ISSUES IN ASSESSING SHORT-TERM WATER SUPPLY CAPABILITIES OF RESERVOIR SYSTEMS

A Thesis

by

SPENCER THOMAS SCHNIER

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

MASTER OF SCIENCE

May 2010

Major Subject: Civil Engineering

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ABSTRACT

Issues in Assessing Short-Term Water Supply Capabilities of Reservoir Systems.

(May 2010)

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The Texas Commission on Environmental Quality (TCEQ) uses a Water Availability Modeling System (WAM) to support long-term regional and statewide water resources planning and management. The water availability studies are based on the modeling capabilities of the Water Rights Analysis Package (WRAP). This research improves the understanding of decision support tools for short-term river basin management. Current reservoir storage levels must be considered to assess short-term frequencies and reliabilities. Conditional reliability modeling (CRM) is used to assess the likelihood of meeting targets for instream flow, reservoir storage, water supply diversion and hydroelectric power generation in the near future (next month to next several years), conditioned upon preceding storage.

This study uses data for the Brazos River Basin from the TCEQ WAM System to assess key complexities of water supply reliability analysis in general and conditional reliability modeling in particular. These complexities include uncertainties associated with river basin hydrology, estimating yield-reliability relationships for individual reservoirs and multiple reservoir systems, conventional long-term planning versus short-term adaptive management and other modeling and analysis issues.

The modeling capabilities of WRAP were expanded to support near real-time operation of dams under various stream flow conditions. The sensitivity to changes in modeling options is assessed for short and long-term simulations. Traditional and newly developed methodologies for estimating firm yields and water supply reliabilities are evaluated. Guidelines are developed regarding the practical application of firm yield analyses and conditional reliability modeling. Important applications of this research include real-time decision support during drought and routinely recurring operational planning activities. A case study of the drought of 2009 uses the CRM features of WRAP for these applications.

To my family

ACKNOWLEDGEMENTS

I am very grateful for all those who have supported me throughout my Master's studies. I am especially thankful to Dr. Ralph Wurbs, my teacher, academic advisor, and Chair of my Graduate Committee. He envisioned the importance of the research, trusted me to run with it and offered valuable guidance.

I would like to acknowledge the institution that funded the research: the Brazos River Authority, particularly Phil Price and Aaron Abel. I appreciate their interest in enhancing the research.

I am thankful for the understanding and support of my family. I thank my colleagues Tae Jin Kim, Angelica Huerta and Richard Hoffpauir for their help. I appreciate all the people who contributed in various ways; I wish I could acknowledge them here.

NOMENCLATURE

BRA	Brazos River Authority
BRAC	Brazos River Authority Condensed dataset
CRM	Conditional Reliability Modeling
FF	Flow Frequency method of assigning probabilities
SFF	Storage Flow Frequency method of assigning probabilities
TCEQ	Texas Commission on Environmental Quality
WAM	Water Availability Modeling
WRAP	Water Rights Analysis Package modeling software

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CHAPTER I

INTRODUCTION

Water availability is of great concern in the state of Texas due to increasing population and water demands. The Texas Commission on Environmental Quality (TCEQ) uses a Water Availability Modeling (WAM) System to support long-term regional and statewide water resources planning and management. The WAM System relies on the modeling capabilities of the Water Rights Analysis Package (WRAP). The conditional reliability modeling (CRM) features of the Water Rights Analysis Package (WRAP) estimate short-term frequency and reliability statistics conditioned upon preceding reservoir storage. The CRM features of WRAP are especially useful for real-time decision support during drought and routinely recurring operational planning activities. The research presented here aims to improve the understanding of CRM and its use in water management.

1.1. Motivation for the Research

Senate Bill 1, passed by the 75th Texas Legislature in 1997, mandates statewide water availability modeling in support of regional water planning and water rights permits. Following an evaluation of river/reservoir models by government regulatory agencies and a team of consulting firms, WRAP was adopted as the statewide water availability modeling system (TNRCC, 1998).

This thesis follows the style of *Journal of Water Resources Planning and Management*.

Typically, WRAP simulates specific water management scenarios for a repetition of historical hydrology. The estimated water supply reliabilities apply to any randomly selected time in the future without regard to current reservoir storage conditions. The conventional modeling approach is intended for evaluation of water rights permits and long-range planning studies. Estimates of water supply reliabilities in the near future can be greatly improved by considering current reservoir storage contents.

In addition to the conventional long-term simulation mode, WRAP may be applied in two alternative modes: yield-reliability mode and CRM. The yield-reliability analysis option develops reliability estimates for specific diversion amounts based on repetition of the long-term simulation mode until a firm yield (100% reliability) is reached, if possible. The CRM option develops estimates of short-term reliabilities based on dividing a long period-of-record into many shorter sequences and starting each sequence with the same initial storage condition. The motivation for this thesis is to improve the understanding of these alternative simulation modes by investigating key complexities involved in their application.

There is great potential for CRM to be a widely-used decision-support tool for drought management, routinely recurring operational planning activities, and various other applications, making this research all the more timely and relevant. CRM can be used to support development of drought contingency plans, annual and seasonal reservoir operating plans. The model can be used by water managers to help determine when to curtail water use and when to make releases from storage.

1.2. Research Objectives

The research focuses on expanding the CRM capabilities of WRAP and evaluating key issues in CRM. Several of the issues noted below are relevant only to CRM while others are relevant to assessing long-term as well as short-term reliabilities.

The objectives of the research are as follows.

1. Enhance the capability of WRAP to predict reservoir system performance in the short-term by updating the CRM features.

2. Use the features developed in Objective 1 to determine the sensitivity of yield-reliability relationships in general and conditional reliability modeling in particular to changes in the following variables:

    2.1 Reservoir system configuration
    2.2 Hydrologic period-of-analysis
    2.3 Initial storage content
    2.4 Method for handling negative incremental flows
    2.5 Choice of cycling option
    2.6 Starting month
    2.7 Length of simulation
    2.8 Methods for assigning probabilities to the sequences
    2.9 Regression options

3. Based on the findings of Objective 2, develop guidelines for the practical application of traditional and newly developed methodologies for determining water supply capabilities of reservoir systems using CRM.

4. Use the guidelines developed in Objective 3 to evaluate the conditional reliability of the Brazos River Authority reservoir system for 2009 conditions.

1.3. Organization of the Thesis

This thesis is divided into eight chapters and three appendices. Chapter II is a review of the history and development of yield-reliability relationships, river/reservoir models, and conditional probability concepts. It also provides a historical context for the research and essential background information. Chapter III describes the modeling system, datasets, and CRM methodologies used in the research.

Strategies for estimating firm yields of individual reservoirs and multiple-reservoir systems are developed and tested in Chapter IV. Chapter IV also addresses key complexities of estimating firm yields and long-term water supply reliabilities. Chapter V documents experiments that assess the effect of modeling decisions on CRM results. The results of Chapter V supported development of guidelines for practical application of the model. These guidelines are presented in Chapter VI.

Chapter VII uses the CRM features of WRAP to analyze the drought of 2009. Chapter VIII presents the summary and conclusions of the research. The input files used in the analysis are provided in Appendix A. These files can be used as examples of how to prepare input files for WRAP. Specific results from the Chapter VII case study are presented in Appendices B and C.

CHAPTER II

LITERATURE REVIEW

This study uses a generalized river/reservoir model to assess yield-reliability relationships and conditional reliability modeling. Key concepts and their historical development are introduced below.

2.1. Yield-Reliability Relationships

Firm yield is the maximum water supply diversion that can be achieved with 100% reliability with the assumptions and approximations reflected in a reservoir system model (Wurbs, 2009a). The numerous methods for calculating yield-reliability relationships including firm yields can be categorized as 1) storage probability theory, 2) optimization techniques, and 3) simulation of a stream/reservoir system for a specified hydrologic sequence.

Volume reliability is used to measure water supply reliabilities. Volume reliability is the percentage of the target demand amount that is actually supplied. That is, volume reliability (R_V) is the ratio of volume of water supplied (v) to the total volume of water demanded (V). Volume reliability is computed using Equation 1.

$$R_V = v/V\ (100\%) \tag{1}$$

Equation 1 applies to both long-term and short-term CRM simulations. For a conventional long-term simulation, Equation 1 is an expression of the capacity to meet water supply needs in the long-term without considering the amount of water currently in storage. For CRM, short-term reliabilities are affected by current storage contents.

River/reservoir simulation models are commonly used to determine yield-reliability relationships of reservoir systems. Wurbs and Bergman (1990) investigated the following three factors that affect the calculation of firm yields: basin hydrology, basin wide water management, and reservoir system simulation. Features of reservoir systems that are particularly important to consider during the calculation of firm yield are changes in the river basin over time, development of stream flows and evaporation rates, sedimentation rates, operating policies of reservoir systems, and interactions between multiple water users.

Dandy, Connarty, and Loucks (1997) compare the different methods for calculating firm yield. They argue that simulation models require a set of operating rules to be specified while optimization models automatically determine operating rules thereby maximizing yield estimates. However, application of optimization models to long-term simulations is complicated because results vary greatly depending on the assumptions used to evaluate the critical period.

Hashimoto et al. (1982) discussed three criteria for evaluating the performance of reservoir systems. All three metrics rely on the definition of failure which is typically defined as a water supply shortage. Reliability is a measure of how often the system fails and can be defined as the frequency that a system is in a satisfactory state. Resiliency measures how quickly a system recovers from failure and can be defined as the reciprocal of the average length of consecutive periods of failure (Jinno et al., 1995). Vulnerability measures of how severe a failure is likely to be if one occurs and can be defined as the average maximum shortage that occurred during consecutive periods of failure (Moy et al., 1986). Vogel and Bolognese (1995) developed generalized relationships among storage, yield, reliability and resiliency for water supply systems using a two-state Markov model.

The operation of individual reservoirs as a coordinated system to meet common diversions downstream has been shown to increase total firm yield (Wurbs, 1996). Novel methodologies for calculating individual reservoir and multiple-reservoir system firm yields are developed and evaluated in this thesis. The impact of negative incremental flows and different ways of handling them on firm yield estimates have not been fully addressed in the literature.

2.2. Generalized River / Reservoir Models

The following river/reservoir modeling systems are widely used for water resources planning and management: HEC-ResSim, RiverWare, MODSIM, and WRAP. The discussion that follows focuses on the origin, motivation, input data and computation interval of the models.

2.2.1. HEC-ResSim

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers developed the HEC Reservoir System Simulation (HEC-ResSim) Model and released it to the public in 2003 (HEC, 2007). HEC-ResSim is the successor to the HEC-5 Simulation and Flood Control and Conservation Systems model, which had been in use for 20 years prior. HEC-ResSim is composed of a Windows-based graphical user interface (GUI), a map-based schematic to view the physical river/reservoir system, and rule-based reservoir operations. ResSim is coded in Java and uses HEC-DSS (HEC, 2009) to manage input and output datasets. Flood control and conservation pools are defined in a set of operating rules.

One of the primary objectives of the model is to provide real-time decision support for reservoir control operations. However, the model can also be used to support planning studies. The primary input to HEC-ResSim includes streamflows, reservoir storage capacity curves, evaporation, outlet characteristics, and routing parameters. The computation interval can range from 15 minutes to one day. There is no monthly time-step in HEC-ResSim.

The HEC-ResSim model was used to create a georeferenced reservoir network in Iraq (Hanbali, 2004). The Ministry of Water Resources is interested in using the model to inform management decisions regarding their 6 major reservoirs, 3 large off-channel reservoirs and several run-of-river diversions, as well as to determine water availability for possible marsh restoration. While the reservoirs are operated for hydropower and flood control, their primary purpose is irrigation.

The Center for Research in Water Resources at the University of Texas at Austin linked GIS to HEC-ResSim in order to model the Forgotten River segment of the Rio Grande/Bravo River (Teasley et al, 2004). A water balance simulation was conducted for this segment of the river by using HEC-DSS to transfer hydrologic time-series data from ArcGIS to HEC-ResSim. There is interest from both sides of the border among governmental and non-governmental agencies in using these models to aid in restoring the Forgotten River.

2.2.2. RiverWare

RiverWare is a general river and reservoir modeling tool developed from 1993 to the present at the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). The modeling system is sponsored jointly by the Tennessee Valley Authority (TVA), U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers.

The C++ code is not open source in order to assure a single official version. The software is maintained by a team of professional software developers and water resources engineers. A commercial license for a single computer costs $7,500 with an annual renewal fee of $3,000 (CADSWES webpage). The capabilities and applications of RiverWare are described in various papers (Zagona et al, 2001; Fulp and Harkins, 2001; Eschenbach et al, 2001; Frevert et al, 2000; Zagona et al, 2005; and others).

RiverWare can be used for a variety of applications including planning, mid-term forecasting, routine reservoir system operations, policy evaluation, and water rights.

Input hydrology can be historical, forecasted, or stochastic flows. RiverWare has three different simulation environments: 1) Conventional simulation which models physical processes, 2) Rule-based simulation which is driven by user-specified operating rules (i.e. policies), and 3) Optimization which searches for a linear programming solution. The time-step can range from hourly to monthly.

Much of the literature on RiverWare focuses on operational planning studies. The TVA owns and operates 29 hydropower plants in the Tennessee Valley. In 1996, TVA became the first agency to adopt RiverWare to schedule reservoir operations. TVA models reservoir operations using RiverWare’s Goal Programming algorithm. Simulations are repeated several times per day as power and water conditions change as part of the scheduling process. TVA implements two models that use the optimization method: a 2 day model with an hourly time step and a 9-day model with 6-hour time steps (Magee et al, 2002). The Lower Colorado River Authority (LCRA) is developing a daily RiverWare model of the Colorado River to supplement the monthly WAM. This model will be used to design more efficient and detailed operating plans for the six reservoir system (Hall et al, 2006).

2.2.3. MODSIM

MODSIM is a generalized river/reservoir system and network flow model developed at Colorado State University to simulate priority-based water allocation (Labadie et al, 2000). MODSIM simulates instream flow requirements, direct diversion rights, reservoir storage rights, and multiple-reservoir system operations. The reservoir system configuration can be built through a GUI which interacts with the user to prepare input data using a network flow optimization model. Given the appropriate data, MODSIM can run on a monthly, weekly or daily time-step.

MODSIM has been linked with groundwater models for analysis of conjunctive use of ground and surface water, water quality models for assessment of pollution control strategies, and Geographic Information Systems (GIS) for managing spatial data.

2.2.4. WRAP

The Water Rights Analysis Package (WRAP) modeling system was developed at Texas A&M University for simulation of water resources management using a priority-based water allocation system (Wurbs, 2009a). WRAP is specially designed to address water rights. The Texas Commission on Environmental Quality (TCEQ) maintains the Texas Water Availability Modeling (WAM) System which consists of the generalized WRAP model and input datasets for all of the river basins of the state. River basin hydrology is represented by sequences of naturalized streamflows and net reservoir evaporation. Naturalized flow is the flow that would occur if no humans were present. WRAP uses a monthly time-step, however there is an auxiliary program under development called SIMD that computes sub-monthly time-steps (Wurbs et al., 2009).

WRAP was chosen for this study for various reasons. Several datasets with complete operating rules exist with long periods-of-analysis. These datasets include the TCEQ-sponsored WAMs, as well as extended, condensed or otherwise modified versions of the WAMs. The modeling system was specifically designed for priority allocation according to water rights and determines the amount of water a water right owner is legally entitled to use. WRAP also has built-in functions to calculate firm yield, reliability and other metrics. Finally, it is the only generalized model that has built-in features for performing conditional reliability analysis.

2.3. Conditional Reliability Modeling

Moran (1954) developed a model that uses known initial storage conditions to predict the probability distribution of storage at the end of consecutive years. To obtain the probability distribution one time-step in the future, the model uses a Markov chain and multiplies the probability distribution at the current time-step by a transition matrix. The model assumes independent annual inflows and constant reservoir outflows and losses. Gould (1961) addressed some of the limitations of Moran's model by modifying the derivation of the transition matrix for a monthly time-step which considers reservoir evaporation and precipitation, varying surface area to storage capacity relationships, and monthly operating policies. The model developed by Gould still assumes independent annual inflows.

The TVA developed the model HYDROSIM to model week-to-week variations in water level, discharge and hydropower generation for the TVA's 42 reservoir system. The model is described by Shane and Gilbert (1982) and Gilbert and Shane (1982). The TVA Act assigns priorities to water use in the valley with flood control and navigation being the highest priority. These priorities were used by HYDROSIM to determine an optimal reservoir operating schedule for the coming week based on initial storage.

HYDROSIM made short-term storage forecasts for up to one year. After the first week HYDROSIM assumes any of the sequences of historical hydrology could occur again. This model has since by replaced by RiverWare (Zagona et al., 2001).

The computer program PROSTOR developed by Vaugh and Maidment (1987) predicts future storage distributions conditioned upon known initial storage using transient analysis. Given initial storage, operating rules, monthly water demands, and simulation length (i.e. period over which storage is being forecast), transient analysis routes historical hydrology through the reservoir system one sequence at a time using a monthly time-step and generates possible future storages. Transient analysis improved upon Gould's probability matrix method for simulation lengths greater than one year by inherently considering the autocorrelation between hydrologic data from one year to the next by analyzing hydrologic inputs in their historical order. Transient analysis assumes that each sequence of historical hydrology is equally likely to occur. The assumption in transient analysis that all sequences of historical hydrology are equally likely to occur may not always be valid (Salazar 2002).

Brandes and Sullivan (1998) developed a Conditional Probability Model (CPM) for two reservoirs on the Rio Grande River in Texas. The CPM uses Moran's model to develop yield-reliability relationships conditioned upon a known beginning-of-the-year storage condition. The storage capacity of each reservoir was divided into 41 horizontal layers of equal volume. The CPM uses monthly inflows, operating rules, and demands to develop two relationships. The first relationship is developed using a long-term simulation and describes the probability of starting a forecast period at or below one of the 41 predefined storage levels. The second relationship describes the reliability of meeting demands from owners of water rights in Texas and Mexico.

Salazar and Wurbs (2004) modified the transient analysis method by assigning weights to each of the sequences of historical hydrology using conditional frequency duration curves (CFDC). A CFDC is the exceedance frequency table for streamflows following a specified initial storage content determined using the Weibull formula. Similar to Brandes and Sullivan (1998), CFDCs are developed using the results of a long-term simulation for specific storage intervals. Short-term water supply reliabilities and storage frequencies are determined based on current reservoir storage by dividing the hydrology into many shorter sequences and running each sequence with the same initial storage. These short-term hydrologic responses are weighted according to the probabilities predicted using the CFDC. The conditional reliability analysis used two programs called WRAP-CON and TAB-CON which are conditional probability versions of the WRAP modeling system WRAP-SIM and TABLES.

Olmos (2004) and Wurbs et al. (2009) developed a similar approach to Salazar but used a different method for assigning probabilities to each sequence of streamflows called the Storage-Flow Frequency (SFF) array. The SFF array uses the log-normal or Weibull distribution to relate exceedance probabilities to the random variable R. R is the ratio of simulated streamflows to flows predicted using a regression relationship between preceding storage and naturalized flows. Within WRAP, four regression equations can be used to relate naturalized flows to initial storage volume: exponential, linear, power and combined. The conditional reliability analysis uses built-in CRM features of the WRAP modeling system and data from the TCEQ WAM system.

The work presented in this thesis uses a monthly time-step and inherently considers the autocorrelation between annual hydrologic data by considering sequences longer than 12 months in their historic order similar to Vaugh and Maidment (1987). Like Salazar and Wurbs (2004), weights are assigned to the sequences of historical hydrology. Brandes and Sullivan (1998) and Salazar (2002) considered 50 years (1945-1994) and 58 years (1940-1998) of historical hydrology, respectively. This study considers 108 years (1900-2007). Consideration of additional hydrology can affect the assigning of conditional probabilities to sequences of stream flows. Comparisons are made between the following methods for assigning probabilities: equal weight approach, an approach similar to the CFDC (Salazar, 2002) based on flow frequency and storage intervals, and the SFF array (Olmos, 2004). A sensitivity analysis is conducted to determine the effect modeling choices have on key variables. Guidelines are developed for when the choice of modeling option can significantly affect the results. The summer of 2009 in the Brazos River basin is used as a case-study to illustrate how CRM can be used to adaptively manage droughts.

CHAPTER III

DESCRIPTION OF THE MODEL

This thesis uses the conditional reliability modeling (CRM) features of the Water Rights Analysis Package (WRAP) and data from the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System. The study uses a simplified version of the TCEQ WAM full authorization dataset called the Brazos River Authority Condensed (BRAC) dataset (Wurbs and Kim, 2008a).

3.1.The Water Rights Analysis Package

WRAP is a river and reservoir modeling system that simulates priority based water allocation. The modeling system is documented by Wurbs (2009a) and Wurbs (2009b). WRAP consists of the monthly simulation model SIM, the post-processor TABLES, and several auxiliary programs. SIM simulates basin-wide water use scenarios for input sequences of monthly naturalized flows and net evaporation rates. TABLES reads the output of SIM and develops frequency relationships, reliability estimates, and numerous other tables for displaying simulation results.

SIM may be applied in three alternative modes (Wurbs, 2009a):

1) A single long-term simulation
2) A yield-reliability analysis option
3) A conditional reliability modeling (CRM) option

The yield-reliability simulation is based on repeating the long-term simulation to develop a diversion target (yield) versus reliability table that includes the firm yield if a firm (100% reliability) yield is possible. CRM is based on many short-term simulations starting with the same initial storage condition. The latter two modes are the focus of this thesis.

Long-term simulations are simulations conducted using a conventional single execution of the program SIM, where the length of simulation is the full period-of-record. Short-term simulations are simulations conducted using the CRM features of WRAP. These features divide the full period-of-record into shorter sequences. The differences between a conventional long-term simulation and a conditional short-term simulation are discussed below.

3.1.1.Conventional Long-Term Simulation

In a conventional long-term simulation, WRAP allocates water for each month of a single hydrologic sequence starting with the first month of the period-of-analysis. For example, for a hydrologic period-of-analysis of 1900 to 2007 (1296 months), water is allocated during each sequential month of a single 1,296-month hydrologic sequence beginning in January 1900. The conventional approach is commonly used to support long-term planning studies and evaluate water right permits.

3.1.2. Conditional Short-Term Simulation

CRM is used to predict the likelihood of meeting water supply demands in the near future, which is highly dependent on current reservoir storage levels. In CRM, naturalized flows and net evaporation rates are divided into short sequences beginning with the same initial reservoir storage. CRM can be used to support operational planning activities, drought management plans, and many other applications. The mechanics of CRM are discussed in Section 3.4.

To date, CRM has been used in a few studies performed using early versions of the software (Salazar and Wurbs, 2004). This is mainly because the features have been in developmental stages. Initial CRM research and development efforts are described in Technical Report 284 (Wurbs et al., 2009). This project will expand and implement the CRM features of WRAP to improve short-term river basin management.

3.2.Texas Water Availability Modeling System

The TCEQ uses the WAM System to support long-term regional and statewide water resources planning and management. The WAM consists of the modeling program WRAP and basin-specific input files containing information about water rights, flows and evaporation. Between 1998 and 2003, engineering firms under contract with the TCEQ, developed input files for the 23 river basins in Texas.

Data from the TCEQ WAM System for the Brazos River Basin (Brazos WAM) is used to investigate, test, evaluate and further develop the methodologies outlined below. There are two sets of input files for the Brazos WAM: the Full Authorization dataset (Bwam3) in which all water rights utilize their maximum authorized amounts, and the Current Conditions (Bwam8) dataset which reflects current diversions and return flows. The Brazos WAM dataset was originally developed by HDR Engineering, Inc., under contract with the TCEQ (HDR, 2001a; HDR, 2001b). The Bwam3 dataset for the Brazos WAM contains 3,830 control points, 1,634 water rights and 670 reservoirs. The Bwam8 dataset contains 2,396 control points, 2,021 water rights and 510 reservoirs. The original datasets cover a period-of-record from 1940 to 1997. The hydrology of this dataset was expanded by Wurbs and Kim (2008b) to cover a period-of-record from 1900 to 2007.

3.3. Brazos River Authority System Condensed Dataset

The Brazos River Basin extends across Texas from New Mexico to the Gulf of Mexico, covering an area of 44,620 square miles. The climate, hydrology, and geography of the basin vary significantly throughout the region. Mean annual precipitation is 19 inches in the upper basin and 45 inches in the lower basin.

This study also uses simplified versions of the Bwam3 and Bwam8 datasets called the Brazos River Authority Condensed datasets (BRAC3 and BRAC8, respectively) (Wurbs and Kim, 2008). The BRAC datasets have a hydrologic period-of-record of 1900-2007 and naturalized flows that inherently consider the respective TCEQ WAM datasets. The BRAC3 dataset contains only 48 control points, 113 water rights and 15 reservoirs. The BRAC8 dataset contains 48 control points, 114 water rights and 19 reservoirs. Condensed datasets like these preserve the essential characteristics of the system while allowing for a much simpler model that facilitates operational planning studies and other decision support activities including CRM.

The analyses presented in Chapter IV utilized the four aforementioned Brazos WAM datasets (i.e. Bwam3, Bwam8, BRAC3, and BRAC8). The simulation results presented in Chapter V are generated using the BRAC3 dataset. The case study presented in Chapter VII uses a significantly modified version of the BRAC8 dataset.

3.4.Conditional Reliability Modeling

Section 3.1.2 provided a brief introduction to the concepts of CRM. CRM uses preceding reservoir storage to develop short-term reliabilities and frequency estimates. The input hydrology is divided into several short hydrologic sequences (months or a few years). The program SIM repeats the simulation for each hydrologic sequence always beginning with the same initial storage condition. The program TABLES uses the simulation results to develop flow and storage frequency relationships and water supply and hydropower reliabilities.

Within WRAP, there are two options for dividing a long period of hydrology into several shorter sequences: the annual cycle and monthly cycle. The annual cycle simulates one sequence per year and each sequence always begins in the same month. The maximum sequence length is equal to the number of months in the period-of-analysis. The number of sequences that can be obtained using the annual cycle option (N_{AS}) is given by Equation 2.

$$N_{AS} = N_{YRS} - \text{Int}((L_{sim}+M^{o}-2)/12) \qquad (2)$$

where N_{yrs} is the number of years in the period-of-analysis, L_{sim} is the length of the simulation period in months, and M^{o} is the starting month. For example, a 1900 to 2007 period-of-analysis could be organized into 6-month sequences starting with the month of September. The resulting 107 sequences would be defined as follows.

Sequence 1: September 1900 through February 1901
Sequence 2: September 1901 through February 1902
Sequence 3: September 1902 through February 1903
…
Sequence 106: September 2005 through February 2006
Sequence 107: September 2006 through February 2007

The annual cycle captures seasonality because all the sequences reflect the same season. However, the number of sequences is limited by the number of years in the period-of-analysis (Eq 2).

The monthly cycle simulates one sequence per month. The first sequence begins in the first month of the first year and has a length specified by the user. The second sequence begins in the next month following completion of the first sequence. After reaching the end of the last year, the sequencing begins again, one month after the preceding cycle began. The number of complete monthly sequences (N_{MS}) can be calculated using Equation 3.

$$N_{MS} = N_{yrs} * 12 - L_{sim} + 1 \quad (3)$$

The terms are as defined in Equation 2.

Applying the monthly cycle option to the 1900 to 2007 example, for a simulation length of 6 months, will result in 1,291 sequences being computed. The monthly cycle allows up to 12 times more sequences than the annual cycle but at the loss of seasonality (Equation 4).

There are three approaches within WRAP for assigning probabilities to hydrologic sequences: The Equal-Weight option, Flow-Frequency (FF) option, and Storage-Flow-Frequency (SFF) option. The Equal-Weight option, as the name implies, weighs each sequence as equally likely. A flow-frequency (FF) relationship assigns probabilities directly to naturalized flows using either a log-normal probability distribution or the Weibull formula. The storage-flow-frequency (SFF) relationship uses log-normal or Weibull to relate exceedance probabilities to the random variable known as the flow ratio, R. R is the ratio of observed flows (Q) over expected flows (Qs) (Eq. 4). The expected flows are developed using a regression relationship between preceding storage and naturalized flows which is discussed in more detail below.

$$R = Q/Qs \quad (4)$$

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

Three indices of goodness-of-fit are used to evaluate the strength of the relationship between naturalized flows and initial storage. The standard linear correlation coefficient (r) is shown in Equation 5. This index is commonly presented as the coefficient of determination (r^2).

$$r = \frac{n\sum S_i Q_i - (\sum S_i)(\sum Q_i)}{\sqrt{n\sum S_i^2 - (\sum S_i)^2}\sqrt{n\sum Q_i^2 - (\sum Q_i)^2}} \tag{5}$$

Spearman’s rank correlation coefficient ranks the values of Q_i and S_i, with the largest value receiving a rank of 1 and the lowest value a rank of n. The ranks of of Q_i and S_i are then substituted for Q_i and S_i in Equation 5.

The linear correlation coefficient and the Spearman rank correlation coefficient are used to determine the correlation between total naturalized flows and initial storage. The coefficients are independent of the regression option chosen. The regression relationship is used to develop the flow ratio (R). R is the ratio of observed flows (Q) over expected flows (Qs) (Eq. 4). The expected flows are developed using a regression relationship between preceding storage and naturalized flows (Equations 6 - 9).

$$Q_S = a \times e^{S/b} \tag{6}$$

$$Q_S = b\,S^c \tag{7}$$

$$Q_S = a + b\,S \tag{8}$$

$$Q_S = a + bS^c \tag{9}$$

Equations 6 - 9 are transformed into Equations 10 - 13, respectively, in order to determine the y-intercept (a) and slope (b) of a straight line plot.

$$\ln Q = \ln a + \frac{1}{b} S \tag{10}$$

$$\log Q = \log b + c \log S \tag{11}$$

$$Q = a + bS \tag{12}$$

$$Q = a + b(S^c) \tag{13}$$

The linear regression equations (Eqs. 14 - 16) are applied to transformed variables to obtain the coefficients a, b, and c.

$$E(Q|S) = a + bS \tag{14}$$

$$b = \frac{n\sum S_i Q_i - (\sum S_i)(\sum Q_i)}{n\sum S_i^2 - (\sum S_i)^2} \tag{15}$$

$$a = \bar{Q} - b\bar{S} \tag{16}$$

E(Q|S) is the expectation of Q given S, and Qbar and Sbar are the means of initial storage (S) and flow (Q), respectively.

The linear regression method does not need to be transformed in order to find the values of the coefficients (Equation 3 is Equation 12). In other words, the linear correlation coefficient (r) equals the square root of r^2 only when the regression relationship is linear. The regression relationship in Equation 13 occurs in two steps. First, the value for c is found by assuming *a* equals 0 and applying equation 11. Next, S^c is treated as a single variable and linear regression is applied to find *a* and *b*.

The FF and SFF options are termed the probability array options because these two methods are used to assign probabilities to streamflow sequences. Probabilities are assigned based either on the log-normal probability distribution or the Weibull formula.

The log-normal distribution consists of the normal distribution applied to the logarithms of X, as expressed in Equation 17.

$$\log X = \log X_{avg} + z\, S_{\log X} \tag{17}$$

Where $\log X_{avg}$ is the mean, $S_{\log X}$ is the standard deviation and z is still derived from the normal distribution. The frequency factor, z, is used to obtain the cumulative probability (P) (Eq. 18), which is then converted to exceedance probabilities.

$$P = 0.5 * (1 + \mathrm{erf}(z/\mathrm{sqrt}(2)) \tag{18}$$

The Weibull relative frequency formula is another option that can be used to assign exceedance probabilities directly to naturalized flows (FF option) or the random flow ratio (SFF option) (Equation 19).

$$P = m / (N + 1) \tag{19}$$

P is the exceedance probability, *m* is the rank of the value, and *N* is the total number of values. Value refers to naturalized flow volume in the case of the FF option, and the flow ratio R in the case of the SFF option. The highest value is assigned a rank of 1, and the smallest is assigned a rank of N. The Weibull formula weighs each value equally when developing the frequency relationship. For this reason, a FF relationship developed using this formula is conceptually similar to the equal-weight option. Equation 20 is the basis of the equal weight option

$$P = n / N \tag{20}$$

where *n* is the number of time periods that a specified amount is equaled or exceeded and *N* is the total number of time periods considered. When the Weibull formula is used with the FF option, each sequence is assigned the same incremental probability. Relatively few sequences reflect infrequent extremely wet or dry conditions.

In the probability array options, the incremental probabilities (which add up to one) are used to weight the sequences for calculation of frequency and reliability statistics. The incremental probability is multiplied by 10^6 so that each sequence is counted proportional to its probability of occurrence, with the total number of sequences equaling 1,000,000. For example, the 108 hydrologic sequences may be assigned the incremental probabilities shown in Table 3.1. The counts used in the frequency and reliability calculations are shown in the "Ns Count" column.

Table 3.1. Example of Applying Probability Array in Reliability and Frequency Counts

Simulation Sequence	Incremental Probability	Ns Count
1	0.013398	13,398
2	0.001621	1,621
3	0.007891	7,891
4-106	not shown	
107	0.002411	2,411
108	0.004325	4,325
Totals	1.000000	1,000,000

The modeling options discussed briefly here are explored in greater detail in Chapters V and VI. The choices involved in assigning probabilities to streamflow sequences are outlined below (Wurbs et al., 2009).

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

CHAPTER IV

ISSUES IN ESTIMATING FIRM YIELDS AND YIELD-RELIABILITY RELATIONSHIPS

This chapter determines the sensitivity of firm yields and yield-reliability relationships to changes in key variables. Firm yield is the maximum water supply diversion that can be achieved with a volume and period reliability of one-hundred percent based on the premises reflected in the model (Wurbs, 2009a). The sensitivity analysis determines how the choice of modeling option impacts the results of conventional long-term simulations. Finally, the results of the analyses and implications for conditional reliability modeling are discussed.

4.1. Hydrologic Period-of-Record

Development of hydrologic input data such as stream flow and reservoir evaporation rates are a key factor in reservoir yield studies (Wurbs and Bergman, 1990). Wurbs and Kim (2008) extended the hydrologic simulation period in the Brazos WAM from 1940-1997 forward to 2007 and backward to 1900. The updated dataset covers a period-of-analysis from 1900 to 2007. This section determines the effect different hydrologic periods-of-analysis have on the estimated firm yield and reliabilities of long-term simulations.

Several hydrologic periods-of-analysis all ending in 2007 and starting with reservoirs full to capacity were applied to the BRAC3 dataset. The periods-of-analysis tested in this example are 5 years (2003-2007), 10 years (1998-2007), 20 years (1988-2007), 40 years (1968-2007), 60 years (1948-2007), 80 years (1928-2007), 100 years (1908-2007), and 108 years (1900-2007). The average overall volume reliability for all reservoirs in the dataset is shown in Figure 4.1.

Several observations can be made from Figure 4.1. Predicted reliabilities behave more erratically when the period-of-analysis is shorter, and likewise tend to stabilize as the period-of-analysis increases. In other words, the difference between successive predictions generally decreases as the period-of-analysis increases. This implies that a longer period-of-analysis will provide a better prediction for long-term reliability.

The year in which a simulation begins can significantly affect predicted reliabilities. For example, when the simulation starts in 1998, a year preceded by wet conditions, lower reliabilities are predicted compared to starting in 1988, a year preceded by dry conditions. This result is due to the assumption that all reservoirs start full to capacity at the beginning of the simulation, which is unrealistic for years preceded by dry conditions. The effect of starting years on long-term water supply reliabilities is explored further in Section 4.3.

When using a period-of-analysis greater than 80 years for the BRAC3 dataset, Figure 1 shows the reliabilities continually increasing. Although 1900 (starting year for the 108 year simulation) to 1928 (starting year for the 80 year simulation) are slightly dryer years than average, they are wet enough to dilute the influence of the drought of the 1950s. When these 29 relatively wet years are factored into the analysis, higher average volume reliabilities are predicted. A superficial analysis of this phenomenon may lead one to believe that the Brazos River Basin has become increasing dry in recent decades. Figure 4.2 shows evidence to the contrary. On average, the annual naturalized flows for the past 50 years have increased compared to the long-term average (4,953,763 ac-ft/yr compared to 4,642,490 ac-ft/yr).

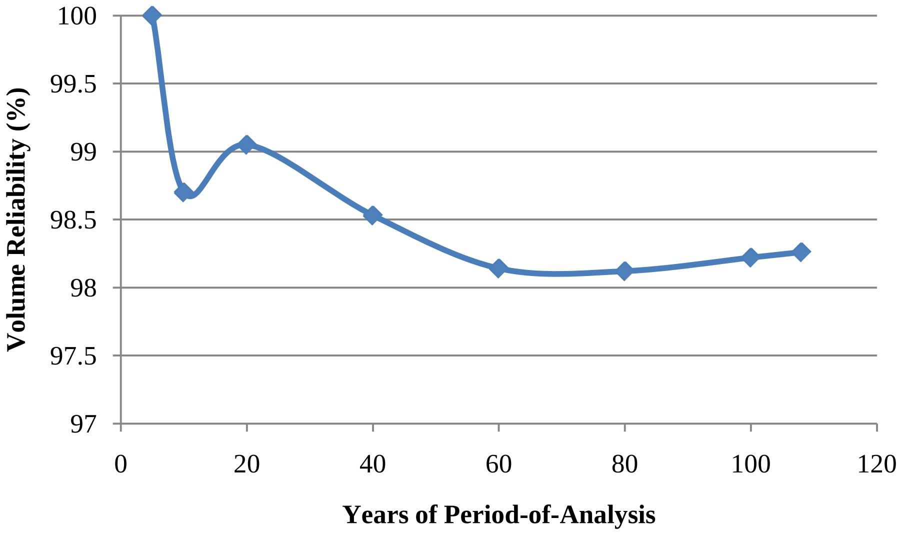

Figure 4.1. Effect of Length of Period-of-Analysis on Long-Term Water Supply Reliabilities

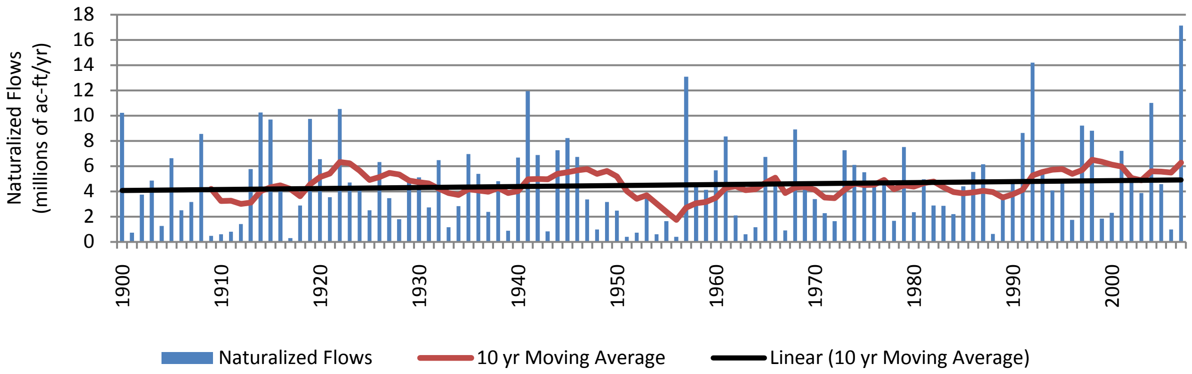

Figure 4.2. Annual Naturalized Flows at the Richmond Gage

The actual period-of-analysis for the Brazos WAM is 1940 to 1997 (Table 4.1). The average period-of-analysis for the Texas WAMs is 55 years and most of the WAMs begin in 1940, a wet period. The hydrologic period-of-analysis for the Brazos River Basin was extended backward to include 1900 to 1939, which is a slightly dryer than average period. The Brazos WAM was also extended forward from 1998 to 2007, which are wet years on average characterized by large standard deviations (Wurbs and Kim, 2008). This means that the water supply reliabilities predicted using the official 58 year period-of-analysis are lower than the reliabilities predicted for the expanded dataset.

It is important to note that if the months leading up to the beginning of the simulation are wet months, the assumption that the reservoirs are full to capacity is more valid. For example, if the simulation starts full to capacity in a dry year, the system will experience fewer shortages (higher reliability) compared to a simulation that starts a decade earlier and is allowed to achieve more realistic storage levels. This phenomenon can be observed in Figure 4.1 with the 20 year simulation that begins in 1988.

Table 4.1
Texas WAM Systems
(Reproduced from Wurbs, 2009a)

	Major River Basin or Coastal Basin	Period of Analysis	Number of					Reservoir Storage Capacity (acre-feet)	Mean Natural Flow (ac-ft/yr)
			Primary Control Points	Total Control Points	Model Water Rights	Instream Flow Rights	Model Reser-voirs		
1	Canadian River Basin	1948-98	12	85	56	0	47	966,000	190,000
2	Red River Basin	1948-98	47	447	489	103	245	4,124,000	11,049,000
3	Sulphur River Basin	1940-96	8	83	85	5	53	753,000	2,498,000
4	Cypress Bayou Basin	1948-98	10	189	163	1	91	902,000	1,748,000
5	Rio Grande Basin	1940-00	55	957	2,584	4	113	23,918,000	3,724,000
6	Colorado River Basin and Brazos-Colorado Coastal	1940-98	45	2,395	1,922	86	511	4,763,000	2,999,000
7	Brazos River and San Jacinto-Brazos Coastal	1940-97	77	3,830	1,634	122	670	4,695,000	6,357,000
8	Trinity River Basin	1940-96	40	1,334	1,169	23	703	7,504,000	6,879,000
9	Neches River Basin	1940-96	20	318	333	17	176	3,904,000	6,235,000
10	Sabine River Basin	1940-98	27	376	310	21	207	6,401,000	6,887,000
11	Nueces River Basin	1934-96	41	542	373	30	121	1,040,000	868,000
12	Guadalupe and San Antonio River Basins	1934-89	46	1,349	860	184	237	808,000	2,101,000
13	Lavaca River Basin	1940-96	7	185	71	30	22	235,000	943,000
14	San Jacinto River Basin	1940-96	16	411	148	13	114	637,000	2,207,000
15	Lower Nueces-Rio Grande	1948-98	16	119	70	6	42	101,700	249,000
16	Upper Nueces-Rio Grande	1948-98	13	81	34	2	22	11,000	342,000
17	San Antonio-Nueces	1948-98	9	53	12	2	9	1,480	565,000
18	Lavaca-Guadalupe Coast	1940-96	2	68	10	0	0	0	134,000
19	Colorado-Lavaca Coastal	1940-96	1	111	27	4	8	7,230	142,000
20	Trinity-San Jacinto	1940-96	2	94	24	0	13	4,880	181,000
21	Neches-Trinity Coastal	1940-96	4	245	138	9	31	58,000	607,000

4.2. Initial Storage Content

An advantage to having a long hydrologic period-of-analysis is that the effect of an arbitrary initial storage condition is unlikely to persist long enough to significantly affect the results (Salazar, 2002). This section addresses the questions, how long does the effect of the initial condition persist in a long-term simulation and what factors influence the answer. Simulations were run for different initial storage conditions using various hydrologic periods-of-analysis to determine the effect of initial storage conditions on storage frequencies and long-term water supply reliabilities.

Three different storage conditions are tested. The first of the three storage conditions assumes that all reservoirs are at full capacity at the beginning of the simulation. This is the default option in WRAP. The second storage condition assumes the reservoirs are empty at the beginning of the simulation. The third storage condition uses the beginning-ending storage options within WRAP to cycle through the entire period-of-analysis once, record the ending storage contents of each reservoir and use those as the beginning storages for a second simulation (Wurbs, 2009). The analysis uses the Brazos River Authority Condensed (BRAC3) dataset.

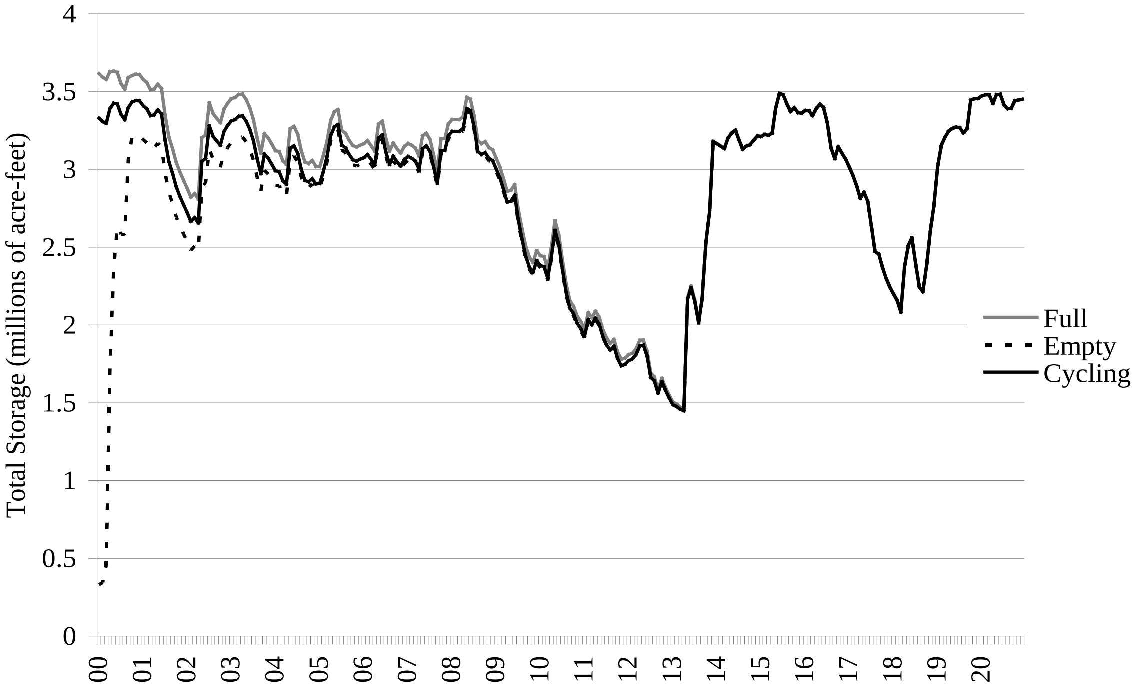

Figure 4.3. Total Storage in the Brazos River Basin for Different Initial Storages

The simulated storage contents for the first 20 years of a long-term simulation are shown in Figure 4.3. It takes twelve years for the simulation with the reservoir starting empty to equal the simulation with the cycling option activated. It takes 18 years for the simulation starting full to equal the cycling option. The length of time that an initial condition affects the results is also influenced by starting year and subsequent hydrology. The effect on storage frequency estimates of building the probability array based on these three versions of the long-term simulation is investigated in (5.2).

To determine how long-term water supply reliabilities are affected by initial storage content, two different simulations were run on the Brazos River Authority Condensed (BRAC3) dataset. The first simulation assumes all reservoirs are at full capacity at the beginning of the simulation. The second simulation assumes the reservoirs are empty (0% capacity) at the beginning of the simulation.

The overall reliabilities for the simulation in which beginning storage equals reservoir capacity (100% capacity) were higher than for the simulation in which the reservoirs begin empty (0% capacity). The differences between these reliabilities decrease as the period-of-analysis increases (Figure 4.4).

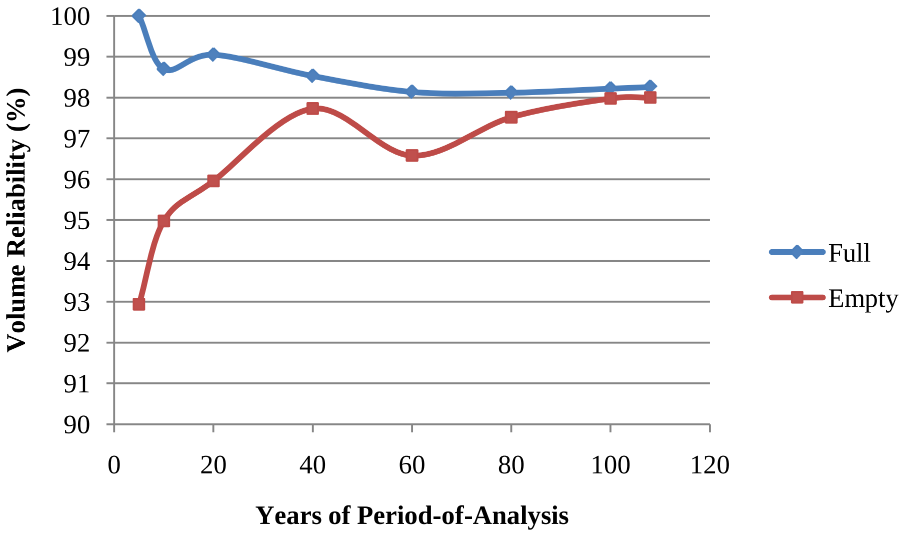

Figure 4.4. Effect of Initial Storage Content on Long-Term Water Supply Reliabilities

4.3. Starting Year

The effect of starting years on long-term water supply reliabilities can be seen more clearly when a reservoir is assumed to start full during a dry period. This situation can be contrasted with results for the same period-of-analysis assuming the reservoir starts empty (Figure 4.5). Figure 4.5 shows reliabilities for simulations starting in eight different dry years. These have the lowest naturalized flows at the Richmond Gage (most downstream gage in the Brazos Basin) for 5 years into the future excluding any overlapping years. These conditions are expected to show the greatest difference in predicted reliabilities.

Figure 4.6 shows reliabilities for simulations starting in eight different wet years. Wet years are years which start full to capacity in a large majority of reservoirs. These years would best satisfy the assumption that reservoirs begin full to capacity, and can be expected to show small differences in predicted reliabilities. In both Figures 4.5 and 4.6, the difference in reliabilities increases as the period-of-analysis decreases.

Figure 4.7 shows the difference in reliabilities between simulations starting in dry and wet years. It is possible to see that the difference in predicted reliabilities is consistently higher for simulations beginning in dry years. Figures 4.5 through 4.7 highlight the importance of beginning a simulation in a wet period in which the assumption of all reservoirs being full to capacity is more accurate. These figures also suggest that any errors introduced by this assumption can be overcome with a long enough period-of-analysis.

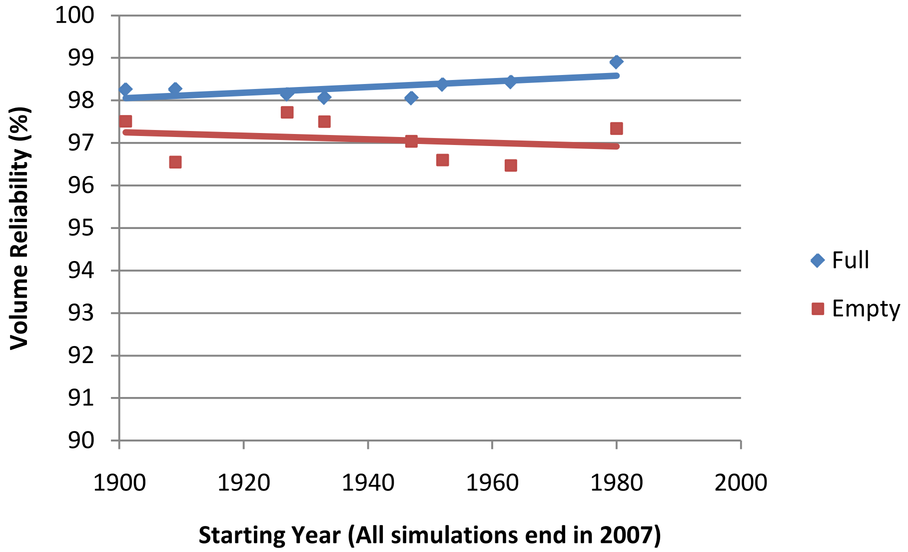

Figure 4.5. Volume Reliabilities for Two Reservoir Capacities Based on Periods-of-Analysis Starting in Dry Years

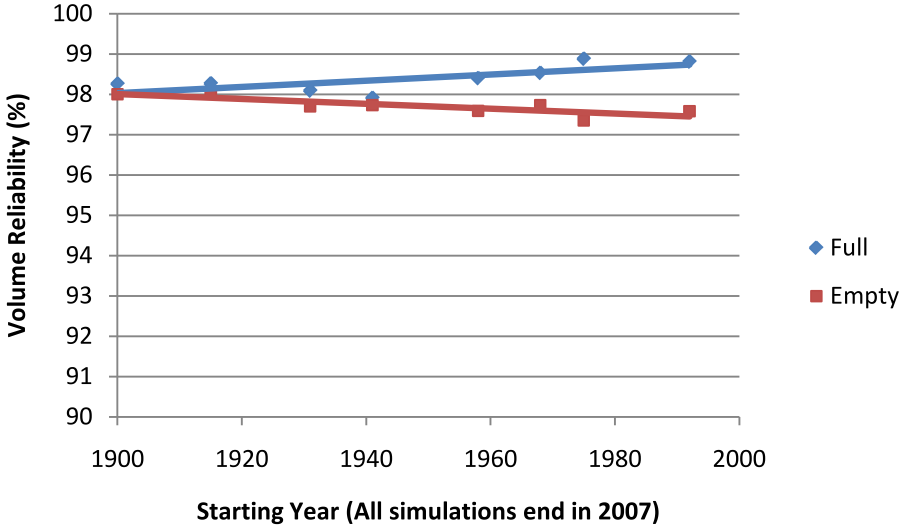

Figure 4.6. Volume Reliabilities for Two Reservoir Capacities Based on Periods-of-Analysis Starting in Wet Years

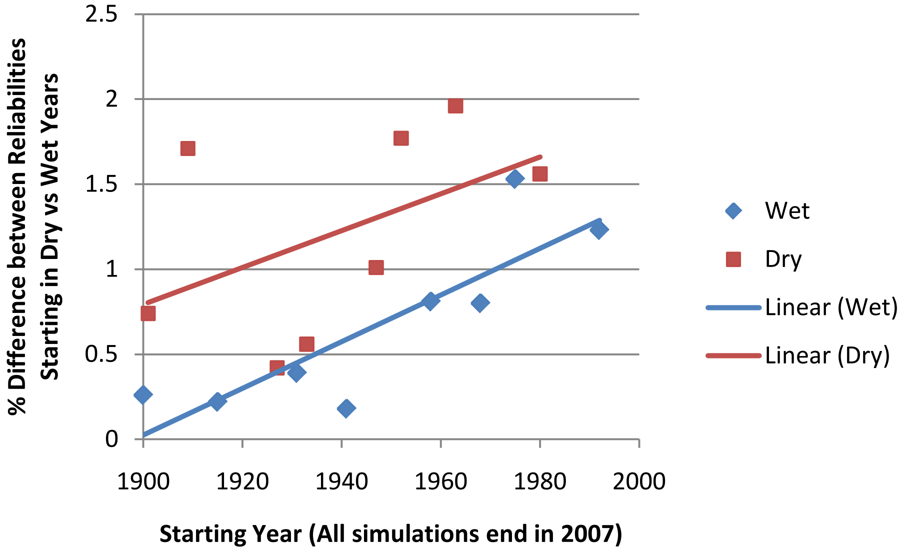

Figure 4.7. Differences in Reliabilities between Reservoirs Starting Full and Empty in Dry and Wet Years

The hydrologic period-of-analysis affects long-term water supply reliabilities in a number of ways. Figure 4.1 shows that as the period-of-analysis increases, the variability in reliability predictions decreases. More accurate estimates of long-term water supply reliabilities are obtained as the computation become less influenced by initial storage content and starting year and more representative of the range of hydrologic responses of the basin.

The initial storage content also affects long-term water supply reliabilities. Figure 4.4 suggests that the difference between long-term reliabilities approaches zero asymptotically as the period-of-analysis increases. Two conclusions may be drawn from this information: 1) with a long enough period-of-analysis (e.g. over 100 years), initial storage content will not significantly affect long-term water supply reliabilities, and 2) if the period-of-analysis is too short (e.g. less than 30 years), initial storage content must be taken into consideration.

The year in which a simulation starts affects long-term water supply reliabilities. Figure 4.7 shows that differences for predictions of volume reliabilities for reservoirs that start full versus empty are greater for simulations that start in dry years compared to simulations that start in wet years. Simulations that start in dry years experience greater variance in differences between reliability predictions compared to simulations that start in wet years (0.32 versus 0.22). Figures 4.5 and 4.6 show that both wet and dry years show greater differences between reservoirs starting full versus empty when the period-of-analysis is shortened. These results are attributable to the assumption that reservoirs start full to capacity. The effect of this assumption is mitigated by starting the simulation in a wet year and using a long period-of-analysis.

4.4. Reservoir System Configuration and Negative Incremental Flow Options

This section determines the effect operating multiple reservoirs as a system has on firm yields compared to individual reservoir operations. The section also examines how these effects change with the hydrologic period-of-analysis and the method for handling negative incremental flows. Multiple simulations are repeated using built-in features for calculating firm yield with the diversion amount requested each year being systematically changed until a maximum diversion amount is reached that is met with 100% reliability (Wurbs, 2009).

The firm yields shown in Tables 4.2 through 4.8 and Tables 4.10 through 4.14 are calculated using two distinct strategies for finding the firm yield of a reservoir. The calculations are performed using modified versions of the BRAC3, BRAC8, and Bwam3 datasets. The two strategies are:

1) The firm yield for a single diversion that replaces permitted diversions
2) The firm yield for an additional new diversion without removing or impacting any of the existing permitted diversions.

Strategy 1 is applied to the BRAC3 and BRAC8 datasets. This type of firm yield calculation represents one of the various applications of a condensed dataset. Strategy 2 is applied to both the Bwam and BRAC datasets. These two strategies are used to compute the firm yield for individual reservoirs and multiple reservoir systems. The firm yield for an individual reservoir is computed for a diversion supplied only by that reservoir. The firm yield for multiple reservoir systems is computed for a diversion that is met by releases from two or more reservoirs.

Two multiple reservoir systems are modeled. The first system is a diversion at the Cameron gage supplied by four upstream reservoirs: Lakes Belton, Stillhouse Hollow, Georgetown, and Granger. The second system is a diversion at the Richmond gage supplied by nine upstream reservoirs: Lakes Possum Kingdom, Granbury, Aquilla, Limestone, Somerville, Belton, Stillhouse Hollow, Georgetown, and Granger (Wurbs and Kim, 2008).

Streamflows generally increase in a downstream direction. An incremental flow is the difference between total flows at two or more adjacent points along a river or stream. Negative incremental flow occurs when the flow at a downstream point is less than the flow at a point located upstream. Within WRAP there are several options for handling negative incremental flows (Wurbs, 2009b). The choice of negative incremental flow option can significantly affect water availability. It is important to note that the negative incremental flows in condensed datasets have a different physical meaning than full WAM datasets. This is because the inflows of a condensed dataset consider the effects of secondary reservoirs. The Bwam3 dataset has 3,842 control points while the BRAC3 has only 48. This tends to decrease the number and magnitude of negative incremental flows.

Three negative incremental flow options are applied to the Run 3 and Run 8 datasets. With the first option (Option 1), no adjustments are made to negative incremental flow. Streamflow depletions made by junior water rights are allowed to affect the water available to senior water rights. With another option (Option 4), as each water right is considered, upstream negative incremental flow adjustments are applied at downstream control points but not the control point of the right being considered (Wurbs, 2009). Upstream flow adjustments arbitrarily add the amount of water necessary to remove all negative incremental flows. With option 4 junior water rights do not affect the amount of water available to senior water rights.

Another option for handling negative incrementals considered in this analysis is Option 5. Option 5 is equivalent to Option 1 except when there is no downstream senior water right that affects upstream water availability or when there is a discontinuity of flow between the downstream senior water right and the point being computed. In these cases, it is equivalent to Option 4.

Option 1 is considered most appropriate choice for condensed datasets because negative incremental flows will be primarily due to channel losses. Negative incremental flows are expected to be less of an issue with a condensed dataset for two reasons: 1) In a condensed dataset like the BRAC, negative incremental flows account for the effects of secondary water rights not included in the primary system that may be causing some of the negative incremental flows. 2) The condensed dataset has far fewer control points that are more widely spaced, allowing fewer opportunities for negative incremental flows to occur.

4.4.1. Firm Yield Analysis Strategy 1

4.4.1.1. Individual Reservoir Firm Yield

Firm yields for individual reservoirs computed using the BRAC3 and BRAC8 datasets are presented in Tables 4.2 - 4.5. Negative incremental flow option 1 is activated in Tables 4.2 and 4.3, and option 4 is activated in Tables 4.4 and 4.5. Each reservoir is modeled individually with a single diversion and storage refilling water right (Wurbs and Kim, 2008). The annual diversion is distributed among the twelve months of the year according to the monthly use coefficients in the BRAC datasets. The annual diversion is iteratively adjusted until the firm yield is found.

For reservoirs with no other reservoir located upstream, the firm yield is calculated with all other water rights removed. Of the 13 major reservoirs in the Brazos River Basin, this procedure is applied to Hubbard Creek, Proctor, Aquilla, Waco, Limestone, Stillhouse Hollow, Georgetown and Somerville. To calculate individual reservoir firm yield for a downstream reservoir, all upstream reservoir must be given their firm yields as a diversion. Priorities are assigned in upstream to downstream order. This is necessary to model the effect upstream reservoirs have on inflows to downstream ones. The procedure to find the firm yield of downstream reservoirs is applied to the remaining 5 reservoirs in the Brazos River Basin: Possum Kingdom, Granbury, Whitney, Belton, and Granger. For example, Hubbard Creek is upstream of Possum Kingdom, which is upstream of Granbury, which is upstream of Whitney. The procedure outlined above dictates that individual reservoir firm yield should be calculated for

Hubbard Creek first ignoring all other water rights. Next, Hubbard Creek is assigned a diversion equal to the firm yield calculated in the previous step and the firm yield for a single diversion from Possum Kingdom is found ignoring all water rights but Hubbard Creek. The firm yield for Granbury has to consider the firm yield diversions made at Hubbard Creek and Possum Kingdom but nothing else. The same goes for Whitney. This procedure must be applied to Granger, which is downstream of Georgetown, and Belton, which is downstream of Proctor.

In the Brazos WAM, both Whitney and Waco are modeled as composite reservoirs, or reservoirs made up of separate pools that each behave as independent reservoirs. For the purposes of the firm yield analysis using strategy 1, Whitney and Waco are modeled as single reservoirs. Lake Whitney is only permitted to make water supply diversions from 50,000 ac-ft of storage, despite having a much larger conservation pool. Tables 4.2 and 4.3 include firm yields considering a diversion made only from the 50,000 ac-ft of permitted storage and a diversion made from the entire conservation pool.

Table 4.2. Individual Reservoir Firm Yields for BRAC3 Dataset Using Negative Incremental Flow Option 1

Reservoir	Storage Capacity (acre-feet)	Permitted Diversion (acre-feet)	Firm Yield 1940-1997 (ac-ft/yr)	Firm Yield 1900-2007 (ac-ft/yr)	Firm Yield 1940-2007 (ac-ft/yr)
Hubbard Creek	317,750	56,000	21,100	21,100	21,100
Possum Kingdom	724,739	230,750	347,500	332,100	347,500
Granbury	155,000	64,712	62,800	64,000	62,800
Whitney (permit)	50,000	18,336	34,400	30,300	34,400
Whitney (total)	636,100	−	173,200	134,000	173,200
Aquilla	52,400	13,896	14,800	14,800	14,800
Waco	206,562	79,877	89,900	85,500	89,900
Proctor	59,400	19,658	21,200	21,200	21,200
Belton	457,600	112,257	115,500	115,500	115,500
Stillhouse Hollow	235,700	67,768	64,400	64,400	64,400
Georgetown	37,100	13,610	11,400	11,400	11,400
Granger	65,500	19,840	18,800	18,800	18,800
Limestone	225,400	65,074	68,100	68,100	68,100
Somerville	160,110	48,000	43,800	43,800	43,800

Table 4.3. Individual Reservoir Firm Yields for BRAC8 Dataset Using Negative Incremental Flow Option 1

Reservoir	Storage Capacity (acre-feet)	Firm Yield 1940-1997 (ac-ft/yr)	Firm Yield 1900-2007 (ac-ft/yr)	Firm Yield 1940-2007 (ac-ft/yr)
Hubbard Creek	317,750	35,000	35,000	35,000
Possum Kingdom	552,013	250,900	193,300	250,900
Granbury	132,821	57,900	57,900	57,900
Whitney (permit)	50,000	36,500	36,500	36,500
Whitney (total)	561,074	160,400	147,100	160,400
Aquilla	41,700	12,900	11,800	12,900
Waco	206,562	69,500	69,500	69,500
Proctor	54,702	20,800	20,800	20,800
Belton	432,978	125,600	125,600	125,600
Stillhouse Hollow	224,279	68,000	68,000	68,000
Georgetown	36,980	12,400	12,400	12,400
Granger	50,540	13,300	13,300	13,300
Limestone	208,017	69,300	69,300	69,300
Somerville	154,254	45,300	45,300	45,300

Table 4.4. Individual Reservoir Firm Yields for BRAC3 Dataset Using Negative Incremental Flow Option 4

Reservoir	Storage Capacity (acre-feet)	Permitted Diversion (acre-feet)	Firm Yield 1940-1997 (ac-ft/yr)	Firm Yield 1900-2007 (ac-ft/yr)	Firm Yield 1940-2007 (ac-ft/yr)
Hubbard Creek	317,750	56,000	21,100	21,100	21,100
Possum Kingdom	724,739	230,750	351,800	335,000	351,800
Granbury	155,000	64,712	84,600	65,300	84,600
Whitney (permit)	50,000	18,336	34,400	29,900	34,400
Whitney (total)	636,100	–	168,400	133,600	168,400
Aquilla	52,400	13,896	14,800	14,800	14,800
Waco	206,562	79,877	90,100	85,900	90,100
Proctor	59,400	19,658	21,200	21,200	21,200
Belton	457,600	112,257	115,500	115,500	115,500
Stillhouse Hollow	235,700	67,768	64,400	64,400	64,400
Georgetown	37,100	13,610	11,400	11,400	11,400
Granger	65,500	19,840	18,800	18,800	18,800
Limestone	225,400	65,074	68,100	68,100	68,100
Somerville	160,110	48,000	43,800	43,800	43,800

Table 4.5. Individual Reservoir Firm Yields for BRAC8 Dataset Using Negative Incremental Flow Option 4

Reservoir	Storage Capacity (acre-feet)	Firm Yield 1940-1997 (ac-ft/yr)	Firm Yield 1900-2007 (ac-ft/yr)	Firm Yield 1940-2007 (ac-ft/yr)
Hubbard Creek	317,750	35,100	35,100	35,100
Possum Kingdom	552,013	265,100	201,200	265,100
Granbury	132,821	80,100	78,300	80,100
Whitney (permit)	50,000	38,100	38,100	38,100
Whitney (total)	561,074	162,100	147,700	162,100
Aquilla	41,700	12,900	11,900	12,900
Waco	206,562	72,400	72,400	72,400
Proctor	54,702	20,800	20,800	20,800
Belton	432,978	127,800	127,800	127,800
Stillhouse Hollow	224,279	70,800	70,800	70,800
Georgetown	36,980	12,700	12,700	12,700
Granger	50,540	14,300	14,300	14,300
Limestone	208,017	69,300	69,300	69,300
Somerville	154,254	45,400	45,400	45,400

Flows downstream of a point being considered affect the water availability at that point. Within the BRAC datasets secondary water rights are inherently accounted for. Strategy 1, however, ignores flows at other primary reservoirs. Thus, the firm yields presented in Tables 4.2 through 4.5 may be high for some reservoirs.

Tables 4.2 - 4.5 show the firm yields calculated for 3 different periods of analysis: 1940-1997, 1900-2007, and 1940-2007. These periods correspond to the hydrologic simulation period in the Brazos WAM (1940-1997), the forward extended dataset (1940-2007) (Wurbs and Kim, 2008), and the forward extension plus the backward extended dataset (1900-2007) (Wurbs and Kim, 2008). Lakes Possum Kingdom, Granbury, Whitney, Aquilla, and Waco have firm yields that are controlled by critical draw-downs occurring between 1900 and 1940 in one or more of Tables 4.2 though 4.5. This period is characterized by few stream gaging stations and thus greater uncertainties are introduced. The firm yields of the other eight reservoirs are controlled by critical draw-downs occurring between 1940 and 1997. The forward extension (1998-2007) does not affect firm yield estimates.

A comparison of Negative Incremental Flow Option 1 (Tables 4.2 and 4.3) and Option4 (Tables 4.4 and 4.5) shows that the firm yields change for some reservoirs and are the same for the others. The greatest differences are at Possum Kingdom and Granbury Reservoir. Whitney and Waco reservoirs also show significant differences.

4.4.1.2. Multiple-Reservoir System Firm Yield

The firm yield of a multiple reservoir system is computed for a diversion that is met by releases from two or more reservoirs located upstream. Within WRAP, reservoirs are coordinated as a system by making releases from the fullest reservoir in terms of storage as a percent of capacity. Negative Incremental Flow Options 1 and 4 are used when finding the firm yields of the two multiple-reservoir systems described above. The analyses are based on the BRAC datasets.

Two multiple reservoir systems are modeled here. The first system is a diversion at the Cameron gage supplied by four upstream reservoirs: Lakes Belton, Stillhouse Hollow, Georgetown, and Granger. These four reservoirs are operated to meet the firm yield diversion at the Cameron gage. Proctor Reservoir is included in the model because it affects the inflows to Belton and the flows at the Cameron gage. It is assigned a senior priority date with a diversion equal to its firm yield shown in Tables 4.2 and 4.3. The effects of reservoirs not included in the system are ignored. The second system is a diversion at the Richmond gage supplied by nine upstream reservoirs: Lakes Possum Kingdom, Granbury, Aquilla, Limestone, Somerville, Belton, Stillhouse Hollow, Georgetown, and Granger. The four remaining reservoirs (i.e. Hubbard Creek, Proctor, Whitney and Waco) are included in the model, each with a diversion equal to its firm yield shown in Tables 4.2 and 4.3. For both systems, priorities are set in upstream to downstream order regardless of the date listed in the water right permits.

Within WRAP, there are several water right types. With type 1 water rights, diversions are met by streamflow depletions and supplemented by storage. Also the reservoir can be refilled by streamflow depletions, if the water is available. The individual reservoir analyses presented above are type 1 water rights. Type 1 water rights, however, are limited to diversions made at reservoirs. Diversions for multiple-reservoir systems are made at some point downstream of reservoirs and so preclude the use of type 1 rights. Types 2 and 3 water rights do not refill storage. Type 2 water rights make streamflow depletions, if available, and supplement shortages with releases from storage. Type 3 water rights are supplied only by releases from reservoir storage. Type 2 and 3 water rights are applied to the system diversions presented in Table 4.6.

Tables 4.7 and 4.8 show the same information as Tables 4.2, 4.3, and 4.6, reorganized to compare individual reservoir and multiple reservoir firm yields for BRAC3 and BRAC8 datasets. In some cases firm yields for the BRAC8 datasets are higher than the BRAC3 firm yields, in other cases they are not. The BRAC8 dataset has reservoir storage capacities that reflect year 2000 sedimentation conditions, while the BRAC3 dataset has the originally permitted storage capacities. The datasets also differ in the amount of naturalized flows. The BRAC3 dataset is based on the authorized use scenario (run 3) in which secondary water rights inherently considered in the flow amounts are given their full permitted amounts subject to water availability. The BRAC8 dataset is based on the current use scenario (run 8) in which secondary water rights divert their maximum diversion amount subject to water availability.

Table 4.6. Multiple-Reservoir System Firm Yields

Water Right Type 1 or 2	BRAC3 Firm Yield 1940-1997 (ac-ft/yr)	 1900-2007 (ac-ft/yr)	 1940-2007 (ac-ft/yr)	BRAC8 Firm Yield 1940-1997 (ac-ft/yr)	 1900-2007 (ac-ft/yr)	 1940-2007 (ac-ft/yr)
Negative Incremental Flow Option 1						
Diversion at the Cameron Gage						
Type 2	263,800	263,800	263,800	265,600	265,600	265,600
Type 3	252,000	252,000	252,000	247,900	247,900	247,900
Diversion at the Richmond Gage						
Type 2	1,132,000	1,070,600	1,132,000	954,300	871,800	954,300
Type 3	912,200	855,000	912,200	790,100	679,700	790,100
Negative Incremental Flow Option 4						
Diversion at the Cameron Gage						
Type 2	286,400	286,400	286,400	287,400	287,400	287,400
Type 3	252,000	252,000	252,000	265,600	265,600	265,600
Diversion at the Richmond Gage						
Type 2	1,221,000	1,101,300	1,221,000	1,120,100	963,200	1,120,100
Type 3	957,900	858,800	957,900	889,400	889,400	727,800

Table 4.7. Firm Yield Summary for Five BRA Reservoirs in Little River Subbasin Based on BRAC Datasets with 1940-2007 Period-of-Analysis and Negative Incremental Inflow Option 1

	BRAC3	BRAC8
	Firm Yield	
	(ac-ft/yr)	(ac-ft/yr)
Individual Reservoirs		
Proctor	21,200	20,800
Belton	115,500	125,600
Stillhouse Hollow	64,400	68,000
Georgetown	11,400	12,400
Granger	18,800	13,300
Total − 5 Resevoirs	231,300	240,100
Total − 4 System Reservoirs with the exclusion of Proctor Reservoir	210,100	219,300
Multiple-Reservoir System		
Type 2 diversion at Cameron (4 reservoirs)	263,800	265,600
Proctor Reservoir	21,200	20,800
Total	285,000	286,400
Type 3 diversion at Cameron (4 reservoirs)	252,000	247,900
Proctor Reservoir	21,200	20,800
Total	273,200	268,700

Table 4.8. Firm Yield Summary for 12 Brazos River Authority Reservoirs Based on BRAC Datasets with 1940-2007 Period-of-Analysis and Negative Incremental Inflow Option 1

	BRAC3	BRAC8
	Firm Yield	
	(ac-ft/yr)	(ac-ft/yr)
Individual Reservoirs		
Five reservoirs in Little River Subbasin	231,300	240,100
Possum Kingdom	347,500	250,900
Granbury	62,800	57,900
Whitney (50,000 acre-feet)	34,400	36,500
Aquilla	14,800	12,900
Waco	89,900	69,500
Limestone	68,100	69,300
Somerville	43,800	45,300
Total − 12 BRA Reservoirs	892,600	782,400
Total − 9 System Reservoirs	747,100	655,600
Multiple-Reservoir System		
Type 2 diversion at Richmond (9 reservoirs)	1,132,000	954,300
Proctor Reservoir	21,200	20,800
Waco Reservoir	89,900	69,500
Whitney Reservoir	34,400	36,500
Total	1,277,500	1,081,100
Type 3 diversion at Richmond (9 reservoirs)	912,200	790,100
Proctor Reservoir	21,200	20,800
Waco Reservoir	89,900	69,500
Whitney Reservoir	34,400	36,500
Total	1,057,700	916,900

Multiple-reservoir system operations result in significant increases in firm yields as compared to individual reservoir firm yields. This is because critical draw-down periods differ between component reservoirs and releases are made only from the reservoir that is most full. Type 2 water rights have the additional advantage of being able to deplete excess streamflow to meet diversion targets, thereby reducing demand for releases from storage.

The sum of individual firm yields in Table 4.7 excluding Proctor is 210,100 ac-ft/yr. The firm yield for the four reservoir system (i.e. Belton, Stillhouse Hollow, Georgetown and Granger) using a type 2 water right is 263,800 ac-ft/yr, or 25.6% greater than the sum of individual yields. The firm yield for the four reservoir system using a type 3 water right is 252,000 ac-ft/yr, or 19.9% greater than the sum of individual yields.

The sum of individual firm yields in Table 4.8 for the nine system reservoirs is 747,100 ac-ft/yr. The firm yield for the nine reservoir system (i.e. Belton, Stillhouse Hollow, Georgetown, Granger, Possum Kingdom, Granbury, Aquilla, Limestone, and Somerville) using a type 2 water right is 1,132,000 ac-ft/yr, or 51.5% greater than the sum of individual yields. The firm yield for the nine reservoir system using a type 3 water right is 912,200 ac-ft/yr, or 22.1% greater than the sum of individual yields.

4.4.2. Firm Yield Analysis Strategy 2

In strategy 2, the firm yield is calculated for an additional diversion without changing existing water rights. This approach is applied to the authorized use scenario Bwam3 and BRAC3 datasets. The hydrologic period-of-analysis used in this section is 1940 to 1997 because this is the period-of-analysis for the Bwam3 dataset. Both datasets are adopted without modification except for the addition of a junior water right diversion and the application of the dual simulation option to ensure existing water rights do not increase their streamflow depletions. Individual reservoir firm yields are estimated using negative incremental flow options 5 and 4.

Table 4.9 shows that reliabilities are less than 100% for Hubbard Creek, Waco, Stillhouse Hollow, Georgetown, Granger, and Somerville. These reservoirs are over-permitted and will not be able to provide additional yield. The yields for the Bwam3 dataset are presented in Tables 4.10 and 4.12, respectively. Individual reservoir firm yields for the BRAC3 dataset using negative incremental flow option 1 and 4 are presented in Tables 4.11 and 4.13, respectively. Option 5 is used in the TCEQ-approved Brazos WAM. Option 4 is included for comparison.

Strategy 2 is only relevant when the storage capacity of a reservoir is not being fully utilized. In other words, the firm yield for a new diversion is zero unless all existing water rights are being met with 100% reliability. The last column of Tables 4.10 through 4.13 only represents a firm yield for the reservoir when the new firm yield from the previous column is greater than zero.

A dual simulation is necessary because although the new water right is junior to all existing water rights, it still depletes storage at the reservoir. Without the dual simulation, the following month senior water rights would attempt to make up this storage deficit thereby reducing the amount of water available to other water rights in the basin. A dual simulation, as the name implies, run the model twice. The first simulation is run without considering the new diversion and streamflow depletions made by existing rights are recorded. The second run activates the new diversion but does not allow the preexisting rights to deplete more than they did the first time. The dual simulation option is described in greater detail in the Reference Manual (Wurbs, 2009a).

Table 4.9. Volume Reliabilities for Bwam3 and BRAC3 datasets from 1940 to 2007

	Bwam3	BRAC3
Hubbard Creek	81.92	81.86
Possum Kingdom	100.00	100.00
Granbury	100.00	100.00
Whitney	100.00	100.00
Aquilla	100.00	100.00
Waco	97.86	99.72
Proctor	100.00	100.00
Belton	100.00	100.00
Stillhouse Hollow	99.54	99.54
Georgetown	98.56	98.56
Granger	99.77	99.77
Limestone	100.00	100.00
Somerville	99.66	99.66

Table 4.10. Bwam3 Individual Reservoir Firm Yields - Negative Incremental Option 5

		Diversions		
Reservoir	Storage Capacity (acre-feet)	Existing Rights (ac-ft/yr)	New Firm Yield (ac-ft/yr)	Total (ac-ft/yr)
Hubbard Creek	317,750	56,000	0	56,000
Possum Kingdom	724,739	230,750	149,200	379,950
Granbury	155,000	64,712	26,200	90,912
Whitney	636,100		N/A	
Whitney	50,000	18,336	14,900	33,236
Aquilla	52,400	13,896	700	14,596
Waco	206,562	79,877	7500	87,377
Proctor	59,400	19,658	600	20,258
Belton	457,600	112,257	3200	115,457
Stillhouse Hollow	235,700	67,768	0	67,768
Georgetown	37,100	13,610	0	13,610
Granger	65,500	19,840	0	19,840
Limestone	225,400	65,074	4600	69,674
Somerville	160,110	48,000	0	48,000

Table 4.11. BRAC3 Individual Reservoir Firm Yields - Negative Incremental Option 1

		Diversions		
Reservoir	Storage Capacity (acre-feet)	Existing Rights (ac-ft/yr)	New Firm Yield (ac-ft/yr)	Total (ac-ft/yr)
Hubbard Creek	317,750	56,000	0	56,000
Possum Kingdom	724,739	230,750	114,100	344,850
Granbury	155,000	64,712	25,300	90,012
Whitney	636,100	18,336	163,600	181,936
Whitney	50,000	18,336	16,000	34,336
Aquilla	52,400	13,896	900	14,796
Waco	206,562	79,877	22,500	102,377
Proctor	59,400	19,658	600	20,258
Belton	457,600	112,257	3200	115,457
Stillhouse Hollow	235,700	67,768	0	67,768
Georgetown	37,100	13,610	0	13,610
Granger	65,500	19,840	0	19,840
Limestone	225,400	65,074	4100	69,174
Somerville	160,110	48,000	0	48,000

Table 4.12. Bwam3 Individual Reservoir Firm Yields - Negative Incremental Option 4

Reservoir	Storage Capacity (acre-feet)	Diversions Existing Rights (ac-ft/yr)	New Firm Yield (ac-ft/yr)	Total (ac-ft/yr)
Hubbard Creek	317,750	56,000	0	56,000
Possum Kingdom	724,739	230,750	80,700	311,450
Granbury	155,000	64,712	14,500	79,212
Whitney	636,100		N/A	
Whitney	50,000	18,336	9600	27,936
Aquilla	52,400	13,896	700	14,596
Waco	206,562	79,877	11,400	91,277
Proctor	59,400	19,658	1100	20,758
Belton	457,600	112,257	4000	116,257
Stillhouse Hollow	235,700	67,768	0	67,768
Georgetown	37,100	13,610	0	13,610
Granger	65,500	19,840	0	19,840
Limestone	225,400	65,074	5300	70,374
Somerville	160,110	48,000	0	48,000

Table 4.13. BRAC3 Individual Reservoir Firm Yields - Negative Incremental Option 4

Reservoir	Storage Capacity (acre-feet)	Diversions Existing Rights (ac-ft/yr)	New Firm Yield (ac-ft/yr)	Total (ac-ft/yr)
Hubbard Creek	317,750	56,000	0	56,000
Possum Kingdom	724,739	230,750	122,300	353,050
Granbury	155,000	64,712	23,500	88,212
Whitney	636,100	18,336	162,400	180,736
Whitney	50,000	18,336	16,000	34,336
Aquilla	52,400	13,896	900	14,796
Waco	206,562	79,877	22,500	102,377
Proctor	59,400	19,658	600	20,258
Belton	457,600	112,257	3200	115,457
Stillhouse Hollow	235,700	67,768	0	67,768
Georgetown	37,100	13,610	0	13,610
Granger	65,500	19,840	0	19,840
Limestone	225,400	65,074	4100	69,174
Somerville	160,110	48,000	0	48,000

Multiple reservoir system firm yields are presented in Table 4.14 for diversions at the Cameron and Richmond gages. The multiple reservoir systems make diversions at the respective gages and are supplied by the same reservoirs considered in Table 4.6. However, the firm yields presented in Table 4.13 preserve all existing water rights. Simulations are run for types 2 and 3 water rights previously described.

Table 4.14 Multiple-Reservoir System Firm Yields -
Negative Incremental Flow Option 5 and 1

	Firm Yield (acre-feet/year)			
	Bwam3 (Option 5)		BRAC3 (Option 1)	
Diversion Location	Type 2	Type 3	Type 2	Type 3
Cameron gage (control point LRCA58)	5400	4100	5300	4100
Richmond gage (control point BRRI70)	164,600	92,700	164,400	92,500
Multiple-Reservoir System Firm Yields (Negative Incremental Flow Option 4)				
Cameron gage (control point LRCA58)	18,100	15,500	5300	4100
Richmond gage (control point BRRI70)	164,200	92,800	167,800	92,700

4.4.3. Firm Yield Summary

Firm yield estimates vary depending on the premises reflected in the model. Key factors that can affect firm yield calculations include but are not limited to:

- Strategies for modeling interactions between multiple reservoirs and multiple water rights
- Negative incremental flow options
- Reservoir storage conditions including sedimentation, allocation, system operations and initial storage content
- River basin hydrology including hydrologic period-of-analysis, the philosophy used to allocate naturalized flows, and the effect water management strategies have on critical draw-down period

Contrary to strategy 1, the firm yield for individual reservoirs is not independent of other reservoirs in the basin. It is possible for the diversions and storage at one reservoir to affect water availability at another. It is advisable to include all primary reservoirs in the dataset prior to computing firm yield for either individual reservoirs or multiple reservoir systems. Operating multiple reservoirs in coordination increases the firm yield relative to the sum of individual reservoirs within the system. This is consistent with the findings of previous research (Wurbs, 1996).

Negative incremental flows and options for handling them can significantly influence estimates of firm yield. Negative incremental flows are expected to be less of an issue with a condensed dataset for two reasons: 1) In a condensed dataset like the BRAC, negative incremental flows account for the effects of secondary water rights not included in the primary system that may be causing some of the negative incremental flows. 2) The condensed dataset has far fewer control points that are more widely spaced, allowing fewer opportunities for negative incremental flows to occur. While negative incremental flows is an area of water availability modeling requiring further research, option 4 is recommended for the full WAM datasets and option 1 is probably the most appropriate for condensed datasets.

The majority of critical draw-down periods for the analyses presented above occur during the drought of the 1950s. Greater modeling uncertainties are involved for those that occur prior to 1940 due to the lack of stream gaging stations in operation during this period. No critical draw-down period occurs during the 1998-2007 extension of the hydrologic period-of-analysis.

CHAPTER V

ISSUES IN CONDITIONAL RELIABILITY MODELING

Conditional reliability analysis within WRAP is accomplished by dividing a long period of hydrologic data into several shorter periods. These short sequences are all of the same length and simulated starting with the same initial storages. Salazar (2002) and Olmos (2004) contributed substantial portions of the CRM code for previous versions of WRAP. The efforts of the author and R. A. Wurbs consisted primarily in condensing, updating, and debugging existing code. Several computational enhancements were also made. The capabilities that were added include allowing for simulation lengths greater than one year and calculation of shortage metrics.

The choice of modeling option impacts the results of conditional reliability analysis. This chapter uses modeling experiments to determine CRM's sensitivity to changes in key variables. The analyses presented here are short-term simulations. Long-term simulations are discussed in Chapter IV. For each variable, the context, overall approach and dependent variables are presented followed by descriptions of the procedure and experimental design. Finally, preliminary results are presented and discussed.

5.1. Hydrologic Period-of-Analysis

This section determines the effect of different hydrologic periods-of-analysis on the estimated reliabilities and storage frequencies of short-term simulations. The equal-weight option is applied to the BRAC3 dataset using the same periods-of-analysis as 4.1. Figure 5.1 shows short-term reliabilities and storage frequencies predicted for 6 months into the future, assuming all reservoirs start empty. The reliabilities shown consider the 15 reservoirs in the dataset. Both monthly and annual cycling options are modeled (Figure 5.1).

In every case, predicted reliabilities experience less variability with periods-of-analysis greater than 60 years. The monthly cycle (red line) shows an averaging effect, while simulations starting in wet months (e.g. January) experience above average reliabilities and those starting in dry months (e.g. July) experience lower than average reliabilities.

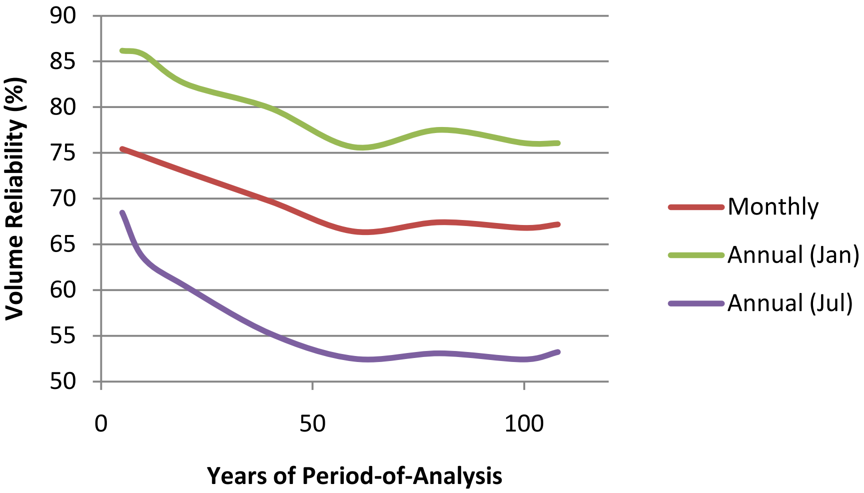

Figure 5.1. Effect of Length of Period-of-Analysis on Short-Term Water Supply Reliabilities

The question of whether or not this pattern is because more recent decades years have been wetter (Figure 4.2) is addressed in Table 5.1. Two simulations with the same length of period-of-analysis were run for two different starting years, 1900 and 1948, respectively. A period-of-analysis of 60 years was chosen so that both simulations include the drought of the 1950s so as not to skew the results one way or the other. Table 5.1 shows that predicted short-term reliabilities are consistently lower for a period-of-analysis containing the first 60 years compared to the last 60 years, regardless of starting month. Furthermore, the difference is greater for simulations starting in January compared to July. This would imply that wet months in recent decades are significantly wetter than decades at the beginning of the century while dry months are only slightly less wet. These results suggest that more recent decades have been wetter and that considering hydrology prior to 1950 may result in more conservative estimates of short-term reliability.

Table 5.1. Effect of First 60 Years versus Last 60 Years Period-of-Analysis on Reliabilities

Period-of-Analysis	1900-1959	1948-2007	Difference
January	73.58	75.61	2.03
Monthly	65.36	66.39	1.03
July	51.24	52.48	1.24

5.2. Initial Storage Content

An advantage to having a long hydrologic period-of-analysis is that the effect of an arbitrary initial storage condition is unlikely to persist long enough to significantly affect the results (Salazar, 2002). Simulations were run for different initial storage conditions to determine the effect of initial storage conditions on storage frequencies on short-term water supply reliabilities.

Conditional reliabilities and storage frequencies are determined with the annual and monthly cycling options. For the annual cycle, each 12-month-long simulation sequence begins alternatively in January. The beginning-of-simulation storage contents are set in alternative executions of the WRAP-SIM simulation model for the 15 reservoirs included in the BRAC3 input file as zero, 10, 25, 50, 75, and 100 percent of the storage capacity.

A comparison of the equal weight and probability array options for Lake Granger shows that differences increase as initial storage decreases (Table 5.2). This relationship is reservoir specific.

Table 5.2. Annual Volume Reliabilities for the Equal Weight Option versus Probability Array as a Function of Initial Storage Starting in January

Initial Storage	Equal Weight	Probability Array	Difference
0%	88%	60%	28
10%	95%	83%	12
25%	99.4%	98.5%	0.9
50%	100%	100%	0
75%	100%	100%	0
100%	100%	100%	0

Table 5.3 shows the storage-frequency relationship developed from 107 short-term simulations in which all 15 reservoirs in the dataset start at 10% of capacity. All sequences are twelve months and begin in April. The left hand side of Table 5.3 is the percent of months that the given storage level is equaled or exceeded. When the reservoir is 10% full, the storage content at the end of April is at least 4,678 ac-ft 100% of the months. By the end of October, there is a 10% chance that the reservoir is full (65,500 ac-ft) and a 10% chance that it is empty.

Table 5.3. Storage-Frequency Relationships for Initial Storage Volume of 10 Percent of Capacity

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Mean	19,698	31,260	33,803	33,139	31,227	31,499	34,631	37,421	40,263	43,221	45,235	47,056
St Dev	4,901	6,747	7,199	7,354	7,308	7,298	7,292	7,317	7,335	7,220	7,005	7,000
100%	4,678	2,711	360	0	0	0	0	0	0	0	0	0
99%	4,707	2,749	403	0	0	0	0	0	0	0	0	0
98%	4,791	2,877	535	0	0	0	0	0	0	0	0	3
95%	4,964	4,311	2,145	0	0	0	0	0	0	0	0	232
90%	5,080	6,264	4,999	2,230	779	584	0	0	161	226	1,971	4,534
75%	6,937	9,790	10,666	8,186	5,526	5,500	9,447	12,487	14,780	17,988	25,352	28,356
60%	9,614	15,041	16,459	18,268	16,109	16,386	23,152	31,139	35,188	43,555	45,517	57,310
50%	13,913	25,244	26,050	27,555	27,812	30,872	35,873	38,603	50,169	55,436	58,382	62,604
40%	17,393	34,256	41,732	46,537	42,785	44,760	50,268	53,666	57,445	64,714	65,500	65,500
25%	27,186	59,546	65,500	62,761	60,442	59,158	62,029	65,500	65,500	65,500	65,500	65,500
10%	48,101	65,500	65,500	65,500	64,374	64,525	65,500	65,500	65,500	65,500	65,500	65,500
Max	65,500	65,500	65,500	65,500	65,500	65,500	65,500	65,500	65,500	65,500	65,500	65,500

5.3. Choice of Cycling Option

Within WRAP, there are two options for organizing CRM simulation sequences: the annual cycle and monthly cycle. The annual cycle option simulates one sequence per year, and each sequence always begins in the same month. The monthly cycle option simulates one sequence per month, generating up to 12 times more sequences than the annual cycle.

Differences between the monthly and annual cycling options are discussed in terms of their relationship to the hydrologic period-of-analysis (Section 5.1.), starting month (Section 5.4.), and length of simulation (Section 5.5.). The extra sequences in the monthly cycle come at a loss of seasonality but can be useful for assigning probabilities.

5.4. Starting Month

When the annual cycle option divides a long period of hydrology into several shorter ones, every short-term sequence starts in a month specified by the user. The annual cycle considers only the hydrologic sequences that begin in that month. The month in which a CRM simulation begins can affect the reliability and storage predictions.

Short-term reliabilities are predicted for 6 months into the future, assuming all reservoirs start empty. The complete period-of-analysis (108 years) was used. Twelve simulations were run; each one starting in a different month of the year. To see how the effect of starting month changes with simulation length, see *length of simulation* (Section 5.5.).

Figure 5.2 shows that short-term reliabilities are higher for simulations starting in wet months (e.g. January through May) and lower for dry months (e.g. July through September). This is because greater shortages are experienced if the reservoir is empty during a month (e.g. July, August) in which stream flows are lower. In other words, although the reservoir is empty for the simulation starting in April, stream flows are large enough to satisfy greater demand. There may be a lag between storage and naturalized flows.

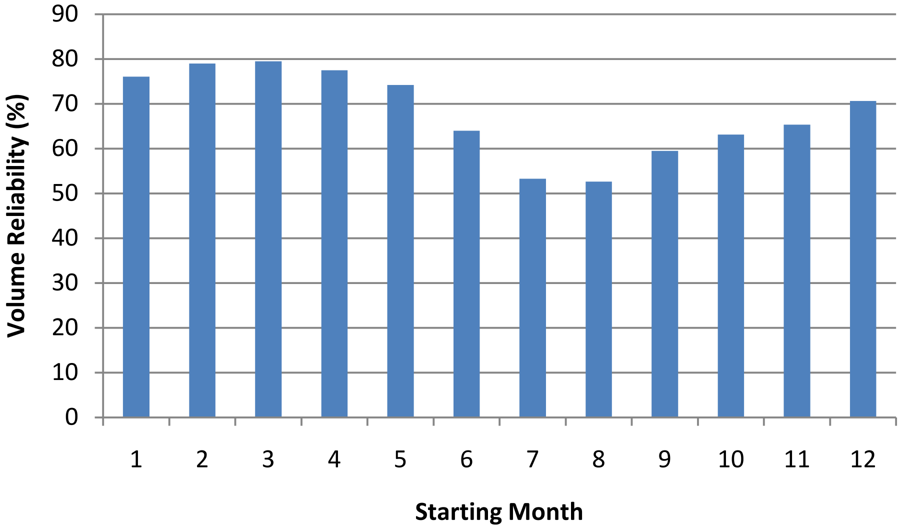

Figure 5.2. Effect of Starting Month on Short-Term Water Supply Reliabilities

Just as long-term simulations are influenced by starting year (Section 4.3), short-term simulations are influenced by starting month. They are both affected by a wet or dry “bias” in the subsequent hydrology. In the case of a long-term simulation, the bias is historical; in the case of a short-term, it is seasonal. Figure 5.3 shows the average flows per month at the Richmond gage. Distinct differences are seen among the summer months.

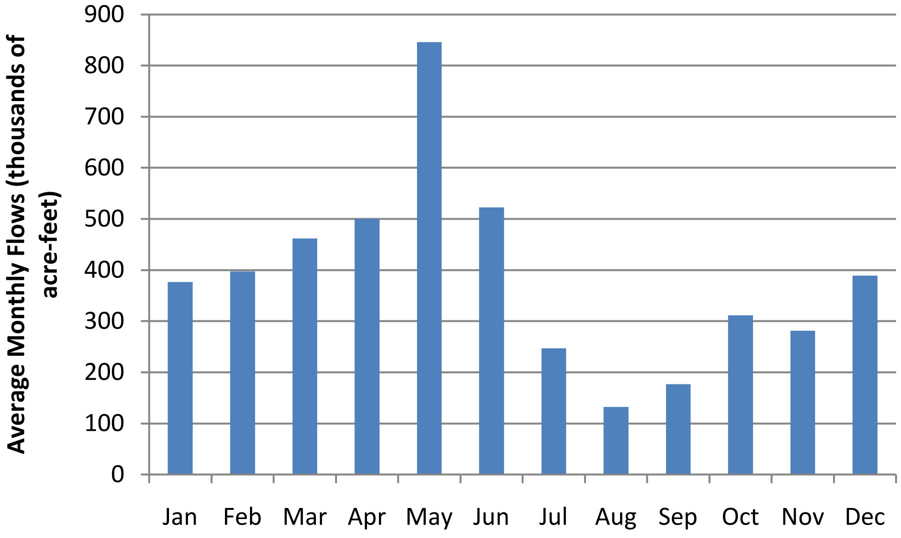

Figure 5.3. Average Monthly Flows at the Richmond Gage

5.5. Length of Simulation

The initial storage content only influences the simulated storage content for a short period of time as determined in Section 4.2. But how short is short? A short-term simulation is affected by the length of simulation in a number of ways. The influence of starting month on predicted storages diminishes with length of simulation. As is suggested by the findings of Section 4.2, with a long enough simulation, the same storage frequencies will be predicted, regardless of initial storage conditions.

The SFF option assigns probabilities to stream flow sequences based on a regression relationship with initial storage. The SFF option assumes reservoir storage is an indicator of preceding hydrologic conditions and that what occurred in the recent past is likely to persist in the near future.

The SFF probability array option is based on the idea that there is a relationship between initial storage and preceding stream flow. The correlation between initial storage and naturalized flows is determined using the Linear Correlation Coefficient and Spearman’s Rank Correlation Coefficient for simulation lengths ranging from 1 month to 10 years and starting in January and April.

The correlation between initial storage and naturalized flows decreases as simulation length increases (Figures 5.4 and 5.5). The correlation coefficient is lower for simulations starting in April, a wet month, compared to January, a dry month. By 18 months the difference between linear correlation coefficients for a simulation starting in January compared to April drops below 0.05.

The reason for the rise around 8 years is unclear, and may be a statistical coincidence. This highlights the importance of using a simulation length with sufficiently high correlation coefficients.

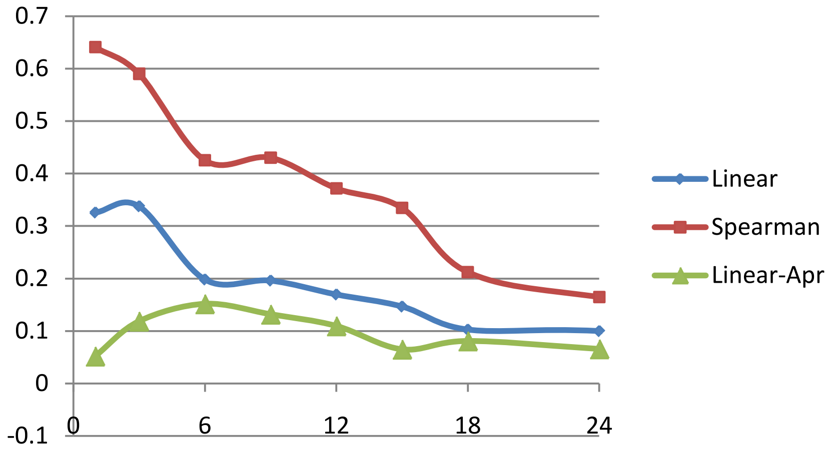

Figure 5.4. Correlations between Initial Storage and Naturalized Flows as a function of Simulation Length for Two Years in the Future

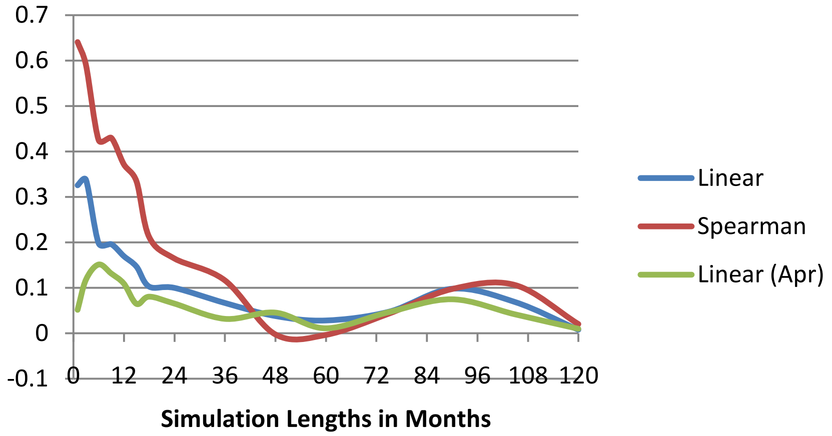

Figure 5.5. Correlations between Initial Storage and Naturalized Flows as a function of Simulation Length for Ten Years in the Future

The effect of length of simulation on short-term water supply reliabilities and average end-of-simulation storage is investigated using the equal weight sequencing option. Simulations were run for simulation lengths ranging from 1 month to 5 years. For Granger Reservoir, the correlation between initial storage and naturalized flows decreases significantly after 6 months and again after 15 months (Figure 5.5). For this reason, the equal weight sequencing option was chosen.

Simulations were run for the following simulation lengths in months: 1, 3, 6, 9, 12, 15, 18, 24, 36, 48, and 60. Two different scenarios are run for these 11 simulation lengths: one assumes the reservoir starts full at the beginning of the simulation; the other scenario assumes it starts empty. The short-term reliabilities and average end-of-period storages apply to Granger Reservoir. All simulations start in January. The CR3=2 option is only relevant when the simulation length is greater than 12 months. When CR3=2, reliabilities are calculated for the entire simulation, otherwise reliabilities are calculated considering only the last 12 months of the simulation.

Figures 5.6 and 5.7 show that as the simulation length increases the impact of initial storage content is reduced. The impact of initial storage on short-term reliabilities becomes negligible around 5 years (60 months) into the future. The reason the blue line is consistently below the green line is because when CR3=2, the low reliabilities at the beginning of the simulation are still factored into the average of the entire simulation and thus result in a lower number. The impact of initial storage on average end-of-simulation storage becomes negligible between 3 and 4 years (36 to 48 months) into the future.

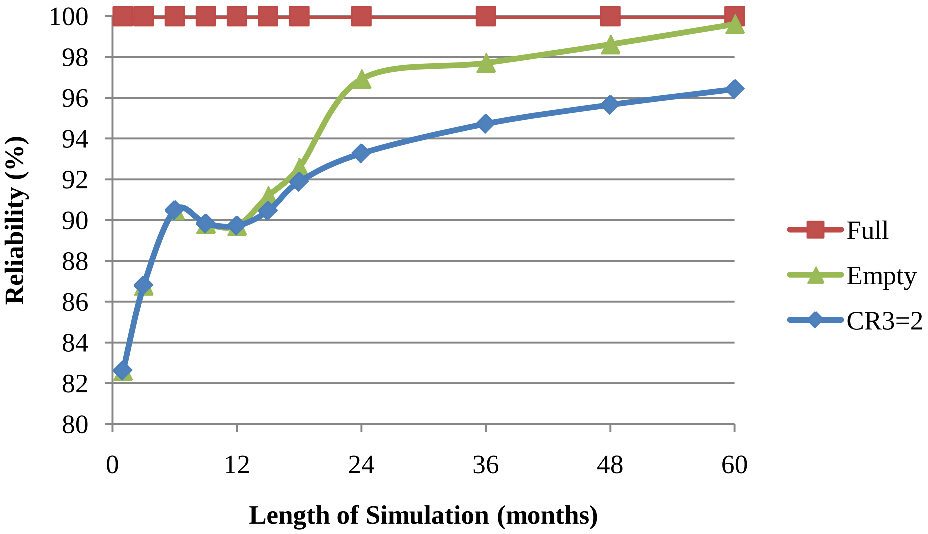

Figure 5.6. Effect of Simulation Length on Short-Term Reliabilities

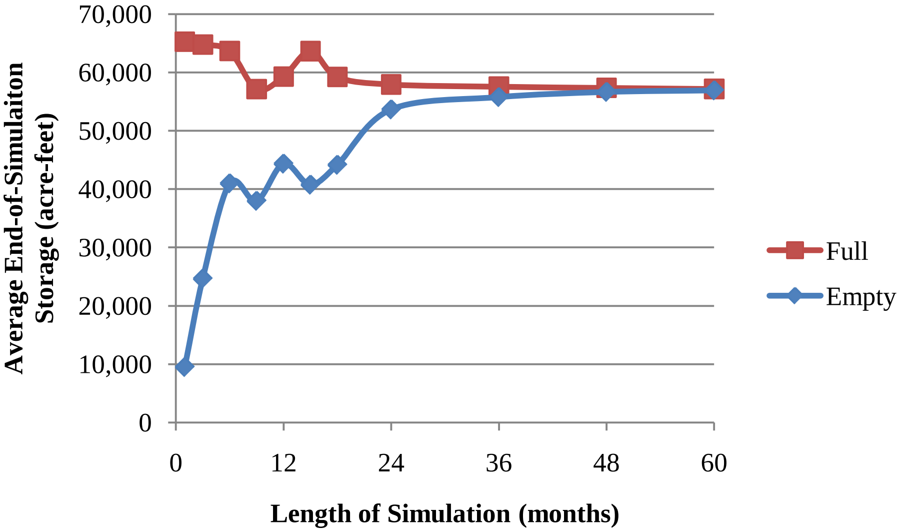

Figure 5.7. Effect of Simulation Length on Average End-of-Simulation Storage Content

5.6. Methods for Assigning Probabilities

Reliability and frequency estimates vary depending on the method used to assign probabilities to the sequences of naturalized flow and net evaporation-precipitation. There are three options in WRAP for assigning weights to short-term sequences: The equal-weight option, the FF relationship, and the SFF relationship. The latter two are referred to as the probability array modeling options.

5.6.1. Equal Weight versus Probability Array

For Granger Reservoir, the difference between equal weight and probability array modeling options is greatest when the reservoir starts empty (Table 5.4). This difference decreases as the initial storage level increases. This is because the equal weight option, as the name implies weights each of the hydrologic sequences as equally likely to occur in the near future. In the case of Granger reservoir, this is a valid assumption when the reservoir starts full to capacity as will be discussed in further detail below. However, when the reservoir begins empty, it can be assumed that recent dry conditions led to that storage level, and that these conditions are likely to persist in the near future. In this case, assuming that each sequence of historical hydrology (both wet and dry) is equally likely is unreasonable. The probability array will identify sequences of historical hydrology beginning with similarly low storage levels and weight those sequences as more likely to occur in the future. The hydrology following a period of low reservoir storage tends to be dry. In Table 5.4 the probability array weights these dry sequences more heavily than wetter sequences. For this reason, the lower the initial storage content the greater the difference in predicted reliabilities.

Table 5.4. Volume Reliabilities for the Equal Weight Option versus Probability Array as a Function of Initial Storage

Initial Storage	Equal Weight	Probability Array	Difference
0%	88%	60%	28
10%	95%	83%	12
25%	99.4%	98.5%	0.9
50%	100%	100%	0
75%	100%	100%	0
100%	100%	100%	0

Figures 5.8 through 5.10 show the differences between storage frequencies for the first month of simulation (April), the sixth month (September), and the last month (March), respectively. The points are fit using third order polynomial regression. The percentages in the legend are the storage contents as a percent of reservoir capacity. The x-axis shows the exceedance frequency or the percentage of months with storage equaling or exceeding a specified value (not shown). The y-axis shows the difference between these values that result when the predicted storage for a given exceedance frequency calculated using the probability array option is subtracted from the storage predicted using the equal weight option. Positive values mean the equal weight option predicts a higher storage level by the amount indicated for a given exceedance frequency.

When initial storage drops below 100% of capacity differences emerge between the two modeling options. For a reservoir starting 10% full in April, a simulation in which all hydrologic sequences are assigned an equal weight predicts that a storage level of 64,525 ac-ft will be equaled or exceeded 10% of the time by the end of September. Whereas a simulation taking advantage of the probability array predicts that by September only 35,858 ac-ft of storage will be equaled or exceeded 10% of the time. The difference of 28,667 ac-ft is shown in Figure 5.9.

The difference between the two modeling options is least when the reservoir is 100% full to capacity. This difference increases as the initial storage decreases. The difference between the predicted storage level that is equaled or exceeded 100% of the time is minimal for the two modeling options regardless of initial storage content. The magnitude of differences is least during the first month of simulation (April) and increases as the simulation proceeds.

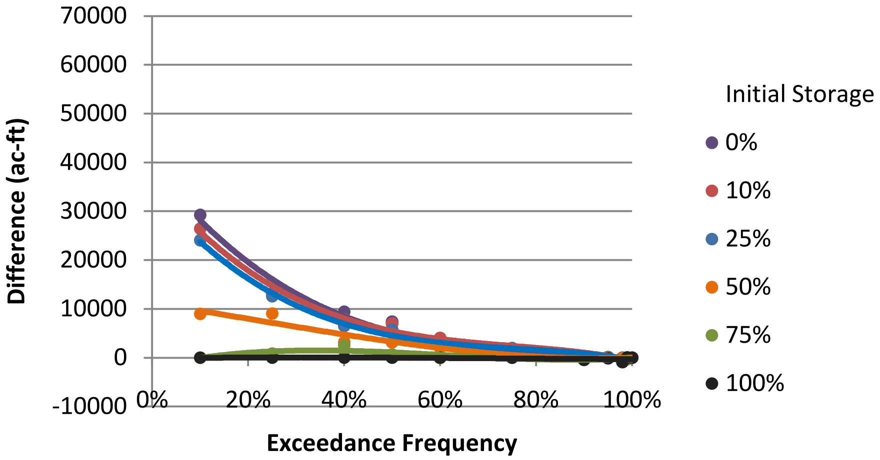

Figure 5.8. Differences Between Storage Frequencies for April for Different Initial Storages

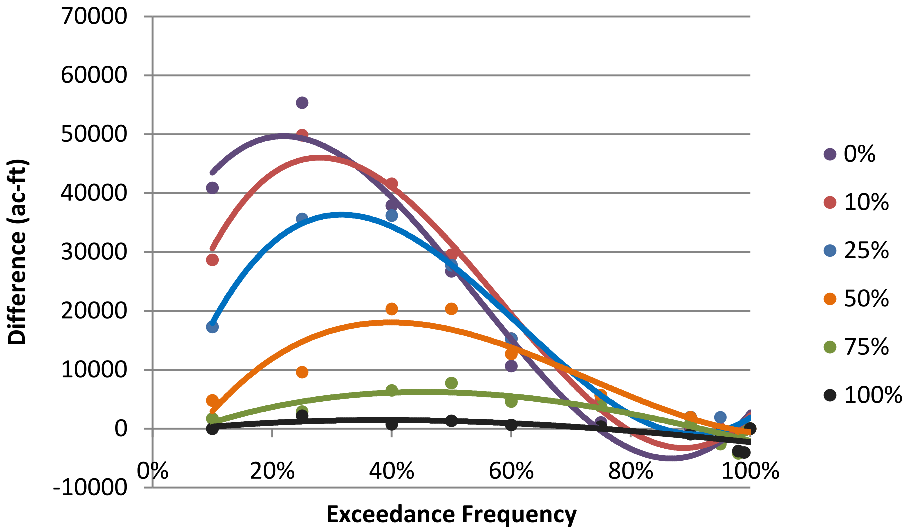

Figure 5.9. Differences Between Storage Frequencies for September for Different Initial Storages

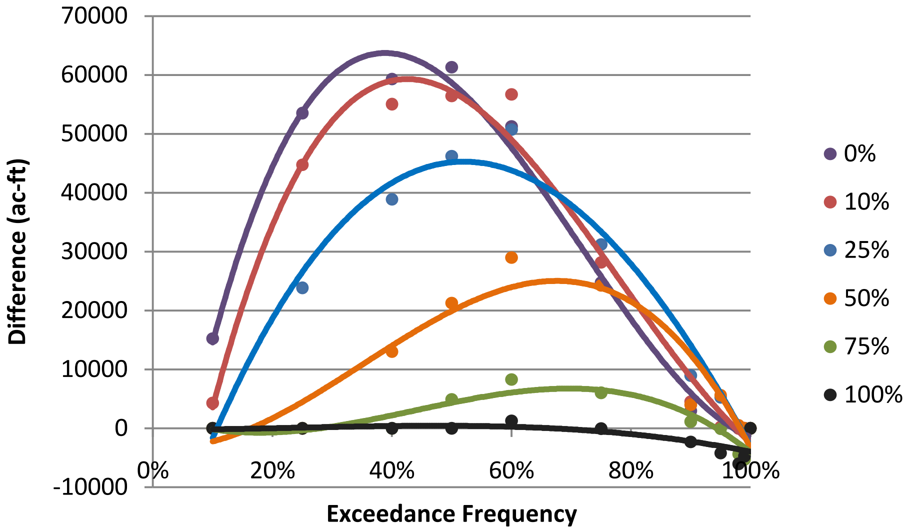

Figure 5.10. Differences Between Storage Frequencies for March for Different Initial Storages

Table 5.5 shows maximum difference between equal weight and probability array modeling options for 6 months (September) and 12 months (March) in the future and the frequency at which it occurs. The difference for March is greater in magnitude than difference in September. The frequency at which the maximum difference occurs is lowest when the reservoir starts 0% full. The value for the frequency at which the maximum difference between equal weight and probability array occurs increases as initial reservoir storage increases. The simulation in which the reservoir starts 100% full is an exception. This pattern is true for both September and March, however the interval between frequencies at which the maximum difference occurs is greater for March.

Table 5.5. Maximum Difference between Equal Weight and Probability Array Modeling Options for 6 Months and 12 Months in the Future and the Frequency at Which It Occurs

	September		**March**	
Initial Storage	Maximum Difference	Frequency at which it occurs	Maximum Difference	Frequency at which it occurs
0%	49,656	22%	63,713	39%
10%	46,018	28%	59,286	43%
25%	36,328	32%	45,270	52%
50%	18,037	40%	25,024	68%
75%	6,222	45%	6,751	70%
100%	1,466	39%	439	47%

5.6.2. Flow-Frequency versus Storage-Flow-Frequency

The FF and SFF options were applied to the 108 year condensed dataset for Lakes Granger and Hubbard Creek.

5.6.2.1. Lake Granger

The probabilities predicted using a log-normal distribution with the FF option for a 6 month simulation starting in January are shown in Figure 5.11. The probabilities assigned during an equal weight simulation are included for comparison. Three storage contents are considered in this example: 0% of capacity, 50% of capacity and 100% full.

In the case of the FF option, Figure 5.11 applies to all three since a range of preceding storages to be considered was not specified. Limiting the flow-frequency analysis to sequences that fall within a specified range of preceding storage conditions is addressed below (Figure 5.14). The probabilities assigned using the SFF option for the three initial storage conditions are shown in Figures 5.12 through 5.14.

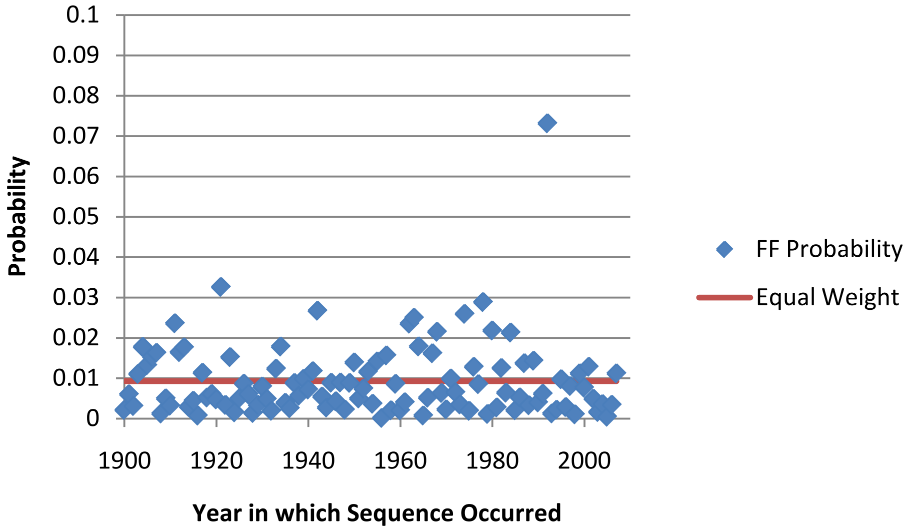

Figure 5.11. Probabilities Predicted Using Log-Normal and the Flow-Frequency (FF) Option

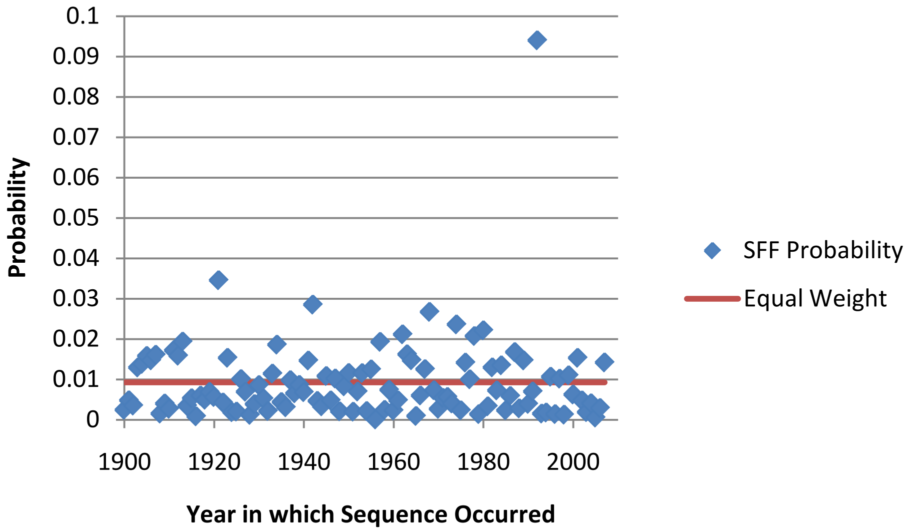

Figure 5.12. Probabilities Predicted Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 100% of Capacity

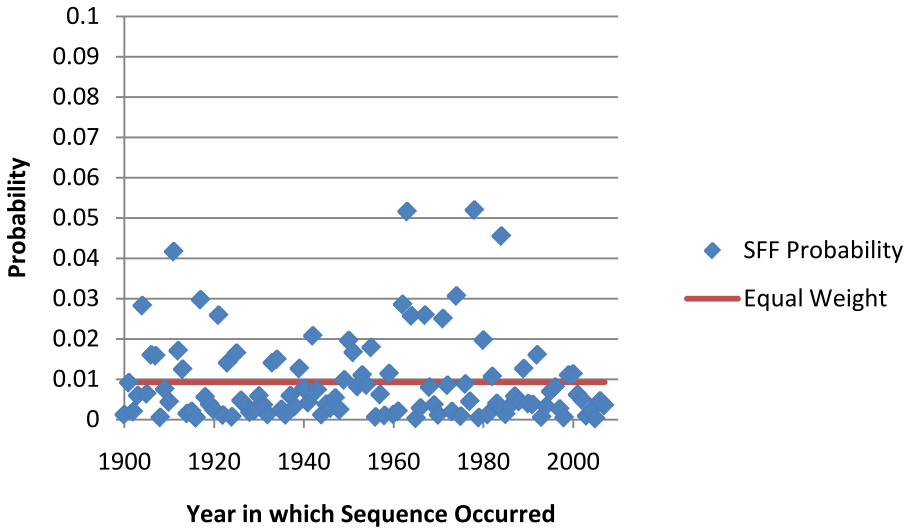

Figure 5.13. Probabilities Predicted Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 50% of Capacity

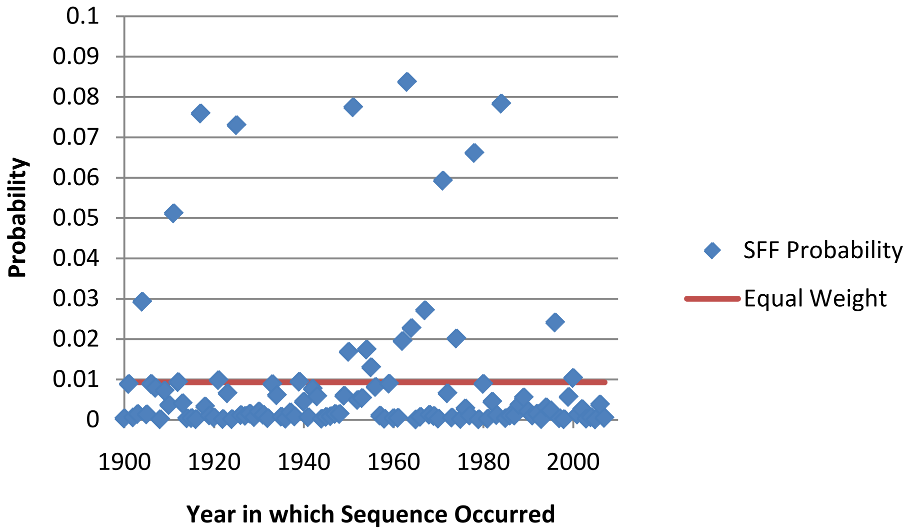

Figure 5.14. Probabilities Predicted Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Zero Initial Storage Contents

The average absolute difference between the FF and SFF options was greatest when the reservoir started empty (difference of 0.0096 between Figures 5.11 and 5.12). This difference was least when the reservoir started full (difference of 0.0016 between Figures 5.11 and 5.14). This could be attributable to the fact that Granger reservoir is more than 75% full 80% of the time and more than 99% full 55% of the time. This relationship does not hold true for a reservoir that is not as full as often. The results of rerunning this analysis for Hubbard Creek are discussed in Section 5.8.2.2.

Preceding reservoir storage can be incorporated into the FF option by considering only those sequences that begin with a preceding storage that falls within a specified range. The analysis for zero initial storage can be improved by only considering those sequences with initial storage content between 0% and 50% of capacity. In the case of Granger reservoir, these conditions are met by 5 of the 108 sequences. The probabilities that result from this analysis are presented in Figure 5.15. The average absolute difference between the two options for the reservoir starting empty drops from 0.0096 to 0.0061. That is, the probabilities using the FF option were closer to the probabilities using the SFF option when the FF analysis was limited to months when storage was below 50% of capacity.

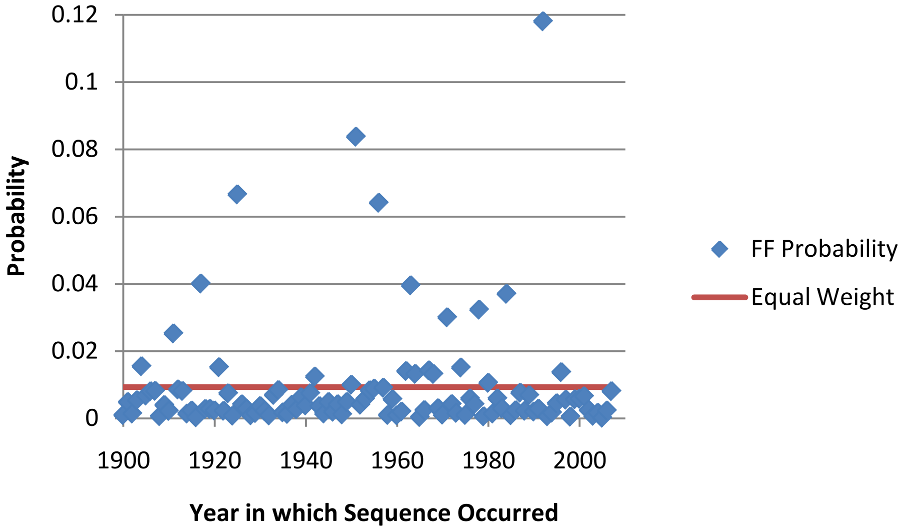

Figure 5.15. Probabilities Predicted Using Log-Normal and the Flow-Frequency (FF) Option Limited to Lower 50% of Storage

5.6.2.2. Hubbard Creek

Hubbard Creek Reservoir is located in the northwestern part of the watershed and has a very different storage frequency curve than Lake Granger. Hubbard Creek Reservoir is more than 75% full only 11% of the time and more than 99% full 1.7% of the time. As in the previous example, the FF and SFF options were applied to the 108 year condensed dataset. The probabilities are predicted using a log-normal distribution and alternatively apply the FF and SFF option for a 6 month simulation starting in January. The three storage contents considered in this example are 0% of capacity, 50% of capacity and 100% full. In the case of the FF option, Figure 5.16 applies to all three since a range of preceding storages to be considered was not specified. The probabilities assigned using the SFF option for the three initial storage conditions are shown in Figures 5.17 through 5.19. The effect of limiting the flow-frequency analysis to sequences that fall within a specified range of preceding storage conditions is also different for Hubbard Creek compared to Granger (Figure 5.20).

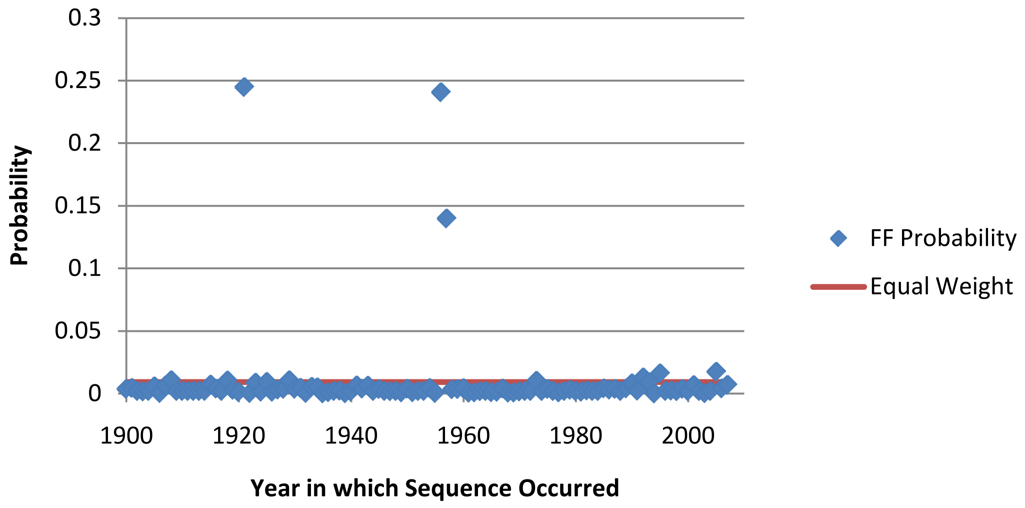

Figure 5.16. Probabilities Predicted for Hubbard Creek Using Log-Normal and the Flow-Frequency (FF) Option

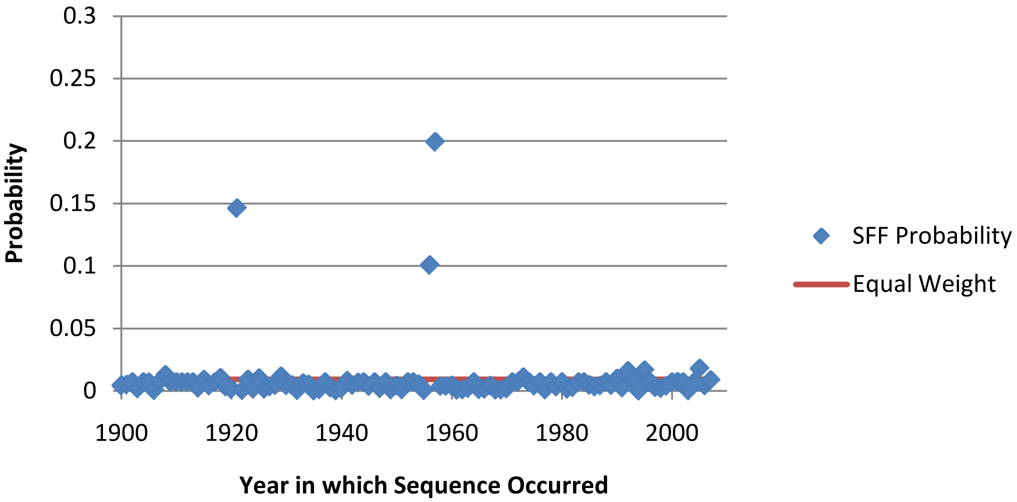

Figure 5.17. Probabilities Predicted for Hubbard Creek Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 100% of Capacity

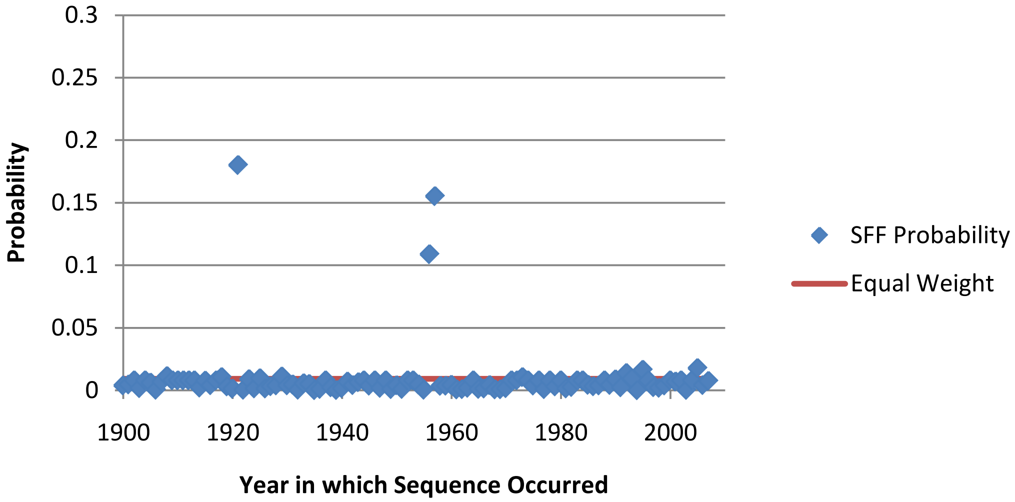

Figure 5.18. Probabilities predicted for Hubbard Creek Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 50% of Capacity

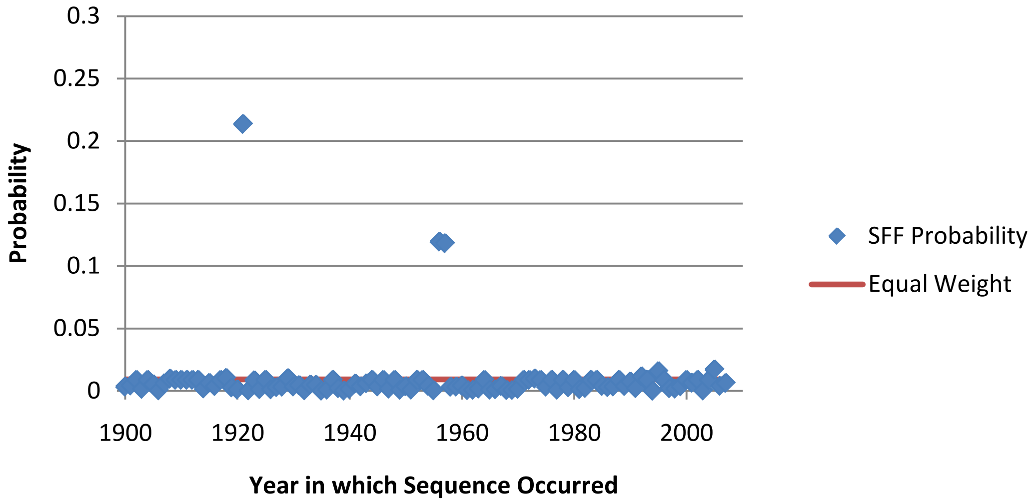

Figure 5.19. Probabilities predicted for Hubbard Creek Using Log-Normal and the Storage-Flow-Frequency (SFF) Option for Zero Initial Storage Contents

The outlier years are 1921, 1956 and 1957. The sum of naturalized flows from January through June, excluding years with zero flow, is lowest for 1921 and 1956. The sum of naturalized flows during these six months is highest in 1957. The log-normal distribution has identified these as the most probable years.

In the case of Hubbard Creek the pattern is the opposite: the average absolute difference between probabilities predicted using the FF and SFF options was greatest when the reservoir started full (difference of 0.0044 between Figures 5.16 and 5.17). This difference was greatest when the reservoir started empty (difference of 0.0035 between Figures 5.16 and 5.19). This could be attributable to the fact that Hubbard Creek reservoir is less than 50% full 77% of the time and 0% full 19% of the time. Comparing the numbers for Lake Granger and Hubbard Creek confirms that the differences between SFF and FF options for assigning probability are reservoir specific.

The largest differences are expected to occur when storage conditions deviate significantly from the norm.

Limiting the FF analysis to when storage is below 50% can significantly affect the results for Granger reservoir because storage is less than 50% full only 5% of the time. Because Hubbard is less than 50% full 80% of the time, the FF analysis will not change the results appreciably. The average absolute difference between the probabilities predicted for Granger reservoir using the FF option and the FF option limited to the bottom 50% of storage is 0.0065. The average absolute difference between the probabilities predicted for Hubbard Creek reservoir using the FF option and the FF option limited to the bottom 50% of storage is 0.0001. The magnitude of these differences indicates that limiting the analysis to the lower 50% of storage has less impact on the results for Hubbard Creek compared to Granger, because Hubbard Creek spends a greater portion of the time less full.

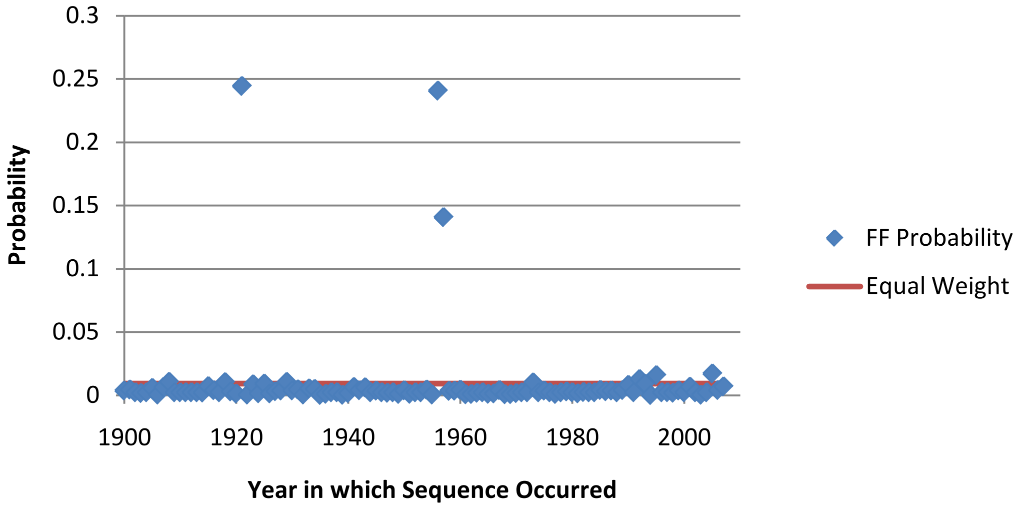

Figure 5.20. Probabilities Predicted for Hubbard Creek Using Log-Normal and the Flow-Frequency (FF) Option Limited to Lower 50% of Storage

The average absolute difference between the FF and SFF options for Lake Granger was greatest when the reservoir started empty. This difference was least when the reservoir started full. This could be attributable to the fact that Granger reservoir is full most of the time. Rerunning this analysis for Hubbard Creek shows that this relationship does not hold true for a reservoir that is not as full as often. Limiting the FF analysis to when storage is below 50% can significantly affect the results for Granger reservoir because storage is less than 50% full only 5% of the time. Because Hubbard is less than 50% full 80% of the time, the FF analysis will not change the results as much.

5.6.3. Log-Normal versus Weibull Formula

The log-normal distribution and the Weibull formula are used to assign exceedance frequencies to streamflows for the FF and SFF options. Simulations are run for different initial storage conditions (0%, 50%, and 100% of capacity) for two reservoirs (Hubbard Creek and Lake Granger) for a six month simulation beginning in January. The results of these runs are compared and contrasted and key differences are discussed.

Figure 5.21 applies the Weibull formula to the FF option, and like Figure 5.11 for the log-normal distribution, it applies to all three storage scenarios (i.e. 0% full, 50% full, and 100% full) since a range of preceding storages to be considered was not specified. Although the values for the Equal Weight option are displayed, the values generated using the Weibull formula are so close (0.0093 and 0.0092, respectively) that they cannot be seen. The two outliers are 1956 and 1992, the driest and wettest years on record, respectively.

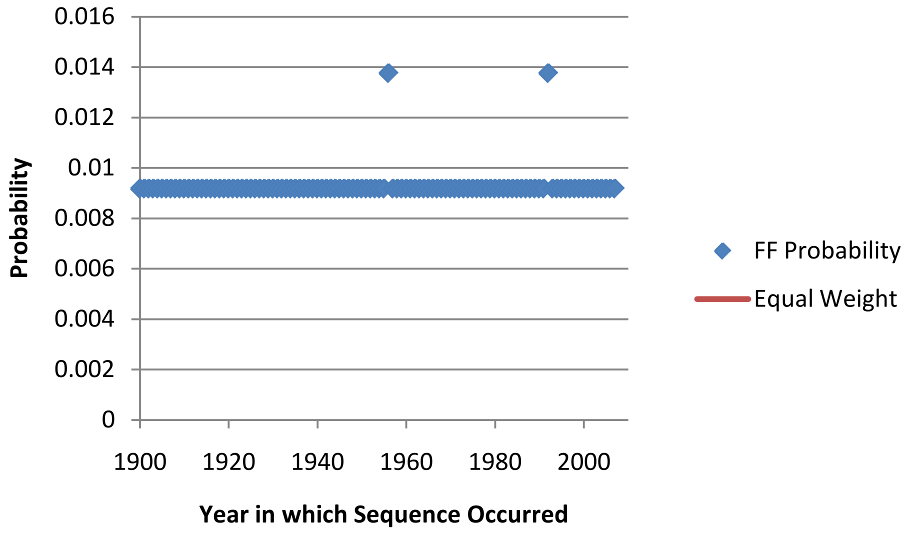

Figure 5.21. Probabilities Predicted Using the Weibull Formula with the Flow-Frequency (FF) Option

The probabilities for the Weibull formula applied to the SFF option for the three storage scenarios (i.e. 0% full, 50% full, and 100% full) are presented in Figures 5.22 through 5.24.

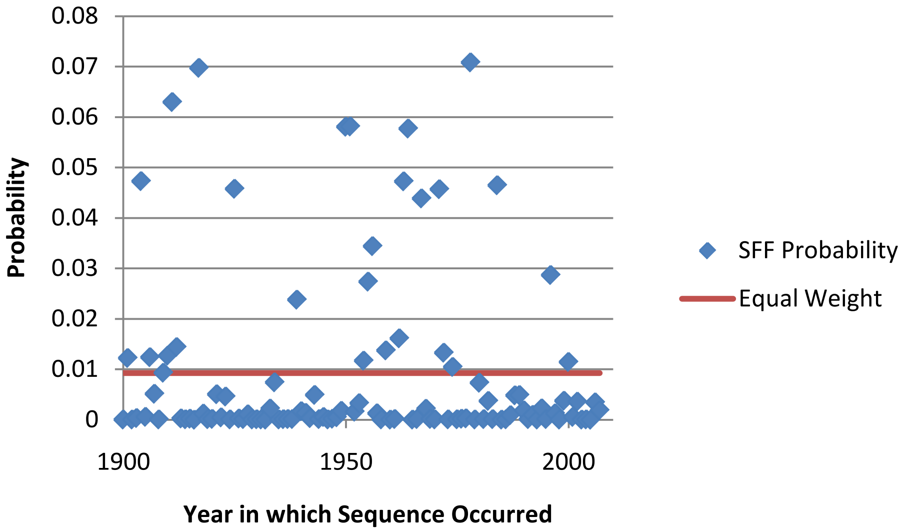

Figure 5.22. Probabilities Predicted Using the Weibull Formula with the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 100% of Capacity

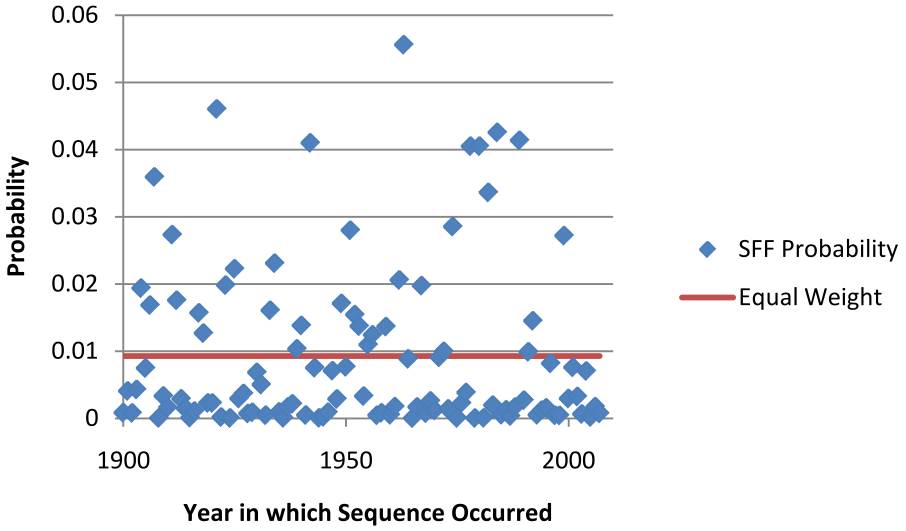

Figure 5.23. Probabilities Predicted Using the Weibull Formula with the Storage-Flow-Frequency (SFF) Option for Initial Storage Contents at 50% of Capacity

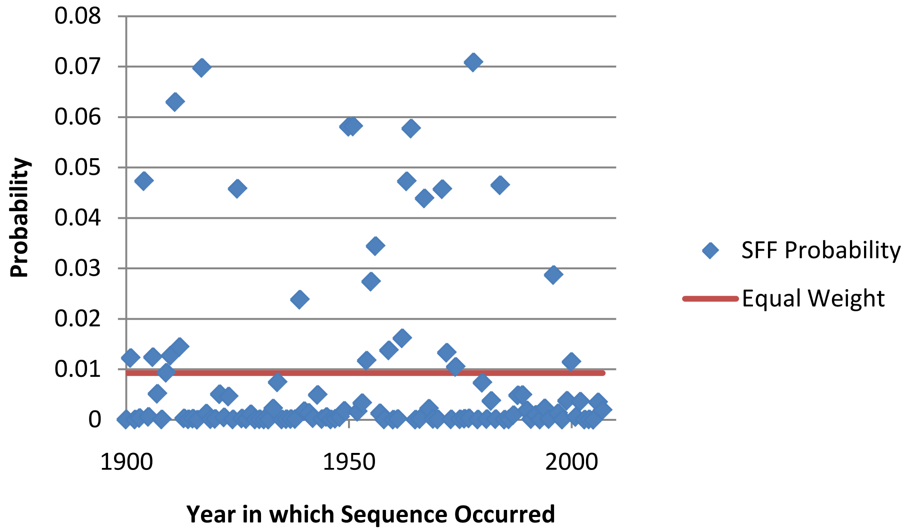

Figure 5.24. Probabilities Predicted Using the Weibull Formula with the Storage-Flow-Frequency (SFF) Option for Zero Initial Storage Contents

As is evident in Figure 5.21, the difference between the FF and Equal Weight option for the Weibull distribution is miniscule. For the Weibull formula, the average absolute difference between the FF and SFF options was greatest when the reservoir started empty (difference of 0.012 between Figures 5.20 and 5.23). This difference was least when the reservoir started full (difference of 0.0049 between Figures 5.21 and 5.22). As mentioned previously, the pattern observed for the difference between FF and SFF options could be reservoir specific.

5.7. Regression Options

The SFF option for assigning probabilities to streamflow sequences is based on exceedance frequencies of the random variable R. R is the ratio of observed flows to predicted flows. Predicted flows are developed by plotting cumulative steam flows against initial storage and fitting the data with a regression line. Four regression equations (i.e. exponential, power, linear, and combined) are used to relate naturalized flows to preceding storage for the SFF option. The parameters for these equations are determined using least squares regression. Two indices of goodness-of-fit are used to assess the strength of the correlations between initial storage and naturalized flows: Linear Correlation Coefficient and Spearman’s Rank Correlation Coefficient. The Coefficient of Determination (R^2) is used to determine how well the regression equations represent the relationship between initial storage and naturalized flows.

The three indices are calculated for the four regression options for various simulation lengths. Cumulative streamflows are affected by the length of simulation, while initial storage is not. Initial storages are recorded at the starting month of the simulations, in this case, January. The analysis is applied to Lake Granger and Hubbard Creek reservoir.

The coefficients of determination presented in Table 5.6 refer to the transformed versions of the regression equations presented in Chapter III (Eq 10 – 13). While none of the relationships are very strong, exponential regression is the best fit of the four. The original and transformed plots for the four regression options are presented in Figures 5.25 – 5.28.

Table 5.6. Coefficients of Determination (R^2) for Four Regression Options for 6 Months Starting in January for Granger Reservoir

	R^2
Exponential	0.0956
Combined	0.0019
Linear	0.0392
Power	0.0057

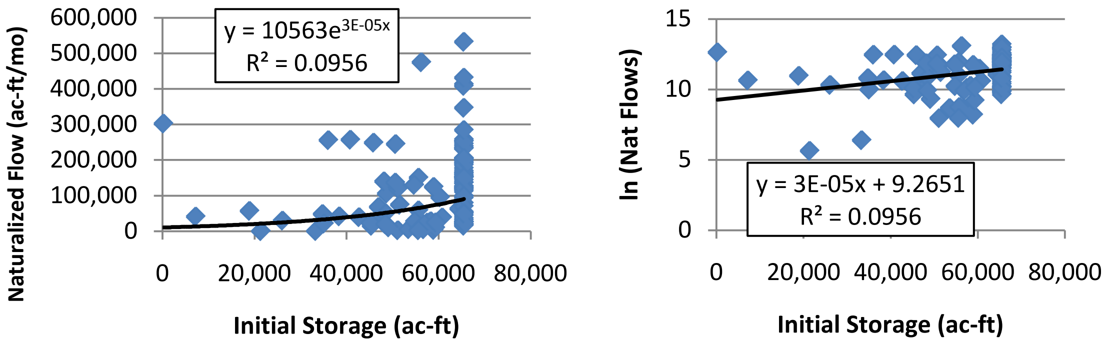

Figure 5.25. Original and Transformed Plots for Exponential Regression

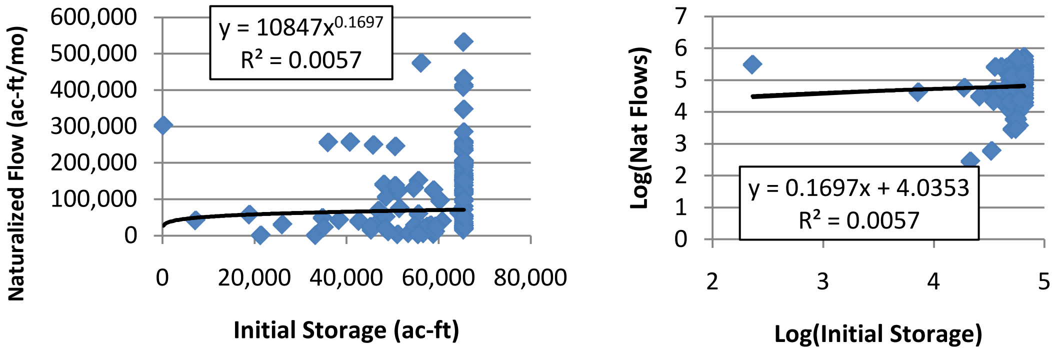

Figure 5.26. Original and Transformed Plots for Power Regression

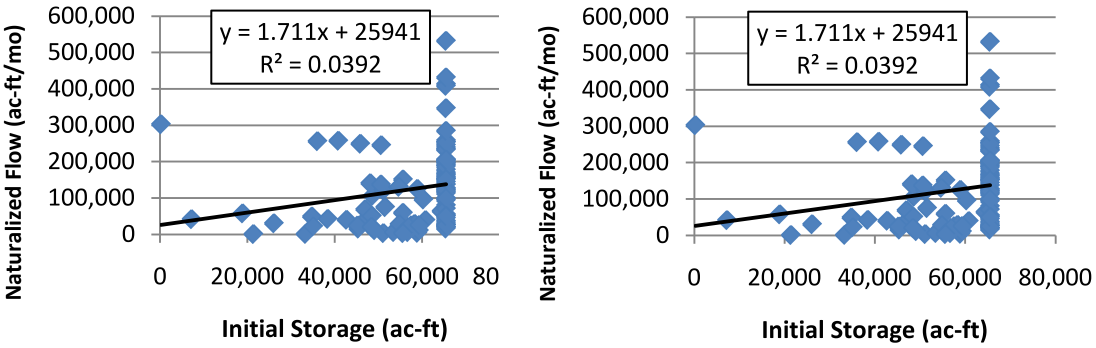

Figure 5.27. Original and Transformed Plots for Linear Regression

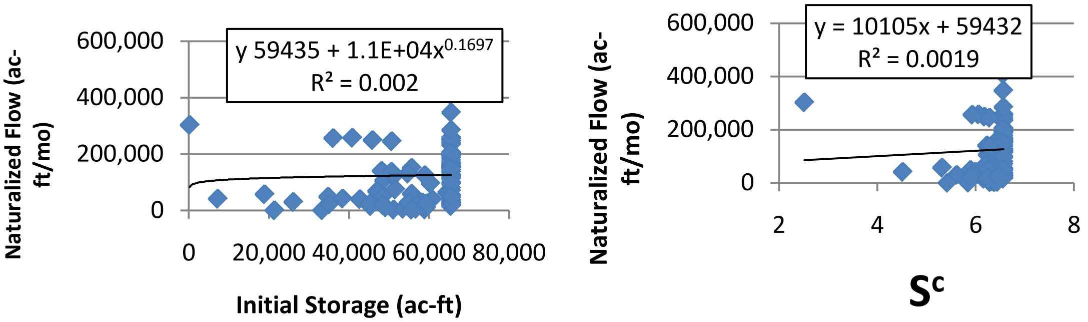

Figure 5.28. Original and Transformed Plots for Combined Regression

The strength of correlation between naturalized flow and initial storage is expected to increase as the simulation length decreases and when the simulation begins in a dry month. For Lake Granger, R^2 is highest for all regression relationships when the simulation length is one month and generally decreases as simulation length increases (Table 5.7). Exponential regression has the best fit for all simulation lengths. R^2 drops significantly in the first 6 months and then slowly approaches zero. After 6 months, a linear regression relationship emerges as the best fit next to exponential regression.

Table 5.7. Coefficients of Determination (R^2) for Four Regression Options Applied to Lake Granger for Different Simulation Lengths Starting in January

	1 Month	3 Months	6 Months	12 Months	24 Months	36 Months
Exponential	0.375	0.253	0.0956	0.0885	0.0353	0.0198
Combined	0.137	0.123	0.0019	0.0009	0.0005	0.0012
Linear	0.106	0.114	0.0392	0.0287	0.01	0.0044
Power	0.221	0.108	0.0057	0.0057	0.0008	0.0005

The strength of correlation between naturalized flow and initial storage is distinct for Hubbard Creek compared to Lake Granger. The coefficients of determination (R^2) for the four regression options were determined for Hubbard Creek for different simulation lengths starting in January (Table 5.8). Power regression is the best fit for a length of simulation period of 1 month, exponential regression is the best fit for 3 months, power regression is the best for 6 months, and the best fit for 12 to 36 months is linear regression followed by combined regression. Unlike Lake Granger, the strength of correlation increases as the simulation length increases.

Table 5.8. Coefficients of Determination (R^2) for Four Regression Options Applied to Hubbard Creek for Different Simulation Lengths Starting in January

	1 Month	3 Months	6 Months	12 Months	24 Months	36 Months
Exponential	0.005	0.008	0.01	0.001	0.019	0.03
Combined	0.003	0.003	0.009	0.011	0.036	0.08
Linear	0.011	0.001	0.012	0.017	0.067	0.099
Power	0.018	0.006	0.024	0.005	0.018	0.026

5.8. Reservoir System Configuration

Operating multiple reservoirs in coordination increases the firm yield relative to the sum of individual reservoirs within the system (Wurbs, 1996). Within WRAP, reservoirs are coordinated as a system by making releases from the fullest reservoir in terms of storage as a percent of capacity. This section determines the effect operating multiple reservoirs as a system has on the correlation between initial storage and naturalized flow compared to individual reservoir operations. For short-term simulations, the correlation between total initial storage at multiple reservoirs and naturalized flows at a common downstream point is expected to increase with reservoir system operations.

Short-term water supply reliabilities and storage frequencies conditioned upon preceding reservoir storage are determined for individual reservoirs and multiple reservoir systems. The analysis of individual reservoirs focuses on Lake Granger and Hubbard Creek Reservoir. A multiple reservoir system considered in this analysis is a diversion at the confluence of the Little River and the San Gabriel River near the Cameron gage supplied by releases from four reservoirs: Lakes Belton, Stillhouse Hollow, Georgetown, and Granger.

Simulations are conducted for a 3 month period starting in January. A best-fit line is determined using exponential regression for the 3-month sum of naturalized flows near the Cameron gage and total initial storages. The total initial storage was changed in successive executions of WRAP to the following combinations: only Georgetown, only Granger, only Belton, only Stillhouse Hollow, Georgetown plus Granger, Belton plus Stillhouse Hollow, and the sum of all four reservoirs.

Table 5.9 shows the values for R^2 for the best-fit lines determined using exponential regression for the seven combinations. R^2 is lowest when only the storage from Georgetown or Granger is considered. R^2 is higher for Belton, Stillhouse Hollow and the combination of these two reservoirs.

Table 5.9. Coefficients of Determination (R^2) for Four Individual Reservoirs and Three Multiple-Reservoir Combinations

	Sum of Storage	Exponential Regression (R2)
1	Georgetown	0.0846
2	Granger	0.0974
3	Belton	0.1522
4	Stillhouse	0.1472
	1 & 2	0.0976
	3 & 4	0.1579
	4 CPs	0.1545

CHAPTER VI

GUIDELINES FOR THE PRACTICAL APPLICATION OF CONDITIONAL RELIABILITY MODELING

This chapter develops guidelines for the practical application of conditional reliability modeling. There are several modeling decisions to consider during application of the model: choice of dataset, control points used to sum flows and initial storages, hydrologic period-of-analysis, starting month, initial storage content, method for generating sequences, simulation length, probability distribution, and regression equation. This chapter offers guidance on choosing the most appropriate modeling options.

6.1. Choice of Dataset

Few decisions impact modeling results as significantly as the choice of dataset. In WRAP, the DAT file contains information on reservoir system configuration, water rights permits, reservoir area-capacity relationships and monthly diversions and return flows. Monthly naturalized flows and net precipitation-evaporation records are in the FLO and EVA files, respectively.

The TCEQ WAM datasets are typically chosen for water availability modeling studies in Texas. For CRM applications, the user may opt to use condensed versions of the full WAM datasets. Condensed datasets are much easier to modify and therefore lend themselves to dynamic CRM modeling studies. For guidance on the development of condensed datasets, see Wurbs and Kim (2008a).

Condensed datasets are limited by their assumptions. For example, it is only possible to make changes to BRA reservoirs using the BRAC3 dataset. The dataset also reflects full authorized use by all secondary water rights, which may be an overly-conservative assumption. On the other hand, updating the full WAM dataset to reflect actual conditions could be very labor-intensive.

The TCEQ maintains two types of datasets for each river basin in Texas: full authorization (Run 3) and current conditions (Run 8). Regional Water Planning datasets for year 2000 and 2060 conditions are developed by consulting firms for each of the 16 planning regions in Texas every 5 years. These runs are variations on Run 3 that are used to evaluate water management strategies. Run 3 is used for legal considerations. The monthly use coefficients (UC records) and annual diversions (WR records) can be used for maximum-*possible*-use modeling scenarios. The monthly diversions from Run 8 can be used for maximum-*likely*-use modeling scenarios. The hydrological sequences contained in the Run 8 FLO and EVA files (stream flows and net evaporation-precipitation, respectively) may be used with Actual Conditions datasets when these files are not available for the latter. Before the Run 8 dataset is used for CRM applications, the storage volume to surface area tables (SV/SA records) and reservoir storage capacities (WS records) should be updated to sediment conditions of the period of interest (typically, present day).

Actual Conditions is the recommended run for CRM applications. With an Actual Conditions dataset, reservoir capacities, monthly diversions, diversions locations, and reservoir system configurations are subject to change. An Actual Conditions dataset can be developed from a Run 8 dataset by making the following modifications:

1. The storage volume to surface area relationships (SV/SA records) should be updated for sediment conditions in the year of interest. Reservoir capacities listed on WS records should be modified accordingly.
2. Monthly use of annual diversions (UC records) can be changed to reflect actual use, projected use, Run 3 (full permitted amounts) or Run8 (maximum used in last 10 years) use coefficients. For the most realistic projections about future reservoir storage contents, actual and projected use coefficients are recommended.
3. Annual diversions (entered in field 3 of WR record) can be actual, projected, a combination of both, Run 3 or Run 8 diversions. For most CRM applications, a summation of actual and projected monthly use will serve as a realistic annual target.
4. The location of a diversion is subject to change (control point entered in field 2 of WR record). For example, the case study presented in the next chapter uses an actual conditions dataset where it was necessary to remove a diversion at the Highbank gage and add one to the Richmond gage.

5. The list of reservoirs that make releases for specific diversions may change. This information is entered in field 2 of successive WS records. The rules for determining which reservoir to release from (OR records) are also subject to change.
6. Initial storages are likely to change. Storages at the beginning of the simulation for all reservoirs are read by WRAP-SIM from a BES file. In the case study presented in the following chapter, a new BES file is required for each of the 4 starting months.
7. Changes to reservoir system configuration may be necessary. For example, the configuration could be modified to include a pipeline connecting two or more reservoirs.
8. Water rights priorities can also be modified or otherwise circumvented. Changes to water rights priorities should be done with caution because priorities in the TCEQ WAM system are lawfully mandated.

The results of a conventional long-term simulation are recorded to an OUT file. The CRM features of WRAP process the OUT file to determine exceedance frequencies for flows (FF option) or flow ratios (SFF option). The choice of how the OUT file is created can affect the assigning of probabilities for the SFF option. This is because the flow ratio depends on the relationship between initial storage and naturalized flow.

There are several options within WRAP for specifying an initial storage condition for long-term simulations. The default assumption is that all reservoirs start full to capacity at the beginning of a simulation. This assumption would result in arbitrarily high storages for sequences at the beginning of the period of hydrology. Option 2 allows user-specified initial storages to be read from a file (BES file). Another option (called Option 5 in WRAP terminology) runs the complete simulation one time, records the end-of-simulation storages, and uses these storages as the initial conditions for a new simulation. For CRM applications, Cycling Option 5 is recommended for creation of the OUT file. Option 5 is preferred over a similar Option 4, because Option 5 does not generate a BES file, which could inadvertently overwrite existing BES files. This is a concern because in a later step, BES files are used by CRM to specify initial conditions.

6.2. Control Points Used to Sum Flows and Initial Storages

The flow at a control point can be correlated to storage at that control point. The model may also be used to relate the flow at a downstream control point to reservoir storage in one or more reservoirs located upstream. This is relevant only for the SFF method of assigning probabilities. Determining which reservoirs influence the flow at a control point of interest is an important issue that requires attention.

The Linear Correlation Coefficient and the Spearman Rank Correlation Coefficient can be used to determine the strength of the relationship between flows at one or more control points and storage at a reservoir or combination of reservoirs. For example, the coefficients can be used to determine if the flow at a point located downstream of two reservoirs is more closely correlated with storage in only one of the reservoirs or the total storage in both.

Correlations between initial storage and naturalized flows tend to be strongest for a single control point, assuming there is storage at the control point. If there is no storage associated with a control point of interest, the correlation coefficients should be used to determine which reservoirs or combination of reservoirs are more highly correlated with flows at that point.

Including more control points in the summation quickly reduces the correlation to an unusable degree. If no clear correlation exists between storage and flow, the SFF option should not be used. The FF or equal weight options should be used instead. Salazar (2002) provides a detailed analysis of reservoir combinations.

6.3. Hydrologic Period-of-Analysis

For CRM applications, a long hydrologic period-of-record is desirable, even if data extension introduces greater modeling uncertainties. Short-term simulations are less sensitive to data extension techniques because the period-of-record is divided into many shorter sequences and each sequence is run by itself. It follows that short-term reliability and frequency estimates are based on the results of many simulations, so each simulation carries less weight. In a long-term simulation, on the other hand, only one long sequence is estimated, so reliabilities and frequencies are more impacted by modeling uncertainties.

The maximum recommended simulation length should consider the length of the hydrological period-of-record in order to ensure sufficient number of hydrologic sequences to perform a meaningful CRM analysis. While there is no minimum number of hydrologic sequences, the more the better. CRM is generally more accurate for shorter simulation lengths. A simulation length equal to the period-of-record is equivalent to a long-term simulation. If the period-of-record is less than 50 years, consider using the monthly cycle to generate more sequences.

6.4. Initial Storage Content

The effect of initial storage content on the assigning of probabilities depends on the storage frequency curve for the individual reservoir. That is, it depends on whether the reservoir tends to be full or empty. Consider a reservoir that is always 10% full. If the initial storage is 10%, then each hydrologic sequence will be equally likely, regardless of the method used to assign probabilities. On the other hand, consider a reservoir that is usually 100% full, but not always. If at the beginning of the simulation, the storage is now at 10%, the probabilities assigned will be very different between methods. The storage frequency curve of the reservoir of interest needs to be studied to determine the influence of the initial storage condition.

The reservoir storage contents of the primary reservoirs can be set to actual storage conditions or any storage condition of interest. The primary reservoirs contain greater than 95% of the storage capacity in the basin. A condensed dataset will contain only primary reservoirs. For the complete WAM, the storage contents of secondary reservoirs can be set to the average percent full of the primary reservoirs. Initial storage conditions are specified in the BES file.

The results presented here apply to Granger reservoir and are generally applicable to reservoirs that tend to be full. If reservoir storage is low, and the simulation length is 6 months or less, the SFF method of assigning probabilities is recommended. If the reservoir storage is low or medium, and the simulation length is between 6 months and 2 years, the FF method with storage intervals is recommended. Beyond 2 years, the unrestricted FF and equal weight methods can be used, as the influence of the initial storage condition on simulation results becomes negligible.

6.5. Choice of Cycling Option

The CRM features of WRAP use two methods for dividing a long period of hydrology into several shorter ones: the monthly cycling option and the annual cycling option. The monthly cycle has up to 12 times more sequences, while the annual cycle preserves seasonality. The choice between the two options is essentially a choice between quantity and quality. The most appropriate cycling option depends on the application.

The time it takes for the influence of starting month to become negligible depends on watershed hydrology. For Lake Granger, the monthly cycling option is recommended for simulations lengths greater than 24 months. It is in the best interest of the user to use as many sequences as possible, because preservation of seasonality is less of an issue. For simulation lengths less than 24 months, the annual cycle is recommended. If the user is interested in average or generalized trends, the monthly cycle can be used for simulation lengths less than 24 months.

6.6. Starting Month

The shorter the length of simulation, the more the starting month influences the computation. With a long enough simulation length, the effect of the starting month becomes negligible. In a drainage area that is wet most of the time, simulations starting in seasonally dry months will differ more from the monthly cycle. The reverse is true for watersheds that tend to be dry.

For modeling studies using the annual cycling option, simulation sequences should start in the month of interest. Alternatively, an appropriate starting month is May, the end of April. April represents a transition from a wet to a dry period. CRM is a practical tool for water management during the dry season.

6.7. Length of Simulation

The SFF option is recommended for use where the correlation between storage and flow permits. Otherwise, the FF option or the equal-weight option should be used. As a general rule, the SFF method for assigning probabilities is applicable to simulation lengths of 6 months or less. However, for certain reservoirs and multiple-reservoir combinations, the recommended length of simulation may be longer or shorter than 6 months.

The Spearman and Linear Correlation Coefficients are calculated by the 5COR record within the CRM features of WRAP. These correlation coefficients should be used to determine the appropriate length of simulation for the SFF option. The higher the correlation, the more accurate the SFF option becomes. The SFF option should not be used for correlations below zero for the Spearman Coefficient and the Linear Coefficient. For Granger reservoir, this occurs around 48 months for a simulation starting in January. The SFF option is recommended for Spearman Coefficients above 0.5. For Granger, this occurs around 5 months for a simulation starting in January. A coefficient above 0.2 is considered strong enough to build the regression relationship. Granger reservoir has a coefficient above 0.2 for simulation lengths up to 19 months for simulations starting in January.

For the purposes of CRM, the user should put more confidence in the Spearman Rank Correlation Coefficient. The Linear Correlation Coefficient (r) assumes that a linear relationship exists between initial storage and naturalized flow, which may not always be the case. The Spearman Correlation assumes that a linear relationship exists between the ranks of the storages and flows, which is more reasonable.

Values for the correlation coefficients change depending on the period-of-analysis, the reservoir or group of reservoirs being analyzed, the cycling option, starting month, and length of simulation.

When the SFF option is unusable, the FF option or the equal-weight option should be used. If the simulation length is between 6 months and 24 months, the FF option is recommended for use with storage intervals. The storage intervals restrict the assigning of probabilities to those hydrologic sequences that occurred while the reservoir storage contents (or sum of reservoir storage contents for multiple reservoir systems) were within the specified interval.

Setting storage intervals for the FF and SFF options can greatly improve a CRM analysis, but may require knowledge of reservoir storage patterns. For Granger, eliminating all of the sequences that occurred while the reservoir was full may be sufficient. For others, like Hubbard, it may be appropriate to eliminate the top 15% and bottom 15%, and only consider the middle 70%.

6.8. Probability Distribution

Several tests for goodness-of-fit can be used to determine the best distribution including Chi Squared, Kolmogorov Smirnov, and Anderson Darling. The goodness-of-fit tests can be facilitated by distribution fitting software like EasyFit (Mathwave website included in references). EasyFit ranks numerous probability distributions according to the results of these tests. Within WRAP, the user has a choice between the log-normal distribution and the Weibull formula. One of these distributions will be identified by EasyFit as the best-fitting. In the case of Granger, the log-normal distribution tends to fit the best.

The FF option used in combination with the Weibull formula is essentially equivalent to the equal-weight option.

6.9. Regression Equation

The choice of regression equation is only relevant for the SFF method of assigning probabilities to hydrologic sequences. Within WRAP, the user has a choice between Linear, Power, Combined and Exponential Regression.

The Coefficient of Determination (R^2) should be used to determine the regression equation that best describes the relationship between initial storage and naturalized flows for each simulation. The regression equation with the highest value for R^2 is recommended. For Granger reservoir, exponential regression tends to fit the data the best. This is not true for all reservoirs.

The equation with the highest R^2 can change depending on the period-of-analysis, the reservoir or group of reservoirs being analyzed, the cycling option, starting month, and length of simulation.

CHAPTER VII

CONDITIONAL RELIABILITY OF THE BRAZOS RIVER AUTHORITY SYSTEM DURING THE DROUGHT OF 2009

The conditional reliability modeling (CRM) features of the Water Rights Analysis Package (WRAP) are used in this chapter to characterize the behavior of the Brazos River Authority (BRA) reservoir system in a repeat of the drought of 2009. The modeling options chosen for this study are shown in Table 7.1. The options in Table 7.1 are discussed in the following paragraphs. For information about other modeling options in the CRM features of WRAP, please refer to Chapters II, V, and VI, or consult the Supplemental Manual (Wurbs et al., 2009).

Table 7.1. Modeling Options Used in Case Study

MODELING OPTION	CHOICE FOR THIS STUDY
Dataset	BRAC2009 dataset
Simulation Length	3 months
Method of Developing Hydrological Sequences	Annual cycle starting alternatively in the beginning of May, June, July, and August
Initial Storage Conditions	Actual BOM reservoir storage conditions for May, June, July, and August, 2009
Random Variable	Flow ratio
Probability Distribution	Log-normal
Regression Equation	Exponential

Would the drought of 2009 be managed differently if the decision support capabilities of CRM were available to the river basin managers? This question is answered by presenting river basin managers from the Brazos River Authority (BRA) with short-term reliability and storage frequencies estimates conditioned upon preceding reservoir storage. Short-term reservoir storage frequencies are developed conditioned upon the storage contents at the beginning of each month of the drought.

7.1. Conditional Reliability Modeling Choices

CRM divides a long period of historical hydrology into several shorter sequences and simulates storage contents of reservoirs if each sequence were to recur. For the purposes of this study, each sequence is three months long. Probabilities of occurrence can be assigned to each sequence. In general, the correlation between initial storage and naturalized flows is stronger for shorter simulation lengths. Simulation lengths of 6 months or less improve the accuracy of the Storage-Flow-Frequency (SFF) method of assigning probabilities to stream flow sequences. It may be worthwhile to investigate longer simulation lengths. With simulation lengths of 6 months to 3 years, the Flow-Frequency (FF) and Equal-Weight methods can be more effective.

Within WRAP, there are two options for dividing hydrology into several shorter sequences: the monthly cycle and the annual cycle. The annual cycle creates one sequence per year, and each sequence begins in the same month every year. In this way, seasonality is preserved. The annual cycle is preferable in this study because of the dry nature of summer months. This study starts the annual cycle alternatively in the beginning of May, June, July, and August.

When a simulation length of three months is used, the SFF method can be used to build the probability array. In this study, the log-normal cumulative distribution function is used to assign exceedance frequencies to the random variable R, also known as the flow ratio (Equation 4, reproduced from Chapter III).

$$R = Q / Qp \tag{4}$$

where Q is the sum of naturalized flows over the simulation length (i.e. 3 months), and Qp is the predicted flow. Qp is calculated using least-squares exponential regression (Equation 6) to fit a line through a plot of initial storage (S) versus Q.

$$Qp = a * \exp(S/b) \tag{6}$$

where a and b are coefficients determined using least-squares linear regression on Equation 10. In this study, S is the reservoir storage volume at the beginning of May, June, July, and August, respectively.

$$Ln(Qp) = 1/b * S + Ln(a) \tag{10}$$

The probability array is based on the initial storage and sum of naturalized flows at individual reservoirs. The correlations between total flows and initial storage are generally strongest when the summations are performed for a single reservoir as opposed to summing the initial storages of multiple reservoirs and the flows at a common downstream point.

The OUT file created by WRAP-SIM is used to determine exceedance frequencies for the flow ratio. Because the flow ratio depends on the relationship between initial storage and naturalized flow, cycling option 5 on the JO record is used to specify an initial condition for the long-term simulation.

7.2. The BRAC2009 Dataset

The BRAC2009 dataset uses the BRAC8 naturalized flows (FLO file) and net evaporation (EVA files) with a period of hydrology from 1900-2007 (Wurbs and Kim, 2008b). The BRAC2008 DAT file used in the Salinity Manual (Wurbs and Lee, 2009) was modified for year 2010's estimated sediment conditions, and a combination of actual and projected use for January through December 2009. A copy of the DAT file used in this study is included in Appendix A.

The BRA provided actual monthly diversions in 2009 by water use type (i.e. municipal, industrial, mining, and irrigation) for January through September, elevation-area-capacity tables for 2010 sediment conditions, and beginning-of-month lake levels for May through September 2009 for the following 11 Reservoirs:

1) Lake Possum Kingdom
2) Lake Granbury
3) Lake Whitney
4) Lake Aquilla
5) Lake Proctor

6) Lake Belton
7) Lake Stillhouse Hollow
8) Lake Georgetown
9) Lake Granger
10) Lake Somerville
11) Lake Limestone

Data on monthly diversions was used to populate the Use Coefficients (UC records) in WRAP. The use coefficients are the percentage of the annual diversion target that is consumed each month. Different types of water users have distinct use patterns. The use coefficients used to build the BRAC2009 dataset are unique to each type of use (i.e. municipal, industrial, mining, and irrigation) at each control point. The use coefficients in the BRAC2009 dataset are the actual use from January 2009 to September 2009.

Elevation-area-capacity tables are used to develop Storage Volume to Surface Area relationships (SV/SA records). The tables are also used to determine the volume at conservation storage elevation (WS record). Reservoir storage conditions are typically reported as lake level elevations. Although there are features for handling elevation-area-capacity data, WRAP computations typically rely on area-capacity relationships. These tables are used to convert raw data (reservoir elevations) into WRAP input (BES and BRS files) and convert WRAP output into reservoir elevations.

Several pieces of information are still needed to build the BRAC2009 dataset. The effect of Lakes Hubbard, Squaw Creek, and Waco on the eleven BRA reservoirs needs to be addressed, use coefficients need to be estimated for October through December, and the dataset must reflect the multiple owners of Lakes Whitney and Waco.

Lakes Hubbard, Squaw Creek, and Waco are included in the BRAC family of datasets. For these lakes, reservoir elevations were taken from the U.S. Geological Survey (USGS) website, Elevation-Area-Capacity tables for the most recent volumetric survey were obtained from the TWDB website, and monthly use coefficients and annual diversions were assumed to be the same as those reported to the TWDB in 2008.

The projected use coefficients for October through December are based on two factors: average monthly use coefficients from 1998 to 2008, and total actual use from January 2009 to September 2009. The use coefficients for October-December are calculated for each water use type at each reservoir in four steps.

1) The historical use data reported to the TWDB is used to determine the average fraction of the annual total that is used before October 1st. That is, the percent used by the end of September averaged over the past 10 years (2002 is excluded due to lack of data). For example, if the water was used uniformly throughout the year, 75% of the annual total would be used before October 1st.

2) The projected total annual diversion (January-December) is obtained by dividing the known total diversion from January-September by the fraction calculated in Step 1. In the example, if we assume that the known amount at the end of September is 900. Then the projected total is 900/0.75 = 1200.

3) The total amount of water diverted from October-December is estimated as the projected total from Step 2 minus the known total at the end of September. For example, 1200 - 900 = 300.

4) The 3 month total from Step 3 is divided among each month (October, November, and December) according to average use during those months. For example, if water was used uniformly throughout the year, 8.3% of the annual total would be used during each month. The total percentage used during the last three months is 25%. That means, on average, 33% (8.3/25) of the amount calculated in Step 3 is used in October. For example, 300 * (8.3/25) = 100.

The technique for generating monthly use coefficients outlined above is broadly applicable to other CRM applications. For example, the BRAC2009 dataset with projected use coefficients for October - December could be used to run a CRM analysis starting October 1st. By November, the actual use coefficients for October can be updated, and the technique outlined above can be used to generate new projected use coefficients for November and December.

Lake Whitney was modeled using the SV/SA record for the entire reservoir (549,579 ac-ft). The storage capacity for BRA diversions (WS record) is limited to 233,079 ac-ft. Use coefficients for the annual diversion are for the BRA water right. Lake Waco was modeled in a similar way. The SV/SA records are based on 2010 conditions for Lake Waco, and the storage capacity for BRA diversions is limited to 65,000 ac-ft.

Another minor adjustment made to the BRAC2008.DAT file includes removing a diversion at the Highbank gage and adding one at the Richmond gage.

7.3. CRM Analysis of 2009 Drought

The beginning-of-month lake levels for the 14 reservoirs are shown in Table 7.2. The volumes shown in Table 7.3 were linearly interpolated from the elevation-area-capacity tables mentioned previously.

The beginning-of-month storage volumes shown in Table 7.3 were used to populate the BES file. The BES file tells WRAP-SIM the initial storage contents in each of the reservoirs at the beginning of the simulation. Four 3-month long simulations are run, so four BES files were used in this study - one for each starting month: May, June, July, and August.

A BRS file is generated that contains the initial storages from the BES file. The post-processing program TABLES, reads the initial storage for the reservoir being analyzed from the BRS file. Initial reservoir storage is used to calculate the random variable R.

Table 7.2. Beginning-of-Month Reservoir Elevations (ft msl) in the Brazos River Basin During the Summer of 2009

Reservoir	Elevation Conservation Pool	Elevation May 1, 2009	Elevation June 1, 2009	Elevation July 1, 2009	Elevation Aug. 1, 2009
Lake Possum Kingdom	1000	995.95	995.85	996.25	996.1
Lake Granbury	693	691.3	691.05	690.6	690.05
Lake Whitney	533	523.6	523.95	523.35	521.1
Lake Aquilla	537.5	538.6	537.45	536.45	535.7
Lake Proctor	1162	1,156.6	1,156.10	1,156.7	1,155.75
Lake Belton	594	593.55	593.50	591.2	588.35
Lake Stillhouse Hollow	622	620.45	620.45	620.15	619.25
Lake Georgetown	791	774.7	774.95	773.55	770.65
Lake Granger	504	501.45	502.05	501.3	500.45
Lake Somerville	238	237.4	236.95	235.4	234.7
Lake Limestone	363	363.0	362.75	361.8	360.85
Lake Hubbard	1,183	1,177.6	1,177.28	1,176.9	1,176.47
Lake Squaw Creek	775	775.3	775.37	775.3	775.45
Lake Waco	462	462.4	462.54	461.7	460.75

Table 7.3. Beginning-of-Month Reservoir Storage Volumes (ac-ft) in the Brazos River Basin during the Summer of 2009

Reservoir	Volume Conservation Pool	Volume May 1, 2009	Volume June 1, 2009	Volume July 1, 2009	Volume Aug. 1, 2009
Lake Possum Kingdom	526,970	462,434	460,917	467,070	464,744
Lake Granbury	123,943	111,248	109,444	106,369	102,637
Lake Whitney	549,579	370,600	376,139	366,644	332,421
Lake Aquilla	44,295	>44,295	44,143	41,157	38,989
Lake Proctor	54,649	33,157	31,522	33,484	30,495
Lake Belton	432,408	427,000	426,400	399,257	367,106
Lake Stillhouse Hollow	226,730	216,903	216,903	215,029	209,502
Lake Georgetown	36,868	19,373	19,588	18,397	16,072
Lake Granger	50,331	40,615	42,745	40,085	37,209
Lake Somerville	144,619	137,948	132,977	117,069	110,284
Lake Limestone	202,952	202,952	199,910	188,434	177,329
Lake Hubbard	324,983	249,349	245,881	240,796	235,653
Lake Squaw Creek	151,273	151,273	151,273	151,273	151,273
Lake Waco	271,638	271,638	271,638	271,638	271,638

A CRM analysis for ten BRA reservoirs is presented for the months of May, June, July, and August (Appendix B). The strategy used to model Lake Whitney excludes this reservoir from the analysis.

In the legend of the graphs in Appendix B, “MHW” stands for Most Heavily Weighted hydrological sequence, as identified by the SFF array. “BFS” stands for Best Fit Sequence as determined using the Mean Absolute Relative Error (MARE) performance statistic described below. The storage trace labeled “Min” refers to the 3-month sequence with the lowest total storage. “Max” refers to the 3-month sequence with the greatest total storage. The sequences identified as Min, Max, MHW, and BFS are the only complete 3-month sequences graphed (4 of 108).

The mean absolute relative error (MARE) is calculated using Eq. 21.

$$MARE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|S_i^o - S_i^s\right|}{S_i^o} \qquad (21)$$

where n is the number of months (in this case, 3), and S_i is the storage at time i, S^o is the actual storage, S^s is the storage simulated by the model and $S^o{}_{avg}$ is the average actual storage. MARE is a non-negative metric with no upper bound. In this study, the MARE is used to describe the error between the observed reservoir storage and the storage simulated with CRM. A value of zero for MARE would mean there is no difference between the output of WRAP and the observed lake levels. Because the metric uses the absolute difference between simulated and observed values, it is not as sensitive to large errors as the difference squared. However, it is still subject to fouling by small numbers (Dawson et al., 2007).

The other three lines (i.e. 25%, 50%, and 75%) on the Appendix B graphs refer to the exceedance frequencies. For example, “75%” means that 75 percent of the 108 predicted storages are greater than or equal to the number shown in the graph. The actual levels have been added for the purposes of comparison.

The tables in Appendix B show end-of-month storages and the exceedance frequencies associated with them. Each table contains four sets of storage frequency relationships. The first set shows actual 2009 end-of-month storages and their respective exceedance frequencies predicted using the SFF method.

The second set of storage-frequency relationships shows simulated storage as a percent of actual storage for the sequences identified as Min, Max, MHW, and BFS. During the CRM computations taking place in WRAP-SIM, sequences of naturalized flow are run through the model individually, regardless of the initial storages conditions that were present at the time the flows occurred. For this reason, it is possible that the 3-month sequence of hydrology occurring in 1980 results in lower total storage than the 3-month sequence from 1956, even though storage was lower in 1956. The post-processor TABLES assigns weights to the hydrologic sequences according to the initial storages that were present at the time the flows occurred. For these reasons, the hydrologic sequences identified as Min, Max, MHW, and BFS are subject to change with each starting month.

The third set of relationships shows exceedance frequencies for a full reservoir and the three drought stage triggers. The fourth set shows the storages associated with specific exceedance frequencies. The sequences in bold in the tables of Appendix B are graphed in the figures.

The initial storage condition for simulations starting in May (end-of-April) is the actual storage on May 1st, 2009. The initial storage condition for simulations starting in June is the actual storage at the end of May, and so on through August. Table B-1, for example, shows results for Possum Kingdom for a simulation starting in May. The actual storage contents at the end of May are shown in the first table. This value is used as the initial storage condition for the simulation starting in June.

An exceedance frequency is the percent of time a given value is equaled or exceeded. If storage frequencies are low (e.g. 0% - 20%), reservoir storage contents are unusually high (e.g. equaled or exceeded only 0% - 20% of the time). This could be a result of a wet period of hydrology. If storage frequencies are high (e.g. 80% - 100%), reservoir storage contents are unusually low. This could be a result of dry hydrology or heavy use.

The frequencies associated with the three drought stage triggers for each reservoir are shown in the tables of Appendix B. The drought stage triggers come from the BRA Drought Contingency Plan (Gooch and Albright, 2005) and are shown in Table 7.4. The reservoir capacities shown in Table 7.4 are the estimated 2010 capacities from the BRAC2009 dataset.

Table 7.4. Drought Stage Triggers

Reservoir	Conservation Storage	Stage 1 - Drought Watch	Stage 2 - Drought Warning	Stage 3 - Drought Emergency
Possum Kingdom	526,970	396,497	320,000	250,000
Granbury	123,943	103,239	88,232	52,872
Whitney	585,782	525,864	489,038	432,758
Aquilla	44,295	33,797	28,155	17,878
Proctor	54,649	32,955	22,525	13,187
Belton	432,408	320,099	217,388	114,737
Stillhouse Hollow	226,730	161,530	91,417	42,276
Georgetown	36,868	26,221	20,740	14,106
Granger	50,331	39,183	30,035	22,959
Somerville	144,619	110,010	83,769	66,164
Limestone	202,952	143,689	107,248	62,941

According to the tables presented in Appendix B, the following four reservoirs have no chance of triggering drought watch status: Possum Kingdom, Belton, Stillhouse and Limestone. The other six reservoirs have at least some chance of triggering one of the drought stages during the summer of 2009.

In the graphs in Appendix B, it is possible to see that three reservoirs have storages during one month or more that are not achievable considering only historical hydrology. These reservoirs are Belton, Somerville and Limestone. In other words, the streamflows at these reservoirs during these months were lower than the lowest on record. The monthly cycling option for organizing streamflow sequences may capture drier sequences of hydrology.

Table 7.5 shows exceedance frequencies predicted for July 2009 actual storages for different starting months. The simulation that starts in May is forecasting storage contents 3 months in the future. The simulation that starts in June forecasts storage contents through August. The values reported in Table 7.5 are frequencies predicted for the second month, July. The frequencies predicted for a 3-month simulation starting in July are shown for the end of the first month. This progression is repeated for exceedance frequencies predicted for August and simulations starting in June, July and August, respectively (Table 7.6). In Table 7.5, four reservoirs converge toward median storage (50%) by the end of July: Possum Kingdom, Granbury, Somerville, and Limestone. In Table 7.6, three reservoirs converge toward median storage by the end of August: Belton, Granger, and Somerville.

Table 7.5. Exceedance Frequencies Predicted for July 2009 Actual Storages

	Starting Month		
Reservoir	**May**	**June**	**July**
Possum Kingdom	92	82	74
Granbury	84	71	51
Aquilla	83	76	85
Proctor	64	24	64
Belton	98	95	100
Stillhouse Hollow	82	53	29
Georgetown	39	26	15
Granger	56	100	97
Somerville	100	100	98
Limestone	96	95	78

Table 7.6. Exceedance Frequencies Predicted for August 2009 Actual Storages

	Starting Month		
Reservoir	**June**	**July**	**Aug**
Possum Kingdom	87	72	99
Granbury	74	47	44
Aquilla	70	94	100
Proctor	28	73	99
Belton	100	100	100
Stillhouse Hollow	42	29	56
Georgetown	22	15	5
Granger	100	98	18
Somerville	100	98	81
Limestone	100	100	100

The frequencies predicted for drought stage trigger 1 are presented in Tables 7.7 through 7.10 for May through August, respectively. Table 7.7 shows the frequencies forecasted for the next three months, as if it were the beginning of May. The months that the reservoirs were actually in Stage 1 drought are shown for purposes of comparison. Lake Georgetown was in Stage 2 drought conditions from May through July and entered Stage 3 drought emergency in August. By the end of September, the lake recovered from emergency conditions. No other reservoirs entered Stage 2 drought.

For Lake Granbury, considerable differences exist (~24%) between the frequencies predicted for simulations starting in June and July (Tables 7.8 and 7.9). The SFF array responds to the storage level being in the rarest 25% during a dry month, which lowers the chances of achieving higher storage levels in the future. For Granbury simulations starting in May, there is a 16% chance of passing drought stage trigger 1 by the end of July. By June 1st, there is a 29% chance of triggering the first stage of drought by the end of July and a 35% chance by the end of August.

Table 7.7. Chances of Entering Drought Stage 1 within the Next 3 Months as of May 1st, 2009

		Starting Month of May		
Month Actually Triggered	Reservoir	May	June	July
Never	Possum Kingdom	0	0	0
July-Aug	Granbury	0	4	16
Never	Aquilla	0	3	8
July-Sept	Proctor	29	33	41
Never	Belton	0	0	0
Never	Stillhouse Hollow	0	0	0
May-Sept	Georgetown	82	74	77
July-Aug	Granger	4	41	67
Aug	Somerville	0	0	0
Never	Limestone	0	0	0

Table 7.8. Chances of Entering Drought Stage 1 within the Next 3 Months as of June 1st, 2009

		Starting Month of June		
Month Actually Triggered	Reservoir	June	July	Aug
Never	Possum Kingdom	0	0	0
July-Aug	Granbury	9	29	35
Never	Aquilla	6	16	26
July-Sept	Proctor	80	81	83
Never	Belton	0	0	0
Never	Stillhouse Hollow	0	0	0
May-Sept	Georgetown	88	88	90
July-Aug	Granger	0	50	82
Aug	Somerville	0	0	0
Never	Limestone	0	0	0

Table 7.9. Chances of Entering Drought Stage 1 within the Next 3 Months as of July 1st, 2009

		Starting Month of July		
Month Actually Trigge red	**Reservoir**	**July**	**Aug**	**Sept**
Never	Possum Kingdom	0	0	0
July-Aug	Granbury	52	58	49
Never	Aquilla	2	4	3
July-Sept	Proctor	95	93	91
Never	Belton	0	0	0
Never	Stillhouse Hollow	0	0	0
May-Sept	Georgetown	94	95	94
July-Aug	Granger	81	88	85
Aug	Somerville	2	95	95
Never	Limestone	0	0	0

Table 7.10. Chances of Entering Drought Stage 1 within the Next 3 Months as of August 1st, 2009

		Starting Month of August		
Month Actually Trigge red	**Reservoir**	**Aug**	**Sept**	**Oct**
Never	Possum Kingdom	0	0	0
July-Aug	Granbury	79	62	42
Never	Aquilla	0	0	0
July-Sept	Proctor	93	91	87
Never	Belton	0	0	0
Never	Stillhouse Hollow	0	0	0
May-Sept	Georgetown	97	95	92
July-Aug	Granger	89	83	74
Aug	Somerville	94	91	87
Never	Limestone	0	0	0

For Lake Aquilla, starting in July and looking out three months, the actual storages in September are exceeded only 9% of the time (Table B-11). This is an unusually high storage, possibly caused by a wet period of hydrology. By August 1st, the actual storage at the end of August was exceeded in 999,600 of the one million sequences used in the probability array (Table B-12). Based on the SFF methods, the extremely low storage made the relatively high September storage even less likely.

Simulations starting May 1st for Lake Proctor forecasted a 41% chance of entering drought stage 1 by the end of July. For water managers, this is cause for alarm. Because the storage by the end of May was in the 25th percentile of low flows (less than 75% of simulated storages), by June 1st the chances of being in stage 1 by the end of July increased to 81%. At this point, water managers can be fairly certain that without a significant rain event they will be in drought watch conditions within 2 months. Proctor entered Stage 1 Drought Watch in July. The persistence of low storages kept the chances of emerging from stage 1 to below 10% through the end of September, which is consistent with actual storages (Tables B-15 and B-16).

The unprecedented low flows at Belton resulted in 100% of simulated storage levels being higher than the actual storage levels several months in a row (Tables B-18 through B-20). It is interesting to note that for a simulation starting in July, the sequences with the minimum total storage, the most heavily weighted sequence, and the best fitting sequence are all the same, 1980 (Table B-19 and Figure B-19).

The modeling of Georgetown, and to a lesser extent Stillhouse, could have been improved by connecting the two reservoirs via pipeline in WRAP. The Williamson

County Raw Water Pipeline now allows these lakes to be operated as a system. For this reason, the specter of drought is not as formidable as it would be otherwise. As of May 1st, 2009 there was a 50% chance of being in Stage 3 Drought Emergency by the end of July (Table B-25). This gives managers a 3 month head start to prepare short-term water management strategies like voluntary conservation and even curtailments. By June 1st, new estimates predicted a 65% chance of drought emergency by the end of July and 80% chance by August. Lake Georgetown entered Stage 3 drought emergency in August, 2009.

For Granger reservoir, there are large differences in exceedance frequencies for actual storages between simulations starting in May and June (Tables B-29 and B-30). This means that when Granger is 80% full (40,615 ac-ft, not shown) on May 1st, there is a 20% chance that the actual storage at the end of the month is greater than 42,745 ac-ft (Table B-29), and an 80% chance that it is lower. So when the reservoir is 85% full at the beginning of June, there is a 99.7% chance that storage is greater than 40,085 ac-ft (Table B-30). Note that the most heavily weighted sequence is the same as the best fit sequence for simulations starting in June (Table B-30). At the beginning of May, there is a 67% chance of entering drought stage 1 within 3 months (Table 7.7). By the next month, the chance of entering drought within the next three months increases to 82% due to the relatively low storages at the beginning of June. Granger entered stage 1 drought in July. In July, the chance of emerging from stage 1 drought by the September was less than 15%.

Somerville shows similar results to Belton, in that unprecedented low flows result in 100% exceedance frequencies associated with the actual storages (Table B-33 and B-34). Consecutive months of extreme (“off-the-charts”) low flows impair the dependability of storage frequency forecasts using the SFF method. For this reason, there is a 0% chance of entering drought watch by the end of August for simulations starting in June, and a 95% chance for simulations starting in July (Tables 7.8 and 7.9). Somerville effectively entered stage 1 drought by the end of July. The severity of this situation may have caught water managers by surprise with less than one month to prepare. Reliance on historical hydrology can have undesired consequences in forecasting short-term storage frequencies for drought management. The SFF recovered when inflows to Belton returned to the historical range.

While one extremely dry or heavy-use month might shift the storage frequency out of the realm of possibility according to the historical analysis, the subsequent hydrology may be well represented by the historical record. There is no reason to suspect future predictions will be less accurate simply because previous ones were. This can be seen in the case of Limestone (Tables B-38 and B-39). In the case of Somerville, consecutive months were out of the realm of possibility, which is a concern.

A review of the actual lake levels shows that the model accurately captures the behavior of many reservoirs during the drought of 2009 up to 3 months in advance (the maximum period analyzed). The storage conditions of the drought of 2009 tend to be in the rarest 25%, oftentimes dropping to the rarest 1%.

Discrepancies between simulated and observed storage levels could be related to the reliance on historical data and the assumption in WRAP that the historical hydrology captures the complete range of possible events. Some of these issues can be addressed by building frequency tables (2FRE record) using the normal or log-normal distribution to assign exceedance frequencies.

The frequency predictions for some reservoirs may be improved using a priori techniques available to CRM. The regression equation with the largest coefficient of determination (R^2) is assumed to be the best fit for the data. While values for R^2 are typically very low for CRM applications, oftentimes power and linear regression can fit the data better. Another option for improving the accuracy of predictions is choosing the probability distribution (i.e. Log-normal or Weibull) that best fits the data. Several tests for goodness-of-fit can be used to determine the best distribution including Chi Squared, Kolmogorov Smirnov, and Anderson Darling.

A challenge to accurately predicting reservoir storage levels in the near future is that the operating rules for multiple-reservoir systems in WRAP may not coincide with where actual releases are made. The HRR file (created by field 4 of the JO record) can be used to determine where releases were made in the WRAP-SIM simulation. The HRR file can be compared to actual releases to determine the applicability of the WRAP operating rules. The issue could be addressed by assigning a monthly pattern to reservoir releases (TS records) similar to the UC records for annual diversion targets.

Limitations of the BRAC2009 dataset include ignoring the pipeline between Stillhouse and Georgetown, the flood-control pool of reservoirs like Aquilla, and the known reservoir releases. Attention to these details will further improve the accuracy of frequency estimates.

An important component of using CRM to adaptively manage droughts is being able to test alternative short-term water management strategies. The dataset can be altered in a variety of ways to test, evaluate, and analyze different strategies. This process is greatly facilitated by the use of condensed datasets like BRAC2009.

The results of the analyses described above and presented in Appendix B were discussed with members of the BRA on January 22, 2010. As a result of these discussions, the need for additional simulations was identified. One of these runs, termed the *Hypothetical Releases* simulation, is described below.

The Hypothetical Releases simulations are an example of how CRM can be used to evaluate short-term water management strategies. The simulations answer the question, “If water managers meet downstream demands with releases from Reservoir X, what are the chances that it will be full in the next few months?”

Simulations were run for the 10 BRA reservoirs that make releases for the 44,631 acft/yr diversion for industrial uses at the Hempstead gage (as modeled in the BRAC2009 dataset). For each reservoir, the storage contents over the next three months were simulated assuming only that reservoir was used to meet the demand at the

Hempstead gage during that time. The CRM analysis is conducted starting in May and predicts 3 months in the future. The results of the Hypothetical Releases simulations are presented in Appendix C.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

This thesis investigated key complexities of estimating short-term water supply capabilities of reservoir systems. The research developed and tested new methodologies for determining individual and multiple-reservoir system firm yields. A sensitivity analysis was performed for modeling decisions involved in application of the conditional reliability modeling features of WRAP. Based on the findings of the sensitivity analysis, recommendations are made to guide the user in application of the model. Finally, a case study of the BRA system is used to illustrate practical application of the model.

8.1. Firm Yields and Yield-Reliability Relationships

Firm yield estimates vary depending on the premises reflected in the model. Key factors that can affect firm yield calculations include evaluation of the critical draw-down period, negative incremental flows, reservoir sedimentation rates, hydrologic period-of-analysis, and interactions between multiple reservoirs.

The firm yield for individual reservoirs is not independent of other reservoirs in the basin. It is possible for the diversions and storage at one reservoir to affect water availability at another. It is advisable to include all primary reservoirs in the dataset prior to computing firm yield for either individual reservoirs or multiple reservoir systems.

Negative incremental flows can significantly influence estimates of firm yield. Negative incremental flows are less of an issue with a condensed dataset. While negative incremental flow is an area of water availability modeling requiring further research, option 4 is recommended for the full WAM datasets and option 1 is probably the most appropriate for condensed datasets.

Multiple-reservoir system operations result in significant increases in firm yields as compared to individual reservoir firm yields (Table 1). This is because critical draw-down periods differ between component reservoirs and releases are made only from the reservoir that is most full. Type 2 water rights have the additional advantage of being able to deplete excess streamflow to meet diversion targets, thereby reducing demand for releases from storage.

Predicted reliabilities tend to stabilize as the period-of-analysis increases. This implies that a longer period-of-analysis will provide a better prediction for long-term reliability. The year in which a simulation begins can affect predicted reliabilities. It is best to start the simulation in a year preceded by wet conditions so that the common assumption that all reservoirs start full to capacity at the beginning of the simulation is more likely to be valid.

Inclusion of the period of extended hydrology from 1900 to 1939 generally increases average reliability because it offsets the effect of the period of low reliabilities during the 1950s. Because greater modeling uncertainties are involved in estimating hydrology prior to 1940, the extended hydrology is not recommended for long-range planning studies. However, the extended hydrology can be used for short-range conditional reliability studies.

8.2. Conditional Reliability Modeling

8.2.1. Hydrologic Period-of-Analysis

Predicted reliabilities experience less variability with periods-of-analysis greater than 60 years. The monthly cycle shows an averaging effect, while simulations starting in wet months experience above average reliabilities and those starting in dry months experience lower than average reliabilities. Predicted short-term reliabilities are consistently lower for a 1900 to 1959 period-of-analysis compared to a 1948 to 2007 period-of-analysis. The difference is greater for simulations starting in wet months compared to dry months.

8.2.2. Initial Storage Content

In a long-term simulation, a long period-of-record is desirable so that an arbitrary initial storage condition is unlikely to persist long enough to significantly affect the results. It is precisely during the time when the initial storage condition affects the results that short-term conditional reliability modeling is most applicable. Simulations were run for different initial storage conditions to determine the effect of initial conditions on storage frequencies and short-term water supply reliabilities. The Lake Granger example illustrates formats for organizing and presenting the results of CRM analyses.

8.2.3. Cycling Option

The annual cycle option simulates one sequence per year and each sequence always begins in the same month. In this way, seasonality is preserved. The monthly cycle option simulates one sequence per month. The monthly cycle generates up to 12 times more sequences than the annual cycle. The extra sequences in the monthly cycle come at a loss of seasonality but can be useful for assigning probabilities.

8.2.4. Starting Month

The month in which a CRM simulation begins can affect the reliability and storage predictions. Short-term reliabilities are higher for simulations starting in wet months and lower for dry months. This is because greater shortages are experienced if the reservoir is empty during a month in which stream flows are lower.

8.2.5. Length of Simulation

A short-term simulation is affected by the length of simulation in a number of ways. The influence of initial storage and starting month on predicted storages diminishes with length of simulation, as does the correlation between initial storage and naturalized flows.

8.2.6. Methods for Assigning Probabilities

There are three options in WRAP for assigning weights to short-term sequences: The equal-weight option, the FF relationship, and the SFF relationship. For a reservoir that tends to be full, the difference between equal weight and the SFF array is greatest when the reservoir starts empty. The relationship is reversed for reservoirs that are empty more often.

Preceding reservoir storage can be incorporated into the FF option by considering only those sequences that begin with a preceding storage that falls within a specified range. The probabilities assigned using the FF option can approach the probabilities using the SFF option when the FF analysis is limited to specific storage intervals. Considerable differences occur between the unrestricted FF option and the FF option with intervals when the analysis is limited to storage intervals that occur more rarely.

The log-normal distribution and the Weibull formula are used to assign exceedance frequencies to streamflows for the FF and SFF options. The Weibull formula used in combination with the FF option is essentially equivalent to the equal-weight option.

8.2.7. Regression Options

The SFF option relies on a regression relationship between initial storage and naturalized flow to develop an array of predicted flows. Four regression equations are used to relate naturalized flows to preceding storage: exponential, power, linear, and combined. The coefficient of determination can be used to determine the best fitting equation. For Granger Reservoir, exponential regression tends to describe the relationship the best. This is not the case for other reservoirs.

8.3. Guidelines for the Practical Application of CRM

Chapter VI developed guidelines for choosing the most appropriate modeling options within conditional reliability modeling. The chapter offers guidance on several modeling decisions including choice of dataset, hydrologic period-of-analysis, starting month, initial storage content, method for generating sequences, simulation length, probability distribution, and regression equation.

8.4. Case Study Results

The case study presented in Chapter VII illustrates an application of the CRM features of WRAP by analyzing the drought of 2009. An Actual Conditions dataset was developed for the purposes of the case study. The chapter documents the procedure used to develop the dataset, which can be used to develop Actual Conditions datasets for other CRM studies. The BRA reservoir system was modeled looking 3 months ahead for simulations starting alternatively in May, June, July and August. Actual beginning-of-month storage conditions were used as the initial condition for each simulation. The case study used the log-normal distribution to assign probabilities to flow sequences based on the flow ratio (calculated using the SFF option).

In addition to development of actual use datasets, the case study demonstrates an appropriate combination of WRAP computation options and format for organizing and presenting the results of CRM analyses. Storages associated with specific frequencies can be determined for each month of the upcoming year. Frequencies associated with specific storages are also useful. Storage levels of interest will include full reservoir capacity, drought stage triggers, and observed storages (for model validation and assessment of past conditions).

8.5 Applications of the Research

The conditional reliability model described in this research has far-reaching implications. The research can be used to answer several classic and emerging questions regarding short-term management of reservoir systems. Perhaps the most important application is real-time decision support during drought (Schnier and Wurbs, 2009). The case study presented in this thesis discussed how CRM can be used to adaptively manage a repeat of the drought of 2009.

Another important application of the research is routinely recurring operational planning. Reservoir operating rules can be based on using initial storage as a trigger mechanism. Water supply commitments like interruptible supplies can be specified as a function of initial storage.

Other operational planning activities supported by CRM include when to overdraft firm yield (Brandes and Sullivan, 1998). Drought contingency plans can be formulated to use CRM to find diversion amounts that would produce a specified reservoir storage in the future with a specified probability (Salazar, 2002).

Another application of the research is determining how long it will take a proposed reservoir to fill up and the effect on downstream water rights during the initial impoundment period. CRM can be used to find the short-term firm yield of a reservoir as a function of initial storage contents. In this capacity, the model can support the management of over-permitted reservoirs. In the event that it is not possible to supply the full permitted amount, projected water supply reliabilities can be provided to water users several months in advance.

CRM can be used to evaluate the feasibility of using water supply reservoirs for temporary flood control. For example, the model could be used to determine how far and how long a reservoir can be lowered during a specific time of year and still maintain 100% reliabilities.

CRM can also provide decision support for the coordination of multiple reservoir systems. The model can help water managers decide which reservoir to release from based on where they want the storage levels to be in a few months.

8.6. Limitations

The predicted short-term reliabilities and storage frequencies reflect the assumptions and premises of the model. The closer these assumptions are to reality, the more accurate the predictions become.

The SFF option and the FF option with storage intervals assume current reservoir storage levels are an indication of recent streamflow conditions. Both options are built on the premise that the role of streamflows is more significant in determining storage levels than operational management policies. These options may not be applicable to reservoirs whose storage contents depend more on operational policies than streamflows. For these reservoirs, the unrestricted FF option or equal-weight options can be used.

The applicability of the SFF option and the FF option with storage intervals is limited by the length of simulation. As the length of simulation increases, the basic assumptions of these options are less likely to be met.

The results of the SFF option depend on the strength of a regression relationship between initial storage and naturalized flows. If a clear relationship does not exist, the model results will be inaccurate.

Another key assumption of the CRM features of WRAP is that historical hydrology represents the complete range of possible events. The model does not account for the possibility that the upcoming months are drier than the driest on record.

If operating rules for multiple-reservoir systems in WRAP do not coincide with where actual releases are made, accurate prediction of reservoir levels would be difficult to obtain for the BRA System. Some of these issues can be addressed using the TS records in WRAP. Multiple reservoir system releases can be verified in the HRR file.

CRM analyses also reflect the assumptions and premises used to generate the results of a long-term simulation (OUT file). The persistence of an arbitrary initial storage condition can foul the generation of a quality OUT file. This issue is addressed with BES cycling option 5. The BRA condensed (BRAC) datasets reflect consumption of full permitted amounts by secondary water rights. This is a conservative assumption.

8.7. Conclusions

The conditional reliability model described in this thesis is an innovative tool for evaluation of short-term water management strategies. The model improves estimates of short-term water supply reliabilities by considering current storage levels. The choice of modeling option can affect the results. This thesis has evaluated the sensitivity of the model to changes in modeling options and developed guidelines for making appropriate choices. The analysis of the drought of 2009 illustrated a practical application of the model.

8.8. Future Research

There are several aspects of the research that require further investigation. Short-term relationships between storage and flow for other BRA reservoirs and multiple-reservoir systems should be investigated. This study showed that the results for Granger reservoir may not be applicable to other reservoirs.

Alternative methods of assigning probabilities to the streamflow sequences should be considered. The log-Pearson type III probability distribution was often identified as fitting the data better than the log-normal or Weibull distributions according to the goodness-of-fit tests.

The short-term reliabilities predicted by CRM depend on an analysis of historical hydrology. This dependency can be limiting in a number of ways. If the period-of-record is too short, the model may not have sufficient streamflow sequences to accurately estimate reliability. Similar issues arise when storage intervals limit the analysis to specific sequences. Also, unprecedented stream flow (as was the case with Somerville in Chapter VII), will impair the models ability to predict reliabilities. For these reasons, further research may be needed on the generation of synthetic streamflow sequences.

The model presented in this thesis could be adapted to operate on a daily time-step in coordination with the program SIMD. SIMD (D for daily) is an expanded version of WRAP-SIM that can compute sub-monthly time intervals (Wurbs et al., 2009). When run on a daily time-step, CRM could be used for real-time decision support during drought or reservoir system operation.

Methods for handling negative incremental flows can change the results of the simulation. Negative incremental flow is an area of water availability modeling requiring further research.

More research is needed to understand the spatial aspects of river basin hydrology and its implications for multiple-reservoir system operations and CRM. Multiple-reservoir system operations increase firm yield because critical periods differ between reservoirs. These differences in critical periods are geographic in origin. With an improved understanding of the spatial aspects of basin hydrology, geographical differences can be exploited to optimize day-to-day operations of reservoir systems. This information would also be helpful for relating flows to storage in multiple reservoirs.

Some of the results presented in this thesis suggest that flow characteristics of Texas rivers have changed over the past 60 years. An improved understanding of how development affects streamflows is useful information for establishing instream flow requirements. An analysis of trends in streamflow over the past 60 to 100 years would also provide a better understanding of the uncertainties related to climate change.

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APPENDIX A

WRAP INPUT FILES

BRAC2009.DAT File

```
T1  BRAC2009.DAT File - BRAC8 DAT File Modified to Incorporate 2009 Water Use for BRA Customers
**
**       1         2         3         4         5         6         7         8         9        10
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**     !       !       !       !       !       !       !       !       !       !       !       !       !
**
JD   108    1900       1      -1       0       0       5
**  Cycling option 5 on JO record ensures a quality OUT file to build the probability array
**JO                             5
**  Cycling option 2 on JO record reads initial storages from BES files for generation of CRM file
**  Creation of BRS file, which is used by TABLES, is activated in column 40
JO                             2       1
**  CRM analysis for May through Aug (CR). Read starting storages from BES file (JO)
CR     3       5               1
**
**  Update UC records to reflect actual 2009 use (BRA)
**  Projected used for Oct through Dec based on analysis of historical use data
**
**  Hubbard use coefficients based on 2008 reported use (TWDB)
UC MUNHB  197.85  152.07  310.41 1011.75 1196.71 1264.97 1753.53  1996.6  1168.8 1144.47 1082.13 1119.32
UC MINHB    5.29    2.19    4.48    2.25    2.84     3.7    5.78    2.12    3.54    6.92    2.84    3.96
**
**  Waco use coefficients based on 2008 reported use (TWDB)
UC MUNWC    2114    2037    2065    2046    2506    3552    4142    3355    3096    2777    2455    2274
UC IRRWC   26.02   32.17   38.39   42.46    25.5  140.93  162.06  109.91   76.52    60.4   45.45   28.04
**
UC MUNPK     134      76      85     100     104     120     107     115     103     125      83      81
UC INDPK     122      69      77      91      94     110      98     105      94      54      59     101
UC MINPK     101      57      64      75      78      91      81      87      78      79      75      74
UC IRRPK      27      15      17      20      21      24      22      23      21      22      13       8
**
UC MIN27       6      43       1      19      37       3      44      19       0      19      18      18
UC IRR27       0       3       0       1       2       0       3       1       0       1       1       0
**
UC MUN29       6       0       8       0       3      16      10      28      43      15      10      10
UC MIN29       1       0       1       0       0       1       1       3       4       1       1       1
UC IRR29       4       0       6       0       2      11       7      20      31       9       5       3
**
UC MUNGB     490      87     447     527     550     561     806     785     493     530     441     416
UC INDGB    3739     665    3410    4021    4204    4282    6157    5994    3763    3713    3050    4202
UC MINGB      47       8      43      51      53      54      78      76      48      33      30      33
UC IRRGB     319      57     291     343     358     365     525     511     321     318     132     112
**
**  Squaw Creek use coefficients based on 2008 reported use (TWDB)
UC INDSQ  1750.6  1553.7  1619.6  1123.3  1738.9  1674.3  1722.3  1720.9    1555  1260.9    1726    1789
**
UC IND30       1       0       0       0       0       0      10      24       8       4       4       5
UC MIN30       0       0       0       0       0       0       0       1       0       0       0       0
UC IRR30       1       0       0       0       0       0       9      20       7       4       2       1
**
UC MUNWT     322     267     329     259     283     260     524     574     441     538     225     136
UC INDWT     193     160     197     155     170     156     314     344     264     275     115      69
UC IRRWT      69      57      71      56      61      56     112     123      95      33      10       5
**
UC MUNAQ     169     157     172     161     182     251     279     295     254     251     216     228
**
UC MUN41     124     211     109       0       0       0      89     226       0     103      68      63
UC IRR41       5       8       4       0       0       0       3       8       0       2       1       1
**
**  No diversions at this point
**UC IRR42       0       0       0       0       0       0       0       0       0       0       0     0
**
UC MUNPR      70      63      78     132     222     402     455     441      69     243     182     178
UC IRRPR     132     119     147     250     420     759     859     833     131     120      20       3
**
```

```
UC MUN49    1465    1627    1297    1553    1579    1522    2141    2261    2074    2049    1720    1740
UC IRR49       7       8       6       8       8       8      11      11      10       4       1       1
**
UC MUNBN    3141    2832    3232    3382    3815    5202    5879    5290    4252    4890    4104    4151
**
UC MUNSH     756     641     749     819     980    1420    1737    1562     941    1322    1215    1282
UC INDSH       0       0       0       0       0       1       1       1       0       1       0       0
UC IRRSH       7       6       7       8      10      14      17      15       9       4       3       7
**
UC MUNGT    1728    1589    1876    1750    1917    2992    4143    4243    2335    1497    1183     902
**
UC MUNGG     216     180     218     219     267     400     451     410     282     298     261     259
**
UC IRRLR       0       0       0       0       6      83      11      91       0       8       6      14
**
UC INDSL       0       0       0       0     588     928    1553    1613     423     238     220     238
**
UC INDLB       0       0       0       0       0       0       2       5       2     0.4     0.4     0.4
UC MINLB       0       0       0       0       0       2       9      20       9       5       4       5
UC IRRLB       0       0       0       0      12      48     262     569     264      54      17       9
**
UC MUNSM     234     231     275     261     313     452     485     401     313     311     282     268
**
UC MUNLS       9       9      13       9      23      13      23      20      18      14      12      12
UC INDLS    1654    1631    2234    1529    4043    2200    4065    3493    3158    2465    2129    2086
UC MINLS       1       1       1       0       1       1       1       1       1       1       0       1
**
UC MUNEA       1       0       1       1       0      23      84      77      16      21      18      18
UC INDEA      14       4      12      16       2     413    1517    1401     297     377     326     319
UC MINEA       0       0       0       0       0       2       7       6       1       1       1       2
UC IRREA       1       0       1       1       0      37     135     125      27       7       3       2
**
UC INDBH    4537     432    6698    4105    1066    6278    8480    5498    2181    1830    1696    1830
UC IRRBH       3       0       4       2       1       4       5       3       1       1       0       0
**
UC MUNBR       0       0       0       0       0    1935    3403    1861     517     895     744     694
UC INDBR       0       0       0       0       0   16002   28145   15391    4278    2973    2756    2973
UC IRRBR       0       0       0       0       0    6696   11777    6440    1790     610     222     194
**
UC IRRRO       0      21      17       0       0      33      28      32      97       5       2       2
**
****************
**
RFRABIL1  0.7226  0.7138  0.5753  0.4824  0.4602  0.4082  0.3228  0.3411  0.4636  0.5381  0.6894  0.6892
RFR42131  0.5556  0.5910  0.6053  0.4697  0.4703  0.4235  0.3051  0.3240  0.3544  0.4142  0.4784  0.5055
RFR50941  0.8119  0.8291  0.8120  0.7529  0.6557  0.6047  0.4785  0.5086  0.6143  0.6568  0.7570  0.7817
**
CPDMAS09  BRSE11                       1            NONE          0.4918
CPBRSE11  CON036                       1            NONE          0.4146
CP421331  CON036                       1                          0.2275
CPCON036  BRSB23                       1            NONE          0.0100
CPBRSB23  515531                       1            NONE          0.0179
CP515531  BRPP27                       1                          0.0050
CPBRPP27  BRDE29                       1            NONE          0.0198
CPBRDE29  515631                       1            NONE          0.0119
CP515631  BRGR30                       1                          0.0060
CPBRGR30  CON063                       1            NONE          0.0010
CP409732  CON063                       1                          0.0000
CPCON063  515731                       1            NONE          0.0198
CP515731  BRAQ33                       1                          0.0000
CPBRAQ33  CON070                       1            NONE          0.0050
CP515831  CON070                       1                          0.0050
CPCON070  433901                       1            NONE          0.0020
CP509431  433901                       1                          0.0199
CP515931  LEHM46                       1                          0.3795
CPLEHM46  LEGT47                       1            NONE          0.0119
CPLEGT47  516031                       1            NONE          0.0252
CP516031  LEBE49                       1                          0.0010
CPLEBE49  CON096                       1            NONE          0.0040
CP516131  LABE52                       1                          0.0010
CPLABE52  CON096                       1            NONE          0.0020
CPCON096  LRLR53                       1            NONE          0.0020
CPLRLR53  CON108                       1            NONE          0.0208
CP516231  516331                       1                          0.0080
CP516331  GALA57                       1                          0.0060
CPGALA57  CON108                       1            NONE          0.0139
CPCON108  LRCA58                       1            NONE          0.0020
CPLRCA58  CON111                       1            NONE          0.0267
CP433901  BRWA41                       1            NONE          0.0020
CPBRWA41  BRHB42                       1            NONE          0.0100
CPBRHB42  CON111                       1            NONE          0.0040
CPCON111  BRBR59                       1            NONE          0.0100
CPBRBR59  CON130                       1            NONE          0.0119
```

```
CP516431  CON130                       1                          0.0110
CP516531  NAEA66                       1                          0.0050
CPNAEA66  NABR67                       1            NONE          0.0100
CPNABR67  CON147                       1            NONE          0.0296
CPCON130  CON147                       1            NONE          0.0040
CPCON147  BRHE68                       1            NONE          0.0090
CPBRHE68  CON234                       1            NONE          0.0177
CP292531  CON234                       1            NONE          0.0040
CPCON234  BRRI70                       1            NONE          0.0060
CPBRRI70  BRRO72                       1            NONE          0.0100
CPBRRO72  BRGM73                       1            NONE          0.0169
CPBRGM73  OUT                          1            NONE          0.0000
**
**  Diversion amounts (WR col 16), storage (WS col 16), and use coefficients (WR col 24)
**  updated for Jan to Sept 2009
**
**  Lake Hubbard Creek
**
**  Update storage (WS col 16) for 2010 conditions
**  Update diversion amounts (WR and UC records) according to 2008 reported use
**  Consolidate HUBBRD into two diversions.
WR421331 12398.6   MUNHB19570528   1   2  0.0000                         C4213_1   C421364213001
WSHUBBRD 324983.
WR421331   45.91   MINHB19720814   1   2  0.0000                         C4213_2   C421364213001
WSHUBBRD 324983.
**
**  Lake Possum Kingdom
**
WR515531   1233.   MUNPK19380406   1   2  0.5000  BRPP27                   PKmun   C515565155001
WSPOSDOM 526970.
WR515531   1074.   INDPK19380406   1   2  0.0000                           PKind   C515565155001
WSPOSDOM 526970.
WR515531    939.   MINPK19380406   1   2  0.0000                           PKirr   C515565155001
WSPOSDOM 526970.
WR515531    232.   IRRPK19380406   1   2  0.0000                           PKmin   C515565155001
WSPOSDOM 526970.
**
WRBRPP27    227.   MIN2719380406   2   2  0.0000                       PalPinMin   C515565155001
WSPOSDOM 526970.
WRBRPP27     12.   IRR2719380406   2   2  0.0000                       PalPinIrr   C515565155001
WSPOSDOM 526970.
**
WRBRDE29    149.   MUN2919380406   2   2  0.0000                       DennisMun   C515565155001
WSPOSDOM 526970.
WRBRDE29     15.   MIN2919380406   2   2  0.0000                       DennisMin   C515565155001
WSPOSDOM 526970.
WRBRDE29     99.   IRR2919380406   2   2  0.0000                       DennisIrr   C515565155001
WSPOSDOM 526970.
**
**  Lake Proctor
**
WR515931   2535.   MUNPR19631216   1   2  0.0000                      ProctorMun   C515965159001
WSPRCTOR  54649.
WR515931   3793.   IRRPR19631216   1   2       0                      ProctorIrr   C515965159001
WSPRCTOR  54649.
**
**  Lake Granbury
**
WR515631   6133.   MUNGB19640213   1   2  0.0000                     GranburyMun   C515665156001
WSGRNBRY 123943.
WR515631  47200.   INDGB19640213   1   2  0.0000                     GranburyInd   C515665156001
WSGRNBRY 123943.
WR515631    554.   MINGB19640213   1   2  0.0000                     GranburyIrr   C515665156001
WSGRNBRY 123943.
WR515631   3651.   IRRGB19640213   1   2  0.0000                     GranburyMin   C515665156001
WSGRNBRY 123943.
**
WRBRGR30     56.   IND3019640213   2   2  0.0000                     GlenRoseInd   C515665156001
WSGRNBRY 123943.
WRBRGR30      1.   MIN3019640213   2   2  0.0000                     GlenRoseMin   C515665156001
WSGRNBRY 123943.
WRBRGR30     44.   IRR3019640213   2   2  0.0000                     GlenRoseIrr   C515665156001
WSGRNBRY 123943.
**
**  Squaw Creek Reservoir
**
WR409732 19234.5   INDSQ19730425   1   2  0.0000                         C4097_1   C409764097002
WSSQWCRK 151273.
**
**  Lake Whitney
**
**  SV/SA is for whole lake but WS and WR col 16 from just BRA portion
WR515731   4157.   MUNWT19820830   1   2  0.0000                      WhitneyMun   C515765157001
```

```
WSWHITNY 233079.
WR515731   2412.   INDWT19820830   1   2  0.0000                      WhitneyInd   C515765157001
WSWHITNY 233079.
WR515731    700.   IRRWT19820830   1   2  0.0000                      WhitneyIrr   C515765157001
WSWHITNY 233079.
**
**  Lake Aquilla
**
WR515831   2615.   MUNAQ19761025   1   2  0.0000                      AquillaMun   C515865158001
WSAQUILA  44295.
**
**  Lake Waco
**
**  SV/SA from 2010 conditions for whole lake, storage capacities (WS col 16) from BRAC2008 dataset
**  for just BRA portion
WR509431  32419.   MUNWC19290110   1   4  R50941  BRHB42                 C2315_1   C231562315001
WSLKWACO  39100.
WR509431  787.85   IRRWC19790221   1   2  0.0000                         C2315_5   C231562315001
WSLKWACO  65000.
**
**  Lake Belton
**
WR516031  50169.   MUNBN19530824   1   2  0.0000                       BeltonMun   C293662936001
WSBELTON 432408.
**
WRLEBE49  21028.   MUN4919530824   2   2  0.0000                    LeonRiverMun   C293662936001
WSBELTON 432408.
WRLEBE49     82.   IRR4919530824   2   2  0.0000                    LeonRiverIrr   C293662936001
WSBELTON 432408.
**
**  Lake Stillhouse Hollow
**
WR516131  13424.   MUNSH19631216   1   2  0.0000                   StillhouseMun   C516165161001
WSSTLHSE 226730.
WR516131      4.   INDSH19631216   1   2  0.0000                   StillhouseInd   C516165161001
WSSTLHSE 226730.
WR516131    107.   IRRSH19631216   1   2  0.0000                   StillhouseIrr   C516165161001
WSSTLHSE 226730.
**
**  Lake Georgetown
**
WR516231  26155.   MUNGT19680212   1   2  0.0000                   GeorgetownMun   C516265162001
WSGRGTWN  36868.
**
**  Lake Granger
**
**  Use by irrigation of 0.3 ac-ft/yr is ignored.
WR516331   3461.   MUNGG19680212   1   2  0.0000                      GrangerMun   C516365163001
WSGRNGER  50331.
**
**  Lake Somerville
**
WR516431   3825.   MUNSM19631216   1   2  0.0000                   SomervilleMun   C516465164001
WSSMRVLE 144619.
**
**  Lake Limestone
**
WR516531    176.   MUNLS19740506   1   2  0.0000                    LimestoneMun   C516565165001
WSLMSTNE 202952.
WR516531  30686.   INDLS19740506   1   2  0.0000                    LimestoneInd   C516565165001
WSLMSTNE 202952.
WR516531     10.   MINLS19740506   1   2  0.0000                    LimestoneMin   C516565165001
WSLMSTNE 202952.
**
WRNAEA66    260.   MUNEA19740506   2   2  0.0000                     EasterlyMun   C516565165001
WSLMSTNE 202952.
WRNAEA66   4699.   INDEA19740506   2   2  0.0000                     EasterlyInd   C516565165001
WSLMSTNE 202952.
WRNAEA66     21.   MINEA19740506   2   2  0.0000                     EasterlyMin   C516565165001
WSLMSTNE 202952.
WRNAEA66    340.   IRREA19740506   2   2  0.0000                     EasterlyIrr   C516565165001
WSLMSTNE 202952.
**
**  Multiple-Reservoir System Diversions from the Little River
**
WRLRLR53    219.   IRRLR88888888   2   2  0.0000                     LittleRiver
WSBELTON 432408.
WSSTLHSE 226730.
**
**  Use by mining of 0.08 ac-ft/yr is ignored
WRCON108   5801.   INDSL88888888   2   2  0.0000                   SanGabriel&LR
WSGRGTWN  36868.
WSGRNGER  50331.
```

```
WSBELTON 432408.
WSSTLHSE 226730.
**
**  Multiple-Reservoir System Diversions from the Brazos River
**
WRBRWA41    993.   MUN4188888888   2   2  0.0000                     WacoGageMun
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WRBRWA41     32.   IRR4188888888   2   2  0.0000                     WacoGageIrr
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
**
**  There were no diversions at this CP during 2009
**WRBRHB42      0.   IRR4288888888   2   2  0.0000                     HighbankIrr
**WSAQUILA  44295.
**WSWHITNY 233079.
**WSGRNBRY 123943.
**WSPOSDOM 526970.
**
WRCON111     10.   INDLB88888888   2   2  0.0000                   ConfluenceInd
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WRCON111     53.   MINLB88888888   2   2  0.0000                   ConfluenceMin
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WRCON111   1235.   IRRLB88888888   2   2  0.0000                   ConfluenceIrr
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
**
WRBRHE68  44631.   INDBH88888888   2   2  0.0000                    HempsteadInd
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WRBRHE68     24.   IRRBH88888888   2   2  0.0000                    HempsteadIrr
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
**
**  In BRAC2008 dataset there is no diversion at Richmond Gage, so add in for BRAC2010 dataset
WRBRRI70  10050.   MUNBR88888888   2   2  0.0000                     RichmondMun
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
```

```
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WRBRRI70  72518.   INDBR88888888   2   2  0.0000                     RichmondInd
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
WRBRRI70  27729.   IRRBR88888888   2   2  0.0000                     RichmondIrr
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
**
WRBRRO72    237.   IRRRO88888888   2   2  0.0000                     RosharonIrr
WSSMRVLE 144619.
WSLMSTNE 202952.
WSGRGTWN  36868.
WSGRNGER  50331.
WSBELTON 432408.
WSSTLHSE 226730.
WSAQUILA  44295.
WSWHITNY 233079.
WSGRNBRY 123943.
WSPOSDOM 526970.
**
**  Refilling Storage in System Reservoirs
**
**  Update storage (WS col 16) for Jan to Sept 2009
WR516431                99999999
WSSMRVLE 144619.
WR516531                99999999
WSLMSTNE 202952.
WR516231                99999999
WSGRGTWN  36868.
WR516331                99999999
WSGRNGER  50331.
WR516031                99999999
WSBELTON 432408.
WR516131                99999999
WSSTLHSE 226730.
WR515831                99999999
WSAQUILA  44295.
WR515731                99999999
WSWHITNY 233079.
WR515631                99999999
WSGRNBRY 123943.
WR515531                99999999
WSPOSDOM 526970.
**
**  SV/SA record tables of reservoir storage volume (acre-feet) versus surface area (acres)
**
**  Update SV/SA records to reflect 2010 sedimentation conditions.
**
SVHUBBRD      0.   1330.  12917.  38522.  79494. 128181. 184376. 268457. 282106. 296100. 310386. 324983.
SA            0.    245.   1823.   3487.   5771.   8168.  10567.  13441.  13811.  14181.  14551.  14922.
SVPOSDOM      0.  56050. 343897. 367749. 392807. 405835. 433341. 463193. 478702. 494504. 510577. 526970.
SA            0.   3337.  11637.  12217.  12854.  13202.  14365.  15356.  15663.  15941.  16205.  16581.
SVGRNBRY      0.    798.   3671.  11053.  24816.  47164.  90020.  95955. 102298. 109084. 116299. 123943
SA            0.    203.    539.   1135.   1939.   3155.   5754.   6115.   6570.   7000.   7429.   7859.
SVWHITNY      0.   3269.  18374.  60447. 149218. 316500. 376930. 446023. 464915. 484671. 505407. 549579.
SA            0.    463.   1633.   4396.   7643.  14249.  16088.  18515.  19268.  20244.  21228.  23168.
SVAQUILA      0.    959.   4571.  10535.  19339.  29467.  31849.  34369.  37026.  39831.  42778.  44295.
SA            0.    296.    772.   1229.   1748.   2312.   2453.   2588.   2726.   2885.   3010.   3059.
SVLKWACO      0.   2041.  24107.  42707.  55637.  80266.  91200. 102801. 121660. 142227. 196317. 271638.
SA            0.    418.   3322.   4083.   4533.   5311.   5625.   5992.   6573.   7193.   8393.  10449.
SVPRCTOR      0.   6215.  23609.  25940.  28395.  31195.  34465.  38067.  41921.  45984.  50228.  54649.
SA            0.   1154.   2277.   2384.   2526.   3075.   3465.   3739.   3971.   4154.   4334.   4509.
SVBELTON      0.  25185. 221627. 263684. 311117. 331394. 352422. 374276. 396931. 408559. 420391. 432408.
SA            0.   1858.   7922.   8962.   9971.  10280.  10720.  11136.  11517.  11738.  11925.  12108.
SVSTLHSE      0.  16661.  94410. 114825. 138070. 164876. 169750. 179902. 190631. 201995. 214092. 226730.
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SA            0.    952.   3163.   3629.   4140.   4809.   4939.   5221.   5508.   5892.   6182.   6474.
SVGRGTWN      0.   3247.  21416.  23299.  25286.  26319.  28470.  30738.  33117.  34344.  35594.  36868.
SA            0.    287.    917.    967.   1021.   1047.   1105.   1163.   1216.   1240.   1261.   1287.
SVGRNGER      0.    504.   1623.   5053.  11005.  19850.  32602.  35722.  39026.  42557.  46313.  50331.
SA            0.    180.    420.    925.   1465.   2105.   3028.   3212.   3398.   3664.   3849.   4188.
SVSMRVLE      0.   1819.   9578.  23686.  43691.  86267.  94743. 103696. 113107. 123011. 133501. 144619.
SA            0.   1089.   2799.   4207.   5958.   8232.   8719.   9189.   9633.  10176.  10804.  11432.
SVLMSTNE      0.  20544. 109097. 117813. 126930. 136434. 146361. 156761. 167662. 179035. 190784. 202952.
SA            0.   3053.   8515.   8918.   9315.   9695.  10158.  10643.  11160.  11585.  11913.  12424.
**  No 2010 SV/SA records for Squaw Creek. Use most recent volumetric survey
SVSQWCRK       0     432    2561    7003   13622   23229   36350   53731   75972  103242  130144  151273
SA             0      80     286     450     660     946    1249    1656    2055    2494    2885    3169
ED
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APPENDIX B

RESULTS FOR CONDITIONAL RELIABILITY ANALYSIS OF THE BRA SYSTEM DURING THE DROUGHT OF 2009

The conditional reliability modeling (CRM) features of the Water Rights Analysis Package (WRAP) develop hydrologic sequences to estimate the storage conditions of reservoirs in the near future. Chapter VII uses these features to assess the behavior of the Brazos River Authority (BRA) reservoir system in a repeat of the drought of 2009. This appendix displays the results of the case study. Storage frequency estimates are developed for the following BRA reservoirs.

1) Lake Possum Kingdom
2) Lake Granbury
3) Lake Aquilla
4) Lake Proctor
5) Lake Belton
6) Lake Stillhouse Hollow
7) Lake Georgetown
8) Lake Granger
9) Lake Somerville
10) Lake Limestone

Table B-1. Storage-Frequency Relationships for Possum Kingdom starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**460,917**	**467,070**	**464,744**
Frequency (%)	98.57	89.52	91.78

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1984**	3	0.00914	**99.5**	**96.6**	**95.1**
Maximum	**1900**	296	0.01340	**114.3**	**112.8**	**113.4**
Highest Weight	**1934**	9	0.05074	**101.4**	**99.3**	**97.9**
Best Fit	**1996**	27	0.01258	**100.4**	**101.0**	**98.3**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	526,970	35.1	41.2	34.8
Trigger 1	396,497	100.0	100.0	100.0
Trigger 2	320,000	100.0	100.0	100.0
Trigger 3	250,000	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	493,153	504,504	499,723	105.6	108.0	107.5
Std Dev	1,476,362	1,331,974	1,431,090	316.1	285.2	307.9
Minimum	458,384	451,089	441,775	98.1	96.6	95.1
99.50%	458,384	451,089	441,775	98.1	96.6	95.1
99%	458,875	461,490	453,610	98.2	98.8	97.6
98%	462,567	461,490	454,963	99.0	98.8	97.9
95%	464,540	461,490	454,963	99.5	98.8	97.9
90%	467,033	463,737	469,238	100.0	99.3	101.0
85%	467,430	476,676	470,336	100.1	102.1	101.2
80%	468,005	477,634	470,775	100.2	102.3	101.3
75%	**469,633**	**481,454**	**476,873**	100.5	103.1	102.6
70%	471,595	488,440	480,803	101.0	104.6	103.5
60%	475,885	502,796	491,881	101.9	107.6	105.8
50%	**492,318**	**511,423**	**508,256**	105.4	109.5	109.4
40%	511,731	526,970	523,061	109.6	112.8	112.5
30%	526,970	526,970	526,970	112.8	112.8	113.4
25%	**526,970**	**526,970**	**526,970**	112.8	112.8	113.4
20%	526,970	526,970	526,970	112.8	112.8	113.4
15%	526,970	526,970	526,970	112.8	112.8	113.4
10%	526,970	526,970	526,970	112.8	112.8	113.4
5%	526,970	526,970	526,970	112.8	112.8	113.4
2%	526,970	526,970	526,970	112.8	112.8	113.4
1%	526,970	526,970	526,970	112.8	112.8	113.4
0.50%	526,970	526,970	526,970	112.8	112.8	113.4
Maximum	526,970	526,970	526,970	112.8	112.8	113.4

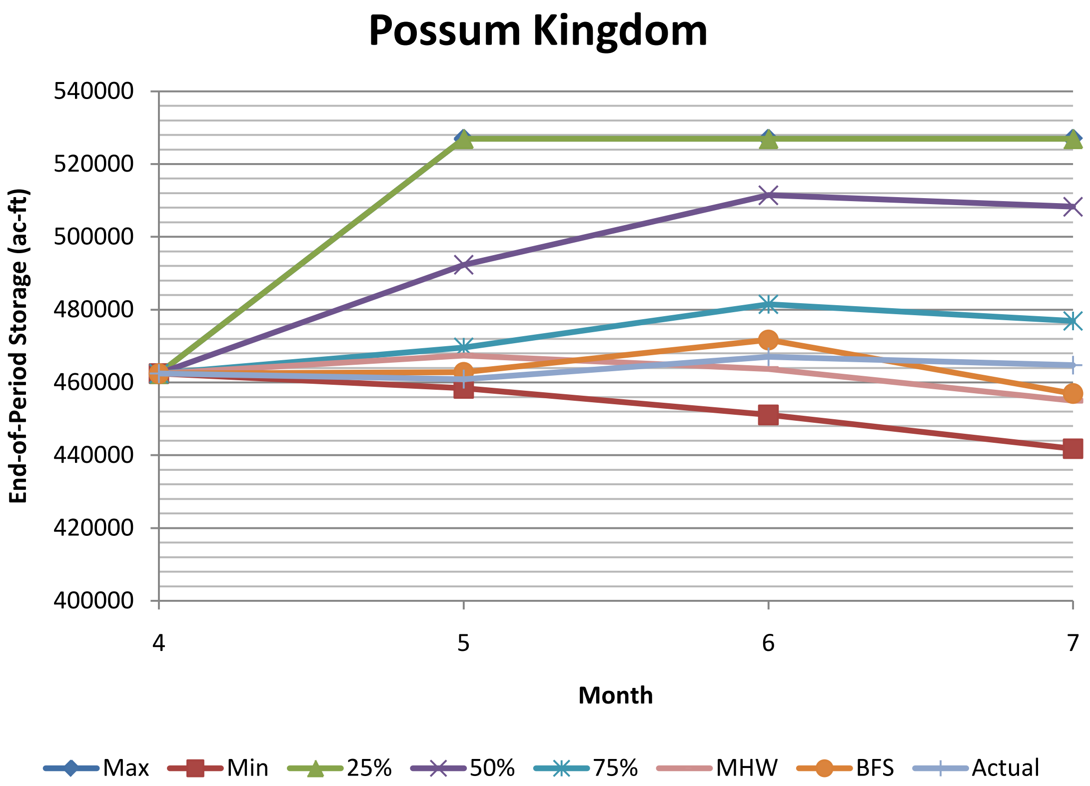


Figure B-1. Selected Storage Plots and Frequency Relationships for Possum Kingdom starting in May

Table B-2. Storage-Frequency Relationships for Possum Kingdom starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**467,070**	**464,744**	**449,536**
Frequency (%)	87.97	82.31	87.42

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1956**	15	0.02964	**99.4**	**97.1**	**93.4**
Maximum	**1900**	253	0.00817	**112.8**	**113.4**	**117.2**
Highest Weight	**1981**	153	0.04693	**112.8**	**113.4**	**115.7**
Best Fit	**1925**	53	0.00147	**100.2**	**100.2**	**100.7**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	526,970	34.1	30.0	24.4
Trigger 1	396,497	100.0	100.0	100.0
Trigger 2	320,000	100.0	100.0	100.0
Trigger 3	250,000	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	492,432	498,041	492,367	106.0	107.2	109.5
Std Dev	1,500,974	1,561,193	1,881,217	323.0	335.9	418.5
Minimum	446,874	444,217	419,759	96.2	95.6	93.4
99.50%	453,582	444,217	419,759	97.6	95.6	93.4
99%	453,582	444,217	419,759	97.6	95.6	93.4
98%	453,582	444,217	419,759	97.6	95.6	93.4
95%	461,665	451,495	420,202	99.3	97.1	93.5
90%	464,036	461,552	439,351	99.8	99.3	97.7
85%	468,047	462,305	454,218	100.7	99.5	101.0
80%	468,699	469,968	458,025	100.9	101.1	101.9
75%	**470,030**	**471,849**	**461,474**	101.1	101.5	102.7
70%	471,020	478,084	472,380	101.4	102.9	105.1
60%	477,078	485,995	485,435	102.7	104.6	108.0
50%	**486,907**	**499,060**	**493,166**	104.8	107.4	109.7
40%	509,496	525,451	514,877	109.6	113.1	114.5
30%	526,970	526,967	526,720	113.4	113.4	117.2
25%	**526,970**	**526,970**	**526,961**	113.4	113.4	117.2
20%	526,970	526,970	526,970	113.4	113.4	117.2
15%	526,970	526,970	526,970	113.4	113.4	117.2
10%	526,970	526,970	526,970	113.4	113.4	117.2
5%	526,970	526,970	526,970	113.4	113.4	117.2
2%	526,970	526,970	526,970	113.4	113.4	117.2
1%	526,970	526,970	526,970	113.4	113.4	117.2
0.50%	526,970	526,970	526,970	113.4	113.4	117.2
Maximum	526,970	526,970	526,970	113.4	113.4	117.2

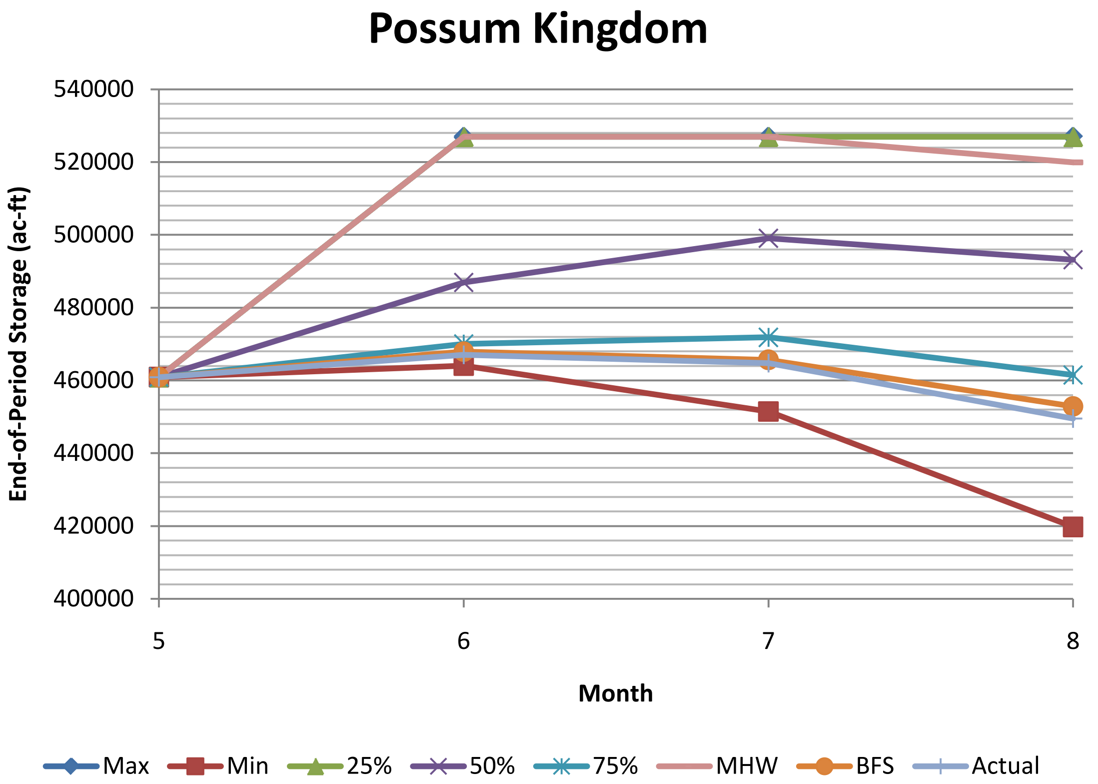


Figure B-2. Selected Storage Plots and Frequency Relations for Possum Kingdom starting in June

Table B-3. Storage-Frequency Relationships for Possum Kingdom starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**464,744**	**449,536**	**450,295**
Frequency (%)	73.61	72.22	70.68

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1956**	3	0.01220	**97.8**	**94.0**	**91.5**
Maximum	**1902**	743	0.00699	**113.4**	**117.2**	**117.0**
Highest Weight	**1976**	156	0.03719	**104.1**	**109.9**	**117.0**
Best Fit	**1947**	43	0.02918	**99.1**	**99.8**	**99.5**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	526,970	14.7	10.6	26.1
Trigger 1	396,497	100.0	100.0	100.0
Trigger 2	320,000	100.0	100.0	100.0
Trigger 3	250,000	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	478,846	477,304	483,043	106.5	106.2	107.3
Std Dev	1,310,227	1,821,690	2,176,751	291.5	405.2	483.4
Minimum	454,466	422,643	411,895	101.1	94.0	91.5
99.50%	454,466	422,643	411,895	101.1	94.0	91.5
99%	454,466	422,643	411,895	101.1	94.0	91.5
98%	455,935	427,763	414,589	101.4	95.2	92.1
95%	457,446	431,668	421,714	101.8	96.0	93.7
90%	458,775	435,789	428,650	102.1	96.9	95.2
85%	460,460	441,326	436,236	102.4	98.2	96.9
80%	461,021	445,498	440,032	102.6	99.1	97.7
75%	**463,953**	**448,655**	**442,992**	103.2	99.8	98.4
70%	465,236	451,410	452,203	103.5	100.4	100.4
60%	468,242	457,257	468,162	104.2	101.7	104.0
50%	**476,449**	**469,522**	**482,234**	106.0	104.4	107.1
40%	476,925	485,917	511,666	106.1	108.1	113.6
30%	481,025	494,249	520,964	107.0	109.9	115.7
25%	**483,931**	**502,359**	**526,970**	107.7	111.8	117.0
20%	503,564	515,356	526,970	112.0	114.6	117.0
15%	524,008	523,557	526,970	116.6	116.5	117.0
10%	526,970	526,970	526,970	117.2	117.2	117.0
5%	526,970	526,970	526,970	117.2	117.2	117.0
2%	526,970	526,970	526,970	117.2	117.2	117.0
1%	526,970	526,970	526,970	117.2	117.2	117.0
0.50%	526,970	526,970	526,970	117.2	117.2	117.0
Maximum	526,970	526,970	526,970	117.2	117.2	117.0

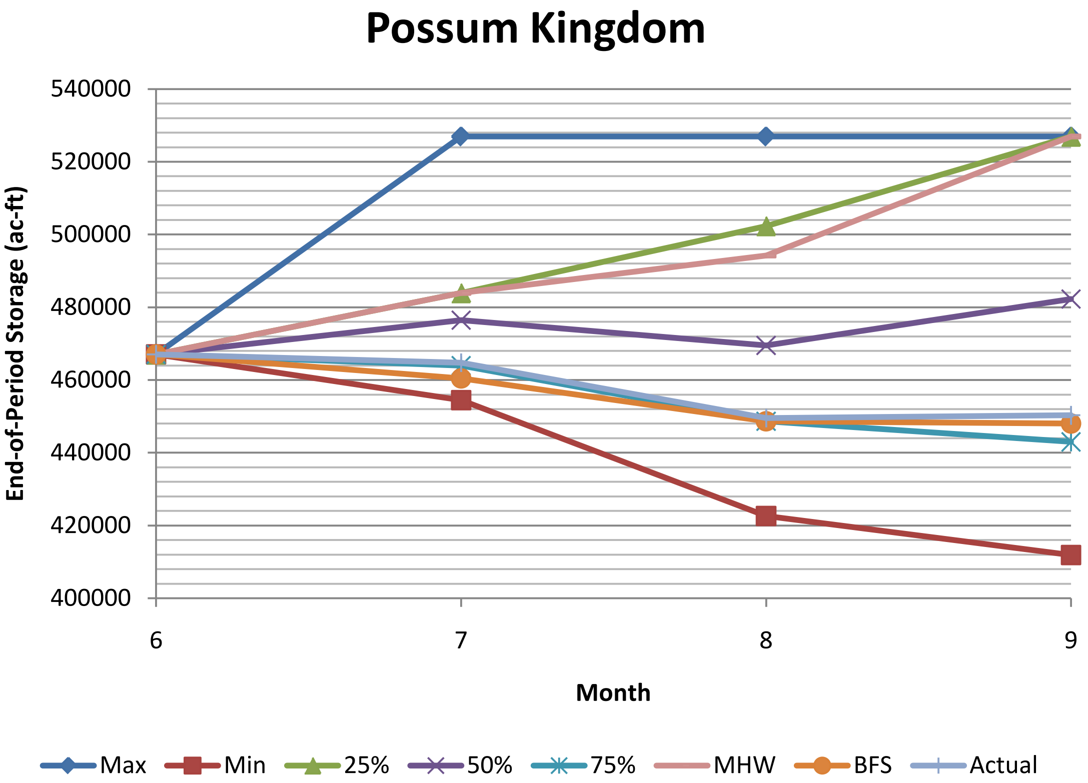


Figure B-3. Selected Storage Plots and Frequency Relationships for Possum Kingdom starting in July

Table B-4. Storage-Frequency Relationships for Possum Kingdom starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**449,536**	**450,295**	N/A
Frequency (%)	99.38	88.37	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	14	0.00619	**99.0**	**96.5**	**417,705**
Maximum	**1905**	441	0.00194	**117.2**	**117.0**	**526,970**
Highest Weight	**1987**	47	0.04369	**103.9**	**106.2**	**472,128**
Best Fit	**1947**	88	0.00430	**100.8**	**100.5**	**478,154**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	526,970	10.2	18.7	33.0
Trigger 1	396,497	100.0	100.0	100.0
Trigger 2	320,000	100.0	100.0	100.0
Trigger 3	250,000	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	474,574	482,937	491,314	105.4	107.2	
Std Dev	1,181,350	1,633,434	1,840,658	262.4	362.7	
Minimum	444,898	434,453	417,705	98.8	96.5	
99.50%	444,898	434,453	417,705	98.8	96.5	
99%	449,842	437,825	432,027	99.9	97.2	
98%	449,842	442,629	436,928	99.9	98.3	
95%	455,932	446,472	437,923	101.3	99.2	
90%	456,518	447,527	450,486	101.4	99.4	
85%	457,072	452,706	453,708	101.5	100.5	
80%	459,204	453,530	455,509	102.0	100.7	
75%	**459,826**	**459,425**	**457,574**	102.1	102.0	
70%	462,552	460,934	465,522	102.7	102.4	
60%	466,146	469,112	475,341	103.5	104.2	
50%	**466,995**	**476,571**	**499,649**	103.7	105.8	
40%	469,429	480,289	515,494	104.2	106.7	
30%	474,104	505,952	526,970	105.3	112.4	
25%	**475,429**	**514,025**	**526,970**	105.6	114.2	
20%	480,124	522,858	526,970	106.6	116.1	
15%	489,097	526,970	526,970	108.6	117.0	
10%	526,970	526,970	526,970	117.0	117.0	
5%	526,970	526,970	526,970	117.0	117.0	
2%	526,970	526,970	526,970	117.0	117.0	
1%	526,970	526,970	526,970	117.0	117.0	
0.50%	526,970	526,970	526,970	117.0	117.0	
Maximum	526,970	526,970	526,970	117.0	117.0	

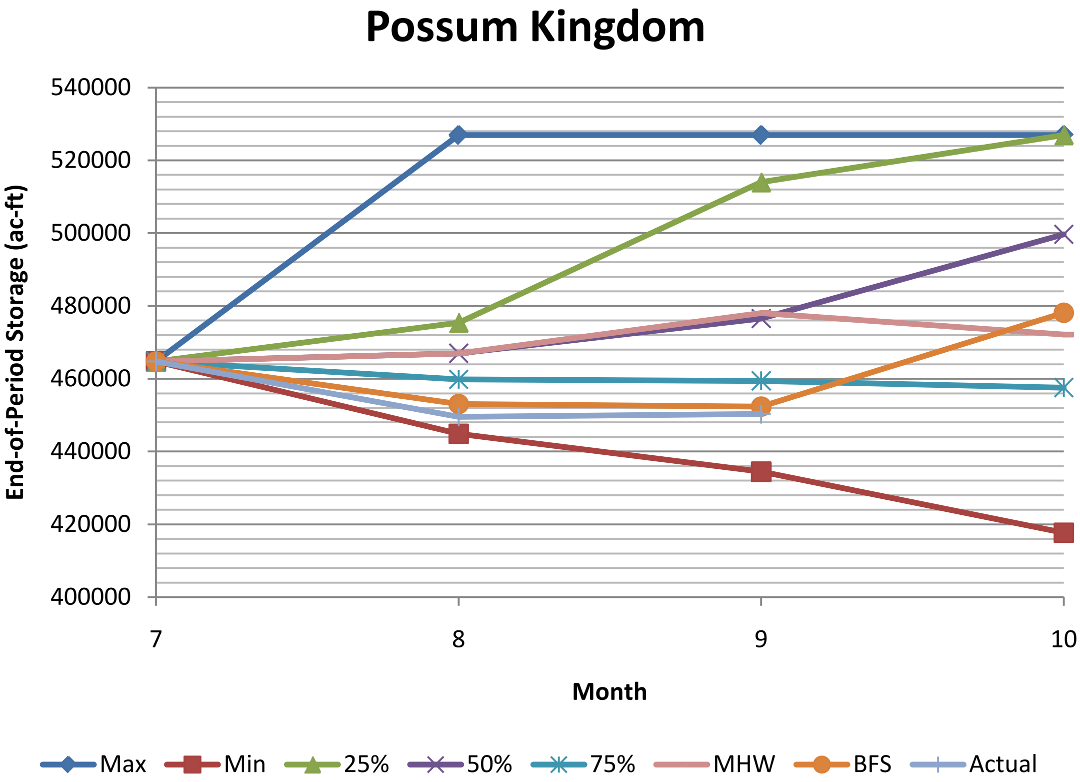


Figure B-4. Selected Storage Plots and Frequency Relationships for Possum Kingdom starting in August

Table B-5. Storage-Frequency Relationships for Granbury starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**109,444**	**106,369**	**102,637**
Frequency (%)	81	92.55	83.58

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1978**	17	0.02758	**96.2**	**94.6**	**86.6**
Maximum	**1900**	194	0.00856	**113.2**	**116.5**	**120.8**
Highest Weight	**1971**	54	0.03570	**100.9**	**108.3**	**108.9**
Best Fit	**2002**	47	0.00717	**100.1**	**102.1**	**103.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	123,943	62.2	59.6	40.5
Trigger 1	103,239	100.0	96.4	83.6
Trigger 2	88,232	100.0	100.0	100.0
Trigger 3	52,872	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	118,333	119,142	114,436	108.1	112.0	111.5
Std Dev	401,442	380,985	585,210	366.8	358.2	570.2
Minimum	103,596	98,588	88,923	94.7	92.7	86.6
99.50%	103,828	100,629	88,923	94.9	94.6	86.6
99%	103,828	100,629	88,923	94.9	94.6	86.6
98%	103,828	100,629	88,923	94.9	94.6	86.6
95%	105,333	105,034	93,984	96.2	98.7	91.6
90%	109,089	108,448	96,791	99.7	102.0	94.3
85%	109,380	108,891	101,332	99.9	102.4	98.7
80%	109,482	113,739	105,665	100.0	106.9	102.9
75%	**110,407**	**116,501**	**107,099**	100.9	109.5	104.3
70%	113,106	118,164	110,500	103.3	111.1	107.7
60%	123,943	123,582	111,834	113.2	116.2	109.0
50%	**123,943**	**123,943**	**115,951**	113.2	116.5	113.0
40%	123,943	123,943	123,943	113.2	116.5	120.8
30%	123,943	123,943	123,943	113.2	116.5	120.8
25%	**123,943**	**123,943**	**123,943**	113.2	116.5	120.8
20%	123,943	123,943	123,943	113.2	116.5	120.8
15%	123,943	123,943	123,943	113.2	116.5	120.8
10%	123,943	123,943	123,943	113.2	116.5	120.8
5%	123,943	123,943	123,943	113.2	116.5	120.8
2%	123,943	123,943	123,943	113.2	116.5	120.8
1%	123,943	123,943	123,943	113.2	116.5	120.8
0.50%	123,943	123,943	123,943	113.2	116.5	120.8
Maximum	123,943	123,943	123,943	113.2	116.5	120.8

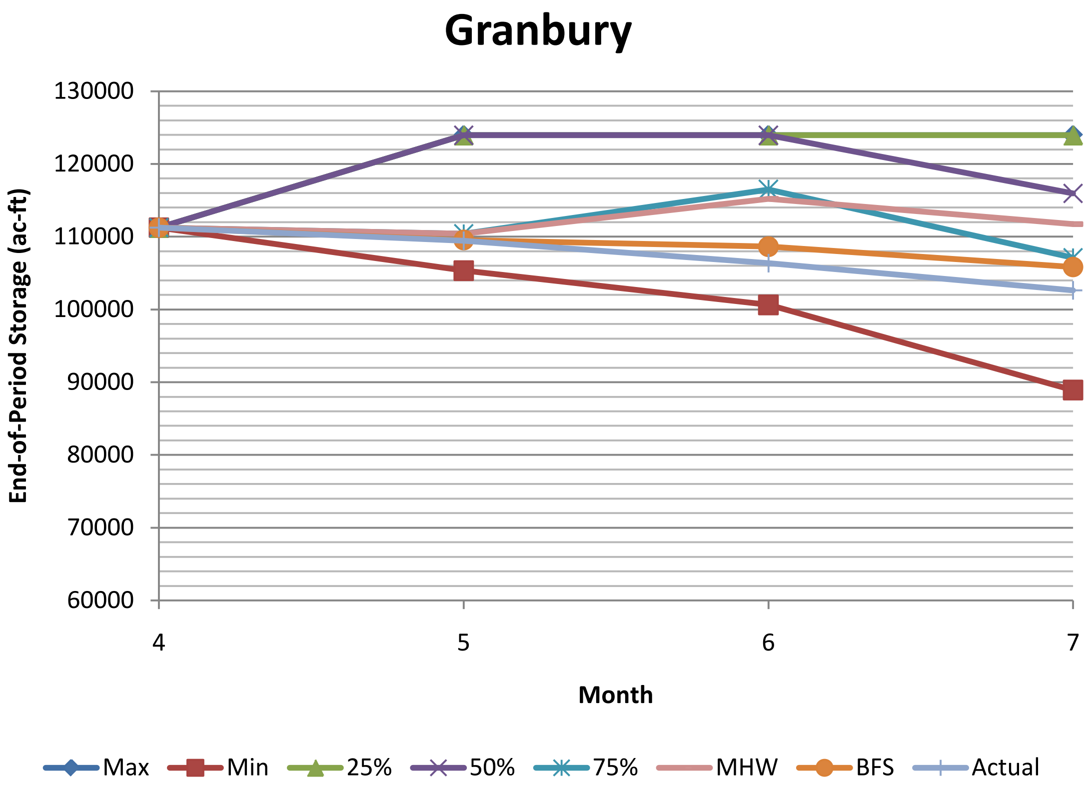


Figure B-5. Selected Storage Plots and Frequency Relationships for Granbury starting in May

Table B-6. Storage-Frequency Relationships for Granbury starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**106,369**	**102,637**	**97,858**
Frequency (%)	86.15	71.47	74.45

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1952**	19.7	0.02680	**93.8**	**85.7**	**77.0**
Maximum	**1900**	223.0	0.00797	**116.5**	**120.8**	**126.7**
Highest Weight	**1927**	112.3	0.03390	**116.5**	**120.8**	**121.3**
Best Fit	**1912**	51.5	0.00799	**102.0**	**95.2**	**100.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	123,943	50	33	19
Trigger 1	103,239	91	71	65
Trigger 2	88,232	100	96	82
Trigger 3	52,872	100	100	100

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	115,066	112,392	107,584	112.1	109.5	109.9
Std Dev	489,210	672,004	833,869	476.6	654.7	852.1
Minimum	99,241	88,010	75,356	96.7	85.7	77.0
99.50%	99,241	88,010	75,356	96.7	85.7	77.0
99%	99,241	88,010	75,356	96.7	85.7	77.0
98%	99,803	88,010	75,356	97.2	85.7	77.0
95%	100,243	91,680	81,758	97.7	89.3	83.5
90%	103,610	96,254	84,763	100.9	93.8	86.6
85%	107,297	96,709	87,276	104.5	94.2	89.2
80%	108,472	97,682	89,169	105.7	95.2	91.1
75%	**108,511**	**99,323**	**94,328**	105.7	96.8	96.4
70%	108,554	103,605	99,131	105.8	100.9	101.3
60%	108,965	110,347	108,506	106.2	107.5	110.9
50%	**123,943**	**113,537**	**112,969**	120.8	110.6	115.4
40%	123,943	121,132	116,089	120.8	118.0	118.6
30%	123,943	123,943	118,693	120.8	120.8	121.3
25%	**123,943**	**123,943**	**121,004**	120.8	120.8	123.7
20%	123,943	123,943	123,712	120.8	120.8	126.4
15%	123,943	123,943	123,943	120.8	120.8	126.7
10%	123,943	123,943	123,943	120.8	120.8	126.7
5%	123,943	123,943	123,943	120.8	120.8	126.7
2%	123,943	123,943	123,943	120.8	120.8	126.7
1%	123,943	123,943	123,943	120.8	120.8	126.7
0.50%	123,943	123,943	123,943	120.8	120.8	126.7
Maximum	123,943	123,943	123,943	120.8	120.8	126.7

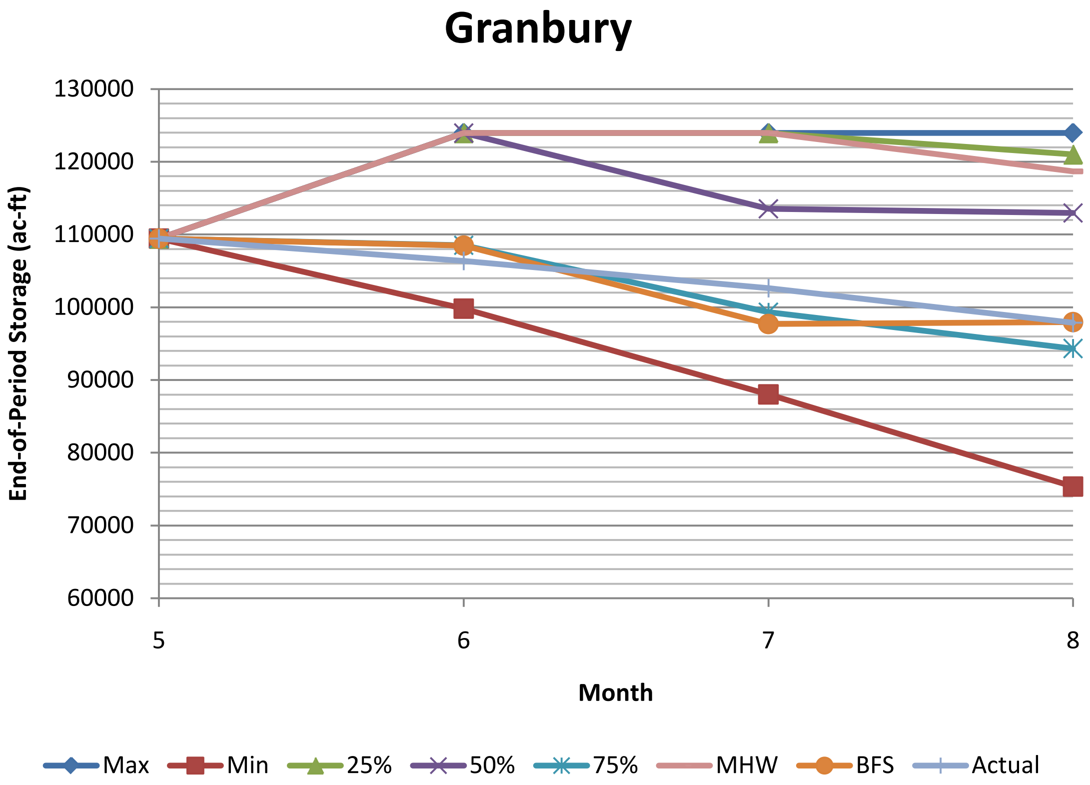


Figure B-6. Selected Storage Plots and Frequency Relationships for Granbury starting in June

Table B-7. Storage-Frequency Relationships for Granbury starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**102,637**	**97,858**	**109,805**
Frequency (%)	50.63	47.09	45.99

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1952**	18	0.00855	**91.9**	**83.0**	**66.8**
Maximum	**1902**	647	0.00899	**120.8**	**126.7**	**112.9**
Highest Weight	**1932**	1154	0.03138	**120.8**	**126.4**	**112.9**
Best Fit	**1949**	125	0.00648	**101.5**	**95.7**	**97.8**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	123,943	25.9	13.4	30.0
Trigger 1	103,239	48.3	41.6	51.3
Trigger 2	88,232	100.0	67.6	68.4
Trigger 3	52,872	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	106,653	101,272	104,024	109.0	103.5	94.7
Std Dev	669,008	910,271	1,049,554	683.7	930.2	955.8
Minimum	93,631	81,266	73,352	95.7	83.0	66.8
99.50%	93,631	81,266	73,352	95.7	83.0	66.8
99%	93,631	82,418	74,618	95.7	84.2	68.0
98%	93,631	82,418	74,900	95.7	84.2	68.2
95%	93,969	82,463	76,031	96.0	84.3	69.2
90%	94,290	84,689	78,137	96.4	86.5	71.2
85%	94,724	84,904	79,608	96.8	86.8	72.5
80%	95,275	85,641	79,678	97.4	87.5	72.6
75%	**95,688**	**85,661**	**84,127**	97.8	87.5	76.6
70%	95,733	85,763	86,136	97.8	87.6	78.4
60%	96,256	92,376	100,404	98.4	94.4	91.4
50%	**103,167**	**95,930**	**107,182**	105.4	98.0	97.6
40%	104,075	105,590	117,202	106.4	107.9	106.7
30%	111,946	119,142	123,943	114.4	121.7	112.9
25%	**123,943**	**121,004**	**123,943**	126.7	123.7	112.9
20%	123,943	123,703	123,943	126.7	126.4	112.9
15%	123,943	123,799	123,943	126.7	126.5	112.9
10%	123,943	123,943	123,943	126.7	126.7	112.9
5%	123,943	123,943	123,943	126.7	126.7	112.9
2%	123,943	123,943	123,943	126.7	126.7	112.9
1%	123,943	123,943	123,943	126.7	126.7	112.9
0.50%	123,943	123,943	123,943	126.7	126.7	112.9
Maximum	123,943	123,943	123,943	126.7	126.7	112.9

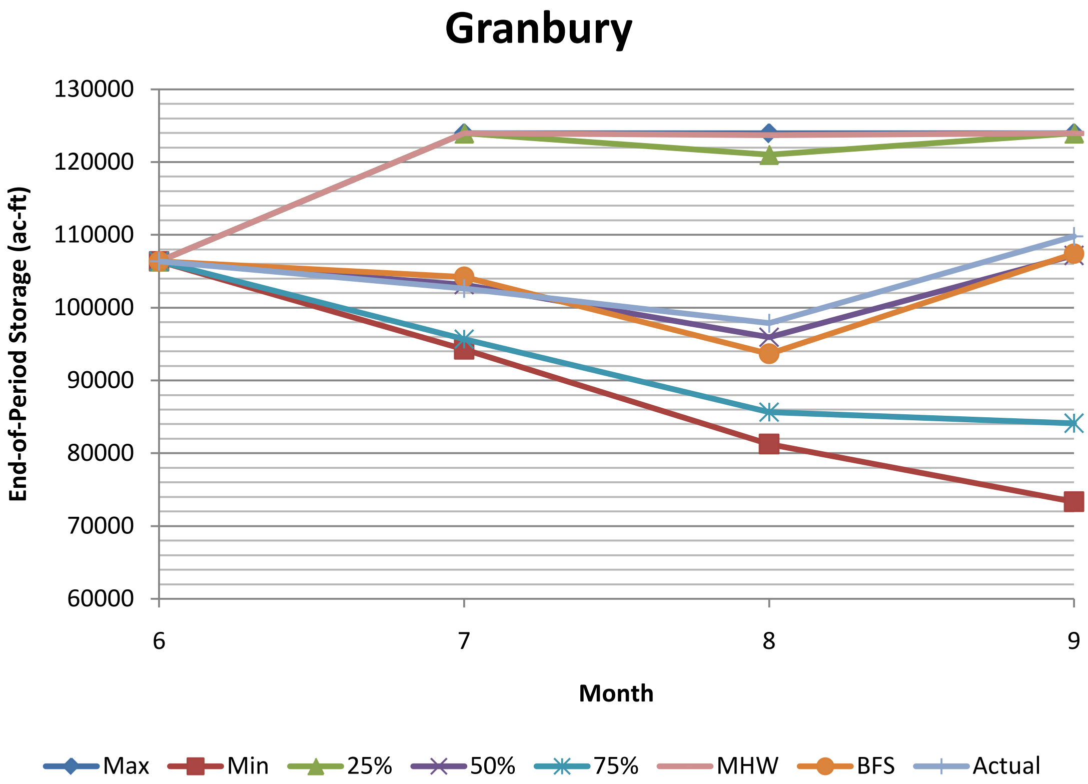


Figure B-7. Selected Storage Plots and Frequency Relationships for Granbury starting in July

Table B-8. Storage-Frequency Relationships for Granbury starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**97,858**	**109,805**	N/A
Frequency (%)	43.93	29.72	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	7	0.00245	**91.0**	**73.6**	**72,910**
Maximum	**1905**	315	0.00717	**126.7**	**112.9**	**123,943**
Highest Weight	**1999**	55	0.03786	**102.8**	**85.2**	**87,612**
Best Fit	**1965**	146	0.02020	**101.0**	**98.1**	**123,943**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	123,943	11.2	25.3	34.8
Trigger 1	103,239	21.0	38.4	58.0
Trigger 2	88,232	100.0	71.5	71.9
Trigger 3	52,872	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	99,328	101,832	106,583	90.5	92.7	
Std Dev	599,431	871,948	1,022,835	545.9	794.1	
Minimum	89,088	80,868	72,910	81.1	73.6	
99.50%	90,064	82,392	75,327	82.0	75.0	
99%	90,064	82,607	76,185	82.0	75.2	
98%	90,463	82,607	76,383	82.4	75.2	
95%	90,789	82,624	76,776	82.7	75.2	
90%	91,069	84,848	79,356	82.9	77.3	
85%	92,022	86,095	80,740	83.8	78.4	
80%	92,329	86,228	82,095	84.1	78.5	
75%	**92,366**	**86,232**	**87,612**	84.1	78.5	
70%	92,385	88,393	90,235	84.1	80.5	
60%	92,699	93,510	102,180	84.4	85.2	
50%	**94,265**	**96,051**	**113,426**	85.8	87.5	
40%	99,767	101,961	123,343	90.9	92.9	
30%	100,315	109,671	123,943	91.4	99.9	
25%	**100,608**	**123,943**	**123,943**	91.6	112.9	
20%	108,263	123,943	123,943	98.6	112.9	
15%	113,301	123,943	123,943	103.2	112.9	
10%	123,943	123,943	123,943	112.9	112.9	
5%	123,943	123,943	123,943	112.9	112.9	
2%	123,943	123,943	123,943	112.9	112.9	
1%	123,943	123,943	123,943	112.9	112.9	
0.50%	123,943	123,943	123,943	112.9	112.9	
Maximum	123,943	123,943	123,943	112.9	112.9	

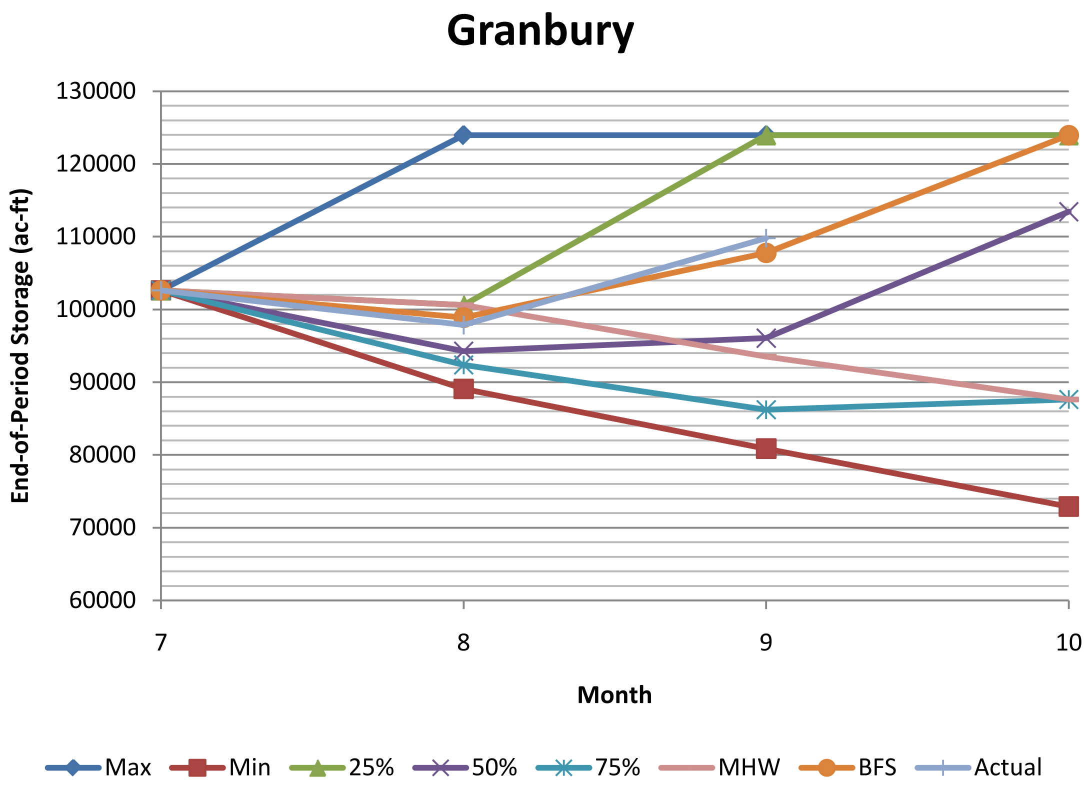


Figure B-8. Selected Storage Plots and Frequency Relationships for Granbury starting in August

Table B-9. Storage-Frequency Relationships for Aquilla starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**44,143**	**41,157**	**38,989**
Frequency (%)	85.14	92.27	83.18

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**2005**	12	0.01472	**100.3**	**65.5**	**65.7**
Maximum	**1900**	308	0.00922	**100.3**	**107.6**	**113.6**
Highest Weight	**2007**	2995	0.10174	**100.3**	**107.6**	**113.6**
Best Fit	**1934**	3	0.01951	**100.3**	**99.8**	**100.9**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	44,295	72.4	49.1	23.5
Trigger 1	33,797	100.0	97.0	92.4
Trigger 2	28,155	100.0	97.0	94.9
Trigger 3	17,878	100.0	100.0	98.9

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	44,661	42,884	40,505	101.2	104.2	103.9
Std Dev	32,403	172,730	290,698	73.4	419.7	745.6
Minimum	42,775	26,970	12,345	96.9	65.5	31.7
99.50%	42,775	26,970	12,411	96.9	65.5	31.8
99%	42,775	26,970	12,411	96.9	65.5	31.8
98%	43,095	27,017	25,603	97.6	65.6	65.7
95%	43,163	37,507	27,823	97.8	91.1	71.4
90%	43,735	41,979	34,345	99.1	102.0	88.1
85%	44,186	42,265	37,933	100.1	102.7	97.3
80%	44,289	42,724	39,461	100.3	103.8	101.2
75%	**44,292**	**42,762**	**39,930**	100.3	103.9	102.4
70%	44,295	43,143	40,807	100.3	104.8	104.7
60%	44,295	43,471	41,463	100.3	105.6	106.3
50%	**44,295**	**44,263**	**42,242**	100.3	107.5	108.3
40%	44,295	44,295	42,682	100.3	107.6	109.5
30%	44,295	44,295	43,446	100.3	107.6	111.4
25%	**44,295**	**44,295**	**44,139**	100.3	107.6	113.2
20%	44,295	44,295	44,295	100.3	107.6	113.6
15%	44,295	44,295	44,295	100.3	107.6	113.6
10%	44,295	44,295	44,295	100.3	107.6	113.6
5%	44,295	44,295	44,295	100.3	107.6	113.6
2%	44,295	44,295	44,295	100.3	107.6	113.6
1%	44,295	44,295	44,295	100.3	107.6	113.6
0.50%	44,295	44,295	44,295	100.3	107.6	113.6
Maximum	44,295	44,295	44,295	100.3	107.6	113.6

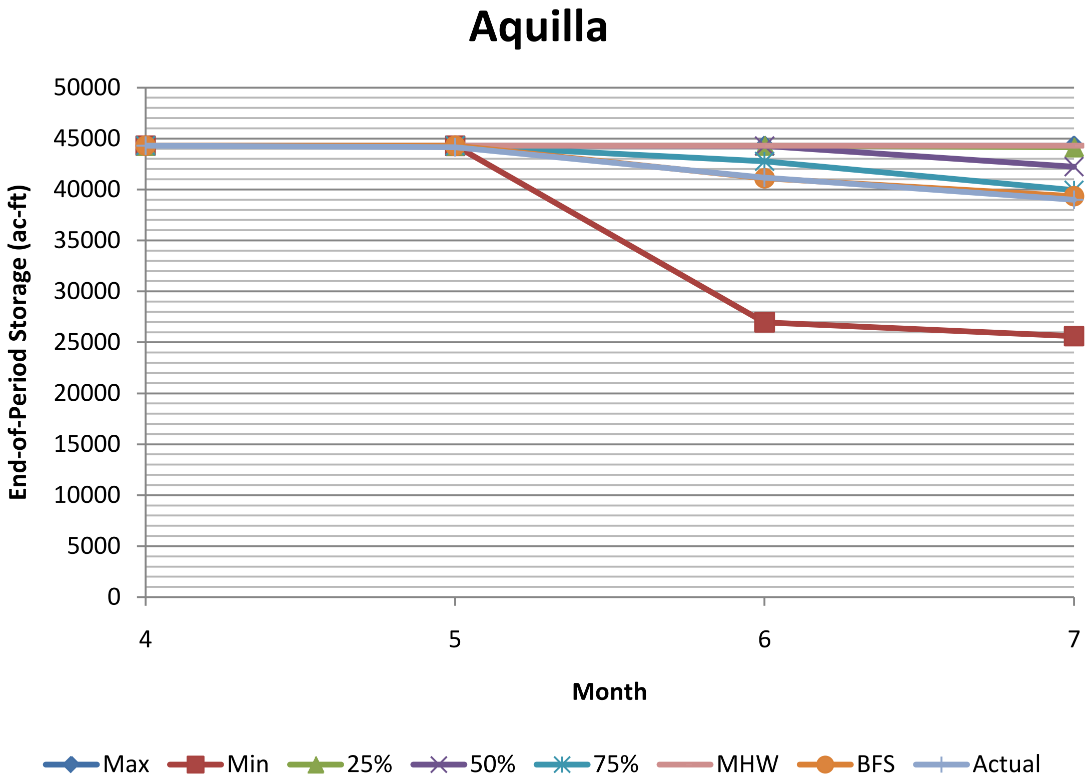


Figure B-9. Selected Storage Plots and Frequency Relationships for Aquilla starting in May

Table B-10. Storage-Frequency Relationships for Aquilla starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**41,157**	**38,989**	**36,229**
Frequency (%)	85.4	75.71	70.11

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1984**	1	0.00575	**103.7**	**26.9**	**26.3**
Maximum	**1941**	1395	0.00351	**107.6**	**113.6**	**122.3**
Highest Weight	**2007**	10363	0.08977	**107.6**	**113.6**	**122.3**
Best Fit	**1925**	1	0.00575	**99.5**	**100.5**	**103.5**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	44,295	43.7	18.1	12.6
Trigger 1	33,797	93.5	83.8	74.1
Trigger 2	28,155	93.5	92.6	86.2
Trigger 3	17,878	100.0	99.1	99.1

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	41,935	39,404	37,784	107.6	101.1	104.3
Std Dev	248,764	339,950	366,552	638.0	871.9	1011.8
Minimum	24,987	10,502	9,520	64.1	26.9	26.3
99.50%	24,987	10,502	9,520	64.1	26.9	26.3
99%	26,041	23,000	21,216	66.8	59.0	58.6
98%	26,041	24,670	23,373	66.8	63.3	64.5
95%	28,028	26,263	24,435	71.9	67.4	67.4
90%	36,894	28,386	27,143	94.6	72.8	74.9
85%	41,965	33,294	30,258	107.6	85.4	83.5
80%	42,116	36,588	32,180	108.0	93.8	88.8
75%	**42,385**	**39,196**	**33,784**	108.7	100.5	93.3
70%	42,541	39,766	36,298	109.1	102.0	100.2
60%	43,017	40,661	38,613	110.3	104.3	106.6
50%	**43,377**	**41,789**	**39,852**	111.3	107.2	110.0
40%	44,295	42,472	41,125	113.6	108.9	113.5
30%	44,295	42,742	41,508	113.6	109.6	114.6
25%	**44,295**	**43,275**	**42,225**	113.6	111.0	116.6
20%	44,295	44,206	42,803	113.6	113.4	118.1
15%	44,295	44,295	43,710	113.6	113.6	120.7
10%	44,295	44,295	44,295	113.6	113.6	122.3
5%	44,295	44,295	44,295	113.6	113.6	122.3
2%	44,295	44,295	44,295	113.6	113.6	122.3
1%	44,295	44,295	44,295	113.6	113.6	122.3
0.50%	44,295	44,295	44,295	113.6	113.6	122.3
Maximum	44,295	44,295	44,295	113.6	113.6	122.3

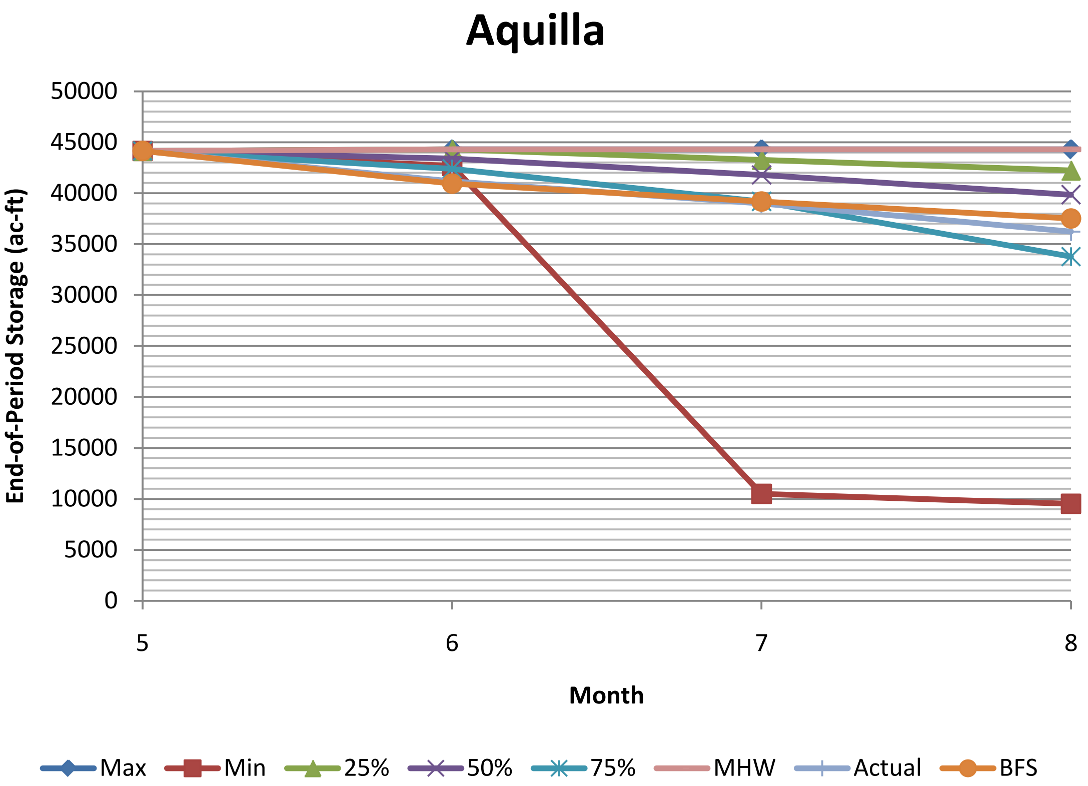


Figure B-10. Selected Storage Plots and Frequency Relationships for Aquilla starting in June

Table B-11. Storage-Frequency Relationships for Aquilla starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**38,989**	**36,229**	**43,385**
Frequency (%)	84.89	94.12	8.9

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**2006**	872	0.01389	**29.0**	**28.7**	**22.6**
Maximum	**1995**	4054	0.00359	**113.6**	**122.3**	**102.1**
Highest Weight	**1929**	16	0.10883	**101.0**	**104.1**	**84.7**
Best Fit	**1974**	6661	0.00529	**100.0**	**99.7**	**102.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	44,295	13.6	6.0	7.4
Trigger 1	33,797	98.2	96.4	96.9
Trigger 2	28,155	98.6	97.3	97.3
Trigger 3	17,878	98.6	98.6	98.6

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	39,663	37,883	37,647	109.5	104.6	86.8
Std Dev	215,636	250,292	263,947	595.2	690.9	608.4
Minimum	11,306	10,406	9,817	31.2	28.7	22.6
99.50%	11,306	10,406	9,817	31.2	28.7	22.6
99%	11,306	10,406	9,817	31.2	28.7	22.6
98%	38,433	21,244	20,475	106.1	58.6	47.2
95%	38,796	36,144	34,994	107.1	99.8	80.7
90%	38,969	37,019	35,508	107.6	102.2	81.8
85%	38,971	37,227	35,917	107.6	102.8	82.8
80%	39,127	37,318	36,451	108.0	103.0	84.0
75%	**39,187**	**37,318**	**36,587**	108.2	103.0	84.3
70%	39,396	37,711	36,691	108.7	104.1	84.6
60%	39,399	37,728	36,729	108.7	104.1	84.7
50%	**39,399**	**37,728**	**36,743**	108.7	104.1	84.7
40%	39,549	38,062	37,416	109.2	105.1	86.2
30%	40,108	38,641	38,263	110.7	106.7	88.2
25%	**40,349**	**39,196**	**39,559**	111.4	108.2	91.2
20%	41,133	40,095	40,470	113.5	110.7	93.3
15%	42,236	41,711	42,325	116.6	115.1	97.6
10%	44,295	42,842	43,117	122.3	118.3	99.4
5%	44,295	44,295	44,295	122.3	122.3	102.1
2%	44,295	44,295	44,295	122.3	122.3	102.1
1%	44,295	44,295	44,295	122.3	122.3	102.1
0.50%	44,295	44,295	44,295	122.3	122.3	102.1
Maximum	44,295	44,295	44,295	122.3	122.3	102.1

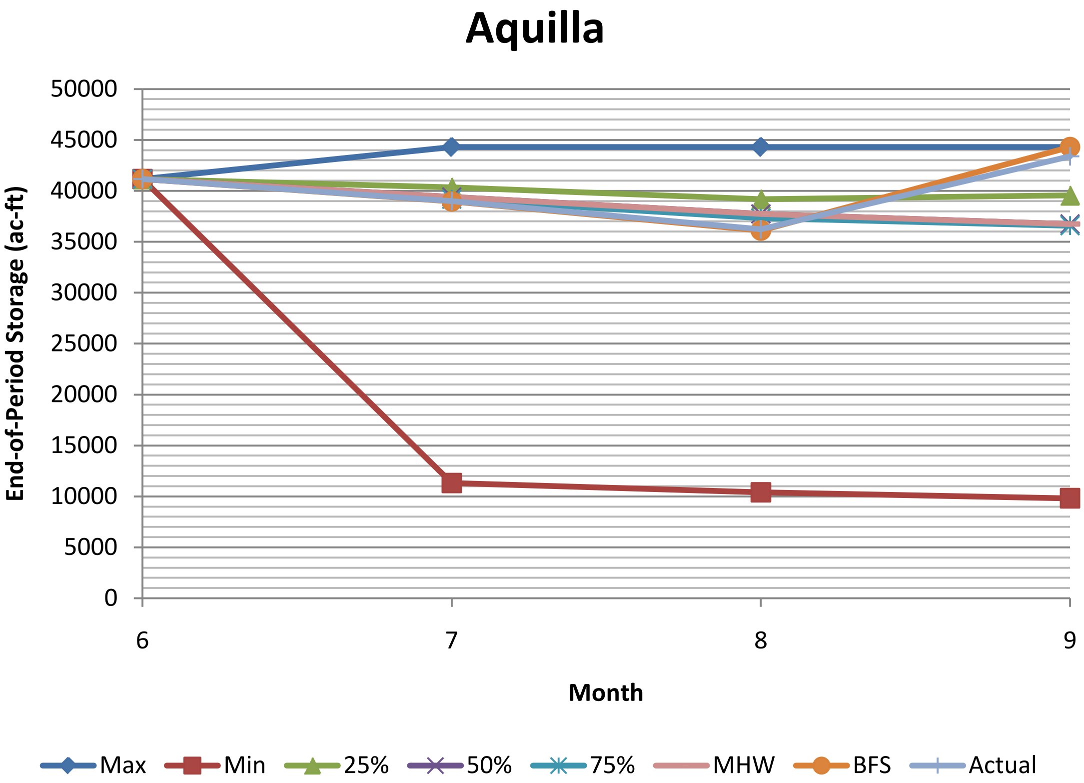


Figure B-11. Selected Storage Plots and Frequency Relationships for Aquilla starting in July

Table B-12. Storage-Frequency Relationships for Aquilla starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**36,229**	**43,385**	N/A
Frequency (%)	99.96	2.75	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	1	0.00019	**99.5**	**78.0**	**31,775**
Maximum	**2007**	8958	0.00300	**122.3**	**102.1**	**44,108**
Highest Weight	**1969**	24	0.13104	**103.9**	**84.8**	**36,677**
Best Fit	**1906**	6917	0.00658	**103.0**	**102.1**	**44,295**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	44,295	0.8	2.0	15.0
Trigger 1	33,797	100.0	100.0	99.9
Trigger 2	28,155	100.0	100.0	100.0
Trigger 3	17,878	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	37,610	37,554	37,587	86.7	86.6	
Std Dev	59,389	98,691	185,421	136.9	227.5	
Minimum	36,064	33,854	31,775	83.1	78.0	
99.50%	36,464	35,216	34,064	84.0	81.2	
99%	36,485	35,379	34,064	84.1	81.5	
98%	36,719	35,379	34,064	84.6	81.5	
95%	36,719	35,561	34,753	84.6	82.0	
90%	36,719	35,935	34,753	84.6	82.8	
85%	37,093	35,935	35,403	85.5	82.8	
80%	37,206	36,304	35,403	85.8	83.7	
75%	**37,330**	**36,312**	**35,403**	86.0	83.7	
70%	37,330	36,372	35,458	86.0	83.8	
60%	37,361	36,527	35,929	86.1	84.2	
50%	**37,547**	**36,607**	**36,557**	86.5	84.4	
40%	37,644	36,772	36,677	86.8	84.8	
30%	37,644	37,258	37,549	86.8	85.9	
25%	**37,763**	**37,470**	**39,152**	87.0	86.4	
20%	38,058	37,851	41,157	87.7	87.2	
15%	38,583	38,905	44,295	88.9	89.7	
10%	38,664	38,905	44,295	89.1	89.7	
5%	39,100	41,165	44,295	90.1	94.9	
2%	41,383	44,295	44,295	95.4	102.1	
1%	42,805	44,295	44,295	98.7	102.1	
0.50%	44,295	44,295	44,295	102.1	102.1	
Maximum	44,295	44,295	44,295	102.1	102.1	

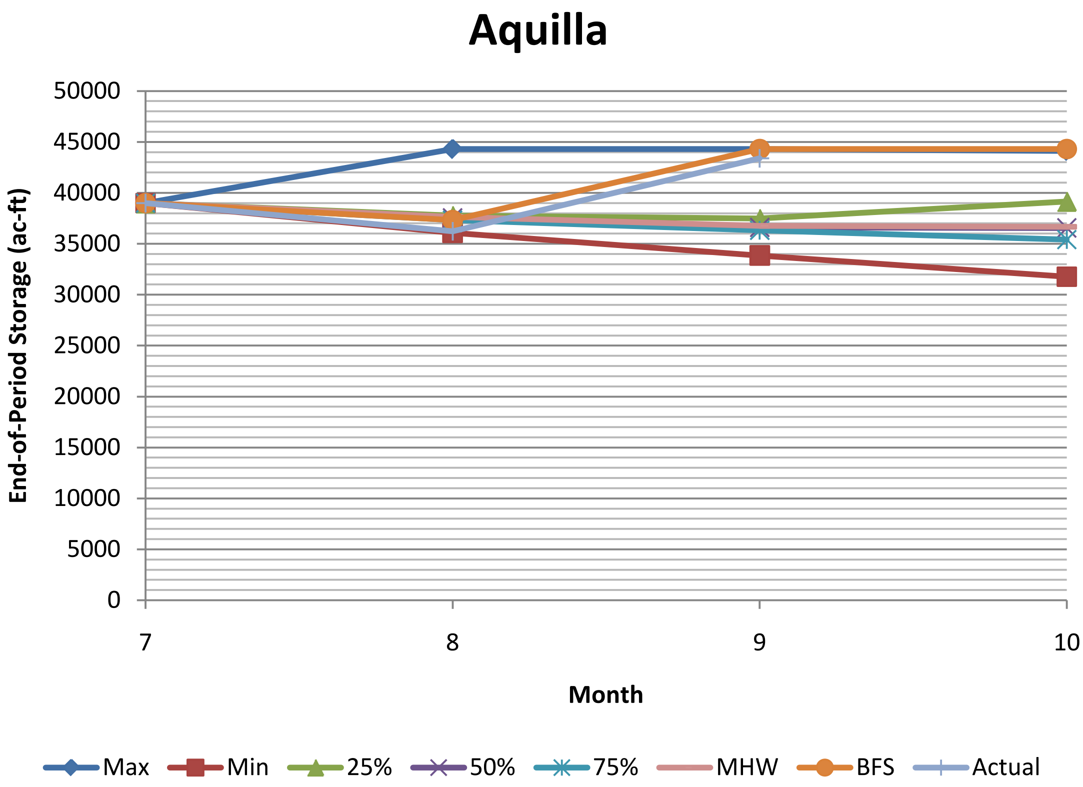


Figure B-12. Selected Storage Plots and Frequency Relationships for Aquilla starting in August

Table B-13. Storage-Frequency Relationships for Proctor starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**31,522**	**33,484**	**30,495**
Frequency (%)	97.78	62.99	63.87

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1974**	1	0.02058	**99.2**	**85.8**	**83.3**
Maximum	**1905**	431	0.00649	**173.4**	**163.2**	**179.2**
Highest Weight	**1964**	6	0.05278	**101.5**	**87.6**	**84.9**
Best Fit	**2003**	29	0.01197	**100.7**	**99.0**	**98.2**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	54,649	25.9	31.2	14.5
Trigger 1	32,955	71.1	66.7	59.0
Trigger 2	22,525	100.0	100.0	100.0
Trigger 3	13,187	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	41,541	41,459	39,778	131.8	123.8	130.4
Std Dev	535,534	579,314	620,528	1698.9	1730.1	2034.9
Minimum	30,932	28,712	25,405	98.1	85.8	83.3
99.50%	31,275	28,712	25,405	99.2	85.8	83.3
99%	31,275	28,712	25,405	99.2	85.8	83.3
98%	31,275	28,712	25,405	99.2	85.8	83.3
95%	31,747	29,341	25,885	100.7	87.6	84.9
90%	31,987	30,046	27,340	101.5	89.7	89.7
85%	32,141	30,410	27,864	102.0	90.8	91.4
80%	32,355	30,506	27,949	102.6	91.1	91.7
75%	**32,401**	**31,662**	**28,849**	102.8	94.6	94.6
70%	32,973	32,224	29,551	104.6	96.2	96.9
60%	33,908	34,893	32,405	107.6	104.2	106.3
50%	**35,828**	**38,705**	**36,995**	113.7	115.6	121.3
40%	40,995	45,691	46,030	130.1	136.5	150.9
30%	53,867	54,649	51,278	170.9	163.2	168.2
25%	**54,649**	**54,649**	**52,158**	173.4	163.2	171.0
20%	54,649	54,649	54,004	173.4	163.2	177.1
15%	54,649	54,649	54,632	173.4	163.2	179.2
10%	54,649	54,649	54,649	173.4	163.2	179.2
5%	54,649	54,649	54,649	173.4	163.2	179.2
2%	54,649	54,649	54,649	173.4	163.2	179.2
1%	54,649	54,649	54,649	173.4	163.2	179.2
0.50%	54,649	54,649	54,649	173.4	163.2	179.2
Maximum	54,649	54,649	54,649	173.4	163.2	179.2

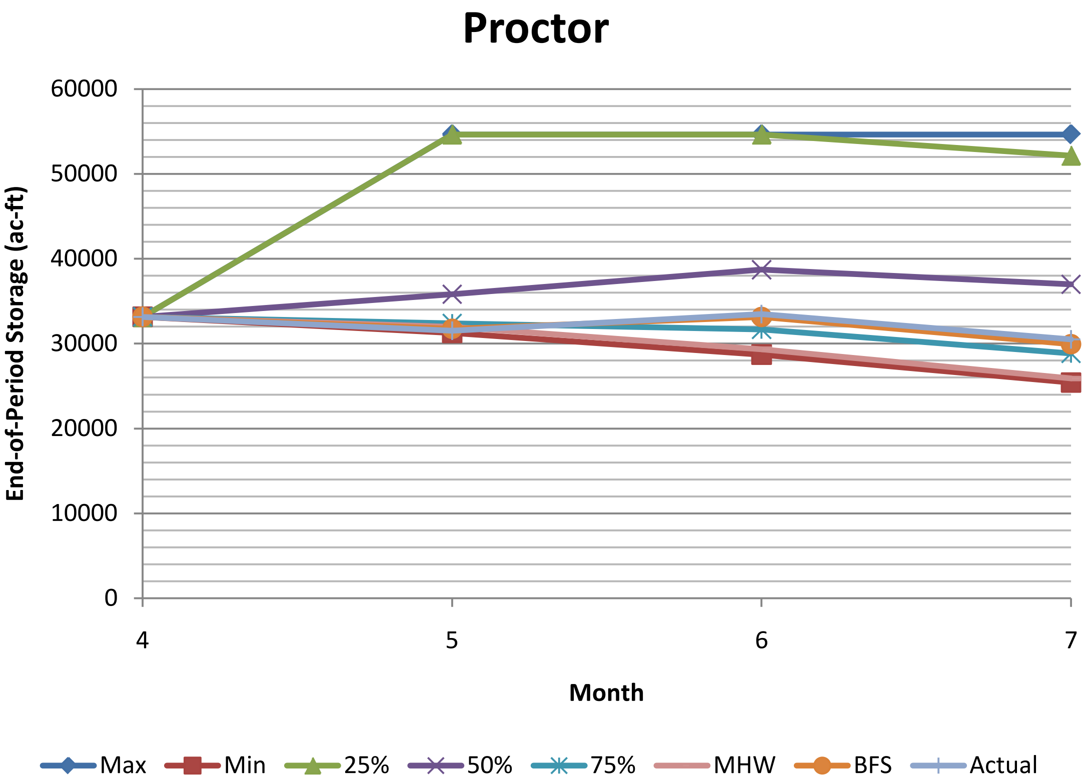


Figure B-13. Selected Storage Plots and Frequency Relationships for Proctor starting in May

Table B-14. Storage-Frequency Relationships for Proctor starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**33,484**	**30,495**	**27,290**
Frequency (%)	17.36	24.13	28.23

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1964**	17	0.07323	**86.4**	**83.6**	**84.0**
Maximum	**1919**	8555	0.00687	**163.2**	**179.2**	**200.3**
Highest Weight	**1952**	34	0.07559	**86.9**	**87.1**	**87.2**
Best Fit	**1967**	485	0.00195	**99.5**	**100.9**	**100.8**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	54,649	7.5	7.0	5.8
Trigger 1	32,955	20.0	19.2	17.3
Trigger 2	22,525	100.0	100.0	100.0
Trigger 3	13,187	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	32,720	30,994	29,177	107.3	101.6	106.9
Std Dev	417,285	482,456	517,085	1368.4	1582.1	1894.8
Minimum	28,783	25,455	22,723	94.4	83.5	83.3
99.50%	28,843	25,455	22,723	94.6	83.5	83.3
99%	28,843	25,503	22,723	94.6	83.6	83.3
98%	28,843	25,503	22,723	94.6	83.6	83.3
95%	28,906	25,503	22,926	94.8	83.6	84.0
90%	28,917	25,792	22,926	94.8	84.6	84.0
85%	29,093	26,225	23,788	95.4	86.0	87.2
80%	29,112	26,575	23,969	95.5	87.1	87.8
75%	**29,229**	**26,575**	**24,194**	95.8	87.1	88.7
70%	29,423	27,020	24,660	96.5	88.6	90.4
60%	29,586	27,077	24,860	97.0	88.8	91.1
50%	**29,597**	**27,081**	**24,874**	97.1	88.8	91.1
40%	29,609	27,298	25,756	97.1	89.5	94.4
30%	30,890	29,063	26,941	101.3	95.3	98.7
25%	**32,647**	**30,037**	**28,018**	107.1	98.5	102.7
20%	32,917	32,337	31,004	107.9	106.0	113.6
15%	36,756	37,609	39,716	120.5	123.3	145.5
10%	47,362	48,515	49,214	155.3	159.1	180.3
5%	54,649	54,649	54,649	179.2	179.2	200.3
2%	54,649	54,649	54,649	179.2	179.2	200.3
1%	54,649	54,649	54,649	179.2	179.2	200.3
0.50%	54,649	54,649	54,649	179.2	179.2	200.3
Maximum	54,649	54,649	54,649	179.2	179.2	200.3

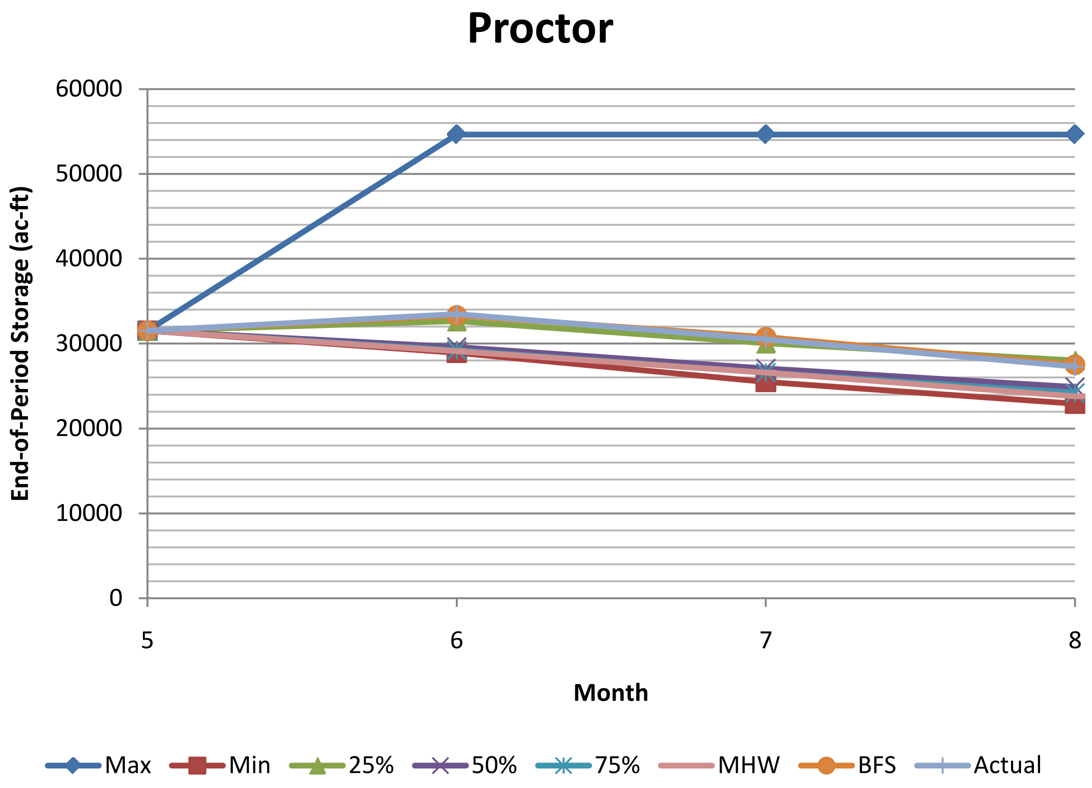


Figure B-10. Selected Storage Plots and Frequency Relationships for Proctor starting in June

Table B-15. Storage-Frequency Relationships for Proctor starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**30,495**	**27,290**	**26,185**
Frequency (%)	63.8	72.84	93.26

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1980**	1	0.01318	**97.1**	**96.4**	**98.6**
Maximum	**2007**	167643	0.01802	**179.2**	**200.3**	**208.7**
Highest Weight	**1963**	56	0.17959	**98.4**	**99.4**	**102.7**
Best Fit	**1999**	143	0.03762	**99.5**	**100.5**	**100.0**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	54,649	2.8	3.8	5.1
Trigger 1	32,955	4.7	7.2	9.5
Trigger 2	22,525	100.0	100.0	100.0
Trigger 3	13,187	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	31,563	29,391	29,401	115.7	107.7	112.3
Std Dev	234,344	318,728	402,037	858.7	1167.9	1535.4
Minimum	29,468	26,316	25,439	108.0	96.4	97.2
99.50%	29,468	26,316	25,439	108.0	96.4	97.2
99%	29,468	26,316	25,454	108.0	96.4	97.2
98%	29,567	26,807	25,454	108.3	98.2	97.2
95%	29,891	26,853	25,745	109.5	98.4	98.3
90%	30,012	27,113	26,187	110.0	99.4	100.0
85%	30,012	27,113	26,577	110.0	99.4	101.5
80%	30,012	27,113	26,877	110.0	99.4	102.6
75%	**30,012**	**27,126**	**26,896**	110.0	99.4	102.7
70%	30,234	27,426	26,896	110.8	100.5	102.7
60%	30,552	27,951	27,025	112.0	102.4	103.2
50%	**30,708**	**28,339**	**27,357**	112.5	103.8	104.5
40%	30,723	28,376	27,677	112.6	104.0	105.7
30%	30,730	28,381	27,697	112.6	104.0	105.8
25%	**30,821**	**28,384**	**27,700**	112.9	104.0	105.8
20%	30,891	28,497	27,705	113.2	104.4	105.8
15%	30,980	29,042	28,486	113.5	106.4	108.8
10%	31,333	29,764	29,819	114.8	109.1	113.9
5%	31,923	43,842	54,649	117.0	160.7	208.7
2%	54,649	54,649	54,649	200.3	200.3	208.7
1%	54,649	54,649	54,649	200.3	200.3	208.7
0.50%	54,649	54,649	54,649	200.3	200.3	208.7
Maximum	54,649	54,649	54,649	200.3	200.3	208.7

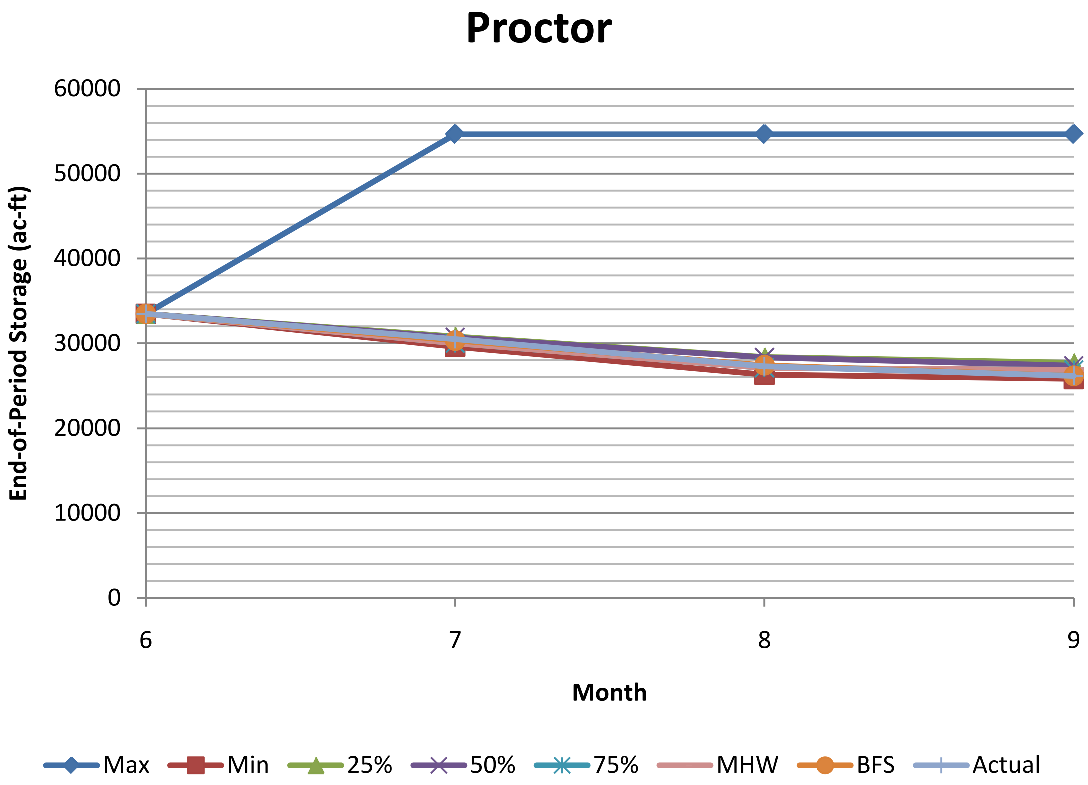


Figure B-11. Selected Storage Plots and Frequency Relationships for Proctor starting in July

Table B-16. Storage-Frequency Relationships for Proctor starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**27,290**	**26,185**	N/A
Frequency (%)	98.62	97.49	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1982**	324	0.00115	**100.9**	**99.1**	**24,752**
Maximum	**1995**	21197	0.00451	**200.3**	**208.7**	**54,649**
Highest Weight	**1998**	13	0.11979	**102.9**	**103.3**	**26,507**
Best Fit	**1985**	312	0.01217	**100.3**	**99.6**	**25,587**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	54,649	6.3	8.3	9.8
Trigger 1	32,955	6.7	9.5	13.0
Trigger 2	22,525	100.0	100.0	100.0
Trigger 3	13,187	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	29,962	29,632	29,921	114.4	113.2	
Std Dev	366,276	429,279	492,390	1398.8	1639.4	
Minimum	27,116	25,900	24,638	103.6	98.9	
99.50%	27,116	25,900	24,638	103.6	98.9	
99%	27,116	25,900	24,638	103.6	98.9	
98%	27,359	26,083	25,069	104.5	99.6	
95%	27,519	26,326	25,380	105.1	100.5	
90%	27,569	26,609	25,587	105.3	101.6	
85%	27,721	26,928	25,954	105.9	102.8	
80%	27,833	27,045	26,091	106.3	103.3	
75%	**28,016**	**27,045**	**26,214**	107.0	103.3	
70%	28,072	27,045	26,425	107.2	103.3	
60%	28,080	27,337	26,507	107.2	104.4	
50%	**28,145**	**27,458**	**26,761**	107.5	104.9	
40%	28,158	27,480	26,793	107.5	104.9	
30%	28,161	27,491	26,999	107.5	105.0	
25%	**28,342**	**27,574**	**27,172**	108.2	105.3	
20%	28,342	27,684	27,617	108.2	105.7	
15%	28,567	28,298	27,712	109.1	108.1	
10%	29,021	28,753	54,594	110.8	109.8	
5%	54,649	54,649	54,649	208.7	208.7	
2%	54,649	54,649	54,649	208.7	208.7	
1%	54,649	54,649	54,649	208.7	208.7	
0.50%	54,649	54,649	54,649	208.7	208.7	
Maximum	54,649	54,649	54,649	208.7	208.7	

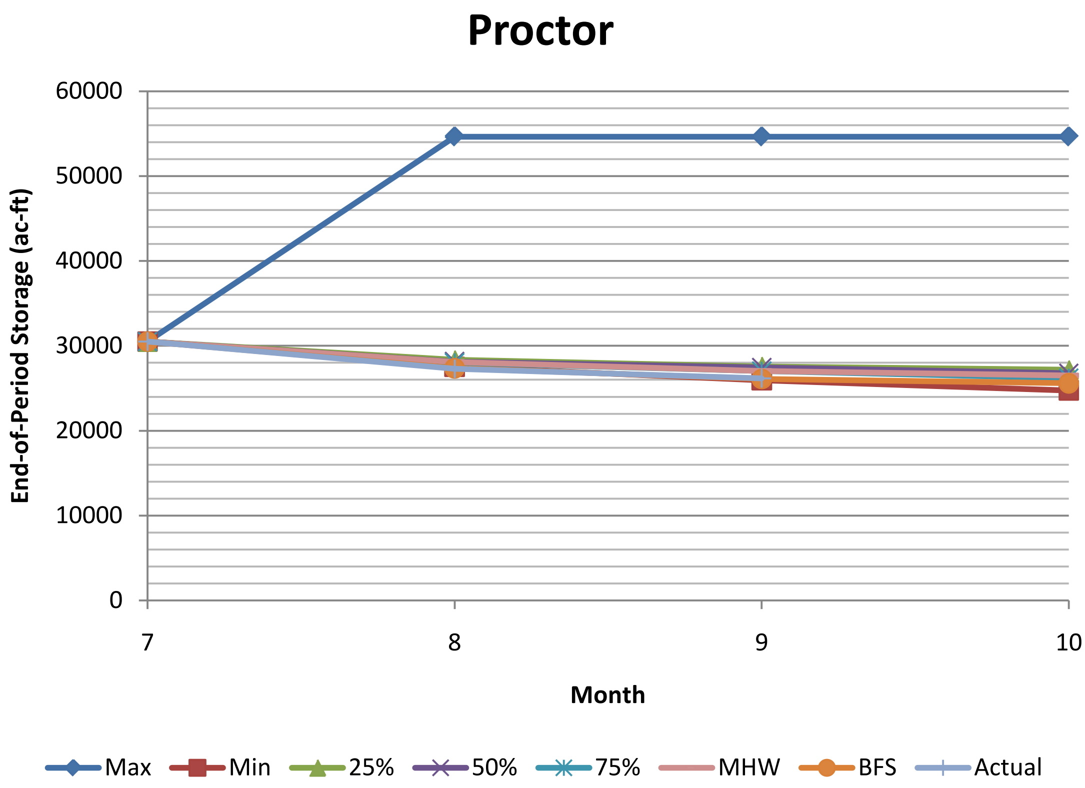


Figure B-12. Selected Storage Plots and Frequency Relationships for Proctor starting in August

Table B-17. Storage-Frequency Relationships for Belton starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**426,400**	**399,257**	**367,106**
Frequency (%)	90.81	99.26	98.17

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1984**	4	0.01095	**97.9**	**102.1**	**97.6**
Maximum	**1900**	187	0.01246	**101.4**	**108.3**	**117.8**
Highest Weight	**2007**	1176	0.03045	**101.4**	**108.3**	**117.8**
Best Fit	**1974**	4	0.00217	**99.5**	**103.1**	**99.5**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	432,408	64.8	67.3	39.5
Trigger 1	320,099	100.0	100.0	100.0
Trigger 2	217,388	100.0	100.0	100.0
Trigger 3	114,737	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	428,425	426,342	418,545	100.5	106.8	114.0
Std Dev	233,887	444,675	1,011,380	54.9	111.4	275.5
Minimum	417,567	397,073	358,463	97.9	99.5	97.6
99.50%	417,567	397,073	358,463	97.9	99.5	97.6
99%	417,567	402,587	358,463	97.9	100.8	97.6
98%	417,854	402,587	375,995	98.0	100.8	102.4
95%	421,875	409,084	380,870	98.9	102.5	103.7
90%	427,941	421,364	389,789	100.4	105.5	106.2
85%	430,996	422,560	395,685	101.1	105.8	107.8
80%	431,150	424,757	401,192	101.1	106.4	109.3
75%	**431,378**	**425,806**	**406,926**	101.2	106.6	110.8
70%	431,798	431,024	414,415	101.3	108.0	112.9
60%	432,408	432,408	418,745	101.4	108.3	114.1
50%	**432,408**	**432,408**	**422,739**	101.4	108.3	115.2
40%	432,408	432,408	432,007	101.4	108.3	117.7
30%	432,408	432,408	432,408	101.4	108.3	117.8
25%	**432,408**	**432,408**	**432,408**	101.4	108.3	117.8
20%	432,408	432,408	432,408	101.4	108.3	117.8
15%	432,408	432,408	432,408	101.4	108.3	117.8
10%	432,408	432,408	432,408	101.4	108.3	117.8
5%	432,408	432,408	432,408	101.4	108.3	117.8
2%	432,408	432,408	432,408	101.4	108.3	117.8
1%	432,408	432,408	432,408	101.4	108.3	117.8
0.50%	432,408	432,408	432,408	101.4	108.3	117.8
Maximum	432,408	432,408	432,408	101.4	108.3	117.8

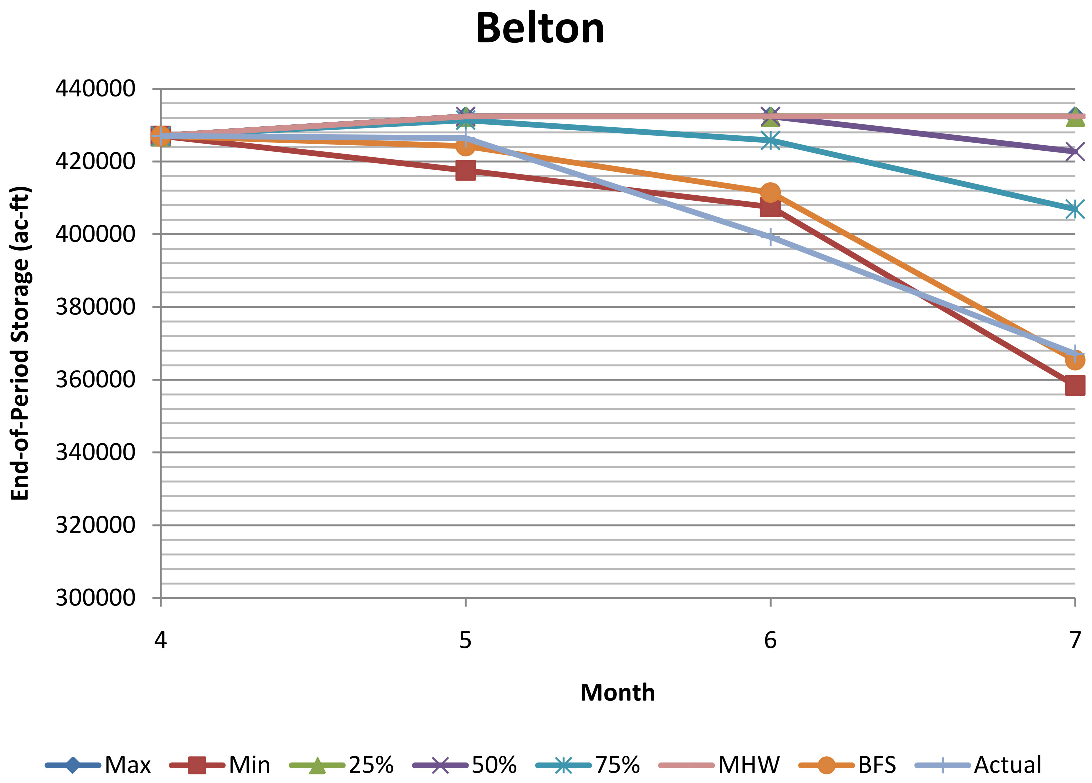


Figure B-13. Selected Storage Plots and Frequency Relationships for Belton starting in May

Table B-18. Storage-Frequency Relationships for Belton starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**399,257**	**367,106**	**338,156**
Frequency (%)	96.74	95.29	100

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1956**	1	0.00686	**100.7**	**96.3**	**100.1**
Maximum	**1900**	306	0.00940	**108.3**	**117.8**	**127.9**
Highest Weight	**2007**	3490	0.11160	**108.3**	**117.8**	**127.9**
Best Fit	**1956**	1	0.00686	**100.7**	**96.3**	**100.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	432,408	47.9	36.1	26.2
Trigger 1	320,099	100.0	100.0	100.0
Trigger 2	217,388	100.0	100.0	100.0
Trigger 3	114,737	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	426,523	409,762	400,008	116.2	111.6	118.3
Std Dev	541,911	1,324,583	1,628,353	147.6	360.8	481.5
Minimum	391,926	353,631	338,351	106.8	96.3	100.1
99.50%	391,926	353,631	338,351	106.8	96.3	100.1
99%	391,926	357,898	343,094	106.8	97.5	101.5
98%	398,008	357,898	343,094	108.4	97.5	101.5
95%	406,182	369,337	352,035	110.6	100.6	104.1
90%	413,380	369,610	358,098	112.6	100.7	105.9
85%	415,967	379,052	362,317	113.3	103.3	107.1
80%	416,325	386,401	365,474	113.4	105.3	108.1
75%	**418,579**	**396,974**	**375,416**	114.0	108.1	111.0
70%	420,059	398,350	379,957	114.4	108.5	112.4
60%	423,866	407,698	393,221	115.5	111.1	116.3
50%	**432,325**	**414,178**	**399,673**	117.8	112.8	118.2
40%	432,408	428,271	418,123	117.8	116.7	123.6
30%	432,408	432,408	428,839	117.8	117.8	126.8
25%	**432,408**	**432,408**	**432,408**	117.8	117.8	127.9
20%	432,408	432,408	432,408	117.8	117.8	127.9
15%	432,408	432,408	432,408	117.8	117.8	127.9
10%	432,408	432,408	432,408	117.8	117.8	127.9
5%	432,408	432,408	432,408	117.8	117.8	127.9
2%	432,408	432,408	432,408	117.8	117.8	127.9
1%	432,408	432,408	432,408	117.8	117.8	127.9
0.50%	432,408	432,408	432,408	117.8	117.8	127.9
Maximum	432,408	432,408	432,408	117.8	117.8	127.9

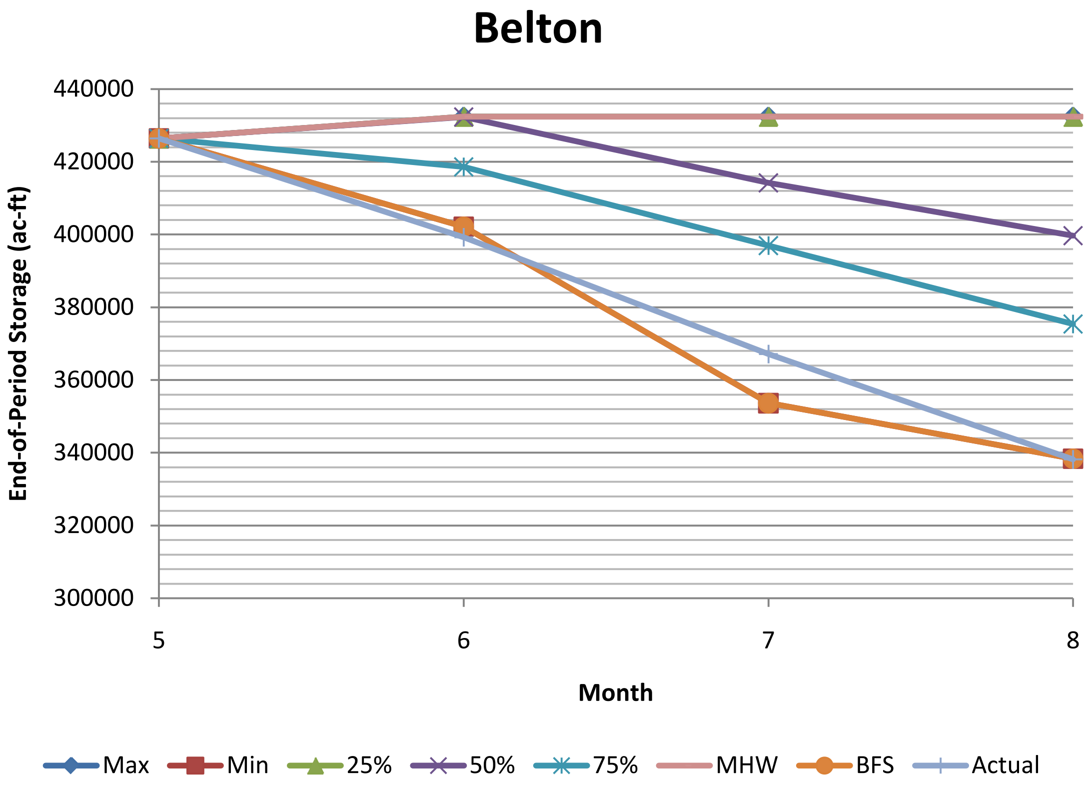


Figure B-10. Selected Storage Plots and Frequency Relationships for Belton starting in June

Table B-19. Storage-Frequency Relationships for Belton starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**367,106**	**338,156**	**348,172**
Frequency (%)	100	100	74.38

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1980**	20	0.15755	**104.3**	**102.7**	**97.1**
Maximum	**1919**	13041	0.00151	**117.8**	**127.9**	**124.2**
Highest Weight	**1980**	20	0.15755	**104.3**	**102.7**	**97.1**
Best Fit	**1980**	20	0.15755	**104.3**	**102.7**	**97.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	432,408	8.5	7.7	9.4
Trigger 1	320,099	100.0	100.0	100.0
Trigger 2	217,388	100.0	100.0	100.0
Trigger 3	114,737	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	398,180	378,517	366,884	117.8	111.9	105.4
Std Dev	867,911	1,313,797	1,588,656	256.7	388.5	456.3
Minimum	377,994	347,371	334,454	111.8	102.7	96.1
99.50%	380,372	347,371	334,454	112.5	102.7	96.1
99%	382,140	347,371	334,454	113.0	102.7	96.1
98%	382,161	347,371	338,168	113.0	102.7	97.1
95%	382,785	347,371	338,168	113.2	102.7	97.1
90%	382,785	347,371	338,168	113.2	102.7	97.1
85%	382,785	347,371	338,168	113.2	102.7	97.1
80%	383,374	353,008	340,779	113.4	104.4	97.9
75%	**384,262**	**357,827**	**347,138**	113.6	105.8	99.7
70%	385,528	364,911	355,567	114.0	107.9	102.1
60%	385,813	369,866	359,011	114.1	109.4	103.1
50%	**385,847**	**372,701**	**364,091**	114.1	110.2	104.6
40%	387,674	375,056	366,383	114.6	110.9	105.2
30%	390,024	378,555	369,601	115.3	111.9	106.2
25%	**392,555**	**379,389**	**374,046**	116.1	112.2	107.4
20%	396,859	385,752	382,725	117.4	114.1	109.9
15%	403,173	396,193	406,134	119.2	117.2	116.6
10%	417,117	417,739	426,207	123.4	123.5	122.4
5%	432,408	432,408	432,408	127.9	127.9	124.2
2%	432,408	432,408	432,408	127.9	127.9	124.2
1%	432,408	432,408	432,408	127.9	127.9	124.2
0.50%	432,408	432,408	432,408	127.9	127.9	124.2
Maximum	432,408	432,408	432,408	127.9	127.9	124.2

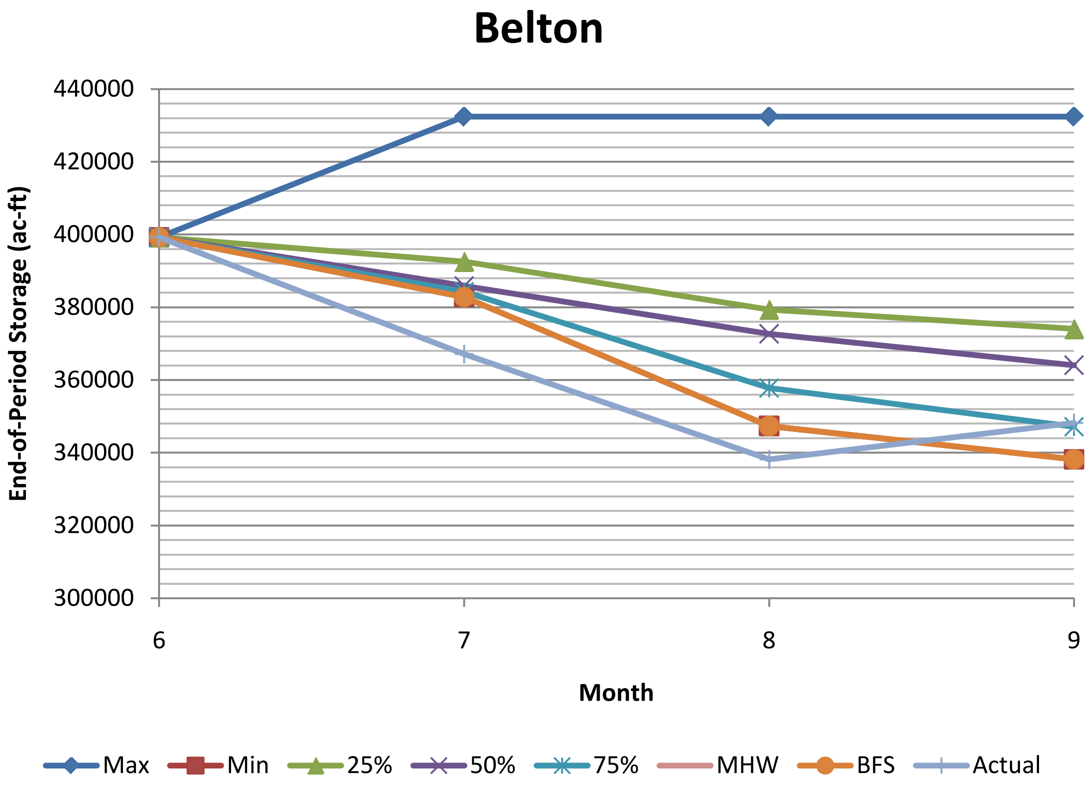


Figure B-11. Selected Storage Plots and Frequency Relationships for Belton starting in July

Table B-20. Storage-Frequency Relationships for Belton starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**338,156**	**348,172**	N/A
Frequency (%)	100	27.4	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1956**	1	0.01669	**104.0**	**97.2**	**327,340**
Maximum	**1995**	21027	0.00100	**127.9**	**124.2**	**432,408**
Highest Weight	**1988**	28	0.16574	**104.6**	**98.5**	**333,639**
Best Fit	**1973**	7602	0.00424	**104.5**	**100.0**	**391,537**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	432,408	2.7	4.7	6.0
Trigger 1	320,099	100.0	100.0	100.0
Trigger 2	217,388	100.0	100.0	100.0
Trigger 3	114,737	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	362,674	348,910	346,504	104.2	100.2	
Std Dev	836,222	1,200,162	1,502,102	240.2	344.7	
Minimum	350,255	338,300	327,340	100.6	97.2	
99.50%	350,255	338,300	327,340	100.6	97.2	
99%	350,255	338,300	327,340	100.6	97.2	
98%	351,029	339,480	327,774	100.8	97.5	
95%	351,631	340,733	329,408	101.0	97.9	
90%	352,817	341,409	330,458	101.3	98.1	
85%	352,871	342,909	333,639	101.3	98.5	
80%	353,606	342,909	333,639	101.6	98.5	
75%	**353,606**	**342,909**	**333,639**	101.6	98.5	
70%	353,606	343,237	333,684	101.6	98.6	
60%	353,901	344,371	335,230	101.6	98.9	
50%	**354,776**	**346,227**	**338,611**	101.9	99.4	
40%	354,851	346,314	338,998	101.9	99.5	
30%	355,242	347,098	341,136	102.0	99.7	
25%	**355,958**	**348,497**	**343,480**	102.2	100.1	
20%	358,246	351,624	349,443	102.9	101.0	
15%	360,206	358,434	356,979	103.5	102.9	
10%	366,535	361,942	383,329	105.3	104.0	
5%	385,966	423,270	432,408	110.9	121.6	
2%	432,408	432,408	432,408	124.2	124.2	
1%	432,408	432,408	432,408	124.2	124.2	
0.50%	432,408	432,408	432,408	124.2	124.2	
Maximum	432,408	432,408	432,408	124.2	124.2	

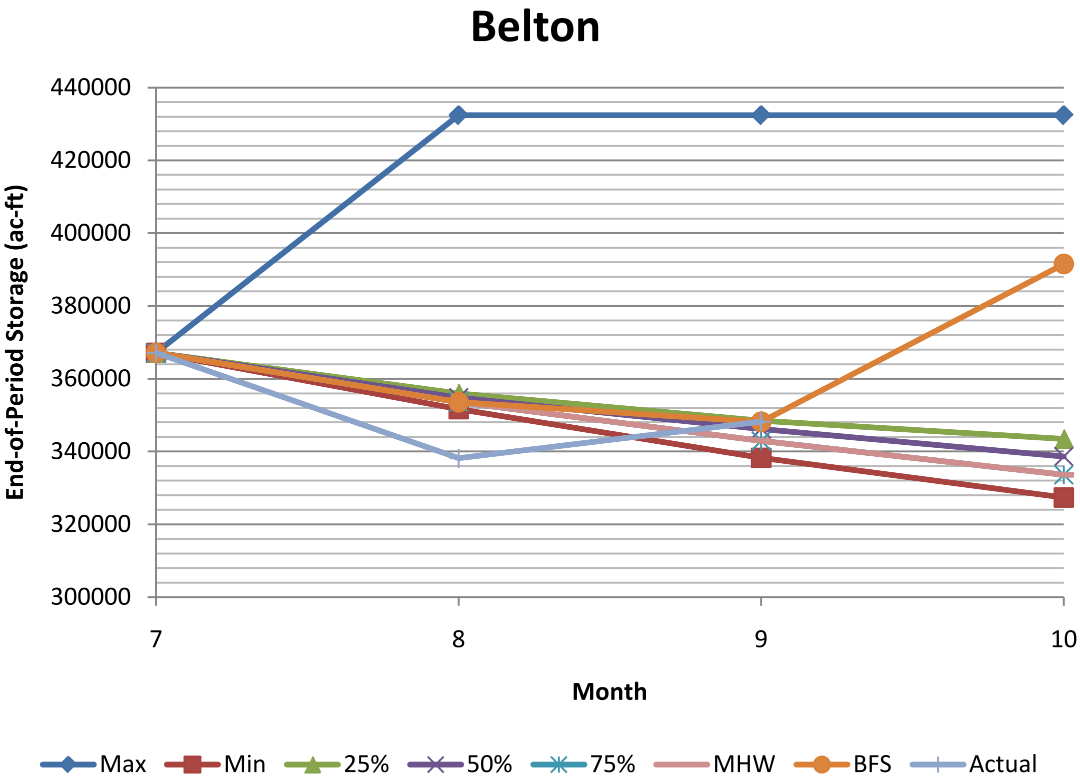


Figure B-12. Selected Storage Plots and Frequency Relationships for Belton starting in August

Table B-21. Storage-Frequency Relationships for Stillhouse Hollow starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**216,903**	**215,029**	**209,502**
Frequency (%)	93.44	93.28	81.75

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1978**	213	0.00683	**98.9**	**99.5**	**83.7**
Maximum	**1900**	597	0.00583	**104.5**	**105.4**	**108.2**
Highest Weight	**1951**	27	0.03593	**101.8**	**102.9**	**102.8**
Best Fit	**1963**	48	0.00484	**100.7**	**100.4**	**100.5**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	226,730	51.3	60.8	31.1
Trigger 1	161,530	100.0	100.0	100.0
Trigger 2	91,417	100.0	100.0	100.0
Trigger 3	42,276	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	222,189	224,263	217,567	102.4	104.3	103.8
Std Dev	219,334	251,080	606,139	101.1	116.8	289.3
Minimum	213,863	208,216	175,363	98.6	96.8	83.7
99.50%	213,863	209,981	181,219	98.6	97.7	86.5
99%	213,863	209,981	182,245	98.6	97.7	87.0
98%	213,937	213,306	182,245	98.6	99.2	87.0
95%	216,522	213,976	194,352	99.8	99.5	92.8
90%	219,214	215,718	203,819	101.1	100.3	97.3
85%	220,600	218,649	207,811	101.7	101.7	99.2
80%	220,867	218,814	210,683	101.8	101.8	100.6
75%	**220,998**	**220,704**	**212,314**	101.9	102.6	101.3
70%	221,028	222,631	214,922	101.9	103.5	102.6
60%	222,170	226,730	217,085	102.4	105.4	103.6
50%	**226,730**	**226,730**	**221,087**	104.5	105.4	105.5
40%	226,730	226,730	223,964	104.5	105.4	106.9
30%	226,730	226,730	226,730	104.5	105.4	108.2
25%	**226,730**	**226,730**	**226,730**	104.5	105.4	108.2
20%	226,730	226,730	226,730	104.5	105.4	108.2
15%	226,730	226,730	226,730	104.5	105.4	108.2
10%	226,730	226,730	226,730	104.5	105.4	108.2
5%	226,730	226,730	226,730	104.5	105.4	108.2
2%	226,730	226,730	226,730	104.5	105.4	108.2
1%	226,730	226,730	226,730	104.5	105.4	108.2
0.50%	226,730	226,730	226,730	104.5	105.4	108.2
Maximum	226,730	226,730	226,730	104.5	105.4	108.2

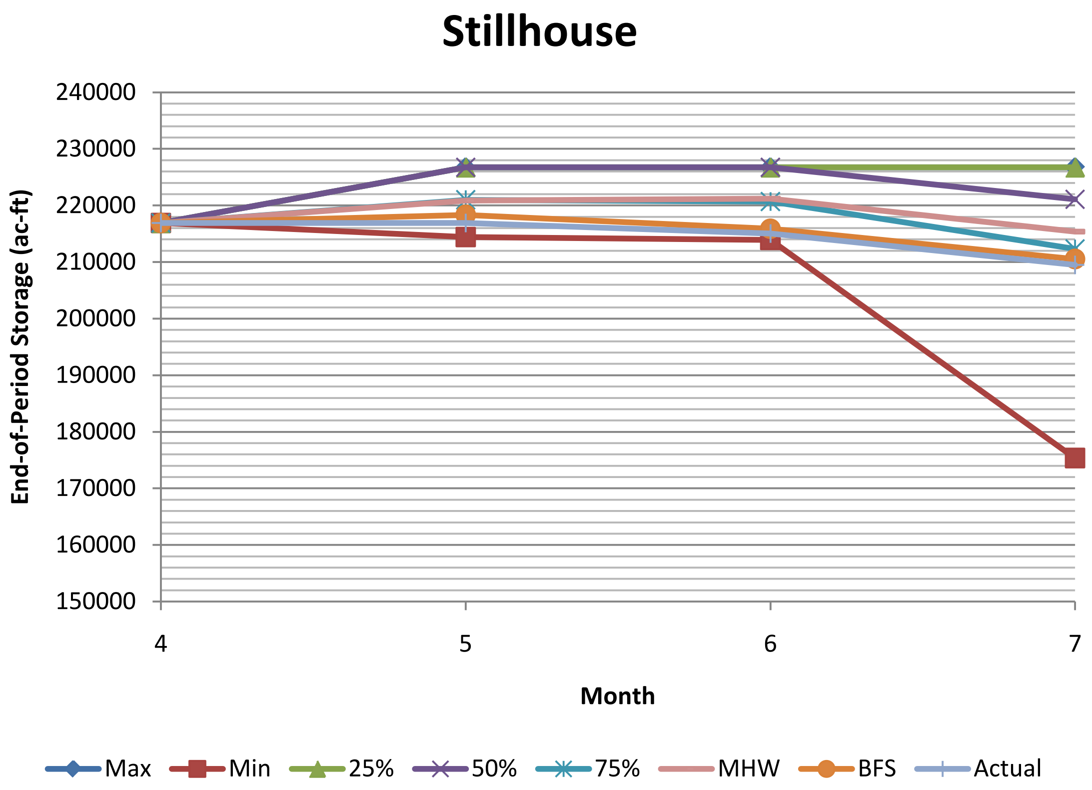


Figure B-21. Selected Storage Plots and Frequency Relationships for Stillhouse Hollow starting in May

Table B-22. Storage-Frequency Relationships for Stillhouse Hollow starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**215,029**	**209,502**	**202,593**
Frequency (%)	64.18	52.66	42.37

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1934**	1	0.01613	**99.6**	**82.5**	**83.5**
Maximum	**1900**	1826	0.00285	**105.4**	**108.2**	**111.9**
Highest Weight	**1984**	15	0.09755	**100.6**	**92.2**	**93.6**
Best Fit	**1963**	26	0.03672	**99.7**	**99.8**	**97.8**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	226,730	22.6	18.9	15.0
Trigger 1	161,530	100.0	100.0	100.0
Trigger 2	91,417	100.0	100.0	100.0
Trigger 3	42,276	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	217,938	209,138	203,253	104.0	99.8	100.3
Std Dev	327,626	837,798	911,964	156.4	399.9	450.1
Minimum	200,693	172,842	169,131	95.8	82.5	83.5
99.50%	201,906	172,842	169,131	96.4	82.5	83.5
99%	201,906	172,842	169,131	96.4	82.5	83.5
98%	201,906	172,871	169,159	96.4	82.5	83.5
95%	211,965	176,661	172,909	101.2	84.3	85.3
90%	212,071	189,102	182,196	101.2	90.3	89.9
85%	212,463	193,101	187,156	101.4	92.2	92.4
80%	214,157	193,101	189,533	102.2	92.2	93.6
75%	**214,169**	**195,931**	**189,533**	102.2	93.5	93.6
70%	214,859	198,286	193,677	102.6	94.6	95.6
60%	216,031	207,295	197,383	103.1	98.9	97.4
50%	**216,348**	**211,048**	**201,508**	103.3	100.7	99.5
40%	217,583	211,491	205,750	103.9	100.9	101.6
30%	222,064	214,992	209,763	106.0	102.6	103.5
25%	**225,278**	**220,830**	**216,777**	107.5	105.4	107.0
20%	226,730	225,561	221,045	108.2	107.7	109.1
15%	226,730	226,730	226,730	108.2	108.2	111.9
10%	226,730	226,730	226,730	108.2	108.2	111.9
5%	226,730	226,730	226,730	108.2	108.2	111.9
2%	226,730	226,730	226,730	108.2	108.2	111.9
1%	226,730	226,730	226,730	108.2	108.2	111.9
0.50%	226,730	226,730	226,730	108.2	108.2	111.9
Maximum	226,730	226,730	226,730	108.2	108.2	111.9

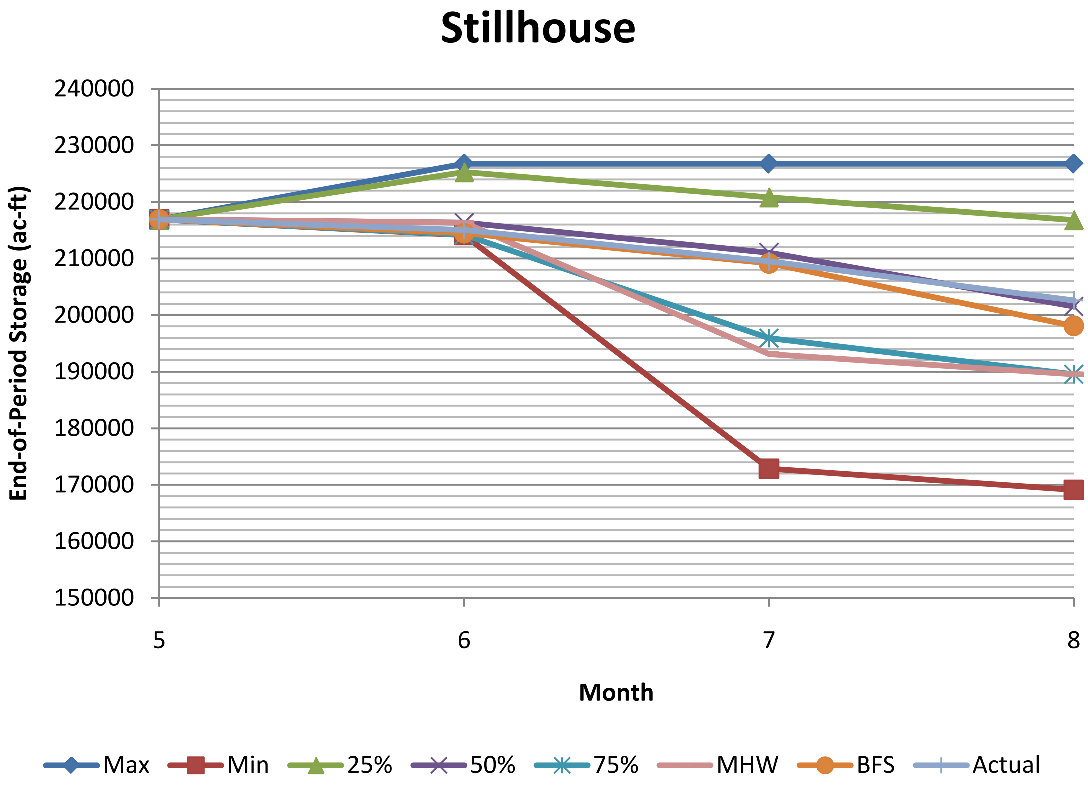


Figure B-22. Selected Storage Plots and Frequency Relationships for Stillhouse Hollow starting in June

Table B-23. Storage-Frequency Relationships for Stillhouse Hollow starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**209,502**	**202,593**	**219,401**
Frequency (%)	28.83	29.2	14.77

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1951**	1	0.01546	**84.2**	**84.4**	**76.7**
Maximum	**1902**	2907	0.00057	**108.2**	**111.9**	**103.3**
Highest Weight	**1912**	24	0.16721	**84.7**	**85.8**	**78.5**
Best Fit	**1962**	967	0.00424	**100.8**	**101.2**	**97.6**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	226,730	12.5	9.8	12.6
Trigger 1	161,530	100.0	100.0	100.0
Trigger 2	91,417	100.0	100.0	100.0
Trigger 3	42,276	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	195,650	191,013	189,905	96.6	94.3	86.6
Std Dev	1,051,509	1,056,261	1,121,773	519.0	521.4	511.3
Minimum	175,921	170,897	168,323	86.8	84.4	76.7
99.50%	175,921	170,897	168,323	86.8	84.4	76.7
99%	175,921	170,897	168,323	86.8	84.4	76.7
98%	175,921	171,691	168,977	86.8	84.7	77.0
95%	175,921	171,691	170,889	86.8	84.7	77.9
90%	176,729	172,365	170,889	87.2	85.1	77.9
85%	177,427	173,739	171,775	87.6	85.8	78.3
80%	177,512	173,750	172,172	87.6	85.8	78.5
75%	**177,518**	**173,751**	**172,172**	87.6	85.8	78.5
70%	177,523	173,751	172,172	87.6	85.8	78.5
60%	177,523	173,761	173,508	87.6	85.8	79.1
50%	**191,119**	**186,404**	**183,481**	94.3	92.0	83.6
40%	195,872	194,461	193,511	96.7	96.0	88.2
30%	208,830	201,075	199,804	103.1	99.3	91.1
25%	**210,595**	**204,438**	**204,205**	103.9	100.9	93.1
20%	212,754	207,966	210,537	105.0	102.7	96.0
15%	216,954	212,938	219,183	107.1	105.1	99.9
10%	226,730	225,478	226,730	111.9	111.3	103.3
5%	226,730	226,730	226,730	111.9	111.9	103.3
2%	226,730	226,730	226,730	111.9	111.9	103.3
1%	226,730	226,730	226,730	111.9	111.9	103.3
0.50%	226,730	226,730	226,730	111.9	111.9	103.3
Maximum	226,730	226,730	226,730	111.9	111.9	103.3

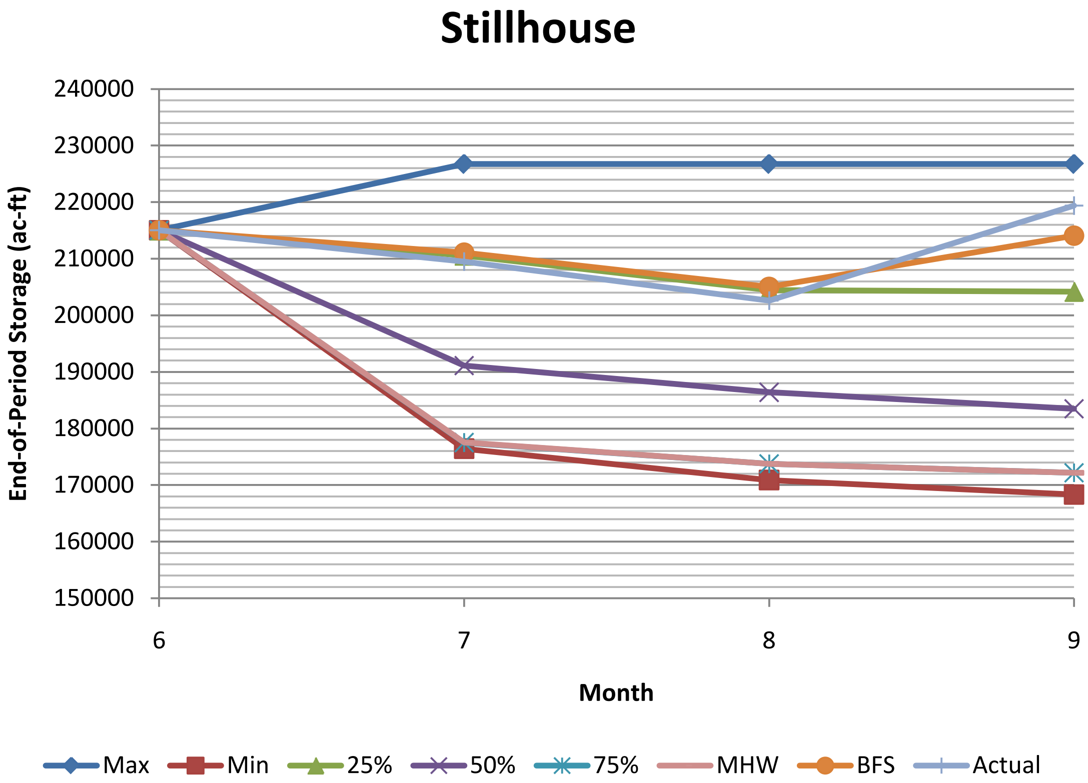


Figure B-23. Selected Storage Plots and Frequency Relationships for Stillhouse Hollow starting in July

Table B-24. Storage-Frequency Relationships for Stillhouse Hollow starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**202,593**	**219,401**	N/A
Frequency (%)	56.05	16.93	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	1	0.00357	**95.9**	**83.5**	**178,600**
Maximum	**1900**	2894	0.00410	**111.9**	**103.3**	**226,730**
Highest Weight	**1931**	6	0.08856	**97.1**	**87.3**	**189,352**
Best Fit	**1942**	939	0.00417	**99.9**	**99.1**	**226,730**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	226,730	10.2	14.1	24.0
Trigger 1	161,530	100.0	100.0	100.0
Trigger 2	91,417	100.0	100.0	100.0
Trigger 3	42,276	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	205,458	205,553	207,092	93.6	93.7	
Std Dev	543,842	663,592	815,292	247.9	302.5	
Minimum	194,375	183,117	178,600	88.6	83.5	
99.50%	195,221	187,314	184,229	89.0	85.4	
99%	195,221	191,372	185,522	89.0	87.2	
98%	195,221	191,564	189,351	89.0	87.3	
95%	195,837	191,564	189,351	89.3	87.3	
90%	195,837	191,564	189,351	89.3	87.3	
85%	196,205	192,743	191,097	89.4	87.8	
80%	196,421	193,888	191,586	89.5	88.4	
75%	**196,433**	**193,980**	**191,586**	89.5	88.4	
70%	196,666	194,532	193,643	89.6	88.7	
60%	201,446	197,932	195,813	91.8	90.2	
50%	**203,841**	**201,287**	**200,400**	92.9	91.7	
40%	205,710	205,418	207,330	93.8	93.6	
30%	207,668	208,853	217,639	94.7	95.2	
25%	**208,346**	**211,062**	**226,247**	95.0	96.2	
20%	212,819	215,670	226,730	97.0	98.3	
15%	214,333	222,140	226,730	97.7	101.2	
10%	226,730	226,730	226,730	103.3	103.3	
5%	226,730	226,730	226,730	103.3	103.3	
2%	226,730	226,730	226,730	103.3	103.3	
1%	226,730	226,730	226,730	103.3	103.3	
0.50%	226,730	226,730	226,730	103.3	103.3	
Maximum	226,730	226,730	226,730	103.3	103.3	

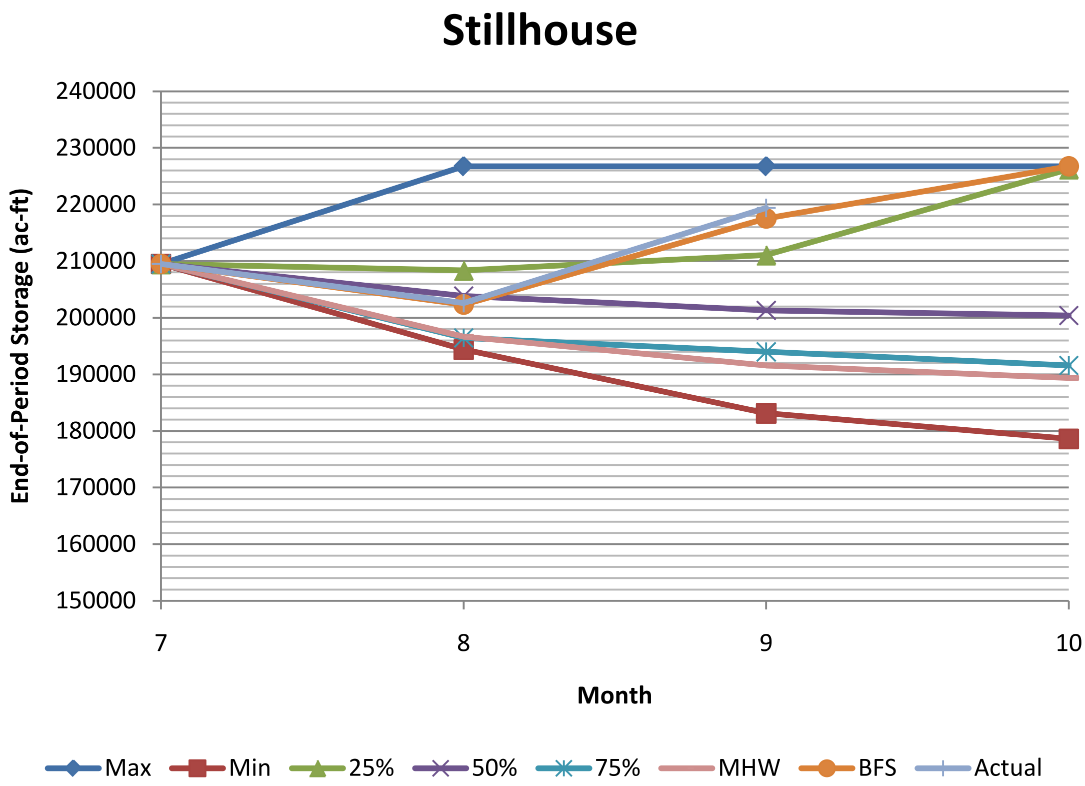


Figure B-24. Selected Storage Plots and Frequency Relationships for Stillhouse Hollow starting in August

Table B-25. Storage-Frequency Relationships for Georgetown starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**19,588**	**18,397**	**16,072**
Frequency (%)	40.21	43.84	39.49

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1956**	1	0.00902	**88.6**	**77.1**	**60.5**
Maximum	**1936**	2056	0.00484	**188.2**	**200.4**	**229.4**
Highest Weight	**1954**	9	0.04489	**90.1**	**77.8**	**61.0**
Best Fit	**1962**	243	0.00850	**94.8**	**101.2**	**97.0**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	36,868	9.0	13.9	9.7
Trigger 1	26,221	18.4	26.0	22.5
Trigger 2	20,740	35.2	36.2	28.7
Trigger 3	14,106	100.0	98.8	49.1

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	22,184	21,360	18,243	113.3	116.1	113.5
Std Dev	347,306	451,054	519,643	1773.1	2451.8	3233.3
Minimum	17,243	13,899	9,411	88.0	75.6	58.6
99.50%	17,243	13,899	9,411	88.0	75.6	58.6
99%	17,293	14,083	9,716	88.3	76.5	60.5
98%	17,352	14,142	9,810	88.6	76.9	61.0
95%	17,360	14,309	9,810	88.6	77.8	61.0
90%	17,641	14,500	10,094	90.1	78.8	62.8
85%	17,645	14,771	10,269	90.1	80.3	63.9
80%	18,004	15,070	10,656	91.9	81.9	66.3
75%	**18,213**	**15,303**	**10,883**	93.0	83.2	67.7
70%	18,449	15,813	11,387	94.2	86.0	70.9
60%	18,464	16,464	12,393	94.3	89.5	77.1
50%	**18,621**	**16,841**	**13,566**	95.1	91.5	84.4
40%	19,937	19,083	15,855	101.8	103.7	98.7
30%	21,726	23,325	20,074	110.9	126.8	124.9
25%	**25,003**	**26,636**	**24,718**	127.6	144.8	153.8
20%	25,664	31,032	28,288	131.0	168.7	176.0
15%	30,397	35,141	33,396	155.2	191.0	207.8
10%	35,946	36,868	36,826	183.5	200.4	229.1
5%	36,868	36,868	36,868	188.2	200.4	229.4
2%	36,868	36,868	36,868	188.2	200.4	229.4
1%	36,868	36,868	36,868	188.2	200.4	229.4
0.50%	36,868	36,868	36,868	188.2	200.4	229.4
Maximum	36,868	36,868	36,868	188.2	200.4	229.4

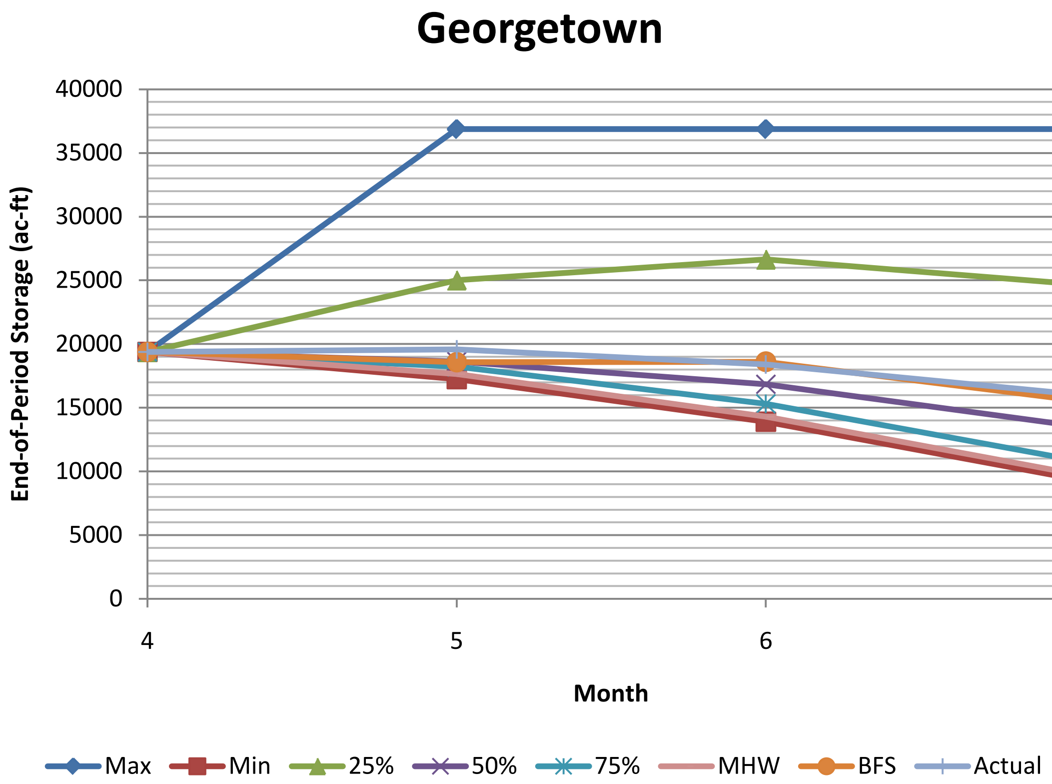


Figure B-25. Selected Storage Plots and Frequency Relationships for Georgetown starting in May

Table B-26. Storage-Frequency Relationships for Georgetown starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**18,397**	**16,072**	**13,714**
Frequency (%)	28.82	25.91	22.26

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1956**	1	0.00518	**88.1**	**72.6**	**52.1**
Maximum	**2007**	12371	0.01708	**200.4**	**229.4**	**268.8**
Highest Weight	**1954**	3	0.08854	**88.2**	**72.7**	**52.1**
Best Fit	**1904**	486	0.00476	**97.6**	**104.9**	**100.0**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	36,868	6.3	7.3	1.9
Trigger 1	26,221	12.1	11.9	10.0
Trigger 2	20,740	21.0	16.5	13.1
Trigger 3	14,106	100.0	36.7	21.3

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	19,656	16,368	12,327	122.3	101.8	89.9
Std Dev	319,860	409,645	434,865	1990.2	2548.8	3171.0
Minimum	16,111	11,668	7,147	100.2	72.6	52.1
99.50%	16,111	11,668	7,147	100.2	72.6	52.1
99%	16,204	11,682	7,147	100.8	72.7	52.1
98%	16,222	11,682	7,147	100.9	72.7	52.1
95%	16,222	11,682	7,147	100.9	72.7	52.1
90%	16,222	11,789	7,323	100.9	73.4	53.4
85%	16,417	11,995	7,558	102.1	74.6	55.1
80%	16,540	12,003	7,622	102.9	74.7	55.6
75%	**16,543**	**12,013**	**7,759**	102.9	74.7	56.6
70%	16,543	12,103	7,814	102.9	75.3	57.0
60%	16,704	12,408	8,214	103.9	77.2	59.9
50%	**17,346**	**13,126**	**8,625**	107.9	81.7	62.9
40%	17,907	13,843	9,716	111.4	86.1	70.8
30%	18,212	14,639	11,174	113.3	91.1	81.5
25%	**19,095**	**16,576**	**12,723**	118.8	103.1	92.8
20%	21,502	18,526	14,787	133.8	115.3	107.8
15%	23,767	21,341	18,411	147.9	132.8	134.3
10%	29,021	30,105	25,959	180.6	187.3	189.3
5%	36,868	36,868	33,294	229.4	229.4	242.8
2%	36,868	36,868	34,960	229.4	229.4	254.9
1%	36,868	36,868	36,868	229.4	229.4	268.8
0.50%	36,868	36,868	36,868	229.4	229.4	268.8
Maximum	36,868	36,868	36,868	229.4	229.4	268.8

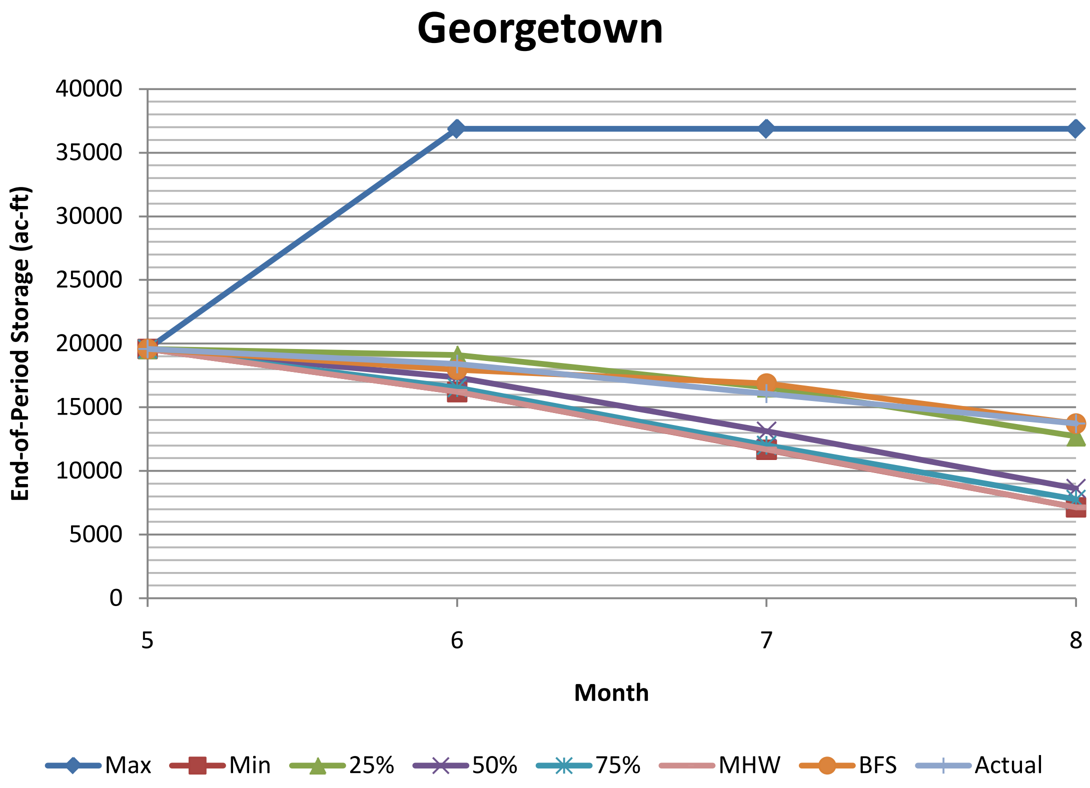


Figure B-26. Selected Storage Plots and Frequency Relationships for Georgetown starting in June

Table B-27. Storage-Frequency Relationships for Georgetown starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**16,072**	**13,714**	**15,919**
Frequency (%)	15.11	14.5	10.58

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1951**	1	0.00644	**85.6**	**66.0**	**41.2**
Maximum	**2007**	37031	0.02647	**229.4**	**268.8**	**231.6**
Highest Weight	**1978**	6	0.15357	**86.1**	**68.7**	**44.4**
Best Fit	**1945**	1918	0.00250	**105.0**	**102.0**	**82.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	36,868	4.1	2.7	3.5
Trigger 1	26,221	6.1	5.4	6.0
Trigger 2	20,740	9.5	7.1	8.4
Trigger 3	14,106	35.6	14.1	12.8

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	15,996	11,845	10,275	116.6	86.4	64.5
Std Dev	285,032	328,961	387,733	2078.4	2398.8	2435.6
Minimum	13,498	9,050	6,565	98.4	66.0	41.2
99.50%	13,735	9,050	6,565	100.2	66.0	41.2
99%	13,757	9,188	6,694	100.3	67.0	42.0
98%	13,772	9,238	6,724	100.4	67.4	42.2
95%	13,772	9,238	6,988	100.4	67.4	43.9
90%	13,772	9,238	6,988	100.4	67.4	43.9
85%	13,822	9,321	6,988	100.8	68.0	43.9
80%	13,830	9,418	7,054	100.8	68.7	44.3
75%	**13,830**	**9,418**	**7,069**	100.8	68.7	44.4
70%	13,830	9,418	7,069	100.8	68.7	44.4
60%	13,931	9,465	7,306	101.6	69.0	45.9
50%	**13,960**	**9,749**	**7,401**	101.8	71.1	46.5
40%	14,065	9,858	7,659	102.6	71.9	48.1
30%	14,486	10,243	8,342	105.6	74.7	52.4
25%	**14,955**	**11,006**	**9,016**	109.0	80.3	56.6
20%	15,432	11,771	10,351	112.5	85.8	65.0
15%	16,289	13,703	12,255	118.8	99.9	77.0
10%	20,122	16,044	18,138	146.7	117.0	113.9
5%	29,662	27,632	27,861	216.3	201.5	175.0
2%	36,868	36,868	36,868	268.8	268.8	231.6
1%	36,868	36,868	36,868	268.8	268.8	231.6
0.50%	36,868	36,868	36,868	268.8	268.8	231.6
Maximum	36,868	36,868	36,868	268.8	268.8	231.6

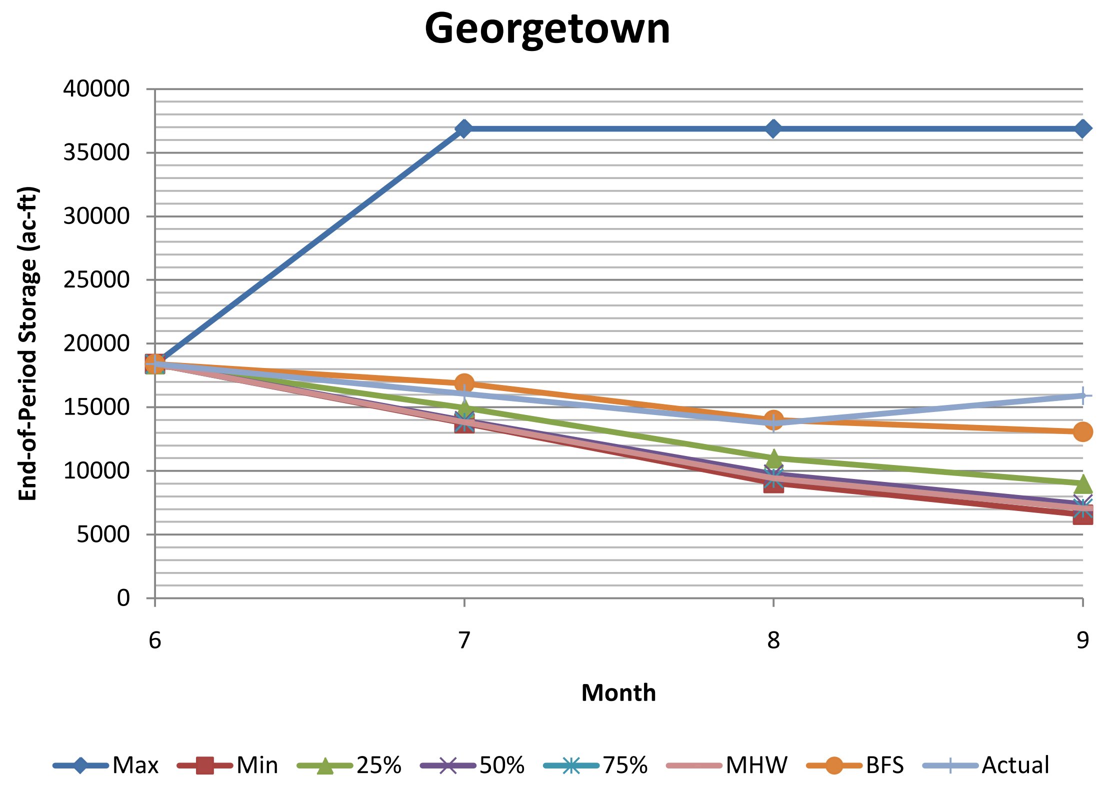


Figure B-27. Selected Storage Plots and Frequency Relationships for Georgetown starting in July

Table B-28. Storage-Frequency Relationships for Georgetown starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**13,714**	**15,919**	N/A
Frequency (%)	4.68	7.95	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1951**	1	0.00654	**82.4**	**55.2**	**7,112**
Maximum	**2007**	18444	0.03094	**268.8**	**231.6**	**36,868**
Highest Weight	**1955**	4	0.06207	**84.9**	**57.6**	**7,522**
Best Fit	**1919**	3999	0.00087	**109.8**	**100.5**	**25,011**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	36,868	3.1	4.1	5.6
Trigger 1	26,221	3.1	4.8	7.7
Trigger 2	20,740	3.1	5.1	10.6
Trigger 3	14,106	6.2	7.7	15.9

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	12,707	11,361	11,347	79.8	71.4	
Std Dev	246,471	332,127	437,073	1548.3	2086.3	
Minimum	11,300	8,789	7,077	71.0	55.2	
99.50%	11,300	8,789	7,077	71.0	55.2	
99%	11,307	8,822	7,112	71.0	55.4	
98%	11,410	8,868	7,235	71.7	55.7	
95%	11,449	8,957	7,425	71.9	56.3	
90%	11,498	8,975	7,425	72.2	56.4	
85%	11,509	9,146	7,522	72.3	57.5	
80%	11,509	9,154	7,617	72.3	57.5	
75%	**11,571**	**9,172**	**7,663**	72.7	57.6	
70%	11,575	9,189	7,675	72.7	57.7	
60%	11,635	9,243	7,872	73.1	58.1	
50%	**11,648**	**9,431**	**7,953**	73.2	59.2	
40%	11,702	9,528	8,536	73.5	59.9	
30%	12,010	10,039	9,242	75.4	63.1	
25%	**12,178**	**10,571**	**10,628**	76.5	66.4	
20%	12,489	10,811	12,228	78.5	67.9	
15%	12,761	11,698	14,829	80.2	73.5	
10%	13,137	13,073	22,040	82.5	82.1	
5%	15,059	23,897	36,868	94.6	150.1	
2%	36,868	36,868	36,868	231.6	231.6	
1%	36,868	36,868	36,868	231.6	231.6	
0.50%	36,868	36,868	36,868	231.6	231.6	
Maximum	36,868	36,868	36,868	231.6	231.6	

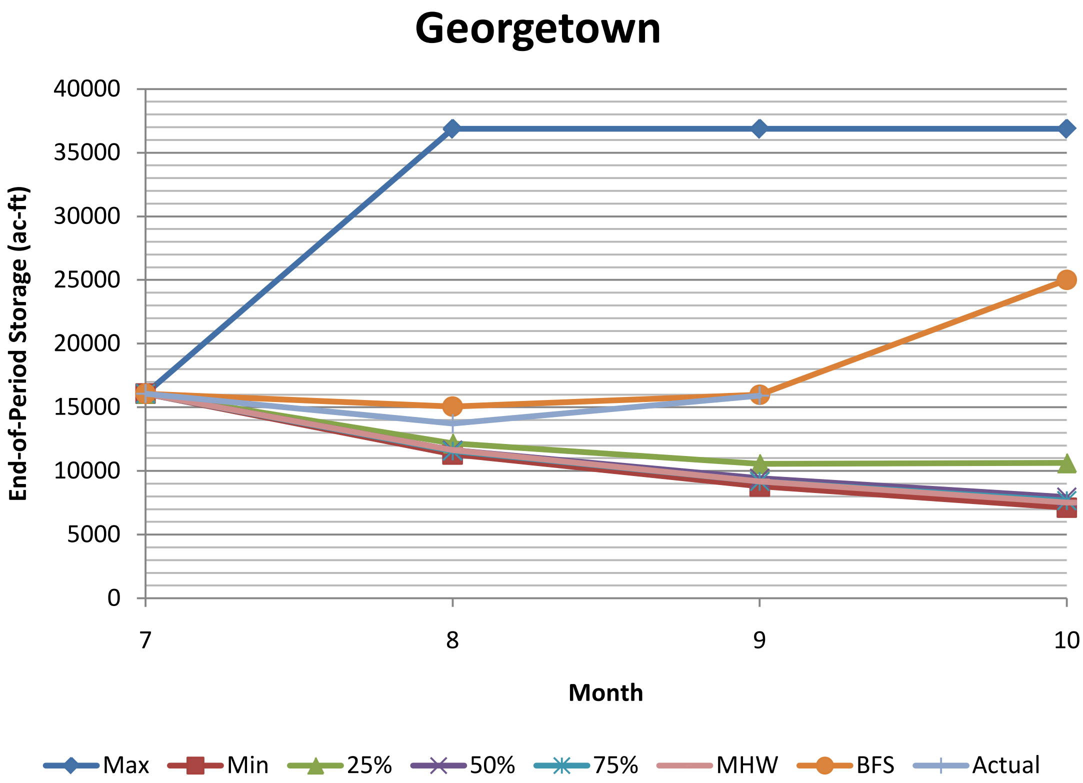


Figure B-28. Selected Storage Plots and Frequency Relationships for Georgetown starting in August

Table B-29. Storage-Frequency Relationships for Granger starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**42,745**	**40,085**	**37,209**
Frequency (%)	21.07	33.47	55.57

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1956**	1	0.01780	**99.8**	**109.7**	**111.1**
Maximum	**1900**	3404	0.00221	**117.7**	**125.6**	**135.3**
Highest Weight	**1911**	19	0.10410	**94.3**	**97.7**	**99.7**
Best Fit	**1953**	366	0.01205	**100.6**	**100.5**	**102.0**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	50,331	13.9	13.9	7.6
Trigger 1	39,183	96.4	59.1	33.3
Trigger 2	30,035	100.0	100.0	99.8
Trigger 3	22,959	100.0	100.0	99.8

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	42,498	41,591	40,134	99.4	103.8	107.9
Std Dev	206,055	241,554	280,282	482.1	602.6	753.3
Minimum	39,037	37,202	18,390	91.3	92.8	49.4
99.50%	39,037	37,202	34,530	91.3	92.8	92.8
99%	39,037	37,202	34,530	91.3	92.8	92.8
98%	39,082	37,423	35,186	91.4	93.4	94.6
95%	39,359	37,610	35,233	92.1	93.8	94.7
90%	40,272	39,022	36,410	94.2	97.3	97.9
85%	40,274	39,123	37,059	94.2	97.6	99.6
80%	40,274	39,136	37,059	94.2	97.6	99.6
75%	**40,282**	**39,136**	**37,075**	94.2	97.6	99.6
70%	40,288	39,168	37,075	94.3	97.7	99.6
60%	40,290	39,181	37,115	94.3	97.7	99.7
50%	**40,292**	**39,730**	**37,835**	94.3	99.1	101.7
40%	40,350	39,923	38,077	94.4	99.6	102.3
30%	40,437	40,290	39,742	94.6	100.5	106.8
25%	**40,558**	**44,785**	**44,031**	94.9	111.7	118.3
20%	43,019	46,670	46,188	100.6	116.4	124.1
15%	47,541	49,750	48,155	111.2	124.1	129.4
10%	50,331	50,331	49,809	117.7	125.6	133.9
5%	50,331	50,331	50,331	117.7	125.6	135.3
2%	50,331	50,331	50,331	117.7	125.6	135.3
1%	50,331	50,331	50,331	117.7	125.6	135.3
0.50%	50,331	50,331	50,331	117.7	125.6	135.3
Maximum	50,331	50,331	50,331	117.7	125.6	135.3

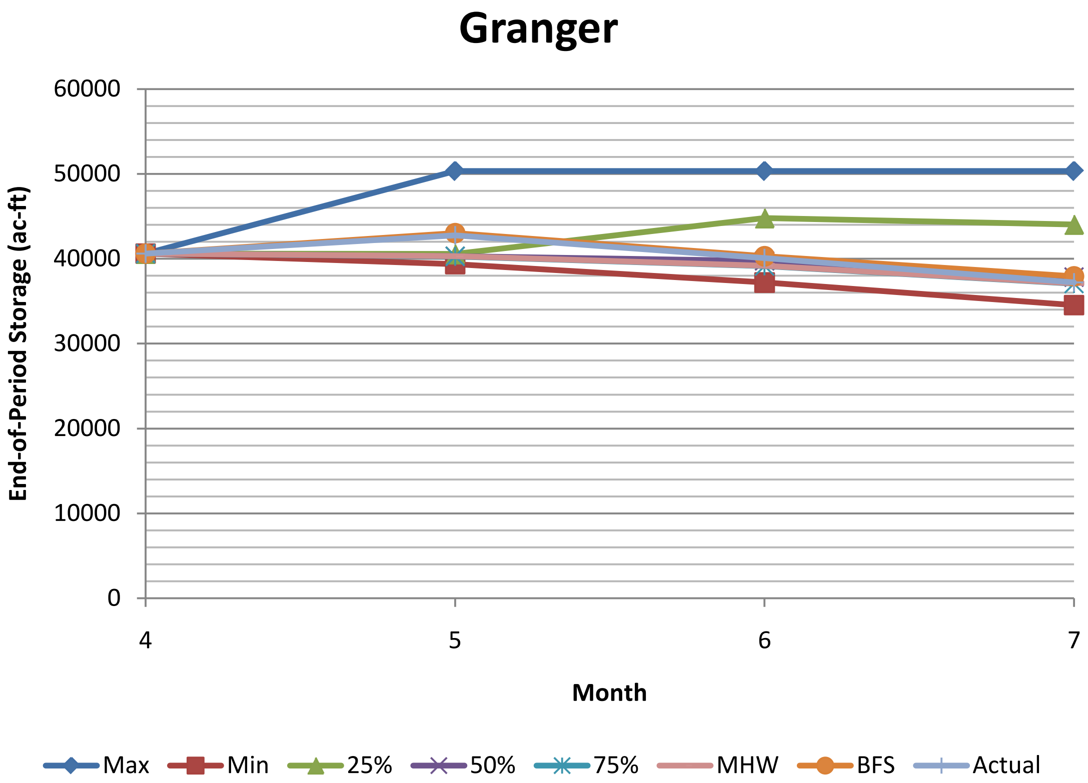


Figure B-29. Selected Storage Plots and Frequency Relationships for Granger starting in May

Table B-30. Storage-Frequency Relationships for Granger starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**40,085**	**37,209**	**34,474**
Frequency (%)	99.7	99.5	99.8

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1916**	4410	0.00004	**125.6**	**56.4**	**56.9**
Maximum	**1907**	4261	0.00060	**125.6**	**135.3**	**146.0**
Highest Weight	**1954**	24	0.20442	**100.6**	**101.3**	**102.1**
Best Fit	**1954**	24	0.20442	**100.6**	**101.3**	**102.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	50,331	4.6	2.4	1.7
Trigger 1	39,183	100.0	49.8	17.6
Trigger 2	30,035	100.0	100.0	99.8
Trigger 3	22,959	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	42,080	39,779	37,831	113.1	106.9	109.7
Std Dev	130,802	162,617	191,727	351.5	437.0	556.2
Minimum	40,029	20,986	19,620	107.6	56.4	56.9
99.50%	40,317	37,661	35,168	108.4	101.2	102.0
99%	40,317	37,661	35,168	108.4	101.2	102.0
98%	40,317	37,695	35,187	108.4	101.3	102.1
95%	40,317	37,695	35,187	108.4	101.3	102.1
90%	40,317	37,695	35,187	108.4	101.3	102.1
85%	40,317	37,695	35,187	108.4	101.3	102.1
80%	40,317	37,695	35,187	108.4	101.3	102.1
75%	**41,169**	**38,609**	**35,260**	110.6	103.8	102.3
70%	41,191	38,609	35,260	110.7	103.8	102.3
60%	41,600	38,635	36,784	111.8	103.8	106.7
50%	**41,703**	**38,892**	**37,470**	112.1	104.5	108.7
40%	41,716	39,500	37,645	112.1	106.2	109.2
30%	42,150	39,991	38,023	113.3	107.5	110.3
25%	**42,343**	**40,160**	**38,075**	113.8	107.9	110.4
20%	42,346	40,166	38,251	113.8	107.9	111.0
15%	42,409	41,315	40,094	114.0	111.0	116.3
10%	43,951	42,092	42,095	118.1	113.1	122.1
5%	48,876	47,907	46,397	131.4	128.8	134.6
2%	50,331	50,331	49,242	135.3	135.3	142.8
1%	50,331	50,331	50,331	135.3	135.3	146.0
0.50%	50,331	50,331	50,331	135.3	135.3	146.0
Maximum	50,331	50,331	50,331	135.3	135.3	146.0

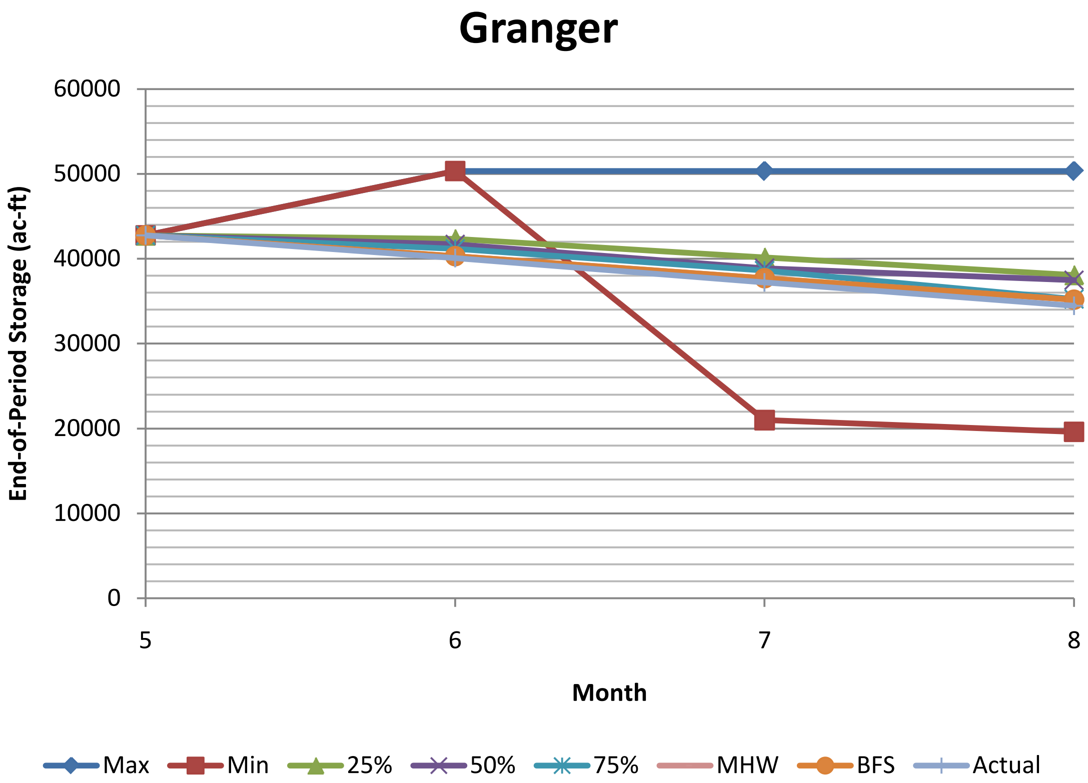


Figure B-30. Selected Storage Plots and Frequency Relationships for Granger starting in June

Table B-31. Storage-Frequency Relationships for Granger starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**37,209**	**34,474**	**46,514**
Frequency (%)	96.54	98.36	8.11

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1951**	1	0.01641	**99.6**	**98.0**	**69.8**
Maximum	**1961**	15835	0.00081	**135.3**	**146.0**	**108.2**
Highest Weight	**1978**	51	0.18164	**100.7**	**103.3**	**75.7**
Best Fit	**1970**	3132	0.00043	**101.1**	**102.3**	**90.2**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	50,331	5.4	4.7	6.0
Trigger 1	39,183	18.8	12.3	14.7
Trigger 2	30,035	100.0	100.0	100.0
Trigger 3	22,959	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	38,856	37,293	36,789	112.7	108.2	79.1
Std Dev	171,609	200,704	243,024	497.8	582.2	522.5
Minimum	36,225	33,799	32,489	105.1	98.0	69.8
99.50%	37,070	33,799	32,489	107.5	98.0	69.8
99%	37,070	33,799	32,489	107.5	98.0	69.8
98%	37,199	34,663	32,723	107.9	100.5	70.4
95%	37,295	34,973	33,060	108.2	101.4	71.1
90%	37,359	35,021	33,872	108.4	101.6	72.8
85%	37,479	35,628	34,587	108.7	103.3	74.4
80%	37,479	35,628	35,160	108.7	103.3	75.6
75%	**37,479**	**35,628**	**35,166**	108.7	103.3	75.6
70%	37,479	35,628	35,193	108.7	103.3	75.7
60%	37,988	36,128	35,193	110.2	104.8	75.7
50%	**37,994**	**36,131**	**35,262**	110.2	104.8	75.8
40%	38,127	36,244	35,430	110.6	105.1	76.2
30%	38,270	36,451	36,055	111.0	105.7	77.5
25%	**38,477**	**36,489**	**36,400**	111.6	105.8	78.3
20%	38,600	37,708	37,096	112.0	109.4	79.8
15%	39,890	38,374	39,129	115.7	111.3	84.1
10%	39,930	40,346	43,163	115.8	117.0	92.8
5%	50,331	49,014	50,331	146.0	142.2	108.2
2%	50,331	50,331	50,331	146.0	146.0	108.2
1%	50,331	50,331	50,331	146.0	146.0	108.2
0.50%	50,331	50,331	50,331	146.0	146.0	108.2
Maximum	50,331	50,331	50,331	146.0	146.0	108.2

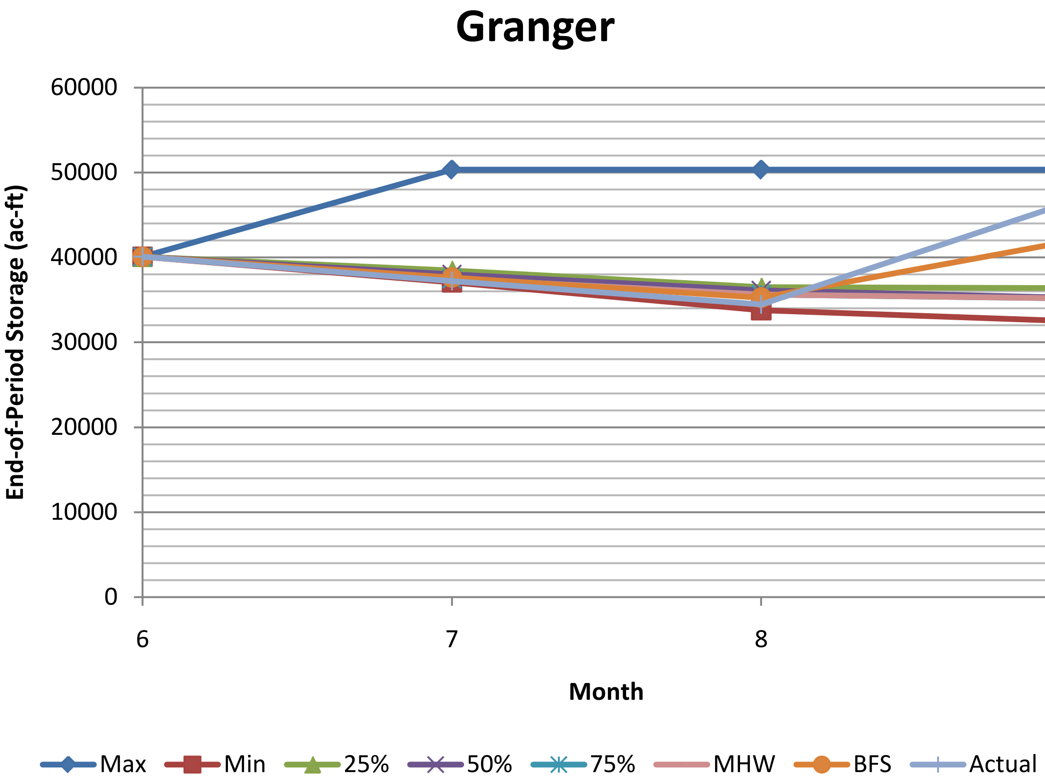


Figure B-31. Selected Storage Plots and Frequency Relationships for Granger starting in July

Table B-32. Storage-Frequency Relationships for Granger starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**34,474**	**46,514**	N/A
Frequency (%)	17.96	57.96	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	1	0.01401	**98.8**	**69.1**	**30,001**
Maximum	**2007**	18611	0.04851	**146.0**	**108.2**	**50,331**
Highest Weight	**1910**	11	0.10163	**102.6**	**74.0**	**33,866**
Best Fit	**1942**	3550	0.00014	**106.1**	**99.1**	**50,331**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	50,331	5.2	7.6	15.1
Trigger 1	39,183	11.2	17.1	26.3
Trigger 2	30,035	100.0	100.0	98.6
Trigger 3	22,959	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	36,474	36,903	37,807	78.4	79.3	
Std Dev	202,638	273,024	363,349	435.7	587.0	
Minimum	33,931	32,146	30,001	72.9	69.1	
99.50%	33,931	32,146	30,001	72.9	69.1	
99%	33,931	32,146	30,001	72.9	69.1	
98%	34,065	32,618	31,030	73.2	70.1	
95%	34,615	32,671	31,297	74.4	70.2	
90%	34,786	33,570	32,993	74.8	72.2	
85%	35,030	33,872	33,233	75.3	72.8	
80%	35,292	33,872	33,331	75.9	72.8	
75%	**35,356**	**34,359**	**33,704**	76.0	73.9	
70%	35,362	34,403	33,866	76.0	74.0	
60%	35,362	34,410	33,968	76.0	74.0	
50%	**35,622**	**34,664**	**34,257**	76.6	74.5	
40%	35,645	34,931	35,189	76.6	75.1	
30%	36,074	35,965	36,998	77.6	77.3	
25%	**36,738**	**36,572**	**39,884**	79.0	78.6	
20%	37,065	37,422	44,648	79.7	80.5	
15%	37,468	40,693	50,331	80.6	87.5	
10%	39,876	44,915	50,331	85.7	96.6	
5%	50,331	50,331	50,331	108.2	108.2	
2%	50,331	50,331	50,331	108.2	108.2	
1%	50,331	50,331	50,331	108.2	108.2	
0.50%	50,331	50,331	50,331	108.2	108.2	
Maximum	50,331	50,331	50,331	108.2	108.2	

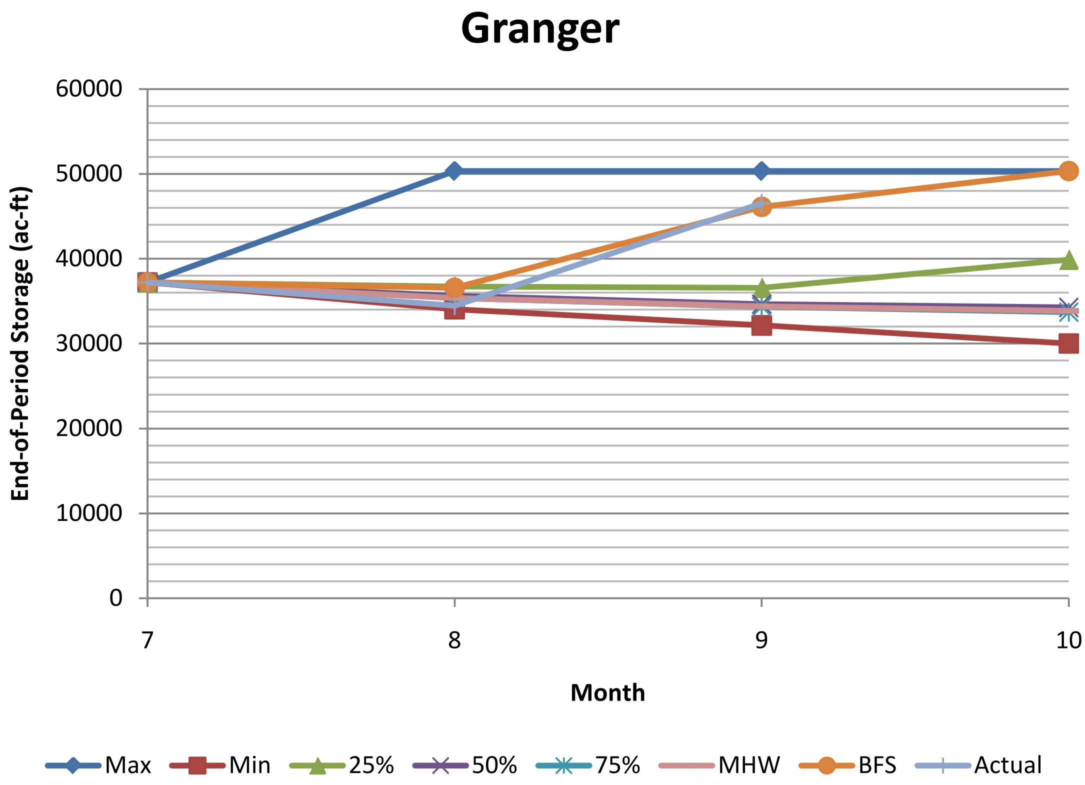


Figure B-32. Selected Storage Plots and Frequency Relationships for Granger starting in August

Table B-33. Storage-Frequency Relationships for Somerville starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**132,977**	**117,069**	**110,284**
Frequency (%)	99.9	100	100

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1996**	0.001	0.00097	**99.8**	**109.7**	**111.1**
Maximum	**1900**	712	0.00515	**108.8**	**123.5**	**131.1**
Highest Weight	**1914**	2807	0.05363	**108.8**	**123.5**	**131.1**
Best Fit	**1996**	0.001	0.00097	**99.8**	**109.7**	**111.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	144,619	48.9	38.0	20.3
Trigger 1	110,010	100.0	100.0	100.0
Trigger 2	83,769	100.0	100.0	100.0
Trigger 3	66,164	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	141,704	140,476	134,851	106.6	120.0	122.3
Std Dev	175,646	253,368	467,576	132.1	216.4	424.0
Minimum	132,652	126,834	110,418	99.8	108.3	100.1
99.50%	135,643	126,834	111,225	102.0	108.3	100.9
99%	135,643	126,834	111,225	102.0	108.3	100.9
98%	135,643	128,799	112,474	102.0	110.0	102.0
95%	136,498	132,582	119,038	102.6	113.3	107.9
90%	136,883	132,995	124,310	102.9	113.6	112.7
85%	137,784	135,728	126,542	103.6	115.9	114.7
80%	138,052	136,280	127,120	103.8	116.4	115.3
75%	**139,084**	**136,528**	**128,787**	104.6	116.6	116.8
70%	139,226	137,335	131,735	104.7	117.3	119.5
60%	142,250	139,566	134,190	107.0	119.2	121.7
50%	**144,159**	**142,144**	**136,998**	108.4	121.4	124.2
40%	144,619	143,777	139,225	108.8	122.8	126.2
30%	144,619	144,619	140,243	108.8	123.5	127.2
25%	**144,619**	**144,619**	**141,600**	108.8	123.5	128.4
20%	144,619	144,619	144,619	108.8	123.5	131.1
15%	144,619	144,619	144,619	108.8	123.5	131.1
10%	144,619	144,619	144,619	108.8	123.5	131.1
5%	144,619	144,619	144,619	108.8	123.5	131.1
2%	144,619	144,619	144,619	108.8	123.5	131.1
1%	144,619	144,619	144,619	108.8	123.5	131.1
0.50%	144,619	144,619	144,619	108.8	123.5	131.1
Maximum	144,619	144,619	144,619	108.8	123.5	131.1

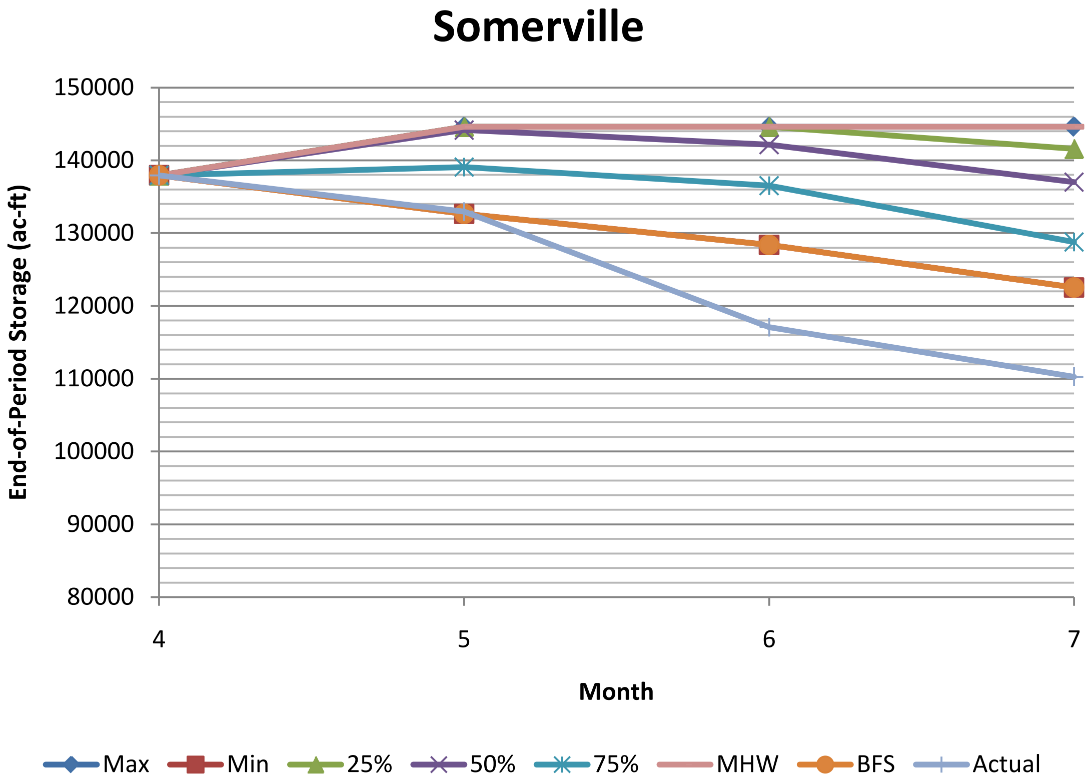


Figure B-33. Selected Storage Plots and Frequency Relationships for Somerville starting in May

Table B-34. Storage-Frequency Relationships for Somerville starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**117,069**	**110,284**	**104,637**
Frequency (%)	100	100	100

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1990**	42	0.08835	**108.0**	**110.8**	**111.5**
Maximum	**1919**	8266	0.00090	**123.5**	**131.1**	**138.2**
Highest Weight	**1917**	14	0.16465	**112.0**	**114.6**	**117.0**
Best Fit	**1990**	42	0.08835	**108.0**	**110.8**	**111.5**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	144,619	7.9	4.6	2.5
Trigger 1	110,010	100.0	100.0	100.0
Trigger 2	83,769	100.0	100.0	100.0
Trigger 3	66,164	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	132,290	127,362	124,301	120.0	115.5	118.8
Std Dev	262,358	316,337	378,540	237.9	286.8	361.8
Minimum	125,895	118,457	115,903	114.2	107.4	110.8
99.50%	126,390	121,794	115,903	114.6	110.4	110.8
99%	126,390	121,794	115,903	114.6	110.4	110.8
98%	126,390	121,918	115,903	114.6	110.5	110.8
95%	126,390	122,027	116,702	114.6	110.6	111.5
90%	127,609	122,236	116,702	115.7	110.8	111.5
85%	128,756	123,009	117,754	116.7	111.5	112.5
80%	129,279	124,154	118,845	117.2	112.6	113.6
75%	**130,886**	**124,968**	**120,334**	118.7	113.3	115.0
70%	130,897	126,209	122,282	118.7	114.4	116.9
60%	131,071	126,379	122,448	118.8	114.6	117.0
50%	**131,419**	**126,379**	**122,448**	119.2	114.6	117.0
40%	131,747	127,116	123,209	119.5	115.3	117.7
30%	132,240	128,211	124,636	119.9	116.3	119.1
25%	**133,231**	**129,842**	**125,589**	120.8	117.7	120.0
20%	134,798	131,464	128,046	122.2	119.2	122.4
15%	137,203	133,340	130,385	124.4	120.9	124.6
10%	139,496	137,616	134,906	126.5	124.8	128.9
5%	144,619	143,971	140,182	131.1	130.5	134.0
2%	144,619	144,619	144,619	131.1	131.1	138.2
1%	144,619	144,619	144,619	131.1	131.1	138.2
0.50%	144,619	144,619	144,619	131.1	131.1	138.2
Maximum	144,619	144,619	144,619	131.1	131.1	138.2

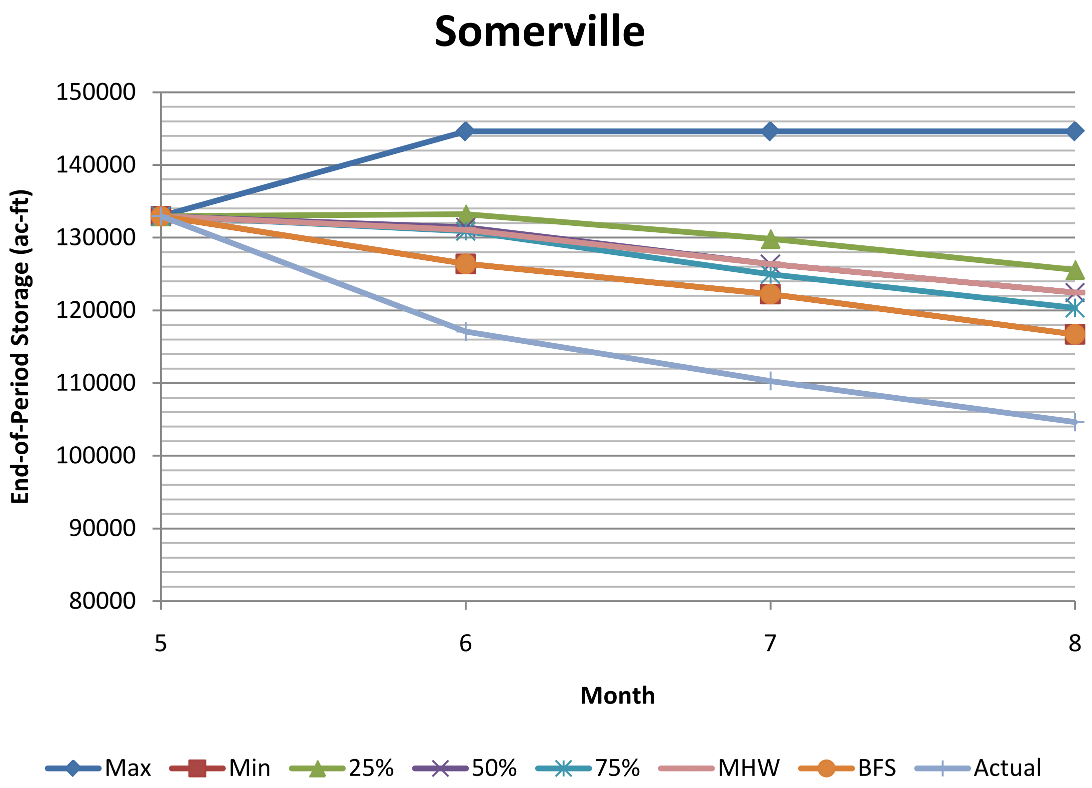


Figure B-34. Selected Storage Plots and Frequency Relationships for Somerville starting in June

Table B-35. Storage-Frequency Relationships for Somerville starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**110,284**	**104,637**	**115,088**
Frequency (%)	98.35	98.35	2.39

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1951**	447	0.01652	**99.6**	**99.2**	**88.8**
Maximum	**1919**	539867	0.00004	**131.1**	**138.2**	**125.7**
Highest Weight	**1952**	2	0.27192	**102.1**	**100.4**	**86.9**
Best Fit	**1964**	7038	0.00336	**101.6**	**103.1**	**96.8**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	144,619	0.2	0.1	0.2
Trigger 1	110,010	98.4	5.3	5.3
Trigger 2	83,769	100.0	100.0	100.0
Trigger 3	66,164	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	114,133	108,734	105,054	109.1	103.9	91.3
Std Dev	122,342	170,539	260,467	116.9	163.0	226.3
Minimum	109,895	103,780	99,989	105.0	99.2	86.9
99.50%	109,895	103,780	99,989	105.0	99.2	86.9
99%	109,895	103,780	99,989	105.0	99.2	86.9
98%	110,449	104,928	99,989	105.6	100.3	86.9
95%	111,250	105,083	99,989	106.3	100.4	86.9
90%	111,633	105,083	99,989	106.7	100.4	86.9
85%	112,605	105,083	99,989	107.6	100.4	86.9
80%	112,605	105,083	99,989	107.6	100.4	86.9
75%	**112,605**	**105,083**	**99,989**	107.6	100.4	86.9
70%	112,605	105,111	103,276	107.6	100.5	89.7
60%	112,643	108,394	105,903	107.7	103.6	92.0
50%	**112,733**	**108,875**	**105,903**	107.7	104.0	92.0
40%	112,843	108,875	105,903	107.8	104.0	92.0
30%	112,843	109,004	107,519	107.8	104.2	93.4
25%	**112,843**	**109,047**	**107,565**	107.8	104.2	93.5
20%	112,843	109,076	107,642	107.8	104.2	93.5
15%	112,905	109,127	107,697	107.9	104.3	93.6
10%	112,984	109,224	107,773	108.0	104.4	93.6
5%	113,423	110,033	110,058	108.4	105.2	95.6
2%	116,044	113,181	117,245	110.9	108.2	101.9
1%	118,304	117,384	122,386	113.1	112.2	106.3
0.50%	121,353	122,627	127,915	116.0	117.2	111.1
Maximum	144,619	144,619	144,619	138.2	138.2	125.7

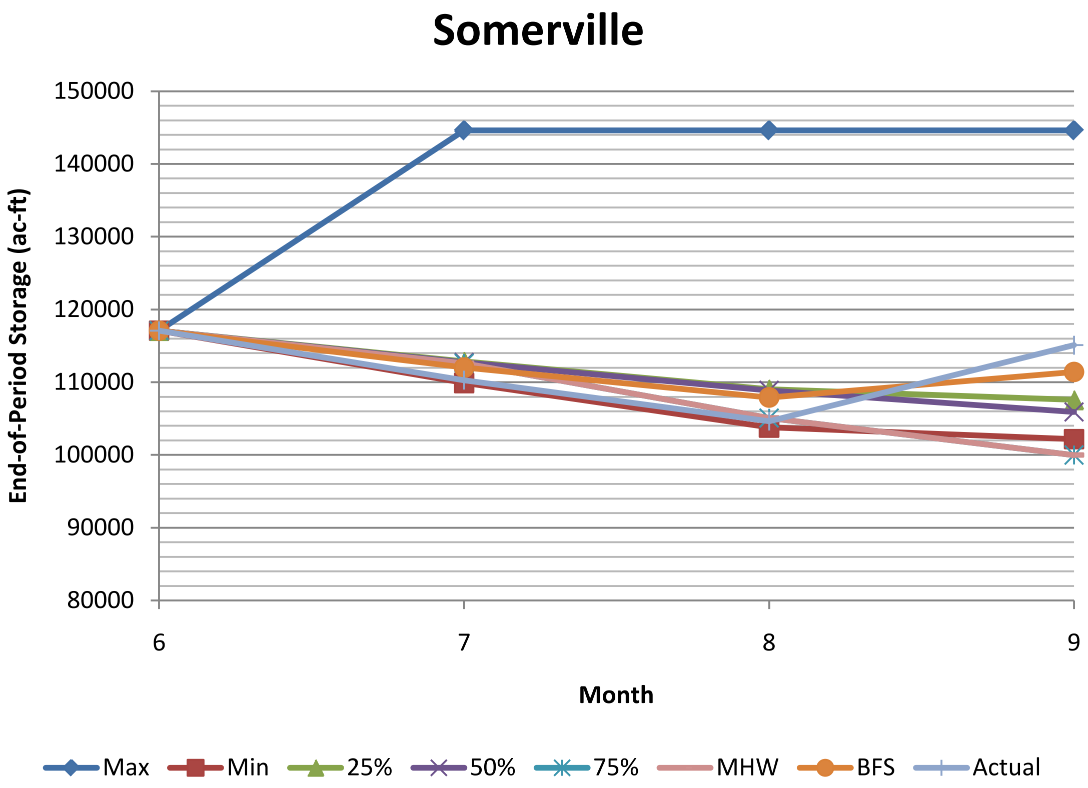


Figure B-35. Selected Storage Plots and Frequency Relationships for Somerville starting in July

Table B-36. Storage-Frequency Relationships for Somerville starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**104,637**	**115,088**	N/A
Frequency (%)	81.11	5.98	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	0.15	0.01927	**98.3**	**85.0**	**92,117**
Maximum	**1945**	18735	0.00223	**138.2**	**125.7**	**144,619**
Highest Weight	**1948**	11	0.07966	**100.6**	**87.8**	**97,274**
Best Fit	**1950**	3232	0.00059	**100.1**	**100.5**	**111,376**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	144,619	0.4	1.5	3.4
Trigger 1	110,010	6.3	8.8	13.4
Trigger 2	83,769	100.0	100.0	100.0
Trigger 3	66,164	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	107,507	105,716	105,607	93.4	91.9	
Std Dev	231,259	379,110	556,137	200.9	329.4	
Minimum	102,845	97,810	92,117	89.4	85.0	
99.50%	102,845	97,810	92,117	89.4	85.0	
99%	102,845	97,810	92,117	89.4	85.0	
98%	103,578	99,779	97,071	90.0	86.7	
95%	104,158	99,779	97,071	90.5	86.7	
90%	104,398	100,574	97,274	90.7	87.4	
85%	104,499	101,067	97,809	90.8	87.8	
80%	104,943	101,387	98,181	91.2	88.1	
75%	**105,069**	**101,910**	**98,969**	91.3	88.5	
70%	105,069	103,423	101,614	91.3	89.9	
60%	105,324	104,021	103,125	91.5	90.4	
50%	**106,635**	**105,174**	**104,335**	92.7	91.4	
40%	106,683	105,397	104,598	92.7	91.6	
30%	106,834	105,953	105,787	92.8	92.1	
25%	**106,919**	**106,889**	**106,801**	92.9	92.9	
20%	107,628	107,413	107,386	93.5	93.3	
15%	108,453	108,418	109,014	94.2	94.2	
10%	108,975	109,715	113,963	94.7	95.3	
5%	111,801	116,792	126,529	97.1	101.5	
2%	115,533	133,863	144,619	100.4	116.3	
1%	119,962	144,619	144,619	104.2	125.7	
0.50%	142,410	144,619	144,619	123.7	125.7	
Maximum	144,619	144,619	144,619	125.7	125.7	

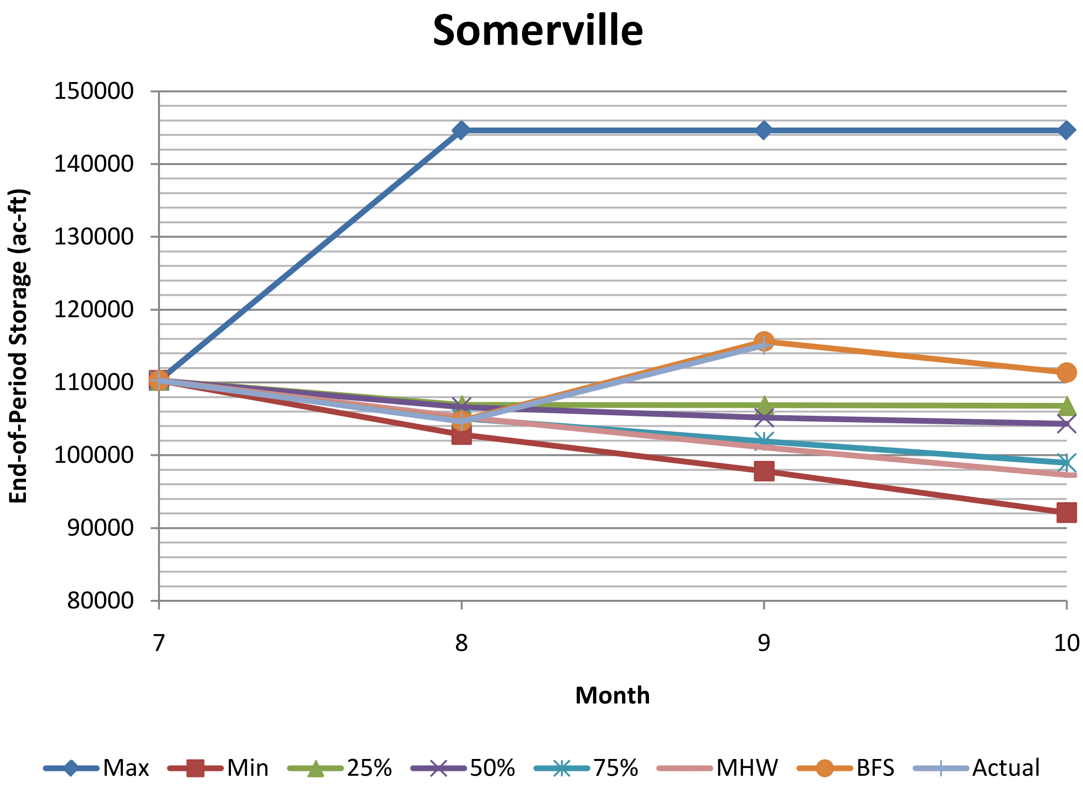


Figure B-36. Selected Storage Plots and Frequency Relationships for Somerville starting in August

Table B-37. Storage-Frequency Relationships for Limestone starting in May

Actual 2009 End-of-Month Storage and Exceedance Frequency

	May	June	July
Actual (ac-ft)	**199,910**	**188,434**	**177,329**
Frequency (%)	84.58	94.7	95.83

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	May (%)	June (%)	July (%)
Minimum	**1934**	3	0.00989	**100.1**	**103.3**	**86.5**
Maximum	**1915**	787	0.01016	**101.5**	**107.7**	**114.4**
Highest Weight	**1922**	1267	0.08512	**101.5**	**107.7**	**112.1**
Best Fit	**2003**	44	0.01043	**100.1**	**98.5**	**100.4**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	May (%)	June (%)	July (%)
Capacity	202,952	67.1	50.8	13.5
Trigger 1	143,689	100.0	100.0	100.0
Trigger 2	107,248	100.0	100.0	100.0
Trigger 3	62,941	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	May (ac-ft)	June (ac-ft)	July (ac-ft)	May (%)	June (%)	July (%)
Mean	201,778	200,074	190,646	100.9	106.2	107.5
Std Dev	103,686	274,510	491,215	51.9	145.7	277.0
Minimum	192,983	182,768	153,413	96.5	97.0	86.5
99.50%	195,418	184,150	153,413	97.8	97.7	86.5
99%	195,418	184,150	171,819	97.8	97.7	96.9
98%	196,578	184,775	172,895	98.3	98.1	97.5
95%	197,665	187,055	177,811	98.9	99.3	100.3
90%	199,270	192,473	180,325	99.7	102.1	101.7
85%	199,856	194,540	181,957	100.0	103.2	102.6
80%	201,257	195,663	183,563	100.7	103.8	103.5
75%	**202,273**	**197,103**	**187,163**	101.2	104.6	105.5
70%	202,493	198,529	187,436	101.3	105.4	105.7
60%	202,952	199,920	189,490	101.5	106.1	106.9
50%	**202,952**	**202,952**	**191,557**	101.5	107.7	108.0
40%	202,952	202,952	193,212	101.5	107.7	109.0
30%	202,952	202,952	197,302	101.5	107.7	111.3
25%	**202,952**	**202,952**	**198,814**	101.5	107.7	112.1
20%	202,952	202,952	198,814	101.5	107.7	112.1
15%	202,952	202,952	202,343	101.5	107.7	114.1
10%	202,952	202,952	202,952	101.5	107.7	114.4
5%	202,952	202,952	202,952	101.5	107.7	114.4
2%	202,952	202,952	202,952	101.5	107.7	114.4
1%	202,952	202,952	202,952	101.5	107.7	114.4
0.50%	202,952	202,952	202,952	101.5	107.7	114.4
Maximum	202,952	202,952	202,952	101.5	107.7	114.4

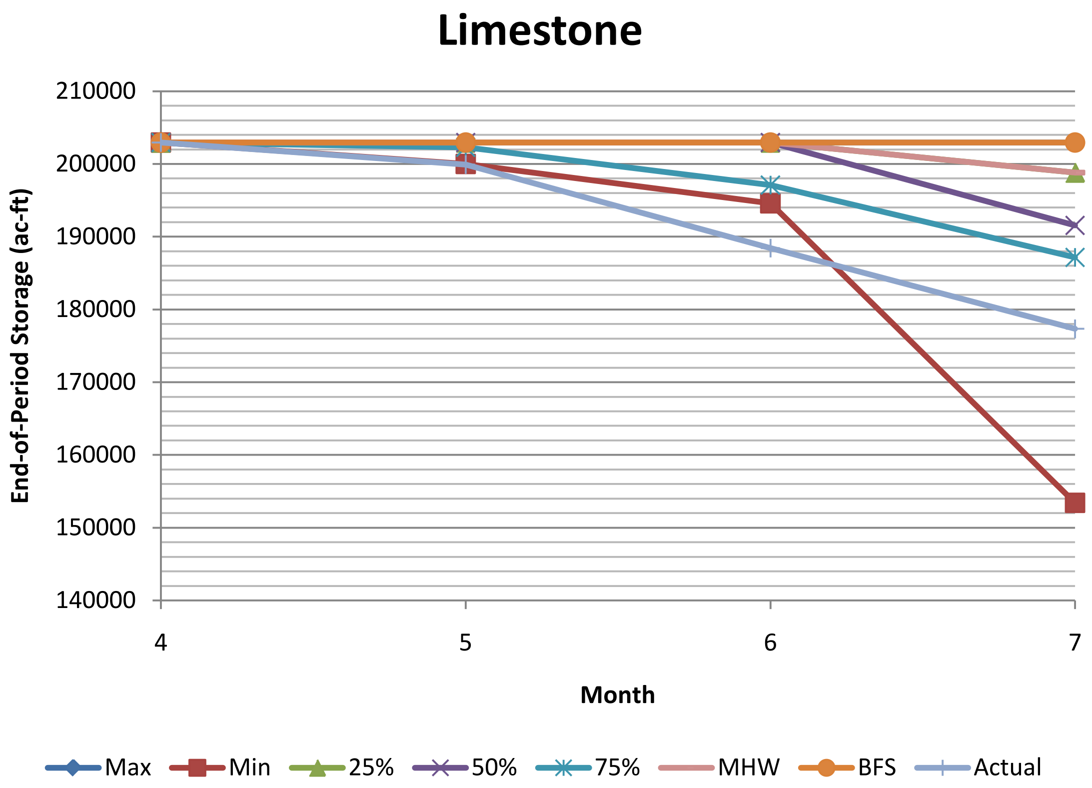


Figure B-37. Selected Storage Plots and Frequency Relationships for Limestone starting in May

Table B-38. Storage-Frequency Relationships for Limestone starting in June

Actual 2009 End-of-Month Storage and Exceedance Frequency

	June	July	Aug
Actual (ac-ft)	**188,434**	**177,329**	**158,941**
Frequency (%)	99.69	94.67	100

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	June (%)	July (%)	Aug (%)
Minimum	**1954**	1	0.01884	**100.7**	**99.5**	**103.1**
Maximum	**1945**	435	0.00410	**107.7**	**114.4**	**127.7**
Highest Weight	**2007**	2734	0.07016	**107.7**	**114.4**	**127.7**
Best Fit	**1954**	1	0.01884	**100.7**	**99.5**	**103.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	June (%)	July (%)	Aug (%)
Capacity	202,952	39.5	16.2	7.5
Trigger 1	143,689	100.0	100.0	100.0
Trigger 2	107,248	100.0	100.0	100.0
Trigger 3	62,941	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	June (ac-ft)	July (ac-ft)	Aug (ac-ft)	June (%)	July (%)	Aug (%)
Mean	200,097	190,203	181,997	112.8	107.3	114.5
Std Dev	255,568	460,085	596,412	144.1	259.5	375.2
Minimum	187,315	173,186	160,104	105.6	97.7	100.7
99.50%	188,599	173,186	160,104	106.4	97.7	100.7
99%	189,713	175,845	160,104	107.0	99.2	100.7
98%	189,713	175,845	160,104	107.0	99.2	100.7
95%	191,683	177,277	163,797	108.1	100.0	103.1
90%	192,171	180,599	169,881	108.4	101.8	106.9
85%	192,901	180,998	171,744	108.8	102.1	108.1
80%	194,686	182,186	174,041	109.8	102.7	109.5
75%	**195,238**	**184,468**	**174,936**	110.1	104.0	110.1
70%	195,755	185,210	175,649	110.4	104.4	110.5
60%	197,332	185,838	176,896	111.3	104.8	111.3
50%	**198,774**	**189,500**	**180,434**	112.1	106.9	113.5
40%	202,760	191,915	183,444	114.3	108.2	115.4
30%	202,952	194,109	188,605	114.4	109.5	118.7
25%	**202,952**	**196,973**	**189,618**	114.4	111.1	119.3
20%	202,952	201,304	191,881	114.4	113.5	120.7
15%	202,952	202,952	193,306	114.4	114.4	121.6
10%	202,952	202,952	196,746	114.4	114.4	123.8
5%	202,952	202,952	202,952	114.4	114.4	127.7
2%	202,952	202,952	202,952	114.4	114.4	127.7
1%	202,952	202,952	202,952	114.4	114.4	127.7
0.50%	202,952	202,952	202,952	114.4	114.4	127.7
Maximum	202,952	202,952	202,952	114.4	114.4	127.7

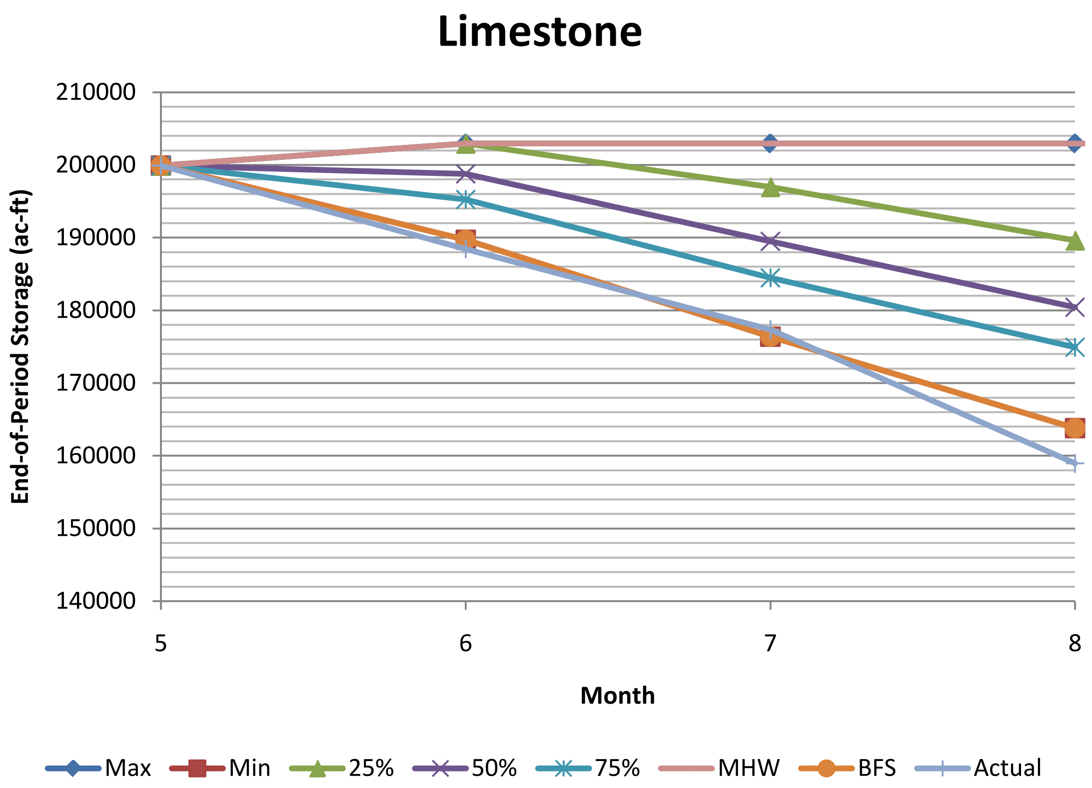


Figure B-38. Selected Storage Plots and Frequency Relationships for Limestone starting in June

Table B-39. Storage-Frequency Relationships for Limestone starting in July

Actual 2009 End-of-Month Storage and Exceedance Frequency

	July	Aug	Sept
Actual (ac-ft)	**177,329**	**158,941**	**153,121**
Frequency (%)	77.58	99.71	99.32

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	July (%)	Aug (%)	Sept (%)
Minimum	**1951**	131	0.00288	**97.8**	**99.3**	**99.6**
Maximum	**2007**	15041	0.01513	**114.4**	**127.7**	**130.7**
Highest Weight	**1909**	7	0.06881	**100.1**	**105.6**	**105.8**
Best Fit	**1952**	0.17	0.00368	**100.1**	**103.1**	**100.1**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	July (%)	Aug (%)	Sept (%)
Capacity	202,952	3.4	2.9	3.5
Trigger 1	143,689	100.0	100.0	100.0
Trigger 2	107,248	100.0	100.0	100.0
Trigger 3	62,941	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	July (ac-ft)	Aug (ac-ft)	Sept (ac-ft)	July (%)	Aug (%)	Sept (%)
Mean	182,644	171,561	169,419	114.9	107.9	110.6
Std Dev	391,860	494,357	681,356	246.5	311.0	445.0
Minimum	173,419	157,762	151,507	109.1	99.3	98.9
99.50%	174,460	161,751	153,002	109.8	101.8	99.9
99%	174,460	161,751	153,289	109.8	101.8	100.1
98%	175,036	163,867	155,427	110.1	103.1	101.5
95%	175,858	164,472	157,295	110.6	103.5	102.7
90%	176,109	165,606	157,983	110.8	104.2	103.2
85%	176,533	166,485	159,328	111.1	104.7	104.1
80%	177,094	166,963	161,139	111.4	105.0	105.2
75%	**177,369**	**167,440**	**161,596**	111.6	105.3	105.5
70%	177,415	167,851	161,948	111.6	105.6	105.8
60%	177,490	167,883	161,982	111.7	105.6	105.8
50%	**177,648**	**168,168**	**162,438**	111.8	105.8	106.1
40%	178,535	169,452	164,482	112.3	106.6	107.4
30%	179,225	170,473	167,222	112.8	107.3	109.2
25%	**179,847**	**173,326**	**170,160**	113.2	109.1	111.1
20%	182,459	175,602	175,099	114.8	110.5	114.4
15%	186,902	179,057	178,327	117.6	112.7	116.5
10%	190,027	188,180	190,526	119.6	118.4	124.4
5%	201,543	193,157	200,146	126.8	121.5	130.7
2%	202,952	202,952	202,952	127.7	127.7	132.5
1%	202,952	202,952	202,952	127.7	127.7	132.5
0.50%	202,952	202,952	202,952	127.7	127.7	132.5
Maximum	202,952	202,952	202,952	127.7	127.7	132.5

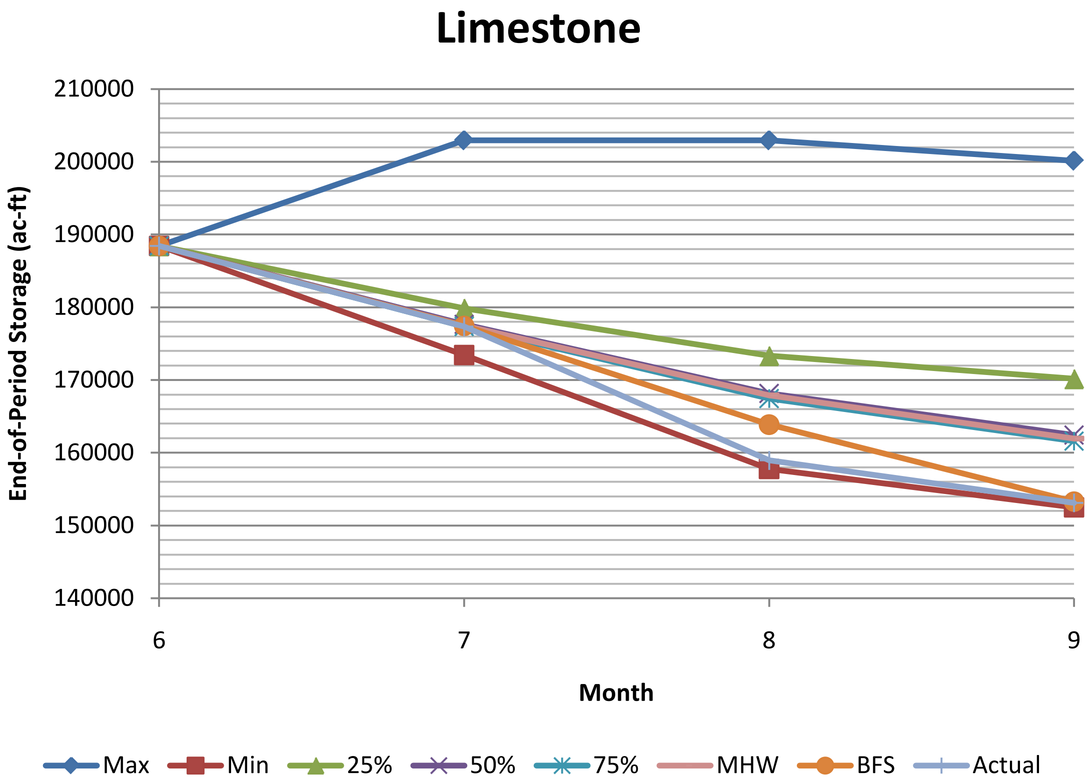


Figure B-39. Selected Storage Plots and Frequency Relationships for Limestone starting in July

Table B-40. Storage-Frequency Relationships for Limestone starting in August

Actual 2009 End-of-Month Storage and Exceedance Frequency

	Aug	Sept	Oct
Actual (ac-ft)	**158,941**	**153,121**	N/A
Frequency (%)	100	100	N/A

Simulated Storage as Percent of Observed Storage for Selected Sequences

	Sequence	Flow Ratio	Probability	Aug (%)	Sept (%)	Oct (ac-ft)
Minimum	**1952**	0	0.01641	**103.0**	**100.0**	**143,835**
Maximum	**1945**	5203	0.00383	**122.5**	**132.5**	**202,952**
Highest Weight	**1910**	4	0.05641	**105.4**	**105.6**	**157,694**
Best Fit	**1952**	0	0.01641	**103.0**	**100.0**	**143,835**

Exceedance Frequency for Specified Storages

	Storage (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Capacity	202,952	0.1	4.5	4.5
Trigger 1	143,689	100.0	100.0	100.0
Trigger 2	107,248	100.0	100.0	100.0
Trigger 3	62,941	100.0	100.0	100.0

Storages and Percent of Observed for Specified Exceedance Frequencies

	Aug (ac-ft)	Sept (ac-ft)	Oct (ac-ft)	Aug (%)	Sept (%)	Oct (%)
Mean	166,623	166,763	163,715	108.8	108.9	
Std Dev	231,054	566,688	808,819	150.9	370.1	
Minimum	161,517	153,197	143,835	105.5	100.0	
99.50%	161,517	153,197	143,835	105.5	100.0	
99%	161,517	153,197	143,835	105.5	100.0	
98%	163,772	154,968	148,613	107.0	101.2	
95%	164,702	156,661	149,701	107.6	102.3	
90%	165,828	158,178	152,567	108.3	103.3	
85%	166,681	159,843	154,291	108.9	104.4	
80%	167,234	161,100	155,703	109.2	105.2	
75%	**167,560**	**161,402**	**157,092**	109.4	105.4	
70%	167,582	161,673	157,694	109.4	105.6	
60%	167,582	161,894	158,153	109.4	105.7	
50%	**167,709**	**162,225**	**159,245**	109.5	105.9	
40%	168,040	163,021	161,034	109.7	106.5	
30%	168,400	163,994	163,941	110.0	107.1	
25%	**168,653**	**165,388**	**168,380**	110.1	108.0	
20%	168,798	166,770	172,053	110.2	108.9	
15%	169,580	169,404	177,085	110.7	110.6	
10%	171,407	174,661	194,954	111.9	114.1	
5%	172,610	198,041	201,864	112.7	129.3	
2%	176,693	202,952	202,952	115.4	132.5	
1%	189,378	202,952	202,952	123.7	132.5	
0.50%	194,650	202,952	202,952	127.1	132.5	
Maximum	202,952	202,952	202,952	132.5	132.5	

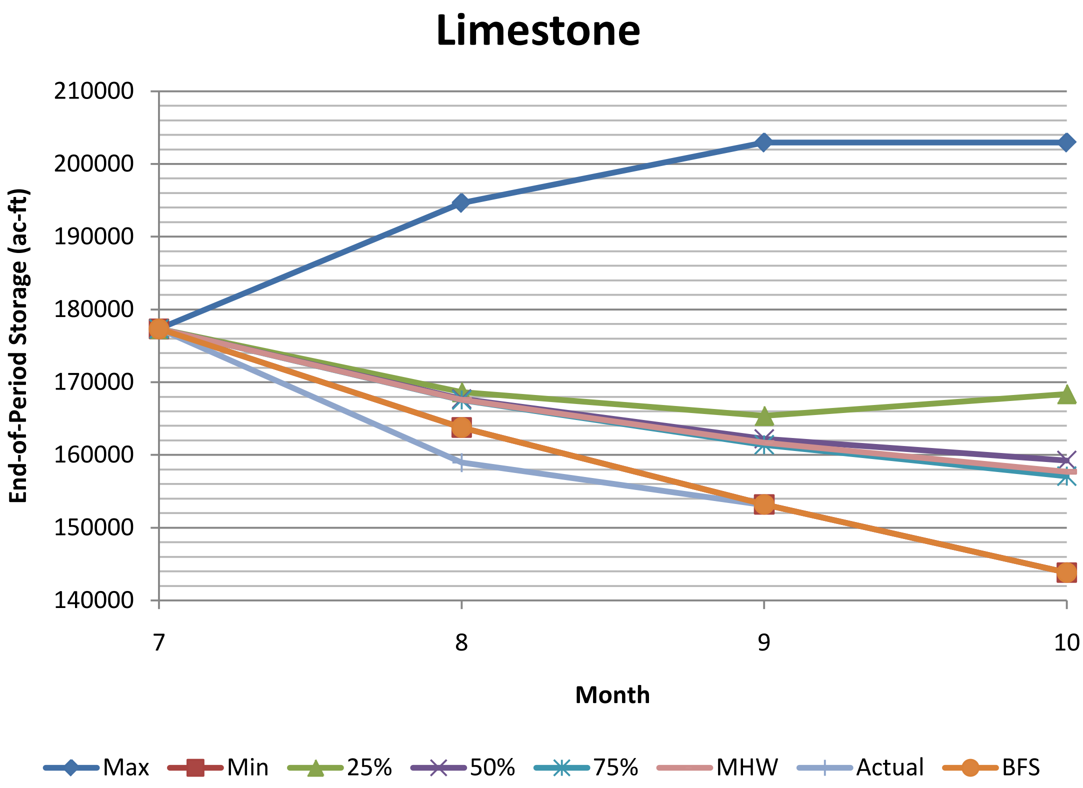


Figure B-40. Selected Storage Plots and Frequency Relationships for Limestone starting in August

APPENDIX C

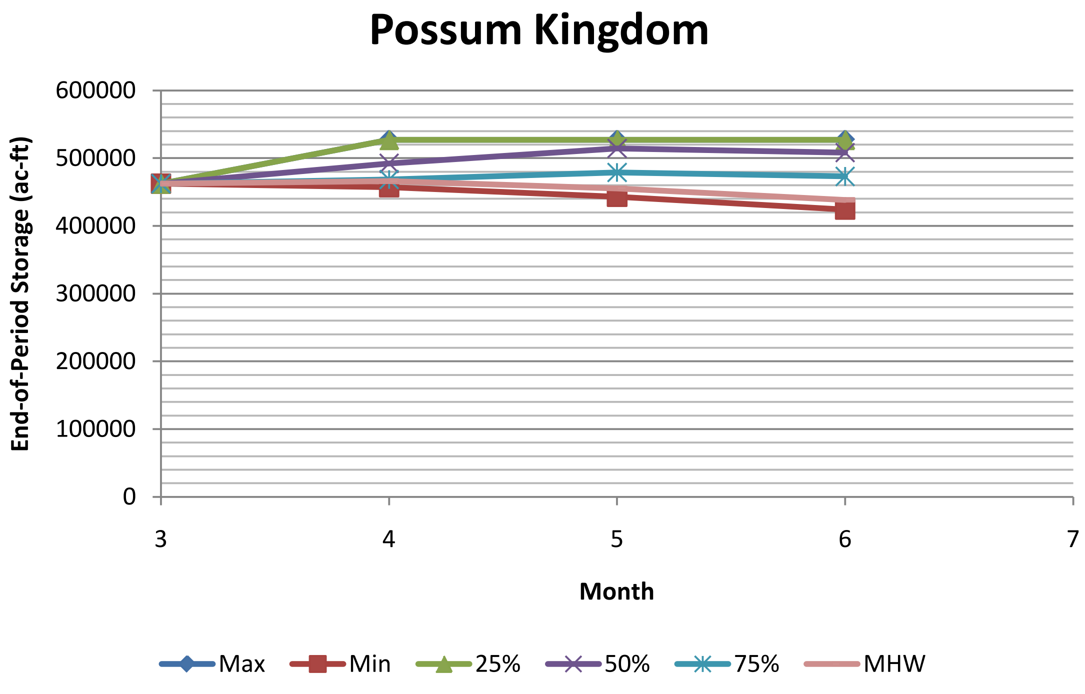
RESULTS FOR HYPOTHETICAL RELEASES OF THE BRA SYSTEM DURING THE DROUGHT OF 2009

The conditional reliability modeling (CRM) features of the Water Rights Analysis Package (WRAP) develop hydrologic sequences to estimate the storage conditions of reservoirs in the near future. Chapter VII uses these features to assess the behavior of the Brazos River Authority (BRA) reservoir system in a repeat of the drought of 2009. The Hypothetical Releases simulations answer the question, “If I meet down-stream demands with releases from Reservoir X, what are the chances that it will be full in the next 3 months?” This appendix displays the results of the study. Simulations were run for the 10 BRA reservoirs that make releases for the 44,631 acft/yr diversion for industrial uses at the Hempstead gage as modeled in the BRAC2009 dataset.

1) Lake Possum Kingdom
2) Lake Granbury
3) Lake Aquila
4) Lake Whitney
5) Lake Belton
6) Lake Stillhouse Hollow
7) Lake Georgetown
8) Lake Granger
9) Lake Somerville
10) Lake Limestone

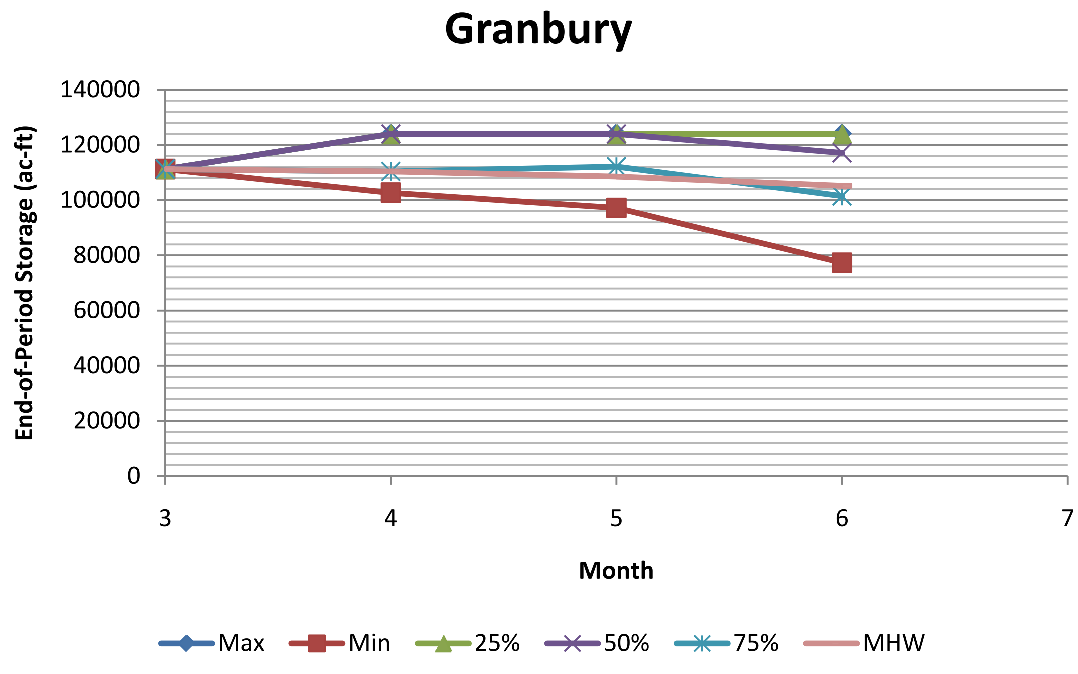
Possum Kingdom	MAY	JUN	JUL
Mean	493,153	503,580	496,857
Std Dev	1,487,444	1,423,753	1,648,589
Minimum	457,188	442,875	424,271
99.50%	457,188	442,875	424,271
99%	458,866	455,491	438,480
98%	461,626	455,491	438,480
95%	463,732	455,491	438,480
90%	466,227	461,490	458,684
85%	467,033	470,459	460,834
80%	467,305	475,992	470,193
75%	468,430	478,751	473,042
70%	471,525	488,210	478,060
60%	475,885	502,915	486,065
50%	492,318	514,182	508,256
40%	511,731	526,970	523,111
30%	526,970	526,970	526,970
25%	526,970	526,970	526,970
20%	526,970	526,970	526,970
15%	526,970	526,970	526,970
10%	526,970	526,970	526,970
5%	526,970	526,970	526,970
2%	526,970	526,970	526,970
1%	526,970	526,970	526,970
0.50%	526,970	526,970	526,970
Maximum	526,970	526,970	526,970

Possum Kingdom	STORAGE	MAY	JUN	JUL
Capacity	526,970	35.09	40.1	34.78
Trigger 1	396,497	100	100	100
Trigger 2	320,000	100	100	100
Trigger 3	250,000	100	100	100



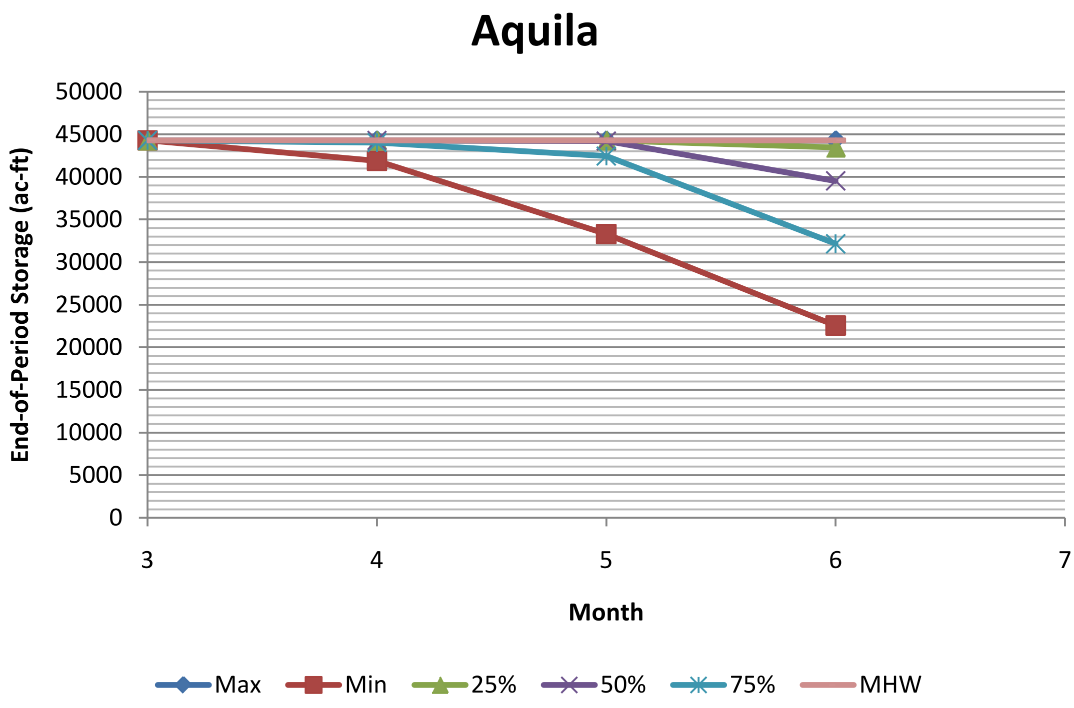
Granbury	MAY	JUN	JUL
Mean	118,333	117,913	110,827
Std Dev	414,082	476,849	833,914
Minimum	102,448	94,284	75,927
99.50%	102,679	97,185	77,323
99%	102,679	97,185	77,323
98%	102,679	97,185	77,323
95%	104,285	99,614	78,906
90%	108,220	102,671	85,886
85%	108,785	107,882	92,106
80%	109,395	108,483	98,464
75%	110,407	112,078	101,491
70%	113,106	117,869	103,772
60%	123,943	123,582	106,896
50%	123,943	123,943	117,165
40%	123,943	123,943	123,943
30%	123,943	123,943	123,943
25%	123,943	123,943	123,943
20%	123,943	123,943	123,943
15%	123,943	123,943	123,943
10%	123,943	123,943	123,943
5%	123,943	123,943	123,943
2%	123,943	123,943	123,943
1%	123,943	123,943	123,943
0.50%	123,943	123,943	123,943
Maximum	123,943	123,943	123,943

Granbury	STORAGE	MAY	JUN	JUL
Capacity	123,943	62.15	59.6	40.59
Trigger 1	103,239	96.67	89.66	72.41
Trigger 2	88,232	100	100	87.97
Trigger 3	52,872	100	100	100



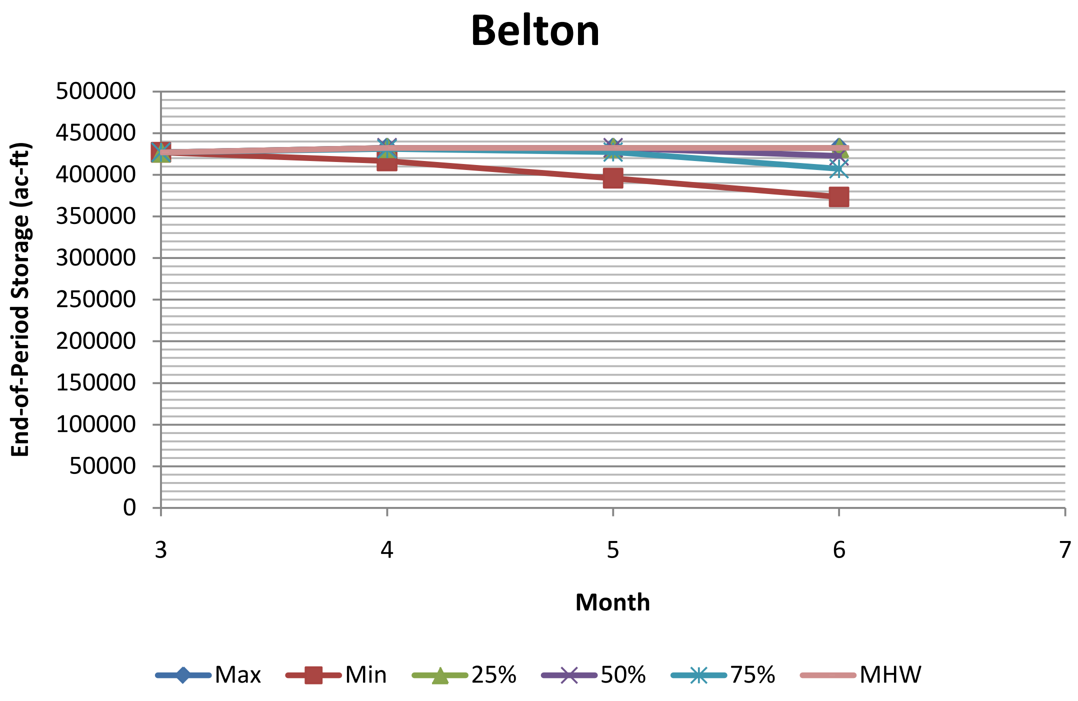
Aquilla	MAY	JUN	JUL
Mean	44,420	42,250	36,917
Std Dev	40,835	179,144	391,363
Minimum	41,655	33,291	22,556
99.50%	41,655	33,291	22,556
99%	41,655	33,755	23,349
98%	41,972	33,945	23,428
95%	42,713	35,676	25,342
90%	43,162	36,142	26,254
85%	43,166	37,207	27,287
80%	43,672	38,158	29,846
75%	44,009	42,446	32,148
70%	44,295	42,743	32,369
60%	44,295	43,201	33,599
50%	44,295	44,209	39,535
40%	44,295	44,295	42,682
30%	44,295	44,295	43,395
25%	44,295	44,295	43,467
20%	44,295	44,295	44,295
15%	44,295	44,295	44,295
10%	44,295	44,295	44,295
5%	44,295	44,295	44,295
2%	44,295	44,295	44,295
1%	44,295	44,295	44,295
0.50%	44,295	44,295	44,295
Maximum	44,295	44,295	44,295

Aquilla	STORAGE	MAY	JUN	JUL
Capacity	44,295	70.36	49.06	22.91
Trigger 1	33,797	100	98.26	57.08
Trigger 2	28,155	100	100	81.44
Trigger 3	17,878	100	100	100



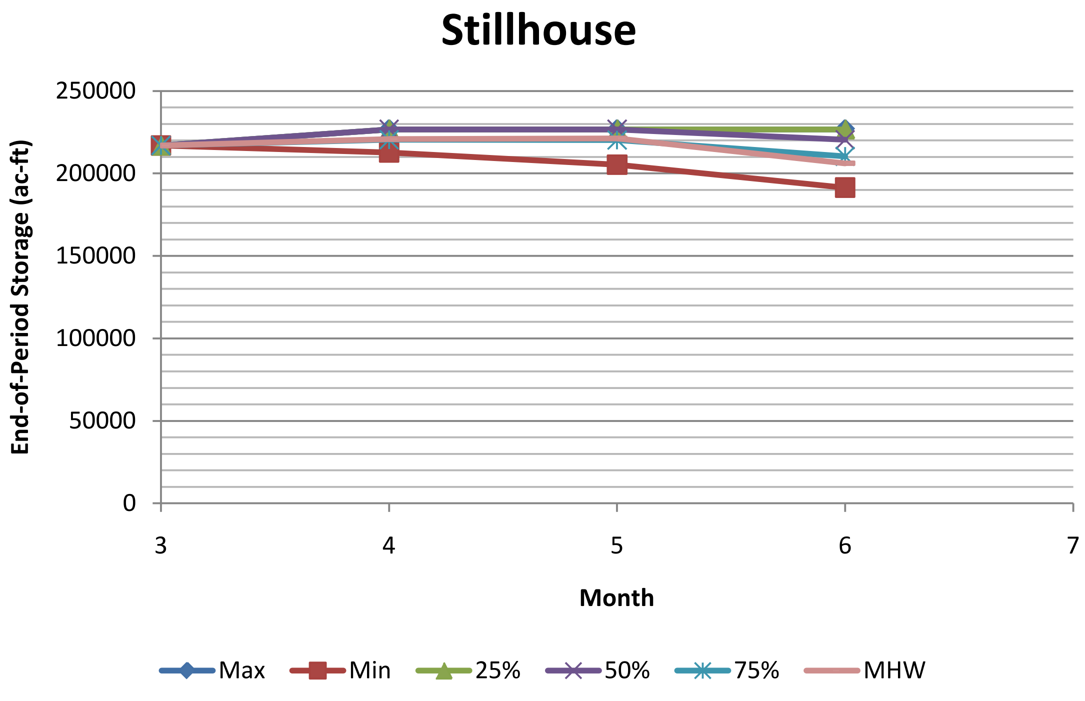
Belton	MAY	JUN	JUL
Mean	428,425	427,748	417,825
Std Dev	235,799	381,816	864,124
Minimum	416,401	395,912	373,356
99.50%	416,401	395,912	373,356
99%	416,401	406,400	383,379
98%	416,687	408,381	384,345
95%	421,875	412,487	386,202
90%	427,131	419,715	393,108
85%	429,828	422,031	400,849
80%	430,554	424,902	405,153
75%	431,150	427,181	407,226
70%	431,337	431,024	409,469
60%	432,408	432,408	417,981
50%	432,408	432,408	422,739
40%	432,408	432,408	432,007
30%	432,408	432,408	432,408
25%	432,408	432,408	432,408
20%	432,408	432,408	432,408
15%	432,408	432,408	432,408
10%	432,408	432,408	432,408
5%	432,408	432,408	432,408
2%	432,408	432,408	432,408
1%	432,408	432,408	432,408
0.50%	432,408	432,408	432,408
Maximum	432,408	432,408	432,408

Belton	STORAGE	MAY	JUN	JUL
Capacity	432,408	64.4	65.36	39.46
Trigger 1	320,099	100	100	100
Trigger 2	217,388	100	100	100
Trigger 3	114,737	100	100	100



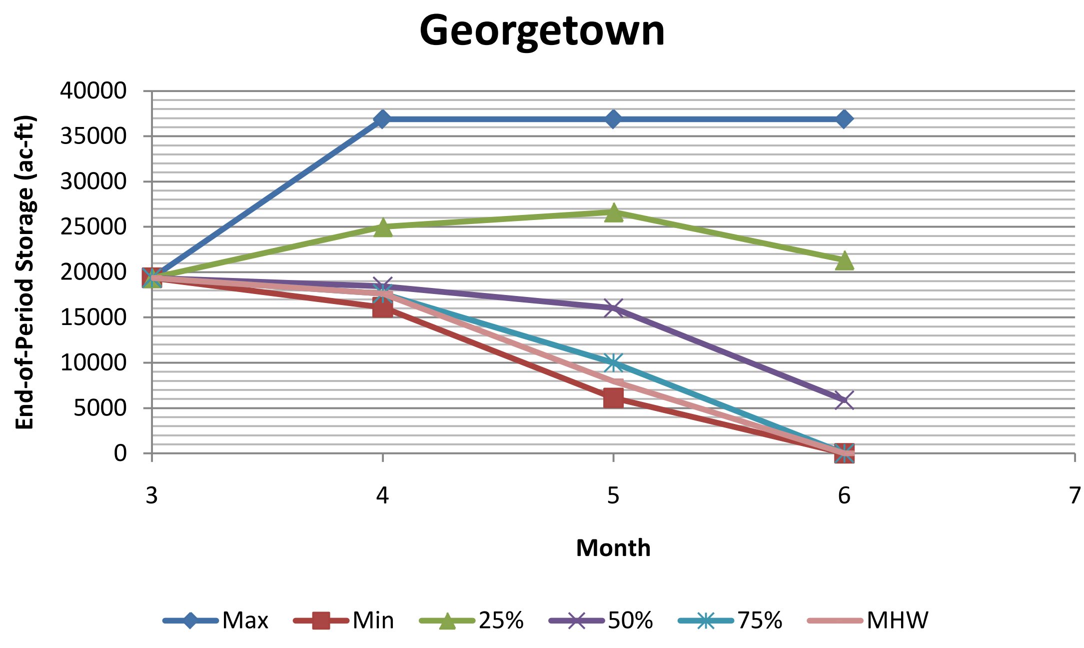
Stillhouse Hollow	MAY	JUN	JUL
Mean	221,992	224,163	216,817
Std Dev	232,288	319,567	567,865
Minimum	212,701	205,271	191,445
99.50%	212,701	205,271	191,445
99%	212,701	205,271	191,445
98%	212,775	205,983	191,856
95%	216,522	211,069	197,322
90%	219,214	214,474	200,650
85%	219,832	217,363	205,256
80%	219,892	218,129	206,853
75%	220,437	220,305	210,326
70%	220,842	221,681	210,896
60%	222,170	226,730	213,317
50%	226,730	226,730	220,425
40%	226,730	226,730	223,964
30%	226,730	226,730	226,730
25%	226,730	226,730	226,730
20%	226,730	226,730	226,730
15%	226,730	226,730	226,730
10%	226,730	226,730	226,730
5%	226,730	226,730	226,730
2%	226,730	226,730	226,730
1%	226,730	226,730	226,730
0.50%	226,730	226,730	226,730
Maximum	226,730	226,730	226,730

Stillhouse Hollow	STORAGE	MAY	JUN	JUL
Capacity	226,730	51.34	60.12	30.46
Trigger 1	161,530	100	100	100
Trigger 2	91,417	100	100	100
Trigger 3	42,276	100	100	100



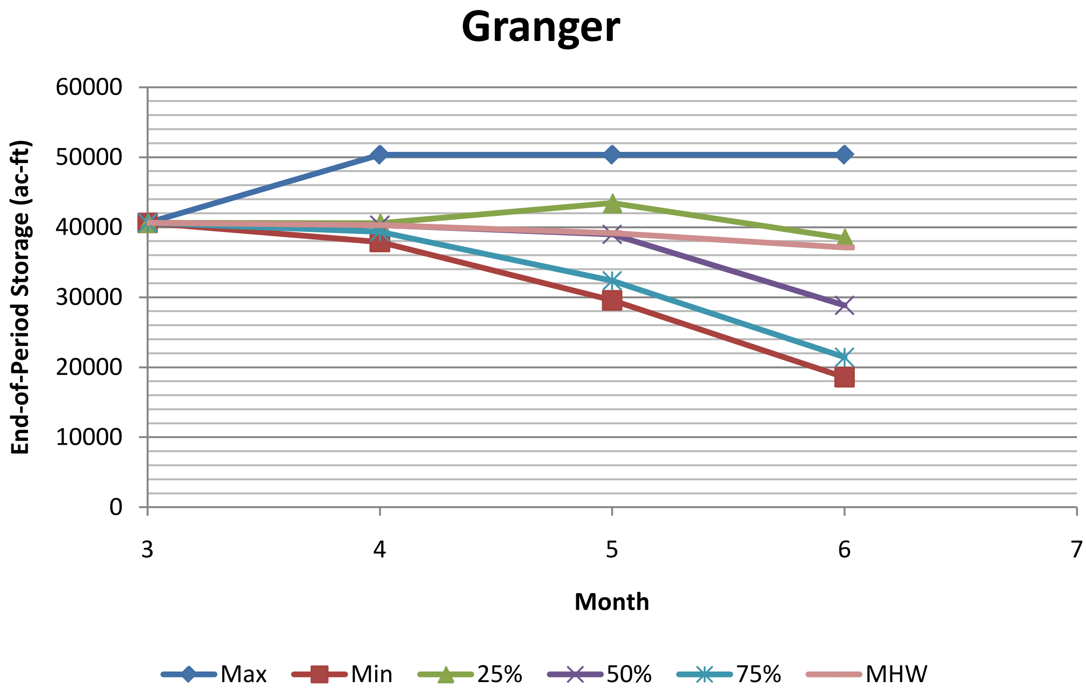
Georgetown	MAY	JUN	JUL
Mean	21,837	19,074	12,022
Std Dev	356,302	559,128	728,144
Minimum	16,128	6,128	-
99.50%	16,128	6,128	-
99%	16,186	6,179	-
98%	16,206	7,073	-
95%	17,146	7,282	-
90%	17,282	7,931	-
85%	17,365	7,951	-
80%	17,460	8,826	-
75%	17,641	10,012	-
70%	17,710	12,956	-
60%	18,213	15,291	2,796
50%	18,453	16,047	5,870
40%	19,355	18,408	13,108
30%	21,726	23,325	17,776
25%	25,003	26,636	21,345
20%	25,664	30,407	24,718
15%	30,397	34,433	31,503
10%	35,946	36,868	36,826
5%	36,868	36,868	36,868
2%	36,868	36,868	36,868
1%	36,868	36,868	36,868
0.50%	36,868	36,868	36,868
Maximum	36,868	36,868	36,868

Georgetown	STORAGE	MAY	JUN	JUL
Capacity	36,868	8.95	13.88	9.7
Trigger 1	26,221	18.38	26	18.2
Trigger 2	20,740	34.63	34.5	25.69
Trigger 3	14,106	100	67	38.98



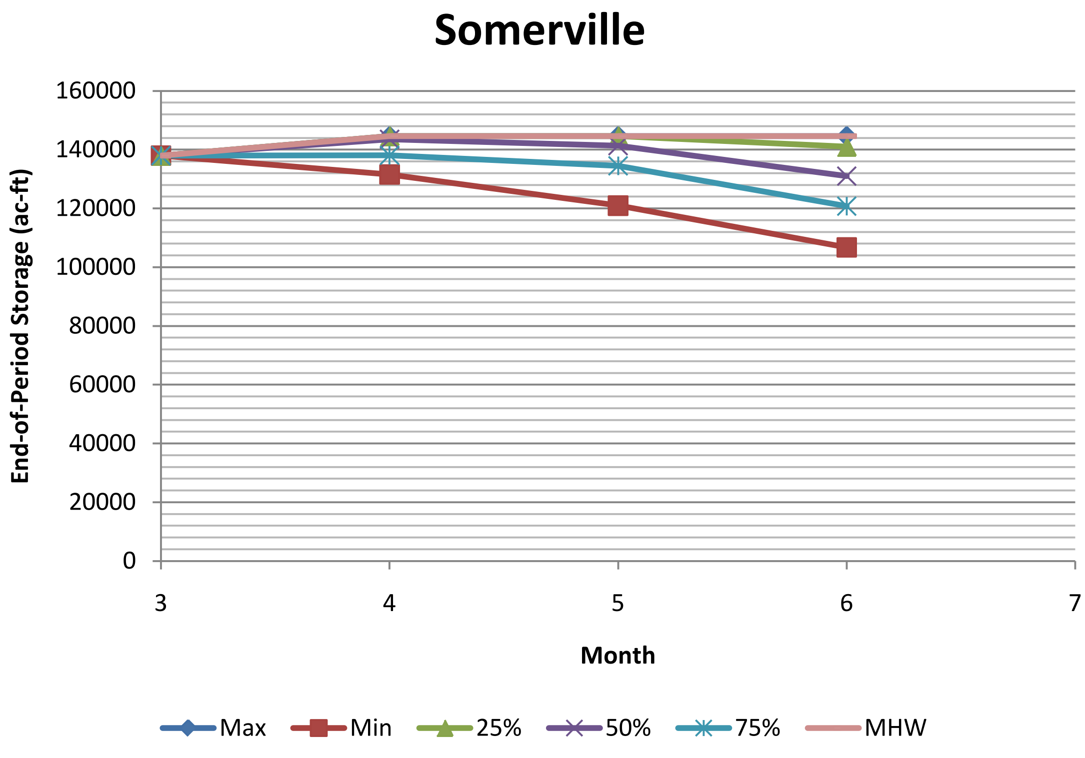
Granger	MAY	JUN	JUL
Mean	42,012	38,681	31,713
Std Dev	214,522	377,090	590,657
Minimum	37,890	29,549	18,581
99.50%	37,890	29,549	18,581
99%	37,890	29,549	18,581
98%	37,934	29,723	18,582
95%	38,828	30,483	20,653
90%	39,116	31,196	21,021
85%	39,117	31,967	21,356
80%	39,237	32,280	21,418
75%	39,359	32,351	21,418
70%	39,750	32,351	22,536
60%	40,288	33,724	27,004
50%	40,292	38,977	28,823
40%	40,295	39,181	33,085
30%	40,395	39,968	37,115
25%	40,558	43,431	38,435
20%	43,019	46,670	44,516
15%	47,541	48,770	46,747
10%	50,331	50,331	49,809
5%	50,331	50,331	50,331
2%	50,331	50,331	50,331
1%	50,331	50,331	50,331
0.50%	50,331	50,331	50,331
Maximum	50,331	50,331	50,331

Granger	STORAGE	MAY	JUN	JUL
Capacity	50,331	13.85	13.85	7.62
Trigger 1	39,183	80.32	37.29	24.57
Trigger 2	30,035	100	96.44	45.53
Trigger 3	22,959	100	100	64.34



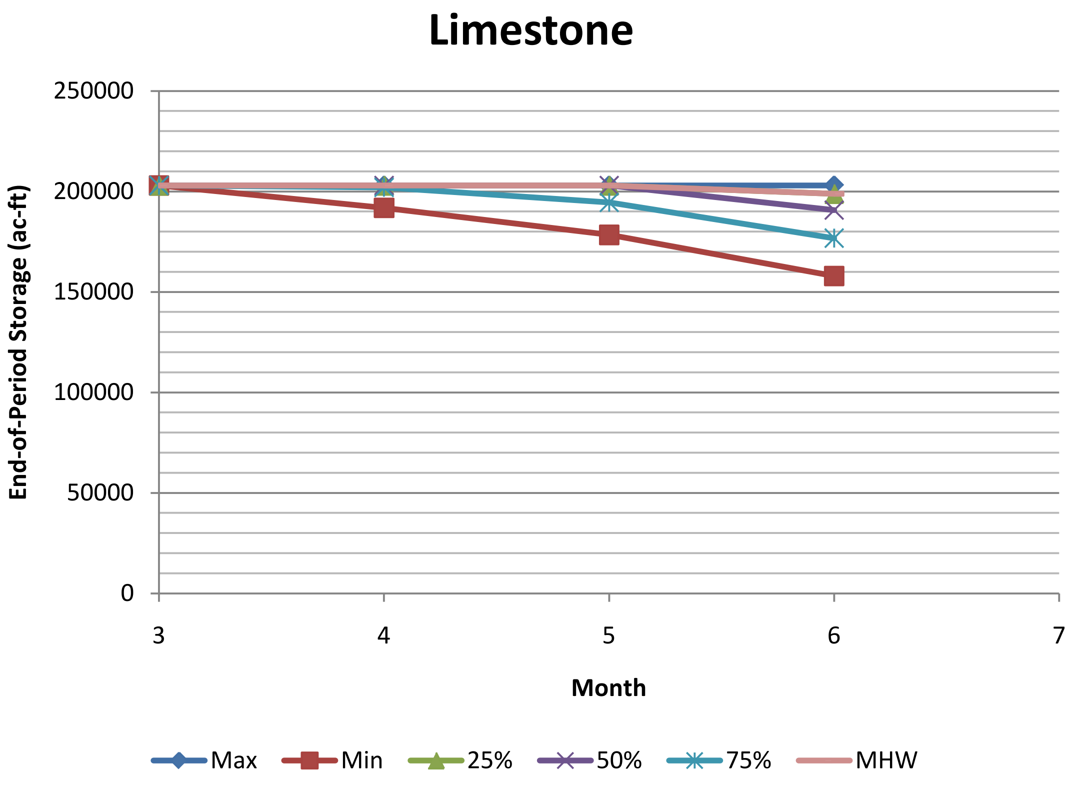
Somerville	MAY	JUN	JUL
Mean	141,629	138,392	130,910
Std Dev	185,589	372,164	624,896
Minimum	131,575	120,956	106,761
99.50%	135,643	125,068	111,731
99%	135,643	125,068	111,731
98%	135,643	125,068	111,867
95%	136,149	126,218	111,867
90%	136,693	128,307	115,578
85%	136,723	128,914	117,549
80%	138,009	130,825	118,601
75%	138,078	134,492	120,769
70%	138,732	135,305	122,216
60%	141,916	138,275	128,533
50%	143,509	141,319	130,982
40%	144,619	143,777	138,885
30%	144,619	144,619	139,884
25%	144,619	144,619	141,032
20%	144,619	144,619	144,619
15%	144,619	144,619	144,619
10%	144,619	144,619	144,619
5%	144,619	144,619	144,619
2%	144,619	144,619	144,619
1%	144,619	144,619	144,619
0.50%	144,619	144,619	144,619
Maximum	144,619	144,619	144,619

Somerville	STORAGE	MAY	JUN	JUL
Capacity	144,619	48.85	37.98	20.33
Trigger 1	110,010	100	100	99.9
Trigger 2	83,769	100	100	100
Trigger 3	66,164	100	100	100



Limestone	MAY	JUN	JUL
Mean	201,778	199,333	187,793
Std Dev	117,378	330,287	669,507
Minimum	191,869	178,376	157,884
99.50%	194,300	182,106	162,946
99%	194,300	182,663	163,392
98%	195,601	183,652	163,540
95%	197,437	186,566	167,242
90%	198,462	188,952	171,501
85%	199,270	191,263	172,455
80%	200,659	193,519	173,689
75%	201,978	194,540	176,766
70%	202,493	196,085	179,330
60%	202,952	199,157	187,181
50%	202,952	202,952	190,682
40%	202,952	202,952	193,068
30%	202,952	202,952	197,302
25%	202,952	202,952	198,814
20%	202,952	202,952	198,814
15%	202,952	202,952	201,923
10%	202,952	202,952	202,952
5%	202,952	202,952	202,952
2%	202,952	202,952	202,952
1%	202,952	202,952	202,952
0.50%	202,952	202,952	202,952
Maximum	202,952	202,952	202,952

Limestone	STORAGE	MAY	JUN	JUL
Capacity	202,952	67.12	50.75	12.08
Trigger 1	143,689	100	100	100
Trigger 2	107,248	100	100	100
Trigger 3	62,941	100	100	100



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