RIVER/RESERVOIR SYSTEM WATER AVAILABILITY MODELING SUPPORT FOR DROUGHT MANAGEMENT

A Thesis

by

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ABSTRACT

The Water Availability Modeling (WAM) System maintained by the Texas Commission on Environmental Quality (TCEQ) consists of the Water Rights Analysis Package (WRAP) and datasets for all the river basins of Texas. The modeling system is used to support long-term regional and statewide planning and evaluation of water right permit applications. The research is designed to explore and improve WRAP/WAM capabilities as a decision-support tool for drought management.

The WRAP/WAM model for the Colorado River Basin is applied in this research in both long-term planning and short-term conditional reliability modeling (CRM) modes. A strategy using iterative long-term simulations is developed for modeling water management plans that combine interruptible and firm water supply commitments. The methodology is tested and demonstrated by application to the LCRA System. Improvements in water supply reliabilities provided by off-channel storage are also investigated in the simulation study. The research is designed to explore and improve modeling capabilities in general, not to support specific decisions regarding water management in this particular river basin.

CRM features in WRAP provide short-term storage frequency and supply reliability analyses conditioned on preceding reservoir storage and can be employed as a decision-support tool for water management during drought or operational planning studies for preparing for future drought. The research explores alternative methods and combinations of options for performing various CRM tasks and develops several additional new options.

Climate teleconnection patterns, drought indices, and flow persistence are investigated from the perspective of potential improvements to WRAP/WAM CRM capabilities. The literature regarding climate cycles and metrics for identifying these cycles is reviewed. Correlation analyses are performed to analyze the relationship between flows at selected sites on the Colorado River and various climate cycle indices. The correlations are generally found to be fairly weak.

The Rapid Intervention Program (RIP) is designed for improving on-farm irrigation management strategies. A new interactive web interface tool being developed by other researchers at Texas A&M University, called the Irrigation Water-Use Efficiency Maximizer (IWEM), will link WRAP with RIP. WRAP CRM methods are tested and compared to determine the optimal combination of options for use with the IWEM platform.

DEDICATION

To the people of Texas.

ACKNOWLEDMENTS

I am very grateful to all those who have supported me during my time at Texas A&M University. I am thankful to all of the professors and fellow students whom I have had the opportunity to work with along the way.

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NOMENCLATURE

CRM	Conditional Reliability Modeling
ENSO	El Nino Southern Oscillation
IWEN	Irrigation Water-Use Efficiency Maximizer
LCRA	Lower Colorado River Authority
NAO	Northern Atlantic Oscillation
OCR	Off Channel Reservoir
PDSI	Palmer Drought Severity Index
TCEQ	Texas Commission on Environmental Quality
RIP	Rapid Intervention Program
ROR	Run of River
WAM	Water Availability Modeling
WRAP	Water Rights Analysis Package
WMP	Water Management Plan
SFF	Storage Flow Frequency
SBU	Storage Back Up

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CHAPTER I

INTRODUCTION

1.1. Background

Population growth and expansion of agricultural and industrial sectors have increased demands on water resources. Environmental demand for water is also expected to rise which will require more water to stay in-stream. Climate change will also be another crucial factor in water management. Various climate change studies project significant change in precipitation intensity and increase in flood and drought frequencies. With declining water supply and increasing water demand, water scarcity is expected to increase manifold times in the future. Extreme weather conditions like floods and droughts will have to be handled carefully. Appropriate water resource planning and management strategies can play a crucial role in mitigating effects of these problems. The Texas Commission on Environmental Quality (TCEQ) is an environmental agency working for the state. It regulates the use of surface water through a system of water rights based on a prior appropriation water rights permitting system.

The Water Availability Modeling (WAM) System maintained by the TCEQ consists of the Water Rights Analysis Package (WRAP) developed at Texas A&M University and WRAP input datasets for the 23 river basins of Texas (Wurbs, 2005). The WRAP/WAM System is used to assess water supply reliability and reservoir storage and stream flow frequency relationships for specified water demands and river/reservoir system management strategies. The modeling system has been applied in Texas since about year 2000 primarily to support long-term regional and statewide planning and evaluation of water right permit applications. Texas suffers from droughts regularly. Since 2010, regions of west Texas are experiencing the worst drought in recorded history. The 2010-2013 drought highlighted needs for expanded modeling and analysis capabilities for decision-support during drought. The research presented here is designed to explore and improve WRAP/WAM capabilities for drought management decision-support.

1.2. Research Objectives

The overall goal of the research is to expand WRAP/WAM capabilities for performing reliability and frequency analyses to support water management during drought. A WRAP simulation study using versions of the Colorado WAM dataset is a central focus of the research. The research includes the following components which address more detailed objectives.

1. The published literature and information available from water agencies are reviewed to compile relevant information regarding drought management and associated modeling capabilities.
2. A comparative evaluation of alternative WRAP conditional reliability modeling (CRM) methodologies is performed. Alternative CRM strategies and methods are tested and compared.
3. Teleconnection patterns of long-term climatic cycles, drought indices, and flow persistence is investigated from the perspective of potential improvements to WRAP CRM capabilities.

4. Identified improvements to the WRAP CRM methodologies are implemented in the software.
5. A modeling strategy based on long-term and short-term simulations is formulated, tested, and applied for combining firm and interruptible water supply commitments governed by reservoir storage contents. A comparative evaluation of alternative water management plans for the LCRA system is performed.
6. Analyses of increases in reliabilities provided by adding off-channel reservoir storage to the LCRA system is incorporated in the simulation studies.
7. Strategies for incorporating WRAP CRM results in the Irrigation Water-Use Efficiency Maximizer (IWEM) are explored and a selected strategy implemented.

1.3. Literature Review

1.3.1. Conditional Reliability Modeling

Moran (1954) presented a model to estimate the probability distribution of storage at the end of consecutive years with known initial storage. The model worked under simplistic assumptions of uniform outflows during dry seasons and independent inflows at an annual time step. The model used a Markov chain in which a transient probability matrix multiplied the current probability distribution of storage for future probability distribution. Gould (1961) addressed seasonal variations and serial correlation of inflows limitation to the Moran model by employing conservation of mass principle based on historical precipitation, evaporation and flow data. The modification could not overcome Moran’s assumption of independent annual flows.

The Tennessee Valley Authority (TVA) (Shane and Gilbert, 1982) developed a computer model called HYDROSIM to model weekly variation in TVA's complex reservoir system. The model could develop optimum reservoir scheduling for weeks in advance using short term storage forecasts, given an initial storage condition. The short term storage forecasts were developed on the basis of frequency statistics from multiple simulations of the reservoir system.

Vaugh and Maidment (1987) used a computer model PROSTOR to compare Gould's probability matrix method and transient analysis method of projecting the probability distribution of reservoirs. A case study was performed on the Highland Lakes System on Lower Colorado River with probability distribution projected up to six years into the future. The transient analysis method works by routing historical hydrologic data sequences through system operation simulations. For a given initial storage conditions, system operation rules, monthly water demands and physical system characteristics, a future storage is computed using a storage equation. The simulation works from upstream to downstream reservoir sequentially at a monthly time step until the end of specified projection period is reached for each year of historical data. Each reservoir is assigned an initial storage value at the beginning of the annual time step and multiple simulations are performed for each time step until the end of specified projection period is reached. This iterative mass balancing procedure results are tabulated and provides a lowest and highest monthly storages attained for the projection period. The study demonstrated the significance of annual correlation of hydrologic data by finding a 5%

less future storage level value in transient analysis than Gould's probability matrix method.

Conditional reliability modeling was developed to expand the WAM system to support short term drought management and operation planning. Brandes and Sullivan (1998) developed a Conditional Probability Model (CPM) for Amistad and Falcon reservoirs on the Rio Grande River. The model worked under the principles of transient analysis method by processing the outputs from simulations done by computerized reservoir operation model (ROM). The CPM model worked by dividing the reservoirs into 40 horizontal layers of equal volume. The historical period of analysis is broken into multiple management time interval based on hydrologic traces. ROM is operated for these independent hydrologic traces with each trace beginning at one of the 40 storage levels. After each simulation ROM records the initial storage condition used and the final storage condition achieved at the end of simulation. It also records the number of months with shortages for each initial storage condition. Using these two relationships relative frequency of occurrence for a storage level and the associated probability of failure is computed.

Salazar and Wurbs (2004) developed the CRM methodology in conjunction with WRAP to assess reliabilities for meeting water demand over future time periods based on previous storage conditions. The WRAP simulates water resource management for priority ordered allocation under the assumption of repetition of past hydrologic conditions. CRM modifies the transient analysis approach by assigning probability estimates to each historical hydrologic sequence based on a conditional frequency duration curve (CFDC). The CDFC is an exceedance frequency table for naturalized flow for known levels of preceding storage. The CDFC curve is developed by dividing the storage capacity and naturalized flows into equal number of intervals. Arrays are developed for flows following the occurrence of each storage level and statistical analysis is performed to assign probabilities to naturalized flows for particular storage levels. Olmos (2004) analyzed different conditional reliability analysis methodologies including the equal weight approach, CDFC curve method and also proposed a new Storage - Flow Frequency (SFF) method. The SFF method works by assigning probability of occurrence to each sequence in the simulation based on relationship between storage volume and naturalized flow volume. A comparative study was performed for Lake Waco in the Brazos River System. The study found SFF model to be more conservative for low initial storage conditions and produce higher reliability for high storage conditions. The CDFC method has now been abandoned in favor of the SFF method due to inconvenience in practical applications. Wurbs, et al. (2007) added further options to assign probabilities to the simulation sequences in CRM called the equal weight option and probability array option.

Schnier (2010) performed a sensitivity analysis for different options available for CRM and also prepared a guideline for practical applications of CRM. The study found CRM to be less sensitive to data extension techniques and recommended longer historical period of record for accurate results. The initial storage content value was found to depend upon the storage reservoir frequency curve for individual reservoirs. The choice of starting month for CRM simulations was influential for short length simulations but seemed to dissipate with increase in simulation lengths. The study also recommended use of SFF for simulation lengths of less than 6 months in general. Wurbs, et al. (2012) did a comparative study of equal weight and probability array method for a condensed version of Brazos WAM system with 108 year hydrologic period of analysis. The study adopted annual cycle option with a 12 month simulation period starting at beginning of July. Storage frequency relationships for Lake Proctor and a four reservoir system was computed for end of September and June using both equal weight and probability array methods. The study found approximately the same values for equal weight and probability array methods at preceding storage levels of 100% and 75% capacity but, for 50% and 25% preceding storage contents the differences were significant.

1.3.2. Teleconnection Patterns, Drought Indices and Flow Persistence

Seasonal and annual hydrologic forecasts are significantly related to large scale atmospheric circulation patterns and regional climate anomalies and their relationship has been studied extensively. The teleconnection patterns influence climatic anomalies and thus affect hydrologic variables like rainfall and runoff. Mishra and Singh (2011) presented an overview of drought modeling approaches with their advantages and limitations. The methodologies reviewed included drought forecasting, probability based modeling, spatial-temporal analysis, and use of Global Climate Models (GCMs) for drought scenarios, and land data assimilation systems for drought modeling and planning. The paper also discussed the role of climate indices in long lead drought forecasting. Accurately forecasting precipitation for longer periods in future is crucial to long lead time drought forecasting. The study found precipitation to be heavily influenced by broad scale atmospheric phenomenon. Strong statistical relationship between climatic indices and rainfall is valuable in long-range rainfall forecasting and hence, better drought forecasting.

Chiew and McMahon (2002) studied the effect of ENSO teleconnection patterns on runoff throughout the world. The study was carried out by correlating two ENSO indices, the Southern Oscillation Index (SOI) and Multivariate ENSO Index (MEI) with streamflow. The study found strong and consistent ENSO and streamflow connections in Australia, New Zealand, and South and Central America. For North America, medium strength correlation between ENSO and streamflow was found in Alberta and Saskatchewan in Canada and in Florida and Gulf of Mexico in USA. The study also found higher serial streamflow correlation in most of the catchments demonstrating streamflow persistence’s effectiveness in flow forecasting. Piechota and Dracup (1996) studied the association of hydrologic variation and drought with ENSO in the United States. The study used PDSI as the drought index and SOI as ENSO index and found strong relations between SOI and PDSI is most regions of US. Texas showed dry hydrologic anomaly before and during the El Nino year and wet anomaly at the end of El Nino year and beginning of next year. La Nina had significant dry effect from November to December. The study also analyzed SOI to streamflow but did not find any significant relationship for Texas. The correlation was not strong enough for predicting streamflow or drought but good enough if expressed as exceedance probabilities. Rajagopalan and Cook (2000) did a similar study of spatial structure of teleconnections between ENSO and SST for the continental US. They found high teleconnection between ENSO and PDSI in the southwestern US but with variability in their relations over time. The study found 1963 to 1995 had weaker teleconnection than the period 1895-1962. The non-stationarity in teleconnections could be a problem for forecasting based on historical records.

A number of studies have investigated the teleconnection effects of ENSO on Central Texas. Most of the studies were done with support from the Lower Colorado River Authority (LCRA). Long lead time prediction of flows is crucial to the LCRA for better planning and management of water supply. Watkins and Connell (2005) investigated the usefulness of teleconnection patterns for long term hydrologic prediction considering ENSO, North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and streamflow persistence for the Highland Lakes system in Central Texas. The study found NAO to be a good indicator of low flows, SOI reliable for mid-range flows and persistence as a bad indicator of annual flows, but pointed to potential improvement in seasonal forecasts using a combination of indices and persistence. Wurbs et al. (2005) studied the potential effects of climate change on water supply capabilities and potential incorporation of climate change in the WAM system. A case study was carried out for the Brazos River Basin to analyze trends and cycles in naturalized streamflow sequences at seven gauge stations with period of analysis extending from 1900-1997. The study detected annual seasonality and multiple year cycles and compared them to ENSO events. The flows during El Nino periods were found to be 168% to 180% higher than those under average conditions. A comparison of flows before and after an ENSO event revealed significantly less flows in years before and after El Nino events.

Walker and Anderson (2011) reviewed the effects of different teleconnection patterns on streamflow in the central Texas region and found persistence to be the strongest indicator of hydrologic conditions. Persistence is directly related to streamflow and indirectly related to the teleconnection patterns, so it was found useful in predicting short term streamflow. However, for long term prediction, consideration of teleconnection patterns was concluded to be a must. Investigation of most prominent teleconnection patterns as indicators of hydrology showed ENSO to be the best indicator. Wei and Watkins (2011) also evaluated climatic indices Nino 3.4, PDO, NAO, AMO and PNA as predictors for seasonal flows in central Texas. The influence of climatic indices was evaluated for inflows from USGS gage measurements and naturalized outflows flow from the Colorado WAM for the Highland Lakes system. The study found hydrologic persistence effectively predicted downstream flows during winter, spring and summer. Also improvement in downstream forecasts could be achieved by including ENSO and PDO SST patterns.

Slade and Chow (2011) also studied the relationship between precipitation and stream runoff for El Nino and La Nina periods in the Texas Hill country. They found occurrence of higher precipitation during summer periods (June- November) of La Nina cycles and El Nino causing higher precipitation in the other seasons but more notably during cooler months (December – May). Monthly precipitation analysis suggested higher rainfall in August for La Nina period and for all other months El Nino precipitation overshadowed La Nina precipitation. Runoff during El Nino event was found to be higher than during a La Nina cycle but annual peak runoff was more influenced by hurricane season than ENSO. He also found spatial variability in mean discharge with Northern parts showing slightly greater discharge during El Nino and substantially higher El Nino discharge at all other locations.

1.4. Colorado River Basin

The Colorado River Basin extends from southeast New Mexico about 600 miles across Texas. Its climate varies from arid in the northwest with an average annual precipitation ranging between 12 and 16 inches to humid subtropical in the southeast with average annual precipitation of 44 inches. The basin has a total drainage area of 42,460 square miles, of which approximately 11,830 square miles are non-contributing. The headwaters of the Colorado River begin in New Mexico and northwest Texas at an elevation of about 4,000 feet. The river flows into Matagorda Bay south of Bay City. The major tributaries of the Colorado River are Beals Creek, Pecan Bayou, Concho River, San Saba River, Llano River, and Pedernales River, all entering the Colorado River upstream of the City of Austin.

Austin with a 2013 population of about 885,400 people is the largest city in the Colorado River Basin. The five-county Austin-Round Rock-San Marcos metropolitan area had a population of about 1,883,051 in 2013. The Colorado River flows through Austin and serves as the primary water supply source for the city. Austin both holds its own water right permits and contracts with the Lower Colorado River Authority (LCRA) for water supplied under LCRA water right permits

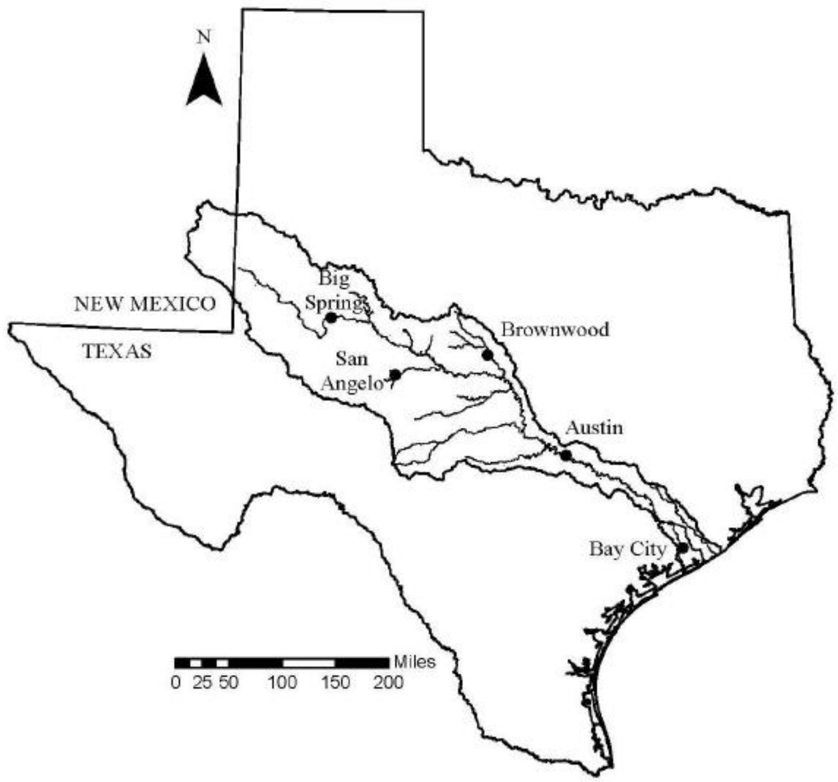

Figure 1.1. Colorado River Basin and Brazos-Colorado Coastal Basin

1.5. Reservoirs in Colorado River Basin

The March 2010 updated authorized use scenario Colorado WAM includes 518 reservoirs, of which 488 are actual reservoirs and 30 are computational reservoirs used for accounting purposes. Two of these actual reservoirs are permitted but not yet constructed. The accounting reservoirs are used primarily in modeling complexities of the LCRA water management plan but also for some of the other water rights. The total capacity of 5,195,460 acre-feet of the 31 major reservoirs account for 97.8% of the total storage capacity of 5,313,882 acre-feet in the 488 reservoirs. Lake Buchanan serves as the divide between the Upper and Lower Colorado River. The Lower Colorado River Authority (LCRA) controls most of the reservoir storage capacity in the lower basin, and the Colorado River Municipal Water District (CRMWD) controls the majority of the reservoir storage capacity in the upper basin. The five largest reservoirs are Travis and Buchanan owned by the LCRA and Ivie, Spence, and Thomas owned by the CRMWD. The six LCRA Highland Lakes contains 50.6% of total permitted capacity of the 488 reservoirs. (Hoffpauir et. al., 2013).

The Colorado River Municipal Water District (CRMWD) and LCRA are the largest reservoir operators and water suppliers in Colorado River Basin. CRMWD created by the Texas Legislature in 1949 operates in the upper Colorado River Basin and is responsible for providing water to its member cities of Odessa, Big Spring, Snyder, Midland, etc. The CRMWD owns and operates Lake J.B. Thomas, E.V. Spence Reservoir, and O.H. Ivie Reservoir, which have permitted water supply storage capacities of 204,000 acre-feet, 488,760 acre-feet, and 554,340 acre-feet. Ivie, Spence, and Thomas contain 25.9% of total permitted capacity of the 488 reservoirs The CRMWD owns nine other reservoirs that are used to prevent low-quality, high salinity water from flowing downstream (Hoffpauir et. al., 2013). Table 1.1 lists the major reservoirs in Colorado River Basin.

This study evaluates the best possible combinations of options in WRAP CRM modeling using the Colorado River Basin as a case study. The five largest reservoir mentioned in Table 1.1 has been simulated as a combined scenario. The combined scenario gives an overall representation of CRM options for the entire Colorado River

Basin. Lake Travis and Lake Buchanan are also analyzed in this study to represent the Highland Lakes

Table 1.1. Selected Major Reservoirs in Colorado River Basin

Reservoir	Capacity (acre-feet)	Surface Area (acres)	Drainage Area (sq. miles)
Travis	1,134,956	19,297	38,130
Buchanan	886,626	22,137	31,250
O.H. Ivie	554,340	19,149	12,647
E.V. Spence	512,272	14,640	2,695
J. B. Thomas	200,604	7,282	3,524
L. B. Johnson	133,090	6,273	36,290
Austin	24,644	1,589	38,240
Inks	14,074	788	31,290
Marbles Falls	7,486	608	36,325

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WRAP simulates the management of water resource for the entire river basin. Hence, all 488 reservoirs are simulated during each simulation of the Colorado WAM. The storage frequency tables are created only for Lake Travis, Lake Buchanan and the combined scenario, but it encompasses the effects of all 488 reservoirs.

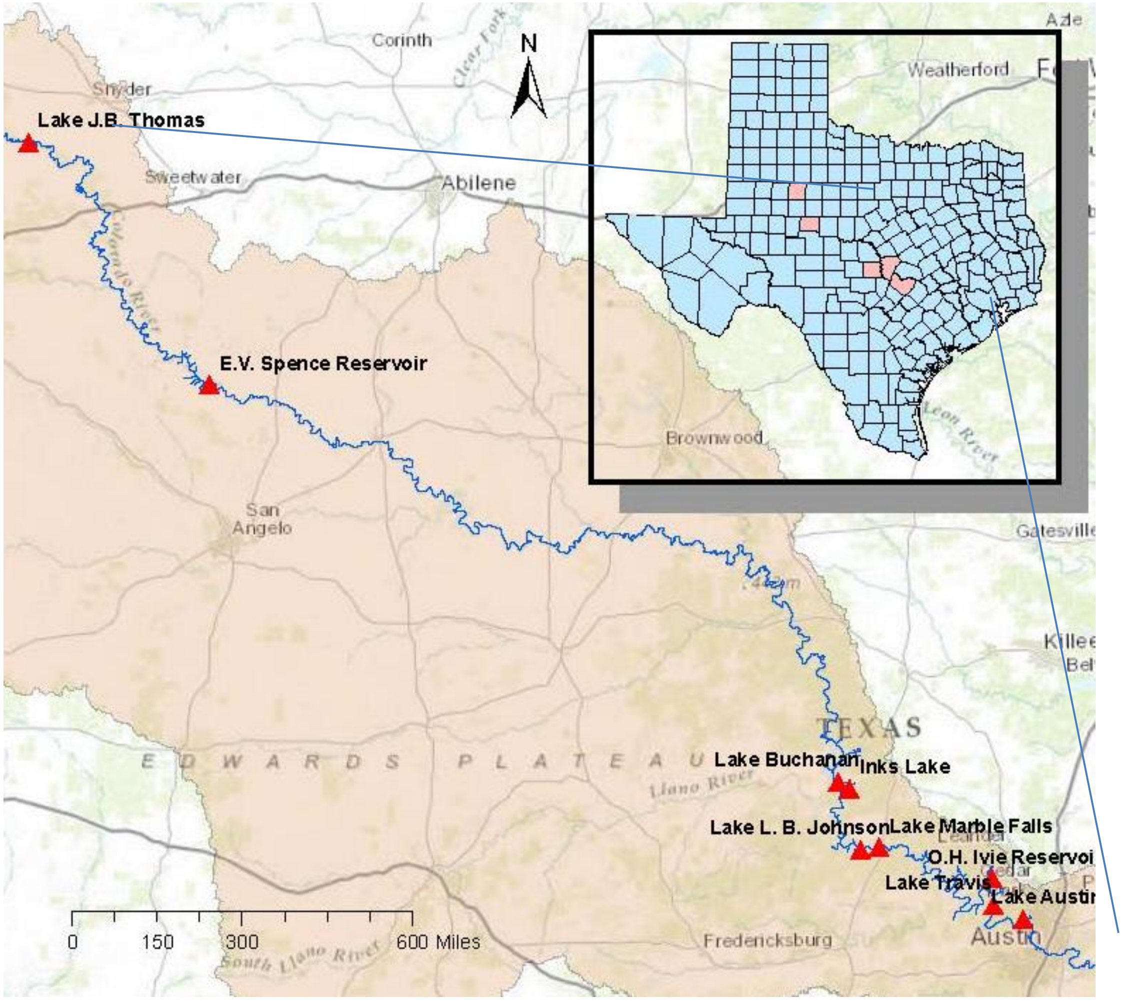

Figure 1.2. Selected Major Reservoirs in Colorado River Basin

1.6. Water Rights in Colorado River Basin

The original Colorado WAM contained 1,287 water rights, including 1,226 water rights in the Colorado River Basin and 61 water rights in the Brazos-Colorado Coastal Basin, with the most junior water right having a priority date of May 5, 2000 (R. J. Brandes Company, 2001). The water rights included authorized diversions totaling 3.3 million acre-feet per year, with approximately 66% used for municipal purposes, 25%

used for irrigation, 8% used for industrial purposes, and 1% used for mining, recreation, and other purposes. Several water rights in the Colorado WAM include authorization to divert and/or impound water only when stream flows at specified locations exceed prescribed levels. These restrictions are designed to protect senior water rights and/or environmental flow needs. The March 2010 authorized use scenario Colorado WAM contains 2,006 water right WR and 99 instream flow IF records. For more complicated water rights, multiple WR and IF records are used to model a single water right permit. Priority numbers range from zero to 99999999, but priorities representing dates range from 18641231 to 20010228.

The water rights associated with the irrigation districts in Colorado River Basin and 3 water rights associated to City of Austin have been used in the reliability analysis of interruptible supply The concerning water rights are further discussed in Chapter 5

1.7. Organization of the Thesis

This thesis is divided into six chapters and one appendix. Chapter I includes background information and research objectives of the thesis. The literature review in Chapter 1 describes the historical background of the development of CRM and essential findings regarding CRM methodologies. The literature review also covers the effects of different hydrologic indicators on precipitation and flow especially for the Colorado River Basin. Chapter II gives a general description of the Texas water rights system and models used in implementation of the system. Chapter III describes the CRM concepts, options and methodologies. It also includes an evaluation of CRM strategies and methodologies for the Colorado River Basin.

Chapter IV focuses on analysis of teleconnection patterns, drought indices, and flow persistence as potential improvement to WRAP CRM methodology. Different hydrologic indicators as well as the result of the analysis is discussed in the chapter. Chapter V presents a comparative analysis of firm and interruptible water supply as a function of available storage. It provides a general description of LCRA WMP and focuses on analysis of interruptible supply at different storage capacities. A demonstrative study is performed for the Highland Lakes system and irrigation districts with/without the presence of off-channel storage. Chapter VI summarizes and integrates topics covered in the preceding chapters. Finally, conclusions and recommendations on various topics of the research are presented in Chapter VII.

CHAPTER II

GENERAL MODEL DESCRIPTION

2.1. Overview of Texas Water Rights System

Water rights in the United States are primarily managed by the State government with the Federal government only governing federal lands. Water right systems vary from state to state and for larger river basins covering multiple states, interstate compacts are developed with the approval of the U.S. Congress. Water right systems also vary between surface and ground water. The two principle water right doctrines most commonly used for surface water are riparian and prior appropriation. In the prior appropriation system, users have to claim their use of water through water rights from the state and normally the priority of water allocation depends upon the date of right granted. This system works on the “first come, first served” basis. The riparian system allows owners of the land adjacent to stream to use flows. Landowners with lands bordering streams are allowed to use the flows for domestic, livestock and irrigation purposes.

Texas had adopted a mix of both riparian and prior appropriation rights as the legal water rights system. Initially Texas had adopted the riparian system but changed to prior appropriation system in 1895. The switch made it mandatory to seek state approval for surface water use for land converted from public to private ownership after 1895. The use of both systems caused problems during the drought of the 1950s with water right claims exceeding water availability. In 1967, the Texas legislature passed the

Water Rights Adjudication Act which merged riparian rights into the prior appropriation system and established the permitting system (TWDB, n.d.). The Texas Commission on Environmental Quality (TCEQ) is the agency responsible for administering the water right system. All persons or organization wanting to divert water or store water have to acquire a water rights permit approval from the TCEQ. A water right allows the holder to divert specified amount of water at a specific location, for a specific purpose, and to store water in reservoirs of specified capacity (Wurbs and James, 2002).The water rights are assigned priorities based on the acceptance date of their application filing. The 75th Texas legislature in 1997 passed Senate Bill 1 which specified the development of Water Availability Models (WAM) for all of the 23 river basins in state. TCEQ thus developed the WAM system and is responsible for managing the water rights permit system in Texas.

2.2. Overview of Texas WAM System and WRAP

The WAM system consists of sets of databases and modeling tools for use in conducting planning studies and in preparing and evaluating water rights permit applications. The Texas WAM system consists of the Water Rights Analysis Package (WRAP) modelling system, 20 sets of WRAP input files covering the 23 river basins of the state, a geographic information system (GIS), and other supporting databases. The generalized model is designed for assessing hydrologic and institutional water availability and reliability for water supply diversions, environmental instream flows, hydro-electric energy generation, and reservoir storage (Wurbs a, 2013). The Texas Water Development Board, TCEQ, river authorities and other water management agencies use the WAM system to conduct various types of studies as well. WRAP simulates management of the water resource for a river basin or multiple-basin region under a priority based water allocation system, under the assumption that historical hydrologic conditions provide satisfactory representation of future hydrologic conditions.

Different river basin development scenarios can be modelled using WRAP with adjustments to the input datasets. Two most commonly used river basin development scenarios are the authorized use (Run 3) and current use (Run 8). The authorized use scenario consists of diversions being made to full amounts with no return flows and no sediment accumulation included in reservoir storage capacity. The current use scenario consists of diversions being made based on maximum annual amount used in a ten year period with estimates of return flows and reservoir storage capacities reflecting year 2000 conditions of sedimentation. The input dataset contains a file with water management information and three hydrology files: naturalized flows, watershed parameters and net reservoir evaporation rates. TCEQ requires that water management entities and their consultants use the WAM system in preparing water right permit applications and, TCEQ use the modeling system in evaluating the applications (Wurbs, 2005).

The Water Rights Analysis Package (WRAP) modeling system simulates management of the water resources of a river basin or multiple-basin region under priority-based water allocation systems. The model facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for various water uses. The river basin hydrology is represented by sequences of naturalized stream flows and net evaporation rates for reservoirs. The spatial configuration of river, reservoir and diversions are represented through control points at required sites. Water Rights in WRAP refers to a set of water management capabilities and use requirement that includes storage refill, instream flow requirements , water diversions, hydroelectric power generation and stream flow return (Wurbs a, 2013). The WRAP system is constantly being modified and improved by adding new modeling capabilities as river system management gets more complicated. Modeling environmental flow requirements required simulations to be performed at daily time steps which led to the addition of daily time step simulation capabilities in WRAP. Datasets are also being modified for major river basins with environmental flow requirements at daily time step level incorporated. Conditional Reliability Modeling (CRM) is another feature that was recently implemented in WRAP modeling system to support drought management and operation planning activities.

WRAP is incorporated in the TCEQ WAM system and consists of the main computer programs SIM and TABLES and other auxiliary programs. The SIM program simulates river systems and water use scenarios and requires sequences of naturalized flows and net evaporation rates. The TABLES program is used for post processing the data obtained from SIM and summarizing simulation results. Other auxiliary programs include programs to develop hydrological inputs and perform simulations at sub monthly time step. The SIM program has three main modes of operation (Wurbs a, 2013).

1. A single long term simulation

2. Firm yield analysis option

3. Conditional reliability modeling (CRM) option

The firm yield analysis option is based on repetition of long term simulation to develop a diversion target (yield) versus reliability table that includes the firm yield if a firm (100% reliability) is feasible.

A conventional SIM simulation works by simulating a water management and use scenario through the entire length of hydrological period-of-analysis in a single simulation. The storage levels for all reservoirs are set at the beginning of the simulation. For example, with a 1940 – 2013 hydrologic period of analysis, the model would allocate water to meet requirements during each sequential month of a single 888 month hydrologic sequence starting in January 1940. CRM mode works by dividing the entire period of analysis into shorter sequences as specified by the user. The SIM simulation is repeated with each hydrologic sequence starting with the same user specified initial reservoir storage contents.

WRAP and its modelling capabilities are very well documented in WRAP User's manual (Wurbs b, 2013) and WRAP Reference manual (Wurbs a, 2013).

2.3. Colorado Water Availability Model

The Colorado Water Availability Model (Colorado WAM) is the WRAP input dataset for the Colorado River Basin and adjoining Brazos – Colorado Coastal Basin in the TCEQ WAM system. It was developed under the provision of the 1997 Senate Bill 1 by the R. J. Brandes Company and its subcontractors under contract with Texas Natural Resource Conservation Commission. The Colorado WAM as originally developed had a hydrologic period of analysis extending from January 1940 through December 1998. Although water rights and other aspects of the modeling system had been updated regularly, updates to hydrologic files were lacking. An auxiliary WRAP program called HYD was designed to develop and update hydrologic files for WRAP SIM during 1999-2001 and has been updated and expanded with addition of new capabilities in 2012. The Colorado WAM used in this study is a modified version of authorized use scenario Colorado WAM dataset with draft revisions by the TCEQ dated March 22, 2010. The modifications included extension of hydrologic period of extension through 2013, development of daily Colorado WAM dataset and addition of environmental flow requirements adopted as per Senate Bill 3 (SB-3) enacted by Texas Legislature in 2007. The original Colorado WAM dataset was last updated by TCEQ in March 2010. The updated dataset has been modified at Texas A&M University under the combined effort of Richard J. Hoffpauir, Ralph A. Wurbs and Mark A. Pauls, to extend the hydrologic period of record to 2013. This modified dataset has been used for the purpose of this study and has two versions: the Fully Authorized and the Current Condition datasets having filename roots C3 and C8 respectively. The Monthly time step Colorado WAM with Fully Authorization condition has been used for the purpose of this study. The C3 dataset for the Colorado WAM contains 2,422 control points, 2006 water rights, 99 Instream flow rights and 518 reservoirs

CHAPTER III

EVALUATION OF CONDITIONAL RELIABILITY MODELING METHODOLOGIES

Conditional Reliability Modeling methodologies were evaluated for the Colorado River Basin using CRM features of WRAP. Key concepts and methodologies concerning CRM are described in this chapter. The study uses the updated fully authorized version of Colorado WAM dataset with hydrologic period of record extending from 1940 to 2013.

3.1. Conditional Reliability Modeling Methodologies

Conditional Reliability Modeling (CRM) is used to develop short term reliability and frequency estimates conditioned on preceding reservoir storage. The SIM simulation model automatically divides a long hydrologic period of analysis into shorter sequences, based on user-specified parameters, and performs repeated simulations for each sequence starting with same reservoir content level. The program TABLES then uses the output from the SIM simulation model to develop flow and storage frequency relationships and water supply and hydropower reliabilities. The main purpose of CRM is to evaluate reliabilities in meeting water needs during the next future period of months or years. Thus CRM can be used as a decision support tool for water management during droughts and developing river and reservoir operation policies. It can be used by regulatory agencies to determine curtailment actions for water supply and develop seasonal or annual operation plans.

WRAP can divide the hydrologic period of analysis into shorter sequences using two options called the annual cycle option and the monthly cycle options. In the monthly cycle options, the simulations begin at the start of a specified month and the next sequence starts in the next month after the completion of the previous sequence. The sequences keep recycling after the completion of preceding month's simulation. The annual cycle option starts at a specified month of the year and for a specified length of simulation period. After the completion of simulation for a sequence of an individual year, the next simulation starts at the specified month of the following year. The monthly cycle option is mostly used to maximize the number of simulation sequences and can provide up to 12 times more sequences than the annual cycle option. The annual cycle option starts at same month for all sequences and is thus able to model seasonal characteristics of hydrology properly but the number of hydrologic sequences is limited to total number of years in the hydrologic period of analysis. The annual option and monthly option provide a choice between capturing seasonality and maximizing the number of simulations. Both options help improve the accuracy of the reliability and frequency estimates and should be chosen as per the need of the user. In this study seasonality is of great importance and hence the annual cycle option has been adopted for CRM simulations.

CRM also allows two alternative strategies to assign probabilities to each flow sequence called the equal weight and probability array option. In the equal weight option, all the simulation sequences are considered equally likely to occur and are assigned probabilities of one out of total number of simulation sequences. No extra features are required in TABLES for the equal weight option and all frequency and reliability computations are the same for a conventional long term simulation and CRM equal weight option. In the probability array option, probabilities are assigned to each hydrologic sequence with either a flow – frequency (FF) relationship or storage-flow-frequency (SFF) relationship. Both relationships assign probabilities to naturalized flow volumes directly using either the log-normal probability distribution or Weibull formula. The probability array option develops incremental probabilities array and assigns probability to each simulation sequence. The FF relationship assigns exceedance probabilities directly to naturalized flow volumes and can only consider preceding storage level by using sequences with preceding storage falling within a specified range. Whereas the SFF relationship option relates exceedance probabilities to a random variable Q% which is a ratio of observed naturalized flow volume (Q) to expected naturalized flow volume (Q_S).

$$Q_{\%} = \frac{Q}{Q_S} \tag{1}$$

Here Q represents the naturalized flow volume over a specified length of months observed in CRM simulation results. Q_S is the corresponding expected value of naturalized flow volume and is determined from a regression equation reflecting preceding storage volume. Additionally four regression equations are available to relate the expected naturalized flow (Qs) to preceding storage volume: exponential (2), power (3), linear (4) and combined (5).

$$Q_s = a \times e^{\frac{S}{b}} \tag{2}$$

$$Q_s = bS^c \tag{3}$$

$$Q_s = a + bS \tag{4}$$

$$Q_s = a + bS^c \tag{5}$$

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

$$E(Y \mid x) = a + bx \tag{6}$$

$$b = \frac{n \sum x_i \, y_i - (\sum x_i)\,(\sum y_i)}{n \sum x_i^2 - (\sum x_i)^2} \tag{7}$$

$$a = \bar{y} - b\,\bar{x} \tag{8}$$

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

The SFF option uses reservoir storage or change in storage as an index of past hydrologic conditions. The SFF option can be effective only if there is some degree of correlation between naturalized flows and preceding storage change or storage contents. The linear correlation coefficient (r) and Spearman rank correlation coefficient are used as index of goodness of fit between naturalized flows (Q) and preceding storage content or change in storage (S).

$$r = \frac{n\sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{n\sum x_i^2 - (\sum y_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}} \tag{9}$$

Where Q_S and S represent x and y variables for linear correlation coefficient. The Spearman rank coefficient (r_r) is calculated based on the relative ranks of Q_S and S using a simplified equation as:

$$r_r = \frac{6\sum d_i^2}{n(n^2 - 1)} \tag{10}$$

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

The probability array options relate exceedance probabilities for the FF or SFF option using either the log normal probability distribution or Weibull formula. The log normal probability distribution is defined by the equation:

$$\log X = \overline{logX} + zS_{\log x} \tag{11}$$

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

$$P = \frac{m}{N+1} \tag{12}$$

Where P is the exceedance probability, m is the rank of variable Q or Q% and N is the total number of variables. The probability array option performs reliability and frequency analyses using the conventional computational routine but it will incorporate an exceedance probability (FF or SFF) relationship to assign an incremental probability to each simulation sequence. The incremental probabilities vary for the sequences and sum to 1.0. To assign probabilities to simulation sequence, Q or Q% values are calculated for each hydrologic sequence and combined with the previously created FF or SFF exceedance probability relationship. Thus, exceedance probability is assigned to each hydrologic sequence and then ranked in order and converted to incremental probabilities.

The SFF option is useful in incorporating correlation between naturalized flow with preceding storage volume and assigning probabilities to the simulation sequence. Relating preceding storage volume to naturalized flow allows WRAP to integrate hydrologic persistence into its simulations and thus accurately predict water availability reliabilities or frequencies for short term periods, usually up to a year into the future. Preceding storage content or change in storage as an indicator of current hydrologic condition can be effective as it is indicative of a number of hydrologic factors such as stream flow, precipitation, evaporation, upstream ground water and surface water interactions etc. However, the storage conditions can only account for short time predictions and becomes a less reliable indicator of hydrologic conditions as we look farther into the future. Inter-annual variability in hydrologic conditions are better explained by wider scale teleconnection patterns than streamflow or storage level persistence.

WRAP is a highly suitable tool for water management and planning, especially during droughts. It can be an effective tool for developing reservoir system operating policies based on preferred level of risk of future outcomes. It can also be used to develop seasonal or annual operation plans and evaluate curtailment of interruptible supply.

3.2. Conditional Reliability Modeling for Colorado River Basin

The motivation behind this study is to evaluate the best possible combinations of options in WRAP CRM modeling using the Colorado River Basin as a case study. CRM will then be used as a tool in conjunction with the IWEN platform to improve irrigation management. The Highland lake system is represented by Lake Travis and Lake Buchanan and the Colorado River Basin is represented by the combined scenario. Hence the selection of different CRM options has been made focusing on irrigation operations in Colorado River Basin.

3.2.1. Simulation Sequence Cycling Options

Out the two cycling options: the annual cycle and the monthly cycle, the annual cycle option has been adopted for the purpose of this study. Most irrigation, municipal and industrial water use are seasonal in characteristics. The annual cycle option is useful in capturing seasonal characteristics of hydrology and is ideal for this study compared to the monthly options. The annual cycle option does lower the number of simulation sequences when compared to monthly cycle option but 74 simulation sequences for hydrologic data from 1940 to 2013 should be sufficient for the purpose of this study. Generally the monthly cycle option is recommended when period of record is less than 50 years (Schnier, 2010)

3.2.2. CRM Strategy for Storage Frequency Relationships

The study focuses on comparative evaluation of equal weight and probability array options for the Highland Lakes in particular and the Colorado River Basin in general. The different modeling option in CRM are compared by developing storage frequency tables for Lake Travis and Lake Buchanan and a combined scenario. Table 3.1 lists the major reservoir in the Colorado River Basin and their respective WAM Identifier and control points used in all CRM analysis.

Table 3.1. Reservoirs and Control Points for CRM Analysis

Reservoir	Identifier	Control Point	Permitted Capacity
Lake Travis	TRAVIS	I20000	1,170,752
Lake Buchanan	BUCHAN	I40000	992,475
O.H. Ivie Reservoir	IVIE	I20050	554,340
E.V. Spence Reservoir	SPENCE	B10050	488,760
Lake J.B. Thomas	THOMAS	A30060	204,000
Combined Scenario		I10000	3,410,327

The control points listed in the Table 3.1 are located just downstream of the location of the lakes. Generally correlation between storage and naturalized flow is strongest for single control points with storage at the control point (Schnier, 2010). Lake Buchanan and Lake Travis are the only lakes in the Highland Lakes system with considerable conservation storage capacity and are discussed in this study. The other reservoirs of the Highland Lake System were ignored because of their minimal storage capacity and absence of conservation storage capacity. The combined scenario is used to represent the Colorado River Basin as a whole. Hence for the combined reservoir scenario the storage volume is the sum of the storage volume of the five major reservoirs in the Colorado River Basin and the control point I10000 is located in Colorado River at Austin just below the most downstream reservoir in the Highland Lakes system. Figure 4.2 shows the location of the lakes and control point I10000.

The storage frequency tables were developed for12 months of naturalized flow volumes starting in the month of July. The annual cycle option has been adopted to capture seasonality. The hydrologic period of analysis is from 1940 – 2013, which provides 74 annual simulation sequences. Multiple simulations were performed with the initial storage content for all the reservoirs set to 100%, 75%, 50% and 25% of their full conservation capacity.

CRM is activated in the simulation model by adding CR record just after the JO record in the DAT file. Alternate versions of the CR record are as follows:

```
CR     12         7         0     1.00
CR     12         7         0     0.75
CR     12         7         0     0.50
CR     12         7         0     0.25
```

3.3. Equal Weight Option

Storage frequency tables for the equal weight option were developed through TABLES. To activate the equal weight option a 5CRM record is required in the TIN file. The 2FRE record is used to develop the frequency tables. Storage frequency relationships for Lake Travis, Buchanan and the combined scenario are presented in Tables 3.2, 3.3 and 3.4 for end of month storage at September and June. The simulation starts at the beginning of July with initial storage set to 100%, 75%, 50% and 25% of full conservation capacity.

The first column of Tables 3.3-3.5 lists the exceedance frequencies and corresponding end of September and June storage contents are tabulated as percentage of storage capacities. The exceedance frequency values represent percentage of 74 simulation sequences with corresponding storage capacity equaled or exceeded.

For example, Table 3.3 indicates that with beginning of July storage set to 75% of full capacity, the end of September storage is 55.34% of capacity at 95% exceedance frequency which means the end of September storage equals or exceeds 55.17% of storage capacity for 95% of the 74 annual simulation sequences. Corresponding end of June storage capacity is 42.14% of capacity. Similarly for Lake Buchanan there is 70% probability that storage will equal or exceed 67.74% of storage capacity by the end of September if storage is at 75% of full capacity at the beginning of July. The equivalent storage capacity at the end of June is 71%. The end of September and end of June storage capacities varies for all three reservoirs and in most cases the end of September values are higher than end of June storage for higher exceedance frequencies and seem to be lower for lower exceedance frequencies.

Equal weight storage frequency results for O.H. Ivie Reservoir, E.V. Spence Reservoir and Lake J.B. Thomas are presented in Appendix A

Table 3.2. Equal Weight Storage Frequency for Lake Travis

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage capacity (%)				End of June storage capacity (%)			
99	68.93	53.17	26.93	3.47	60.74	38.68	11.95	0
98	69.27	53.44	27.54	3.75	61.36	39.71	12.06	0
95	71.88	55.34	32.72	8.41	62.59	42.14	13.52	0
90	73.12	56.45	35.12	10.46	64.89	47.11	14.86	0.54
80	78.43	58.23	38.88	14.37	72.85	55.81	25.3	4.72
70	81.93	59.72	40.83	15.71	80.64	61.66	33.44	8.77
60	84.31	60.85	41.75	16.68	87.95	64.78	39.73	12.04
50	86.49	62.90	43.69	18.03	92.55	70.92	52.59	20.23
40	90.17	64.73	45.9	21.36	95.71	79.77	58.71	29.52
30	92.1	66.51	47.14	23.46	97.22	90.15	66.28	47.64
20	96.84	68.71	52.31	27.73	100	98.25	94.57	68.45
10	100	74.3	57.47	37.77	100	100	100	100

Table 3.3. Equal Weight Storage Frequency for Lake Buchanan

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	87.25	54.61	37.97	10.59	71.12	48.96	33.46	0
98	87.94	55.08	38.18	11.52	72.05	49.09	34.17	0
95	92.02	59.23	38.49	13.53	75.21	49.92	36.18	0.35
90	93.74	61.24	38.9	14.35	80.34	50.38	39.05	3.25
80	95.03	64.94	39.69	15.03	92.33	62.10	45.88	13.00
70	96.56	67.74	41.28	16.28	97.02	71.00	49.78	25.74
60	97.69	69.04	42.57	18.86	97.85	80.68	57.29	33.65
50	98.25	70.59	43.67	20.84	98.62	89.82	63.91	41.10
40	98.80	72.92	46.6	24.24	99.87	97.06	69.11	46.89
30	99.87	76.55	50.29	29.52	99.87	98.26	78.44	51.02
20	99.87	80.31	52.03	39.01	100	99.92	97.80	73.61
10	100	90.38	59.35	52.94	100	100	100	100

Table 3.4. Equal Weight Storage Frequency for Combined Scenario

Exceedance Frequency (%)	Beginning of July Storage capacity percentage							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	81.1	61.85	47.09	20.46	67.81	46.09	25.84	3.19
98	81.46	62.12	47.41	21.02	67.88	46.46	25.92	3.45
95	83.98	64.49	50.06	24.49	69.89	47.90	26.92	3.76
90	85.32	65.82	51.63	26.28	73.18	50.99	29.1	6.63
80	87.43	67.63	53.39	28.48	80.35	58.5	37.01	13.22
70	89.92	69.89	55.52	31.23	85.16	64.88	41.88	20.12
60	91.02	71.02	57.12	33.36	87.75	67.66	45.01	22.07
50	92.3	72.68	58.76	35.93	90.5	73.45	50.28	28.96
40	93.28	73.34	59.71	37.45	92.3	77.90	55.89	34.86
30	95.36	75.98	62.65	42.04	93.56	84.18	62.03	43.08
20	96.34	77.95	65.29	46.53	95.63	87.51	77.91	59.38
10	98.11	83.19	72.11	56.56	99.05	93.84	86.26	84.75

3.4. Probability Array Total Storage Option

The probability array methodology allows multiple options to gauge correlation between naturalized flow and preceding storage content. Higher correlation results in better prediction of flows. It also provides multiple options to compute variable Qs. All of the options are evaluated in the following sections.

3.4.1. Storage-Flow Correlation Comparison

The probability array option assigns probabilities to sequences based on the relationship between preceding storage condition and naturalized flow volume. Higher correlation values suggest the potential for improved accuracy with the probability array approach relative to the equal weight option. The correlation analyses presented here were developed for preceding storage at 100% capacity at the beginning of months January, February, July and October. These four months are representative of winter, fall, summer and spring respectively. Naturalized flow volumes were summed for the 1, 2, 3, 6 and 12 months following the preceding storage. Tables 3.5 to 3.8 provide linear and Spearman correlation coefficients for all the combinations of naturalized flow volume versus preceding storage volume.

The linear correlation coefficients are highly variable and very small, in most cases being close to values of 0.1 and 0.2. The Spearman correlation coefficients values are relatively higher in in comparison to linear correlation coefficients. This implies that the correlation between preceding storage and flow volume may be greater than indicated by the linear correlation coefficient but the relationship is not linear. Nonlinear relationships are explored in the next section.

Table 3.5. Correlation Coefficients for January

Reservoir	Linear Correlation Coefficient No. of months for Naturalized Flow Volume					Spearman Correlation Coefficient No. of months for Naturalized Flow Volume				
	1	2	3	6	12	1	2	3	6	12
Travis	0.067	0.186	0.212	-0.021	-0.033	0.371	0.347	0.364	0.080	0.068
Buchanan	-0.036	0.065	0.086	-0.217	-0.178	0.291	0.290	0.284	-0.061	-0.048
Ivie	-0.001	0.060	0.068	0.056	0.016	0.275	0.294	0.279	0.210	0.071
Spence	-0.159	-0.143	-0.082	0.043	0.121	0.033	0.037	-0.005	-0.067	-0.008
Thomas	-0.045	-0.032	0.071	0.098	0.131	0.186	0.213	0.179	0.073	0.159
Combined	0.006	0.100	0.117	-0.066	-0.064	0.283	0.239	0.245	-0.014	-0.043

Table 3.6. Correlation Coefficients for April

Reservoir	Linear Correlation Coefficient No. of months for Naturalized Flow Volume					Spearman Correlation Coefficient No. of months for Naturalized Flow Volume				
	1	2	3	6	12	1	2	3	6	12
Travis	0.010	-0.228	-0.082	-0.097	-0.098	0.273	0.028	0.110	0.061	-0.000
Buchanan	-0.151	-0.324	-0.259	-0.245	-0.193	0.206	-0.072	-0.049	-0.119	-0.140
Ivie	0.113	0.107	0.142	0.106	0.045	0.329	0.234	0.284	0.207	0.146
Spence	0.112	0.039	0.077	0.161	0.135	0.030	0.013	-0.006	0.085	0.056
Thomas	0.141	0.067	0.109	0.121	0.138	0.160	0.164	0.134	0.248	0.253
Combined	0.010	-0.188	-0.085	-0.088	-0.093	0.259	0.053	0.043	0.065	0.044

Table 3.7. Correlation Coefficients for July

Reservoir	Linear Correlation Coefficient No. of months for Naturalized Flow Volume					Spearman Correlation Coefficient No. of months for Naturalized Flow Volume				
	1	2	3	6	12	1	2	3	6	12
Travis	0.240	0.193	-0.094	0.037	-0.149	0.384	0.321	0.102	0.054	-0.162
Buchanan	0.134	0.048	-0.051	0.032	-0.105	0.292	0.144	0.015	0.005	-0.156
Ivie	0.015	0.075	-0.047	-0.050	-0.056	0.184	0.100	0.008	-0.104	-0.074
Spence	0.221	0.232	0.1391	0.135	0.116	0.223	0.270	0.170	0.120	0.063
Thomas	0.021	0.056	-0.001	0.022	0.109	0.187	0.197	0.123	0.056	0.050
Combined	0.233	0.176	-0.049	0.051	-0.078	0.370	0.311	0.089	0.059	-0.101

Table 3.8. Correlation Coefficients for October

Reservoir	Linear Correlation Coefficient No. of months for Naturalized Flow Volume					Spearman Correlation Coefficient No. of months for Naturalized Flow Volume				
	1	2	3	6	12	1	2	3	6	12
Travis	0.188	0.214	0.167	0.088	-0.105	0.168	0.208	0.219	0.176	-0.105
Buchanan	0.222	0.178	0.136	0.038	-0.161	0.222	0.217	0.196	0.128	-0.163
Ivie	-0.008	0.003	-0.012	-0.009	-0.047	0.148	0.017	-0.017	0.030	-0.014
Spence	0.175	0.091	0.079	0.048	0.145	0.146	0.108	0.096	0.041	-0.000
Thomas	0.096	0.050	0.053	0.068	0.154	0.123	0.177	0.163	0.168	0.102
Combined	0.252	0.205	0.155	0.065	-0.075	0.199	0.215	0.213	0.192	-0.067

The Spearman coefficient is a standard statistic commonly used to assess how well the relationship between two variables can be described by a monotonic function that may be either linear or nonlinear. The Spearman correlation coefficients in the tables show a clear trend of decreasing values with increase in months over which flow volume is summed. This is expected as initial storage is more closely related to nearer months than months farther in the future.

3.4.2. Regression Equations Evaluation

The probability array SFF option assigns probabilities to each of the simulation sequences on the basis of correlation between preceding storage volume and the variable Q%. Q% represents the deviation of flow volume from the expected values of flow volume condition on preceding storage volume as modeled by regression equation (Wurbs a, 2013). All four types of available regression equations were analyzed for their suitability in the Highland Lakes and combined scenario. The linear correlation coefficients are already presented in the tables above. The exponential, power and combined correlation coefficient are presented below for simulation sequences starting at the four months mentioned earlier. The linear correlation coefficients are obtained by using equation 9 where variable x and y are log transformed values of Q_S and storage (S) .The linear correlation coefficients thus developed is an index of the linear correlation between these transformed variables. For all reservoirs the exponential correlation coefficient has relatively higher correlation values for all seasons. Power correlation coefficients are also comparatively higher than linear and combined correlation coefficients. The linear and combined correlation coefficients show negligible correlation between flow and storage.

Table 3.9. Exponential Correlation Coefficient for Beginning of January

Reservoir	No. of months for flow volume summation				
	1	2	3	6	12
Travis	0.3146	0.3298	0.3614	0.0049	0.0131
Buchanan	0.1061	0.1121	0.1433	0.2254	0.1930
Ivie	0.1799	0.2191	0.2025	0.1791	0.1136
Spence	0.1306	0.0609	0.0468	0.0404	0.1378
Thomas	0.1585	0.2273	0.2312	0.1407	0.1417
Combined	0.2122	0.2254	0.2452	0.0370	0.0567

Table 3.10. Power Correlation Coefficient for Beginning of January

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.3313	0.3314	0.3627	0.0612	0.0843
Buchanan	0.0993	0.1131	0.1445	0.2087	0.1843
Ivie	0.1336	0.1536	0.1579	0.2054	0.0371
Spence	0.0626	0.0903	0.0847	0.0184	0.0046
Thomas	0.1396	0.2213	0.1924	0.0551	0.1562
Combined	0.2348	0.2404	0.2715	0.0894	0.1112

Table 3.11. Combined Correlation Coefficient for Beginning of January

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.0773	0.1779	0.2055	0.0829	0.1156
Buchanan	0.0255	0.0670	0.0880	0.1857	0.1673
Ivie	0.1123	0.0487	0.0770	0.1367	0.0345
Spence	0.0654	0.0663	0.0721	0.0218	0.0436
Thomas	0.0110	0.0508	0.0785	0.0939	0.1926
Combined	0.0170	0.1076	0.1277	0.1220	0.1293

Table 3.12. Exponential Correlation Coefficient for Beginning of April

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.1686	0.1128	0.0029	0.0353	0.0450
Buchanan	0.0065	0.2418	0.1973	0.2053	0.1930
Ivie	0.2837	0.1636	0.2399	0.1954	0.1586
Spence	0.0437	0.0759	0.1012	0.1910	0.1547
Thomas	0.1910	0.1905	0.1648	0.1698	0.1413
Combined	0.1644	0.0423	0.0051	0.0111	0.0034

Table 3.13. Power Correlation Coefficient for Beginning of April

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.0541	0.2007	0.0977	0.1671	0.1096
Buchanan	0.0244	0.2397	0.1905	0.2025	0.1760
Ivie	0.3788	0.2736	0.3384	0.3006	0.2012
Spence	0.0041	0.0452	0.0284	0.1140	0.0316
Thomas	0.1045	0.1803	0.1266	0.2336	0.2405
Combined	0.1166	0.1228	0.0196	0.1022	0.0571

Table 3.14. Combined Correlation Coefficient for Beginning of April

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.0745	0.2933	0.1809	0.2425	0.1618
Buchanan	0.1442	0.2343	0.2060	0.2059	0.1627
Ivie	0.1496	0.1569	0.2164	0.1873	0.0671
Spence	0.0319	0.0319	0.0079	0.0412	0.0093
Thomas	0.0417	0.1104	0.1264	0.1891	0.2199
Combined	0.0090	0.2174	0.1009	0.1645	0.1139

Table 3.15. Exponential Correlation Coefficient for Beginning of July

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.3946	0.3627	0.1293	0.1069	0.1505
Buchanan	0.2696	0.1810	0.0195	0.0111	0.1458
Ivie	0.1859	0.1817	0.1254	0.0943	0.0766
Spence	0.1763	0.3092	0.2255	0.1895	0.1702
Thomas	0.1326	0.2152	0.1704	0.1572	0.1460
Combined	0.3531	0.3213	0.0916	0.0913	0.0463

Table 3.16. Power Correlation Coefficient for Beginning of July

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.3743	0.3635	0.0289	0.0613	0.1397
Buchanan	0.2966	0.2278	0.0469	0.0209	0.1127
Ivie	0.0194	0.0848	0.1248	0.2723	0.2119
Spence	0.1921	0.2648	0.1697	0.0888	0.0131
Thomas	0.1740	0.2023	0.1792	0.1307	0.0673
Combined	0.3448	0.3244	0.0091	0.0207	0.0772

Table 3.17. Combined Correlation Coefficient for Beginning of July

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.2356	0.1974	0.1854	0.0004	0.1216
Buchanan	0.1346	0.0550	0.0479	0.0326	0.0572
Ivie	0.0695	0.1523	0.2547	0.2958	0.2333
Spence	0.2685	0.1827	0.0549	0.0377	0.0753
Thomas	0.1707	0.1038	0.0091	0.0422	0.0012
Combined	0.2545	0.1926	0.1906	0.0176	0.0727

Table 3.18. Exponential Correlation Coefficient for Beginning of October

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.2186	0.2441	0.2306	0.2076	0.1107
Buchanan	0.2266	0.1898	0.1530	0.0711	0.1821
Ivie	0.2475	0.1996	0.1829	0.1678	0.0838
Spence	0.1365	0.1137	0.0924	0.1466	0.1607
Thomas	0.2178	0.2160	0.1760	0.2253	0.1534
Combined	0.2490	0.2529	0.2321	0.1943	0.0507

Table 3.19. Power Correlation Coefficient for Beginning of October

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.2320	0.2524	0.2404	0.2418	0.1278
Buchanan	0.2334	0.1896	0.1444	0.0779	0.1682
Ivie	0.0460	0.2889	0.2537	0.2002	0.1003
Spence	0.1342	0.0960	0.0791	0.0456	0.0048
Thomas	0.1059	0.1185	0.1162	0.1498	0.0859
Combined	0.2553	0.2549	0.2322	0.2124	0.0832

Table 3.20. Combined Correlation Coefficient for Beginning of October

Reservoir	No. of months for Naturalized flow volume				
	1	2	3	6	12
Travis	0.1845	0.2066	0.1676	0.1047	0.1074
Buchanan	0.2194	0.1731	0.1330	0.0487	0.1288
Ivie	0.3321	0.3914	0.2966	0.1916	0.1514
Spence	0.0289	0.0547	0.0651	0.1051	0.0691
Thomas	0.0094	0.0525	0.0524	0.0459	0.0751
Combined	0.2226	0.1895	0.1436	0.0754	0.0756

3.4.3. Storage Flow Frequency Using Total Storage

Storage frequency tables were developed using the probability array SFF option and the exponential regression was chosen to compute Q_S values. The SFF was developed considering total storage at the start of July. The reservoir identifiers and control point used for summation of flow volumes are same as mentioned in Table 3.1. As seen from correlation coefficient values, there is small but enough correlation between initial storage and flow volumes to justify use of the probability array option. For the storage frequency tables, the initial storage contents were set to 100%, 75%, 50% and 25% of their full capacity at the beginning of July, and naturalized flows were summed for 12 months to develop a SFF array. The Weibull formula was chosen to assign exceedance probabilities to the flow ratio Q% as flows are being summed for 12 months.

As Table 3.22 indicates that with beginning of July storage set to 75% of full capacity, the end of September storage is 55.17% of capacity at 95% exceedance frequency. Similarly for Lake Buchanan there is 70% probability that storage will equal or exceed 67.17% of storage capacity by the end of September if storage is at 75% of full capacity at the beginning of July.

Probability array storage frequency results for O.H. Ivie Reservoir, E.V. Spence Reservoir and Lake J.B. Thomas are presented in Appendix A

Table 3.21. Storage Frequency Relationship for Lake Travis based on SFF Array Option

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	68.78	52.95	25.80	3.40	60.47	36.90	11.91	0
98	68.98	53.25	27.35	3.50	60.84	39.34	11.96	0
95	71.56	55.17	31.97	6.62	62.32	41.38	13.47	0
90	72.78	56.4	35.11	10.18	64.82	47.03	14.81	0.48
80	78.22	57.91	38.73	14.04	71.77	52.91	24.98	4.44
70	81.78	59.37	40.02	15.69	79.28	61.26	32.66	8.74
60	84.21	60.84	41.74	16.59	87.56	64.68	39.53	12.01
50	86.19	62.86	43.44	17.97	92.21	70.89	51.68	19.19
40	89.92	64.48	45.72	20.87	95.67	79.4	58.05	28.46
30	92.04	66.49	47.12	23.38	97.11	89.92	65.88	47.34
20	96.67	68.17	52.22	27.34	100	97.11	94.53	68.00
10	100	73.98	56.13	36.3	100	100	100	100

Table 3.22. Storage Frequency Relationship for Lake Buchanan based on SFF Array Option

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	87.21	53.94	37.67	9.91	70.45	48.9	32.91	0
98	87.26	54.86	38.09	10.84	71.36	48.98	33.67	0
95	91.4	58.50	38.45	13.28	73.14	49.5	35.75	0
90	93.59	61.22	38.89	14.34	80.26	50.37	39.01	3.11
80	94.92	64.89	39.59	14.96	91.72	58.57	45.88	10.79
70	96.21	67.17	40.97	16.16	97.02	70.66	49.25	22.42
60	97.69	69.01	42.5	18.81	97.81	80.19	57.22	33.49
50	98.24	70.48	43.51	20.64	98.62	89.71	63.59	40.87
40	98.74	71.91	45.65	23.10	99.87	96.97	68.43	46.38
30	99.87	76.49	50.28	29.33	99.87	98.23	78.42	50.94
20	99.87	79.99	52.03	37.99	100	99.87	97.51	72.65
10	100	88.05	59.19	51.68	100	100	100	100

Table 3.23. Storage Frequency Relationship for Combined Scenario based on SFF Array Option

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	81	61.69	46.81	20.27	67.77	45.69	25.84	2.96
98	81.13	61.91	47.19	20.53	67.82	46.24	25.84	3.28
95	83.82	64.39	49.84	23.94	68.26	47.04	26.31	3.74
90	85.3	65.78	51.55	26.18	72.92	50.60	29.03	6.38
80	87.29	67.48	53.25	28.39	79.98	57.36	34.92	10.44
70	88.99	69.07	55.52	30.94	84.96	63.30	41.88	20.07
60	91.02	71.00	57.12	33.29	87.73	67.57	44.82	21.92
50	92.24	72.66	58.71	35.65	90.48	72.91	50.13	28.81
40	93.18	73.29	59.42	37.38	92.07	77.28	55.11	33.59
30	95.33	75.97	62.62	42.04	93.54	84.16	61.95	43.03
20	96.31	77.79	64.65	45.84	95.5	87.34	77.13	59.06
10	97.7	82.76	71.84	54.5	98.66	92.04	83.57	81.15

3.5. Probability Array Storage Change Option

Total storage used as a hydrologic indicator shows appreciable correlation with naturalized flows for only up to 3 months. Correlation coefficients tend to be small for all time periods. A different approach to using storage as hydrologic indicator has been tested in this study. The new approach utilizes change in storage as an indicator for prevalent hydrologic conditions. The total storage option uses the preceding storage volume at an instant in time (beginning of month) to develop the SFF array, whereas the new approach develops the SFF array from change in storage levels of reservoirs during one or multiple preceding months. Change in storage over a specified length of time can be considered from the beginning of the starting month of analysis back to any number of preceding months. An increase in storage level indicates wet hydrologic conditions, while a decrease represents dry conditions. As with total storage option, correlation between naturalized flow volume and storage condition is important for probability array option to provide meaningful estimates of future conditions.

3.5.1. Change in Storage versus Flow Correlation Analysis

Linear correlation and Spearman rank correlation analyses were performed to analyze the relationship between different naturalized flows volumes and change in storage during preceding months. Naturalized flow volumes summed over 1, 2, 3, 6, 9 and 12 month periods were considered in combination with 1, 2, 3, 6, 9 or 12 preceding months of change in storage. Linear and Spearman correlation coefficients developed for these sums of naturalized flows and preceding storage change are presented in Tables 3.24–3.29. The linear correlation coefficients provide a comparative measure of how closely the simulated preceding change in storage versus flow volume quantities can be fit with a linear equation. The Spearman coefficients provide a comparative measure of how closely the storage change versus flow volume relationship can be described with a monotonic function without regard to the linearity or nonlinearity of the function.

Table 3.24. Correlation Coefficients for 1 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient Change in storage for preceding months						Spearman Correlation Coefficient Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	0.181	-0.002	0.020	0.132	0.128	0.090	0.307	0.170	0.187	0.269	0.271	0.297
Buchanan	0.041	-0.039	0.026	0.064	0.036	-0.032	0.341	0.053	0.116	0.177	0.221	0.126
Ivie	0.036	-0.053	-0.056	0.024	0.025	0.039	0.081	-0.045	-0.002	0.103	0.111	0.113
Spence	-0.064	-0.107	-0.114	-0.141	-0.176	-0.240	0.191	0.174	0.113	0.106	0.064	0.051
Thomas	-0.085	-0.127	-0.144	-0.194	-0.247	-0.323	0.175	0.086	-0.008	0.011	-0.003	0.016
Combined	0.225	0.030	0.050	0.141	0.129	0.096	0.408	0.167	0.178	0.269	0.271	0.253

Table 3.25. Correlation Coefficients for 2 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient Change in storage for preceding months						Spearman Correlation Coefficient Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	-0.041	-0.076	-0.056	0.009	0.019	-0.002	0.040	0.013	0.044	0.076	0.151	0.202
Buchanan	-0.037	-0.124	-0.065	-0.038	-0.059	-0.088	0.170	-0.036	0.023	0.050	0.104	0.022
Ivie	0.153	0.014	-0.035	0.053	0.194	0.184	0.010	-0.115	-0.171	-0.068	0.077	0.041
Spence	-0.083	-0.102	-0.106	-0.120	-0.038	-0.076	0.018	0.068	0.035	0.007	0.073	0.052
Thomas	-0.110	-0.128	-0.137	-0.166	-0.147	-0.204	0.068	0.015	-0.066	-0.047	0.001	-0.027
Combined	0.042	-0.057	-0.041	0.024	0.046	0.027	0.124	0.005	0.0314	0.072	0.1650	0.177

Table 3.26. Correlation Coefficients for 3 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient Change in storage for preceding months						Spearman Correlation Coefficient Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	-0.130	-0.065	-0.068	-0.064	-0.069	-0.102	-0.032	0.032	0.068	0.046	0.067	0.073
Buchanan	-0.005	-0.041	-0.013	-0.036	-0.079	-0.157	0.032	0.016	0.061	0.012	0.043	-0.089
Ivie	0.051	-0.039	-0.084	0.011	0.117	0.091	-0.053	-0.085	-0.152	-0.058	0.067	-0.006
Spence	-0.112	-0.120	-0.129	-0.139	-0.087	-0.072	-0.102	-0.055	-0.083	-0.099	-0.037	-0.021
Thomas	-0.134	-0.171	-0.182	-0.209	-0.201	-0.183	-0.052	-0.110	-0.173	-0.165	-0.126	-0.122
Combined	-0.042	-0.035	-0.036	-0.030	-0.042	-0.101	0.013	-0.007	0.005	0.014	0.043	-0.014

Table 3.27. Correlation Coefficients for 6 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient Change in storage for preceding months						Spearman Correlation Coefficient Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	0.053	0.131	0.161	0.095	0.096	0.050	0.058	0.080	0.150	0.087	0.071	0.067
Buchanan	0.173	0.070	0.132	0.053	0.001	-0.070	0.079	0.016	0.079	-0.002	0.011	-0.068
Ivie	0.121	-0.012	-0.040	-0.002	0.090	0.054	0.111	-0.082	-0.179	-0.098	0.028	-0.045
Spence	-0.082	-0.057	-0.030	-0.034	-0.006	0.003	-0.086	-0.049	-0.090	-0.078	-0.028	-0.024
Thomas	-0.118	-0.151	-0.150	-0.183	-0.171	-0.153	-0.069	-0.160	-0.212	-0.210	-0.163	-0.144
Combined	0.200	0.146	0.170	0.117	0.100	0.049	0.104	-0.013	0.038	0.014	-0.002	-0.012

Table 3.28. Correlation Coefficients for 9 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient Change in storage for preceding months						Spearman Correlation Coefficient Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	0.043	0.108	0.132	0.059	0.042	0.004	0.031	0.039	0.098	0.007	-0.007	-0.027
Buchanan	0.137	-0.014	0.031	-0.039	-0.088	-0.086	-0.011	-0.065	-0.020	-0.119	-0.117	-0.163
Ivie	0.170	0.011	-0.017	0.007	0.060	0.041	0.093	-0.120	-0.231	-0.168	-0.038	-0.095
Spence	-0.077	-0.061	-0.036	-0.034	-0.010	0.007	-0.057	-0.047	-0.087	-0.068	-0.025	-0.020
Thomas	-0.115	-0.161	-0.162	-0.190	-0.177	-0.156	-0.078	-0.185	-0.255	-0.235	-0.190	-0.162
Combined	0.174	0.094	0.112	0.059	0.030	0.009	0.053	-0.099	-0.069	-0.097	-0.116	-0.111

Table 3.29. Correlation Coefficients for 12 Month Naturalized Flow Summation

Reservoir	Linear Correlation Coefficient						Spearman Correlation Coefficient					
	Change in storage for preceding months						Change in storage for preceding months					
	1	2	3	6	9	12	1	2	3	6	9	12
Travis	0.053	0.076	0.083	-0.017	-0.070	-0.059	0.067	0.023	0.064	-0.060	-0.136	-0.101
Buchanan	0.002	0.152	0.122	-0.006	-0.093	-0.028	-0.069	0.115	0.095	0.003	-0.123	-0.077
Ivie	0.133	0.003	-0.029	-0.034	0.001	-0.029	0.048	-0.101	-0.197	-0.158	-0.042	-0.117
Spence	-0.043	-0.066	-0.050	-0.029	-0.034	-0.009	-0.087	-0.083	-0.099	-0.066	-0.056	-0.051
Thomas	-0.087	-0.129	-0.141	-0.130	-0.136	-0.058	-0.094	-0.143	-0.145	-0.091	-0.083	-0.043
Combined	0.117	0.117	0.105	0.014	-0.050	-0.030	-0.008	-0.009	0.005	-0.081	-0.196	-0.131

The correlation coefficients vary for all periods of naturalized flows considered and show minimal degree of linear correlation with change in storage. Correlation between naturalized flow volume for 1 or 2 months and change in storage over 9 and 12 months is close to 0.3. This period of naturalized flow volume also shows minimal correlation to shorter periods of change in storage. Naturalized flow volume for 3 months shows insignificant correlation to all preceding periods of change in storage considered. The naturalized flow volume for 6 and 9 months show correlation values close to 0.15 for change in storage periods of 3 and 2 months. Naturalized flow volume for 6 months has a correlation coefficient of 0.161 for a change in storage period of 3 months. All of the other change in storage periods show negligible correlation. The 12 month period of naturalized flows shows slight correlation to change is storage over 3 months. The linear correlation coefficient for this period is 0.0838. The other periods of analysis shows insignificant correlation.

3.5.2. Storage Flow Frequency Using Change in Storage

Storage frequency tables were developed using the probability array SFF option with change in storage as the hydrologic indicator. Exponential regression was chosen to compute Q_S values. The reservoir identifiers and control point used for summation of flow volumes are the same as mentioned in Table 3.1. As seen from correlation coefficient values, there is slight correlation between particular periods of change in storage and naturalized flow volumes.

The storage frequency tables were developed with initial storage at total capacity for naturalized flow volume of 12 months starting in July. The change in storage period of 3 months shows best correlation with naturalized flows of 12 months, and is used in this analysis. The change in storage values were specified using field 10 of 5CR2 record with CSVO parameter set to the option that allows change in storage to be specified as a fraction of initial storage capacity, in the CSV field. For this study CSV values were set to 0.5, 0.66, 1.5 and 2.0 meaning change in storage is set by multiplying the initial storage by these factors. Table 3.30 lists the different storage change scenarios considered in developing storage flow frequency tables.

Table 3.30. Change is Storage CSV factors

Initial storage as Capacity %	CSV value	Preceding Storage as Capacity %	Change in Storage
50	0.5	25	25% Increase
50	0.66	33	17% Increase
50	1.5	75	25% Decrease
50	2	100	50% Decrease

The storage capacity frequency for end of September and end of June does not show large variations. The exceedance frequency for all reservoirs varies only around 2% for increase as well as decrease in storage from March to June. The difference is relatively higher for lower exceedance frequencies. Table 3.31 shows end of September storage capacity is at 27.76% of total capacity at 99% exceedance frequency. Similarly, Table 3.33 indicates a probability of 95% for storage capacity at end of June to equal or exceed 29.61% percent of total capacity, when storage changes from 75% at March to 50% at start of June.

Table 3.31. Storage Change Probability Array Storage Frequency for Lake Travis

Exceedance Frequency (%)	Change in storage from March to 50% of capacity in July (% capacity)									
	-50	-25	+17	+25	0	-50	-25	+17	+25	0
	End of September storage (% capacity)					End of June storage (% capacity)				
99	27.76	27.35	25.8	25.8	25.8	13.47	11.96	11.96	11.96	11.91
98	31.97	27.76	27.35	25.8	27.35	13.55	11.96	12.18	11.96	11.96
95	37.65	35.12	35.11	31.97	31.97	27.43	14.59	14.59	13.55	13.47
90	39.37	37.84	35.42	35.42	35.11	34.04	30.51	17.52	14.99	14.81
80	41.11	40.02	39.53	38.98	38.73	56.57	41.87	30.51	27.43	24.98
70	41.11	41.11	41.11	40.08	40.02	69.85	58.05	39.84	37.07	32.66
60	42.41	42.71	42.41	41.56	41.74	92.2	69.85	55.23	45.36	39.53
50	45.97	46.21	44.9	44.65	43.44	94.63	90.18	59.85	58.05	51.68
40	47.1	47.1	46.48	47.1	45.72	100	94.63	69.85	64.11	58.05
30	52.22	51.81	48.11	49.56	47.12	100	100	92.2	92.2	65.88
20	60.23	58.04	52.56	53.47	52.22	100	100	100	100	94.53
10	83.45	83.45	75.46	75.46	56.13	100	100	100	100	100

Table 3.32. Storage Change Probability Array Storage Frequency for Lake Buchanan

Exceedance Frequency (%)	Change in storage from March to 50% of capacity in July (% capacity)									
	-50	-25	+17	+25	0	-50	-25	+17	+25	0
	End of September storage (% capacity)					End of June storage (% capacity)				
99	38.45	38.29	38.09	38.09	37.67	35.75	33.67	32.91	32.91	32.91
98	38.53	38.45	38.45	38.29	38.09	39.15	36.41	34.76	34.76	33.67
95	39.39	39.37	38.89	38.53	38.45	45.88	39.7	38.1	36.41	35.75
90	41.55	40.06	39.38	38.91	38.89	51.43	48.85	39.7	39.15	39.01
80	42.86	42.5	41.32	39.75	39.59	67.23	59.11	50.07	48.85	45.88
70	42.89	42.89	42.86	42.47	40.97	73.01	68.43	58.09	57.61	49.25
60	43.19	43.19	43.19	42.89	42.5	78.59	77.99	64.23	62.6	57.22
50	45.65	44.92	44.41	44.09	43.51	98.23	85.86	68.43	68.43	63.59
40	50.29	50.25	50.08	49.74	45.65	99.87	98.23	78.42	75.97	68.43
30	52.57	52.57	51.72	51.43	50.28	100	100	91.32	86.52	78.42
20	59.19	59.19	58.98	55.02	52.03	100	100	99.23	99.23	97.51
10	95.87	95.47	60.92	60.92	59.19	100	100	100	100	100

Table 3.33. Storage Change Probability Array Storage Frequency for Combined Scenario

Exceedance Frequency (%)	Change in storage from March to 50% of capacity in July (% capacity)									
	-50	-25	+17	+25	0	-50	-25	+17	+25	0
	End of September storage (% capacity)					End of June storage (% capacity)				
99	81.74	61.69	46.81	20.27	46.81	67.67	45.69	25.84	2.96	25.84
98	83.72	61.91	46.81	20.27	47.19	67.84	46.32	25.84	3.65	25.84
95	85.2	64.39	49.84	24.78	49.84	71.64	49.63	27.46	3.77	26.31
90	86.32	66.19	51.81	26.18	51.55	73.73	51.91	29.24	7.23	29.03
80	88.88	68.82	53.6	28.39	53.25	83.49	60.1	38.41	15.08	34.92
70	90.54	70.21	55.52	31.96	55.52	85.97	65.57	41.88	20.13	41.88
60	91.64	71.13	57.15	33.29	57.12	87.74	70.03	44.18	21.92	44.82
50	92.88	72.96	59	35.42	58.71	91.86	73.98	50.13	30.25	50.13
40	93.59	75.12	61.95	37.01	59.42	93.18	78.06	59.34	37.08	55.11
30	96.13	76.19	63.58	41.43	62.62	95.18	84.72	62.77	45.57	61.95
20	96.67	79.55	67.17	48.13	64.65	96.98	89.5	79.93	59.85	77.13
10	98.72	88.39	78.18	66.4	71.84	99.62	94.61	87.42	86.29	83.57

3.6. Comparison between Equal Weight and Probability Array Methods

The initial reservoir storage is set to the same amounts and the hydrologic period of analysis is divided into 74 sequences for both the equal weight and probability array methods. However, the probability array method will assign probabilities to each simulation sequence based on the correlation between naturalized flow volume and storage condition. If the probability array methodology is to improve reliability and frequency analyses over the equal weight option, the correlation between available streamflow volume and preceding simulated change in storage volume is vital.

Correlation analyses of the total storage option performed for the Highland Lakes and combined scenario suggests that there is small degree of correlation for all individual reservoirs as well as the reservoir system as a whole. The correlation is small when considering 1, 2 or 3 months of naturalized flow volumes and becomes insignificant for 6 and 12 month time intervals. This is expected as initial storage volume has higher influence on storage of closer months than storage at months 12 or 6 which are more influenced by hydrologic factors such as stream inflows and net evaporation rates.

Initial storage conditions of 100%, 75%, 50% and 25% of capacity were selected to represent a full range of reservoir drawdowns At all initial storage conditions and different exceedance probabilities, the storage levels are very close to each other for both the different equal weight and probability array option. At initial storage levels of 100% and 75% of capacity, the storage levels are approximately the same, but slight differences can be seen for initial storage of 50% and 25% of capacity.

There is no significant difference in storage-frequency relationships for preceding storage levels set at 100% and 25% of storage capacity. The equal weight option shows slightly lesser values of storage capacity than the probability array option when initial storage is set to 100% of capacity. Also relatively smaller values of storage are seen for the probability array option when initial storage is at 25% of capacity. Probability array will assign higher probabilities to high flow simulation sequences when storage is near full capacity and higher probabilities to low flow simulation sequences when storage is close to being empty.

The change in storage option correlation analysis shows 1, 2 and 3 months of naturalized flow volume correlates better with longer preceding months of change in storage, whereas longer 6, 9 and 12 months of naturalized flow volumes has better correlation with shorter preceding months of change in storage. The storage frequency table shows lesser variation in storage capacity for both wet and dry periods of change in storage. In Tables 3.31- 3.33 exceedance frequencies are developed for March storage of 100% capacity reduced to 50% at the end of May, which indicates a dry hydrologic condition. Similarly, March storage capacity of 25% increasing to 50% at end of May indicates wet conditions. For both of these dry and wet conditions, the end of September and June storage at different exceedance frequencies do not vary significantly. A dry hydrologic condition is expected to have less end of month storage capacities than wet hydrologic conditions. This can be clearly seen in storage frequencies developed using the total storage option.

The exceedance frequencies for end of June and September storage capacities were developed with initial storage at 50% of total capacity. The end of June and September exceedance frequencies for the total storage option at 50% of capacity are presented in Tables 3.21- 3.23. The change in storage method also is applied with an assumed initial storage of 50% of capacity. The smallest change in storage analyzed in this study is an increase of 17% i.e. from 33% at March to 50% at end of May. The variation in higher exceedance frequencies for both of these options are minimum, indicating that for smaller changes in storage, initial storage condition still significantly affects the results of the SFF analysis. The end of month storage capacities for larger changes in storage show significant variation when compared to total storage but these drastic changes in storage levels within a short time interval may not reflect practical reservoir operation conditions. Hence, for the Highland Lakes and combined scenario, the probability array option using total storage is the better alternative.

CHAPTER IV

ANALYSIS OF HYDROLOGIC INDICATORS

The probability array option feature of CRM is useful for assigning probabilities to simulation sequences based on correlation between naturalized flow and preceding storage volume or change in storage volume. Relating change in preceding storage volume to naturalized flow allows WRAP to integrate hydrologic persistence into its simulations and thus predict reliabilities for water availability for short term periods, usually up to a year into the future. The chances of meeting future reservoir storage, instream flow, water supply and hydroelectric targets are conditioned upon the preceding storage levels. Storage as an indicator of current hydrologic condition can be effective as it is indicative of a number of hydrologic parameters such as stream flow, precipitation, evaporation, upstream ground water, surface water interactions, etc. The reservoir storage level at a particular time is the product of cumulative influence of these hydrologic parameters over a longer preceding time period. Hence reservoir storage levels can act as an index of prevailing hydrologic conditions. The WAM simulated storage volume is computed from naturalized flow, spring flow and net evaporation rates inputs which already are reflective of fluctuation in climatic signals and hydrologic conditions. However, the storage conditions can only account for short time predictions and become a less reliable indicator of hydrologic conditions as we look further into the future (Schnier, 2010). The preceding reservoir storage level is only affects flows for a few months into the future after which its influence on flows disappears.

Inter-annual variability in hydrologic conditions may possibly be better explained by wider scale climatic patterns and their anomalies than streamflow or storage level persistence. The climatic patterns and their anomalies greatly effect hydrological and metrological conditions over vast areas and can have global reach. They exhibit substantial variability and can occur on many time scales, lasting from a few weeks to several decades. The term "teleconnection pattern" refers to a recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas. Teleconnection patterns are also referred to as preferred modes of low-frequency (or long time scale) variability."(Climate Prediction Center a, n.d.). Teleconnection patterns reflect large scale changes in atmospheric circulations from average conditions and are recurring in nature. The causes of these teleconnection patterns are hard to ascertain given the chaotic nature of atmospheric circulations. Although most seem to be influenced by changes in sea surface temperature (SST) and consequent changes in air and ocean currents. A large number of studies have analyzed the effects of teleconnection patterns, most of these prominent patterns are now well understood with data available for long time periods. As such, teleconnection patterns are being studied and applied as a predictive indicator of future hydrologic conditions.

4.1. Teleconnection Patterns and Indices

The Climate Prediction Center has extensively researched teleconnection patterns and lists ten such patterns as being influential in the Northern Hemisphere. Of these, four have been found to be significantly influential in the northern hemisphere in general and the Central Texas region in particular: El Nino-Southern Oscillation (ENSO), North

Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) (Watkins and O'Connell, 2005, Wei and Watkins, 2011, TWDB, 2012)

4.1.1. El Nino Southern Oscillation (ENSO)

El Nino and the Southern Oscillation is a periodic fluctuation in sea surface temperature (El Nino) and air pressure of the overlying atmosphere (Southern Oscillation) over the equatorial pacific (National Climate Data Center a, n.d.). Under normal conditions the sea surface temperature is about 14°F higher in the Western Pacific than in the waters off South America caused by trade winds blowing towards the west across the tropical Pacific and the atmospheric pressure at Darwin Australia is lower than at Tahiti. This difference in SST at the two ends of the tropical pacific causes a upwelling effect on a thermocline close to the South American edge of tropical pacific region. This rise of nutrient rich cold water is extremely important for the diverse marine ecosystem and major fisheries.

During El Nino conditions the situation reverses i.e. the pressure at Darwin is higher than at Tahiti which leads to reduction in Trade wind strengths. This results in decrease in the normal flow of warm water from South America to the western Pacific, further leading to an above average increase in sea surface temperature in the eastern Pacific. This phase is the warm phase of ENSO and is better known as El Nino. This rise in SST in the eastern pacific pushes the thermocline deeper away from the sea surface causing weak upwelling of cold water.

La Nina is the cool phase of ENSO and functions exactly opposite of El Nino. La Nina phase sees lower than normal sea surface temperatures at the Eastern Pacific and can be understood as a more intensified version of average conditions. During La Nina conditions the pressure difference at Tahiti is higher than at Darwin. Thus trade winds that blow west across the tropical pacific are stronger than normal which causes larger flows of cold water. This leads to stronger upwelling of colder thermocline than under average conditions. The sea surface temperature fluctuations mentioned are not very large, only about 6°F (NWS, n.d., NOAA, n.d.).

The Southern Oscillation (SO) is the bimodal variation in sea level barometer pressure between observation stations at Darwin, Australia and Tahiti. Under the warm ENSO phase the air pressure at Darwin is higher than at Tahiti and is the opposite for the cool phase. The change in pressure gradient during warm phase causes the decline in strength of trade winds leading to warmer sea surface temperature and warmer sea surface temperature further leads to decrease in atmospheric pressure above it. Thus the El Nino and SO enforce each other. Figure 4.1 shows variation in SST during El Nino and La Nina phases.

A variety of indicators are used to measure ENSO that utilize different climatic variables, such as the Oceanic Nino Index (ONI), Southern Oscillation Index (SOI), Multivariate ENSO Index (MEI), Nino 3.4 Index etc. The ONI and Nino 3.4 indices use SST anomalies as indicators of ENSO cycles. The SOI index is based on atmospheric pressure anomalies at Darwin, Australia and Tahiti. The MEI index uses six variables:

sea level pressure, zonal and meridional component of surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky (ESRL, n.d.)

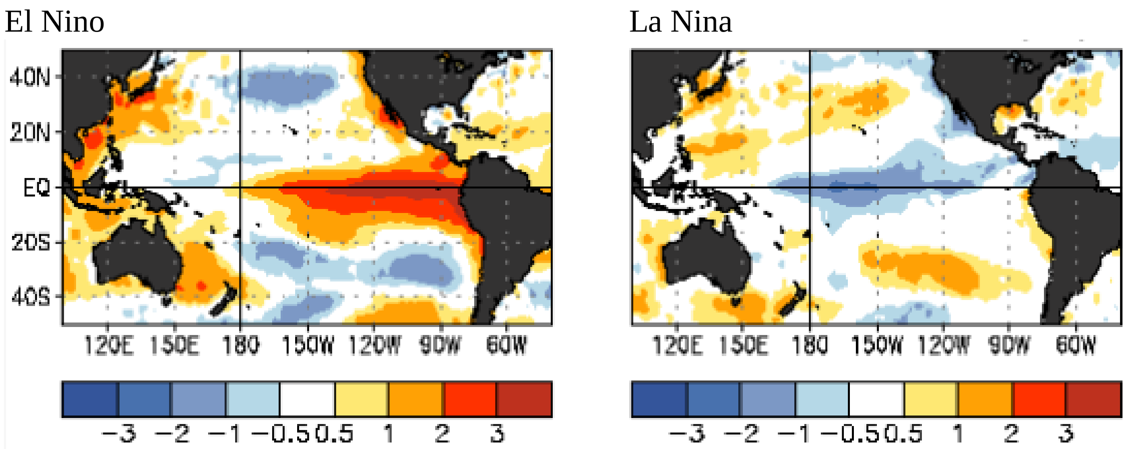

Figure 4.1. Ocean temperature departures during El Nino and La Nina (CPC a , n.d.)

Among these SOI and ONI have been widely used in studies and the data is available for long historical periods. No definitive classification of ENSO periods can be found. The classification criteria varies based on the index representing ENSO and also on the time scale being used.

4.1.2. ENSO Indices

4.1.2.1. Oceanic Nino Index (ONI)

The NOAA defines El Nino (La Nina) based on the ONI index as episodes of five consecutive 3-month running sea surface temperature (SST) anomalies in the Nino 3.4 region above (below) the threshold of +0.5°C (-0.5°C) (NCDC, n.d.). The National Weather Service, Climate Prediction Center (CPC) maintains the ONI index. Data is available from 1950 to the current month, online at the CPC website. The monthly ONI index values are rolling 3 month averages: December-January-February, January-February-March, etc. The average values used for defining anomalies are calculated for 30 year base periods. Each five years period has a 30 year average centered on the first year in the period. For example, 1950-1955 period would have average from 1936-1965 30 year period. For recent five year periods whose base period data are not available, the CPC uses the most recently available calculated climatology (Lindsey, 2013).

4.1.2.2. Southern Oscillation Index (SOI)

The SOI measures large scale fluctuation in air pressure occurring between the western Pacific (Tahiti) and eastern Pacific (Darwin, Australia). Negative phases of SOI values have been found to coincide with warm waters across the eastern tropical Pacific and positive phases of SOI coincides with cold waters across eastern tropic Pacific (Climate Prediction Center b, n.d.).). The Troup SOI index is maintained by the Bureau of Meteorology (BOM), Australian Government with data from 1876 to present, available online at BOM website. A sustained value of -8 (+8) indicates El Nino (La Nina) episode. SOI maintained by BOM is standardized values computed by dividing the difference in mean sea level pressure difference between Tahiti and Darwin by long term standard deviation for the month. The value obtained is multiplied by a convention of 10 so that SOI ranges from -35 to +35 (BOM, n.d.)

.

$$SOI = 10\frac{P_{diff} - P_{diffav}}{SD(P_{diff})} \quad (13)$$

Where

Pdiff = (average Tahiti MSLP for the month) – (average Darwin MSLP for the month)

Pdiffav = long term average of Pdiff for the month

SD (Pdiff) = long term standard deviation of Pdiff for the month

The NOAA also maintains a SOI index and the standardization process is similar. The difference being NOAA uses standardized pressure difference between Tahiti and Darwin instead of the monthly average used by BOM. The NOAA also does not use any convection multiplier. For this study the BOM data is used given its longer historical records and popularity in research studies.

4.1.3. North Atlantic Oscillation (NAO) Index

North Atlantic Oscillation (NAO) is an inter-annual fluctuation in sea level pressure between the Green Land and tropical regions in North Atlantic. The positive phase of NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above normal heights and pressure over the central North Atlantic, the United States and Western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions (Climate Prediction Center c, n.d.). The positive phase is associated with intense weather systems over the North Atlantic and wet periods in Western Europe. The NAO is one the most important atmospheric variability over the North Atlantic Ocean and affects climate variation in Eastern North America, North Atlantic and Europe. It strongly affects the North Atlantic Jet Stream and significantly affects climate variations like storm tracks and precipitation patterns. NAO has significantly higher influence in winter precipitation than in warmer months (Greatbach, 2000). In the US, a high pressure system of NAO called the Bermuda High influences the formation and path of tropical cyclones and climate patterns across Texas and eastern United States (TWDB, 2012). O' Connell (2002) and Watkins and Wei (2011) analyzed scholastic streamflow forecasts using teleconnection patterns including the NAO for Central Texas. In both cases NAO was found to be a weak potential predictor of stream flow and showed weak concurrent correlation with streamflows. O'Connell did find NAO to be better for high and low flow prediction and found a 49% improvement in predictions with an optimal linear combination of ENSO and NAO over individual teleconnections patterns but noted probable occurrence of skill inflation as forecast was not tested on independent data set.

The NAO data was obtained from National Center for Atmospheric Research, Hurrell NAO station based index. The index computed based on difference of normalized sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland. Positive values reflect above normal westerlies over middle latitude and negative values reflect the opposite. The data is available from 1899 to present at monthly, seasonal and annual time scales (NCAR, n.d.)

4.1.4. Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO)

Many studies have proven significant hydrometerological effects of AMO and PDO for central Texas. The AMO and PDO exhibit multidecadal periodicity of about 25 – 60 years (Gary et. al., 2004, Kerr , 2000) and thus its influence on streamflow over a lead time of a month to a year can be insignificant. However the combined effect of PDO and ENSO on streamflow could be substantial and studies have shown that coinciding warm phases of PDO and ENSO result in extreme hydrologic anomalies. The cool conditions of ENSO and PDO also cause significantly higher streamflow. But the frequency of occurrence of these coincidental events is very low, about five warm phases and four cool phases during the past 60 years, and so may not be of much use for streamflow predictions for shorter lead time (Watkins and O'Connell, 2005)

4.2. Palmer Drought Severity Index (PDSI)

PDSI is a drought index based on precipitation and temperature. It is derived using a soil moisture/water balance algorithm that requires a time series of daily air temperature and precipitation data and information on the available water content of the soil (Quiring et. al., 2007). PDSI is one of the most widely used meteorological drought indexes in the United States for drought monitoring and research. It is a standardized measure with values ranging from –6 (dry) to +6 (wet). Values greater than -4 indicate extreme drought and positive values indicate degree of wet spells (National Climate Data Center b, n.d.). PDSI is a better indicator of precipitation and temperature anomalies than SST and pressure differential indexes and, also can be used as a hydrological drought index (Quiring et.al. 2007). Two previous studies (Piechota and Dracup, 1996, Rajagopalan, et al., 2000) have found significant correlation between SOI and PDSI. However, Piechota and Dracup did not find any significant correlation between PDSI and streamflow. Its high correlation with SOI and relation to precipitation and temperature could make it a suitable indicator for unregulated flow. The PDSI data can be obtained from NOAA website from 1895 to present but varies spatially. The climatic divisions and the reservoirs considered in this study are presented in Figure 4.2. Given the location of reservoirs, climatic divisions 6, 7 and 2 for Texas were adopted for the analyses presented in the next section. The values were averaged for combined computations.

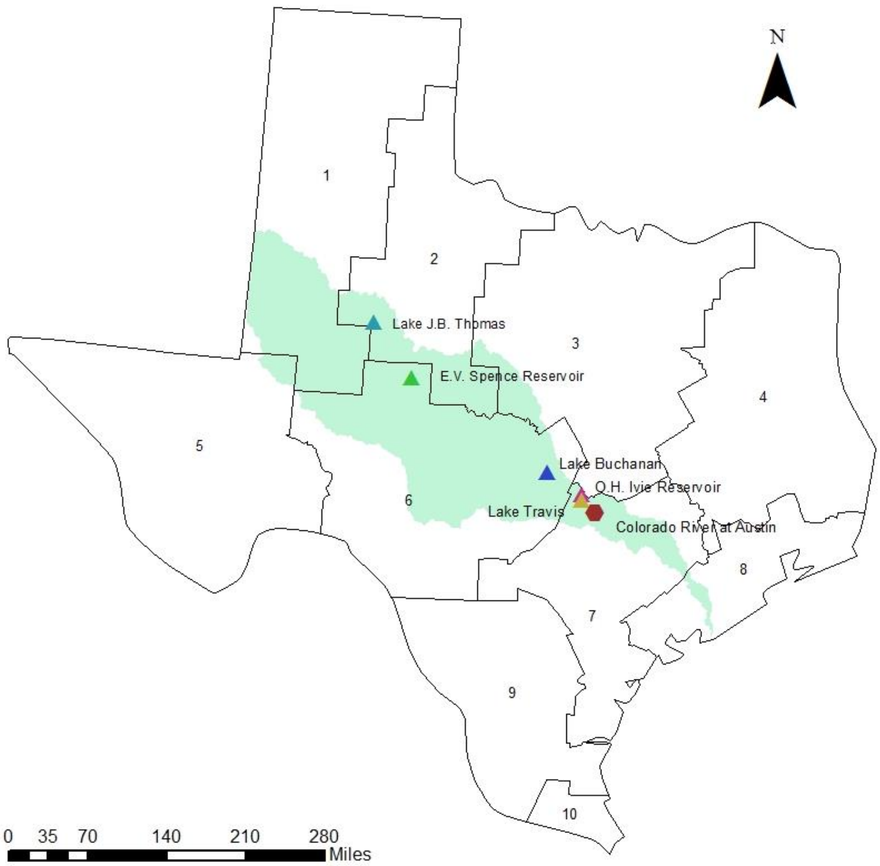

Figure 4.2. Climatic Divisions of Texas

4.3. Linear Correlation Comparison of Hydrologic Indicators

The effectiveness of using the probability array option in CRM largely depends upon the degree of relationship between preceding storage volume and naturalized flow volume. Without significant correlation the more complex probability array strategy will not provide improvements in accuracy over the simpler equal weight strategy. Likewise, the potential usefulness of incorporation of other hydrologic indicators in the CRM probability array computations depends upon having indices with a significant degree of correlation with naturalized flows.

Linear correlation coefficient measures the strength of linear relationship between the paired x and y values. The paired x and y data in CRM is represented by storage volume at the beginning of a period and naturalized flows summed for the specified number of months included in that period for each simulation sequence. For example, a CRM simulation from 1940 to 2013 with annual option selected for with initial storage specified for the beginning of July and naturalized flow volume for 3 months would have 73 pairs of storage volume for the beginning of July and naturalized flows summed for July, August, and September. The linear correlation coefficient is calculated using equation 9, where r represents the degree of linear correlation between variable x and y and ranges from -1 to +1. A values of -1 shows negative correlation between x and y data i.e. x decreases as y increases or vice versa. A values of +1 represents high degree of positive correlation between data x and y and values close to 0 represents random scatter. The Spearman rank correlation coefficient is also computed as supplemental information. It is calculated based on the rank of the x and y data rather than the actual data itself.

The Colorado WAM has a hydrologic period of analysis covering from 1940 through 2013 extended from the original 1940-1998 period using methods developed at TAMU. The correlation coefficient r was computed for reservoirs running multiple

CRM simulations of the Colorado WAM. Correlation coefficient r values were also developed for combined storage and flow volumes for all Highland Lakes.

The annual cycle option was adopted to capture seasonality i.e. to capture seasonal variation in hydrologic characteristics. Each sequence began in the same month and extended across the same sequence of months. The seasons have been defined as shown in Table 4.1.

Table 4.1. Months Used in Correlation Comparison

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

Input records and files are explained in the WRAP Users Manual (Wurbs, 2103b). A CR record was inserted in the DAT file with starting month being the first month for each season and length of simulation varying between one-, two-, three-, six and twelve months. The storage volume was set to 100% of capacity for all simulations. Alternate CR records for summer season are as follows:

```
CR    1     7     0     1
CR    2     7     0     1
CR    3     7     0     1
CR    6     7     0     1
CR   12     7     0     1
```

For each season, the storage volume at the beginning of the month was correlated to sums of naturalized flow volumes for subsequent one-, two-, three-, six and twelve months. The r value was computed for each case using the 5CR1 and 5CR2 record in the TABLES program. The 5CR1 record FIT option allows selection of regression equations for developing storage-flow functions. Option 3 was selected to use linear regression. The FILE2 option in 5CR1 record allows regression and correlation statistics to be written to the Tables Output (TOU) file. Value 2 for FILE2 option in 5CR1 record was used to develop the required r values for naturalized flows and storage.

An option on the 5CR1 record allows storage and flow volumes to be written in the TMS file. This option when selected generates a table of sequence number, storage volume, flow volume, storage rank and flow rank. Multiple runs of the Colorado WAM was performed to compute the flow volumes starting at specific months and for desired time period at control point just downstream of the reservoirs. The control points listed below in the Table 3.1 are located just downstream of the location of the lakes. The combined scenario is used to represent the Colorado River Basin as a whole. Hence for the combined reservoir scenario the storage volume is the sum of the storage volume of the two reservoirs in the Highland Lakes system and the three other large reservoirs in the basin. Control point I10000 is located on the Colorado River at Austin just below the most downstream reservoir in the Highland Lakes system. The flow volumes thus obtained were regressed with different indices to check the degree of correlation between indices and flow volumes.

A sample of records added to TIN file to generate specific and combined flow volumes for the summer season and subsequent flows for 12 months is as follows:

```
5CR1  1  1  7 12 0  3                               4
5CR1FLOW  I20000
5CR1STRE  TRAVIS
5CR2  1  1  1  0  2  0  1
5CR2FLOW  I20000
5CR2STRE  TRAVIS
5CR1  1  1  7 12 0  3                               4
5CR1FLOW  I40000
5CR1STRE  BUCHAN
5CR2  1  1  1  0  2  0  1
5CR2FLOW  I40000
5CR2STRE  BUCHAN
5CR1  1  1  7 12 0  3                               4
5CR1FLOW  I20050
5CR1STRE  OHIVIE
5CR2  1  1  1  0  2  0  1
5CR2FLOW  I20050
5CR2STRE  OHIVIE
5CR1  1  1  7 12 0  3                               4
5CR1FLOW  B10050
5CR1STRE  SPENCE
5CR2  1  1  1  0  2  0  1
5CR2FLOW  B10050
5CR2STRE  SPENCE
5CR1  1  1  7 12 0  3                               4
5CR1FLOW  A30060
5CR1STRE  THOMAS
5CR2  1  1  1  0  2  0  1
5CR2FLOW  A30060
5CR2STRE  THOMAS
5CR1  5  5  7 12 0  3                               4
5CR1FLOW  I10000
5CR1STRE  TRAVIS  BUCHAN  OHIVIE  SPENCE  THOMAS
5CR2  5  5  1  0  2  0  1
5CR2FLOW  I10000
5CR2STRE  TRAVIS  BUCHAN  OHIVIE  SPENCE  THOMAS
ENDF
```

4.4. Linear Correlation Comparison Results

The Index versus Sum Flow Volume correlation coefficient r was computed and plotted in excel using the equation 9. The storage–flow correlation used data from 1940 to 2013 whereas the climatic index–flow correlation is based on data from 1950 to 2013. All of the indices, except PDSI and naturalized flow persistence, do not show any significant linear correlation with naturalized flows for all considered months. Correlation is highly variable for these indices. However the climate indices do show slightly higher correlation than storage. Lakes Thomas and Spence are located in the upper reaches of the catchment and have significant periods of zero flows. Consequently, their correlation coefficients may not be reliable for comparison.

- Storage and naturalized flows show high variability and low correlation between them. For flow volume over 6 and 12 months, the correlation is insignificant and mostly negative. For 1, 2 and 3 months, the correlation is around 0.2.
- The SOI index has comparatively higher r values than storage especially for 6 and 12 month flows. The SOI index also performs better in January and April which is expected given the influence of ENSO on winter season. However the SOI values for July (Fall) are weaker than storage values. SOI values varies between seasons without any conclusive pattern.
- The ONI index has values similar to the SOI index as both indices represent ENSO. Between ONI and SOI indices, ONI has better values for April and SOI for January. ONI values are also weak for July but is better than storage for six and twelve month flows in general.

- The PDSI correlation coefficients are significantly high for flow volumes over one, two, three and six months compared to storage in particular. PDSI also has higher values for the month of July when compared to the ENSO indices. PDSI r values are slightly higher for 12 months except for Lake Buchanan.
- The NAO index does not show any improvement in r values over storage. In most cases the NAO values are close to or less than storage values and also has high seasonal variability.
- Naturalized Flow Persistence has the highest correlations among all the indices. For months 2, 3 and 6 the correlation coefficients are close to 0.7 and even for month 12 the coefficient is close to 0.4

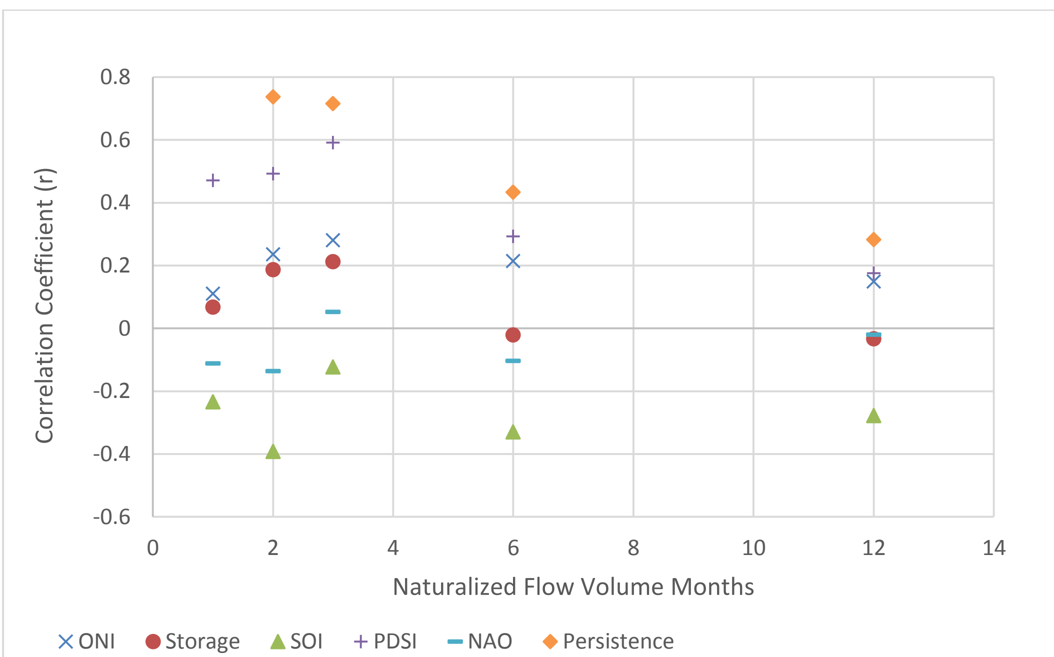

Figure 4.3. Correlation Coefficients for Lake Travis Starting in January

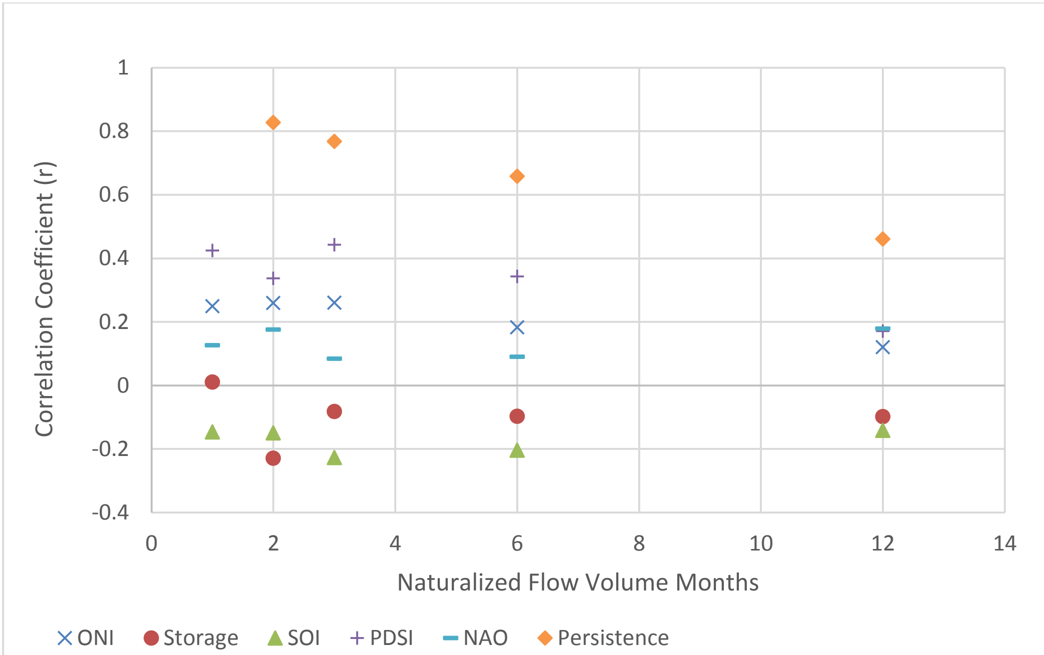

Figure 4.4. Correlation Coefficients for Lake Travis Starting in April

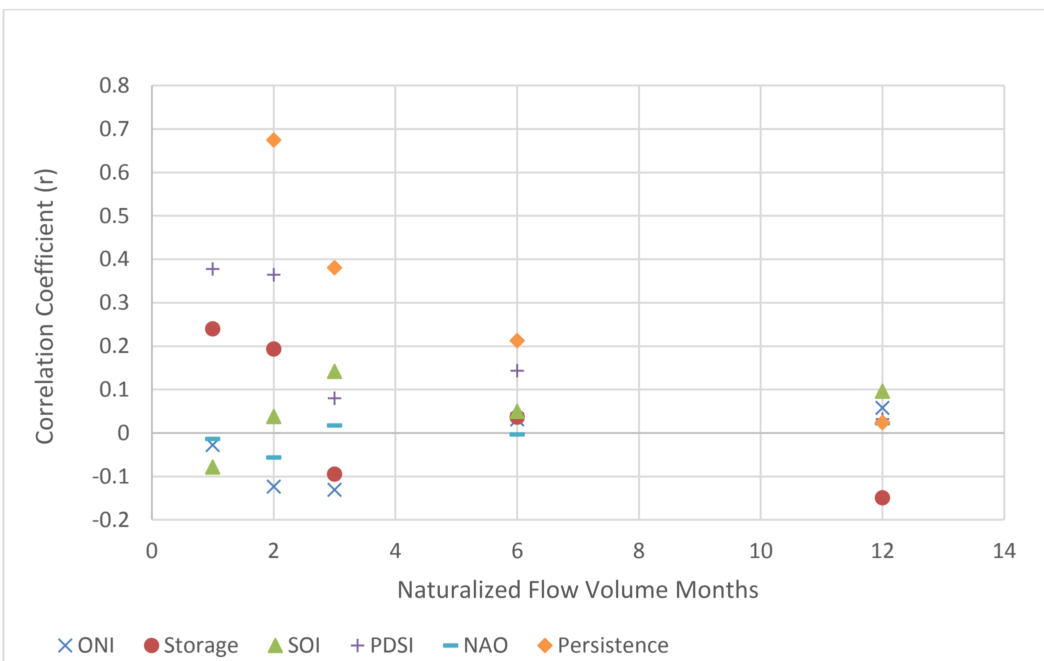

Figure 4.5. Correlation Coefficients for Lake Travis Starting in July

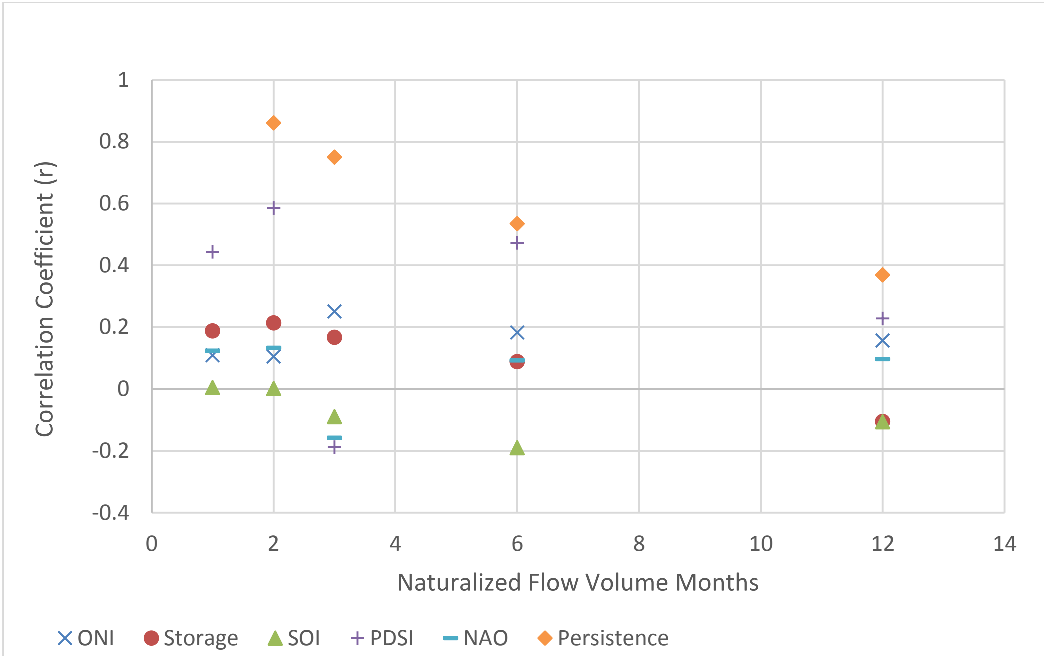

Figure 4.6. Correlation Coefficients for Lake Travis Starting in October

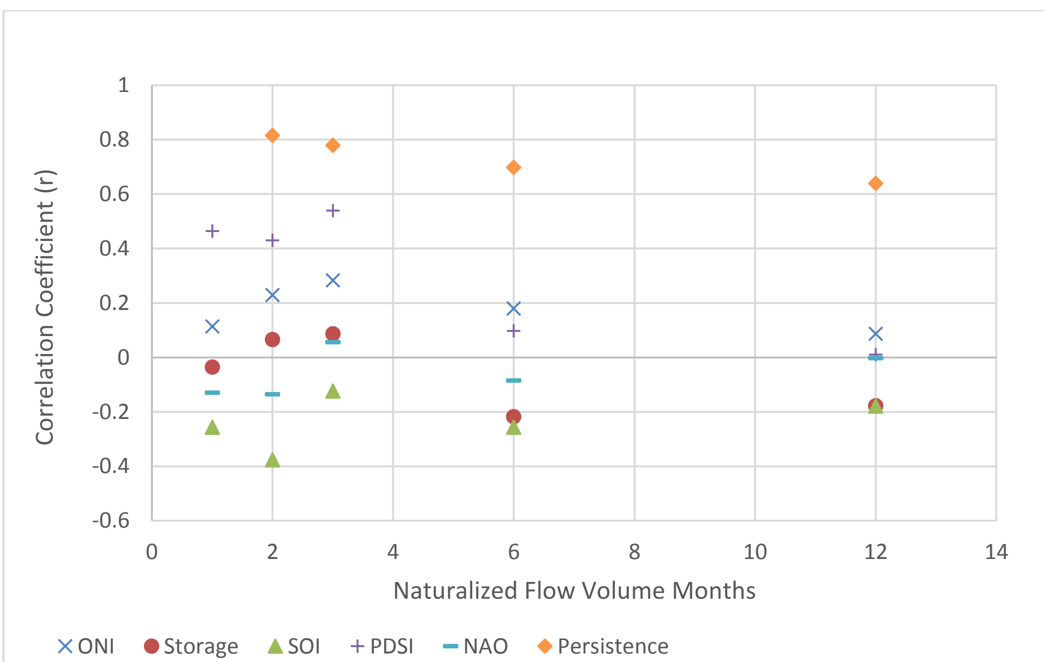

Figure 4. 7 Correlation Coefficients for Lake Buchanan Starting in January

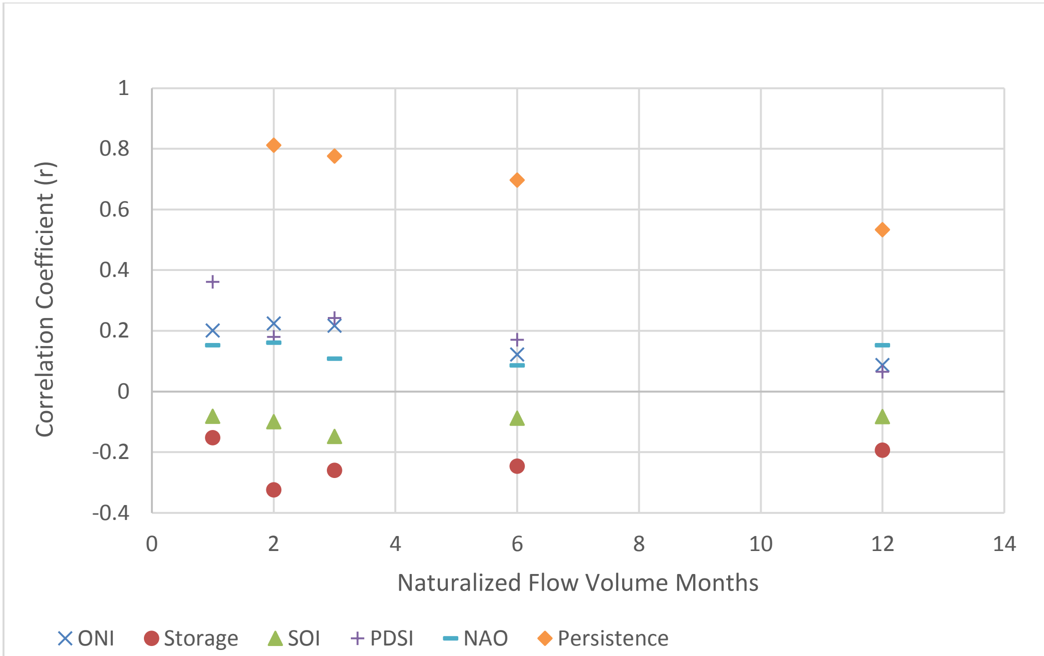

Figure 4.8. Correlation Coefficients for Lake Buchanan Starting in April

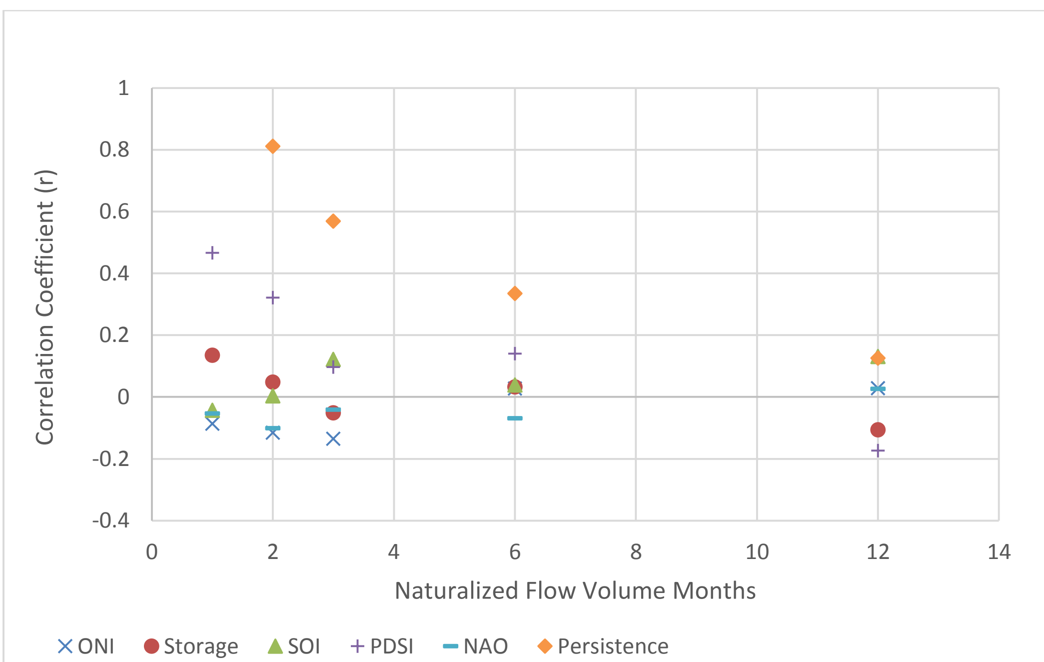

Figure 4.9. Correlation Coefficients for Lake Buchanan Starting in July

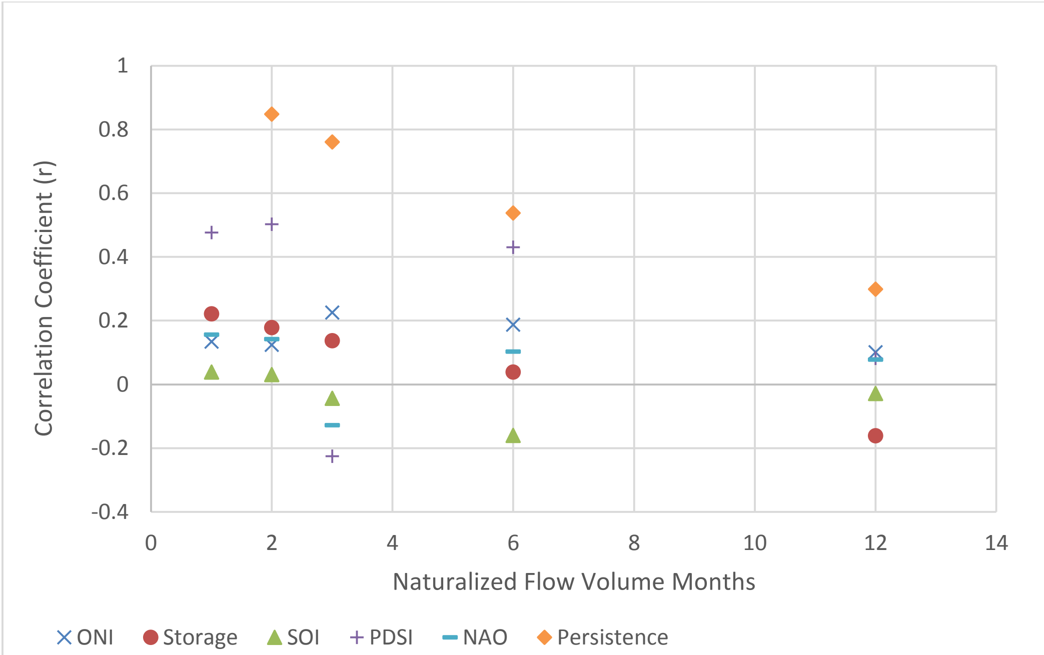

Figure 4.10. Correlation Coefficients for Lake Buchanan Starting in October

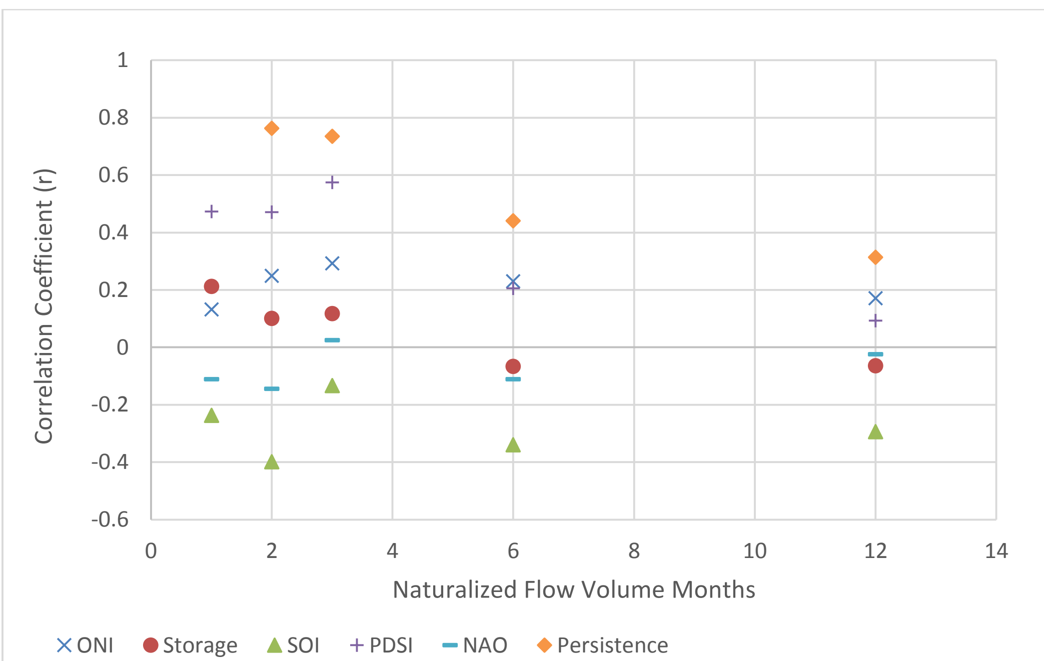

Figure 4.11. Correlation Coefficients for Combined Scenario Starting in January

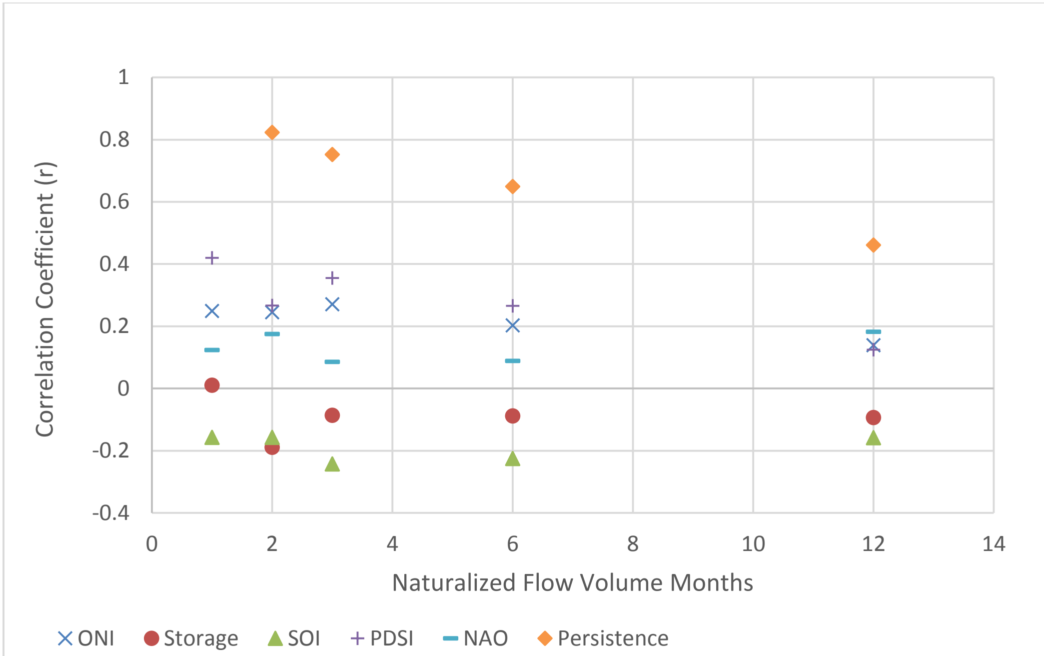

Figure 4.12. Correlation Coefficients for Combined Scenario Starting in April

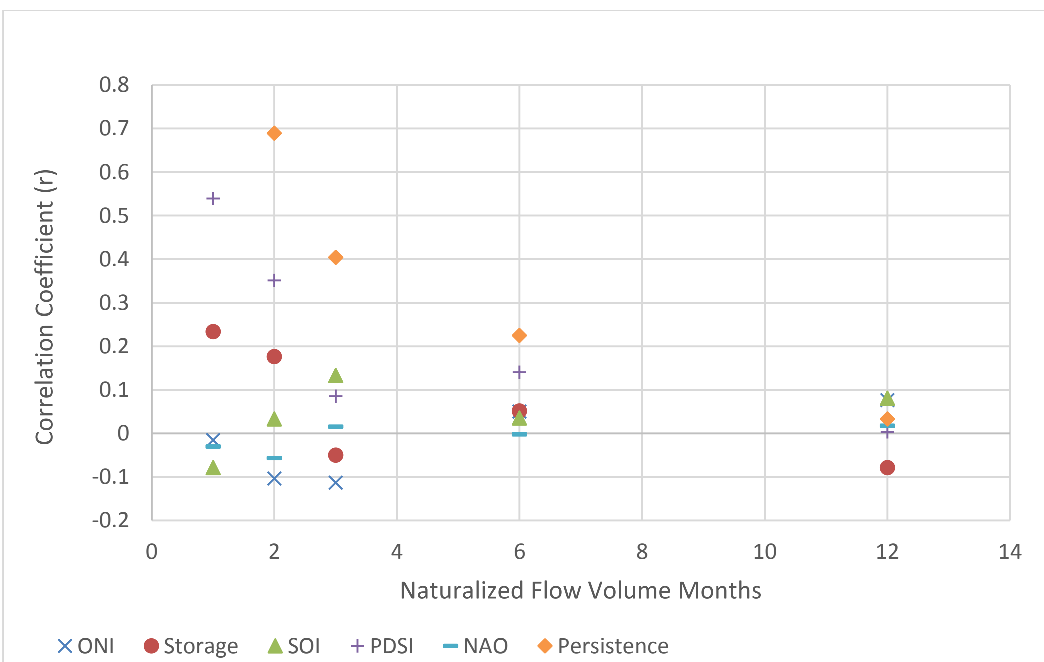

Figure 4.13. Correlation Coefficients for Combined Scenario Starting in July

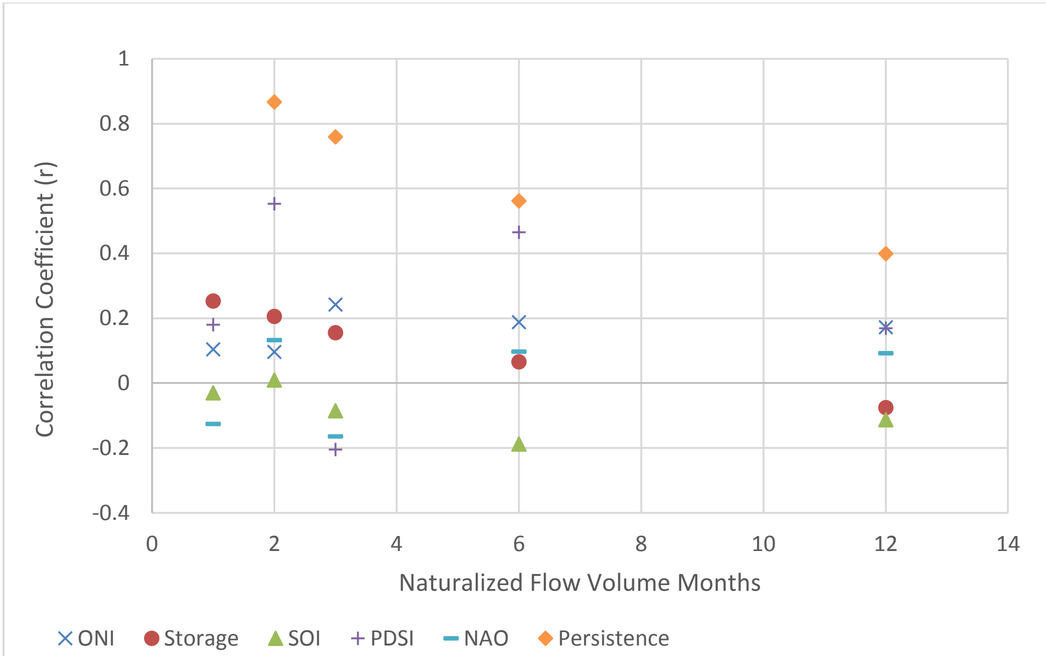

Figure 4.14. Correlation Coefficients for Combined Scenario Starting in October

As can be seen from the graphs, climate indices do not show clear improvement over storage based on linear correlation coefficients. ENSO indices are marginally better correlated than storage, and there is slight variation among the 2 indices used to represent ENSO. The PDSI shows clear improvement over storage and climatic indices. The PDSI values depend upon climatic divisions and hence are localized. PDSI values are also representative of the effect of climate indices. The lag effect on hydrological and meteorological conditions from changes to climatic patterns is captured by PDSI values. Naturalized flow correlation shows higher values over all other indices for nearly all seasons and time period.

4.5. QX Multiplication Factor

The teleconnection patterns and PDSI do not show clear linear correlation to naturalized flow volumes. There is large variation in linear correlation coefficients depending upon the period of analysis and location of the control points. Hence, using different indices directly to develop a SFF relationship by replacing storage with index values can be problematic and may not provide any improvement over storage. Initial naturalized flow volume does show clear improvement in correlation compared to other indices including storage. However, naturalized flow values for current time period cannot be estimated outside of WRAP and makes it inconvenient for real time applications of CRM. This study tested another approach to incorporating teleconnection pattern effects into CRM.

4.5.1. Storage Frequency Analysis for QX Multiplication Factor

The new approach incorporated in the WRAP program TABLES allows the use of a multiplication factor for adjusted the expected value of naturalized flows. The expected value of naturalized flow Q_S is computed using one of the regression equations (2) – (5), which relates naturalized flow volumes to preceding storage volume. The 5CR2 record has been modified by the addition of a new variable called QX. Which is a multiplier factor. The Q_S computed with the regression equation is multiplied by QX. The QX value can be the expected increase or decrease in flow volume due to the effects of teleconnection patterns such as ENSO. Storage frequency tables were developed for the month of September with initial storage capacity set to 100% and 25% of total storage capacity in June, as in previous study. The 100% storage capacity reflects wet hydrologic conditions, and hence the QX values were set to 1.25, 1.75, 2.5 and 0.5. Similarly for storage capacity at 25%, QX values of 0.25, 0.5, 0.75 and 1.5 were used to represent dry hydrologic conditions.

In Table 4.2, a QX multiplication factor of 2.5 represents an increase in flow volume by 2.5 times than average conditions represented by QX value of 1. Under this conditions, there is 90% probability of storage content in Lake Travis being 79.44% of storage capacity at the end of September if the initial storage capacity is at 100% of capacity in the beginning of July. Table 4.2 shows a 6.66% increase in storage capacity from average conditions, at 90% exceedance frequency for Lake Travis at end of September.

Table 4.2 Storage Frequency with QX Multiplication Factor for Lake Travis

Exceedance Frequency (%)	Regression Equation Multiplication Factor (QX)									
	0.5	1.0	1.25	1.75	2.5	0.25	0.5	0.75	1.0	1.5
	Initial Storage at 100% capacity					Initial Storage at 25% capacity				
99	68.87	68.78	68.87	68.87	69.49	0	0	0	3.4	0
98	71.4	68.98	71.4	69.49	69.49	0	0	0	3.4	0
95	72.48	71.56	72.48	72.48	76.06	0	0	0	4.04	4.44
90	73.85	72.78	76.06	79.44	79.44	0	0	0	9.88	9.21
80	79.78	78.22	79.49	81.87	81.87	0	0	0	14.04	16.72
70	81.78	81.78	81.87	81.87	81.87	0	0	2.09	15.69	29.79
60	82.33	84.21	85.01	86.04	82.92	0	0	6.46	16.59	52.13
50	82.33	86.19	89.92	91.04	88.49	0	0.69	8.88	17.97	69.11
40	82.33	89.92	92.04	92.67	91.40	0	2.57	11.38	20.86	75.63
30	84.37	92.04	95.89	95.89	95.89	0	6.93	18.47	24.46	82.52
20	89	96.67	98.77	100	100	0	10.7	38.08	27.81	100
10	96.67	100	100	100	100	2.57	35.5	75.63	38.74	100

Table 4.3 Storage Frequency with QX Multiplication Factor for Lake Buchanan

Exceedance Frequency (%)	Regression Equation Multiplication Factor (QX)									
	0.5	1.0	1.25	1.75	2.5	0.25	0.5	0.75	1.0	1.5
	Initial Storage at 100% capacity					Initial Storage at 25% capacity				
99	87.04	87.21	87.04	87.04	88.50	0	0	0	9.91	0
98	91.23	87.26	91.23	88.50	88.50	0	0	0	9.91	0
95	92.92	91.4	92.92	94.80	94.83	0	0	0	12.31	10.23
90	94.1	93.59	94.80	95.76	97.64	0	0	0	14.34	26.11
80	94.92	94.92	95.69	98.12	98.74	0	0	2.06	14.96	37.55
70	95.75	96.21	97.64	98.74	99.73	0	0	5.52	16.85	49.45
60	95.76	97.69	98.64	99.73	99.80	0	0.54	14.48	19.16	51.69
50	95.76	98.24	99.45	99.8	99.80	0	3.56	26.11	21.04	67.73
40	95.76	98.74	99.80	99.8	99.80	0	9.22	33.49	24.53	90.20
30	97.2	99.87	99.87	99.87	99.87	0	18.76	39.19	32.4	98.62
20	98.64	99.87	100	100	100	0.54	31.32	50.25	45.35	100
10	99.87	100	100	100	100	9.22	42.90	98.10	53.48	100

Table 4.4 Storage Frequency with QX Multiplication Factor for Combined Scenario

Exceedance Frequency (%)	Regression Equation Multiplication Factor (QX)									
	0.5	1.0	1.25	1.75	2.5	0.25	0.5	0.75	1.0	1.5
	Initial Storage at 100% capacity					Initial Storage at 25% capacity				
99	80.89	81	81.03	81.03	81.74	2.96	2.96	2.96	20.27	3.65
98	83.72	81.13	83.72	81.74	81.74	2.96	2.96	2.96	20.53	6.38
95	84.6	83.82	84.60	85.64	86.88	2.96	2.96	3.28	23.94	10.44
90	85.32	85.3	86.32	88.78	90.16	3.65	3.28	3.65	26.18	20.13
80	88.06	87.29	88.90	90.54	90.91	3.65	3.65	5.27	28.39	28.81
70	88.88	88.99	90.54	91.64	91.64	3.65	3.65	7.95	30.94	40.58
60	88.88	91.02	91.64	92.14	91.64	3.65	3.77	15.75	33.29	45.57
50	88.88	92.24	93.14	93.27	91.64	3.65	6.38	20.13	35.65	58.42
40	90.02	93.18	95.33	95.6	95.53	3.65	8.67	20.64	37.38	70.19
30	90.95	95.33	96.17	96.13	96.17	3.65	15.08	28.81	42.04	73.41
20	92.7	96.31	97.23	97.7	97.7	3.74	20.64	43.03	45.84	86.29
10	96.37	97.7	98.72	99.53	99.53	8.67	40.58	71.43	54.5	91.01

The storage frequency tables show an increase in storage values for all exceedance frequencies when QX values greater than 1 are used. A decrease in storage capacity is observed for QX values less than 1. Large decrease in flow, represented by QX value of 0.25 shows 0% of storage capacity for exceedance frequency from 20% to 99%. The QX value of 2.5 implies the flow is expected to increase by 2.5 times the average expected flow volume. From Table 3.21, the storage capacity without QX factor is 72.78% of total capacity for 90% exceedance frequency, which increases to 79.44 for QX factor of 2.5.

CHAPTER V

WATER MANAGEMENT PLANS AND RELIABILITY ANAYSIS FOR INTERRUPTIBLE SUPPLY

This chapter explores the concept of combining firm and interruptible water supplies from the same reservoir system using reservoir storage as a trigger mechanism. The basic water management concept is that some water uses such as municipal must be supplied with a very high level of reliability while other water uses such as irrigated agriculture may benefit from interruptible supplies even if reliabilities are significantly less than 100 percent. Trading a decrease in reliability for an increase in quantity of water usually supplied may also be beneficial. Certain water supply customers such as farmers are provided interruptible supplies while protecting the reliability of firm supply customers such as cities and certain industries.

Though also applicable in other river basins, the LCRA water management plan for operation of the High Lakes System is the most notable example in Texas of coordinating firm and interruptible supplies. LCRA operations are explored to understand actual water management strategies. The LCRA System is also adopted as a case study for developing, testing, and demonstrating the modeling strategy presented in this chapter. However, the objective is to explore modeling and analysis techniques, not recommend or support a particular variation of water management plans for the LCRA System.

A WRAP/WAM modeling strategy is presented in this chapter for developing a relationship between interruptible water demand quantities versus associated supply reliability. Interruptible supplies are curtailed to protect firm supplies any time reservoir storage contents fall below a specified trigger level. Given that firm demands must be supplied with a reliability of 100.00 percent, a reservoir storage trigger level is determined that results in an interruptible supply with a corresponding reliability. The modeling strategy is based on iterative executions of the simulation model in long-term simulation mode.

The effects of off-channel reservoir storage in improving water supply reliabilities are also investigated in this chapter. The role of off-channel reservoirs in river/reservoir system management is discussed. Long-term WRAP/WAM simulations are performed with and without hypothetical off-channel reservoirs. Reliabilities with various levels of off-channel storage are compared.

5.1. Lower Colorado River Authority (LCRA)

The Lower Colorado River Authority (LCRA) is a conservation and recreation district created by the Texas Legislature in 1934 with the purpose of supplying water, generating electricity, flood mitigation and reforestation and soil conservation. It has jurisdiction over the lower part of the basin and operates solely on utility revenues and fees generated from supplying electrical energy, water, and community services. LCRA supplies wholesale electrical power to 43 city-owned utilities and electric cooperatives that serve 1.1 million people in Central Texas. LCRA manages more than 16,000 acres of recreational lands along the Colorado River and administers other programs supporting community and economic development. The agency operates the off-channel Lakes Bastrop and Fayette County (Cedar Creek) to provide cooling water for thermal-electric power plants as well as operating the six Highland Lakes.

LCRA owns five and operates all six of the Highland Lakes on the Colorado River, which are listed in Table 5.1. Hydroelectric power plants at each of the six dams are operated to help meet peak power demands. Lake Travis has a flood control pool. Lake LBJ provides cooling water for a LCRA thermal-electric power plant. Lakes Buchanan and Travis contain water supply storage used primarily to supply municipal and industrial users in Austin and vicinity and agricultural irrigation between the towns of Columbus and Bay City near the Gulf Coast. LCRA holds water right permits to divert and use up to 1.5 million acre-feet/year from Lakes Buchanan and Travis and 636,750 acre-feet/year under downstream run-of-river water rights from the Gulf Coast, Lakeside, Garwood, and Pierce Ranch irrigation operations (Hoffpauir et. al., 2013).

Table 5.1. Highland Lakes Reservoirs

Dam	Lake	Permitted Capacity (acre-feet)	Current Capacity (acre-feet)	Reservoir Surface Area (acres)	Top of Dam Elevation (feet msl)
Buchanan	Buchanan	992,475	875,588	22,017	10265
Inks	Inks	17,545	13,668	777	922
Wirtz	LBJ	138,500	133,216	6,275	838
Starke	Marble Falls	8,760	7,186	591	738
Mansfield	Travis	1,170,752	1,134,956	19,297	750
Tom Miller	Austin	21,000	24,644	1,830	519

The reservoir storage capacities in the third column of Table 5.1 are from the water right permits. The information in the last three columns of Table 5.1 is provided at the LCRA website. The lakes are listed in upstream-to-downstream order. Among the Highland Lakes, only Lake Travis and Lake Buchanan have conservation storage capacity. The WRAP/WAM simulations include 488 major reservoirs in the Colorado River Basin and their impacts on the water supply capabilities of the LCRA System. However, reliabilities are presented in this chapter for only Lakes Travis and Buchanan.

5.2. LCRA Irrigation Operations

LCRA operates and maintains 3 irrigation divisions: Lakeside Irrigation District, Garwood Irrigation District and Gulf Coast Irrigation District. Pierce Ranch is another irrigation district owned by LCRA but operated privately. The irrigation districts lie in Matagorda, Wharton and Colorado Counties as shown in Figure 5.1 and collectively constitute the “Rice Belt” in the Colorado River Basin of Texas. Rice is usually planted in March or early April and the first crop is harvested in July. The plants are again regrown from their roots and second crop is harvested around October or November.

Water supply is available for irrigation from 3 sources: run-of-river (ROR) supplies, stored water from the reservoirs listed in Table 5.1, and groundwater. The irrigation districts each have several water rights including run-of-river and supplemental interruptible supply. When shortages are incurred from ROR supply, shortages are met through drawdowns from Lake Travis and Buchanan. Table 5.2 describes the different water rights associated with each irrigation district. The rights are categorized in the last column of Table 5.2 as either run-of-river (ROR) or reservoir storage backup (SBU).

Table 5.2. Irrigation District Water Rights

Irrigation District	Water Right ID	Priority Date	WAM Control Point ID	Maximum Permitted Diversion (ac-ft/yr)	Water Right Type
Garwood	61405434201RR	19001101	K20061	133,000	ROR
	61405434201BU	19871101			SBU
Gulf Coast	61405476003RRS	19001201	K10020	228,570	ROR
	61405476003RRL	19130629			ROR
	61405476003RRR	19380308			ROR
	61405476003SBU	19871101			SBU
	61405476003RRJ	19871101		33,930	ROR
	61405476003JBU	19871101			SBU
Lake Side (1)	61405475001LRRS	19010104	K20080	52,500	ROR
	61405475001LRRL	19130629			ROR
	61405475001LRRR	19380308			ROR
	61405475001LSBU	19871101			SBU
Lake Side (2)	61405475001WRR	19070902	K20080	55,000	ROR
	61405475001WRRL	19130629			ROR
	61405475001RRRR	19380308			ROR
	61405475001WBU	19871101			SBU
Pierce Ranch	61405477001RR	19070901	K20030	55,000	ROR
	61405477001RRL	19130629			ROR
	61405477001RRR	19380308			ROR
	61405477001BU	19871101			SBU

A water management plan governs the operation of Highland Lakes including the interruptible supply for irrigation use. LCRA is permitted to develop contractual commitments with water users whose demands do not have to be fully met 100% of the time which includes the irrigation water rights.

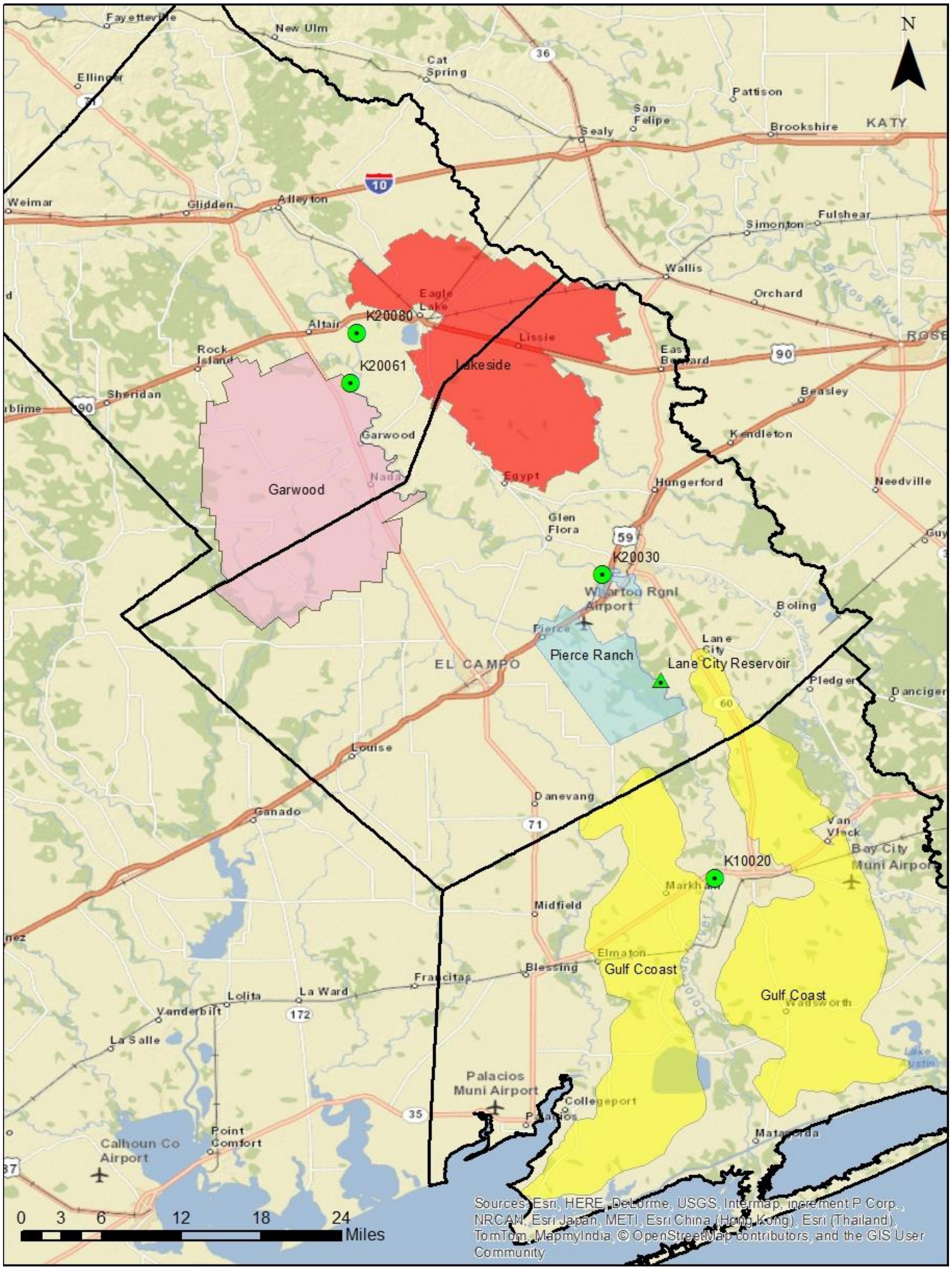

Figure 5.1. LCRA Irrigation Districts

5.3. LCRA Water Management Plan (WMP)

LCRA water supply operations in the lower Colorado River Basin are governed by the WMP which is defined in a document entitled Water Management Plan for the Lower Colorado River Basin, Effective September 20, 1989 including Amendments through January 27, 2010. The purpose of the WMP is to define LCRA's water management programs and policies in accordance with requirements set by a 1988 Final Judgment and Decree related to LCRA and City of Austin water rights. The LCRA petitioned to use up to 1.5 million acre-feet per year of water from the Highland Lakes system which was in excess of the firm yield of the reservoirs. But the Texas Water Commission (TWC) authorized this use contingent on a WMP for interruptible supply. The decree required LCRA to submit a reservoir operation plan which would define firm and interruptible stored water and management of water in Lakes Buchanan and Travis (Hoffpauir et. al., 2013).

Combined Firm Yield (CFY): The Highland Lakes are operated together as a system and only Lakes Travis and Buchanan have conservation storage capacity. The remaining four reservoirs are used strictly for hydropower generation, recreation and power plant cooling. The term Combined Firm Yield (CFY) refers to the portion of Lake Travis and Buchanan storage capacity left after upstream and downstream senior firm demands are satisfied to the full extent under the most severe drought of record (1947-1957). The 2010 WMP established the CFY as 445,266 acre-feet/ year after fulfilling required commitments to the O.H. Ivie Reservoir owned and operated by the Colorado River Municipal Water District. Firm demands currently include municipal, domestic, industrial, stream- electric power generation, nonagricultural irrigation and environmental instream flow requirements.

Interruptible Water Supply (IWS): The CFY is determined under conditions of the most severe drought of record and senior water right holders utilizing their full permitted diversions. However, senior water rights may not necessarily use their full authorized diversions amounts and hydrologic conditions may be wetter than the drought of record. This allows LCRA to supply water above the CFY levels on an annual interruptible basis as long as firm diversion demands are less than CFY. LCRA is allowed to withdraw water in excess of CFY up to 1,500,000 acre-feet. The interruptible water supply (IWS) is used to fulfill irrigation water demands to the four major rice irrigation districts and has increased the average usable yield. The IWS is also used for maintenance of minimum instream flows in rivers and bay and estuaries fresh water inflows.

5.3.1. 2010 Water Management Plan

The WMP ensures that firm water supply from the Highland Lakes never exceeds the CFY and interruptible supply is maintained as long as firm supply is not impaired. In 2010 WMP, the supply of interruptible water to irrigation districts is based on the volume of water in Lakes Travis and Buchanan at semiannual periods. Interruptible Supply is available for January to June period based on January 1st storage levels in Lakes Buchanan and Travis taken separately and July through December period supply depends upon minimum of the maximum storage levels in April, May and June, taken separately for Lake Buchanan and Travis. Interruptible supply is completely cutoff if either reservoir is less than 94% of its maximum conservation capacity and limited proportionally between 94% and 100% storage capacity. Firm supply and Interruptible supply are also used to maintain instream flows requirements at an average of 27,380 acre-feet/year.

Table 5.3. 2010 WMP Interruptible Supply Curtailment Triggers (LCRA. 2010)

Storage Level	Date	Action
Less than 94% Full	Jan. 1 or July 1	Interruptible supplies cutoff for all customers except irrigation operation
Less than 1.7 million acre-feet	Jan. 1	Environmental releases for bays and estuaries meet 150% of critical needs
Less than 1.4 million acre-feet	Jan. 1	Gradual Curtailment of interruptible supply to irrigation operations proportional to storage levels. Environmental releases for bays and estuaries are reduced to critical needs
Less than 1.1 million acre-feet	Jan. 1	Environmental releases for bays and estuaries meet critical needs
900,000 acre-feet	At any time	Firm users implement mandatory conservation restrictions and develop curtailment plan if drought worsens
600,000 acre-feet	At any time	If criteria for drought worse than DOR is met, full curtailment of interruptible supply and pro rata curtailment of firm supply
325,000 acre-feet	Jan. 1	No interruptible supply
200,000 acre-feet	At any time	No interruptible supply

The WMP also includes a Drought Management and Drought Contingency Plan (DMP/DCP). The DMP/DCP established criteria for stored water releases to water rights under LCRA contracts. It permits gradual curtailment of interruptible stored water supply to protect firm demands under conditions of the drought of record (DOR). The DMP/DCP also establishes a Reserve Storage Pool and clearly defines the criteria for curtailment of water demands. The 2010 WMP curtailment thresholds are defined by drought triggers. The drought triggers are established based on storage conditions from Lakes Buchanan and Travis on a semiannual basis. LCRA also has specific metrics to gauge drought conditions and if drought characteristics meet requirements for being a worse drought than the DOR, interruptible supply is fully curtailed and firm supply is pro rata curtailed. Table 5.3 shows the drought triggers for the 2010 WMP. For irrigation water rights belonging to the irrigation districts, the 2010 WMP currently cuts off interruptible supply when storage at Lake Travis and Buchanan drops below 325,000 acre-feet. The storage supply is also limited proportionally to storage level between 325,000 acre-feet and 1,400,000 acre feet. For example, only 50% of total storage demand is supplied if the storage level is at 537,500 acre-feet. Full supply of interruptible supply is resumed only after the storage level reaches 1,400,000 acre-feet.

The irrigation water rights also subordinate water supply to the City of Austin as per the WMP. The City of Austin has access to water supply meant for irrigation districts except for Garwood. The subordination is done at the highest priority date of the irrigation water right for each district just before water is supplied to them. The subordination amount is limited to defined maximum allowable limits for each month (LCRA, 2010)

5.3.2. Proposed 2014 Water Management Plan

As firm demand increases, LCRA will have to amend its WMP to adjust the curtailment triggers for interruptible water supply to satisfy new requirements. The LCRA WMP has been revised and updated as required by the changing conditions and new information and studies. Updates have been approved in 1992, 1999 and most recently in 2010. The severity of the drought that started in 2010 has forced LCRA to adopt emergency measures and depart from the 2010 WMP. LCRA also submitted an updated WMP to TCEQ on February 2012. TCEQ evaluated the updated WMP and recommended LCRA to make further revisions to it. LCRA then made the required changes as proposed by TCEQ and submitted an amended and restated application for update to WMP on October 2014. The revised 2014 WMP is currently under review by TCEQ.

The update proposed by LCRA has significant changes from the 2010 WMP. The 2014 WMP maintains storage above 600,000 acre-feet during DOR which used to be 350,000 to 420,000 acre feet in the 2010 WMP. The interruptible supply amount is also defined in terms of strict volumetric limits which could result in mid-crop cutoff in first crop if there is no second crop stored water. The semiannual dates for determining interruptible supply for irrigation has been fixed as March 1st for first crop and July 1st for second crop. It also has separate curtailment curves for different drought conditions and crop condition. The curtailment thresholds have been defined for three different drought conditions: Extraordinary Drought, Less Severe Drought and Normal conditions. The criterions defining drought conditions and the different threshold are presented below (curtailment thresholds do not apply to Garwood Irrigation District):

5.3.2.1. Normal Conditions

Table 5.4. Curtailment Triggers under Normal Conditions

1st Crop			2nd Crop		
Storage Level	Date	Interruptible Supply (acre-feet)	Storage Level	Date	Interruptible Supply (acre-feet)
Greater than 1.4 million acre-feet	March 1st	202,000	Greater than 1.55 million acre-feet	July 1st	76,500
1.0 to 1.4 million acre-feet	March 1st	121,500 to 156500	1.0 to 1.55 million acre-feet	July 1st	46,000 to 59,500
Below 1.0 million acre-feet	March 1st	No interruptible supply	Below 1.0 million acre-feet	July 1st	No interruptible supply
Below 900,000 acre-feet	At any time	No interruptible supply	Below 900,000 acre-feet	At any time	No interruptible supply

5.3.2.2. Less Severe Drought Conditions

The curtailment triggers are presented in Table 5.5. Criteria for entering Less Severe Drought Condition:

- Combined storage below 1.6 MAF on March 1 or July 1 and cumulative three-month inflows total less than 50,000 acre-feet
- Combined storage below 1.4 MAF on March 1 or July 1 and cumulative three-month inflows total less than 33 percent for the three month period

5.3.2.3. Extraordinary Drought Conditions

Criteria for entering Extraordinary Drought Conditions

- Combined storage below 1.4 million acre-feet on March 1 or July 1, and at least 24 months since the combined storage was 98 percent full or more, and the intensity criteria indicates a drought of severity equal to or exceeding the 1950s DOR

Table 5.5. Curtailment Trigger under Less Severe Drought Conditions

1st Crop			2nd Crop		
Storage Level	Date	Interruptible Supply (acre-feet)	Storage Level	Date	Interruptible Supply (acre-feet)
1.5 to 1.599 million acre-feet	March 1st	155,000	1.4 to 1.599 million acre-feet	July 1st	55,000
1.4 to 1.499 million acre-feet	March 1st	145,000	1.1 to 1.399 million acre-feet	July 1st	46,000
1.3 to 1.399 million acre-feet	March 1st	130,000	Below 1.1 million acre-feet	July 1st	No interruptible supply
1.2 to 1.299 million acre-feet	March 1st	115,000	Below 900,000 acre-feet	At any time	No interruptible supply
1.1 to 1.199 million acre-feet	March 1st	100,000			
Below 1.1 million acre-feet	March 1st	No interruptible supply			
Below 900,000 acre-feet	At any time	No interruptible supply			

Interruptible Supply is completely cutoff during extraordinary drought conditions except for the Garwood Irrigation District (LCRA, 2010).

The proposed 2014 application also has clearly defined exit criteria for above mentioned drought conditions and has updated the environmental supply criteria. More detailed information regarding the proposed 2014 WMP can be found at LCRA and TCEQ websites.

The extreme severity of the recent drought has also made it necessary to recalculate the CFY for the Highland Lakes. The record low inflows and dry conditions as of 2014 show that the Highland Lakes are now in a new critical period, with current drought shadowing the 1947-1957 DOR. The recalculated CFY is 500,000 acre-feet per year which is 100,000 acre-feet per year less that 1947-1957 DOR. Furthermore, the CFY may see additional reductions as drought continues.

5.4. Comparative Study of Firm and Interruptible Supply

This illustrative study compares volume reliability for interruptible supplies for alternative operating plans defined by reservoir storage triggers. Volume reliability (R_v) is defined as the percentage of total target demand amount that is actually supplied in the long-term simulation model. It is the ratio of volume of water supplied (v) to the diversion target (V) expressed as percentage.

$$R_v = \frac{v}{V}\,(100\%) \tag{14}$$

Volume reliability was developed in the study based on long-term simulation of interruptible supply for different trigger storage capacities. The reliability values represent the maximum volume reliability for interruptible supply that can be achieved without reducing the firm supply for the given storage capacity. The storage capacities vary from full access to zero availability. Proportional access to storage is also considered and varies from 0 to 1,400,000 acre feet. A graph representing volume reliabilities for maximum interruptible supply at different interruptible storage capacities is developed. Complete storage capacity cutoff level is indicated by “<” sign and full access level is represented by “>”. The numbers in between represent proportional storage capacity. For firm supply, three water rights were chosen that represent the backup water rights for the city of Austin municipal supply and are shown in Table 5.6. Interruptible supply consists of the water rights listed in Table 5.2 for each irrigation district. The volume reliabilities are developed for maximum diversion of irrigation water rights so that City of Austin (COA) water rights still get their supply at 100% reliability.

Table 5.6. Firm Supply Water Rights

Water Right	Water Right ID	Priority Date	WAM Control Point ID	Maximum Permitted Diversion (acre-feet)	Type
City of Austin	61405471005RMBU	19380307	I10340	250000	SBU
	61405471005LMBU	19380307	I10341	21403	SBU
	61405489003MBU	19450820	J30530	20300	SBU

In Figure 5.2, the Garwood Irrigation District can increase its diversion target by 4% and have a volume reliability of 99.85% without affecting the hypothetical firm supply represented by water rights in Table 5.6, if it has full supply for storage content above 1.4 million acre-feet, proportional supply between 0.325 and 1.4 million acre-feet and complete cutoff below 0.325 million acre feet. The change in reliability is largest for Lake Side 1 and Peirce Ranch at 42.69% and 43.37% respectively. Both of these irrigation districts have the lowest priority dates in comparison to other districts.

Conversely, Garwood shows the least change in reliability and also has the most senior priority. As can be seen from the graph Garwood Irrigation District supply is not highly affected by changes to storage capacity and only varies from 99.92% to 98.01% under full to zero storage capacity availability. This can be attributed to Garwood being one of the most senior water rights in the Colorado WAM and not having any subordination responsibility to COA.

All irrigation districts show relatively smaller changes in reliability up until storage access is cutoff below 1,400,000 acre-feet. After the 1,400,000 acre-feet mark the irrigation districts do not have access to proportional supply from storage capacity. The removal to proportional access causes relatively larger reductions in reliability values. The supply of water proportional to storage capacity greatly helps in maintaining higher reliability even at higher cutoff levels. Peirce Ranch has a reliability difference of 7.39% only between unlimited access and proportional access from 325,000 to 1,400,000 acre-feet. It has full access after 1,400,000 acre-feet. Similar graphs can be used as a tool in developing curtailment plans as it gives a comprehensive picture of storage volume’s effect on interruptible supply.

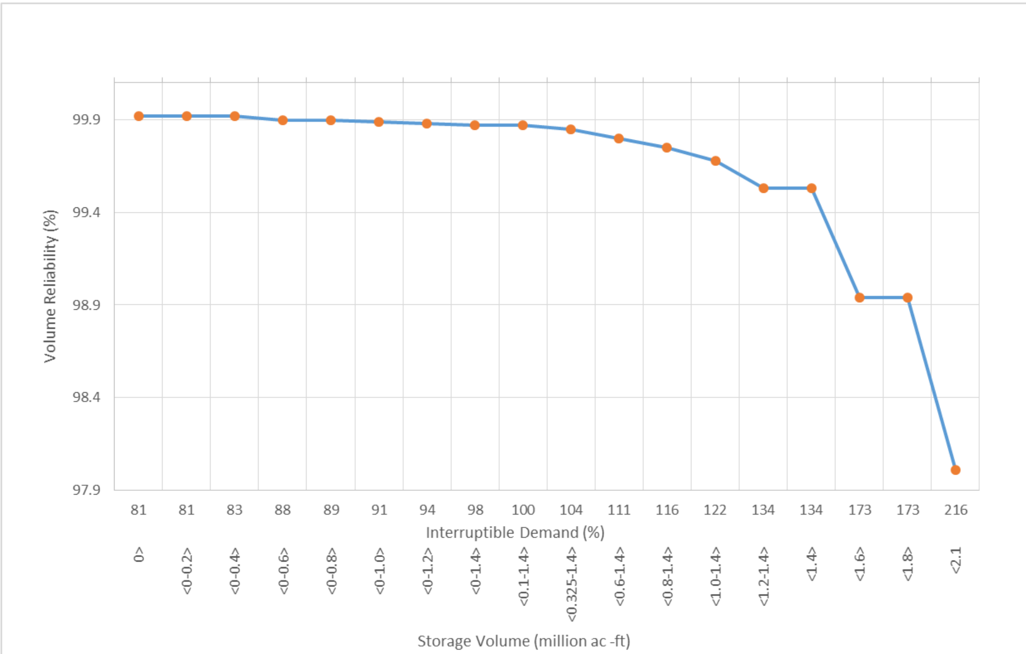

Figure 5.2. Reliability Graph for Garwood Irrigation District

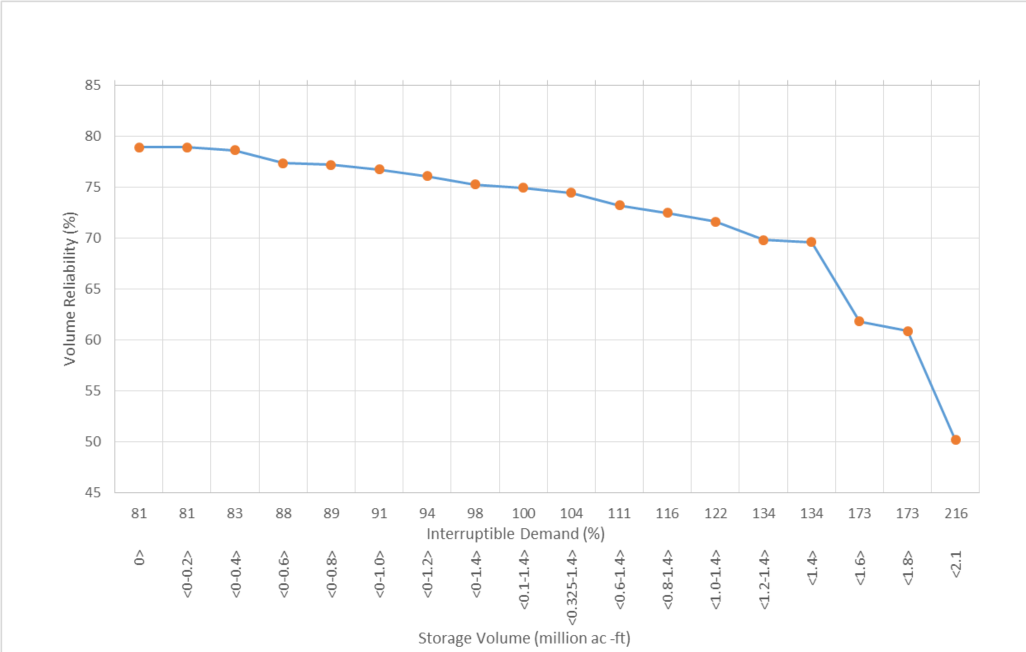

Figure 5.3. Reliability Graph for Gulf Coast Irrigation District

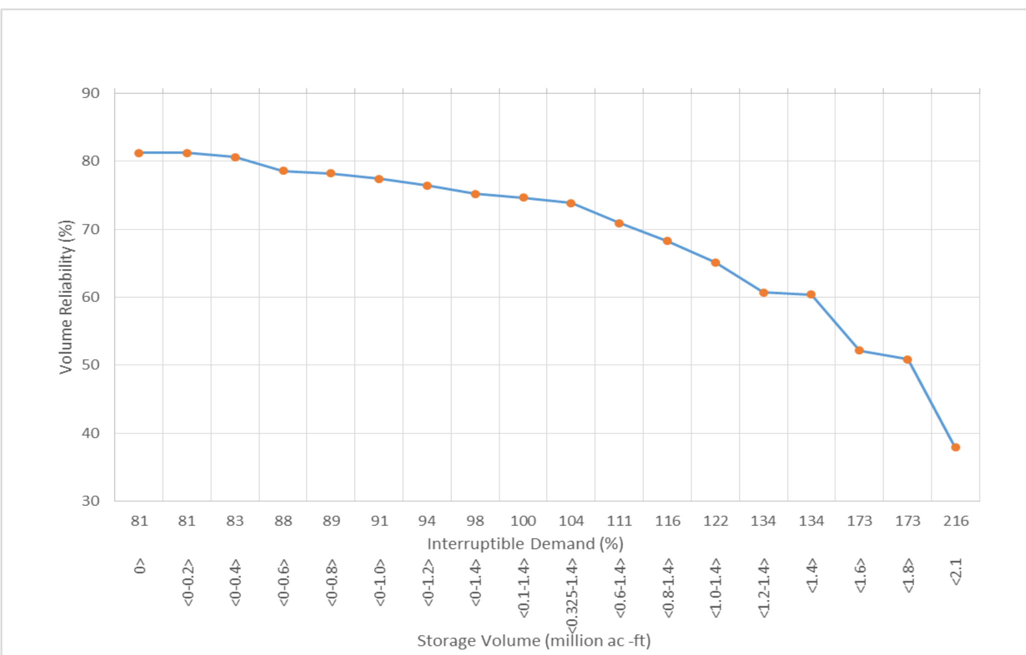

Figure 5.4. Reliability Graph for Pierce Ranch Irrigation District

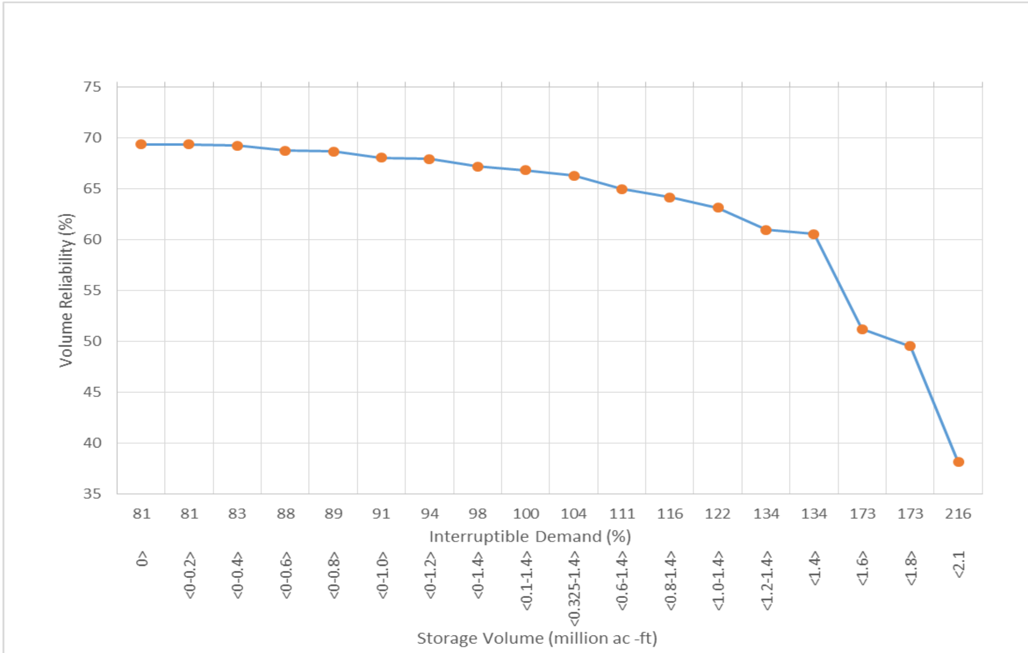

Figure 5.5. Reliability Graph for Lake Side 1 Irrigation Supply

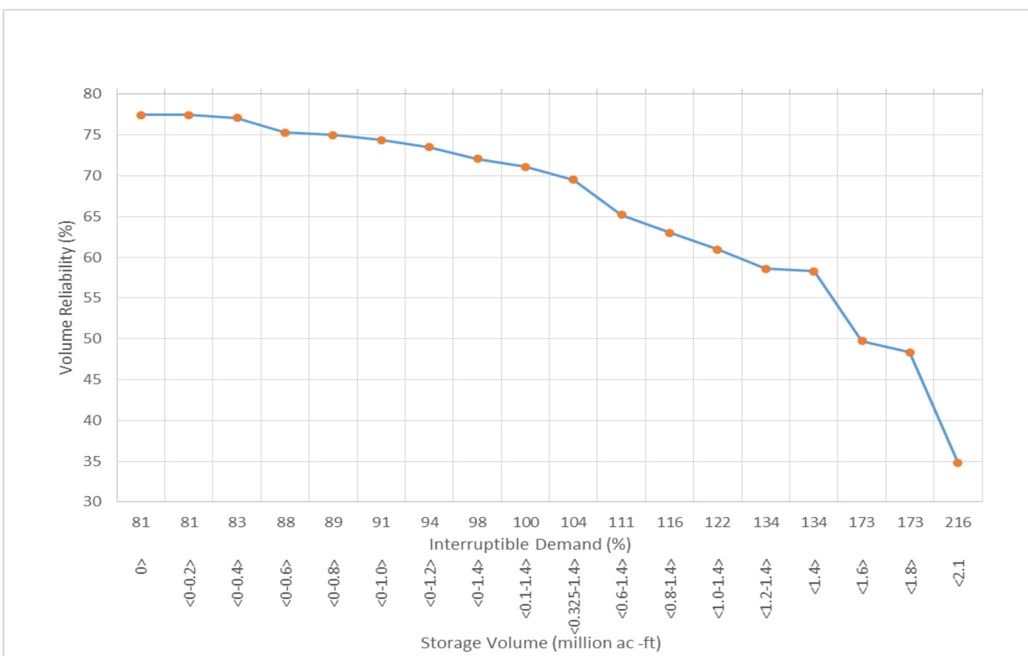

Figure 5.6. Reliability Graph for Lake Side 2 Irrigation Supply

5.5. Off-Channel Reservoirs (OCR)

Population growth and expansion of agricultural and industrial sectors has increased demand on water resources. Water supply will also be affected by depleting ground water tables and sediment accumulation in existing on-channel reservoirs. Environmental demand for water is also expected to rise which will require more water to stay in-stream as more stringent environment protection laws are passed. On-channel reservoirs act as barriers to fish passage and drown riparian habitats. As such construction of new on-channel reservoirs are likely to be met with opposition from different conservation groups. Under these circumstances, off-channel reservoirs are becoming an important alternative for water storage.

Off channel reservoirs (OCR) are reservoirs constructed outside of the main river channel, usually on a smaller tributary stream. Water is diverted to an OCR by gravity or pumping during high flows and used to meet supply when flow is depleted in the main channel. OCR have higher construction and operation and maintenance cost but can be environmentally friendly. OCR can be constructed in a non-environmentally sensitive areas. OCR also reduces adverse water quality effects on rivers. However, it does require larger conveyance infrastructures and seepage control measures. The primary disadvantage of an OCR is the requirement of pump station and extensive conveyance system to divert water into the reservoir.

LCRA already has a water right permit to construct up to 500,000 acre-feet of OCR storage with a priority date of February 28, 2001. OCRs can be built at multiple sites and is authorized to use up to 327,591 acre-feet/year (Hoffpauir et. al., 2013). OCR is also likely to be used under LCRA – San Antonio Water System Water Project (LSWP). The irrigation water demand will be reduced by using conservation and other programs. The irrigation water rights could be amended and additional firm yield available could be reallocated by use of OCR to meet municipal and industrial needs. . This measure is expected to create an additional yield of 100,000 acre-feet per year. Moreover, OCR will also be used to supply portions of water rights not used to meet in-basin demands to San Antonio Water System (LCRWPG, 2010).

Private on-farm OCR can provide farmers with additional water during dry seasons. The study compared the effect of OCR for each irrigation district. Reservoirs of different capacity were added as personal storage to each irrigation district and reliabilities were developed at all trigger points considered in previous study. The study shows a larger increase in reliability as access to highland lakes storage decreases. Under drought conditions the reservoirs function as an alternate source of water when supply from Highland Lakes are completely or partially cutoff. The graphs show a marginal increase in reliability for storages of 1000 acre-feet even when highland lake storage is completely cut off. Lake Side and Pierce Ranch Irrigation Districts have relatively smaller diversion targets and seem to be affected by OCR the most. Both show 11% and 13% increase in reliability between 1000 acre-feet and 75,000 acre-feet storages. Garwood and Gulf Coast have higher diversion targets and consequently exhibit less sensitivity to addition of storage. For other irrigation diversions of lesser volume, small storage reservoirs could significantly affect reliabilities.

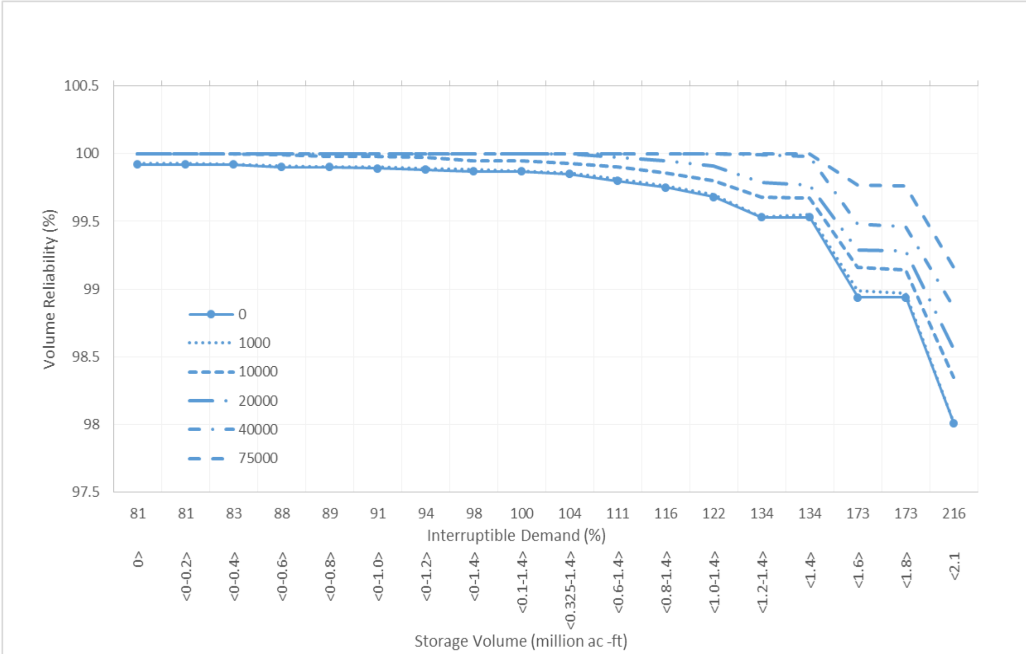

Figure 5.7. Reliability Graph for Garwood Irrigation District with OCR

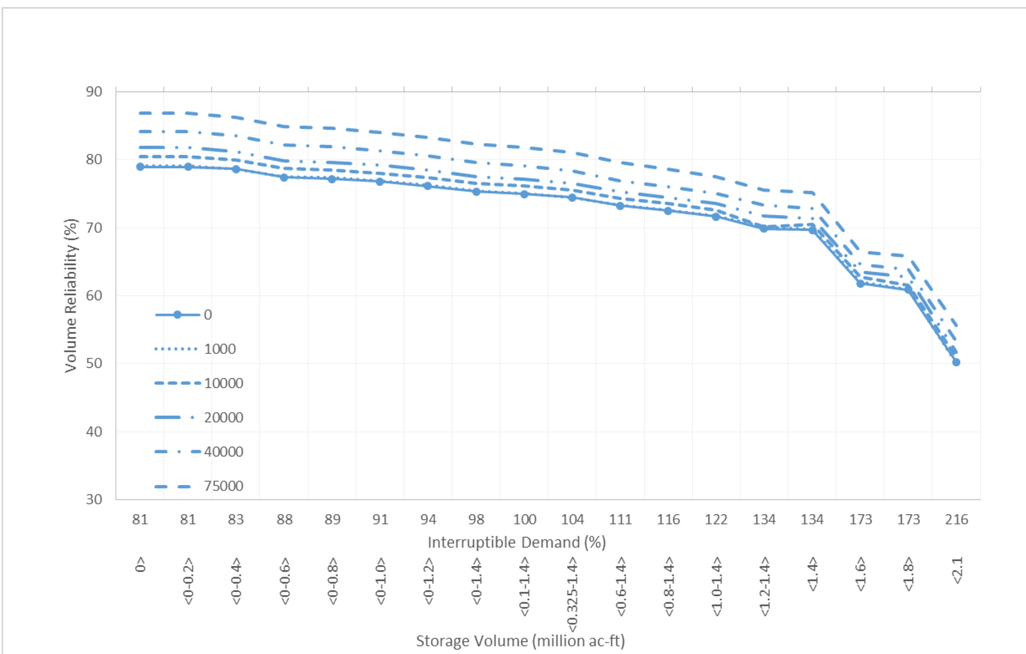

Figure 5.8. Reliability Graph for Gulf Coast Irrigation District with OCR

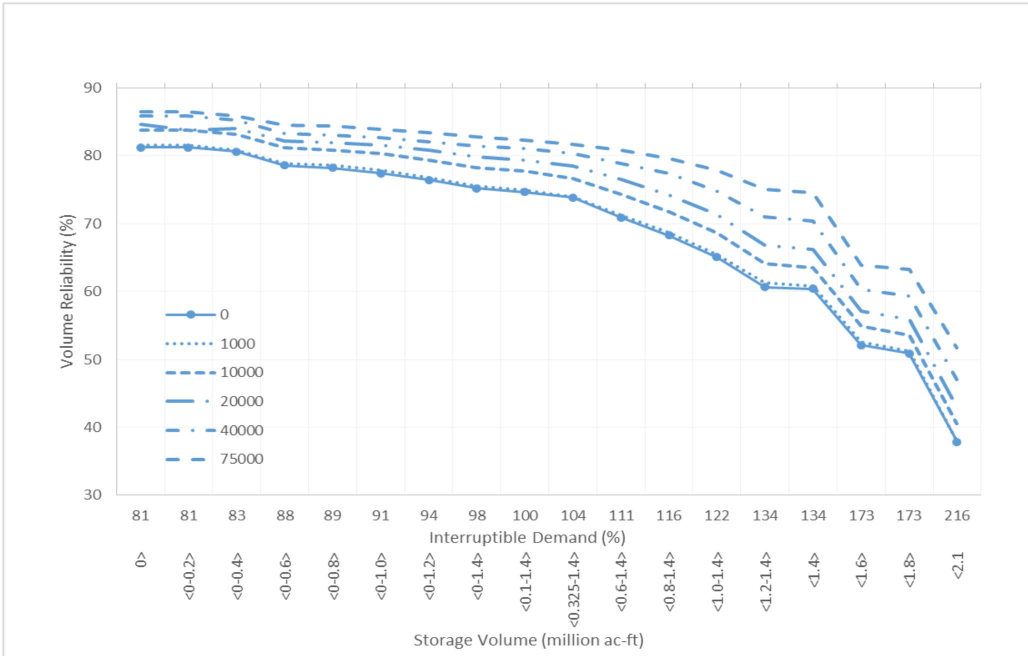

Figure 5.9. Reliability Graph for Pierce Ranch Irrigation District with OCR

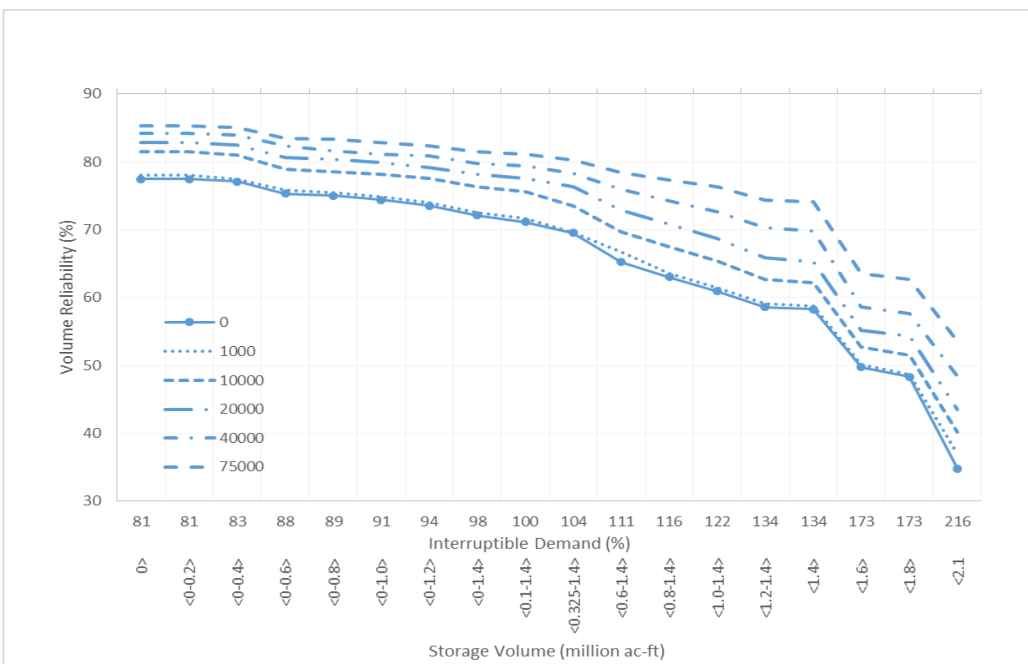

Figure 5.10. Reliability Graph for Lake Side 2 Irrigation Supply with OCR

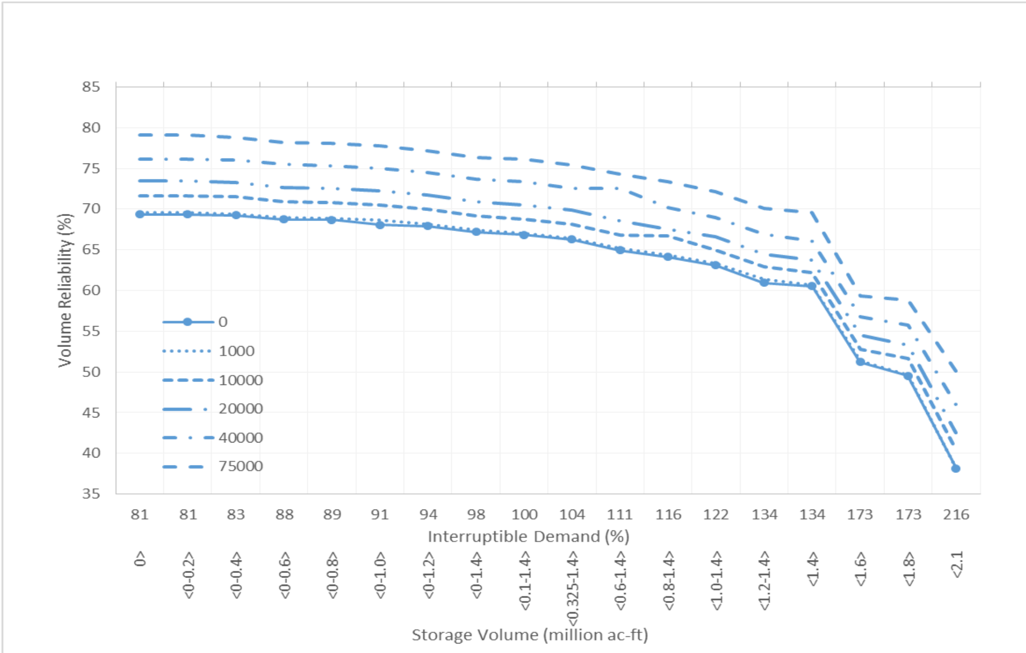

Figure 5.11. Reliability Graph for Lake Side 1 Irrigation Supply with OCR

5.6. Lane City Reservoir

Lane City Reservoir is an off channel reservoir currently under construction in Wharton County. The reservoir is being constructed by LCRA as part of its plan to add at least 100,000 acre-feet per year of new firm water supply by 2017. The reservoir will have storage capacity of 40,000 acre-feet and is expected to supply 90,000 acre feet per year of firm water. Its main purpose is to capture unused stored water released to customers downstream of Highland Lakes, especially to Garwood, Lakeside and Pierce Ranch Irrigation Districts. The stored water will then be used to supply demands from Gulf Coast Irrigation District, firm water customers in Matagorda County, South Texas Project and environmental requirements at Matagorda Bay.

Simulations of Lane City Reservoir shows an increase in reliability from 74.91% to 76.34% for Gulf Coast District. The modeling of Lane City Reservoir has been done in a simplistic way with refill priority date of 99999999 and storage capacity of 40,000 acre-feet. In reality its operations could be more complex based on how LCRA manages the reservoir. Lane City Reservoir was used to analyze the effect of curtailment triggers as well and showed slight increase in reliability from no reservoir conditions. Reliabilities are also lower than the values for 40,000 acre-feet storage reservoir as it was modeled to fulfill environmental as well as South Texas Project demands.

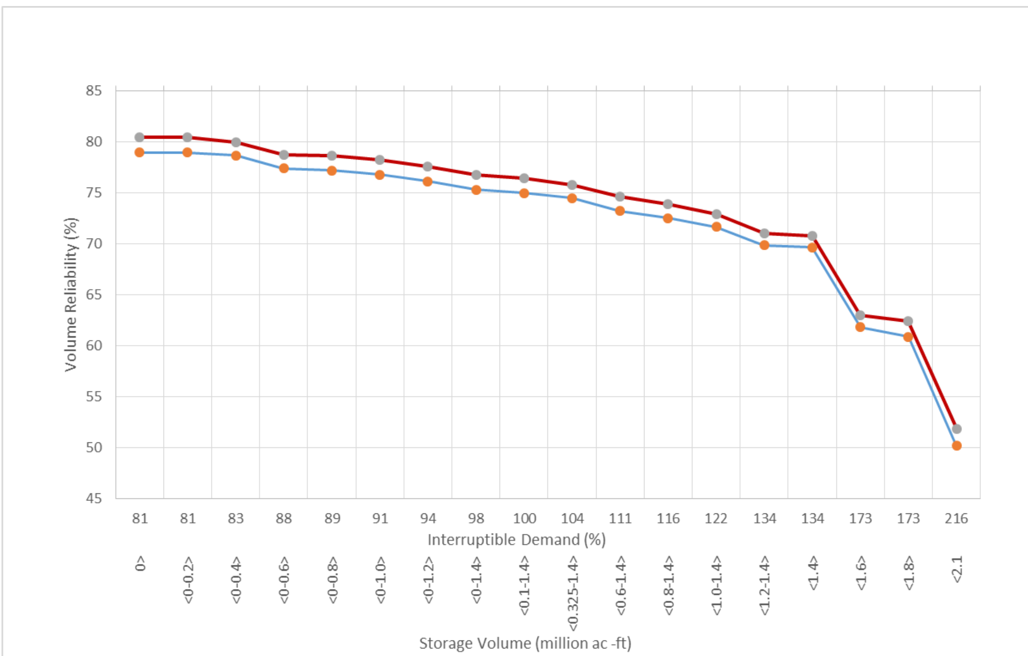

Figure 5.12. Reliability Graph for Gulf Coast Irrigation District with Lane City Reservoir

CHAPTER VI

SUMMARY AND INTEGRATION OF MODELING STRATEGIES

The overall goal of this study is to expand WRAP/WAM capabilities for supporting drought management which includes both decision-support during droughts and planning studies to prepare for future droughts. The modeling system is applied to simulate river/reservoir systems and perform supply reliability and stream flow and reservoir storage frequency analyses based on the results of the simulations. The WRAP/WAM simulations and associated reliability and frequency analyses may be performed in either a conventional long-term simulation mode or short-term CRM mode.

6.1. Long-Term WRAP/WAM Simulation Studies

Conventional long-term WRAP/WAM simulations are routinely applied in Texas to evaluate water right permit applications and in regional and statewide planning studies. The preceding Chapter V focuses on two water management strategies: (1) coordination of firm and interruptible supplies and (2) off-channel reservoir storage. The LCRA System is adopted as a case study.

The modeling and analysis strategy presented in Chapter V is based on iterative WRAP/WAM simulations in the long-term analysis mode. The modeling strategy is designed for developing long-term reliability metrics for interruptible supplies at particular reservoir storage trigger levels. A water management plan that accommodates interruptible supplies while protecting firm supplies is based on setting storage triggers that activate specified curtailment actions for the interruptible supplies.

For a particular water management plan with one or more reservoir storage levels designated to trigger curtailment of interruptible water supply diversions to protect firm supply, an interruptible diversion target and corresponding volume reliability are computed based on iterative executions of the simulation model with different interruptible diversion target amounts. For the plan of curtailment defined by the one or more specified storage triggers, the iteratively computed diversion target is the maximum quantity of interruptible supply possible while satisfying the constraint of allowing no shortage to be incurred by the firm supply targets. The volume reliability for the interruptible target is computed by regular post-simulation reliability analysis.

The illustrative case study in Chapter V includes creation of interruptible yield reliability graphs which are presented in Figures 5.2-5.6 for the four irrigation districts. The reliability graphs are repeated in Figures 5.7-5.12 to show the effects of various volumes of off-channel reservoir storage capacity. The WRAP/WAM model was executed repeatedly with alternative volumes of off-channel storage, generating the simulation results from which the reliability graphs were developed.

The interruptible yield diversion target and volume reliability quantities for the Gulf Coast Irrigation District plotted in Figure 5.3 of Chapter V are reproduced in tabular form in Table 6.1. Table 6.1 shows the interruptible demands that can be supplied at the reliabilities shown while still maintaining 100.0 percent reliabilities for the firm yield municipal demands. The first column of Table 6.1 shows the curtailment triggers that are required for supplying the interruptible yields in the second column, at the reliabilities shown in the third column.

Table 6.1. Long Term Volume Reliability for Gulf Coast Irrigation District

Storage Triggers	Diversion Amount as a Percentage of Actual Target	Volume Reliability
0>	81	78.94
<0-0.2>	81	78.94
<0-0.4>	83	78.68
<0-0.6>	88	77.41
<0-0.8>	89	77.21
<0-1.0>	91	76.79
<0-1.2>	94	76.12
<0-1.4>	98	75.32
<0.1-1.4>	100	74.97
<0.325-1.4>	104	74.48
<0.6-1.4>	111	73.24
<0.8-1.4>	116	72.53
<1.0-1.4>	122	71.66
<1.2-1.4>	134	69.86
<1.4>	134	69.66
<1.6>	173	61.84
<1.8>	173	60.90
<2.1	215	50.20

As in the previous chapter, the storage curtailment column represents different curtailment actions for interruptible supply. All the irrigation district water rights presented in Table 5.2 are aggregated together to represent the interruptible supply. The city of Austin storage backup water rights presented in Table 5.6 make up the firm water supply that is protected by the curtailment triggers. The volume reliability is developed for the six water rights belonging to Gulf Coast Irrigation District listed in Table 5.2, which have permitted diversions totaling 262,500 acre-feet/year. The Gulf Coast Irrigation District water rights include four run-of-river and two rights supplied by diversions from the river backed up by releases from Lakes Travis and Buchanan.

The alternative reservoir storage trigger mechanisms that produce the different levels of interruptible yield are described in the first column of Table 6.1 in the format <X-Y> indicating two trigger levels set at X million acre-feet and Y million acre-feet. Interruptible diversions supplied by releases from Lakes Travis and Buchanan are:

- Completely cut-off if storage content on a specified date is below X million acre-feet.
- Supplied in proportion to storage content if their storage content on the specified date is between X and Y million acre-feet.
- Fully supplied if the storage content on the specified date is above Y million ac-feet.

The 2010 LCRA Water Management Plan (WMP) is outlined in Table 5.3. A revised WMP proposed by LCRA in 2014 is outlined in Tables 5.4 and 5.5. The 2010 WMP sets storage triggers for different water uses on January 1, July 1, or for some triggers any time of the year. The 2014 proposed revised WMP includes triggers set on March 1, July 1, or in some cases any time of the year. In general, the 2010 LCRA WMP supply of interruptible water to irrigation districts is dependent on the total volume of water in Lakes Travis and Buchanan at semiannual periods. Interruptible supply available for January through June is based on January 1st storage levels. Likewise, storage triggers on July 1st control the amount of water supplied to irrigation districts for the period from July through December.

The Colorado WAM dataset from the TCEQ WAM System includes the 2010 LCRA WMP. The trigger dates from the 2010 LCRA WMP are adopted in the simulations of Chapter V and Table 6.1. All of the 1,287 water rights in the Colorado

WAM remain unchanged in the simulations except for the irrigation rights listed in Table 5.2 and associated storage triggers for Lakes Travis and Buchanan. The diversion amounts for the four irrigation districts are changed in each execution of the WRAP/WAM simulation by multiplying the diversion amounts in the original WAM by the percentages tabulated in the second column of Table 6.1. The storage triggers in the first column are applied to the diversion rights of the four irrigation districts.

The interruptible yield diversion amount specified in the second column of Table 6.1 is the aggregated sum of annual diversion targets for the Gulf Coast Irrigation District interruptible rights of 262,500 acre-feet/year. Corresponding volume reliabilities in percent are shown in the third column.

In Table 6.1, the storage curtailment plan with triggers of 325,000 and 1,400,000 acre-feet (<0.325-1.4>) represents actual storage triggers from the 2010 WMP. Under this plan, water supplied to the interruptible water rights by releases from Lakes Travis and Buchanan is completely cutoff if their combined storage is less than 0.325 million acre-feet. For storage content between 0.325 and 1.4 million acre-feet, interruptible supply from the lakes are reduced in proportion to the storage content. The interruptible supply has full access to storage above 1.4 million acre-feet. For this operating plan, the volume reliability for an interruptible yield diversion target set at 104% of the actual target in the Colorado WAM for the Gulf Coast Irrigation District is 74.48%. The interruptible supply diversion target can be increased by 4% under this curtailment scenario while maintaining a volume reliability of 100% for the firm water supply.

Based on the premises incorporated in the Colorado WAM in this case study, with triggers set at 100,000 and 1,400,000 acre-feet (<0.100-1.4>) combined total storage contents of Lakes Austin and Buchanan and diversion targets set at 100% of actual targets for the four irrigation districts, the diversion targets for the Gulf Coast Irrigation District have a volume reliability of 74.97%. The storage triggers and association irrigation diversion curtailments prevent shortages to the City of Austin firm yield targets in the simulation.

The tradeoffs between targeted supply and reliability are shown in Table 6.1. For example, the last row indicates that the interruptible diversion targets can be increased to 215% of the permitted diversion amounts, with the reliability decreasing to 50.2%. A storage trigger of 2.1 million acre-feet would be required to prevent Austin firm yield demands from experiencing shortages. If all interruptible demands are completely curtailed when the combined storage contents of Lakes Travis and Buchanan fall below 2.1 million acre-feet, interruptible irrigation targets totaling 564,375 acre-feet/year (215% of 262,500 acre-feet/year) can be supplied with an aggregated volume reliability of 50.20 percent. Likewise, the reliability can be increased from 74.48% to 78.95% by decreasing the interruptible diversion demands to 81% of their permitted quantities.

Storage frequency metrics computed with TABLES from the results of the long-term SIM simulation with storage triggers of 325,000 and 1,400,000 acre-feet (<0.325-1.4>) are reproduced as Table 6.2. Frequency metrics are provided for storage in Lakes Travis and Buchanan and the combined total storage in both lakes. These metrics can be compared with the CRM storage metrics presented in the next section.

Table 6.2. Long-Term Storage Frequency Metrics for Lakes Travis and Buchanan for Storage Triggers <0.325-1.4>

Exceedance Frequency (%)	End of June Storage (% capacity)			End of December Storage (% capacity)		
	Travis	Buchanan	Total	Travis	Buchanan	Total
99	12.44	39.19	24.98	11.16	27.32	21.25
98	15.68	47.42	30.91	13.89	33.93	26.59
95	19.82	49.98	46.27	26.28	46.43	39.33
90	47.61	59.41	50.07	35.20	52.94	44.58
80	61.17	74.22	65.69	58.18	60.89	58.58
70	65.46	83.16	74.67	65.61	76.77	72.19
60	75.64	92.55	84.22	72.82	89.97	79.37
50	85.84	97.64	90.55	76.34	94.77	84.79
40	92.00	98.73	94.82	85.48	99.10	90.72
30	96.28	99.87	97.37	92.85	99.87	96.07
20	100.00	100.00	100.00	99.79	99.87	99.83
10	100.00	100.00	100.00	100.00	100.00	100.00

The conservation storage capacities of Lakes Travis and Buchanan are 1,170,752 and 992,475 acre-feet, respectively, which total to 2,163,227 acre-feet. The end-of-June and end-of-December storage contents in Table 6.2 are expressed as a percentage of capacity. The 1940-2013 hydrologic period-of-analysis contain 74 Junes and 74 Decembers. The exceedance frequencies in the first column of Table 6.2 are the percentage of the 74 years of the simulation for which the storage contents shown in the other columns of the table are equaled or exceeded.

The Colorado WAM and all the other WAMS in the TCEQ WAM System begin the long-term simulation with all reservoirs full to capacity. The storage content of each of the 488 reservoirs in the Colorado WAM is set at 100.0% of conservation storage capacity at the beginning of January 1940.

6.2. Short-Term Conditional Reliability Modeling (CRM)

CRM is designed for developing short-term storage frequency and supply reliability metrics conditioned on preceding storage. The array of options included in WRAP for performing various CRM tasks provide both flexibility and complexity. The different CRM options are compared in Chapter III using Colorado WAM simulation results.

The comparative analyses of CRM methodologies in Chapter III include a comparison of the equal weight and probability array strategies. The probability array option potentially provides more accurate frequency and reliability estimates than the equal weight option if there is a significant degree of correlation between naturalized flow volumes and preceding storage contents or change in storage contents. Linear and Spearman rank correlation analyses were performed. Correlation analyses for the nonlinear transforms associated with the nonlinear regression equations incorporated in WRAP CRM were also performed. Simulation sequences starting in January, April, July, and October were adopted to represent the different seasons. The naturalized flow were summed for 1, 2, 3, 6 and 12 months. The analysis indicated that there is some correlation between storage or storage change and subsequent naturalized flow volumes for up to about 3 months but correlation becomes negligible after about 6 months.

Metrics identifying climatic teleconnections and drought indices are investigated in Chapter IV from the perspective of improving CRM. Potential improvements are dependent upon significantly correlated relationships between available climate cycle or drought indices and WAM naturalized flows. The literature implies significant correlations between hydrology and various such climate teleconnection indices in various regions of the world.

However, the correlation analyses with naturalized flows in the Colorado WAM presented in Chapter IV show relatively weak correlations.

The CRM results presented in Tables 6.3 and 6.4 and discussed in the following paragraphs are based on the equal-weight option since the correlation between either storage or change in storage and naturalized flow volume were found to be relatively low. The CRM results presented in Chapter III are similar with the equal-weight versus probability array options employed.

The CRM results of Tables 6.3 and 6.4 are from four alternative executions of the WRAP/WAM simulation model. The first analysis with CR1 of six months and CR2 of January is designed to estimate the likelihood of meeting irrigation diversion targets during the period of January through June as a function of storage level at the beginning of January. The second analysis with CR1 of 36 months and CR2 of January predicts storage frequency metrics 36 months into the future for given storage levels at the beginning of January of the first year. Each of these two analyses are repeated for two different initial storage conditions.

Initial storage is set in CRM at known levels for real-time applications or hypothetical levels of interest in planning studies. For purposes of the discussion here, the initial storage at the beginning of the CRM simulations is set alternatively at 325,000 acre-feet (15.02% of capacity) and 1,400,000 acre-feet (64.71% of capacity) for the two-reservoir Travis/Buchanan system which represents the triggers between complete curtailment, proportional curtailment, and zero curtailment conditions. The initial storage content of each of the other 486 reservoirs in the Colorado WAM is also set at

15.02% and 64.71% of capacity based on the premise that they are generally drawn-down to the same extent as Lakes Travis and Buchanan.

The CRM simulations for the two alternative preceding storage conditions are performed for two alternative periods of six months (January-June) and three years (January through December of third year). Simulation results are summarized with volume reliabilities for the interruptible demands for the 6-month and 36-month simulation periods (Table 6.3) and frequency metrics for storage in Lakes Travis and Buchanan at the end of six months and three years (Table 6.4).

There are 74 simulation sequences for the 6 month simulation period, and the 36 month simulation period has 72 sequences for the hydrologic period of analysis from 1940 through 2013. All simulation sequences start with the same storage contents for all 488 reservoirs at the beginning of each simulation sequence.

Volume reliabilities for the Gulf Coast Irrigation District diversions are presented in Table 6.3 for the last month of the 6-month and 36-month simulations. These computations are based on 74 Junes (6th month) and 72 Decembers (36th month). The volume reliabilities of 90.65% and 92.08% represent the percentage of the June (6th month) and December (36th month) diversion targets that is supplied if the storage content is at the beginning of the simulations is set at 15.02% of capacity.

Table 6.3. Volume Reliability for Gulf Coast Irrigation District using CRM

Period (months)	Initial Storage as % Capacity	
	15.02	64.71
6	90.65	92.82
36	92.08	92.76

The end of month storage capacities at different exceedance frequencies for CRM simulations are presented in Table 6.4. The storage is set to 15.02% and 64.71% of capacity at the start of January and the end of month storage is computed for June of the same year for the 6 month simulation and for December of the third year for the 36 month simulation. Table 6.4 shows that frequency metrics for storage at both 6 months and 36 months in the future are impacted greatly by the present storage contents. However, the difference between the frequency metrics for preceding storage of 64.71% versus 15.02% is much less at 36 months than at 6 months.

Table 6.4. CRM Storage Frequency Metrics for Combined Lakes Travis and Buchanan

Exceedance Frequency (%)	6-Month Simulation		36-Month Simulation	
	Beginning Storage as Percent of Capacity			
	15.02%	64.71%	15.02%	64.71%
	End of June Storage (% capacity)		End of December Storage (% capacity)	
99	0.00	41.97	0.00	8.95
98	0.00	42.76	0.00	16.98
95	0.00	44.30	8.05	32.61
90	0.16	47.97	13.76	48.33
80	2.89	50.76	29.24	59.66
70	7.17	54.26	38.51	67.66
60	10.41	58.12	45.90	74.18
50	14.27	60.97	60.25	82.82
40	18.94	71.27	73.13	90.51
30	23.63	75.65	85.49	97.16
20	34.43	86.40	95.60	99.18
10	71.64	100.00	100.00	100.00

6.3. Comparison of Short and Long Term Analyses

Conventional long-term WRAP/WAM simulations are routinely applied in the preparation and evaluation of water right permit applications and regional and statewide planning. Short-term CRM is designed for decision support during actual droughts and operational planning studies in preparation for future drought. Long-term simulations and CRM may also be applied in combination for operational planning studies and other applications. For example, a comparative evaluation of alternative water management plans such as those reflected in Table 6.1 could be based on long-term simulations. Selected alternative plans could then further analyzed in more detail using CRM.

The long-term Colorado WAM simulation combines the specified water management scenario with river basin hydrology for a single hydrologic period-of-analysis extending from January 1940 through December 2013, with all reservoirs assumed to be full to conservation capacity at the beginning of the simulation. Beginning-of-simulation storage is actually not known and could be set at levels less than full capacity, lowering reliability and frequency relatively metrics relatively small amounts. CRM is based on numerous short-term simulations with initial storage being at the same user-specified level for all of the simulations. Initial storage has a major impact on the results of CRM. The storage frequency metrics provided in Tables 6.2 and 6.4 provide different types of information.

Table 6.2 provides estimates of the likelihood of reservoir storage contents exceeding various levels at unspecified times in the future without consideration of present storage contents. For example, Table 6.2 indicates that the total storage contents of Lakes Travis and Buchanan at the end of June equaled or exceeded 50.07% of their total capacity of 2,163,227 acre-feet during 90% of the 74 years in the 1940-2013 hydrologic period-of-analysis. An estimated end-of-June storage content of 50.07% of the capacity of the two lakes is equaled or exceeded 90% of the time, based on all of the premises reflected in the Colorado WAM. Stated differently, the probability is estimated to be 0.90 that the storage contents of Lakes Travis and Buchanan at the end of June in any randomly selected year in the future will be 50.07% of capacity or greater.

Table 6.4 provides estimates of the likelihood of reservoir storage contents exceeding various levels at specified times in the future given known or assumed present storage contents. For example, for the 6-month simulation, Table 6.4 indicates that with the beginning of January storage at 64.71% of the capacity of 2,163,227 acre-feet, there is a probability of 0.90 that the end-of-June storage will 1,037,700 acre-feet (47.97% of capacity) or greater. Based on all the premises and information incorporated in the model, with the beginning of January storage at 64.71% capacity, the end-of-June storage equals or exceeds 1,037,700 acre-feet during 90% of the 74 simulations.

Likewise, the volume reliabilities in Table 6.1 quantify water supply capabilities over a long period of many years. Long-term reliabilities can also be viewed as representative of a random future point in time not affected by present actual storage conditions. The volume reliabilities in Table 6.3 are estimates of the proportion of the diversion target expected or predicted to be supplied in the sixth and 36th future month, given the amount of water presently in storage. Volume reliability for any future month depends upon streamflow availability as well as preceding storage. The reliabilities in Table 6.3 are the averages during the 74 and 72 simulations. All reliability and frequency metrics are estimates reflecting the assumptions, methodologies, data, and approximations inherent in the WRAP/WAM modeling system.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The WRAP/WAM System is used to assess water supply reliability and reservoir storage and stream flow frequency relationships for specified water demands and river/reservoir system management strategies. The WRAP modeling system includes both long-term and short-term analysis modes. This thesis is designed to explore and improve WRAP/WAM capabilities for drought management decision-support, employing both short-term conditional reliability modeling (CRM) and selected aspects of long-term simulation capabilities. The long-term simulations presented in this thesis focus on a strategy for modeling drought management plans that involve curtailment of interruptible water supply commitments during periods of shortage while protecting firm water supply commitments from experiencing shortage. The thesis research supports incorporation of WRAP CRM capabilities in the Integrated Water Use Efficiency Maximizer (IWEM) being developed by Texas A&M AgriLife Extension as well as expanding CRM capabilities in general.

The Colorado River Basin and the Colorado Water Availability Model (WAM) from the TCEQ WAM System serve as a case study for the research reported in this thesis. The research includes assessments of water supply capabilities of the Highland Lakes System operated by Lower Colorado River Authority (LCRA) and three large reservoirs operated by the Colorado River Municipal Water District (CRMWD). However, the objective of the academic research is to expand generic WRAP/WAM modeling and analysis capabilities. The Colorado WAM simulation studies presented in the thesis are not designed to support permit applications or actual water management decisions; do not necessarily represent the views of the TCEQ, LCRA, CRMWD, or any other agency; and do not necessarily address all of the complexities relevant to any specific application.

The WRAP CRM feature can be a highly effective tool for assessing short-term water supply capabilities of reservoir systems. A major part of the research focused on improving short term analysis of seasonal irrigation diversions under conditions of drought. A case study was performed for the Colorado River Basin and irrigation districts operated by LCRA. Chapter III of this thesis documents a comparative exploration of CRM methodologies, including recently developed options, using the Colorado WAM as a case study. Chapter IV presents an investigation of climatic cycles, drought indices and flow persistence from the perspective of potential improvements to CRM in WRAP. A correlation analysis between different indices and naturalized flow volumes was completed to evaluate the suitability of various hydrologic indicators for use in developing CRM probability arrays.

Chapter V presents an illustrative analysis of interruptible supply for curtailment triggers as employed in water management plans (WMPs) based on storage conditions of the Highland Lakes. A modeling strategy is presented for developing relationships between interruptible supply and different curtailment scenarios based on iterative executions of the WRAP/WAM model in long term simulation mode. The effect of off-channel reservoirs of various storage capacities on interruptible supply reliabilities is also analyzed. A summary of the research and integration of CRM and long term simulation modeling as decision support tools for drought management is presented in Chapter VI.

7.1. CRM Options

The equal weight CRM strategy assigns the same probability to each simulation sequence. The probability array option assigns different probabilities to the simulation sequences by using preceding reservoir storage as indicator of hydrologic condition. The equal weight option is relatively easy to understand and use. It provides valid results but tends to provide conservatively low estimates of future storage exceedance probabilities and supply reliabilities for high initial storage conditions (wet conditions) and inflated (high) estimates for exceedance frequencies and reliabilities for lower initial storage conditions (dry conditions).

The probability array methodology is designed to overcome this limitation by weighing the probabilities associated with simulation sequences by relating current hydrologic conditions (as reflected in naturalized flow volume) to preceding total storage content or change in storage content. Potential improvements in accuracy to be achieved by the probability array option require some degree of correlation between preceding storage content and naturalized flow. In case of low correlation, the simpler equal weight approach is probably the better alternative rather than the probability array option.

Storage frequency analyses for several selected major reservoirs in the Colorado River Basin were performed to compare total storage versus change in storage options used in probability array based CRM. The newly added change in storage option showed considerable variability in correlation between naturalized flow volume and change in storage volumes. Shorter periods of naturalized flow volume required longer preceding periods of change in storage and vice versa. The change in storage option did not show any significant variation in end of month storage content at different exceedance frequencies for decrease in storage content (dry hydrologic conditions) as well as increase in storage content (wet hydrologic conditions). The exceedance frequencies for small values of change in storage from initial storage at 50% of total capacity was found to be very close to the exceedance frequencies developed for the total storage option with initial storage at 50% of capacity. Thus, the storage content specified for the start of the CRM simulations had considerable influence on end of month storage content for small values of change in storage option. Significant variations in exceedance frequencies between total storage and change in storage were observed only for large change of storage content within short time intervals.

For the Colorado River Basin, the choice between equal weight and probability array options depend upon the time scale of analysis and the modeling options being considered. Correlations between naturalized flow volumes and preceding storage volumes are small for flow periods of up to about three months and essentially negligible for longer periods. The probability array option could potentially improve frequency and reliability estimates relative to the equal-weight option for smaller future time periods of a few months but probably not for longer periods. If the probability array option is adopted, the exponential equation should be used as the regression method for computing the predicted (expected) value of flow Q_S in the storage-flow-frequency (SFF) array computations.

For analysis periods over longer time scales, storage-flow correlation values are insignificant for the Colorado WAM and employing the equal weight option makes modeling simpler. There is a slight variation in end of month storage capacities between the two options when initial storage conditions are less than 50% of capacity. Hence, equal weight option could be used when total storage conditions are greater than 50% of capacity. The storage frequency analysis for major reservoirs shows small difference in end of month storage capacity.

The flow frequency (FF) array option was reviewed but not included in the analysis results presented in the thesis. In computing an SFF probability array, the predicted (expected value) flow volume for the months defining the SFF may be set equal to the long-term mean without consideration of preceding storage conditions. In this case, the SFF probably array method as well as the FF array and equal-weight methods reflect the premise of equal probabilities for all of the simulation sequences. With the predicted flow set equal to the long-term mean, the SFF array method yields exactly the same results at the FF array method. Though also conceptually based on equal probabilities, the equal-likely array method results are slightly different due to the details of the computations. However, the SFF option allows the predicted (expected value) flow volume for the months defining the SFF relationship to be computed based on regression of flow volume with storage, which results in assigning different probabilities to each of the hydrologic simulation sequences. The SFF array methodology also allows the expected value of flow to be multiplied by a factor determined based on information regarding climate cycles or other considerations.

7.2. Hydrologic Indicators Analysis

The climate indices analyzed in the study do not show clear improvement over storage in developing a SFF array for CRM. The ENSO indices are slightly better correlated to flow volume than storage but exhibit seasonal variability. Its correlation values are also lower than that of other indices that are compared in the thesis.

ONI and SOI are standardized indices based on SST and pressure differences, respectively. As such, the index values differ based on standardization routines used, which does affect the correlation values. For example, the correlation coefficients will likely be different for SOI index maintained by NOAA and BOM, Australia. Hence a better option could be to use raw SST and pressure differential data. Wei and Watkins (2011) analyzed SOI index and derived SST index with streamflow and found that the derived SST index related to ENSO and PDO improved unregulated flow forecasts for winter spring and summer. Piechota and Dracup (2001) also analyzed the SST series and SOI index and their combinations to forecast streamflows in Australia. They found combined persistence with SST or SOI to be a good predictor for summer.

The correlation analysis presented in Chapter VI uses concurrent values of indices which may not be able to capture lags between climate phases and their effect on streamflows. The thesis study also analyzed only two indices for ENSO and both showed considerable differences. Other indices of ENSO constructed with different climatic variables and different methods of standardization could potentially give different results. The NAO index used did not show better correlation with naturalized flows than storage.

The Palmer Drought Severity Index (PDSI) showed significant higher correlation values than climate patterns for almost all seasons for periods of 1, 2 and 3 months. PDSI being a drought index is directly related to precipitation and soil moisture content. The PDSI values are also localized with index values differing based on the location of the reservoir, whereas the climate pattern indices are computed for variables not directly related to local hydrologic conditions. PDSI is also able to incorporate climate pattern effects as well as lag between climate anomalies and their actual effect on local weather conditions. However, PDSI is a meteorological drought index and it may not completely explain lag between meteorological and hydrological conditions. The Palmer Hydrologic Drought Index (PHDI) could potentially perform better in comparison to PDSI as it is a hydrologic drought index and is closely related to streamflow.

Naturalized streamflow is significantly better correlated than all of the other indices. It has higher correlation values for almost all seasons and all time periods. Naturalized streamflow is a better indicator of hydrologic conditions than storage levels and could improve reliability and frequency analysis for CRM. However, only up to 12 month flow volumes were analyzed and for longer time periods other indices could be the better option. For longer time periods, effects of storage and naturalized flow persistence is likely to disappear and climatic pattern indices could prove to be better indicators. Also linear correlation was used to evaluate all the indicators, more sophisticated statistical analysis considering nonlinear relationships could provide more accurate results.

The teleconnection patterns and PDSI sowed large variation in correlation coefficients depending upon the period of analysis and location of the control points. Hence, the direct use of different indices to develop SFF by replacing storage with index values was found to be unreliable. The use of naturalized flow values for current time period can yield better results, but naturalized flow volumes are not actually observed or measured and are not readily available outside of the WRAP/WAM datasets and thus are inconvenient for real time applications of CRM.

The newly added QX multiplication factor option in WRAP can be helpful in incorporating the effects of teleconnection patterns. The QX option allows the model user to increase or decrease the expected (predicted) value of naturalized flows used in the SSF array computations by a multiplication factor, which allows the probabilities associated with each CRM hydrologic simulation sequence to be adjusted. However, determining the multiplication factor will require further studies about the effects of teleconnection patterns for the location and period of analysis being considered.

7.3. Interruptible Supply Reliability Analysis

Interruptible supply from Highland Lakes system is getting more complicated with changing hydrologic and water use scenarios. With each update of the WMP by LCRA, the criteria for interruptible supply gets more intricate and the curtailment triggers can be difficult to comprehend. The comparative study of firm and interruptible supply for different hypothetical curtailment triggers can provide some assistance in understanding relationships between firm and interruptible supply.

The modeling methodology reflected in the reliability graphs for interruptible supply presented in Chapter IV can be used as a tool to inform water managers and users regarding water supply capabilities. The reliability graphs provide a picture of variations in volume reliability for interruptible supply at different curtailment triggers as well as the maximum diversion amount possible under the same curtailment triggers. The graphs show only slight variation in volume reliability for proportional curtailment of interruptible supply. Large reductions in volume reliability is experienced only when proportional curtailment is removed. Hence, proportional curtailment can be an effective strategy for providing reliable interruptible supply under drought conditions.

The reliability graphs provide information about how much water to expect at different curtailment levels. This information could contribute to more informed decisions regarding water use. Such graphs can also be employed as decision support tool for water supply planning and management, as in the case of WMPs.

As evidenced by reliability graphs in section 5.5, the addition of off-channel reservoir storage (OCR) shows improvements in reliabilities for all irrigation districts. The improvements in reliability are dependent upon storage volumes. Smaller volumes OCR storage capacity relative to diversion targets provide only marginal improvement in reliability in comparison to larger storage capacities.

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APPENDIX A

Equal weight and probability array storage frequency values developed for major reservoirs without conservation capacity are as follows.

Table A.1. Equal Weight Storage Frequency for O.H. Ivie Reservoir

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	85.17	69.96	61.61	42.22	64.53	42.98	21.16	1.80
98	85.38	70.15	61.81	42.39	65.24	43.55	21.57	1.95
95	85.84	70.57	62.23	42.75	66.29	44.43	23.58	4.71
90	87.18	71.80	63.47	43.80	70.88	47.19	25.62	6.70
80	87.99	72.54	64.21	44.42	72.86	52.38	29.46	10.62
70	88.95	73.40	64.53	44.75	74.58	57.46	35.14	17.37
60	89.78	74.34	65.59	45.53	77.23	61.3	38.58	21.49
50	90.8	75.44	66.19	46.12	80.60	64.02	41.26	26.24
40	92.17	77.02	68.54	50.09	82.57	67.65	43.87	29.15
30	92.74	79.68	71.42	55.31	88.61	71.53	47.50	33.42
20	95.29	83.01	75.37	60.98	92.85	78.30	52.19	37.51
10	97.52	90.47	84.86	75.16	100	87.14	63.86	42.04

Table A.2. Equal Weight Storage Frequency for E.V. Spence Reservoir

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	89.85	84.75	91.73	89.39	75.87	54.41	36.67	30.3
98	90.02	84.94	91.99	89.70	76.11	54.52	36.77	30.48
95	90.53	85.32	92.45	90.14	78.04	55.37	37.53	31.33
90	91.19	85.72	93.00	91.07	78.84	56.00	37.95	32.01
80	92.18	86.95	94.53	92.69	80.02	57.01	38.77	32.92
70	92.68	87.39	95.13	93.74	81.45	57.82	39.46	33.95
60	93.1	87.81	95.57	94.36	83.83	58.68	40.18	34.73
50	93.54	88.07	95.96	94.78	85.48	59.28	40.59	35.37
40	93.99	88.45	96.45	95.21	87.35	59.97	41.18	36.11
30	95.04	88.86	96.88	95.82	89.96	61.22	41.73	36.54
20	96.00	89.33	97.52	96.60	93.79	63.22	43.06	38.24
10	97.46	89.79	98.09	97.29	99.82	77.09	50.35	50.39

Table A.3. Equal Weight Storage Frequency for Lake J.B. Thomas

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	85.63	85.48	86.99	80.43	65.42	52.02	39.26	10.54
98	85.98	85.89	87.54	81.37	65.8	52.42	39.78	11.31
95	86.81	86.73	88.4	82.17	67.24	53.23	40.82	12.57
90	87.52	87.52	89.37	83.57	68.77	55.03	42.47	13.75
80	88.43	88.48	90.54	85.78	70.14	56.14	43.38	14.42
70	89.64	89.76	92.21	87.51	72.13	57.27	44.79	15.94
60	89.97	90.21	92.61	88.35	74.16	58.24	45.54	16.85
50	90.56	90.92	93.44	89.53	75.3	58.82	46.66	18.46
40	91.31	91.35	94.10	90.8	77.62	60.47	47.92	19.02
30	92.72	91.69	94.74	91.91	79.05	61.89	49.00	19.71
20	93.5	92.52	95.54	93.19	82.74	63.92	50.15	21.6
10	95.64	94.04	97.14	95.04	92.62	76.43	66.95	26.32

Table A.4. Total Storage Probability Array Storage Frequency for O.H. Ivie Reservoir

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	84.97	69.78	61.42	42.06	63.38	42.35	20.93	1.41
98	85.24	70.03	61.68	42.29	64.95	43.21	21.25	1.94
95	85.66	70.41	62.06	42.6	65.82	44.27	23.34	3.61
90	87.1	71.73	63.41	43.75	70.66	47.1	25.57	6.66
80	87.98	72.53	64.18	44.42	72.62	52.33	29.23	10.15
70	88.93	73.25	64.51	44.71	74.11	56.55	34.23	17.15
60	89.74	74.34	65.57	45.50	77.22	61.28	38.42	21.49
50	90.76	75.33	66.17	46.09	80.43	63.98	41.07	26.17
40	91.7	76.90	68.51	48.82	82.46	66.73	43.79	28.06
30	92.72	79.64	71.33	55.27	88.57	71.31	47.35	33.35
20	95.17	82.9	75.07	60.91	92.43	77.21	52.16	37.41
10	96.9	88.52	82.57	73.58	100	86.05	59.17	41.86

Table A.5. Total Storage Probability Array Storage Frequency for E.V. Spence Reservoir

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	89.67	84.57	91.5	89.11	75.85	54.14	36.51	30.26
98	89.92	84.82	91.81	89.5	75.87	54.51	36.73	30.31
95	90.4	85.32	92.36	89.99	77.74	54.96	37.14	30.93
90	91.18	85.60	92.88	91.06	78.82	55.98	37.90	31.98
80	92.1	86.94	94.53	92.60	79.76	56.95	38.75	32.79
70	92.65	87.37	95.09	93.71	81.43	57.62	39.38	33.91
60	93.08	87.80	95.56	94.31	83.82	58.65	40.17	34.68
50	93.51	88.06	95.96	94.75	85.45	59.27	40.51	35.35
40	93.75	88.43	96.39	95.20	87.31	59.78	41.1	36.1
30	95.03	88.85	96.88	95.81	89.89	61.21	41.72	36.53
20	95.95	89.33	97.48	96.49	93.79	62.81	43.05	38.19
10	97.09	89.71	97.98	97.27	99.4	76.18	49.62	43.18

Table A.6. Total Storage Probability Array Storage Frequency for Lake J.B. Thomas

Exceedance Frequency (%)	Beginning of July Storage as percentage of capacity							
	100	75	50	25	100	75	50	25
	End of September storage (% capacity)				End of June storage (% capacity)			
99	84.92	84.64	85.88	78.52	64.54	51.30	38.42	9.52
98	85.89	85.79	87.4	81.14	65.75	52.29	39.57	10.92
95	86.61	86.5	88.14	81.83	66.53	52.96	40.54	12.47
90	87.52	87.51	89.29	83.27	68.67	54.98	42.4	13.72
80	88.43	88.42	90.49	85.73	70.11	56.1	43.32	14.36
70	89.56	89.69	92.16	87.44	71.93	57.01	44.48	15.62
60	89.96	90.2	92.61	88.33	74.11	58.22	45.53	16.84
50	90.49	90.89	93.36	89.52	75.23	58.80	46.64	18.32
40	91.28	91.3	94.05	90.64	77.6	60.45	47.75	18.96
30	92.72	91.69	94.72	91.86	79.04	61.88	48.99	19.70
20	93.48	92.51	95.49	93.19	81.86	63.69	49.72	21.56
10	95.36	93.82	97.02	94.93	90.34	74.5	64.64	25.27

Reliability tables developed for Highland Lakes are presented below. The reliability values for scenarios with and without OCR are presented in the Tables A.7 to A.11.

Table A.7. Volume Reliability for Garwood Irrigation District

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)					
		No Reservoir	1000	10000	20000	40000	75000
0>	81	99.92	99.93	100	100	100	100
<0-0.2>	81	99.92	99.93	100	100	100	100
<0-0.4>	83	99.92	99.92	100	100	100	100
<0-0.6>	88	99.90	99.91	99.99	100	100	100
<0-0.8>	89	99.90	99.90	99.98	100	100	100
<0-1.0>	91	99.89	99.90	99.98	100	100	100
<0-1.2>	94	99.88	99.89	99.97	100	100	100
<0-1.4>	98	99.87	99.88	99.95	100	100	100
<0.1-1.4>	100	99.87	99.87	99.95	100	100	100

Table A.7. Continued

<0.325-1.4>	104	99.85	99.86	99.93	100	100	100
<0.6-1.4>	111	99.8	99.81	99.9	99.97	100	100
<0.8-1.4>	116	99.75	99.76	99.86	99.95	100	100
<1.0-1.4>	122	99.68	99.70	99.80	99.91	100	100
<1.2-1.4>	134	99.53	99.53	99.68	99.79	99.99	100
<1.4>	134	99.53	99.55	99.67	99.77	99.98	100
<1.6>	173	98.94	98.99	99.16	99.29	99.48	99.77
<1.8>	173	98.94	98.97	99.14	99.28	99.46	99.76
<2.1	216	98.01	98.02	98.35	98.56	98.87	99.16

Table A.8. Volume Reliability for Gulf Coast Irrigation District

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)					
		No Reservoir	1000	10000	20000	40000	75000
0>	81	78.94	79.12	80.44	81.80	84.18	86.81
<0-0.2>	81	78.94	79.12	80.44	81.8	84.18	86.81
<0-0.4>	83	78.68	78.68	79.94	81.22	83.53	86.26
<0-0.6>	88	77.41	77.55	78.73	79.89	82.16	84.85
<0-0.8>	89	77.21	77.36	78.51	79.64	81.92	84.60
<0-1.0>	91	76.79	76.92	78.07	79.18	81.34	84.06
<0-1.2>	94	76.12	76.25	77.36	78.45	80.59	83.29
<0-1.4>	98	75.32	75.44	76.54	77.57	79.62	82.30
<0.1-1.4>	100	74.97	75.1	76.17	77.18	79.16	81.87
<0.325-1.4>	104	74.48	74.46	75.51	76.5	78.32	81.11
<0.6-1.4>	111	73.24	73.35	74.36	75.28	76.91	79.57
<0.8-1.4>	116	72.53	72.64	73.56	74.5	76.07	78.61
<1.0-1.4>	122	71.66	71.76	72.64	73.58	75.12	77.51
<1.2-1.4>	134	69.86	70.10	70.10	71.73	73.34	75.55
<1.4>	134	69.66	69.75	70.53	71.35	72.89	75.22
<1.6>	173	61.84	62.07	62.71	63.45	64.67	66.43
<1.8>	173	60.90	60.97	61.53	62.72	63.93	65.82
<2.1	215	50.20	50.15	50.93	51.72	53.34	55.59

Table A.9. Volume Reliability for Pierce Ranch Irrigation District

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)					
		No Reservoir	1000	10000	20000	40000	75000
0>	81	81.25	81.58	83.82	84.64	85.84	86.47
<0-0.2>	81	81.25	81.58	83.82	83.82	85.84	86.47
<0-0.4>	83	80.64	80.83	83.13	84.03	85.23	85.94
<0-0.6>	88	78.59	78.93	81.16	82.16	83.29	84.59
<0-0.8>	89	78.26	78.63	80.89	81.93	83.06	84.35
<0-1.0>	91	77.46	77.85	80.30	81.52	82.63	83.92
<0-1.2>	94	76.42	76.78	79.42	80.84	82.12	83.39
<0-1.4>	98	75.21	75.55	78.23	79.85	81.51	82.78
<0.1-1.4>	100	74.67	74.99	77.72	79.37	81.12	82.35
<0.325-1.4>	104	73.86	73.95	76.65	78.45	80.36	81.65
<0.6-1.4>	111	70.91	71.31	74.32	76.56	78.93	80.90
<0.8-1.4>	116	68.29	68.70	71.81	74.26	77.38	79.67
<1.0-1.4>	122	65.11	65.51	68.67	71.33	74.82	77.91
<1.2-1.4>	134	60.69	61.30	64.07	66.79	70.98	75.04
<1.4>	134	60.42	60.77	63.53	66.23	70.44	74.63
<1.6>	173	52.14	52.59	54.87	57.08	60.31	63.88
<1.8>	173	50.9	51.19	53.54	55.88	59.37	63.30
<2.1	215	37.88	38.00	40.53	43.01	47.07	51.71

Table A.10. Volume Reliability for Lake Side 2 Irrigation Supply

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)					
		No Reservoir	1000	10000	20000	40000	75000
0>	81	77.45	78.04	81.43	82.78	84.21	85.32
<0-0.2>	81	77.45	78.03	81.43	82.78	84.21	85.32
<0-0.4>	83	77.11	77.46	80.99	82.43	83.91	85.03
<0-0.6>	88	75.31	75.78	78.92	80.58	82.38	83.50
<0-0.8>	89	75.02	75.51	78.48	80.37	81.65	83.28
<0-1.0>	91	74.39	74.84	78.18	79.84	81.13	82.82
<0-1.2>	94	73.51	74.03	77.49	79.2	80.87	82.37
<0-1.4>	98	72.08	72.54	76.31	78.16	79.74	81.46
<0.1-1.4>	100	71.11	71.60	75.53	77.53	79.34	81.08
<0.325-1.4>	104	69.52	69.51	73.52	76.29	78.28	80.27
<0.6-1.4>	111	65.21	66.79	69.74	72.86	75.92	78.43

Table A.10. Continued

<0.8-1.4>	116	63.00	63.49	67.49	70.84	74.22	77.30
<1.0-1.4>	122	60.95	61.43	65.32	68.75	72.62	76.35
<1.2-1.4>	134	58.59	59.14	62.68	65.83	70.26	74.41
<1.4>	134	58.29	58.68	62.18	65.28	69.81	74.08
<1.6>	173	49.73	50.17	52.76	55.18	58.57	63.51
<1.8>	173	48.34	48.63	51.52	54.26	57.60	62.62
<2.1	215	34.76	37.03	40.21	43.45	48.36	53.59

Table A.11. Volume Reliability for Lake Side 1 Irrigation Supply

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)					
		No Reservoir	1000	10000	20000	40000	75000
0>	81	69.33	69.57	71.59	73.47	76.17	79.07
<0-0.2>	81	69.33	69.57	71.59	73.47	76.17	79.07
<0-0.4>	83	69.23	69.41	71.47	73.3	76.03	78.76
<0-0.6>	88	68.74	68.97	70.92	72.69	75.51	78.21
<0-0.8>	89	68.66	68.87	70.79	72.52	75.31	78.07
<0-1.0>	91	68.04	68.63	70.51	72.22	74.96	77.75
<0-1.2>	94	67.92	68.14	69.98	71.71	74.52	77.14
<0-1.4>	98	67.18	67.39	69.19	70.89	73.69	76.35
<0.1-1.4>	100	66.82	67.03	68.80	70.52	73.33	76.08
<0.325-1.4>	104	66.29	66.36	68.16	69.83	72.53	75.44
<0.6-1.4>	111	64.95	65.15	66.82	68.51	72.53	74.26
<0.8-1.4>	116	64.14	64.34	66.66	67.51	70.16	73.36
<1.0-1.4>	122	63.11	63.31	65.00	66.56	68.95	72.17
<1.2-1.4>	134	60.96	61.34	62.91	64.5	66.89	70.05
<1.4>	134	60.52	60.69	62.21	63.76	66.09	69.56
<1.6>	173	51.22	51.39	52.73	54.49	56.74	59.35
<1.8>	173	49.51	49.65	51.66	53.33	55.78	58.83
<2.1	215	38.14	38.29	40.48	42.52	46.01	50.16

Table A.12. Volume Reliability for Gulf Coast Irrigation District with Lane City Reservoir

Storage Cutoff	Percent Change	Off Channel Storage Capacity (ac-ft)	
		No Reservoir	Lane City
0>	81	78.94	80.49
<0-0.2>	81	78.94	80.49
<0-0.4>	83	78.68	80.00
<0-0.6>	88	77.41	78.76
<0-0.8>	89	77.21	78.63
<0-1.0>	91	76.79	78.23
<0-1.2>	94	76.12	77.55
<0-1.4>	98	75.32	76.75
<0.1-1.4>	100	74.97	76.40
<0.325-1.4>	104	74.48	75.79
<0.6-1.4>	111	73.24	74.66
<0.8-1.4>	116	72.53	73.91
<1.0-1.4>	122	71.66	72.93
<1.2-1.4>	134	69.86	71.00
<1.4>	134	69.66	70.78
<1.6>	173	61.84	63.03
<1.8>	173	60.9	62.39
<2.1	215	50.2	51.86