953	--	--	--	--	--	367	1,531	1,222	34	33	208	21	3,416
1954	47	42	364	2,506	7,257	6,959	4,725	3,455	1,072	1,139	23	--	27,589
1955	--	--	28	50	4,437	15,330	4,392	2,939	6,350	12,264	1,931	1,788	49,509
1956	2,376	2,404	2,319	2,473	6,904	2,448	6,533	2,922	2,236	2,446	--	--	33,061
1957	2,350	2,353	2,433	5,298	22,284	22,446	6,649	2,416	2,476	8,773	10,676	7,330	95,484
1958	6,732	4,403	6,920	6,922	15,119	4,810	9,038	4,128	2,493	2,499	2,517	2,435	68,016
1959	2,398	2,474	2,444	2,311	2,491	2,450	6,952	2,973	2,469	12,692	2,949	5,997	48,600
1960	11,563	8,073	3,680	3,984	5,644	2,457	7,746	2,463	2,465	9,208	7,166	5,461	69,910
1961	10,792	12,359	8,226	3,841	2,464	10,791	17,482	7,419	3,248	8,677	3,048	3,562	91,909
1962	2,334	2,501	2,377	2,496	2,365	8,832	5,297	10,786	13,389	8,793	4,197	5,492	68,859
1963	3,637	2,468	2,492	2,452	5,364	15,939	6,209	2,709	2,447	2,434	1,145	776	48,072
1964	740	760	809	1,126	2,508	2,814	2,870	2,658	1,256	836	1,192	2,430	19,999
1965	2,413	6,907	2,451	2,375	15,106	2,939	2,500	2,289	1,956	2,235	3,294	2,184	46,649
1966	2,450	2,127	2,584	3,193	13,739	3,759	3,196	1,733	16,842	6,187	2,474	2,418	60,702
1967	985	558	565	2,522	2,582	3,812	5,528	5,128	1,400	716	2,845	2,705	29,346
--	--	--	--	--	--	--	--	--	--	--	--	--	--
2002	2,872	2,538	2,717	2,676	3,129	3,375	3,768	3,818	3,207	2,477	2,181	2,574	35,334
2003	972	857	851	858	1,021	1,066	1,163	1,229	1,009	915	866	896	11,702
2004	652	1,036	8,036	1,125	6,079	8,356	5,893	4,646	3,160	1,442	8,205	12,575	61,206
2005	5,325	4,604	5,044	4,818	4,358	4,909	5,269	4,459	3,689	3,149	3,370	4,125	53,119
2006	1,404	1,266	1,116	1,214	1,436	1,411	1,479	1,469	953	840	984	1,042	14,616
2007	10,578	11,268	1,329	1,552	7,765	15,814	27,715	19,645	16,649	2,605	2,216	1,721	118,858
2008	115	1,501	5,590	7,388	4,619	4,047	3,600	3,181	2,165	886	438	1,663	35,193
2009	184	123	1,174	1,541	2,557	1,606	1,456	1,191	580	1,294	2,493	2,835	17,035
2010	16,685	6,897	16,699	7,809	8,052	8,631	6,078	4,354	8,335	1,742	1,398	1,472	88,152
2011	217	662	589	1,322	1,722	1,751	1,355	1,412	804	309	160	180	10,482
2012	257	107	4,189	5,106	2,557	1,903	820	1,175	921	3,281	692	716	21,724
2013	623	284	54	20	28	232	297	159	92	39	500	473	2,801
2014	135	162	260	392	411	340	181	285	242	456	93	157	3,113
2015	10,559	654	6,576	11,167	10,482	12,829	3,817	3,550	3,865	1,902	5,256	6,721	77,378
2016	9,634	9,247	10,483	19,092	26,849	30,037	6,010	8,613	8,262	2,716	6,289	3,046	140,277
2017	2,861	2,689	2,594	2,086	2,401	2,745	3,181	2,406	3,432	2,823	2,461	2,745	32,426

Table 87: Historical Hydropower Generation in Possum Kingdom Hydropower Plant

YEAR	JAN (MWh)	FEB (MWh)	MAR (MWh)	APR (MWh)	MAY (MWh)	JUN (MWh)	JUL (MWh)	AUG (MWh)	SEP (MWh)	OCT (MWh)	NOV (MWh)	DEC (MWh)	TOTAL (MWh)
1942	--	--	--	--	329	415	790	681	498	597	466	465	4,241
1943	3,720	6,655	7,454	7,081	3,227	4,215	5,060	3,555	704	292	73	55	42,091
1944	532	342	230	151	670	1,112	1,138	2,151	562	1,646	1,596	1,913	12,043
1945	1,842	1,810	2,077	1,789	2,467	3,568	3,445	3,650	1,486	906	701	1,369	25,110
1946	5,010	874	459	1,298	982	1,116	3,506	3,988	5,351	12,263	5,698	5,015	45,560
1947	4,892	2,365	1,082	1,621	5,601	7,105	4,342	3,453	3,106	1,491	941	1,565	37,564
1948	2,106	2,127	1,539	2,410	1,169	3,052	4,212	5,356	2,194	830	931	897	26,823
1949	1,148	1,179	635	368	6,593	14,430	4,573	6,553	6,182	6,257	2,723	1,584	52,225
1950	799	919	1,477	916	4,093	6,985	10,935	10,357	12,924	4,575	1,580	2,185	57,745
1951	4,144	2,040	372	2,050	1,486	4,161	8,250	6,479	3,129	1,652	940	897	35,600
1952	1,438	275	154	526	235	3,223	4,150	3,257	118	17	8	98	13,499
1953	13	--	28	64	221	1,580	3,182	3,221	4,104	4,189	5,106	2,093	23,801
1954	1,286	904	1,367	3,933	15,677	10,726	5,746	4,694	987	480	111	33	45,944
1955	1,199	336	197	366	4,004	11,980	4,886	3,561	5,027	9,461	1,939	745	43,701
1956	3,175	3,965	4,780	2,705	4,683	1,906	6,555	3,122	216	129	475	806	32,517
1957	1,478	1,246	524	2,773	17,766	16,348	3,285	2,960	1,906	7,700	8,753	4,490	69,229
1958	2,887	2,064	405	1,332	11,638	3,788	8,762	4,005	1,649	3,622	1,793	1,068	43,013
1959	1,191	284	287	410	1,171	5,995	9,991	1,004	1,071	6,799	1,559	1,668	31,430
1960	2,514	4,272	698	1,501	2,100	1,014	9,148	2,523	2,151	8,887	5,646	4,676	45,130
1961	2,977	1,934	3,834	3,868	1,046	10,941	16,257	7,811	5,531	2,837	1,013	1,929	59,978
1962	2,391	1,880	1,777	636	201	6,067	6,386	8,590	12,030	4,528	4,321	5,836	54,643
1963	4,441	2,037	464	272	4,679	17,342	6,175	3,572	1,234	200	29	285	40,730
1964	745	371	548	301	147	2,300	4,450	2,742	1,033	306	414	198	13,555
1965	964	680	490	779	8,047	2,438	2,928	2,471	2,717	1,898	1,621	1,298	26,331
1966	1,392	590	2,030	3,846	7,095	780	3,545	1,972	17,722	3,697	--	1,824	44,493
1967	542	374	257	2,288	420	6,204	9,586	3,056	1,706	624	1,764	458	27,279

APPENDIX B

B.1 FLOOD FREQUENCY ANALYSES FOR NINE USACE RESERVOIRS

Table 88: Waco Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
1,097,646	---	0.2	1,555,162	845,749
920,615	---	0.5	1,265,391	724,473
796,245	---	1	1,067,935	637,291
679,476	---	2	887,821	553,611
535,633	---	5	674,168	447,441
433,590	---	10	529,250	369,367
335,684	---	20	396,790	291,366
205,729	---	50	234,738	180,305
126,084	---	80	145,262	106,667
97,614	---	90	114,586	79,970
79,017	---	95	94,592	62,780
53,155	---	99	66,413	39,632

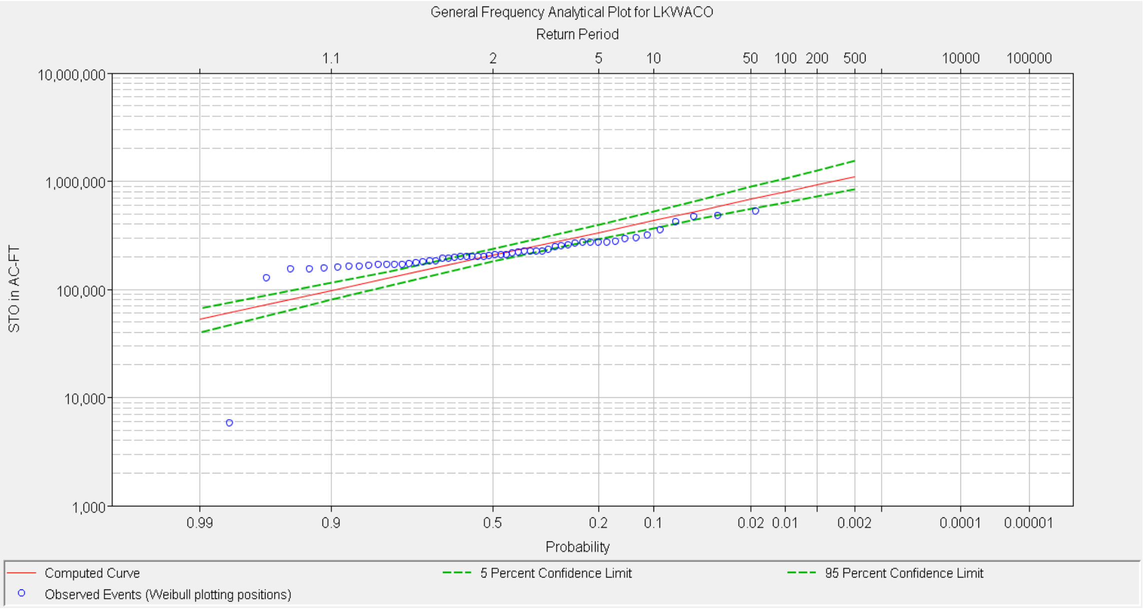

Figure 65: Waco Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 89: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
782,433	868,711	0.2	1,008,699	648,868
648,049	698,648	0.5	807,545	550,537
559,788	591,727	1	679,696	484,328
481,473	500,801	2	569,552	424,217
390,956	399,615	5	446,854	352,639
330,653	334,971	10	368,539	303,172
275,775	277,448	20	300,521	256,175
207,337	207,337	50	222,205	192,935
167,958	167,491	80	181,113	153,629
154,485	153,807	90	167,545	139,881
145,949	145,050	95	159,025	131,147
134,657	133,535	99	147,809	119,604

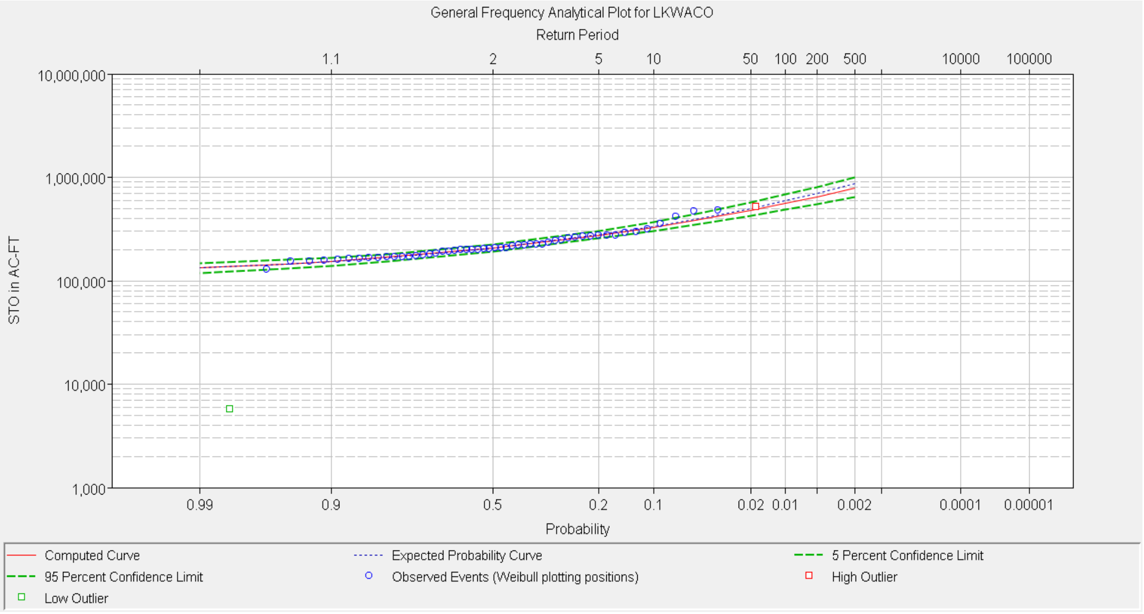

Figure 66: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 90: Whitney Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
2,162,671	---	0.2	2,714,529	1,815,458
1,900,627	---	0.5	2,339,087	1,618,314
1,708,478	---	1	2,069,393	1,471,374
1,520,661	---	2	1,810,926	1,325,445
1,276,932	---	5	1,484,221	1,131,904
1,093,358	---	10	1,245,866	982,111
906,023	---	20	1,011,224	824,270
632,395	---	50	690,161	579,464
441,405	---	80	485,185	395,485
365,776	---	90	407,208	321,000
313,191	---	95	353,320	269,450
234,082	---	99	271,803	193,257

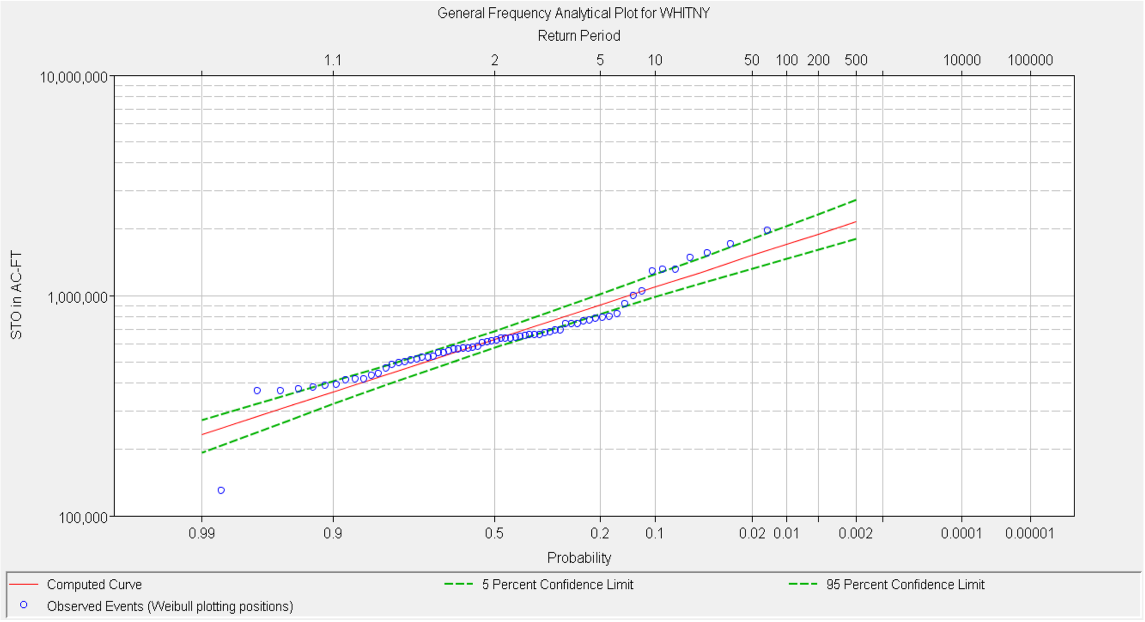

Figure 67: Whitney Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 91: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
3,035,212	3,357,769	0.2	3,994,894	2,463,310
2,423,064	2,606,216	0.5	3,076,758	2,018,944
2,033,042	2,145,824	1	2,511,572	1,728,205
1,696,115	1,762,608	2	2,038,132	1,470,893
1,319,004	1,347,770	5	1,528,038	1,173,867
1,076,218	1,090,126	10	1,213,674	975,446
862,062	867,278	20	948,854	793,025
605,415	605,415	50	654,429	558,635
463,419	462,050	80	504,686	419,639
415,639	413,664	90	455,830	372,023
385,440	382,842	95	425,159	341,910
345,245	341,942	99	384,442	301,954

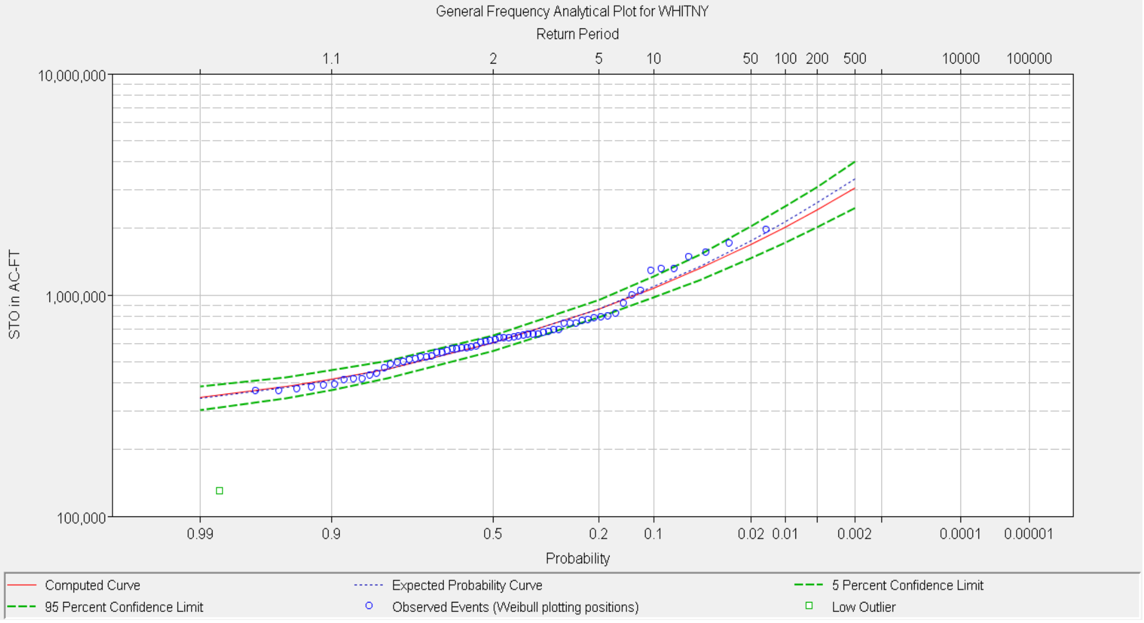

Figure 68: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 92: Aquilla Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
273,515	---	0.2	414,293	204,986
232,906	---	0.5	340,136	178,646
203,978	---	1	289,213	159,388
176,460	---	2	242,429	140,605
141,985	---	5	186,431	116,262
117,049	---	10	148,065	97,904
92,640	---	20	112,666	79,051
59,223	---	50	68,865	50,931
37,860	---	80	44,368	31,131
29,965	---	90	35,824	23,688
24,702	---	95	30,168	18,813
17,195	---	99	22,005	12,127

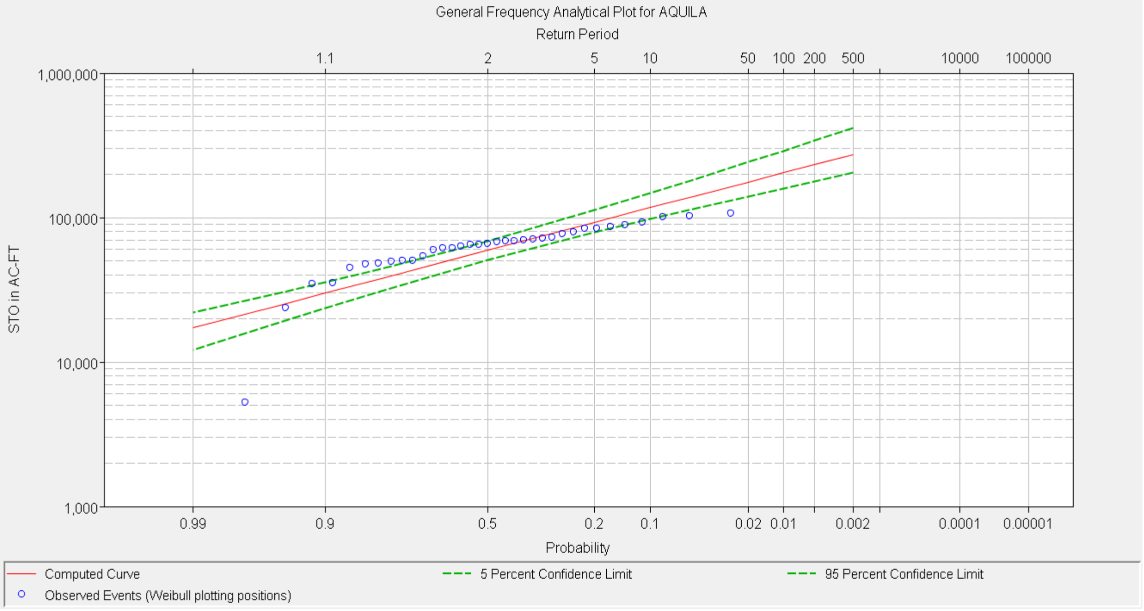

Figure 69: Aquilla Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 93: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
114,511	116,769	0.2	137,489	100,258
111,343	113,337	0.5	132,920	97,818
108,346	110,131	1	128,632	95,494
104,669	106,166	2	123,420	92,620
98,384	99,515	5	114,645	87,645
92,081	92,822	10	106,026	82,562
83,681	84,097	20	94,859	75,610
66,127	66,127	50	73,013	60,157
48,409	47,919	80	53,470	42,898
39,792	38,935	90	44,683	34,126
33,243	32,044	95	38,118	27,507
22,673	20,659	99	27,416	17,235

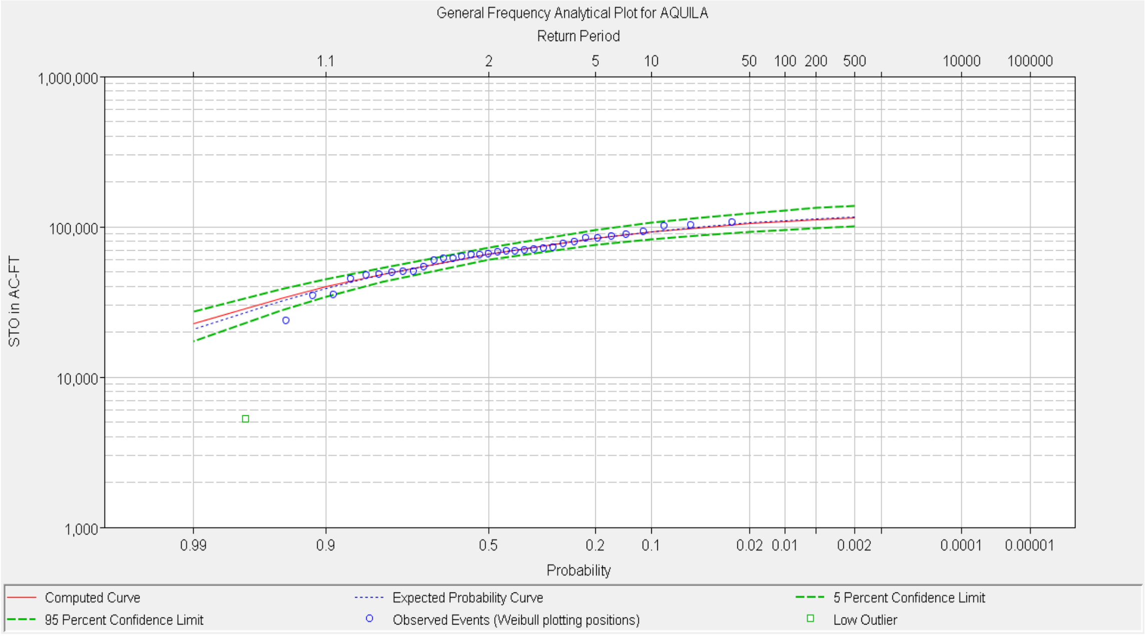

Figure 70: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 94: Proctor Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
531,543	---	0.2	775,978	400,178
438,209	---	0.5	619,013	337,581
373,665	---	1	513,976	293,212
313,959	---	2	419,775	251,190
241,801	---	5	310,432	198,790
191,730	---	10	238,092	161,028
144,766	---	20	173,616	124,091
84,572	---	50	97,618	73,270
49,407	---	80	57,639	41,197
37,305	---	90	44,417	30,041
29,580	---	95	35,980	23,040
19,141	---	99	24,393	13,916

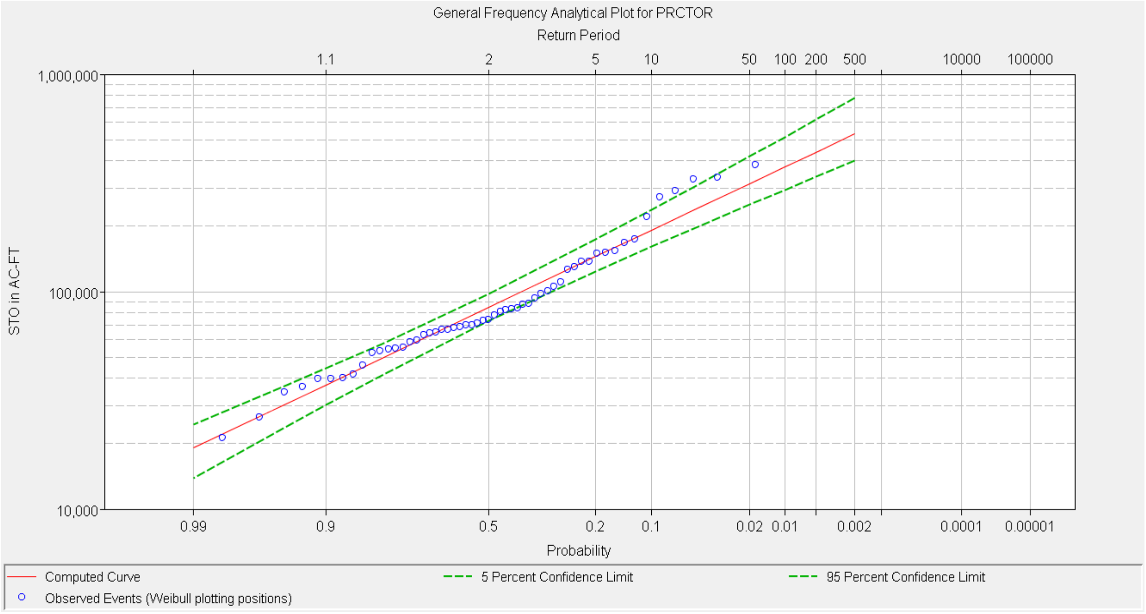

Figure 71: Proctor Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 95: Proctor Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
771,861	896,545	0.2	1,202,548	555,042
582,688	650,461	0.5	864,244	433,822
465,725	506,184	1	664,701	356,212
367,573	390,554	2	504,227	288,971
261,815	271,316	5	340,208	213,532
196,719	201,040	10	245,148	164,855
141,868	143,393	20	169,766	121,749
80,380	80,380	50	92,680	69,530
48,948	48,578	80	57,135	40,772
38,819	38,297	90	46,067	31,427
32,494	31,834	95	39,169	25,663
24,031	23,150	99	29,863	18,127

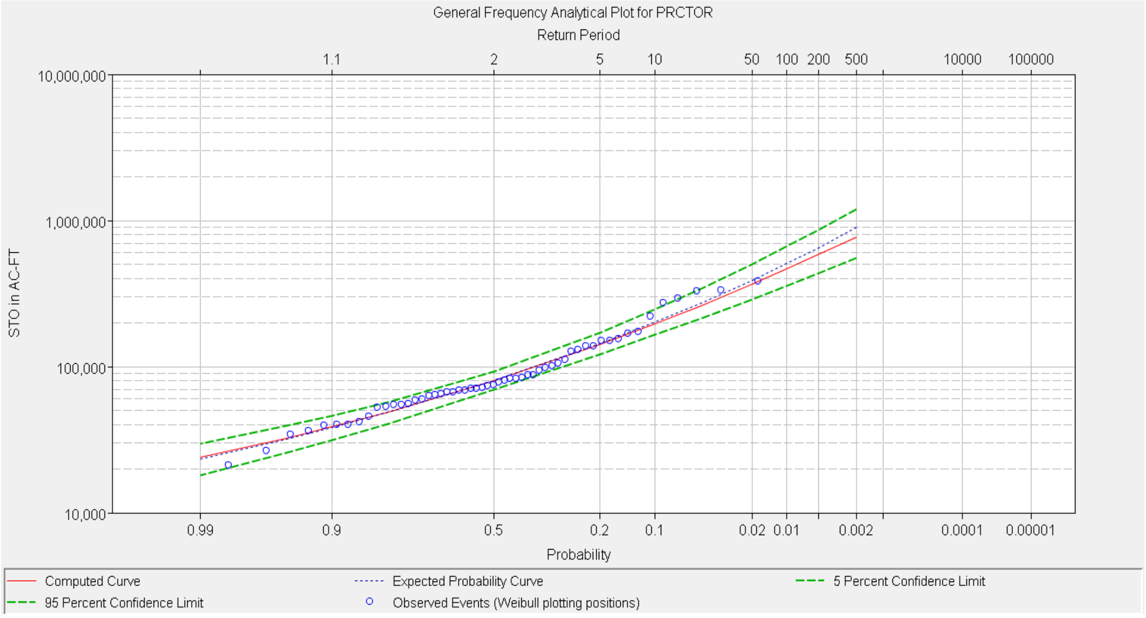

Figure 72: Proctor Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 96: Belton Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
2,261,197	---	0.2	3,074,660	1,786,497
1,904,794	---	0.5	2,521,930	1,533,967
1,653,405	---	1	2,142,434	1,352,093
1,416,494	---	2	1,793,812	1,177,227
1,123,230	---	5	1,376,483	954,888
914,020	---	10	1,090,404	791,010
712,136	---	20	826,046	626,936
441,773	---	50	497,062	392,634
274,054	---	80	311,298	236,262
213,522	---	90	246,727	178,983
173,752	---	95	204,384	141,784
118,037	---	99	144,342	91,094

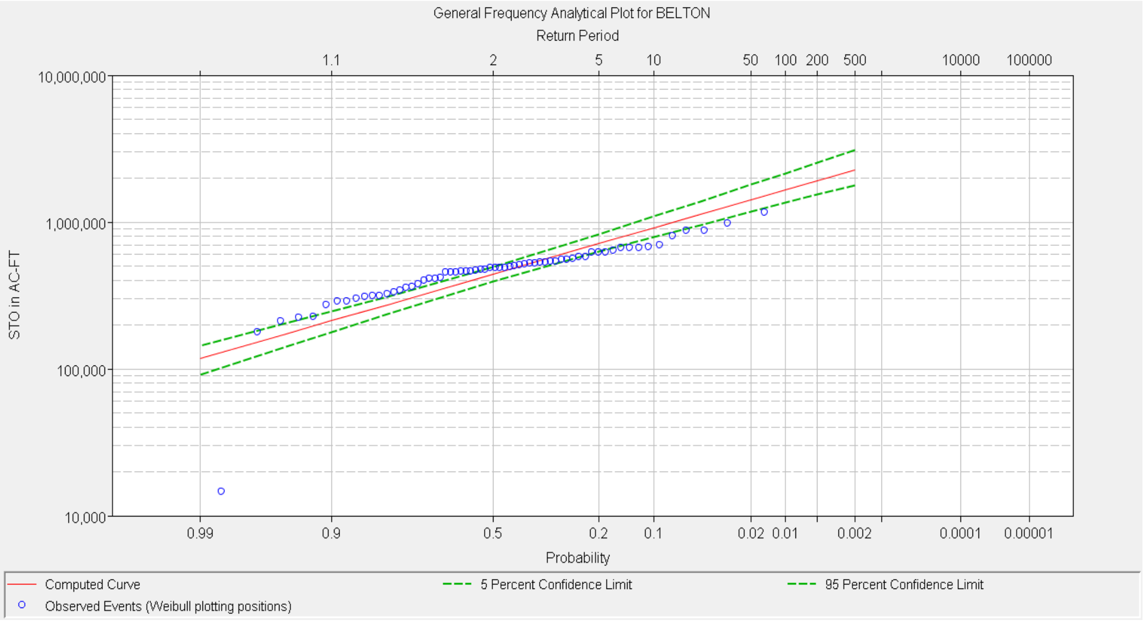

Figure 73: Belton Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 97: Belton Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
1,208,320	1,255,356	0.2	1,451,769	1,048,863
1,105,651	1,138,936	0.5	1,310,535	969,052
1,025,712	1,050,454	1	1,202,219	906,144
943,213	960,699	2	1,092,094	840,410
828,689	838,722	5	942,357	747,535
735,899	741,613	10	824,147	670,552
634,294	636,942	20	698,630	583,852
470,317	470,317	50	507,884	435,797
341,860	340,188	80	371,226	310,632
287,019	284,253	90	315,443	255,714
247,372	243,539	95	275,446	216,116
185,218	178,893	99	212,448	155,103

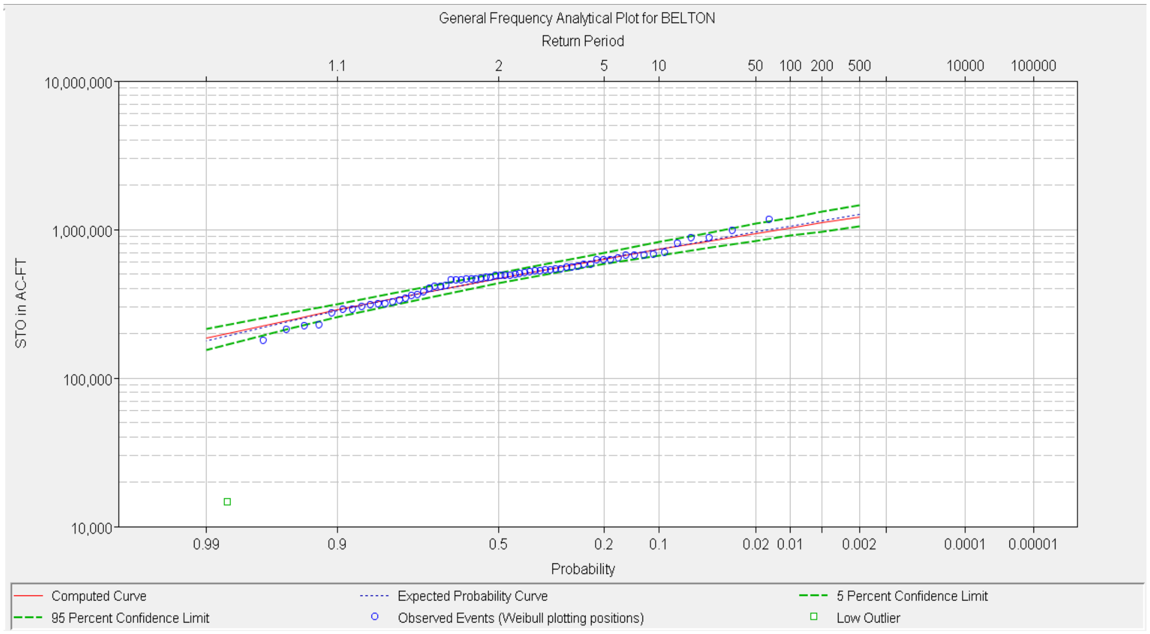

Figure 74: Belton Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 98: Stillhouse Hollow Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
4,162,158	---	0.2	7,733,643	2,625,103
3,065,644	---	0.5	5,397,043	2,006,986
2,381,987	---	1	4,014,404	1,606,729
1,808,018	---	2	2,908,620	1,258,573
1,195,637	---	5	1,799,505	869,797
827,985	---	10	1,179,927	623,541
530,624	---	20	714,098	413,011
226,523	---	50	286,193	179,294
96,703	---	80	124,241	71,857
61,973	---	90	82,292	43,488
42,917	---	95	58,994	28,515
21,542	---	99	31,936	12,782

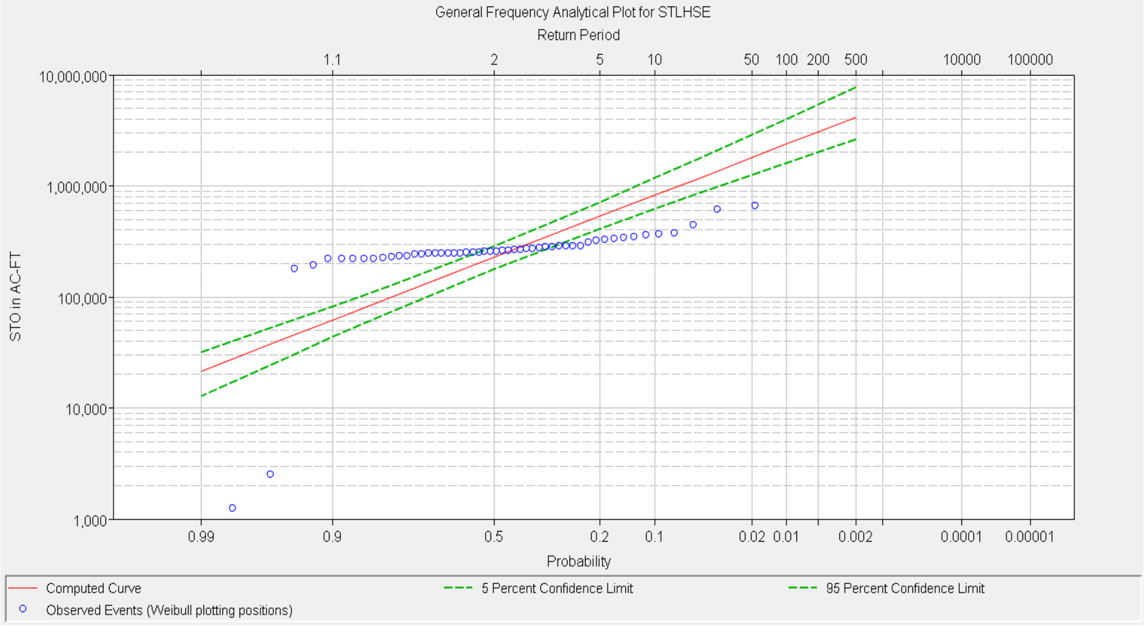

Figure 75: Stillhouse Hollow Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 99: Stillhouse Hollow Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
891,905	1,000,571	0.2	1,132,891	749,127
733,051	795,233	0.5	897,623	631,887
631,105	669,483	1	751,801	554,653
542,501	565,255	2	628,906	485,909
442,728	452,536	5	495,672	406,078
378,268	383,090	10	413,313	352,473
321,568	323,381	20	344,341	303,054
255,312	255,312	50	270,189	240,425
222,074	221,738	80	236,075	206,608
212,569	212,151	90	226,608	196,740
207,431	206,932	95	221,528	191,384
202,221	201,842	99	216,400	185,943

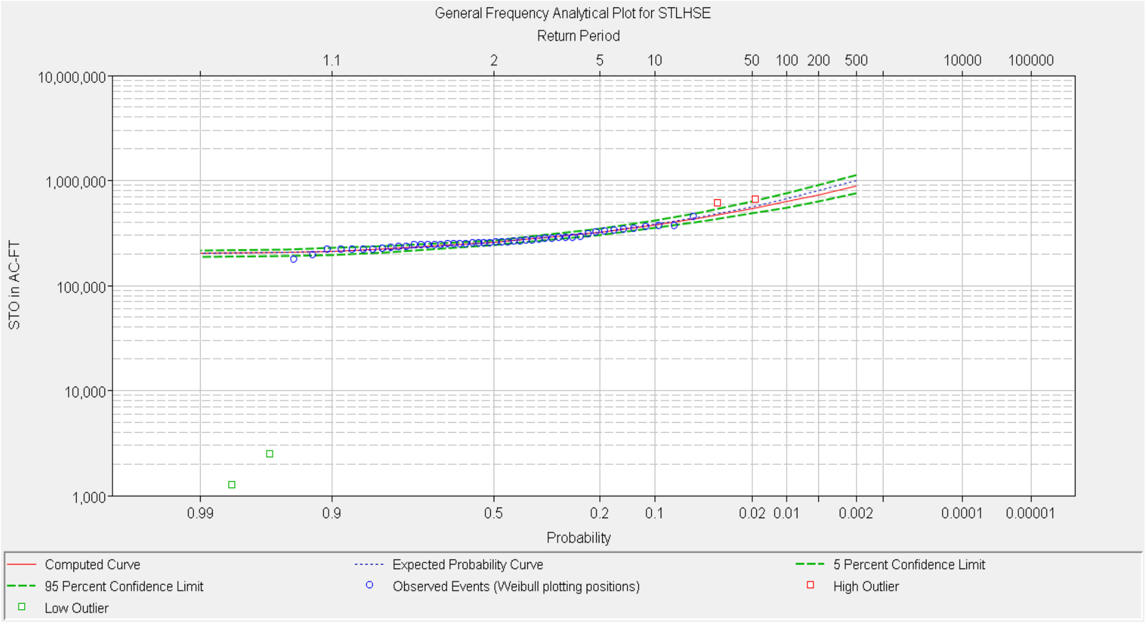

Figure 76: Stillhouse Hollow Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 100: Georgetown Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
141,688	---	0.2	190,870	114,824
125,486	---	0.5	164,682	103,430
113,521	---	1	145,860	94,844
101,747	---	2	127,815	86,229
86,337	---	5	105,000	74,641
74,614	---	10	88,358	65,519
62,529	---	20	71,996	55,718
44,593	---	50	49,738	39,980
31,802	---	80	35,690	27,620
26,651	---	90	30,351	22,506
23,033	---	95	26,641	18,939
17,517	---	99	20,966	13,633

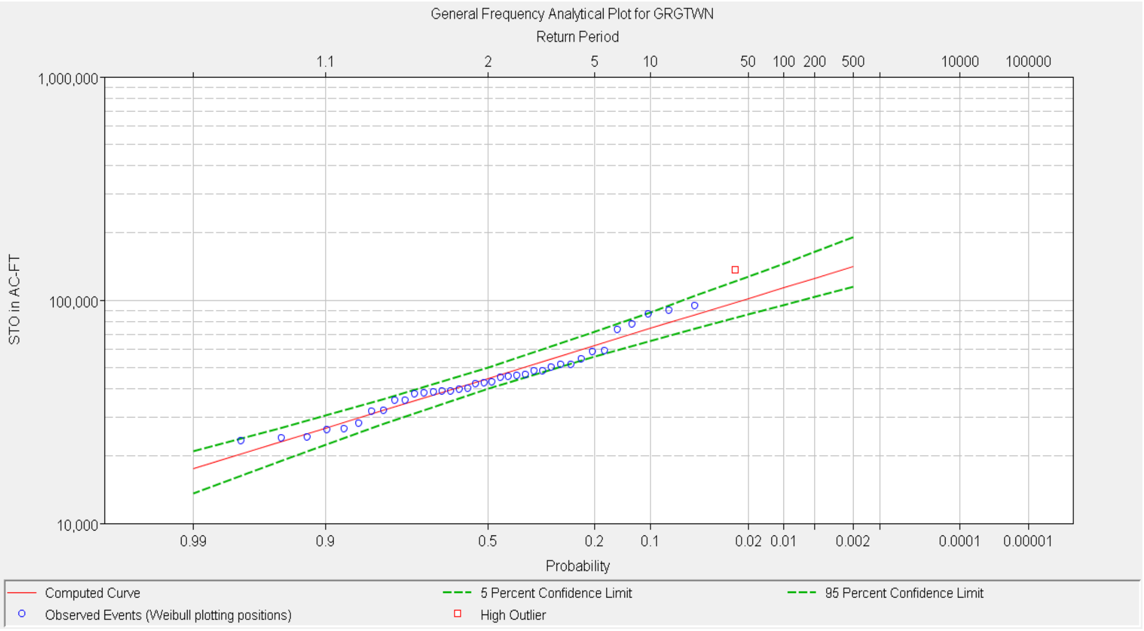

Figure 77: Georgetown Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 101: Georgetown Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
196,822	231,018	0.2	285,114	152,078
161,111	180,916	0.5	223,224	128,189
137,575	150,028	1	184,150	111,955
116,634	124,127	2	150,713	97,094
92,359	95,715	5	113,798	79,217
76,133	77,785	10	90,475	66,719
61,310	61,946	20	70,399	54,701
42,643	42,643	50	47,500	38,154
31,605	31,406	80	35,484	27,425
27,671	27,370	90	31,400	23,517
25,080	24,676	95	28,739	20,952
21,412	20,834	99	24,981	17,359

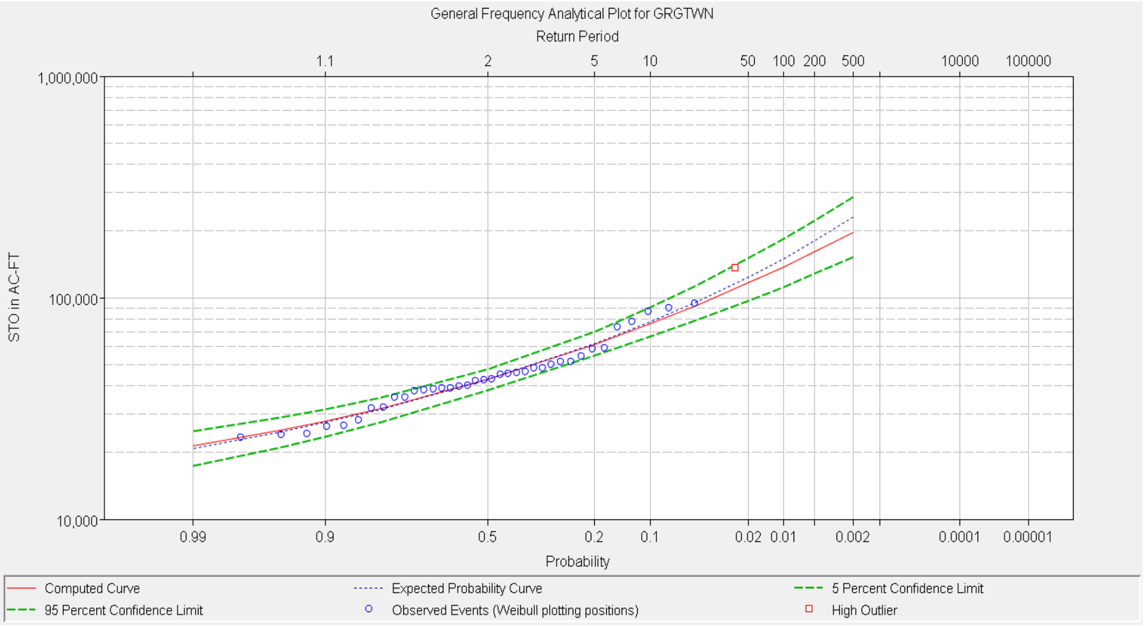

Figure 78: Georgetown Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 102: Granger Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
284,520	---	0.2	380,964	231,565
252,608	---	0.5	329,684	209,029
228,989	---	1	292,726	192,017
205,698	---	2	257,202	174,914
175,127	---	5	212,138	151,853
151,799	---	10	179,143	133,648
127,670	---	20	146,579	114,031
91,678	---	50	102,029	82,378
65,833	---	80	73,707	57,340
55,369	---	90	62,888	46,917
47,993	---	95	55,349	39,620
36,704	---	99	43,772	28,713

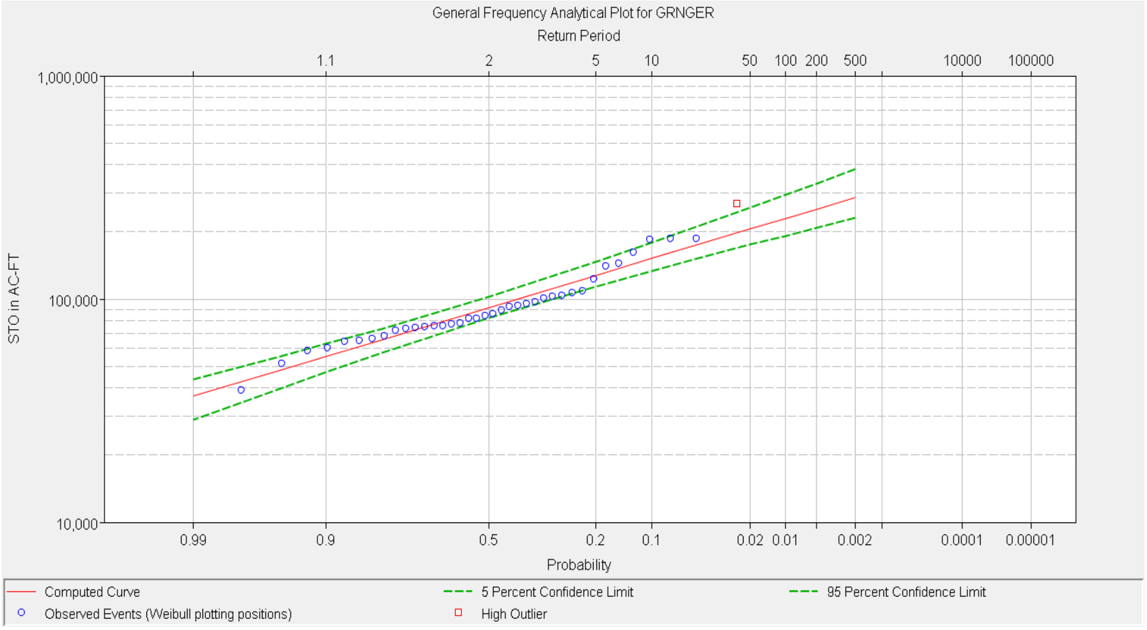

Figure 79: Granger Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 103: Granger Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
392,925	459,772	0.2	565,015	305,161
322,880	361,758	0.5	444,459	258,076
276,557	301,083	1	368,030	225,985
235,216	250,024	2	302,382	196,533
187,113	193,778	5	229,578	160,988
154,831	158,123	10	183,353	136,050
125,224	126,496	20	143,383	111,984
87,740	87,740	50	97,518	78,680
65,434	65,030	80	73,290	56,943
57,450	56,839	90	65,024	48,988
52,181	51,358	95	59,627	43,754
44,705	43,525	99	51,989	36,402

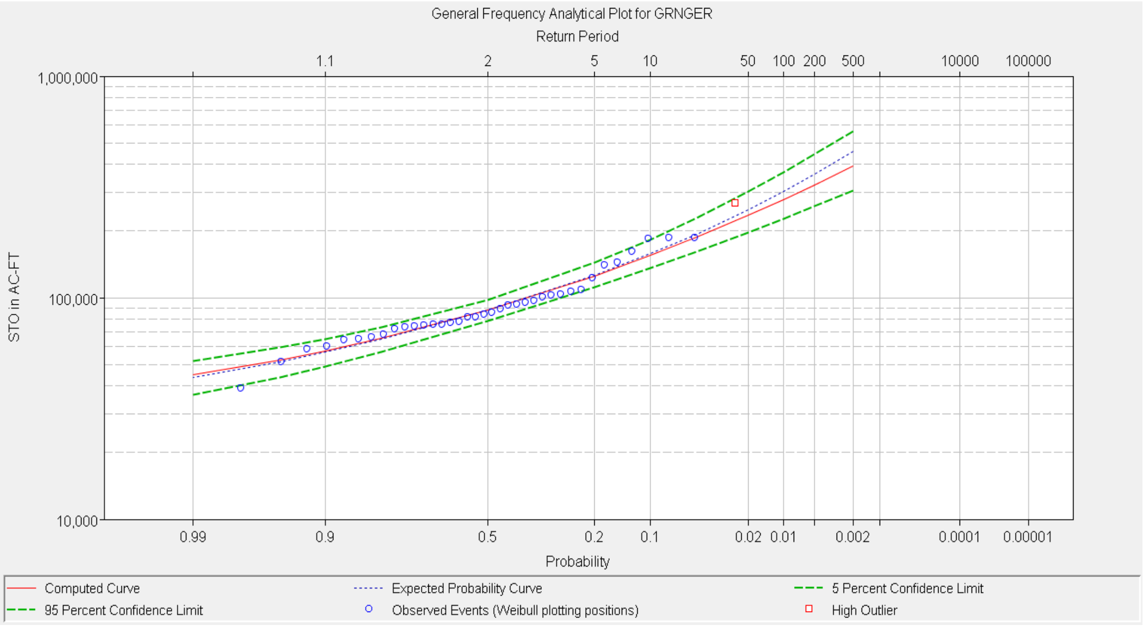

Figure 80: Granger Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 104: Somerville Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
992,062	---	0.2	1,376,406	777,576
844,019	---	0.5	1,138,089	674,707
738,644	---	1	973,290	599,873
638,486	---	2	820,887	527,232
513,129	---	5	636,895	433,704
422,557	---	10	509,554	363,743
334,007	---	20	390,769	292,576
212,997	---	50	241,015	188,236
135,829	---	80	155,063	116,099
107,365	---	90	124,725	89,034
88,414	---	95	104,605	71,233
61,420	---	99	75,629	46,613

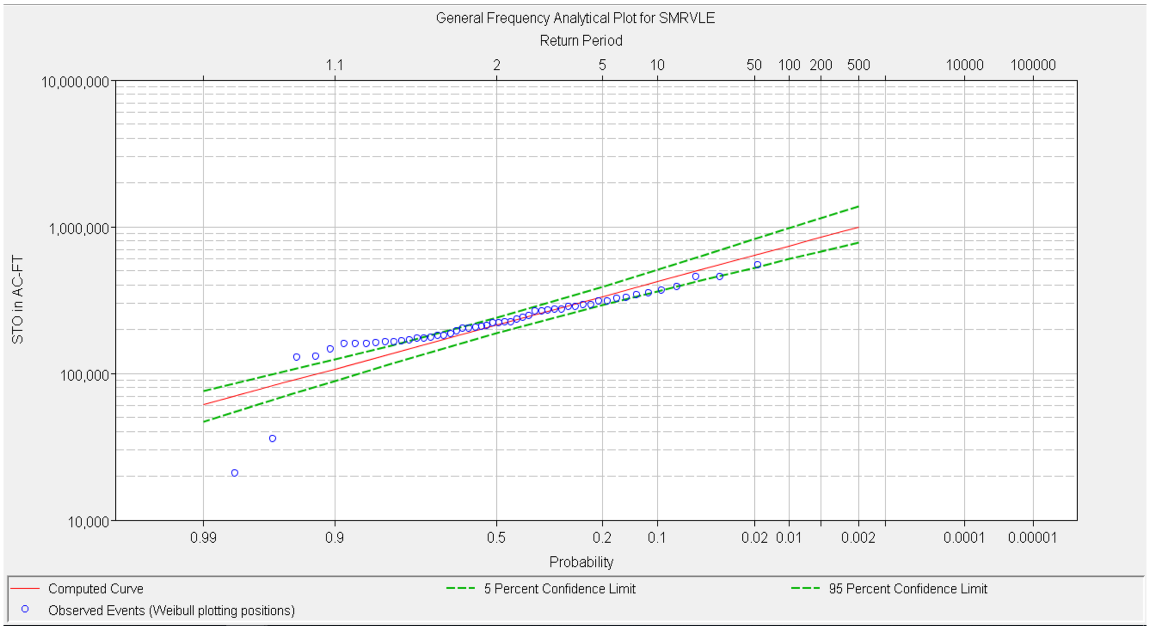

Figure 81: Somerville Reservoir FFA log-normal Probability Distribution for the Daily Observed Storage

Table 105: Somerville Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
735,475	799,238	0.2	938,527	614,422
634,680	674,725	0.5	788,606	540,181
564,198	590,998	1	686,541	487,191
498,094	515,240	2	593,170	436,513
416,384	424,783	5	481,409	372,210
357,842	362,234	10	404,339	324,612
300,706	302,522	20	332,252	276,330
221,764	221,764	50	239,958	204,669
169,502	168,759	80	184,615	153,153
149,309	148,137	90	164,135	132,743
135,379	133,760	95	150,143	118,664
114,474	111,958	99	129,189	97,710

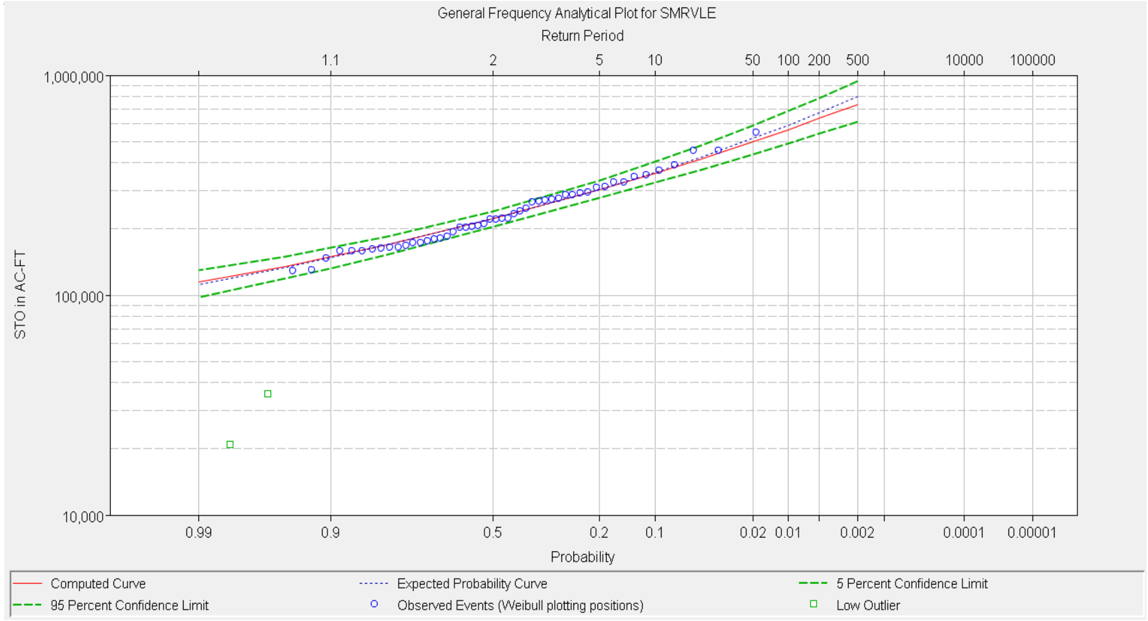

Figure 82: Somerville Reservoir FFA log-Pearson Type III Probability Distribution for the Daily Observed Storage

Table 106: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
295,057	295,090	0.2	341,708	259,910
294,827	294,889	0.5	341,417	259,719
294,385	294,500	1	340,859	259,352
293,386	293,564	2	339,595	258,521
289,880	290,237	5	335,171	255,602
283,078	283,436	10	326,612	249,921
267,219	267,573	20	306,803	236,593
206,078	206,078	50	232,563	183,914
118,854	117,684	80	133,658	104,370
77,261	75,484	90	89,006	65,217
49,918	47,913	95	59,669	39,980
17,869	15,920	99	23,730	12,417

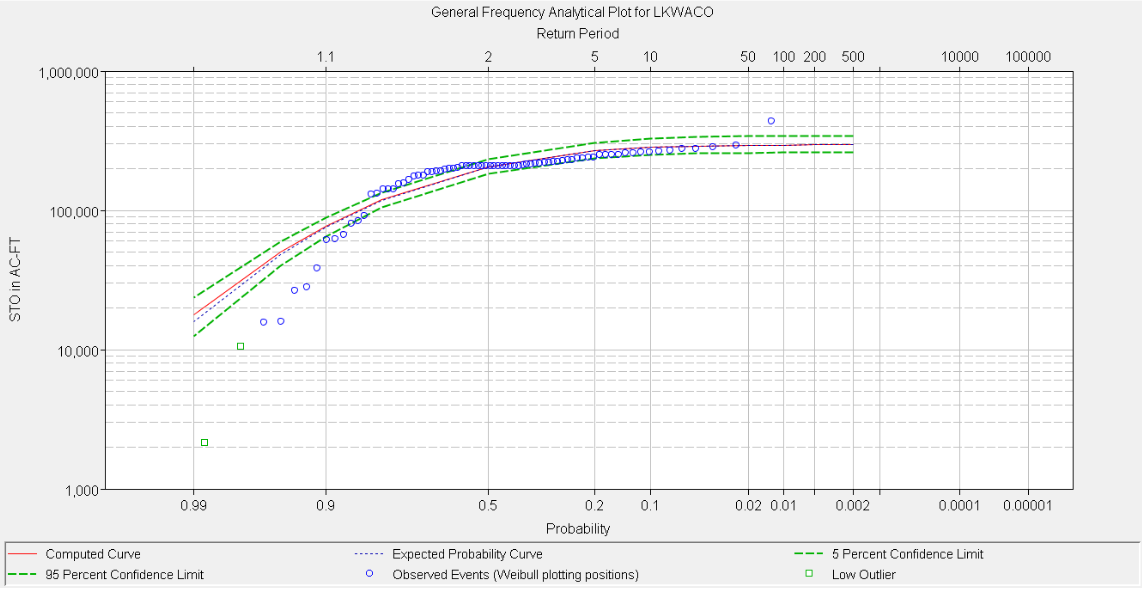

Figure 83: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 107: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
3,224,680	3,582,396	0.2	4,081,005	2,688,346
2,457,604	2,646,093	0.5	2,987,896	2,112,117
2,002,933	2,111,875	1	2,363,685	1,760,458
1,634,081	1,694,623	2	1,873,331	1,467,754
1,251,373	1,275,055	5	1,383,745	1,154,234
1,025,171	1,036,117	10	1,106,766	961,648
842,768	846,567	20	893,694	799,213
657,491	657,491	50	692,255	622,435
586,215	585,883	80	619,377	550,753
571,936	571,635	90	605,019	536,216
566,319	566,036	95	599,390	530,486
562,851	562,769	99	595,919	526,945

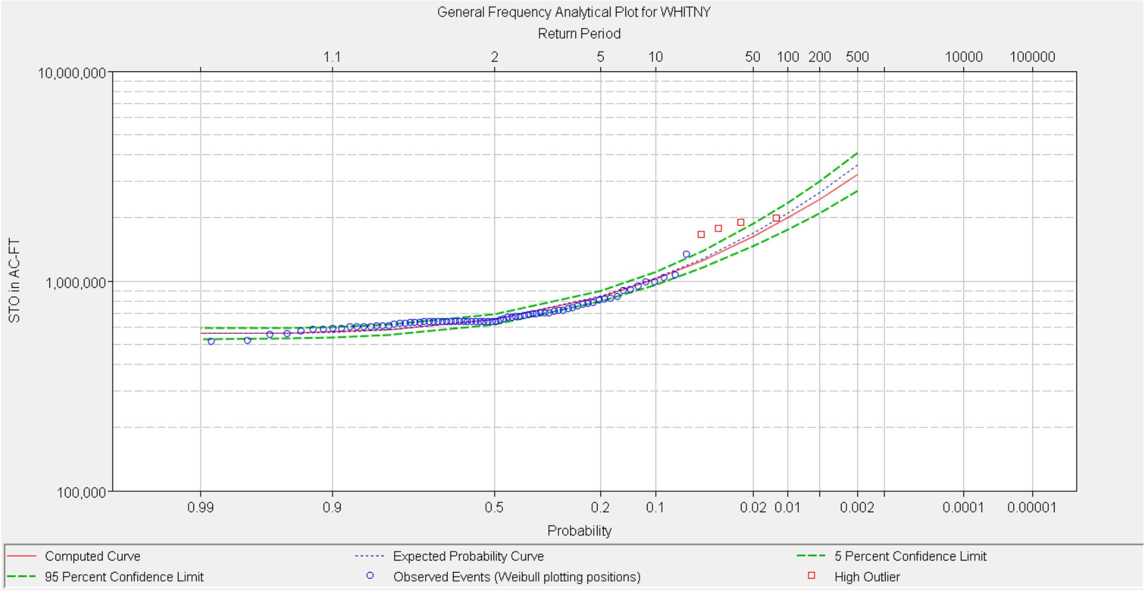

Figure 84: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 108: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
143,175	145,085	0.2	173,190	122,666
136,990	138,645	0.5	164,815	117,816
131,166	132,650	1	156,985	113,223
124,088	125,325	2	147,545	107,603
112,218	113,137	5	131,915	98,075
100,667	101,251	10	116,971	88,661
85,924	86,237	20	98,336	76,400
57,929	57,929	50	64,670	52,065
34,167	33,906	80	38,324	29,992
24,470	24,073	90	28,026	20,786
17,998	17,510	95	21,151	14,738
9,341	8,717	99	11,712	7,002

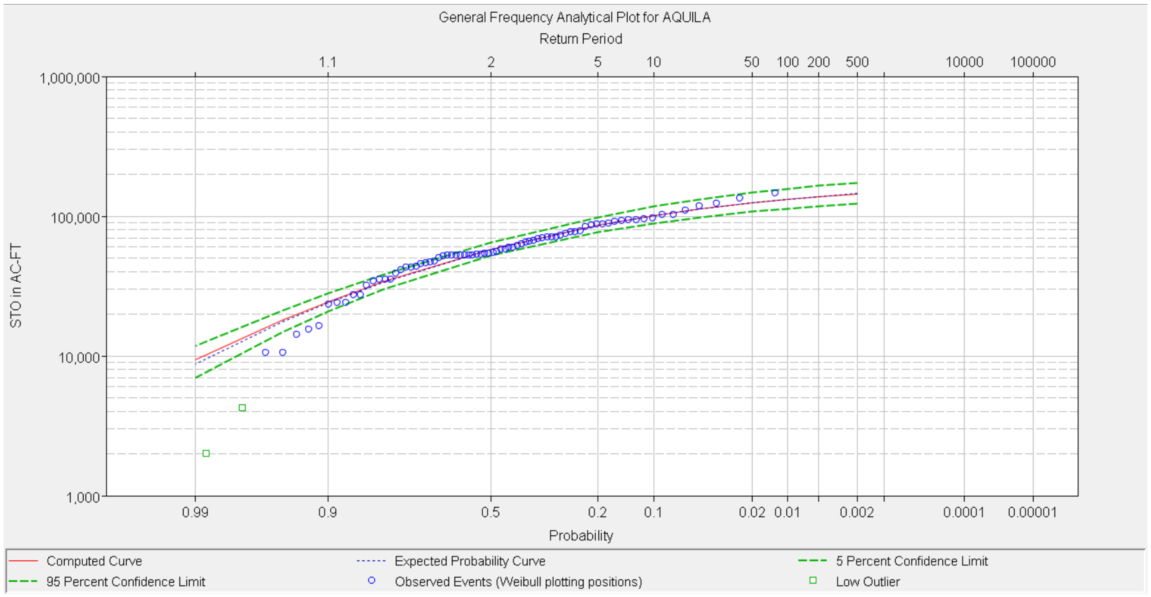

Figure 85: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 109: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
230,409	---	0.2	305,031	184,770
193,290	---	0.5	249,761	157,812
167,207	---	1	211,866	138,498
142,714	---	2	177,098	120,020
112,534	---	5	135,545	96,679
91,119	---	10	107,109	79,608
70,566	---	20	80,871	62,661
43,273	---	50	48,265	38,798
26,537	---	80	29,885	23,155
20,551	---	90	23,523	17,483
16,640	---	95	19,369	13,815
11,199	---	99	13,521	8,839

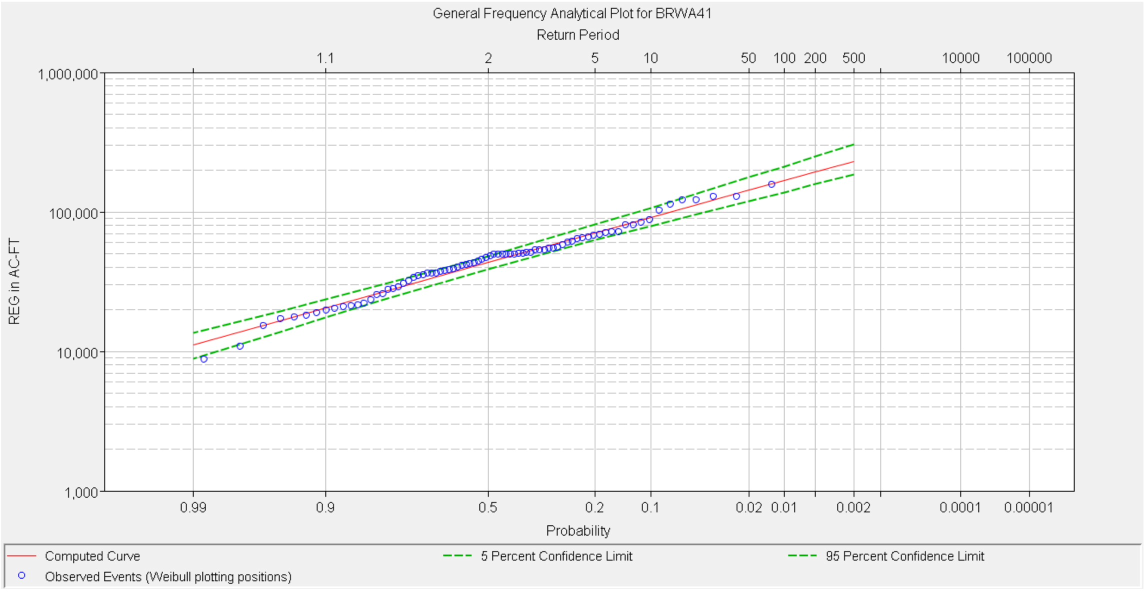

Figure 86: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D5

Table 110: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
195,422	205,175	0.2	252,894	159,376
170,009	176,575	0.5	215,895	140,589
151,114	155,794	1	188,925	126,398
132,464	135,620	2	162,814	112,172
108,073	109,757	5	129,541	93,162
89,653	90,550	10	105,200	78,420
70,948	71,330	20	81,348	62,982
44,268	44,268	50	49,397	39,704
26,746	26,577	80	30,108	23,354
20,285	20,032	90	23,240	17,232
16,033	15,712	95	18,722	13,251
10,139	9,693	99	12,361	7,895

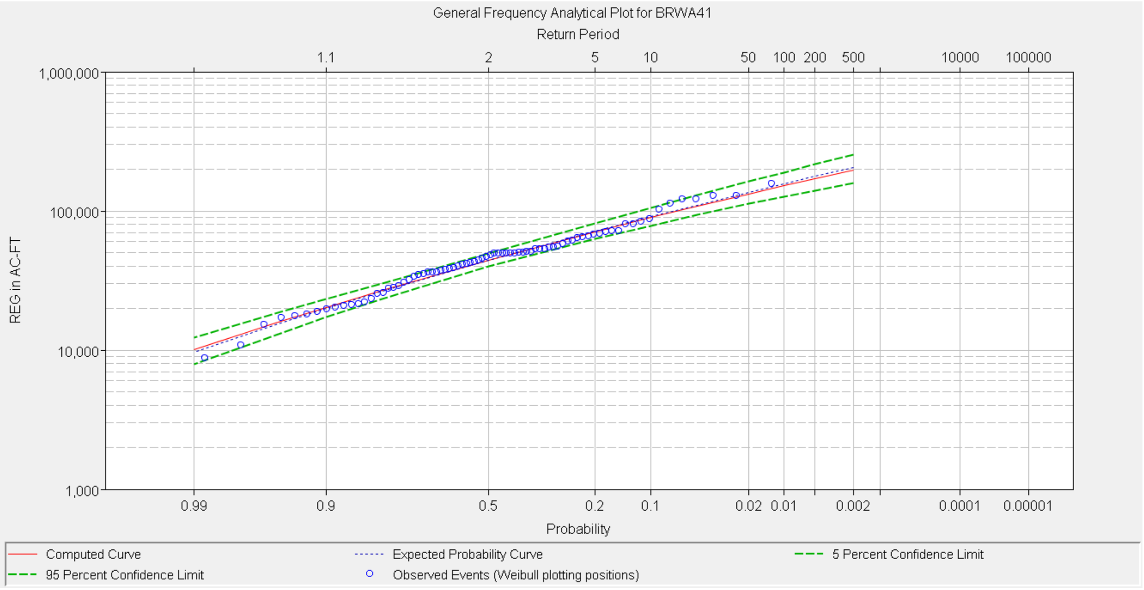

Figure 87: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 111: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
583,613	---	0.2	800,556	455,116
478,825	---	0.5	639,120	381,032
406,681	---	1	530,974	328,918
340,219	---	2	433,884	279,914
260,326	---	5	321,028	219,389
205,228	---	10	246,231	176,263
153,876	---	20	179,417	134,598
88,698	---	50	100,307	78,433
51,128	---	80	58,451	43,849
38,335	---	90	44,634	31,951
30,221	---	95	35,860	24,507
19,345	---	99	23,919	14,817

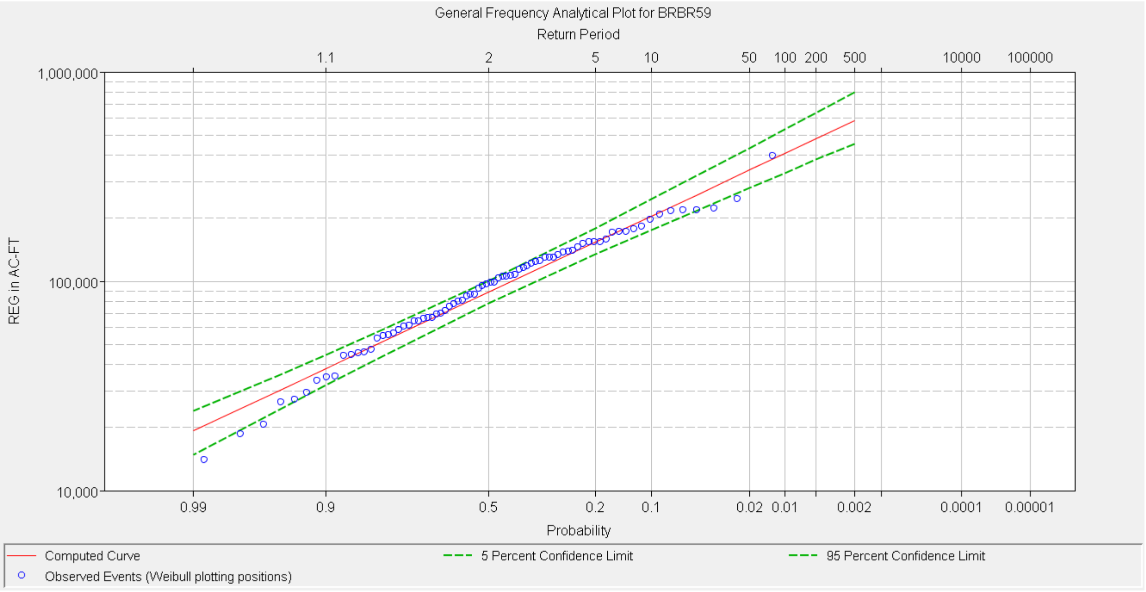

Figure 88: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D5

Table 112: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
388,524	403,290	0.2	504,192	315,633
347,689	358,352	0.5	444,662	285,476
315,277	323,366	1	398,160	261,231
281,434	287,205	2	350,385	235,583
234,195	237,553	5	285,204	199,105
196,157	198,017	10	234,202	169,022
155,401	156,234	20	181,352	135,861
93,886	93,886	50	106,307	83,085
52,325	51,919	80	59,749	44,967
37,276	36,689	90	43,491	30,973
27,670	26,959	95	33,086	22,197
15,130	14,233	99	19,172	11,207

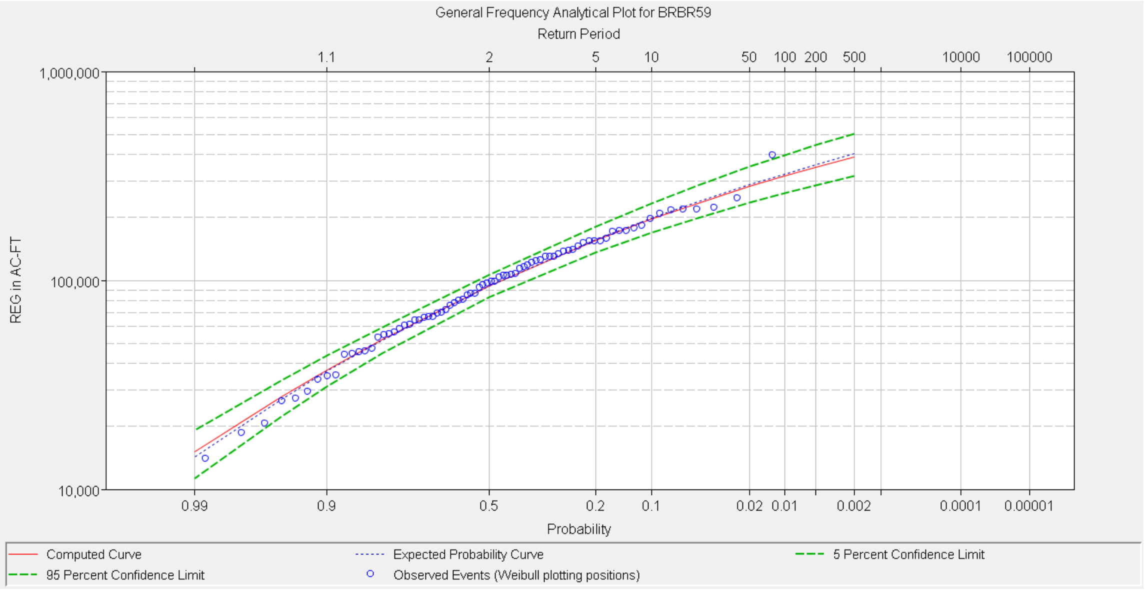

Figure 89: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 113: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
963,247	---	0.2	1,390,531	721,583
765,428	---	0.5	1,070,459	587,029
633,174	---	1	863,086	494,842
514,646	---	2	682,631	410,285
377,127	---	5	481,082	309,158
286,102	---	10	353,514	239,757
204,763	---	20	244,747	175,277
107,979	---	50	124,562	93,604
56,942	---	80	66,520	47,639
40,753	---	90	48,631	32,982
30,917	---	95	37,714	24,236
18,414	---	99	23,562	13,509

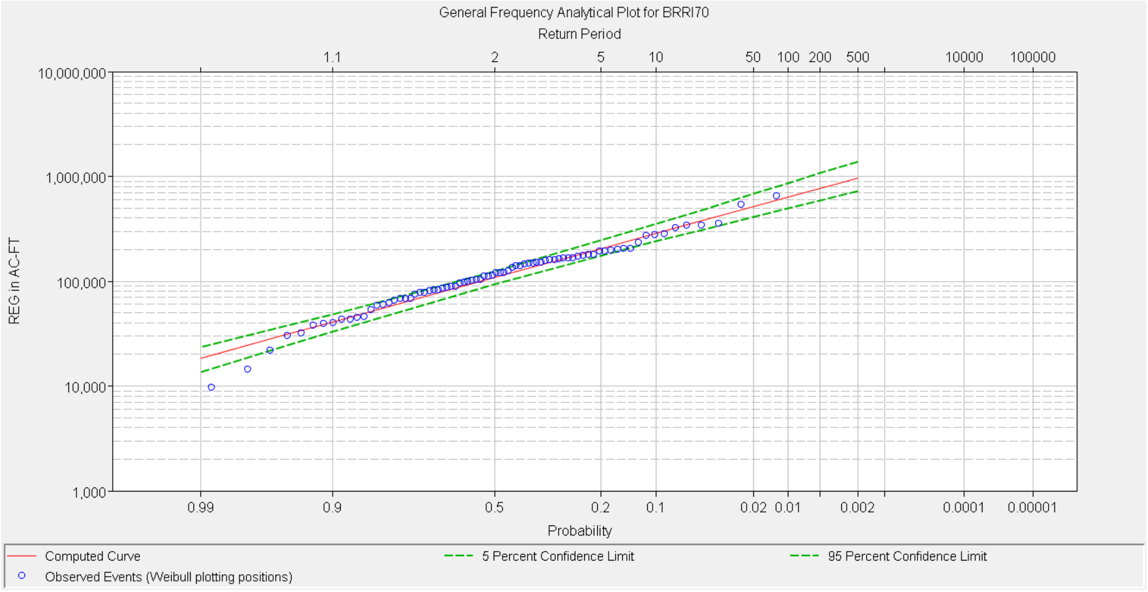

Figure 90: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D5

Table 114: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
705,757	750,038	0.2	968,342	549,633
593,270	621,963	0.5	795,048	470,117
512,449	532,251	1	673,501	411,890
435,226	448,120	2	560,037	355,218
338,421	344,943	5	422,143	282,377
268,832	272,148	10	326,650	228,390
201,702	203,037	20	238,216	174,496
113,373	113,373	50	129,543	99,310
61,511	61,041	80	71,047	52,149
44,044	43,384	90	51,966	36,121
33,175	32,379	95	40,049	26,323
19,137	18,135	99	24,328	14,138

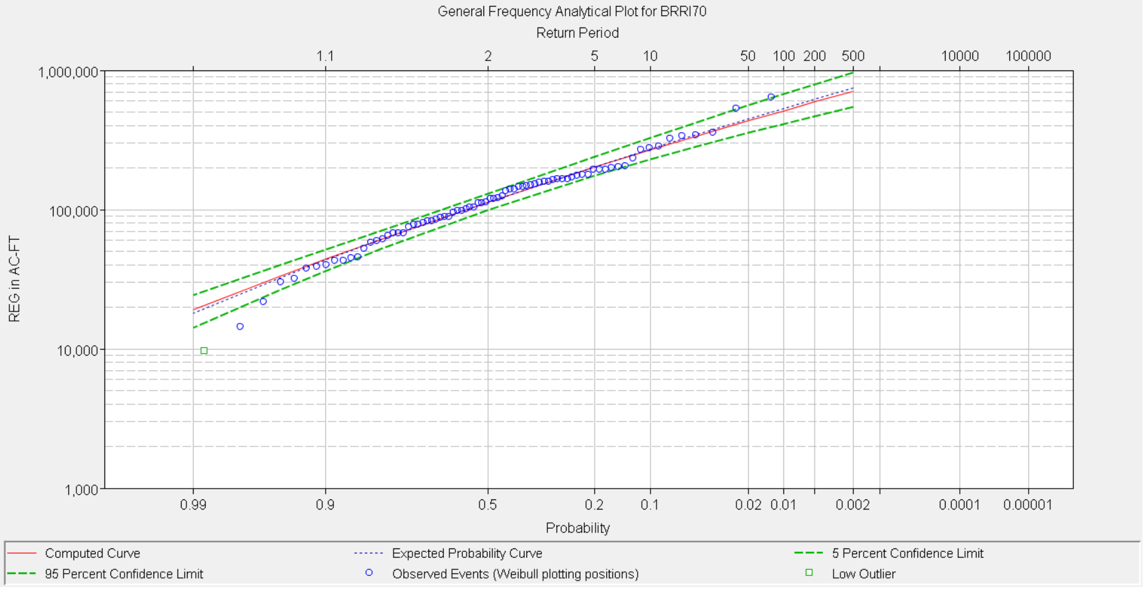

Figure 91: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D5

Table 115: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
299,738	299,785	0.2	350,505	261,902
299,434	299,517	0.5	350,116	261,652
298,870	299,016	1	349,395	261,187
297,630	297,851	2	347,812	260,165
293,440	293,861	5	342,469	256,706
285,578	285,992	10	332,480	250,197
267,810	268,205	20	310,082	235,383
202,148	202,148	50	229,730	179,206
112,667	111,499	80	127,601	98,149
71,554	69,826	90	83,137	59,782
45,216	43,312	95	54,615	35,748
15,410	13,657	99	20,781	10,499

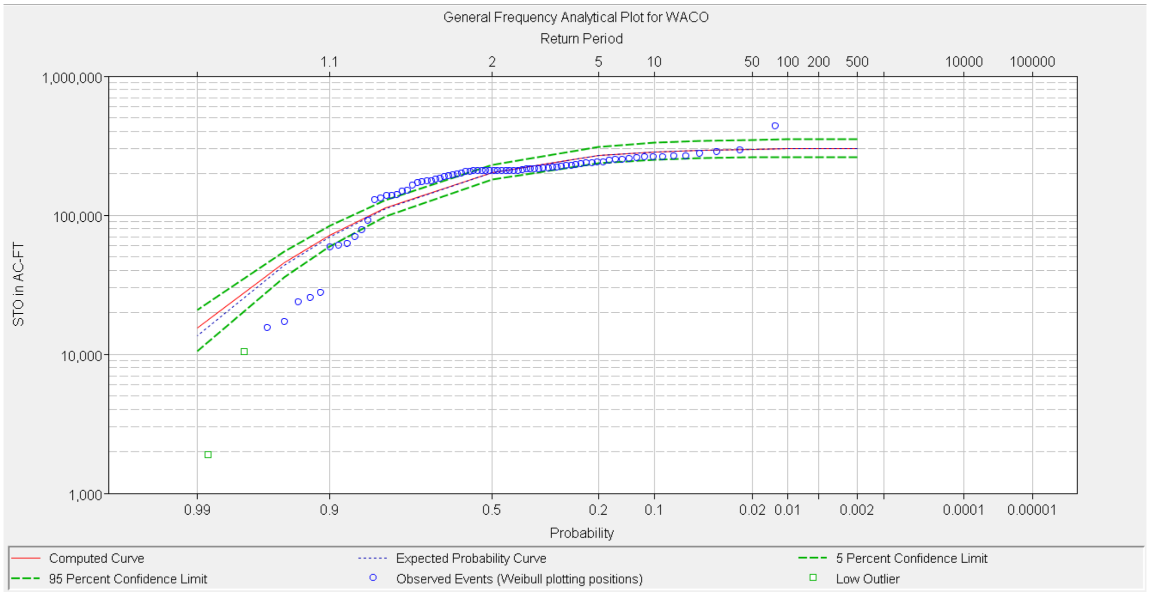

Figure 92: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 116: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
3,106,444	3,448,571	0.2	4,067,402	2,521,020
2,362,964	2,545,521	0.5	2,972,749	1,976,394
1,916,082	2,022,948	1	2,339,038	1,639,276
1,549,037	1,609,048	2	1,835,383	1,355,049
1,162,018	1,186,115	5	1,324,993	1,045,455
928,328	939,497	10	1,030,319	851,209
734,357	738,320	20	796,817	683,000
521,964	521,964	50	558,902	485,968
419,925	419,222	80	452,525	385,464
390,401	389,505	90	422,455	355,954
373,906	372,814	95	405,743	339,434
355,965	355,014	99	387,617	321,461

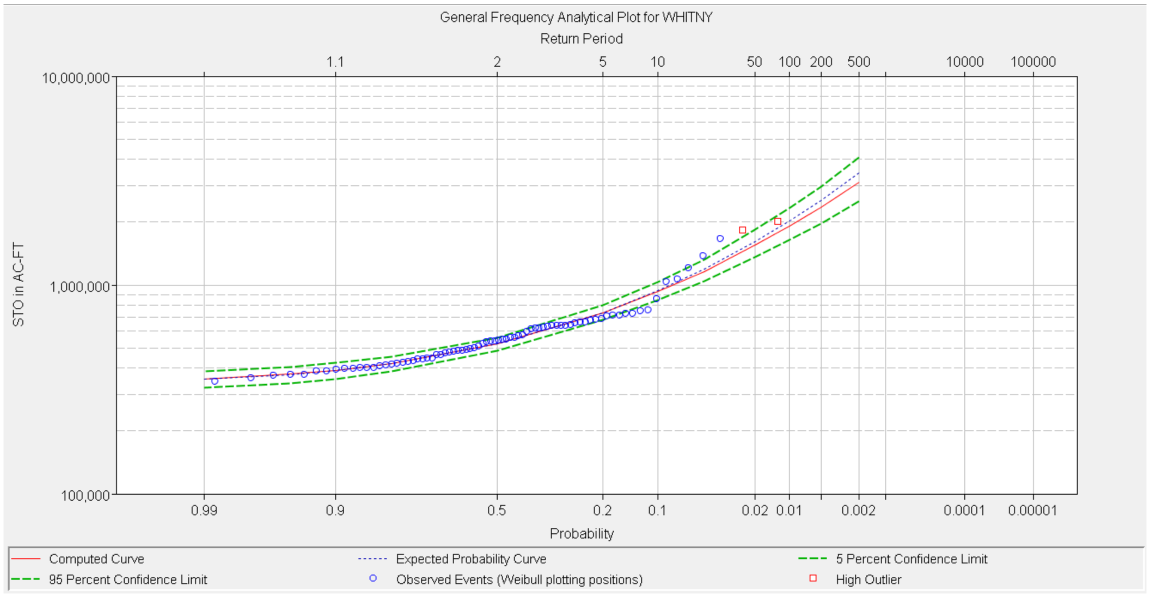

Figure 93: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 117: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
149,269	151,913	0.2	181,945	127,215
141,103	143,279	0.5	170,785	120,863
133,779	135,638	1	160,862	115,123
125,245	126,729	2	149,410	108,381
111,627	112,658	5	131,404	97,489
99,011	99,646	10	115,049	87,226
83,593	83,919	20	95,559	74,406
55,810	55,810	50	62,215	50,211
33,199	32,955	80	37,211	29,159
24,085	23,714	90	27,547	20,495
17,990	17,529	95	21,083	14,785
9,727	9,123	99	12,109	7,362

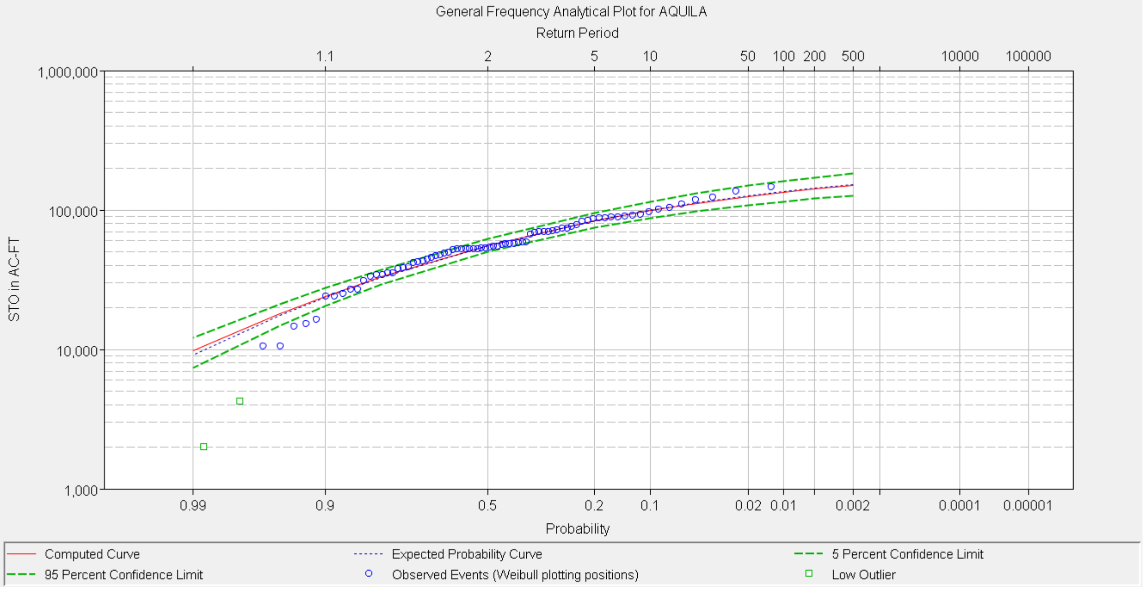

Figure 94: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 118: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
247,904	---	0.2	332,899	196,584
206,120	---	0.5	269,827	166,564
176,999	---	1	226,984	145,213
149,861	---	2	188,017	124,928
116,754	---	5	141,962	99,533
93,528	---	10	110,847	81,154
71,498	---	20	82,508	63,106
42,770	---	50	47,969	38,134
25,585	---	80	28,987	22,171
19,558	---	90	22,540	16,502
15,668	---	95	18,378	12,885
10,335	---	99	12,597	8,059

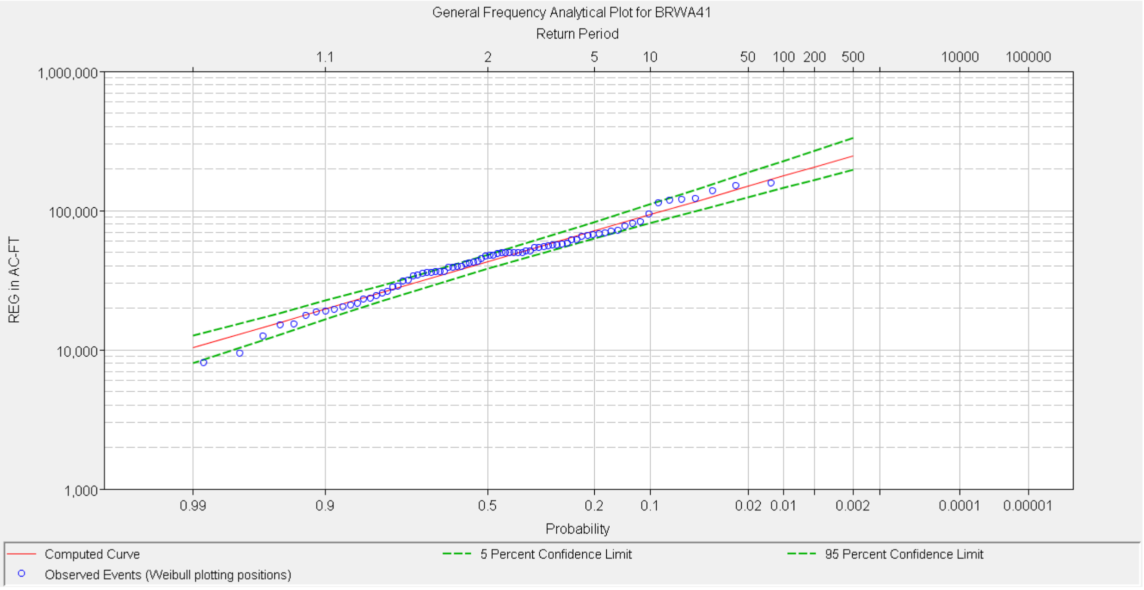

Figure 95: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D6

Table 119: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
202,114	212,178	0.2	263,876	163,650
175,762	182,570	0.5	225,188	144,298
156,079	160,953	1	196,856	129,613
136,583	139,880	2	169,332	114,839
110,998	112,766	5	134,149	95,029
91,634	92,574	10	108,361	79,629
71,961	72,361	20	83,089	63,493
43,995	43,995	50	49,371	39,244
25,842	25,668	80	29,263	22,413
19,251	18,994	90	22,212	16,215
14,966	14,645	95	17,624	12,240
9,136	8,702	99	11,272	7,006

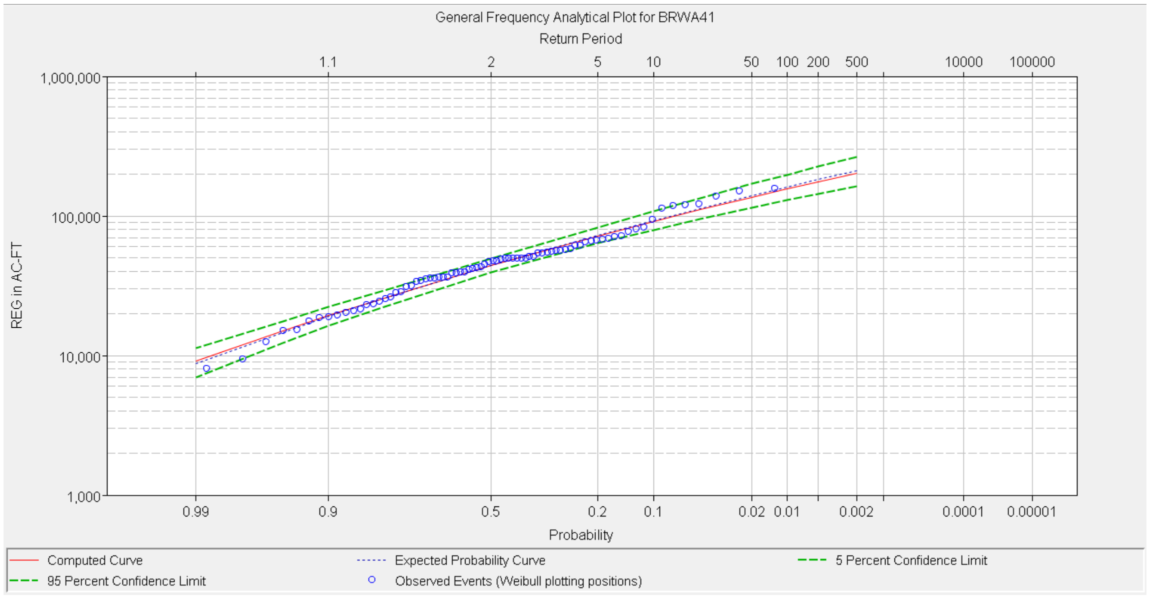

Figure 96: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 120: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
178,369	---	0.2	287,339	122,572
132,331	---	0.5	204,571	93,754
103,436	---	1	154,665	75,099
79,025	---	2	114,049	58,876
52,773	---	5	72,398	40,768
36,864	---	10	48,522	29,304
23,875	---	20	30,098	19,509
10,399	---	50	12,519	8,638
4,530	---	80	5,543	3,593
2,934	---	90	3,690	2,229
2,049	---	95	2,653	1,494
1,046	---	99	1,440	699

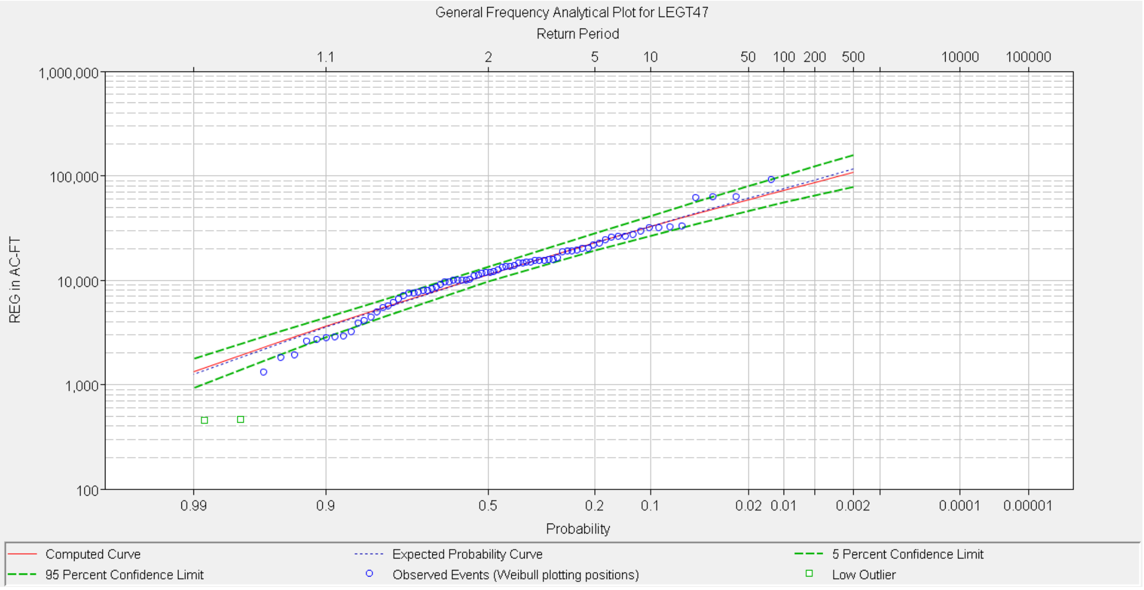

Figure 97: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-normal Probability Distribution for the Scenario D6

Table 121: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
107,019	115,459	0.2	157,639	78,811
86,228	91,447	0.5	123,337	64,890
71,900	75,364	1	100,385	55,074
58,740	60,901	2	79,887	45,856
43,066	44,091	5	56,362	34,551
32,450	32,943	10	41,118	26,619
22,822	23,007	20	27,928	19,142
11,310	11,310	50	13,296	9,630
5,395	5,346	80	6,427	4,415
3,608	3,543	90	4,409	2,836
2,567	2,493	95	3,224	1,940
1,328	1,246	99	1,775	922

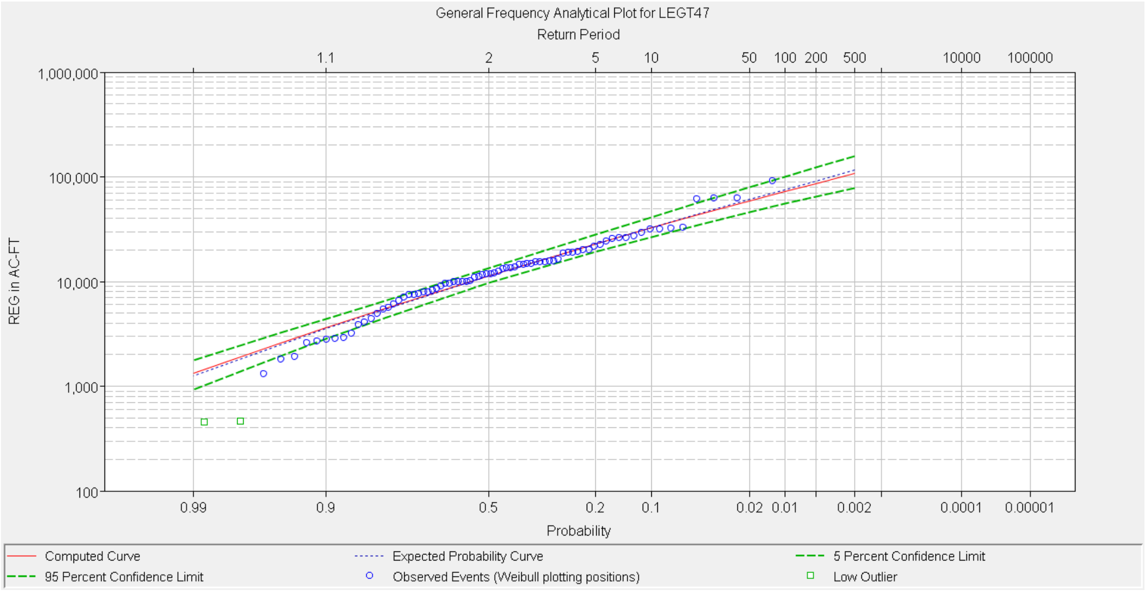

Figure 98: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 122: Stream Gage on the Little River at Little River (LRLR53) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
293,355	---	0.2	459,197	206,193
221,586	---	0.5	333,682	160,281
175,790	---	1	256,563	130,115
136,498	---	2	192,690	103,514
93,396	---	5	125,712	73,280
66,666	---	10	86,309	53,731
44,320	---	20	55,100	36,659
20,295	---	50	24,162	17,048
9,294	---	80	11,236	7,476
6,179	---	90	7,666	4,772
4,410	---	95	5,621	3,277
2,343	---	99	3,166	1,605

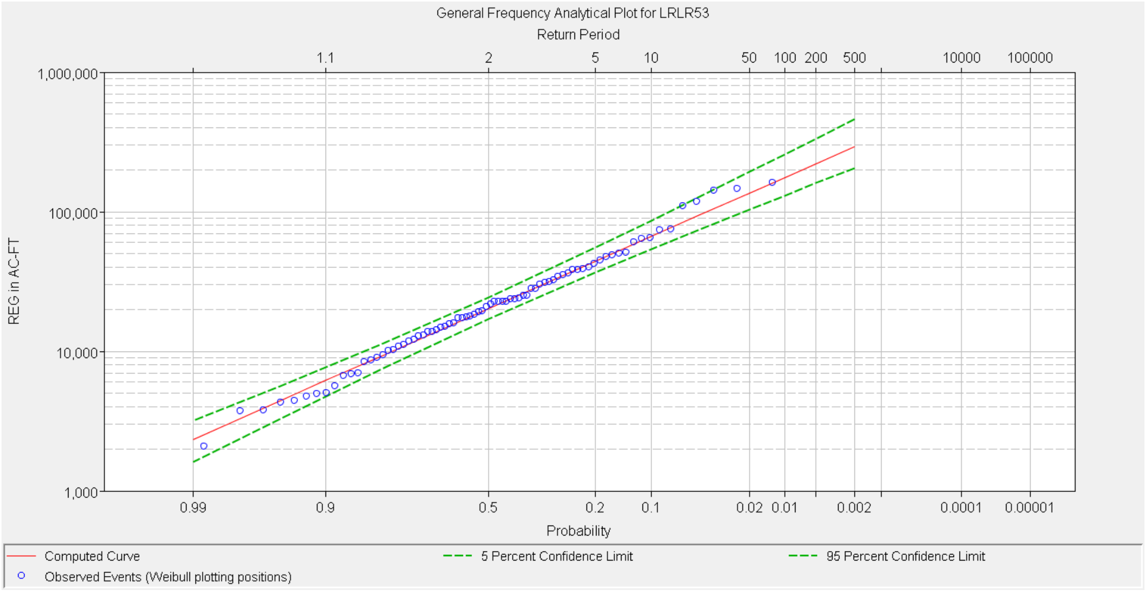

Figure 99: Stream Gage on the Little River at Little River (LRLR53) FFA log-normal Probability Distribution for the Scenario D6

Table 123: Stream Gage on the Little River at Little River (LRLR53) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
299,358	331,576	0.2	469,919	209,971
225,076	243,234	0.5	339,662	162,549
177,948	189,108	1	260,137	131,555
137,713	144,169	2	194,629	104,349
93,832	96,568	5	126,370	73,593
66,780	68,001	10	86,472	53,816
44,281	44,701	20	55,047	36,629
20,239	20,239	50	24,094	17,000
9,287	9,201	80	11,228	7,469
6,190	6,081	90	7,679	4,782
4,432	4,308	95	5,646	3,294
2,372	2,236	99	3,201	1,628

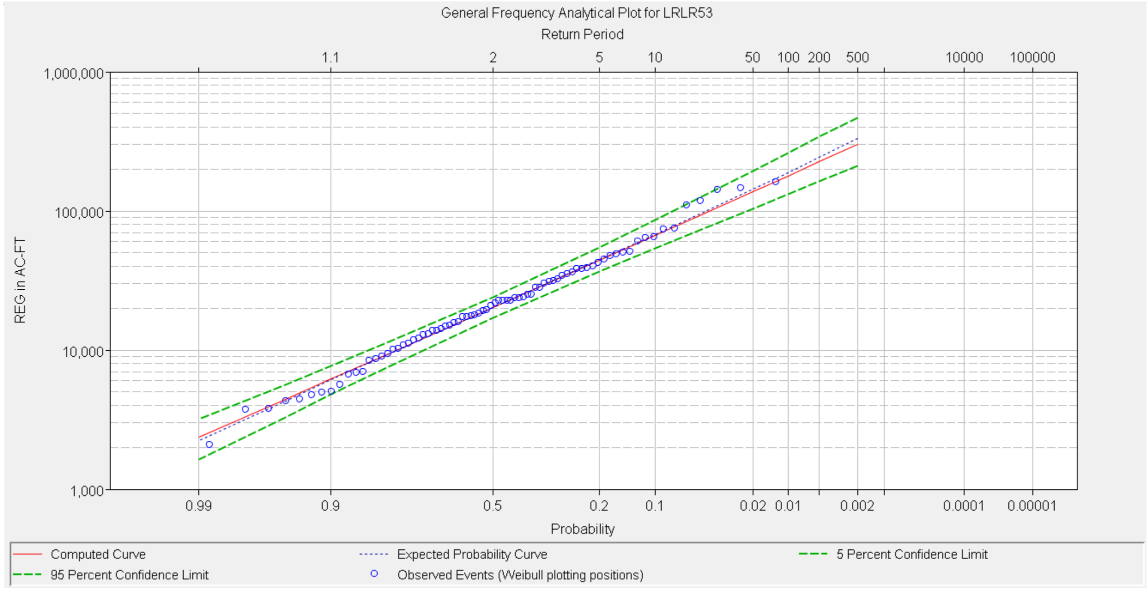

Figure 100: Stream Gage on the Little River at Little River (LRLR53) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 124: Stream Gage on the Little River at Cameron (LRCA58) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
416,215	---	0.2	625,798	301,967
322,417	---	0.5	467,983	240,104
261,159	---	1	368,424	198,601
207,449	---	2	283,915	161,280
146,867	---	5	192,476	117,774
108,059	---	10	136,688	88,798
74,523	---	20	90,853	62,701
36,608	---	50	42,904	31,235
17,983	---	80	21,373	14,750
12,402	---	90	15,092	9,804
9,125	---	95	11,379	6,963
5,131	---	99	6,748	3,637

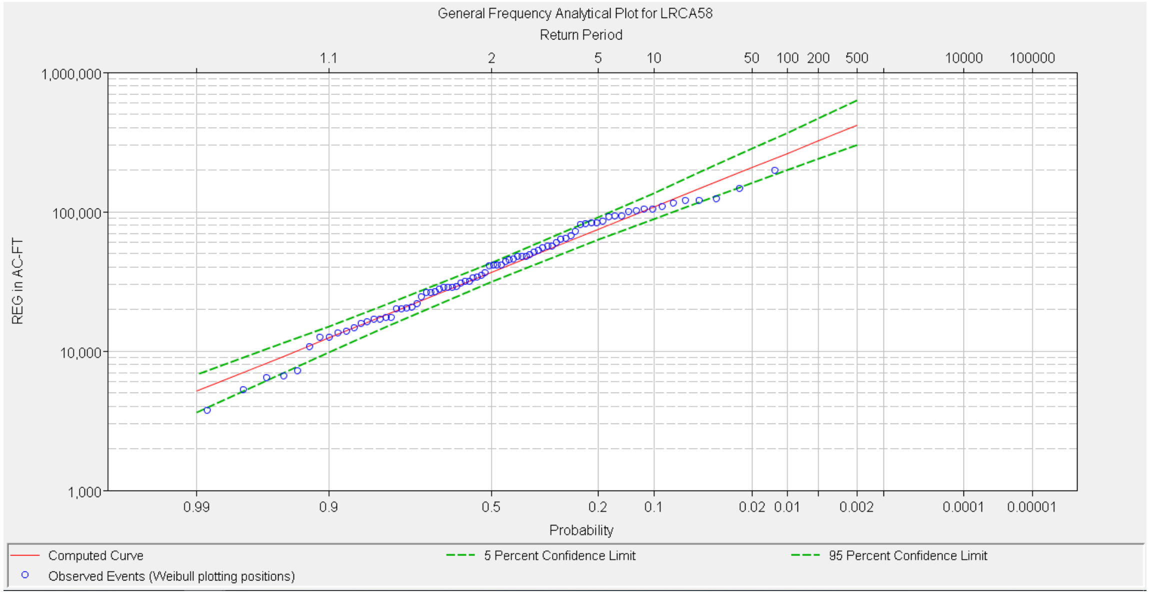

Figure 101: Stream Gage on the Little River at Cameron (LRCA58) FFA log-normal Probability Distribution for the Scenario D6

Table 125: Stream Gage on the Little River at Cameron (LRCA58) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
270,656	286,068	0.2	383,653	205,103
230,091	240,482	0.5	319,190	177,134
199,853	207,278	1	272,204	155,916
170,091	175,065	2	226,974	134,663
131,606	134,229	5	170,237	106,506
103,209	104,554	10	129,906	85,095
75,399	75,945	20	92,017	63,400
38,866	38,866	50	45,609	33,191
18,403	18,224	80	21,847	15,126
12,022	11,787	90	14,663	9,471
8,302	8,039	95	10,437	6,262
3,957	3,674	99	5,340	2,708

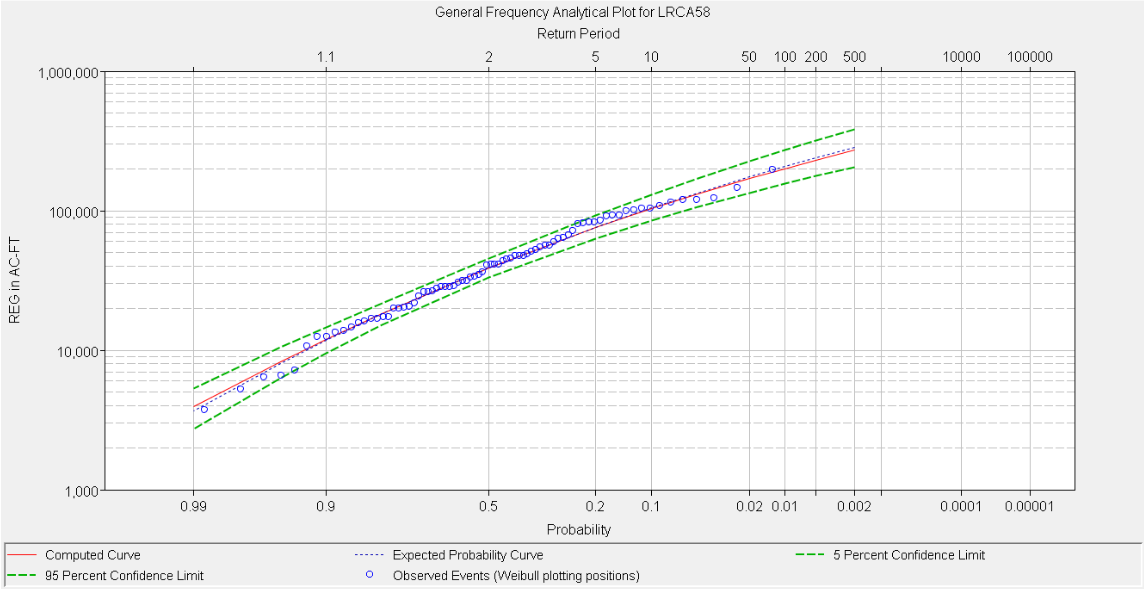

Figure 102: Stream Gage on the Little River at Cameron (LRCA58) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 126: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
574,524	---	0.2	786,108	448,915
472,111	---	0.5	628,712	376,373
401,500	---	1	523,098	325,276
336,362	---	2	428,136	277,171
257,923	---	5	317,536	217,661
203,719	---	10	244,067	175,179
153,096	---	20	178,289	134,058
88,636	---	50	100,138	78,454
51,316	---	80	58,604	44,065
38,564	---	90	44,847	32,189
30,460	---	95	36,094	24,742
19,567	---	99	24,153	15,019

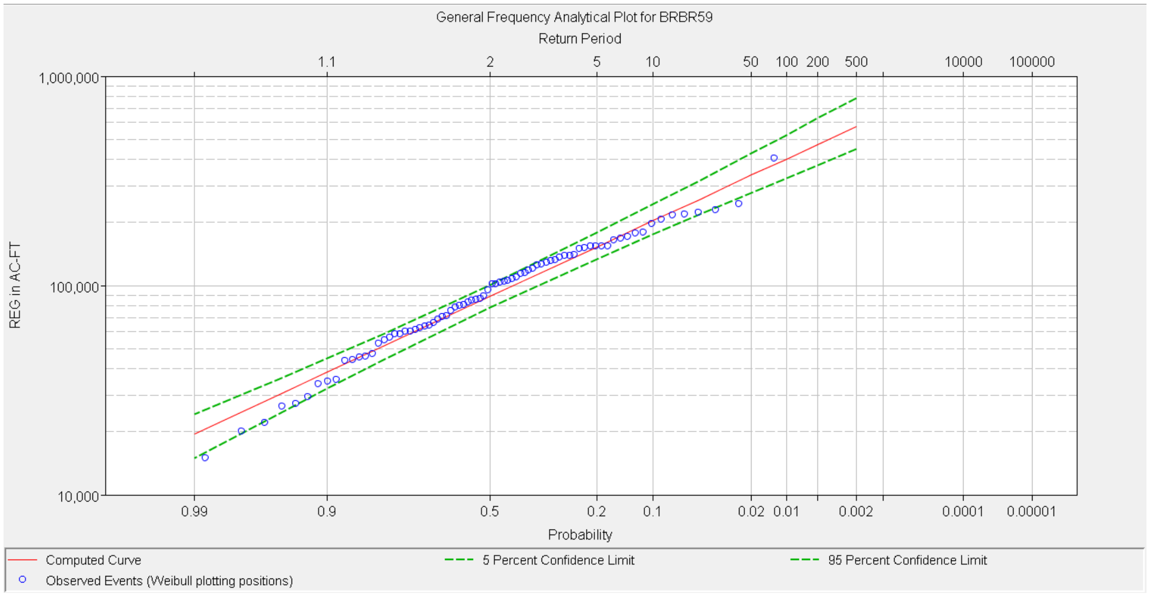

Figure 103: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D6

Table 127: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
403,709	420,553	0.2	526,362	326,890
357,924	369,839	0.5	459,285	293,211
322,277	331,150	1	407,950	266,625
285,679	291,901	2	356,148	238,948
235,605	239,132	5	286,954	200,329
196,097	198,024	10	233,969	169,091
154,521	155,368	20	180,095	135,240
93,101	93,101	50	105,294	82,464
52,317	51,922	80	59,688	45,000
37,607	37,035	90	43,816	31,304
28,197	27,499	95	33,637	22,689
15,812	14,920	99	19,937	11,791

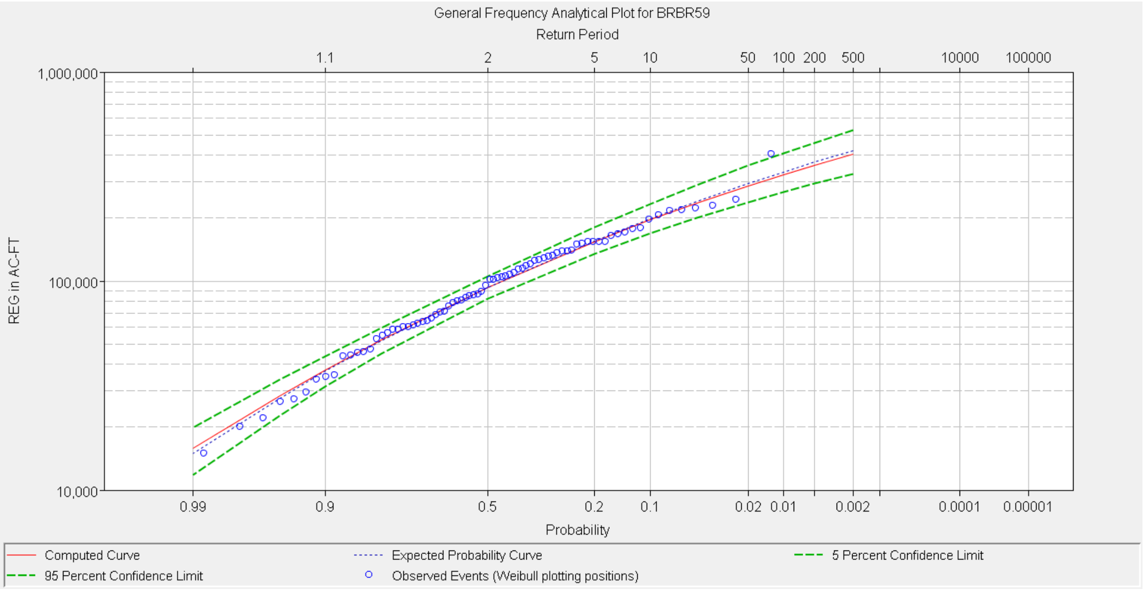

Figure 104: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 128: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
936,364	---	0.2	1,344,701	704,324
746,496	---	0.5	1,039,027	574,669
619,177	---	1	840,306	485,598
504,751	---	2	666,829	403,693
371,511	---	5	472,284	305,414
282,948	---	10	348,569	237,709
203,469	---	20	242,586	174,554
108,275	---	50	124,651	94,051
57,618	---	80	67,163	48,327
41,433	---	90	49,319	33,633
31,556	---	95	38,386	24,823
18,934	---	99	24,142	13,952

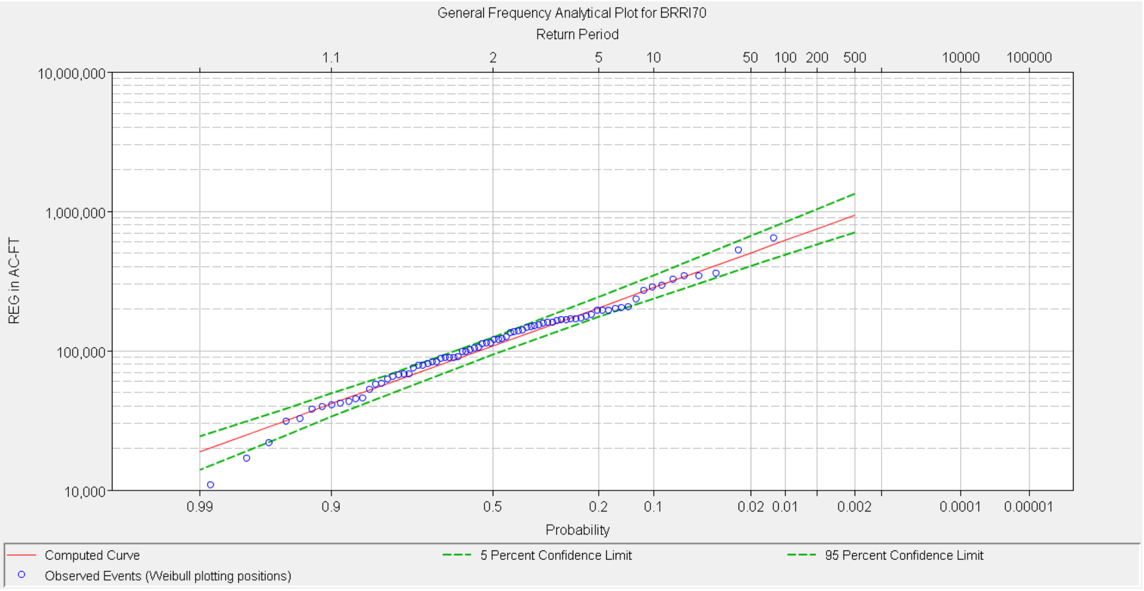

Figure 105: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D6

Table 129: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
733,257	782,395	0.2	1,010,632	569,226
610,152	641,433	0.5	820,131	482,505
523,114	544,379	1	688,828	419,953
441,105	454,756	2	568,088	359,865
339,981	346,740	5	423,922	283,824
268,496	271,893	10	325,863	228,350
200,542	201,890	20	236,456	173,735
112,651	112,651	50	128,543	98,785
61,748	61,290	80	71,238	52,416
44,649	44,005	90	52,585	36,700
33,984	33,202	95	40,914	27,061
20,108	19,112	99	25,426	14,962

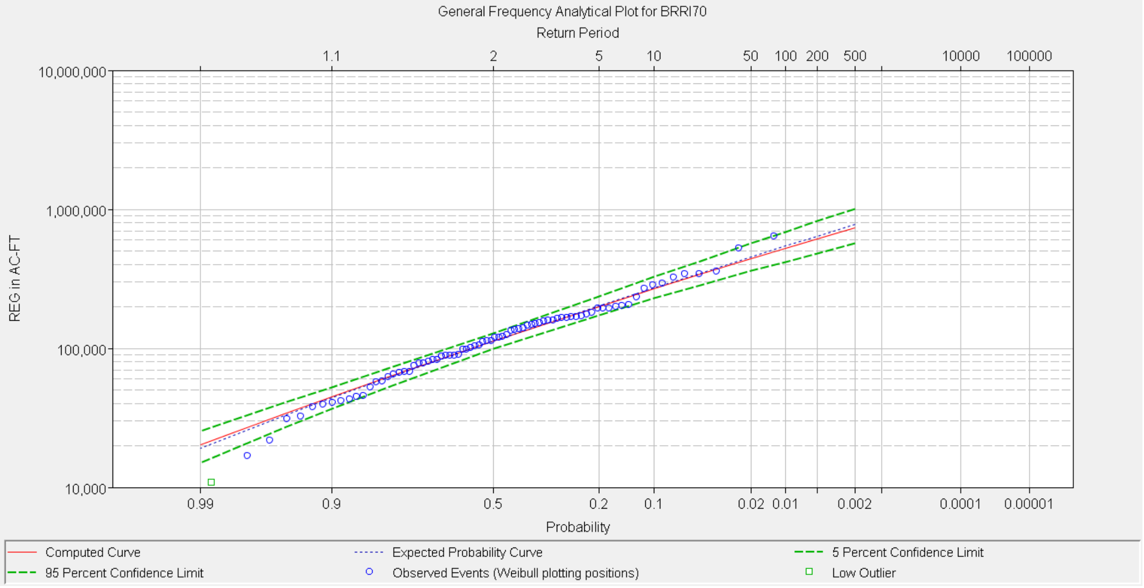

Figure 106: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D6

Table 130: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
310,170	310,245	0.2	367,871	267,851
309,707	309,833	0.5	367,270	267,474
308,890	309,101	1	366,210	266,811
307,176	307,481	2	363,987	265,416
301,690	302,231	5	356,887	260,945
291,911	292,423	10	344,284	252,947
270,834	271,301	20	317,364	235,577
197,848	197,848	50	227,061	173,751
105,021	103,856	80	120,145	90,451
64,602	62,942	90	75,975	53,192
39,625	37,854	95	48,567	30,762
12,658	11,141	99	17,435	8,395

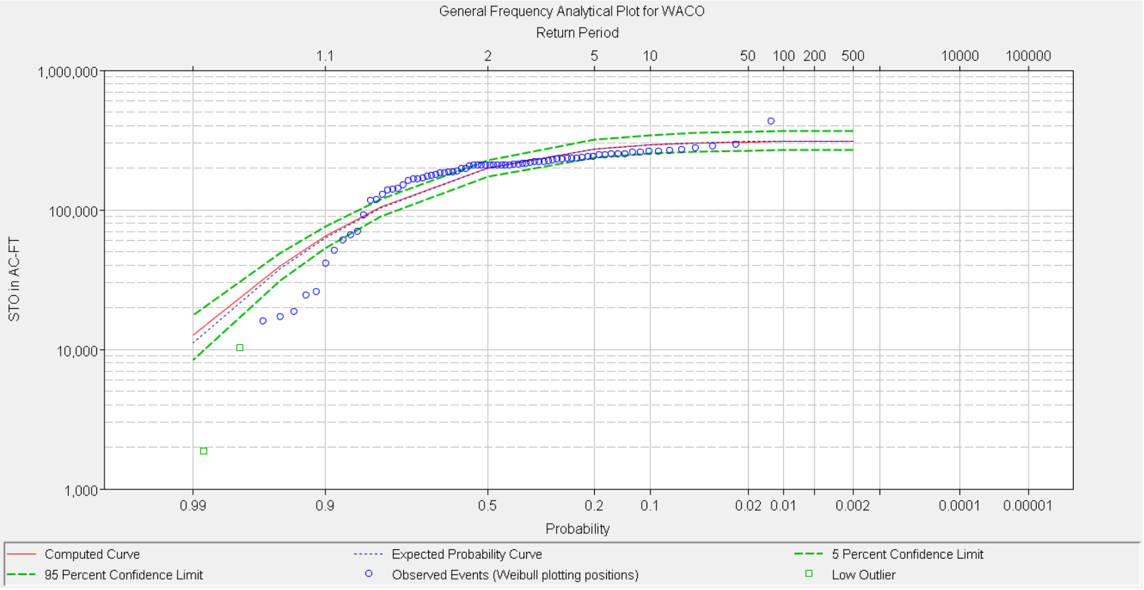

Figure 107: Waco Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 131: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
2,986,142	3,314,216	0.2	3,898,779	2,428,835
2,273,422	2,448,484	0.5	2,852,252	1,905,647
1,845,094	1,947,558	1	2,246,427	1,581,875
1,493,334	1,550,873	2	1,764,938	1,308,960
1,122,498	1,145,589	5	1,277,016	1,011,773
898,648	909,358	10	995,353	825,384
712,958	716,757	20	772,277	664,068
510,059	510,059	50	545,450	475,491
413,272	412,615	80	444,700	380,007
385,604	384,775	90	416,556	352,308
370,329	369,328	95	401,098	336,984
354,065	353,228	99	384,687	320,660

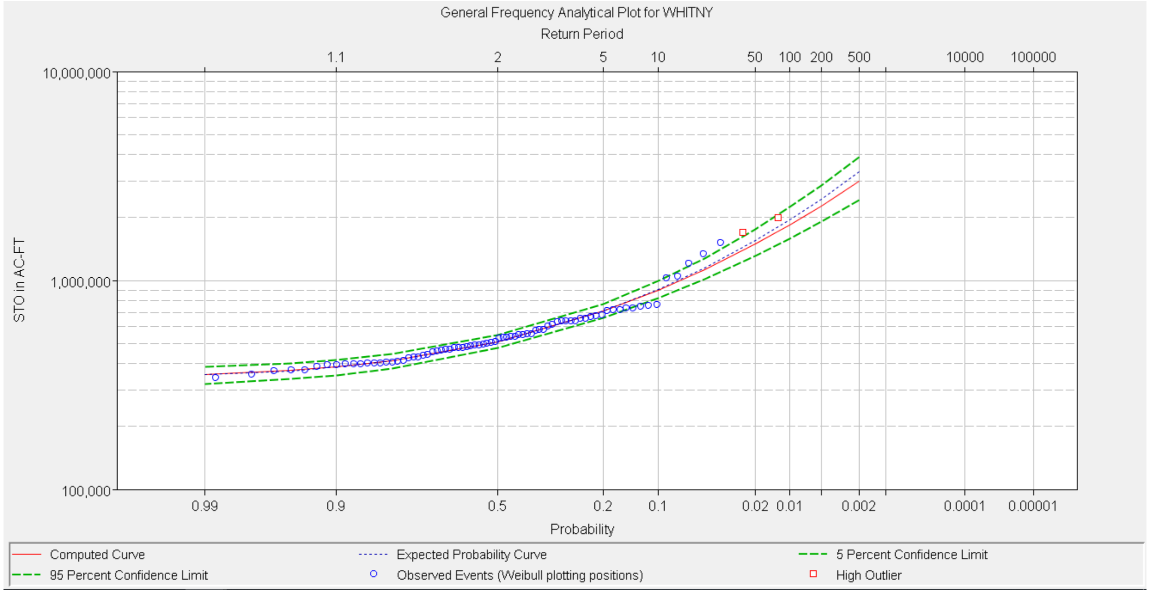

Figure 108: Whitney Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 132: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
145,449	147,775	0.2	177,346	123,877
138,123	140,079	0.5	167,339	118,175
131,420	133,124	1	158,256	112,922
123,475	124,859	2	147,586	106,649
110,541	111,529	5	130,459	96,316
98,326	98,941	10	114,589	86,397
83,152	83,473	20	95,354	73,809
55,320	55,320	50	61,840	49,644
32,445	32,198	80	36,460	28,417
23,253	22,879	90	26,682	19,708
17,149	16,689	95	20,185	14,016
8,992	8,404	99	11,278	6,739

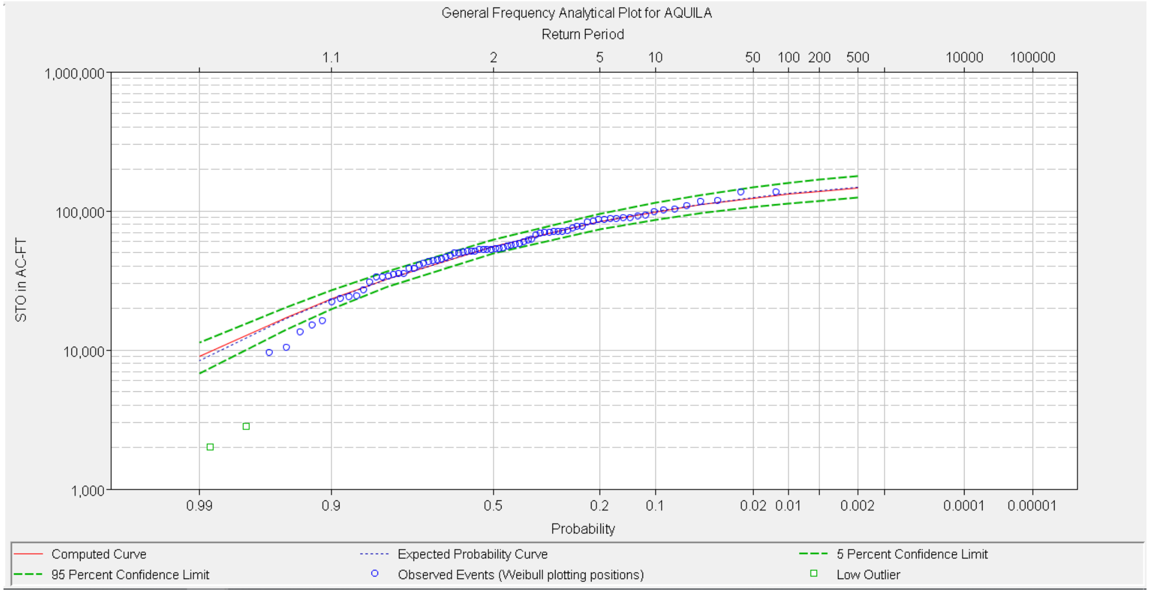

Figure 109: Aquilla Reservoir FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 133: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
235,448	---	0.2	313,781	187,825
196,696	---	0.5	255,711	159,823
169,570	---	1	216,069	139,829
144,188	---	2	179,846	120,763
113,058	---	5	136,778	96,780
91,086	---	10	107,482	79,325
70,115	---	20	80,614	62,085
42,501	---	50	47,527	38,007
25,763	---	80	29,095	22,407
19,831	---	90	22,771	16,806
15,977	---	95	18,664	13,206
10,652	---	99	12,918	8,360

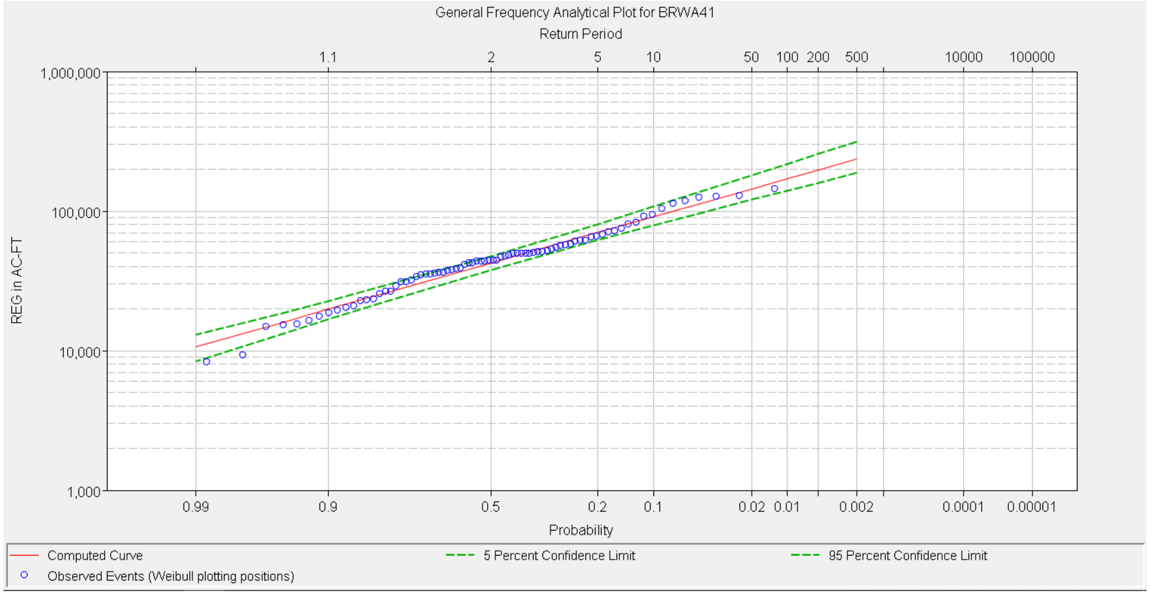

Figure 110: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D9

Table 134: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
188,409	197,156	0.2	243,506	153,753
165,273	171,270	0.5	209,875	136,628
147,780	152,123	1	184,917	123,485
130,261	133,232	2	160,376	110,125
106,953	108,575	5	128,536	91,981
89,048	89,921	10	104,819	77,678
70,596	70,973	20	81,216	62,488
43,833	43,833	50	49,047	39,217
26,051	25,878	80	29,404	22,680
19,496	19,239	90	22,414	16,491
15,201	14,878	95	17,834	12,489
9,311	8,871	99	11,443	7,176

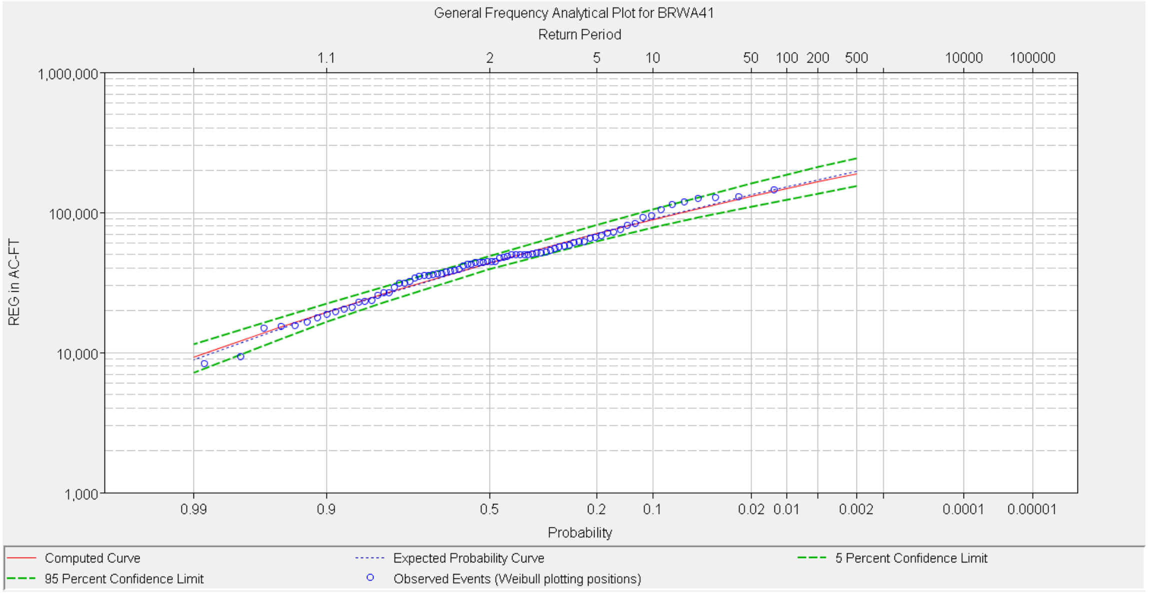

Figure 111: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 135: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
579,821	---	0.2	794,754	452,428
475,940	---	0.5	634,830	378,942
404,388	---	1	527,644	327,229
338,445	---	2	431,371	278,585
259,134	---	5	319,399	218,474
204,405	---	10	245,136	175,620
153,365	---	20	178,755	134,193
88,520	---	50	100,076	78,298
51,092	---	80	58,391	43,835
38,334	---	90	44,617	31,965
30,238	---	95	35,866	24,533
19,377	---	99	23,946	14,850

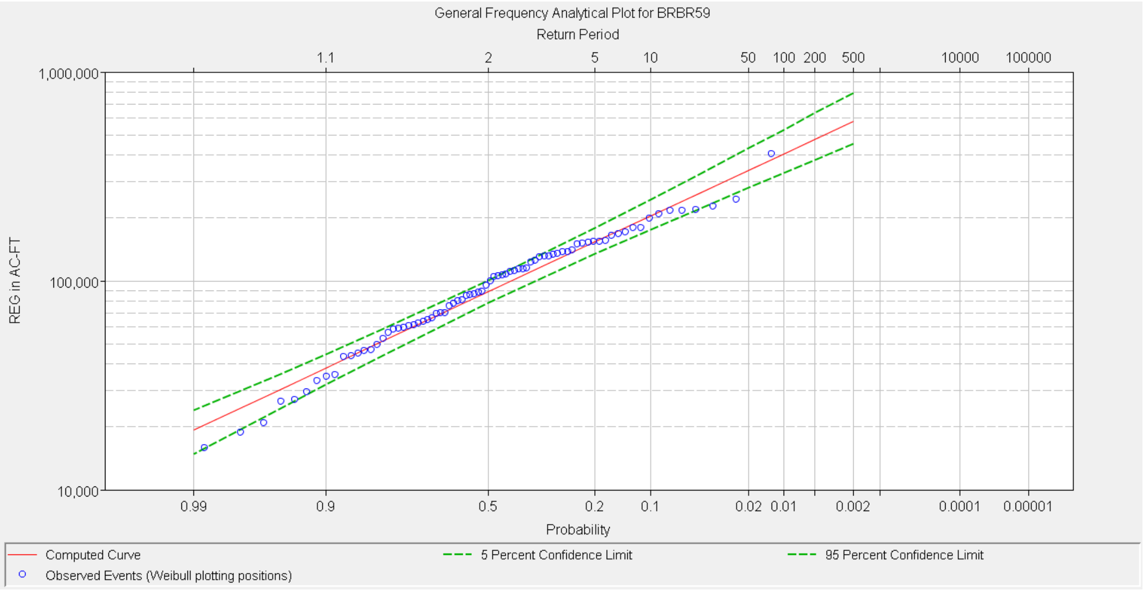

Figure 112: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D9

Table 136: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
402,435	418,987	0.2	524,756	325,803
357,305	369,055	0.5	458,637	292,606
322,047	330,827	1	407,852	266,316
285,744	291,919	2	356,447	238,870
235,906	239,421	5	287,541	200,449
196,453	198,377	10	234,592	169,272
154,820	155,669	20	180,601	135,400
93,141	93,141	50	105,417	82,445
52,131	51,734	80	59,518	44,805
37,356	36,781	90	43,563	31,061
27,921	27,221	95	33,346	22,433
15,542	14,652	99	19,634	11,560

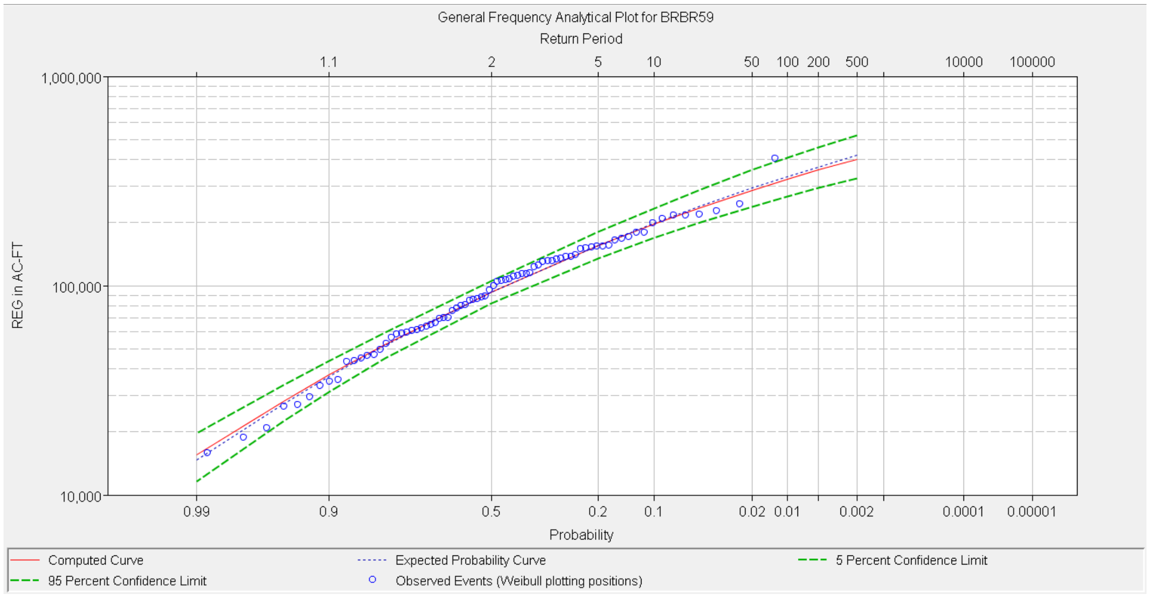

Figure 113: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 137: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
941,984	---	0.2	1,355,317	707,505
750,094	---	0.5	1,045,828	576,655
621,557	---	1	844,875	486,850
506,154	---	2	669,650	404,345
371,951	---	5	473,433	305,465
282,883	---	10	348,867	237,439
203,074	---	20	242,336	174,077
107,712	---	50	124,093	93,493
57,131	---	80	66,648	47,875
41,013	---	90	48,862	33,256
31,192	---	95	37,981	24,506
18,666	---	99	23,830	13,732

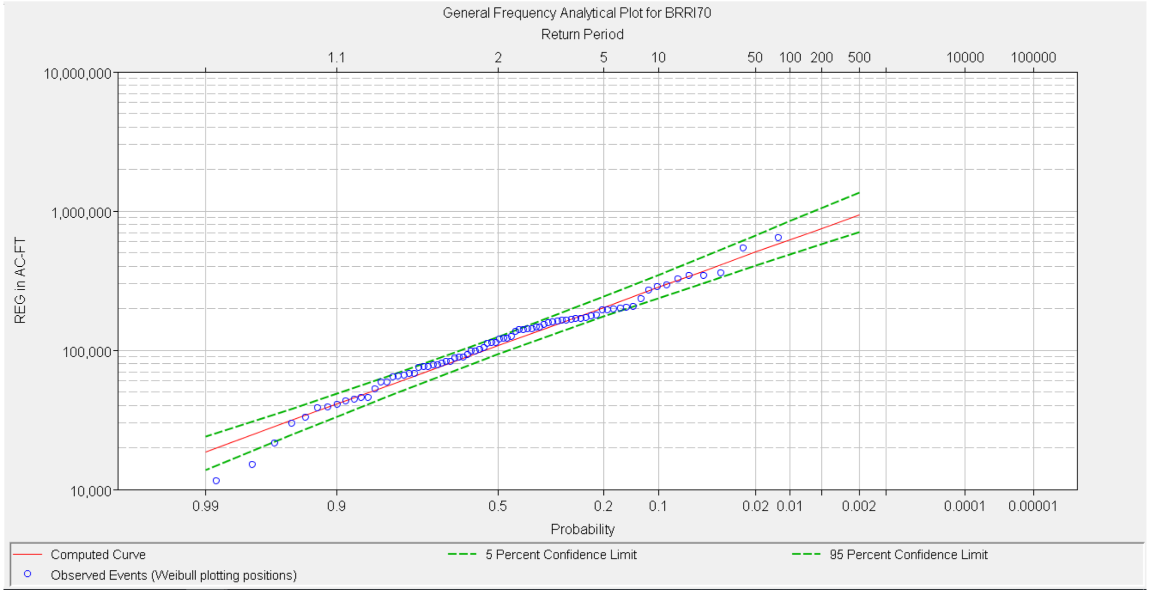

Figure 114: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D9

Table 138: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
731,590	780,155	0.2	1,009,435	567,388
609,589	640,606	0.5	820,450	481,517
523,079	544,222	1	689,784	419,405
441,369	454,974	2	569,320	359,601
340,337	347,098	5	425,074	283,720
268,736	272,138	10	326,701	228,228
200,541	201,893	20	236,832	173,495
112,207	112,207	50	128,202	98,277
61,080	60,621	80	70,561	51,772
43,953	43,308	90	51,850	36,056
33,300	32,519	95	40,171	26,449
19,501	18,514	99	24,734	14,453

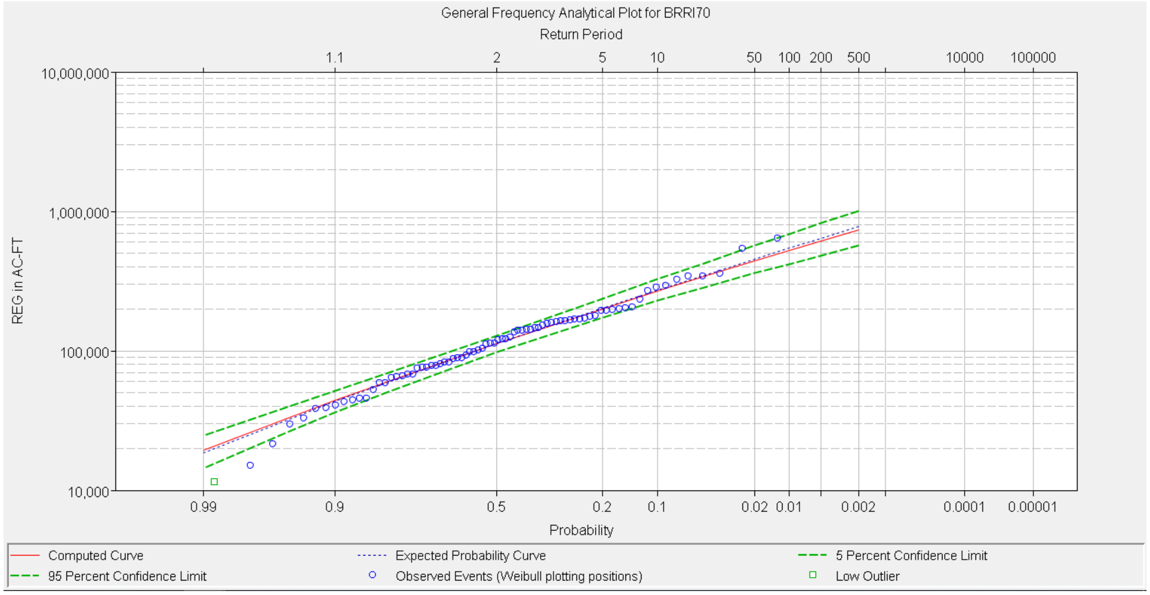

Figure 115: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D9

Table 139: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
249,294	---	0.2	335,687	197,260
206,919	---	0.5	271,555	166,878
177,433	---	1	228,069	145,301
149,996	---	2	188,585	124,828
116,587	---	5	142,018	99,244
93,202	---	10	110,635	80,764
71,070	---	20	82,124	62,656
42,311	---	50	47,505	37,685
25,189	---	80	28,572	21,799
19,208	---	90	22,166	16,181
15,355	---	95	18,039	12,606
10,090	---	99	12,321	7,849

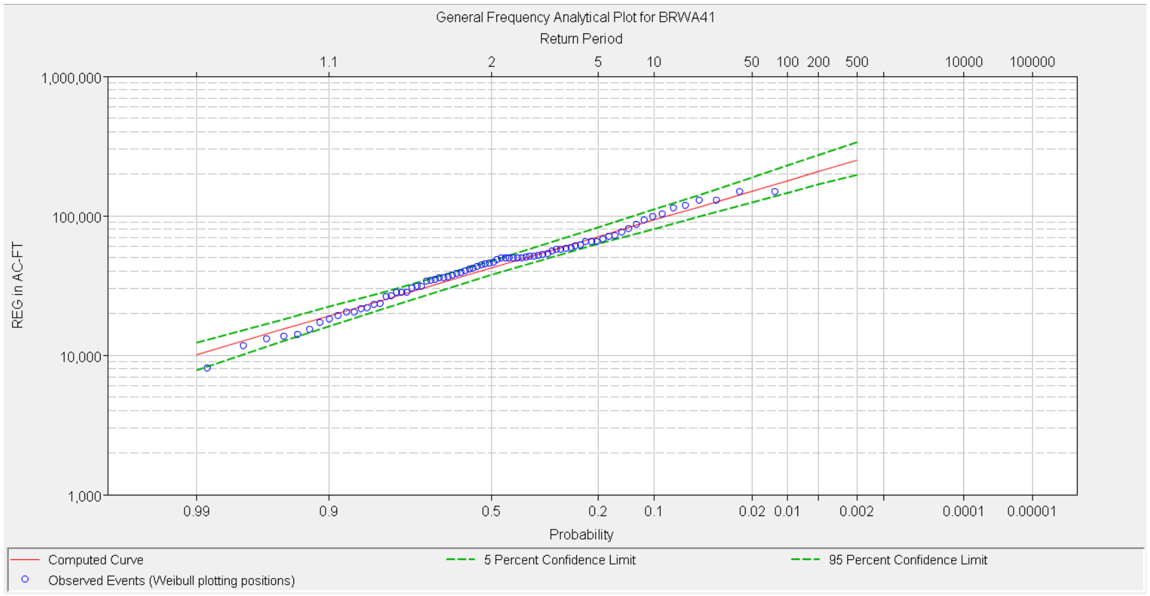

Figure 116: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-normal Probability Distribution for the Scenario D10

Table 140: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
206,451	217,144	0.2	270,856	166,538
178,627	185,801	0.5	229,809	146,183
157,999	163,099	1	199,996	130,844
137,705	141,131	2	171,243	115,510
111,291	113,108	5	134,813	95,106
91,473	92,433	10	108,362	79,374
71,503	71,909	20	82,669	63,018
43,428	43,428	50	48,784	38,695
25,420	25,248	80	28,820	22,016
18,926	18,674	90	21,864	15,918
14,717	14,402	95	17,352	12,019
9,003	8,579	99	11,119	6,898

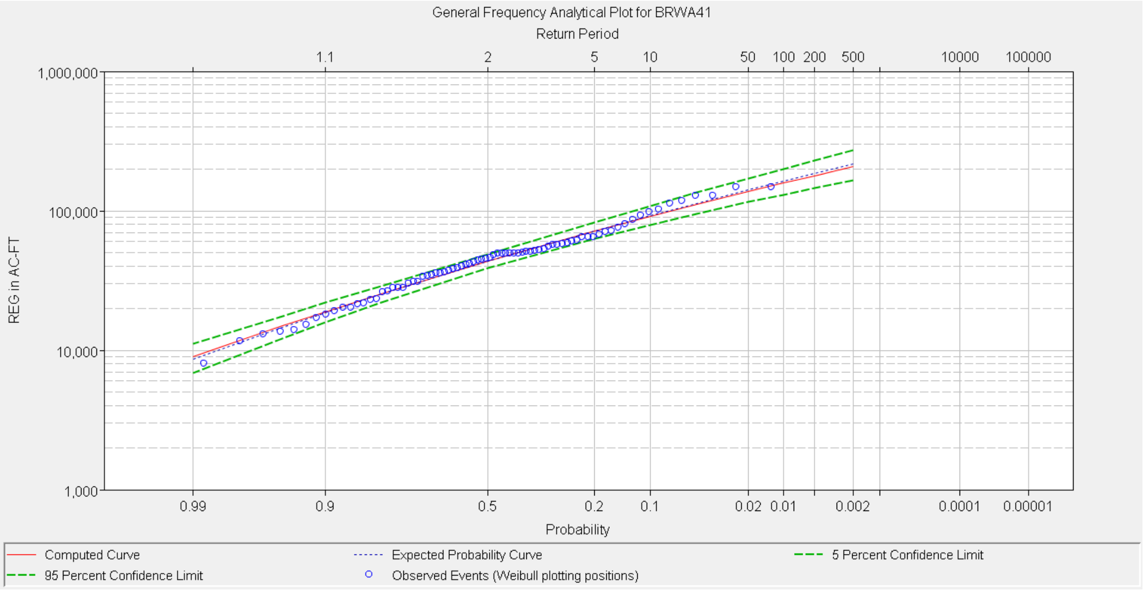

Figure 117: Stream Gage on the Brazos River at Waco (BRWA41) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Table 141: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
178,442	---	0.2	287,591	122,576
132,346	---	0.5	204,682	93,733
103,422	---	1	154,706	75,065
78,994	---	2	114,045	58,836
52,731	---	5	72,363	40,725
36,822	---	10	48,479	29,264
23,837	---	20	30,058	19,475
10,374	---	50	12,492	8,616
4,515	---	80	5,527	3,581
2,923	---	90	3,678	2,220
2,041	---	95	2,643	1,487
1,041	---	99	1,434	696

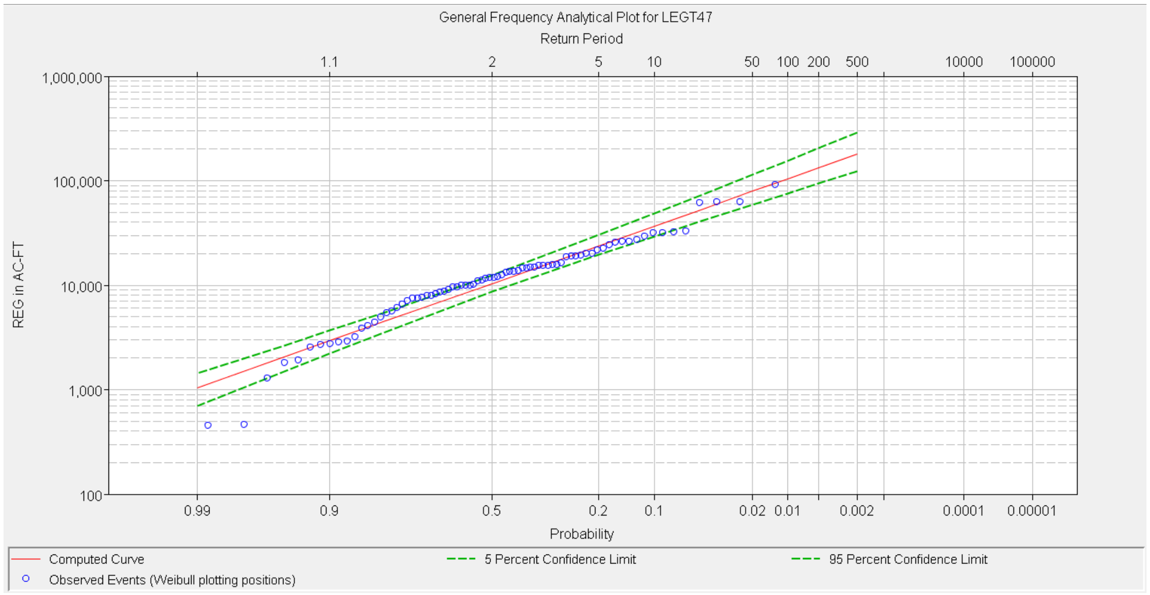

Figure 118: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-normal Probability Distribution for the Scenario D10

Table 142: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
107,325	115,819	0.2	158,226	78,983
86,414	91,661	0.5	123,697	64,991
72,015	75,495	1	100,613	55,132
58,799	60,968	2	80,015	45,880
43,073	44,100	5	56,399	34,543
32,432	32,926	10	41,113	26,595
22,791	22,977	20	27,900	19,111
11,280	11,280	50	13,264	9,602
5,375	5,325	80	6,405	4,397
3,592	3,528	90	4,392	2,823
2,555	2,482	95	3,211	1,930
1,322	1,240	99	1,767	917

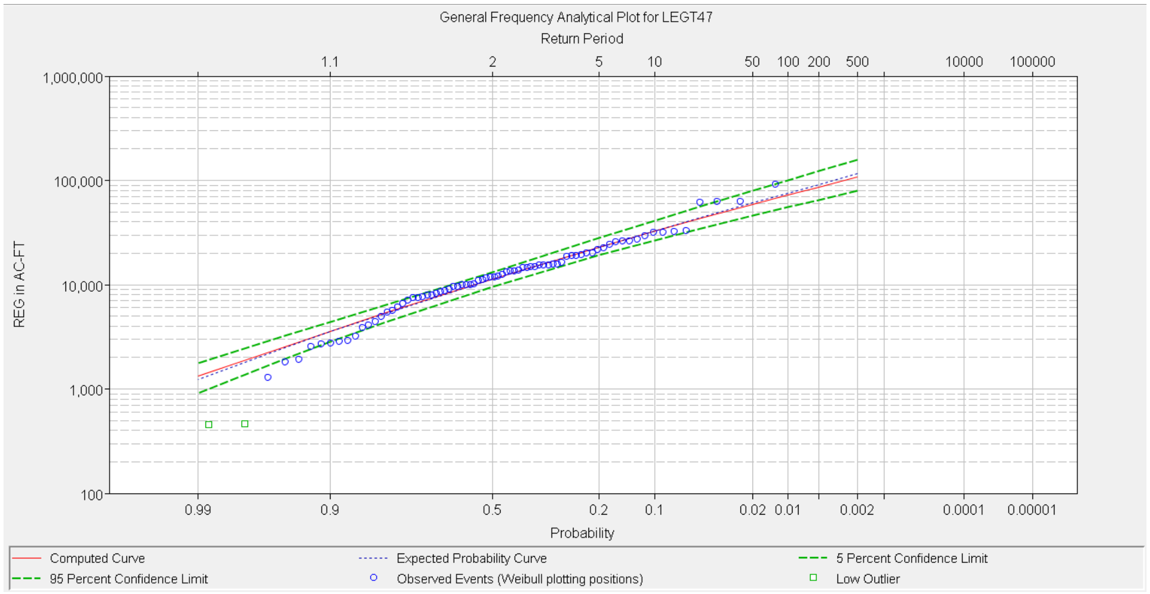

Figure 119: Stream Gage on the Leon River at Gatesville (LEGT47) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Table 143: Stream Gage on the Little River at Little River (LRLR53) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
291,216	---	0.2	455,147	204,938
220,183	---	0.5	331,102	159,444
174,816	---	1	254,809	129,528
135,860	---	2	191,562	103,128
93,081	---	5	125,160	73,094
66,518	---	10	86,041	53,652
44,284	---	20	55,013	36,653
20,333	---	50	24,192	17,090
9,336	---	80	11,280	7,515
6,216	---	90	7,706	4,805
4,442	---	95	5,656	3,303
2,365	---	99	3,192	1,623

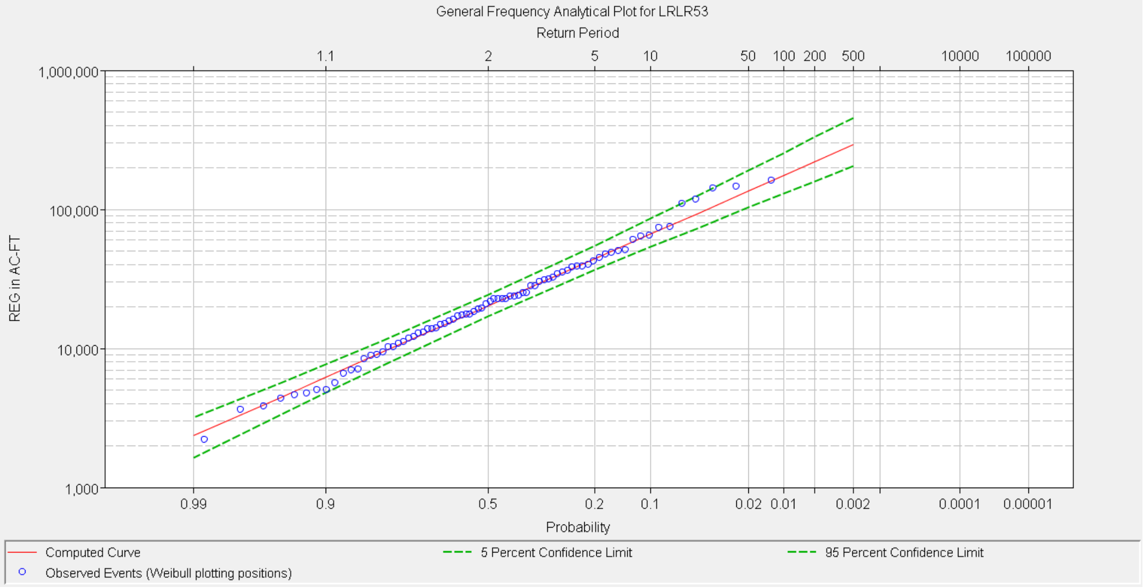

Figure 120: Stream Gage on the Little River at Little River (LRLR53) FFA log-normal Probability Distribution for the Scenario D10

Table 144: Stream Gage on the Little River at Little River (LRLR53) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
301,841	334,678	0.2	474,118	211,628
226,355	244,789	0.5	341,673	163,456
178,630	189,924	1	261,123	132,075
138,007	144,521	2	194,986	104,604
93,850	96,600	5	126,321	73,647
66,719	67,943	10	86,329	53,802
44,216	44,635	20	54,921	36,599
20,234	20,234	50	24,072	17,005
9,324	9,238	80	11,266	7,505
6,236	6,127	90	7,730	4,823
4,480	4,357	95	5,701	3,335
2,417	2,280	99	3,255	1,663

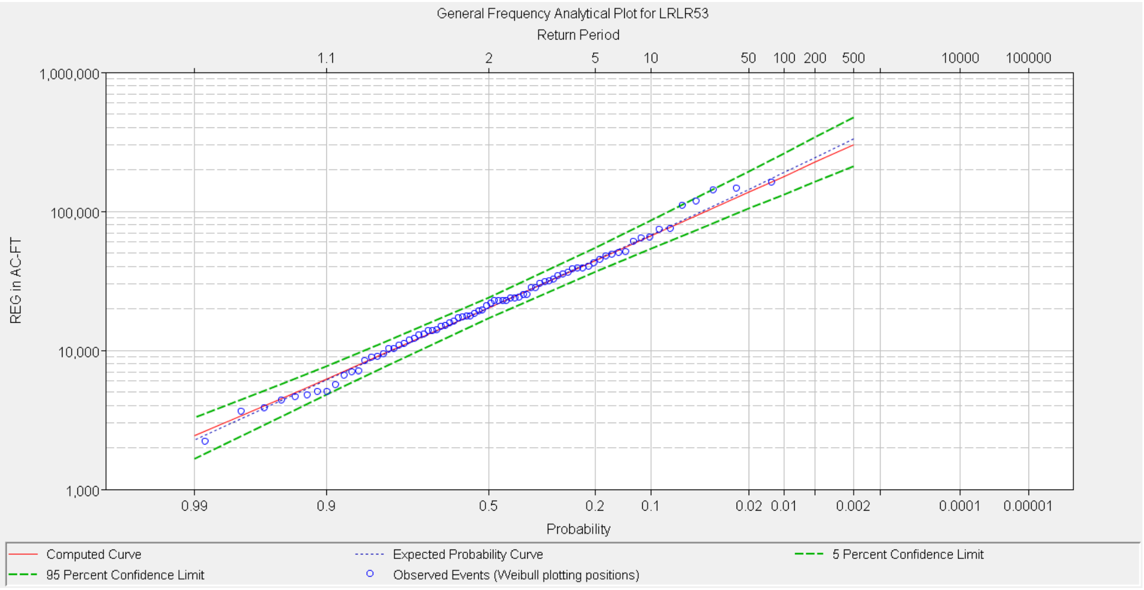

Figure 121: Stream Gage on the Little River at Little River (LRLR53) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Table 145: Stream Gage on the Little River at Cameron (LRCA58) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
415,426	---	0.2	624,302	301,513
321,906	---	0.5	467,030	239,810
260,812	---	1	367,781	198,404
207,232	---	2	283,509	161,160
146,775	---	5	192,292	117,732
108,032	---	10	136,615	88,797
74,538	---	20	90,850	62,727
36,647	---	50	42,941	31,275
18,017	---	80	21,410	14,782
12,431	---	90	15,124	9,830
9,150	---	95	11,407	6,984
5,149	---	99	6,769	3,652

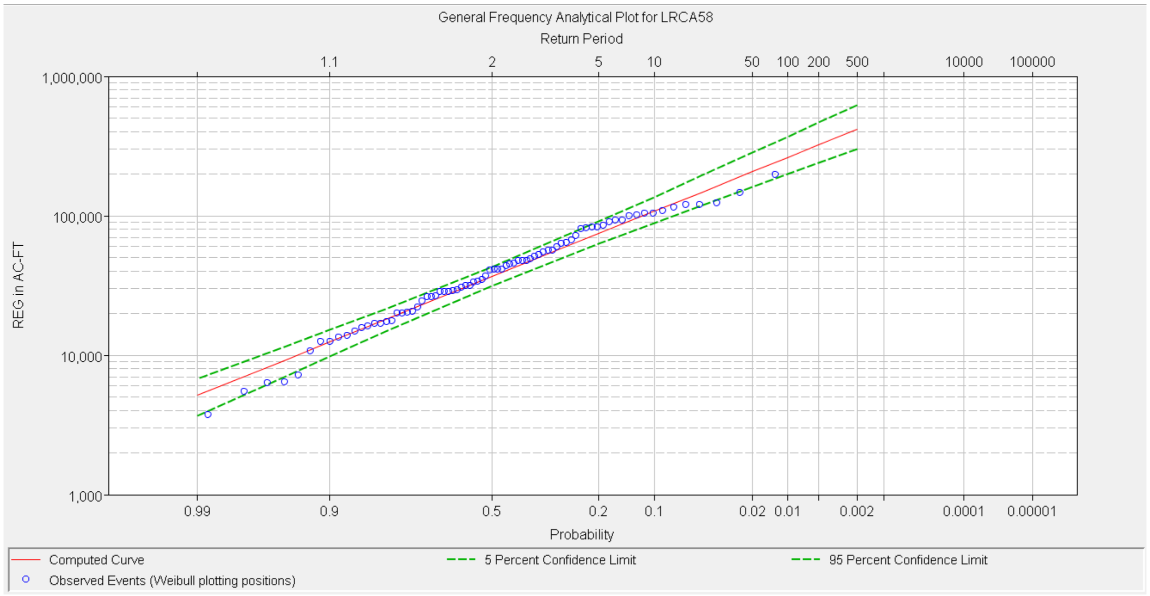

Figure 122: Stream Gage on the Little River at Cameron (LRCA58) FFA log-normal Probability Distribution for the Scenario D10

Table 146: Stream Gage on the Little River at Cameron (LRCA58) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
269,680	284,967	0.2	381,991	204,477
229,411	239,729	0.5	318,045	176,697
199,366	206,745	1	271,388	155,604
169,769	174,717	2	226,434	134,460
131,459	134,071	5	169,981	106,419
103,159	104,500	10	129,803	85,075
75,415	75,960	20	92,014	63,427
38,917	38,917	50	45,660	33,241
18,441	18,262	80	21,888	15,161
12,049	11,814	90	14,693	9,496
8,322	8,058	95	10,460	6,279
3,967	3,683	99	5,352	2,715

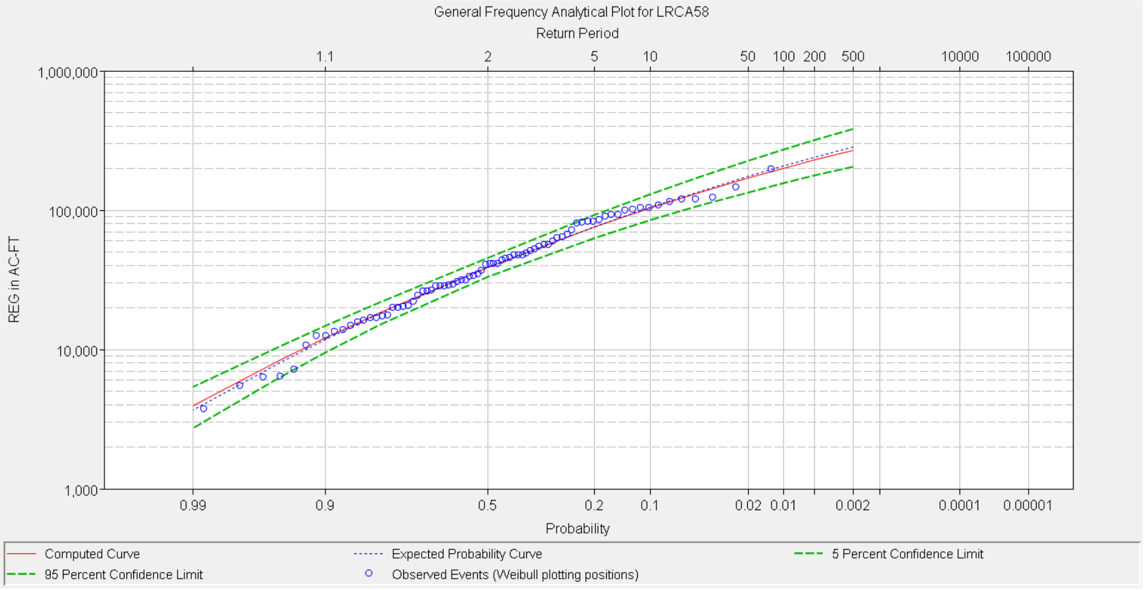

Figure 123: Stream Gage on the Little River at Cameron (LRCA58) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Table 147: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
575,382	---	0.2	787,777	449,363
472,630	---	0.5	629,765	376,615
401,811	---	1	523,781	325,390
336,503	---	2	428,522	277,180
257,894	---	5	317,632	217,562
203,600	---	10	244,012	175,023
152,918	---	20	178,136	133,866
88,436	---	50	99,937	78,258
51,144	---	80	58,423	43,904
38,413	---	90	44,685	32,051
30,326	---	95	35,948	24,623
19,464	---	99	24,035	14,932

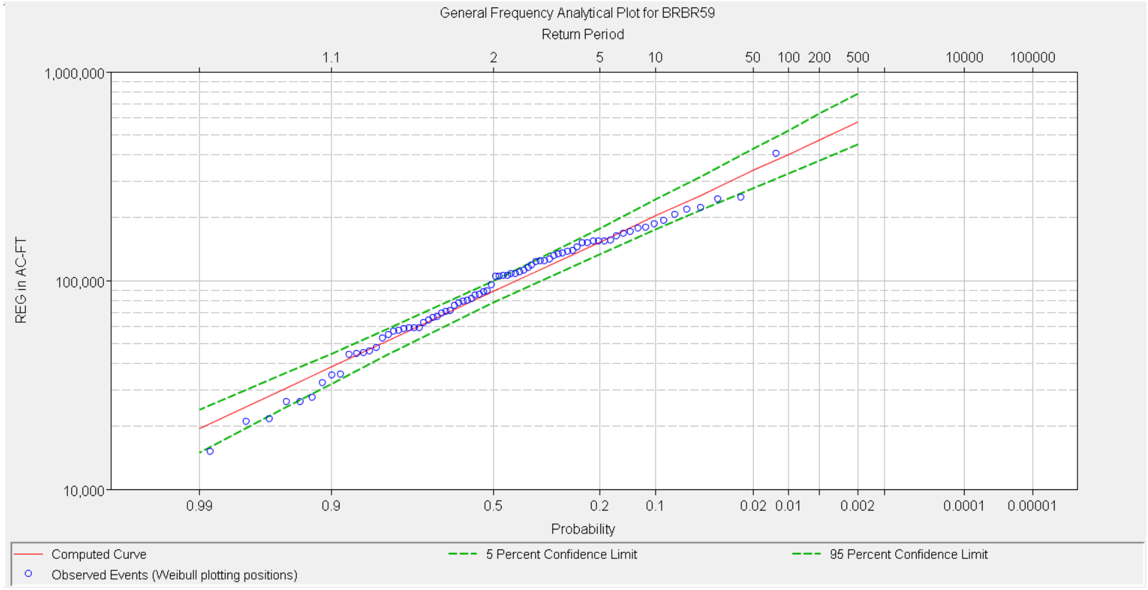

Figure 124: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-normal Probability Distribution for the Scenario D10

Table 148: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
403,227	420,022	0.2	525,875	326,425
357,555	369,441	0.5	458,946	292,835
321,975	330,832	1	407,695	266,306
285,431	291,644	2	355,953	238,676
235,405	238,929	5	286,805	200,102
195,917	197,843	10	233,830	168,888
154,348	155,195	20	179,949	135,052
92,926	92,926	50	105,123	82,290
52,151	51,756	80	59,514	44,844
37,454	36,882	90	43,651	31,164
28,058	27,361	95	33,484	22,565
15,703	14,814	99	19,812	11,701

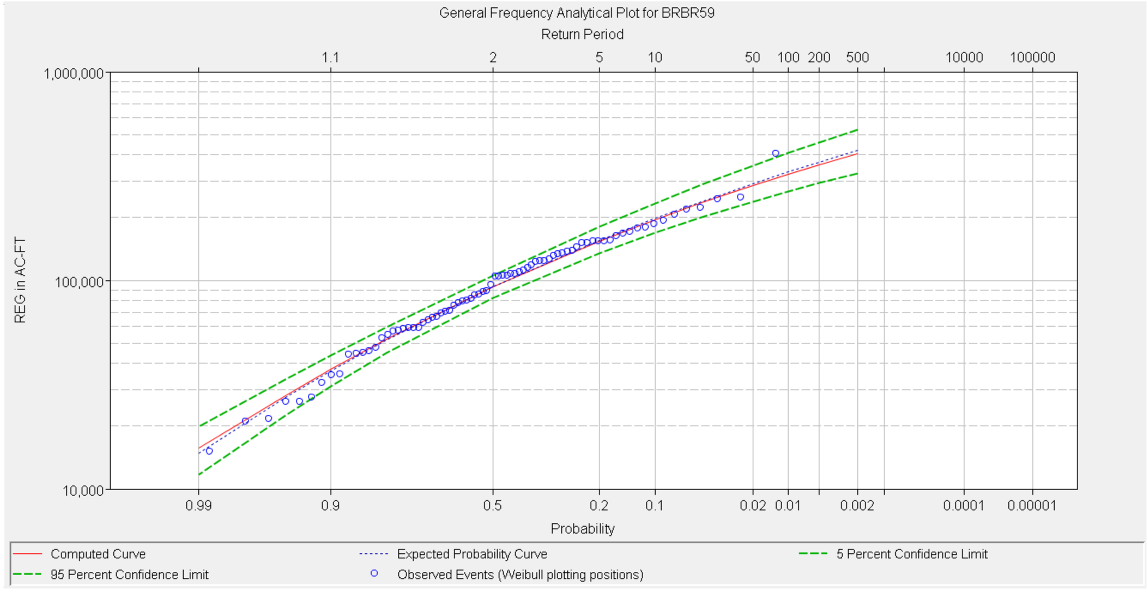

Figure 125: Stream Gage on the Brazos River at Bryan (BRBR59) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Table 149: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits	
			0.05 (ac-ft)	0.95 (ac-ft)
936,406	---	0.2	1,344,647	704,403
746,570	---	0.5	1,039,048	574,761
619,266	---	1	840,366	485,695
504,847	---	2	666,912	403,791
371,608	---	5	472,382	305,509
283,041	---	10	348,666	237,797
203,552	---	20	242,674	174,631
108,335	---	50	124,716	94,106
57,659	---	80	67,208	48,363
41,466	---	90	49,355	33,661
31,583	---	95	38,416	24,845
18,952	---	99	24,164	13,966

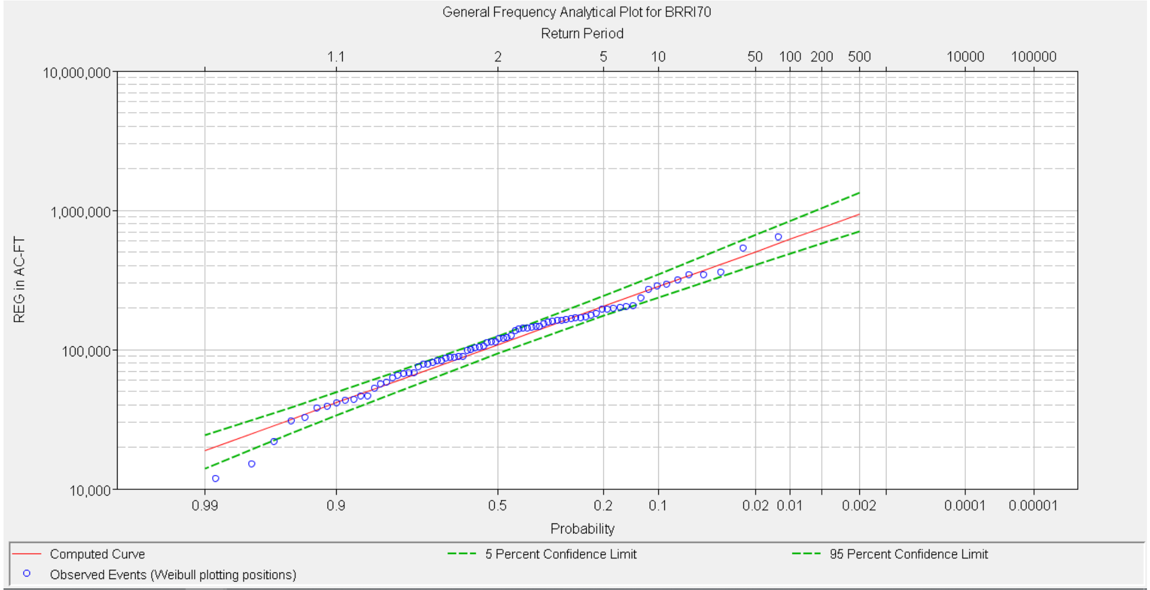

Figure 126: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-normal Probability Distribution for the Scenario D10

Table 150: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D10

Computed Curve (ac-ft)	Expected Probability (ac-ft)	Percent Chance Exceedance	Confidence Limits 0.05 (ac-ft)	Confidence Limits 0.95 (ac-ft)
718,468	764,981	0.2	987,816	558,721
601,086	630,974	0.5	806,611	475,876
517,388	537,868	1	680,562	415,644
437,947	451,192	2	563,732	357,385
339,134	345,767	5	422,931	283,054
268,665	272,019	10	326,252	228,374
201,156	202,497	20	237,375	174,146
113,045	113,045	50	129,080	99,078
61,641	61,176	80	71,155	52,292
44,347	43,694	90	52,276	36,410
33,573	32,783	95	40,474	26,685
19,605	18,605	99	24,858	14,534

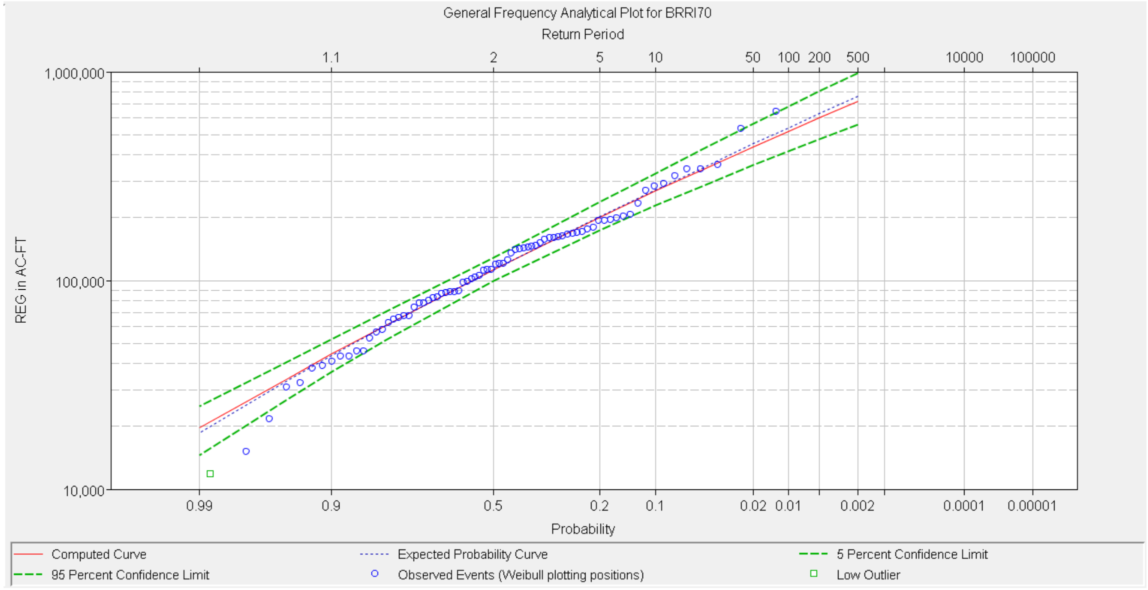

Figure 127: Stream Gage on the Brazos River at Richmond (BRRI70) FFA log-Pearson Type III Probability Distribution for the Scenario D10