INCORPORATING AND EVALUATING ENVIRONMENTAL INSTREAM FLOWS IN A PRIORITY ORDER BASED SURFACE WATER ALLOCATION MODEL

A Thesis

by

MARK ALLEN PAULS

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

MASTER OF SCIENCE

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

May 2014

Major Subject: Civil Engineering

ABSTRACT

As the remaining water resources in river basins around the world are appropriated for human uses, it is critical to protect environmental instream flows in order to preserve aquatic and riparian species and ecosystems. It is widely recognized that an adequate environmental flow regime consists of a range of flow conditions. In Texas, a statewide planning process was established in 2007 for determining environmental flow recommendations for the state's river basins. The environmental flow recommendations, which consist of subsistence flows, base flows, and high flow pulse events, are determined for each basin by a team of scientists and committee of stakeholders. The recommendations are considered by the Texas Commission on Environmental Quality (TCEQ) in developing environmental flow standards which are incorporated into the state's prior-appropriation water rights permitting system. The environmental flow standards for the Colorado River basin and Trinity River basin are incorporated in daily time-step versions of the authorized use scenario water availability models using existing and recently added features of the Water Rights Analysis Package (WRAP). Various metrics are developed by this research to characterize the degree to which the environmental flow standards are attained, given their junior position in the priority sequence. The techniques used to model instream flows in the Colorado and Trinity river basins contribute to the body of knowledge for modeling flow standards in other basins. Metrics describing the degree to which environmental flow standards are

attained will assist scientists and decision-makers in the evaluation and revision of the standards.

To Brittany

ACKNOWLEDGEMENTS

My time at Texas A&M has been a blessing and I am grateful to all of the professors I have had in the Department of Civil Engineering along the way. I am especially grateful to those in the Environmental and Water Resources Engineering Division, including Dr. Brumbelow, Dr. Cahill, Dr. Miller, Dr. Olivera, and Dr. Wurbs. Without their dedication as teachers and mentors, I would not have focused in water resources nor had the opportunity to be involved in research.

I would like to thank Dr. Wurbs, Dr. Brumbelow, and Dr. Singh for their involvement in my committee. I would especially like to thank Dr. Wurbs for the opportunity to be involved in his research group and for his guidance as my advisor. I would also like to extend special thanks to Richard Hoffpauir for all the time he set aside to help me and for his interest and advice regarding my research topic.

I would like to acknowledge the Dwight Look College of Engineering and Department of Civil Engineering for funding opportunities that allowed me to pursue a graduate degree as well as the Texas Commission on Environmental Quality.

I would like to thank my wife, Brittany, for her support and encouragement, as well as my family and friends. Finally, I would like to acknowledge my Lord and savior Jesus Christ and give thanks for the grace he has shown me.

NOMENCLATURE

BBASC	Basin and Bay Area Stakeholder Committee
BBEST	Basin and Bay Expert Science Team
EFAG	Environmental Flows Advisory Group
SAC	Science Advisory Committee
SB3	Senate Bill 3 of the 80th Texas Legislature enacted in 2007
TAMU	Texas A&M University
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

1.1 Background

In the past, environmental flows have typically been specified as constant minimum flows. It is now widely recognized that a range of flow conditions are required to maintain healthy aquatic and riparian ecosystems in rivers and streams (TCEQ, TPWD, and TWDB, 2008). A varied environmental flow regime affects the quantity and quality of habitat for a riverine ecosystem, as well as providing numerous functions, as follows (SAC, 2004).

- Varying flow regimes enhance the diversity of flora and fauna by creating diverse habitat conditions.
- Seasonal high flows influence the life cycle events of aquatic organisms and riparian vegetation.
- Elevated flows and high flow events regulate sediment transport and the processes of channel formation and maintenance.
- Water quality is impacted by the variability of a flow regime, particularly during extended periods of low flows.
- Variability in the flow regime affects the longitudinal, lateral, and vertical connectivity of the riverine ecosystem, impacting the movement of nutrients, sediment, organic matter, and nutrients between the river channel, floodplain, subsurface, and estuaries.

The more that a flow regime departs from the natural flow regime, the more likely the riverine ecosystem will degrade over time (Poff et al., 1997). Much work has been done to characterize the ecological response to changes in various components of a flow regime (Poff et al., 2010). Likewise, much work has been done to develop methodologies for quantifying the flow regime components necessary to support a healthy ecological environment, ranging from rigorous methods which require extensive data collection and computer modeling to simple methods based on statistical analysis of hydrologic data (Tharme, 2003), (Colorado BBEST, 2011).

A variety of legal frameworks are employed globally to govern the allocation of surface water among competing users. The prior appropriation doctrine of water allocation is based on the concept of legal ownership of the water resources of a river basin by individual water users who divert or make use of water for a beneficial purpose. Typical examples of beneficial water uses include agriculture, industry, municipal purposes, hydroelectric power generation, recreation, and mining. Under the prior appropriation system, water users claim access to the water resources of a river basin in the form of water rights on a first-come first-serve basis. Individuals who claim water first have the right to their water before any other users in the event of limited available stream flows. In the context of a prior appropriation water rights system, environmental instream flows represent flows which are allocated to remain in the river for the benefit of ecosystems and aquatic species. The protection of environmental flows is particularly important in increasingly regulated river basins in which demands for water are expected to meet or exceed the available supplies.

In Texas, the surface waters of the state are considered a public resource whose allocation is governed by the Texas Commission on Environmental Quality (TCEQ) according to a prior appropriation water rights permitting system, as documented by the Texas Water Code. The permitting system was established gradually over a period of 20 years, beginning in 1967, when the Texas legislature passed the Water Rights Adjudication Act to consolidate the diverse legal frameworks that had historically been used to allocate water (Wurbs and James, 2002). All entities wishing to divert water for a beneficial purpose must obtain a water right permit from the TCEQ. Each permit is assigned a priority date corresponding to either when the permit application was submitted or when the beneficial use of water was first established historically. Water rights with older priority dates (*senior* water rights) have access to water first in the sequence of allocating the available water within a river basin. *Junior* water rights with more recent priority dates may not make any diversions which impair the ability of senior rights in diverting their specified allocations of water. During times of limited water availability, senior water right holders may legally call on upstream junior water right holders to cease diverting water so that adequate flows are available downstream for diversion.

In 1997, the 75th Texas legislature passed Senate Bill 1, which, among other provisions, specified the development of water availability models for each of the state's river basins (Wurbs, 2005). Twenty-one water availability models were developed by various consultants under contract for the Texas Natural Resources Conservation Commission, now the TCEQ. The development of the water availability models consisted of developing basin specific input datasets for the generalized Water Rights Analysis Package (WRAP) modeling program. The WRAP program simulates the priority-based allocation of water dictated by the water rights permitting system using flows that would have been available historically. Based on the assumption that historical hydrology represents a reasonable approximation of future hydrologic conditions in a river basin, the results of a simulation may be used to provide information about alternate scenarios of river basin development, such as the expected reliability of a proposed new water right permit or the effect of a new permit on the reliabilities of existing water rights. Two scenarios of river basin development commonly analyzed are the authorized use scenario (Run 3) and current use scenario (Run 8). In the authorized use scenario, water rights are assumed to divert their full permitted amount with no return flows and reservoirs are assigned their full conservation capacities from the date they were constructed. In the current use scenario, water right diversions are specified based on the maximum diversions recorded in a recent ten year period. Return flows are included and reservoir storage is determined based on available data from sedimentation surveys performed around the year 2000. Datasets for Run 3 and Run 8 are maintained by the TCEQ. The WAM system is used by individuals in the development of new water right permit applications, the TCEQ in the evaluation of new permit applications, and the Texas Water Development Board (TWDB) and other public or private agencies for water supply planning and other investigations. WRAP program *SIM* operates using a monthly time-step. Additional features have recently been added to

WRAP to enable simulation using a daily time-step, including specific features for modeling environmental instream flows and flood control operations.

Recently, the State of Texas has developed a process for specifying and protecting environmental instream flows and bay and estuary freshwater inflows for the rivers basins and estuaries of the state. In 2003, the 78th Texas legislature passed Senate Bill 2, establishing the Texas Instream Flow Program (TIFP). Under this program, the Texas Parks and Wildlife Department (TPWD), TWDB, and TCEQ were tasked with determining the environmental instream flows and bay and estuary inflows for each of the river basins of the state necessary to support a sound ecological environment, defined as “a resilient, functioning ecosystem characterized by intact, natural processes and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region” (TCEQ, TPWD, TWDB, 2008). A science advisory committee was formed to assist in the evaluation and incorporation of current research in the determination of flow recommendations. One result of the instream flow program was the determination that a flow regime adequate to support a sound ecological environment consists of four components: subsistence flows during drought or periods of extended low flows, base flows during normal hydrologic conditions, short-duration high flow pulses following storm events, and overbank flow events during floods.

In 2007, the 80th Texas legislature passed Senate Bill 3 (SB3), outlining a process for establishing environmental flow standards for the state’s river basins to be incorporated in the water rights permitting system (Texas Water Code Title 2, Subtitle B, Chapter 11). An environmental flows advisory group (EFAG) was appointed by the

Governor, Lieutenant Governor, and members of the House of Representatives. The EFAG defined the boundaries of the basins and bays to be considered and selected members of a science advisory committee (SAC) and the basin and bay area stakeholder (BBASC) committees. The BBASC committees selected members for basin and bay area science teams (BBEST). For each basin, the BBEST developed an initial environmental flow recommendations report based on the best available science considering environmental interests only. The BBASC developed a separate recommendations report based on information provided by the BBEST and expected future needs for human water use. The TCEQ, considering both environmental and human water needs, reviewed the BBEST and BBASC reports and established environmental flow standards that were incorporated in the state water rights permitting system at a priority date corresponding to the submission date of the initial BBEST report. Currently the environmental flow standards are junior to most other water rights and hence will only limit water availability for future permits and major amendments to existing permits. The standards are required to be revised a minimum of once every ten years as part of an adaptive management process that reflects technical and scientific advancements. Although flow recommendations and standards were established separately for each basin, a common framework was employed for defining environmental flow standards. In accordance with results of the TIFP and work of the SAC, initial flow regime recommendations incorporated subsistence flow, base flow, high flow pulse, and overbank flow components, which could optionally be defined to reflect seasonality and hydrologic conditions.

1.2 Problem Identification

The incorporation of environmental flow standards in the Texas WAM system is a key step to their inclusion in the water rights permitting system. In order to properly represent the variability with which various flow components are engaged, in particular the engagement of high flow pulse events, a daily temporal resolution is required, necessitating the development of daily time-step water availability models, as identified in the Colorado and Trinity BBASC work plans (Colorado BBASC, 2012), (Trinity BBASC, 2012). The exploration of techniques for modeling environmental flow standards using recently added features of WRAP is necessary to assist the water management community in the proper incorporation of environmental flow standards in the state WAM system.

Because the priority dates of the flow standards are junior to a large number of existing water rights, it is important to develop metrics for characterizing the degree to which the recommended flow standards are attained under junior regulated flow conditions. In the existing water availability models, the degree to which a water right achieves its target diversion is described by frequency and reliability metrics based on the percentage of time a target is met or the percentage volume that is achieved. This approach for describing the attainment of target diversions is amenable to water rights with constant diversion targets. Some adjustments will be required to evaluate similar statistics for variable targets, such as subsistence and base flow targets that vary by season and hydrologic condition, or targets that are set intermittently, such as high flow pulse event targets.

It could also be helpful for scientists and decision-makers to evaluate other metrics related to the engagement of various components of the specified flow regime. For high flow pulse events, for example, it may be worthwhile to characterize the distribution of time between pulse events or the expected time within a season in which pulse events are typically engaged. For subsistence and base flows, it could be useful to assess the distribution of the consecutive number of days for which flows fall below or exceed a given flow value.

Traditional and new flow metrics used to characterize the attainment of various components of a recommended flow regime will help the science teams, stakeholder committees, and TCEQ in the evaluation and revision of the environmental flow standards. Attainment metrics would also enable the possible development of risk assessment frameworks for characterizing tradeoffs between alternative water allocation scenarios. If efforts are made to improve the attainment of flow standards through the purchase of water rights or other methods, the relative performance of alternative scenarios could be more easily assessed using attainment metrics.

1.3 Literature Review

1.3.1 Incorporation of Environmental Flows in River/Reservoir System Models

Environmental instream flows have been incorporated in numerous simulation models developed for specific river/reservoir systems. Palmer and Snyder (1985) incorporated monthly minimum environmental flows into a computer model of the Seattle water supply system to evaluate the tradeoffs between the performance of the water supply system and specified levels of environmental flows. Gippel and

Stewardson (1995) used the Melbourne Water Corporation water supply simulation model to evaluate the impact of minimum monthly environmental flow requirements on water supply availability. Hughes and Ziervogel (1998) developed a model to simulate daily reservoir conditions for evaluating the effects of reservoir operating rules on demands for abstractions at the reservoir and downstream environmental flow needs. Environmental flow needs were specified as minimum monthly low and high values for maintenance and drought conditions. Pearsall et al. (2005) developed a daily time-step mass balance linear programming model to evaluate the effects of reservoir operations on tree species establishment downstream, related to the frequency and duration of flow events causing inundation of riparian areas during the growing season. Butler (2011) incorporated daily operating requirements for two reservoirs in a monthly time-step planning model for the Colorado River Basin. The daily operating rules reflected environmental flow requirements for base flows and flood flow pulses, which varied based on annual hydrologic conditions. Various flow deviation metrics were evaluated to characterize the expected reliability for meeting the environmental flow requirements.

Optimization techniques have been implemented in several studies to characterize the tradeoff between environmental flow needs and needs for other water uses. Sale et al. (1982) implemented a linear decision rule modeling technique to optimize the operation of a reservoir for traditional water supply objectives and instream flow needs. The objective function for instream flow needs was based on weighted usable area of physical habitat. Cardwell et al. (1996) developed a multi-objective optimization model to characterize the tradeoffs between water supply shortages and fish population capacity in a stream on the west-slope of the Sierra Nevada mountain range. Harman and Stewardson (2005) evaluated a range of reservoir release rules to determine the optimum set of rules for meeting downstream environmental flow requirements, including consideration of tributary inflows below the dam. The environmental flows included seasonal base flows and pulse flows for the Thomson River catchment in Victoria, Australia. Suen and Eheart (2006) used a non-dominated sorting genetic algorithm to find the Pareto set of reservoir operating rules describing the tradeoff between human needs and environmental flow needs. Environmental flow needs were specified by maximizing an ecosystem needs objective function consisting of six equally weighted parameters selected from Fuzzy Gaussian membership functions, including the coefficient of efficiency of the yearly trend of the hydrograph, the dry season ten-day minimum flow, the wet season three-day maximum flow, the number of high flow events, the mean duration of low-flow events, and the wet season rising rate.

Several papers describe the incorporation of environmental instream flows in generalized river/reservoir system water management models. Vogel et al. (2007) implemented a variety of operating rules for multiple reservoirs in a Water Evaluation and Planning (WEAP) model to characterize the relationship between reservoir storage, instream flow, and water supply yield. The “seasonal ecodeficit/ecosurplus” concept, based on analysis of the flow duration curve, was introduced as a simple metric for evaluating the impact of reservoir operations on the environmental flow regime. Palmer (2008) described the manner in which a computer model developed using the Operational Analysis and Simulation of Integrated Systems (OASIS) assisted decision-makers in evaluating alternative river basin development scenarios proposed by the Tennessee Valley Authority for the Duck River, including considerations for future demands and ecosystem health requirements. Gippel et al. (2009) incorporated preferred environmental flow recommendations into a daily time-step Integrated Quality and Quantity Model (IQQM). Using various approaches for assessing the degree of compliance of a flow series with a specified flow regime, a risk assessment approach was used to derive sub-optimal environmental flow regimes. Compliance metrics implemented in the analysis included the frequency of occurrence of high flow pulse events compared to the required frequency, the percentage of years in which all environmental flow components were satisfied, the percentage of time periods of a specified length in which the frequency requirement of a flow component was met, and the percentage of time periods of a specified length for which flows exceeded a specified value a specified percentage of time. Sandoval-Solis and McKinney (2009) incorporated environmental flow requirements in a monthly time-step WEAP model for the Rio Grande/Bravo river basin. The environmental flows consisted of annual "maintenance" and "drought" volumes at five locations. Performance criteria were used to evaluate the achievement of the flows, including metrics for reliability, resilience, and vulnerability. In another paper, Sandoval-Solis and McKinney (2014) incorporated base flows and small flood flows specified according to reservoir storage levels into a monthly time-step WEAP model. Podger et al. (2010) proposed methods for modeling complex environmental flow requirements for basin-scale planning using IQQM, including the incorporation of multiple levels of high flow pulse specifications based on magnitude, frequency, and duration requirements. Black and Podger (2012) developed guidelines for modeling water sharing rules, including common performance metrics to consider for environmental flows such as the frequency and duration of inundation events for wetland areas as well as the duration of intervals between events. The relevance of assessing the likelihood of successful implementation of environmental flow rules was emphasized in the context of risk assessment.

1.3.2 Environmental Flow Modeling Features of Generalized River/Reservoir System Models

Most generalized river/reservoir system water management models include options for incorporating environmental instream flow requirements, however, the complexity with which an environmental flow regime may be specified and evaluated varies greatly between modeling systems. At a minimum, environmental flows are specified as minimum monthly flow targets and evaluated according to the percentage of target volume that is achieved or percentage of time steps in which the target is met. At the other end of the spectrum, environmental flows are specified as a complex flow regime consisting of several components which vary by season and hydrologic condition which are evaluated according to multiple statistical metrics. Common generalized, user-oriented river/reservoir system water management models are described as follows, with an emphasis on available options for incorporating and evaluating environmental instream flows.

The USACE Hydrologic Engineering Center Reservoir Simulation model (HEC-ResSim) is a publicly available program used to simulate multiple-purpose, multiple reservoir systems for real-time decision support or planning studies (Wurbs, 2012). A time-step of 15 minutes to one day may be used. Multiple routing methods are available, including Muskingum, Muskingum-Cunge, and modified Puls. Base flows are used in the model as default reference flow values for calibrating routing parameters (USACE-HEC, 2007). A new pulse flow option allows unique pulse flow levels for different locations to be defined for use in routing computations for reservoir releases (USACE-HEC, 2007). Flow summary reports may be developed for specific locations, listing the average, maximum, and minimum flows from the simulation.

The Hydrologic River Operations Study System (HYDROSS) is a general purpose planning and operations simulation model developed by the U.S. Bureau of Reclamation which operates sequentially through time, space, and priority (TAMU and USBR, 2007). A monthly time-step is utilized. Instream flow demands may be specified at a location in conjunction with demands for diversions.

The Integrated Quality and Quantity Model (IQQM) is a river system model used for planning and evaluating water resource management policies that was developed by the Department of Land and Water Conservation in New South Wales, Australia (Podger and Beecham, 2003). Water movement through a link-node system is simulated, including reservoir operations and allocation to various resources. It is designed to operate at a daily time-step. Routing computations are performed using the Muskingum method or a non-linear method with lag. Wetland and environmental flow requirements can be specified to reflect wetland replenishment and riparian flow requirements, including complex multi-tiered flow regimes and pulse flows specified based on magnitude, frequency, and duration. Statistical metrics for analyzing output include mean, standard deviation, skewness, coefficient of determination, and coefficient of efficiency. Graphical analysis of output includes continuous, histogram, cumulative, ranked, frequency, residual mass, and scatter plots.

MIKE BASIN, a proprietary program developed by the Danish Hydraulic Institute, is a generalized river/reservoir system simulation model used for river basin planning and management. Movement of natural flows are simulated in a river system network, including routing, reservoir operations, water allocation for various purposes, ground water interactions, and water quality from point or non-point sources (TAMU and USBR, 1999). The model operates within ArcGIS at a daily or monthly time scale. Environmental flows can be incorporated as minimum flow requirements at nodes.

MODSIM is a general purpose river/reservoir system simulation model based on network flow linear programming that was developed at Colorado State University (Wurbs, 2012). An objective function is used to assign relative priorities to alternate operating objectives, with the linear programming problem solved individually for each time-step without consideration of previous or future time steps. Daily, weekly, or monthly time steps may be used, with lag flow routing implemented for daily time-step simulations. Instream flows are simulated as demands with 100% return flows and no lag (Labadie, 2010). The instream flow demand can be established within the priority sequence or set as a percentage of the flow at a node. The output from alternate scenarios can be compared using flow duration curves and statistical metrics, including reliability, resiliency, vulnerability, maximum, minimum, average, sum, count, standard deviation, and variance.

The Operational Analysis and Simulation of Integrated Systems (OASIS) model is a proprietary program developed by HydroLogics, Inc. which operates using a linear programming solver in which operating rules for reservoirs or components of the node-arc river system are specified as goals and constraints (Wurbs, 2012). Daily, weekly, and monthly time steps are standard, with flexibility for using any time-step between 5 minutes and one year (HydroLogics, 2009). Environmental instream flows can be described by specifying a minimum target flow in an arc.

The River Basin Simulation Model (RIBASIM) is a proprietary program developed by Deltares which is used to support water resources planning and management. Reservoir operations and allocation of available water are simulated in a link-node river system at a monthly time-step with the assumption that all water flows to the outlet within the time-step. For large river basins, or smaller time-step simulations, some hydrologic routing options are available. Environmental flows are incorporated as water demands and can be specified as fixed or variable low flow requirements or specified using an “event-driven flow module” related to the desired magnitude and frequency of peak discharges (Meijer, 2011).

RiverWare is a river/reservoir system model developed at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado. It primarily simulates volume balances at reservoirs, hydrologic routing in river reaches, losses (including evaporation), diversions, and return flows using pure simulation, rule-based simulation, or optimization based on linear programming and preemptive goal programming (Wurbs, 2012). Daily and hourly time steps are utilized in support of real-time reservoir operations and daily operations. Longer time steps are used for long-term planning and mid-term operations (Wurbs, 2012). Environmental flows are included using instream flow rights (with assigned priority dates) within the instream flow account (CADSWES, 2013). “Control Point Object Methods” can be used to set the instream flow target “Initial Request”, including targets based on upstream reservoir storage (CADSWES, 2013). Shortages are determined for flows less than the initial request.

The Water Evaluation and Planning (WEAP) System, developed as an initiative of the Stockholm Environmental Institute, is a river/reservoir system water balance accounting model which allocates available surface and ground water resources among various demands (Wurbs, 2012). It is designed to be used for comprehensive planning, scenario analysis of alternate development scenarios, evaluation of demand management, and environmental assessments related to water quality (Sieber and Purkey, 2011). The model is flexible to operate at daily, weekly, monthly, or annual time steps. Environmental instream flows can be specified as minimum monthly flow requirements. Output related to characterizing the attainment of environmental flows includes the instream flow requirement delivered, the unmet instream flow requirement, the instream flow requirement coverage (ratio of the amount delivered divided by the flow requirement), and flow requirement reliability (percentage of time steps in which a flow requirement demand was fully satisfied) (Sieber and Purkey, 2011).

The Water Rights Analysis Package (WRAP) is a publicly available program developed at Texas A&M University that simulates water resources development, management, regulation, and use in a river basin according to a priority-based allocation system (Wurbs, 2012). The model has typically been applied using a monthly time-step, however, recently added features, including flow forecasting, routing, and disaggregation of monthly flows to daily, enable the use of a daily or other sub-monthly time interval. In a monthly simulation, environmental instream flows are specified using an instream flow (*IF*) record, which can optionally be modified using a variety of records (Wurbs, 2013). Intermediate target setting water right (*WR*) records can also be used to develop complex instream flow requirements. In a daily simulation, pulse flow (*PF*) and pulse flow options (*PO*) records may be implemented in addition to instream flow records (Wurbs and Hoffpauir, 2013). Pulse flow and pulse flow options records enable the development of complex pulse flow targets, including criteria for pulse event initiation and termination, frequency, and tracking. Options are also available for aggregating instream flow targets developed in a daily simulation to monthly totals for use in a monthly simulation. The WRAP post-processing program *TABLES* may be used to develop tables or plots of time series for variables of interest as well as frequency and reliability metrics for variables of interest.

The WRAP program has been applied extensively in Texas as a result of the development and application of water availability models for the river basins of the state. In general, environmental flows have typically been incorporated in the WAMs as constant minimum target flows used to protect existing instream environmental or other purposes or downstream senior water rights (SAC, 2004).

1.3.3 Modeling Techniques and Metrics Related to SB3 Environmental Instream Flows

Since the development of SB3 multi-tiered environmental flow requirements for the State's river basins, a variety of techniques for incorporating and evaluating the environmental flow requirements in water availability models have been explored. A 2010 report by the Science Advisory Committee entitled *Consideration of Methods for Evaluating Interrelationships between Recommended SB-3 Environmental Flow Regimes and Proposed Water Supply Projects* describes several test cases of methods for incorporating environmental flow requirements in water availability models.

A spreadsheet developed by HDR, Inc., termed HDR-1, assessed the impact of a single multi-tiered environmental flow regime on the yield of a single reservoir. Daily reservoir operations were simulated, including daily pass-through requirements for the reservoir that were derived from monthly WAM regulated and unappropriated flows distributed using a gaged daily flow pattern. The spreadsheet was able to handle subsistence and base flows and three levels of high flow pulse events, varied by season and hydrologic condition, with hydrologic conditions provided as input. A second spreadsheet developed by HDR, Inc., termed HDR-2, was used to sum daily reservoir environmental flow pass-through volumes from the HDR-1 spreadsheet to monthly values for incorporation in a monthly WAM simulation.

The TWDB developed a spreadsheet and process for characterizing the effect of environmental flow requirements on proposed future projects. Environmental flow pass-through requirements were determined in an analysis of daily flows derived from monthly regulated flows from a WAM simulation which excluded the proposed future projects. The pass-through requirements were then summed to monthly values for incorporation in a monthly WAM simulation that included the proposed future projects. High flow pulse and overbank flows were identified using the Indicators of Hydrologic Alteration program.

AECOM also developed a spreadsheet and process for evaluating the impacts of environmental flow requirements on proposed future projects. Monthly regulated flow volumes from a WAM simulation were compared to monthly volumes of environmental flow components to determine monthly pass-through volumes for incorporation in a monthly WAM simulation which included the proposed future projects. Hydrologic conditions in the simulation were determined based on storage in a reservoir.

Consulting engineer Kirk Kennedy developed a monthly WAM in which pass-through requirements were determined within a monthly simulation, including code to track the attainment frequencies for high flow pulse and overbank flow events. Subsistence flows, three base flow levels varied by season, three high flow pulse levels varied by season, and overbank flows were incorporated in the model, with hydrologic conditions determined based on total reservoir storage in the basin.

After reviewing the test cases, the SAC provided guidelines for evaluating interrelationships between recommended environmental flow regimes and proposed future water supply projects. Among other guidelines, the SAC concluded that compliance information related to the attainment of environment flows is important for the BBASCs and TCEQ in the process of balancing environmental and human water needs. The SAC also concluded that daily flows provide a more accurate representation of environmental flow components compared to monthly flows.

Metrics used to describe the attainment of various components of a multi-tiered flow regime are documented in two presentations by the TWDB for SB3 BBEST environmental flow recommendations for the Trinity and San Jacinto river basins (TWDB, 2010a), (TWDB, 2010b). For subsistence and base flows in the San Jacinto River Basin, the attainment frequency was determined using monthly WAM output converted to a daily pattern. Attainment of pulse flows was characterized by the number of events satisfying peak, volume, and duration criteria as well as peak pulse event criteria only using monthly WAM output converted to a daily pattern. For base flow recommendations in the Trinity River Basin, BBEST attainment frequency values were compared to flow duration plots of WAM output. For pulse events, tables were developed to list the total number of events recorded, the number of years in which the pulse event criteria were met, and the percentage of time within the period of record that the criteria were met. The need for "more sophisticated pulse analysis" was identified.

Other efforts have also been made to incorporate complex environmental flow regimes in water availability models. The October 2012 authorized use scenario Trinity WAM includes the environmental flow standards established by TCEQ at four control point locations, including seasonally varying subsistence and base flows and seasonally varying high flow pulse requirements. The environmental flow requirements are modeled using a monthly time-step. The SB3 environmental instream flow requirements are incorporated in the Trinity WAM using 44 water right and 36 instream flow records. Several accounting control points and water rights are used as logic for setting applicable instream flow targets based on monthly flow conditions. If the monthly regulated flow is less than the applicable monthly base flow target volume, then an instream flow target is set equal to the monthly subsistence flow volume. If the monthly regulated flow exceeds the applicable monthly base flow target volume, then an instream flow target is set equal to the monthly base flow volume. If the monthly regulated flow exceeds the applicable monthly target volume associated with engagement of a high flow pulse event and less than two pulse events have been engaged within the season, then an instream flow target is set equal to the monthly volume associated with engagement of a high flow pulse event. The volume associated with engagement of a high flow pulse event is equal to the specified pulse event volume criterion plus the monthly base flow volume minus the fraction of monthly base flow volume that occurred during engagement of the pulse event.

Wurbs and Hoffpauir (2013) describe recently added WRAP instream flow modeling capabilities, including instream flow modeling examples and a case study application to the Brazos WAM in the report entitled *Environmental Flows in Water Availability Modeling*. For the case study application, BBEST and BBASC recommended environmental flow requirements were incorporated at 19 control point locations in a daily version of the Brazos WAM. Monthly aggregated targets from the daily simulation for the BBASC recommended flows were incorporated in the monthly Brazos WAM. The recommended environmental flow requirements were modeled using target setting water right (*WR*), target options (*TO*), flow switch (*FS*), daily data (*DW*), daily options (*DO*), instream flow (*IF*), pulse flow (*PF*), and pulse flow options (*PO*) records to set applicable targets for subsistence flows, base flows that varied by season and hydrologic condition, and multiple high flow pulse events varied by season. The hydrologic condition was determined according to the Palmer Hydrologic Drought Index. Output from the simulation was assessed using the *TABLES* program to determine frequency metrics for environmental flow targets and shortages as well as the number of pulse events initiated.

1.4 Research Objectives

The SB3 environmental flow standards for the Colorado and Trinity river basins were incorporated in daily authorized use scenario versions of the Colorado and Trinity WAMs using existing and recently added features of WRAP. This signifies a key step forward in the process of representing the SB3 environmental flow standards in the State water rights permitting system. Additionally, the modeling techniques described in this thesis serve as examples for incorporating environmental flow standards in water availability models for other river basins. The process of modeling the flow standards highlights strengths and limitations of the WRAP/WAM modeling system.

In order to characterize the degree to which the modeled environmental flow standards were attained, given their junior position in the priority sequence, and to describe the engagement of various components of the flow regime, a variety of metrics were developed using spreadsheets. As the environmental flow standards are revised in the future as part of the adaptive management process, these metrics can be used to inform scientists and decision-makers in the evaluation of alternative river basin development scenarios. The attainment metrics could also serve as the basis of risk assessment approaches for evaluating tradeoffs between environmental and human water needs.

1.5 Thesis Organization

This thesis is organized in four chapters. The present Chapter I includes background information and problem identification regarding environmental instream flows and the environmental flows rulemaking process in Texas, a literature review of models and methodologies used to incorporate environmental instream flows in river/reservoir water management models, and research objectives of this thesis. Chapter II describes the methodologies used to model environmental instream flows in daily time-step versions of the authorized use scenario Colorado and Trinity WAMs. Chapter III describes the attainment metrics that were developed and documents results from several simulations, including comparisons between alternate environmental flow regime components, alternate control points, and alternate water management scenarios. Chapter IV presents conclusions of the thesis, including an evaluation of the environmental flow modeling features of WRAP and an assessment of the attainment metrics that were developed.

CHAPTER II

MODELING ENVIRONMENTAL FLOW STANDARDS

Environmental instream flow standards were modeled using existing and recently added features of WRAP at 14 control points in the Colorado WAM and 4 control points in the Trinity WAM. The flow standards that were modeled are those documented in Texas Administrative Code Title 30, Part 1, Chapter 298, Subchapters B and D for the Trinity and Colorado River basins, respectively. The daily time-step authorized use scenario Colorado and Trinity WAMs were developed under contract with the TCEQ to explore daily time-step water availability modeling features of WRAP. The techniques used to model subsistence flows, base flows, and high flow pulse events that are included in this chapter are also documented in the report entitled *Application of Expanded WRAP Modeling Capabilities to the Colorado WAM* and a forthcoming report entitled *Application of Expanded WRAP Modeling Capabilities to the Trinity WAM*. Modifications to the input files which are not documented in the aforementioned reports were made to facilitate the simulation of alternative scenarios and the generation of appropriate output for the development of attainment metrics.

2.1 Overview of WRAP and the Texas WAM System

The Water Rights Analysis Package is useful for determining water availability and reliability for diversions, environmental flow requirements, hydroelectric power generation, and reservoir storage based on the simulation of priority-order based water allocation for a repetition of historical hydrology (Wurbs, 2005). WRAP is composed of several programs which are used to develop input datasets, perform simulations, and analyze simulation results.

Program *WRAP-HYD* can be used to convert gaged stream flows to naturalized flows, compile net reservoir evaporation less precipitation depths, and extend the period-of-analysis of a dataset of naturalized flows. Program *WRAP-DAY* can be used to calibrate routing parameters and compile hydrology input data for *SIMD*.

WRAP-SIM simulates the priority-order based allocation of the water resources of a river/reservoir system based on a specified scenario of river basin development and a repetition of historical hydrology. Information describing the water use requirements and associated reservoirs and operating rules, as well as the spatial configuration of the system components, is provided in the input DAT file. Historical hydrology is represented by datasets of naturalized flows in the FLO (or INF) file and net reservoir evaporation less precipitation rates in the EVA file. Naturalized flows represent the flows that would have occurred in the absence of human-related activities, including the diversion of water from streams, impoundment of water in and release of water from reservoirs, and evaporation of water from reservoir water surfaces. Regulated flows represent the flows that theoretically would be measured in the river after all diversions and return flows by water users. The DIS input file contains information for distributing flows from gaged locations at which naturalized flows are provided as input (primary control points) to ungagged locations (secondary control points). *WRAP-SIM* performs the simulation using a monthly time-step.

Additional features have recently been developed to enable simulation at a daily or other sub-monthly time-step using program *WRAP-SIMD*. The conversion from a monthly to daily time-step simulation requires several adjustments to the DAT file, the disaggregation of flows from monthly to daily using daily flow patterns, and the calibration of routing parameters. Daily time-step simulations are particularly useful for modeling complex environmental instream flow requirements, specifically high flow pulse events, as well as reservoir flood control operations. Several new DAT file input records are provided specifically for these purposes.

Program *TABLES* is used to process simulation results, including the development of time series tables, frequency and reliability metrics, and various statistics.

The Texas Water Availability Modeling System was authorized in 1997 by Senate Bill 1 of the 75th Texas Legislature. Under the direction of the TCEQ, 21 WRAP input datasets were developed for the state's 23 river basins. The DAT files reflect the institutional arrangements of water diversion and storage specified by the water rights permitting system. The FLO (or INF) files were developed within spreadsheet programs by adjusting historical gaged flows for historical man-related influences. The EVA files were compiled using evaporation and precipitation depths from a database maintained by the TWDB. For a few river basins, including the Colorado River Basin, flows and flow estimates for individual springs were recorded on FAD file records.

The Texas WAM System serves as a common framework and set of datasets for use in administration of the water rights permitting system. As described earlier, it is used by consultants in the development of applications for new water rights permits or amendments to existing permits, the TCEQ in the evaluation of permit applications, and the TWDB and other agencies in planning studies and other investigations.

The techniques described in this chapter for modelling environmental instream flows were developed by assembling WRAP input records in the DAT input files for the Colorado and Trinity WAMs. Input records are entered line-by-line in the DAT file. Each character of a line of code has meaning. The first two characters identify the record type. The remaining characters are assembled according to fields of various lengths, as defined by the record type. Entries within each field of an input record convey information about the system to the program. The required format and definition of input for the fields of each record are provided in the *Users Manual* and *Daily Manual*. The records described in the *Daily Manual* are applicable to *SIMD* simulations only, whereas the records described in the *Users Manual* are generally applicable to both *SIM* and *SIMD* simulations. The recently added features of WRAP that were implemented to model environmental instream flows included new records from the *Daily Manual* as well as existing records from the *Users Manual*. New records from the *Daily Manual* were used to model high flow pulse events, simulate reservoir flood control operations, and set targets on a daily basis. Existing and recently modified records from the *Users Manual* were used to evaluate hydrologic conditions, track the engagement of seasons, build intermediate flow targets, and set the final instream flow target.

2.2 Overview of the Colorado River Basin and Colorado WAM

The Colorado River is approximately 600 miles in length with a drainage area of 42,460 square miles, of which approximately 11,830 square miles is non-contributing. The headwaters of the river originate in New Mexico and west Texas and the river discharges into Matagorda Bay south of Bay City, as seen in Figure 1. Average annual precipitation is between 12 and 16 inches in the arid northwest portion of the basin and 44 inches at the coast. The major tributaries of the Colorado River are Beals Creek, Pecan Bayou, Concho River, San Saba River, Llano River, and Pedernales River. Major cities located near the Colorado River or tributaries of the Colorado River include Austin, Bay City, Brownwood, San Angelo, and Big Spring. Austin and the surrounding 5-county metropolitan area had a combined population of 1,834,000 in 2012 (Hoffpauir et al., 2013).

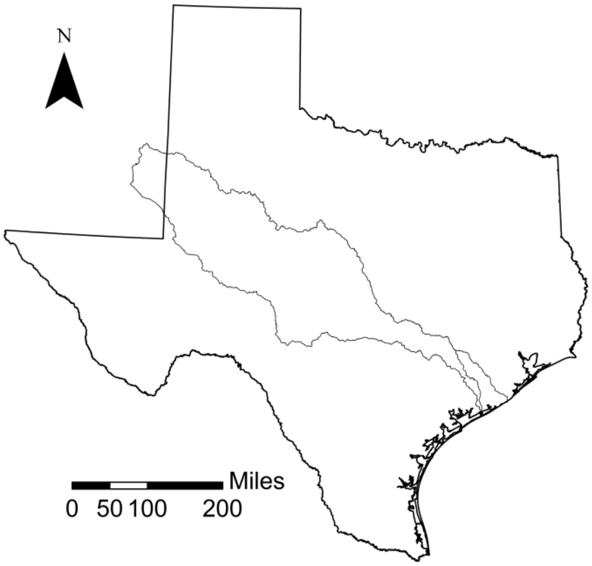

Figure 1. Colorado and Brazos-Colorado River Basins

The largest water suppliers in the basin are the Lower Colorado River Authority (LCRA) and Colorado River Municipal Water District (CRMWD), which both own and operate several multiple-purpose reservoirs. The LCRA operates the six Highland-lake reservoirs in the lower Colorado River Basin and the CRMWD operates J.B. Thomas, E.V. Spence, and O.H. Ivie Reservoirs located in the upper Colorado River Basin. The U.S. Army Corps of Engineers Fort Worth District owns and operates Hords Creek Dam and Reservoir and O.C. Fisher Dam and Reservoir in addition to operating the flood control pools of Lake Travis and Twin Buttes Reservoir. Of the 29 major reservoirs in the Colorado River Basin with storage capacities exceeding 5,000 acre-feet, the six Highland-lake reservoirs operated by the LCRA account for 50% of the combined storage capacity of the 29 reservoirs. Likewise, the three reservoirs operated by the CRMWD account for approximately 26 percent of the combined storage capacity of the 29 large reservoirs (Hoffpauir et al., 2013).

The Colorado WAM includes the WRAP input data files for the Colorado River Basin and Brazos-Colorado Coastal Basin. The original Colorado WAM dataset was developed by R.J. Brandes Company in 2001, as documented by a report (R.J. Brandes Company, 2001). A daily time-step version of the authorized use scenario Colorado WAM was developed for modeling the SB3 environmental instream flow standards. The base WRAP dataset that was modified for daily time-step simulation was the authorized use scenario dataset with draft revisions by TCEQ dated March 2010.

The Colorado WAM has 45 primary control point locations at which naturalized flows are provided as input. Figure 2 is a map indicating the locations of the primary control points. Information for each of the primary control points is given in Table 1. The 14 control points at which environmental flows were modeled are indicated in black. Naturalized flows for each of the primary control points are recorded in the FLO file. Net evaporation less precipitation depths at the locations of 30 reservoirs and 18 quadrangles are provided in the EVA file. The hydrologic period-of-analysis for the original dataset of naturalized flows and net evaporation-precipitation depths was 59 years from 1940 to 1998. For the analyses included in this report, an extended 73-year hydrologic period-of-analysis from 1940 to 2012 was implemented, as documented in a report by Pauls et al. (2013).

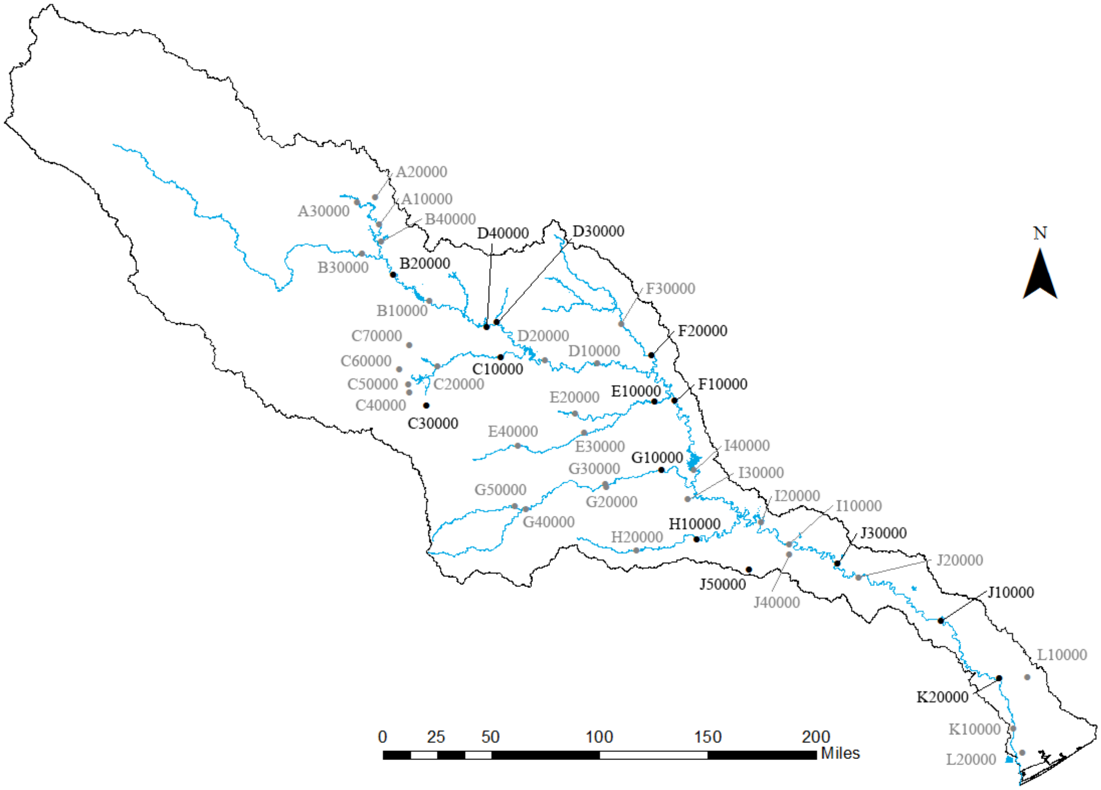

Figure 2. Map of Primary Control Points in the Colorado WAM

Table 1. Primary Control Points in the Colorado WAM

Control Point	USGS Gage No.	Location	Watershed Area (sq. miles)
A30000	08119500	Colorado River near Ira	1,074
A20000	08120500	Deep Creek near Dunn	193
A10000	08121000	Colorado River at Colorado City	1,575
B40000	08123600	Champion Creek Reservoir	176
B30000	08123800	Beals Creek near Westbrook	1,974
B20000	08123850	Colorado River above Silver	4,560
B10000	08124000	Colorado River at Robert Lee	5,046
C70000	08134000	North Concho River near Carlsbad	1,202
C60000	08128400	Middle Concho River above	1,613
C50000	08129300	Spring Creek above Tankersley	340
C40000	08130500	Dove Creek at Knickerbocker	164
C30000	08128000	South Concho River at Christoval	258
C20000	08136000	Concho River at San Angelo	4,139
C10000	08136500	Concho River at Paint Rock	5,185
D40000	08126380	Colorado River near Ballinger	6,090
D30000	08127000	Elm Creek at Ballinger	464
D20000	08136700	Colorado River near Stacy	12,548
D10000	08138000	Colorado River at Winchell	13,788
E40000	08144500	San Saba River at Menard	1,137
E30000	08144600	San Saba River near Brady	1,636
E20000	08145000	Brady Creek at Brady	589
E10000	08146000	San Saba River at San Saba	3,048
F30000	08143500	Pecan Bayou at Brownwood	1,654
F20000	08143600	Pecan Bayou near Mullin	2,074
F10000	08147000	Colorado River near San Saba	19,830
G50000	08148500	North Llano River near Junction	897
G40000	08150000	Llano River near Junction	1,859
G30000	08150700	Llano River near Mason	3,251
G20000	08150800	Beaver Creek near Mason	215
G10000	08151500	Llano River at Llano	4,201
H20000	08152900	Pedernales River near Fredericksburg	370
H10000	08153500	Pedernales River near Johnson City	901
I40000	08148000	Lake Buchanan near Burnet	20,521
I30000	08152000	Sandy Creek near Kingsland	346
I20000	08154500	Lake Travis near Austin	27,357
I10000	08158000	Colorado River at Austin	27,611
J50000	08158700	Onion Creek near Driftwood	124
J40000	08159000	Onion Creek at U.S. Hwy 183	324
J30000	08159200	Colorado River at Bastrop	28,580
J20000	08159500	Colorado River at Smithville	29,062
J10000	08161000	Colorado River at Columbus	30,244
K20000	08162000	Colorado River at Wharton	30,601
K10000	08162500	Colorado River near Bay City	30,862
L20000	08117900	Big Boggy Creek near Wadsworth	14
L10000	08117500	San Bernard River near Boling	725

The major tributaries and largest reservoirs in the Colorado River Basin and Brazos-Colorado Coastal Basin are given in the map of Figure 3. The numbers next to each reservoir in Figure 3 correspond to the map identifiers in Table 2.

Table 2. Major Reservoirs in the Colorado WAM

Map ID	Reservoir Name	WAM Identifier	Authorized Storage Capacity
			(ac-ft)
1	Lake Travis	TRAVIS	1,170,752
2	Lake Buchanan	BUCHAN	992,000
3	O.H. Ivie Reservoir	OHIVIE	554,340
4	E.V. Spence Reservoir	SPENCE	488,760
5	Lake J.B. Thomas	THOMAS	203,600
6	STP Main Cooling Pond	STHTEX	202,600
7	Twin Buttes Reservoir	TWINBU	186,200
8	Lake LBJ	LAKLBJ	138,000
9	Lake Brownwood	BROWNW	135,963
10	O.C. Fisher Lake	OCFISH	119,200
11	Lake Fayette	CEDARC	71,400
12	Champion Creek Reservoir	CHAMPI	42,500
13	Lake Coleman	COLEMA	40,000
14	Oak Creek Reservoir	OAKCRK	39,360
15	Walter E. Long Lake	DECKER	33,940
16	Lake Colorado City	COLOCI	31,805
17	Brady Creek Reservoir	BRADYC	30,430
18	Lake Austin	LKAUST	21,000
19	Inks Lake	ROYINK	17,545
20	Lake Bastrop	BASTRO	16,590
21	Lake Nasworthy	NASWOR	14,604
22	Lake Marble Falls	MARBLE	8,760
23	Hords Creek Lake	HORDSC	8,640
24	Lake Winters	ELMCRK	8,374
25	Ballinger Municipal Lake	BALLIN	6,050
26	Clyde Lake	LCLYDE	5,748

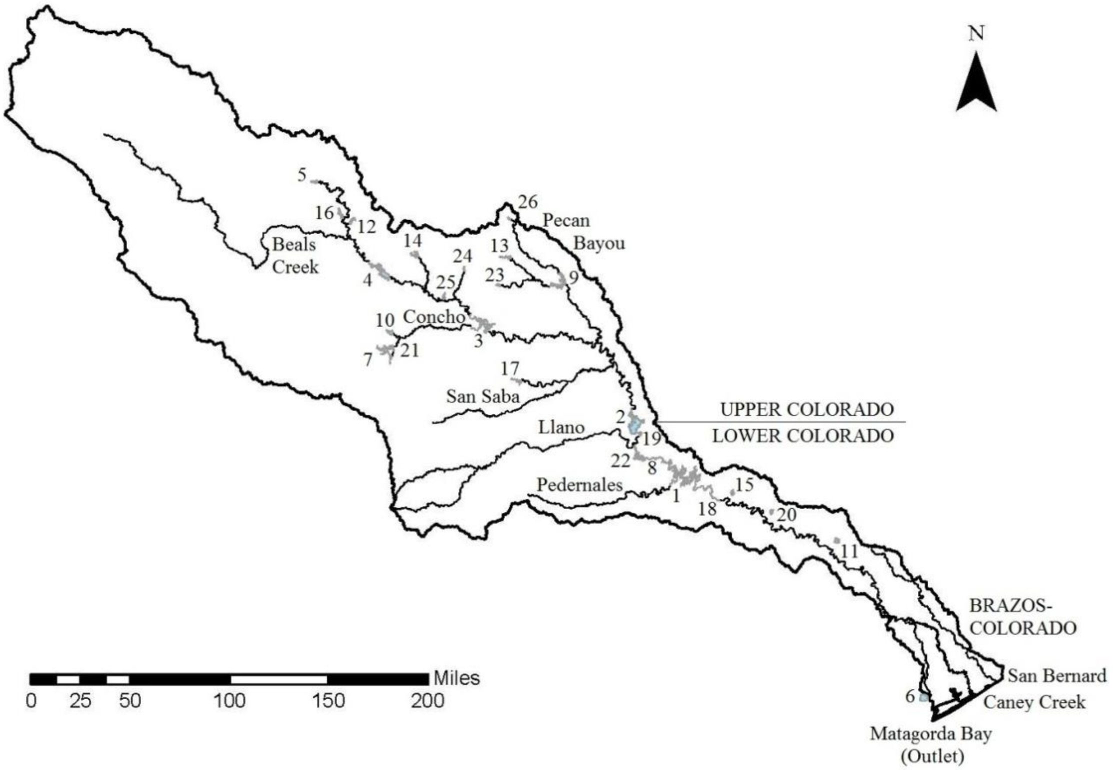

Figure 3. Major Tributaries and Largest Reservoirs in the Colorado/Brazos-Colorado River Basin

The March 2010 authorized use scenario Colorado WAM contains 2,006 water right records and 99 instream flow records, accounting for yearly 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 (Hoffpauir et al., 2013). A number of water rights and DAT-file input records were added in the process of converting to a daily time-step simulation, modeling environmental instream flows, and modeling flood control operations. Several other steps were also required to convert from a monthly to daily time-step simulation, including the implementation of daily naturalized flow patterns and calibration of routing parameters, as described in detail in the report entitled *Application of Expanded WRAP Modeling Capabilities to the Colorado WAM* by Hoffpauir et al. (2013).

2.3 Environmental Flow Standards for the Colorado River Basin

The environmental flow standards for surface water for the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays are documented in Texas Administrative Code Chapter 298, Subchapter D. Flow standards were developed for 21 control point locations, including 14 control points in the Colorado River Basin, 5 control points in the Lavaca River Basin, and 2 control points in the Colorado-Lavaca and Lavaca-Guadalupe Coastal Basins. This thesis focuses on the flow standards developed at the 14 control points located in the Colorado River Basin, as listed in Table 3. New control points were added immediately downstream of the primary control points in order to avoid over-writing any existing instream flow standards. The identifiers of the new control points are the same as the identifiers of the primary control points, with a letter "E" replacing the sixth character. The flow standards became effective August 30, 2012. The priority date used for water availability modeling is March 1, 2011.

The environmental flow standards consist of recommendations for subsistence flows, base flows, and high flow pulse events that vary seasonally and according to hydrologic conditions. The seasons and hydrologic conditions have two definitions based on control point location. For control points located on the Colorado River above Lake Travis and tributaries of the Colorado River, the month of November is included in the winter season and hydrologic conditions are determined using cumulative stream flow for the previous 12 months. For control points located on the Colorado River below Lake Travis, the month of November is included in the fall season and hydrologic conditions are determined using the combined reservoir storage in Lakes Travis and Buchanan. For all control points, the hydrologic condition for a season is determined according to the conditions present on the last day of the preceding season. The hydrologic condition is evaluated once and applied for the entire season. The seasons are defined in Table 4. The parameters used to calculate hydrologic conditions are documented in Table 5.

Table 3. Colorado WAM Control Point Locations for Environmental Flow Standards

Control Point	USGS Gage No.	Gage Name	Watershed Area (sq. miles)
B2000E	08123850	Colorado River above Silver	1,575
C3000E	08128000	South Concho River at Christoval	5,046
C1000E	08136500	Concho River at Paint Rock	5,046
D4000E	08126380	Colorado River near Ballinger	13,788
D3000E	08127000	Elm Creek at Ballinger	464
E1000E	08146000	San Saba River at San Saba	3,048
F2000E	08143600	Pecan Bayou near Mullin	19,830
F1000E	08147000	Colorado River near San Saba	19,830
G1000E	08151500	Llano River at Llano	19,830
H1000E	08153500	Pedernales River near Johnson City	901
J5000E	08158700	Onion Creek near Driftwood	30,244
J3000E	08159200	Colorado River at Bastrop	27,611
J1000E	08161000	Colorado River at Columbus	27,611
K2000E	08162000	Colorado River at Wharton	30,601

Table 4. Months Included in Each Season

Season	Above Lake Travis and Tributaries	Below Lake Travis
Winter	November, December, January, February	December, January, February
Spring	March, April, May, June	March, April, May, June
Summer	July, August	July, August
Fall	September, October	September, October, November

Table 5. Parameters Used for Calculating Hydrologic Conditions

Control Point	Hydrologic Condition			
	Severe	Dry	Average	Wet
Cumulative Stream Flow (ac-ft)				
B2000E	< 4,090	4,090 - 16,600	16,600 - 57,490	> 57,490
C3000E	< 5,270	5,270 - 7,380	7,380 - 21,660	> 21,660
C1000E	< 7,110	7,110 - 17,000	17,000 - 49,900	> 49,900
D4000E	< 3,120	3,120 - 11,150	11,150 - 67,700	> 67,700
D3000E	< 820	820 - 4,990	4,990 - 46,560	> 46,560
E1000E	< 40,550	40,550 - 61,100	61,100 - 149,890	> 149,890
F2000E	< 11,860	11,860 - 26,700	26,700 - 187,740	> 187,740
F1000E	< 80,510	80,510 - 205,110	205,110 - 568,970	> 568,970
G1000E	< 90,810	90,810 - 145,660	145,660 - 364,540	> 364,540
H1000E	< 27,710	27,710 - 70,210	70,210 - 222,700	> 222,700
J5000E	< 810	810 - 10,460	10,460 - 59,610	> 59,610
Combined Reservoir Storage in Lakes Travis and Buchanan (ac-ft)				
J3000E	< 1,103,700	1,103,700 - 1,737,460	> 1,737,460	
J1000E	< 1,103,700	1,103,700 - 1,737,460	> 1,737,460	
K2000E	< 1,103,700	1,103,700 - 1,737,460	> 1,737,460	

For control points located on the Colorado River above Lake Travis and tributaries of the Colorado River, the hydrologic condition parameters were selected in order that severe conditions occur approximately 5% of the time, dry conditions occur approximately 20% of the time, average conditions occur approximately 50% of the time, and wet conditions occur approximately 25% of the time. For control points located on the Colorado River below Lake Travis, the hydrologic condition parameters were selected in order that severe conditions occur approximately 5% of the time, dry conditions occur approximately 45% of the time, and average conditions occur approximately 50% of the time.

2.3.1 Subsistence and Base Flow Standards

The subsistence flow standard is applicable during severe hydrologic conditions when flow at a control point is less than the dry base flow standard. If flow at a control point is below the dry base flow standard and above the subsistence flow standard during severe hydrologic conditions, a junior water right holder may divert water as long as the diversion does not cause the flow to drop below the subsistence flow standard. The subsistence flow standards vary by control point location. For control points located on the Colorado River above Lake Travis and tributaries of the Colorado River, the subsistence flow standard varies seasonally. For control points located on the Colorado River below Lake Travis, the subsistence flow standard varies monthly. Table 6 and Table 7 contain the subsistence flow standards.

Table 6. Subsistence Flow Standards (cfs) for Control Points Located on the Colorado River below Lake Travis

Season	Month	J3000E	J1000E	K2000E
Winter	December	186	301	202
	January	208	340	315
	February	274	375	303
Spring	March	274	375	204
	April	184	299	270
	May	275	425	304
	June	202	534	371
Summer	July	137	342	212
	August	123	190	107
Fall	September	123	279	188
	October	127	190	147
	November	180	202	173

Table 7. Subsistence Flow Standards (cfs) for Control Points Located on the Colorado River above Lake Travis and Tributaries of the Colorado River

Control Point	Winter	Spring	Summer	Fall
B2000E	1	1	1	1
C3000E	2	3	2	2
C1000E	1	1	1	1
D4000E	1	1	1	1
D3000E	1	1	1	1
E1000E	29	22	3	13
F2000E	1	1	1	1
F1000E	50	50	30	30
G1000E	44	35	3	20
H1000E	7	4	1	1
J5000E	1	1	1	1

Base flow standards also vary based on control point location. For control points located on the Colorado River above Lake Travis and tributaries of the Colorado River, base flow standards vary seasonally and are specified according to four hydrologic conditions: severe, dry, average, and wet. For control points located on the Colorado River below Lake Travis, base flow standards vary monthly and are specified according to three hydrologic conditions: severe, dry, and average. For all control points, the dry base flow standard applies during severe hydrologic conditions. If flow at a control point is below any high flow pulse trigger levels and above the applicable base flow standard, a junior water right holder may divert water as long as the diversion does not cause the flow to drop below the applicable base flow standard. Table 8 and Table 9 show the base flow standards.

Table 8. Base Flow Standards (cfs) for Control Points Located on the Colorado River above Lake Travis and Tributaries of the Colorado River

Control Point	Winter				Spring				Summer				Fall			
	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet	Sev	Dry	Avg	Wet
B2000E	2	2	4	7	2	2	5	12	1	1	3	8	1	1	4	10
C3000E	9	9	15	22	9	9	15	22	7	7	12	22	7	7	12	22
C1000E	8	8	20	36	4	4	14	27	1	1	4	12	5	5	16	29
D4000E	4	4	9	14	3	3	9	19	2	2	6	14	4	4	9	17
D3000E	1	1	1	4	1	1	1	5	1	1	1	1	1	1	1	1
E1000E	56	56	81	110	56	56	81	110	32	32	46	62	40	40	64	87
F2000E	3	3	7	12	3	3	9	19	2	2	4	8	3	3	7	12
F1000E	95	95	150	210	120	120	190	360	72	72	120	210	95	95	150	210
G1000E	100	100	150	190	100	100	150	190	67	67	92	130	87	87	120	190
H1000E	23	23	45	80	29	29	60	110	16	16	29	49	16	16	29	49
J5000E	2	2	6	26	4	4	12	34	1	1	3	7	1	1	3	7

Table 9. Base Flow Standards (cfs) for Control Points Located on the Colorado River below Lake Travis

Season	Month	Hydrologic Condition	J3000E	J1000E	K2000E
Winter	December	Severe	311	464	470
		Dry	311	464	470
		Average	450	737	746
	January	Severe	313	487	492
		Dry	313	487	492
		Average	433	828	838
	February	Severe	317	590	597
		Dry	317	590	597
		Average	497	895	906
Spring	March	Severe	274	525	531
		Dry	274	525	531
		Average	497	1,020	1,036
	April	Severe	287	554	561
		Dry	287	554	561
		Average	635	977	1,011
	May	Severe	579	966	985
		Dry	579	966	985
		Average	824	1,316	1,397
	June	Severe	418	967	984
		Dry	418	967	984
		Average	733	1,440	1,512
Summer	July	Severe	347	570	577
		Dry	347	570	577
		Average	610	895	906
	August	Severe	194	310	314
		Dry	194	310	314
		Average	381	516	522
Fall	September	Severe	236	405	410
		Dry	236	405	410
		Average	423	610	617
	October	Severe	245	356	360
		Dry	245	356	360
		Average	433	741	749
	November	Severe	283	480	486
		Dry	283	480	486
		Average	424	755	764

2.3.2 High Flow Pulse Standards

Similar to the subsistence and base flow standards, high flow pulse standards vary based on control point location. For control points located on the Colorado River above Lake Travis and tributaries of the Colorado River, criteria were specified for a two-per-season pulse, a one-per-season pulse, and an annual pulse. If the high flow pulse trigger level has been met, junior water right holders may not divert water until either the specified volume or specified duration time has passed, except when stream flow levels exceed the high flow pulse trigger level. For control points on the Colorado River below Lake Travis, criteria were specified for a two-per-season pulse, a one per 18-month pulse, and a one per 2-year pulse. If the high flow pulse trigger level has been met, junior water right holders may not divert water until the specified duration time has passed, except when stream flow levels exceed the high flow pulse trigger level. Table 10 and Table 11 show the high flow pulse standards.

Table 10. High Flow Pulse Standards for Control Points Located on the Colorado River below Lake Travis

Control Point	Pulse Flow Criteria	Frequency		
		2 per season	1 per 18 mo.	1 per 2 yr.
J3000E	Trigger (cfs):	3,000	8,000	N/A
	Duration (days):	4	2	N/A
J1000E	Trigger (cfs):	3,000	8,000	27,000
	Duration (days):	4	2	2
K2000E	Trigger (cfs):	3,000	8,000	27,000
	Duration (days):	4	2	2

Table 11. High Flow Pulse Standards for Control Points Located on the Colorado River above Lake Travis and Tributaries of the Colorado River

Control Point	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
B2000E	Winter	Trigger (cfs):	18	42	3,000
		Volume (ac-ft):	120	300	13,600
		Duration (days):	13	15	17
	Spring	Trigger (cfs):	600	1,800	
		Volume (ac-ft):	2,500	7,900	
		Duration (days):	9	11	
	Summer	Trigger (cfs):	100	330	
		Volume (ac-ft):	350	1,400	
		Duration (days):	6	9	
	Fall	Trigger (cfs):	100	430	
		Volume (ac-ft):	400	1,800	
		Duration (days):	6	9	
C3000E	Winter	Trigger (cfs):	N/A	N/A	420
		Volume (ac-ft):	N/A	N/A	1,400
		Duration (days):	N/A	N/A	9
	Spring	Trigger (cfs):	N/A	N/A	
		Volume (ac-ft):	N/A	N/A	
		Duration (days):	N/A	N/A	
	Summer	Trigger (cfs):	N/A	N/A	
		Volume (ac-ft):	N/A	N/A	
		Duration (days):	N/A	N/A	
	Fall	Trigger (cfs):	N/A	45	
		Volume (ac-ft):	N/A	190	
		Duration (days):	N/A	7	
C1000E	Winter	Trigger (cfs):	61	160	3,000
		Volume (ac-ft):	400	1,200	13,500
		Duration (days):	10	16	19
	Spring	Trigger (cfs):	500	1,400	
		Volume (ac-ft):	2,000	5,700	
		Duration (days):	8	11	
	Summer	Trigger (cfs):	32	110	
		Volume (ac-ft):	140	520	
		Duration (days):	6	8	
	Fall	Trigger (cfs):	74	300	
		Volume (ac-ft):	330	1,300	
		Duration (days):	7	10	

Table 11 Continued.

Control Point	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
D4000E	Winter	Trigger (cfs):	27	96	3,200
		Volume (ac-ft):	180	660	13,700
		Duration (days):	11	17	10
	Spring	Trigger (cfs):	1,300	3,200	
		Volume (ac-ft):	5,300	13,700	
		Duration (days):	9	10	
	Summer	Trigger (cfs):	130	630	
		Volume (ac-ft):	490	2,600	
		Duration (days):	6	9	
	Fall	Trigger (cfs):	250	1,500	
		Volume (ac-ft):	950	5,700	
		Duration (days):	8	10	
D3000E	Winter	Trigger (cfs):	10	40	1,900
		Volume (ac-ft):	71	270	7,200
		Duration (days):	10		18
	Spring	Trigger (cfs):	380	1,000	
		Volume (ac-ft):	1,400	3,800	
		Duration (days):	10	12	
	Summer	Trigger (cfs):	6	74	
		Volume (ac-ft):	25	300	
		Duration (days):	6	9	
	Fall	Trigger (cfs):	10	190	
		Volume (ac-ft):	46	850	
		Duration (days):	9	15	
E1000E	Winter	Trigger (cfs):	150	330	5,500
		Volume (ac-ft):	980	2,300	27,400
		Duration (days):	14	18	21
	Spring	Trigger (cfs):	810	2,000	
		Volume (ac-ft):	3,600	9,200	
		Duration (days):	9	12	
	Summer	Trigger (cfs):	N/A	210	
		Volume (ac-ft):	N/A	1,100	
		Duration (days):	N/A	9	
	Fall	Trigger (cfs):	150	500	
		Volume (ac-ft):	600	2,300	
		Duration (days):	8	12	

Table 11 Continued.

Control Point	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
F2000E	Winter	Trigger (cfs):	52	250	3,500
		Volume (ac-ft):	230	1,500	25,800
		Duration (days):	7	14	26
	Spring	Trigger (cfs):	710	2,100	
		Volume (ac-ft):	3,600	13,200	
		Duration (days):	10	17	
	Summer	Trigger (cfs):	21	100	
		Volume (ac-ft):	73	440	
		Duration (days):	4	7	
	Fall	Trigger (cfs):	36	250	
		Volume (ac-ft):	110	1,200	
		Duration (days):	3	9	
F1000E	Winter	Trigger (cfs):	520	1,600	18,900
		Volume (ac-ft):	3,100	11,100	129,100
		Duration (days):	9	15	23
	Spring	Trigger (cfs):	5,800	11,000	
		Volume (ac-ft):	31,300	70,200	
		Duration (days):	9	13	
	Summer	Trigger (cfs):	510	1,400	
		Volume (ac-ft):	1,900	6,500	
		Duration (days):	4	7	
	Fall	Trigger (cfs):	890	3,800	
		Volume (ac-ft):	3,500	19,200	
		Duration (days):	6	12	
G1000E	Winter	Trigger (cfs):	390	1,100	9,100
		Volume (ac-ft):	2,500	6,800	46,100
		Duration (days):	13	16	18
	Spring	Trigger (cfs):	1,800	4,800	
		Volume (ac-ft):	8,500	23,200	
		Duration (days):	10	13	
	Summer	Trigger (cfs):	N/A	560	
		Volume (ac-ft):	N/A	2,600	
		Duration (days):	N/A	9	
	Fall	Trigger (cfs):	370	1,400	
		Volume (ac-ft):	1,600	6,300	
		Duration (days):	8	11	

Table 11 Continued.

Control Point	Season	Pulse Flow Criteria	Frequency		
			2 per season	1 per season	Annual
H1000E	Winter	Trigger (cfs): Volume (ac-ft): Duration (days):	270 1,300 9	860 4,700 15	6,980 28,320 15
	Spring	Trigger (cfs): Volume (ac-ft): Duration (days):	1,700 6,300 8	3,700 14,400 10	
	Summer	Trigger (cfs): Volume (ac-ft): Duration (days):	N/A N/A N/A	90 1,100 7	
	Fall	Trigger (cfs): Volume (ac-ft): Duration (days):	160 620 6	860 3,000 8	
J5000E	Winter	Trigger (cfs): Volume (ac-ft): Duration (days):	N/A N/A N/A	170 1,900 20	1,200 8,700 34
	Spring	Trigger (cfs): Volume (ac-ft): Duration (days):	200 1,100 11	620 3,700 19	
	Summer	Trigger (cfs): Volume (ac-ft): Duration (days):	N/A N/A N/A	N/A N/A N/A	
	Fall	Trigger (cfs): Volume (ac-ft): Duration (days):	18 70 5	120 560 11	

For all control points, high flow pulse events are independent of hydrologic conditions and each season is independent of other seasons. Also, if a high flow pulse requirement for a pulse event is satisfied during a season, then one high flow pulse requirement is considered to be satisfied for each smaller event in that season. For example, if an annual pulse flow requirement is met in a season, then the one-per-season pulse flow requirement and one two-per-season pulse flow requirement are met for that season. Water right holders are not required to cease diverting water or release stored water to produce a high flow pulse event if the trigger criterion is not met during a season. Water that was previously stored according to permit conditions may be diverted or released regardless of applicable environmental flow requirements.

2.3.3 Water Right Permit Conditions

For some water right permits issued after the effective date of the environmental flow standards, only a portion of the flow standards apply, depending on the location and conditions of the new permit. For water right permits located on the Colorado River above Lake Travis and tributaries of the Colorado River, all of the environmental flow standards are applicable. For water right permits located on the Colorado River below Lake Travis, all of the subsistence and base flow standards are applicable. The high flow pulse standards are applied as a function of the permitted diversion rate or permitted on-channel storage, as seen in Table 12.

Table 12. Conditions for the Application of High Flow Pulse Standards for New Water Right Permits Located on the Colorado River below Lake Travis

Diversion Rate (cfs)		On-Channel Storage (ac-ft)	Applicable High Flow Pulse Standards
< 500	OR	< 2,500	None
> 500	OR	> 2,500	Protect 1-per year event and smaller
> 800	OR	> 2,500	Prevent impairment* of one per 18-month event
> 2,700	OR	> 2,500	Protect one per 2-year event

*Impairment occurs if the permit reduces the frequency or average volume of the one per 18-month event by more than 10% based on the period of record of the water availability model at the time the first permit subject to the environmental flow standards is evaluated.

2.4 Modeling Environmental Flow Standards in the Colorado WAM

The environmental flow standards at 14 control point locations were incorporated into a daily time-step version of the authorized use scenario Colorado WAM. Two sets of input records are included in this section to describe the alternate methodologies employed for modeling environmental flow standards at control points located on the Colorado River above Lake Travis and tributaries of the Colorado River and control points located on the Colorado River below Lake Travis. Alternate modeling methodologies were used primarily because of the differences associated with calculating hydrologic conditions. Although alternate modeling methodologies were employed based on control point location, a similar modeling paradigm was employed at all control points.

- Subsistence and base flow standards were modeled using target setting water right (*WR*) records in combination with flow switch (*FS*), target options (*TO*), daily data (*DW*), and daily options (*DO*) records.
- Pulse flow standards were modeled using a target setting water right (*WR*) record in combination with pulse flow (*PF*) and pulse flow options (*PO*) records.
- The instream flow target was set using an instream flow (*IF*) record with a target equal to the maximum of the targets set by the target setting water right records.
- A priority number of 20110301 was used for all instream flow (*IF*) and water right (*WR*) records.

2.4.1 Control Points Located on the Colorado River above Lake Travis and Tributaries of the Colorado River

Control point B2000E (USGS Gage 08123850, Colorado River above Silver) is located on the Colorado River above Lake Travis. The environmental flow standards for this location consist of subsistence and base flows that vary seasonally and according to hydrologic conditions, a two-per-season high flow pulse, a one-per-season high flow pulse, and an annual high flow pulse, as seen in Table 13. Four hydrologic conditions are specified based on cumulative stream flow for the previous 12 months, evaluated on the last day of the preceding season. The input records presented here model the winter subsistence and base flow requirements and all of the pulse flow requirements. The records used to model the spring, summer, and fall subsistence and base flow requirements have been omitted for brevity.

The input records used for modeling the environmental flow standards for control point B2000E (see Table 14), are categorized in five sections, as follows.

Section 2.4.1.1 - The hydrologic condition is determined each day considering prior-day cumulative stream flow for the previous 12 months. Four target setting water rights corresponding to severe, dry, average, and wet hydrologic conditions set a target of 1.0 if the prior-day cumulative stream flow falls within the appropriate boundaries. Otherwise a target of 0.0 is set. On any given day, one right sets a target of 1.0 and the other rights set targets of 0.0.

Section 2.4.1.2 - The hydrologic condition is determined for the last day of the fall season (determining the hydrologic condition for the winter season). Four target setting water rights corresponding to severe, dry, average, and wet hydrologic conditions set targets based on whether it is the first day of the winter season. The targets set in Section 2.4.1.1 are multiplied by 1.0 on the first day of the winter season (November 1) and 0.0 on all other days of the year. Because the targets set in Section 2.4.1.1 are based on prior-day stream flow, the hydrologic conditions for the first day of the Winter season correspond to the last day of the Fall season.

Section 2.4.1.3 - Daily subsistence and base flow targets are set. Five target setting water rights are used corresponding to one subsistence flow and four base flow levels. Based on the hydrologic condition on the last day of the fall season determined in Section 2.4.1.2, the appropriate water right sets a positive target and the remaining water rights set targets of 0.0.

Section 2.4.1.4 - The daily high flow pulse target is set. A target setting water right adopts the maximum target set by a series of *PF* and *PO* records. A target of zero is set if no high flow pulse events are triggered.

Section 2.4.1.5 - The final daily instream flow target is set. An instream flow (*IF*) record adopts the maximum target set by the target setting water rights from Sections 2.4.1.3 and 2.4.1.4.

Table 13. Environmental Flow Standard for Control Point B2000E

Season	Hydrologic Condition	Subsistence (cfs)	Base (cfs)	Pulse			
					2 per season	1 per season	Annual
Winter	Severe	1	2	Trigger: (cfs)	18	42	3,000
	Dry	N/A	2	Volume: (ac-ft)	120	300	13,600
	Average	N/A	4	Duration: (days)	13	15	17
	Wet	N/A	7				
Spring	Severe	1	2	Trigger: (cfs)	600	1,800	
	Dry	N/A	2	Volume: (ac-ft)	2,500	7,900	
	Average	N/A	5	Duration: (days)	9	11	
	Wet	N/A	12				
Summer	Severe	1	1	Trigger: (cfs)	100	330	
	Dry	N/A	1	Volume: (ac-ft)	350	1,400	
	Average	N/A	3	Duration: (days)	6	9	
	Wet	N/A	8				
Fall	Severe	1	1	Trigger: (cfs)	100	430	
	Dry	N/A	1	Volume: (ac-ft)	400	1,800	
	Average	N/A	4	Duration: (days)	6	9	
	Wet	N/A	10				

Table 14. Input Records Used to Model Environmental Flow Standards at Control Point B2000E

```
**
** Use Coefficients Used to Specify Seasons and Start of Each Season
**
UC   WIN       1       1       0       0       0       0
UC             0       0       0       0       1       1
UC   SPR       0       0       1       1       1       1
UC             0       0       0       0       0       0
UC   SMR       0       0       0       0       0       0
UC             1       1       0       0       0       0
UC   FAL       0       0       0       0       0       0
UC             0       0       1       1       0       0
UCBEGWIN       0       0       0       0       0       0
UC             0       0       0       0       1       0
UCBEGSPR       0       0       1       0       0       0
UC             0       0       0       0       0       0
UCBEGSMR       0       0       0       0       0       0
UC             1       0       0       0       0       0
UCBEGFAL       0       0       0       0       0       0
UC             0       0       1       0       0       0
```

Table 14 Continued.

```
**
** Section 2.4.1.1 - Determination of Daily Hydrologic Conditions Using Prior-day Cumulative Stream Flow
**
WRB2000E                20110301   8                            B2000E_YSTRDYREG
TO    -2
DO        16
WRB2000E     1.0        20110301   8                            B2000E_ANREG_SEV
FS    10             0.0     1.0    4090           1         364                B2000E_YSTRDYREG
DO                19
DW         1
WRB2000E     1.0        20110301   8                            B2000E_ANREG_DRY
FS    10             1.0     0.0    4090   16600   1         364                B2000E_YSTRDYREG
DO                19
DW         1
WRB2000E     1.0        20110301   8                            B2000E_ANREG_AVG
FS    10             1.0     0.0   16600   57490   1         364                B2000E_YSTRDYREG
DO                19
DW         1
WRB2000E     1.0        20110301   8                            B2000E_ANREG_WET
FS    10             0.0     1.0           57490   1         364                B2000E_YSTRDYREG
DO                19
DW
**
** Section 2.4.1.2 - Hydrologic Condition Determined for Last Day of Fall Season
** (Repeated for spring, summer, and fall seasons, in complete DAT File)
**
WRB2000E     1.0  BEGWIN20110301   8                            B2000E_WIN_SEV
TO    13             MUL                                B2000E_ANREG_SEV
DO        16
DW         2   1
WRB2000E     1.0  BEGWIN20110301   8                            B2000E_WIN_DRY
TO    13             MUL                                B2000E_ANREG_DRY
DO        16
DW         2   1
WRB2000E     1.0  BEGWIN20110301   8                            B2000E_WIN_AVG
TO    13             MUL                                B2000E_ANREG_AVG
DO        16
DW         2   1
WRB2000E     1.0  BEGWIN20110301   8                            B2000E_WIN_WET
TO    13             MUL                                B2000E_ANREG_WET
DO        16
DW         2   1
**
** Section 2.4.1.3 - Winter Subsistence and Base Flow Targets
** (Repeated for spring, summer, and fall seasons in complete DAT File)
**
WRB2000E    7.93     WIN20110301   8                            B2000E_SUB_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E_WIN_SEV
FS     1             0.0     1.0   15.87           1           0
DO                19
DW         2
WRB2000E   15.87     WIN20110301   8                            B2000E_BASES_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E_WIN_SEV
FS     1             1.0     0.0   15.87           1           0
DO                19
DW         2
WRB2000E   15.87     WIN20110301   8                            B2000E_BASED_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E_WIN_DRY
DO                19
DW         2
WRB2000E   31.74     WIN20110301   8                            B2000E_BASEA_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E_WIN_AVG
DO                19
DW         2
```

Table 14 Continued.

```
WRB2000E   55.54     WIN20110301   8                            B2000E_BASEW_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E_WIN_WET
DO                19
DW         2
**
** Section 2.4.1.4 - High Flow Pulse Event Targets
**
WRB2000E       0        20110301   8                            B2000E_PULSE
PF     0           35.70     120  13   2          11   2           2   4                    B2000E_WINTER_S
PO             2
PF     0           83.31     300  15   1          11   2           2   4                    B2000E_WINTER_L
PO             2
PF     0             198     350   6   2           7   8           2   4                    B2000E_SUMMER_S
PO             2
PF     0             198     400   6   2           9  10           2   4                    B2000E_FALL_S
PO             2
PF     0             655    1400   9   1           7   8           2   4                    B2000E_SUMMER_L
PO             2
PF     0             853    1800   9   1           9  10           2   4                    B2000E_FALL_L
PO             2
PF     0            1190    2500   9   2           3   6           2   4                    B2000E_SPRING_S
PO             2
PF     0            3570    7900  11   1           3   6           2   4                    B2000E_SPRING_L
PO             2
PF     0            5950   13600  17   1           1  12           2   4                    B2000E_ANNUAL
PO             2
**
** Section 2.4.1.5 - Final Daily Instream Flow Target
**
IFB2000E                20110301   2            IF-B2000E
TO    13             MAX                                B2000E_SUB_WIN  CONT
TO    13             MAX                                B2000E_BASES_WINCONT
TO    13             MAX                                B2000E_BASED_WINCONT
TO    13             MAX                                B2000E_BASEA_WINCONT
TO    13             MAX                                B2000E_BASEW_WINCONT
TO    13             MAX                                B2000E_SUB_SPR  CONT
TO    13             MAX                                B2000E_BASES_SPRCONT
TO    13             MAX                                B2000E_BASED_SPRCONT
TO    13             MAX                                B2000E_BASEA_SPRCONT
TO    13             MAX                                B2000E_BASEW_SPRCONT
TO    13             MAX                                B2000E_SUB_SMR  CONT
TO    13             MAX                                B2000E_BASES_SMRCONT
TO    13             MAX                                B2000E_BASED_SMRCONT
TO    13             MAX                                B2000E_BASEA_SMRCONT
TO    13             MAX                                B2000E_BASEW_SMRCONT
TO    13             MAX                                B2000E_SUB_FAL  CONT
TO    13             MAX                                B2000E_BASES_FALCONT
TO    13             MAX                                B2000E_BASED_FALCONT
TO    13             MAX                                B2000E_BASEA_FALCONT
TO    13             MAX                                B2000E_BASEW_FALCONT
TO    13             MAX                                B2000E_PULSE
DO        16
```

2.4.1.1 Determination of Daily Hydrologic Conditions

Records for two water rights are reproduced in Table 15 below. The water right (*WR*) record with identifier B2000E_YSTRDYREG is a type 8 target setting water right modified by *TO* and *DO* records. Its purpose is to set a daily target equal to prior-day regulated flow. Target options (*TO*) record field 2 option -2 sets a target based on prior-month regulated stream flow. Daily options (*DO*) record field 3 option 16 applies the *TO* record *TOTARGET* option as step 16 in the target building process.

Table 15. Sample Input Records Used to Evaluate Prior-day Regulated Flow

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-
**       1         2         3         4         5         6         7         8         9
**3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-
WRB2000E                20110301   8                            B2000E_YSTRDYREG
TO    -2
DO        16
WRB2000E     1.0        20110301   8                            B2000E_ANREG_SEV
FS    10             0.0     1.0    4090           1         364                B2000E _YSTRDYREG
DO                19
DW         1
```

The water right (*WR*) record with identifier B2000E_ANREG_SEV is a type 8 target setting water right modified by *FS*, *DO*, and *DW* records. Its purpose is to set a daily target of 1.0 if cumulative prior-day regulated stream flow for the previous 12 months is within the boundaries established for severe hydrologic conditions. Flow switch (*FS*) record field 3 option 10 is used to track cumulative flow for the target set by water right B2000E_YSTRDYREG. If the cumulative total for the current and previous 364 days is greater than 4,090 acre-feet, then the *WR* record target *AMT* is multiplied by 0.0. Otherwise, the *WR* record target *AMT* is multiplied by 1.0. Daily options (*DO*) record field 5 option 19 applies the *FS* record as step 19 in the target building process.

Daily data (*DW*) record field 3 option 1 sets a daily target using the *WR* record target. Water right (*WR*) records with water right identifiers B2000E_ANREG_DRY, B2000E_ANREG_AVG, and B2000E_ANREG_WET are set up in a similar format using the limits for dry, average, and wet hydrologic conditions. In any given day, one of the four water rights sets a target of 1.0 and the remaining water rights set targets of 0.0.

2.4.1.2 Determination of Seasonal Hydrologic Conditions

The water right (*WR*) record shown in Table 16 below with identifier B2000E_WIN_SEV is a type 8 target setting water right modified by *UC*, *TO*, *DO*, and *DW* records. Its purpose is to set a target of 1.0 on the first day of the winter season if the cumulative regulated stream flow on the last day of the preceding season indicates a severe hydrologic condition. If the hydrologic condition is not severe or it is not the first day of the winter season, a target of 0.0 is set. Target options (*TO*) record field 2 option 13 is used to multiply the *WR* record target *AMT* by the target set by water right B2000E_ANREG_SEV. Daily options (*DO*) record field 3 option 16 applies the *TO* record *TOTARGET* option as step 16 in the target building process. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and the *UC* record. Daily data (*DW*) record field 4 variable *ND* equal to 1 distributes the monthly *WR* record target *AMT* across the first day of the month. Thus, a target of 1.0 is set on the first day of November and a target of zero is set for the remaining days of the month. Use coefficient (*UC*) record with identifier BEGWIN sets monthly targets of 0 for all months of the year except November. The same setup is replicated for water right (*WR*) records with identifiers B2000E_WIN_DRY, B2000E_WIN_AVG, and B2000E_WIN_WET.

On the first day of the winter season, one of the four water rights sets a target of 1.0 and the remaining water rights set targets of 0.0. All four water rights set targets of 0.0 every day of the year besides November 1. Because prior-day regulated flow was used in developing the targets, the hydrologic conditions on November 1 indicate hydrologic conditions for the last day of the preceding season.

Table 16. Sample Input Records for Evaluating Seasonal Hydrologic Conditions

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!------
**       1         2         3         4         5         6         7
**345678901234567890123456789012345678901234567890123456789012345678901234567
**-----!-------!-------!-------!-------!-------!-------!-------!-------!------
WRB2000E     1.0  BEGWIN20110301   8                             B2000E_WIN_SEV
TO    13               MUL                                  B2000E_ANREG_SEV
DO        16
DW         2   1
```

2.4.1.3 Subsistence and Base Flow Targets

The water right (*WR*) record reproduced in Table 17 below with identifier B2000E_SUB_WIN is a type 8 target setting water right modified by *UC*, *FS*, *DO*, and *DW* records. Its purpose is to set the winter subsistence flow target. According to the environmental flow standards, the subsistence flow target is set during severe hydrologic conditions if regulated stream flow is less than the dry base flow level. Use coefficient (*UC*) record with identifier WIN distributes the *WR* record target *AMT* equally across the four months included in the winter season. Accordingly, the water right (*WR*) record field 3 target *AMT* is set equal to four times the subsistence flow target, converted from units of cubic feet per second to acre-feet per day.

Table 17. Sample Input Records for Modeling Subsistence Flows

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------
**       1         2         3         4         5         6         7         8         9
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------
WRB2000E    7.93     WIN20110301   8                            B2000E_SUB_WIN
FS    10             1.0     0.0     1.0           1         121                B2000E _WIN_SEV
FS     1             0.0     1.0    3.97           1           0
DO                19
DW         2
```

The first *FS* record determines whether severe hydrologic conditions apply. Flow switch (*FS*) record field 3 option 10 is used to track the cumulative stream flow for the target set by water right B2000E_WIN_SEV. If the cumulative target for the current and previous 121 days is greater than or equal to 1.0, then the *WR* record target *AMT* is multiplied by 1.0. Otherwise the target is multiplied by 0.0.

The second *FS* record determines whether regulated stream flow is less than the dry base flow level. Flow switch (*FS*) record field 3 option 1 is used to track cumulative regulated stream flow for the current day. If current-day regulated stream flow is greater than or equal to the dry base flow level, the water right (*WR*) target *AMT* is multiplied by 0.0. Otherwise the target is multiplied by 1.0. Daily options (*DO*) record field 5 option 19 applies the *FS* records as step 19 in the target building process. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and the *UC* record. If severe hydrologic conditions are indicated by water right B2000E_WIN_SEV on the first day of the Winter season (corresponding to the last day of the preceding season via prior-day regulated flow target setting water right B2000E_YSTRDYREG), then a non-zero subsistence flow target is set every day of the Winter season that regulated flow is less than the dry base flow level. Otherwise a subsistence flow target of zero is set.

A similar setup is used for *WR* records with identifiers B2000E_BASES_WIN, B2000E_BASED_WIN, B2000E_BASEA_WIN, and B2000E_BASEW_WIN, which set winter base flow targets for severe, dry, average, and wet hydrologic conditions. For water right B2000E_BASES_WIN the second *FS* record is used to multiply the *WR* record target *AMT* by 1.0 if the current-day regulated flow is greater than or equal to the dry base flow level. Otherwise the target is multiplied by 0.0. Water rights B2000E_BASED_WIN, B2000E_BASEA_WIN, and B2000E_BASEW_WIN are not modified by a second *FS* record that tracks current-day regulated stream flow. Current-day regulated stream flow is only required to determine whether the subsistence flow or base flow requirement is applicable during severe hydrologic conditions.

2.4.1.4 High Flow Pulse Event Targets

Water right (*WR*) record with identifier B2000E_PULSE, as seen in Table 18, is a type 8 target setting water right modified by *PF* and *PO* records. Its purpose is to set a target equal to the largest applicable daily pulse flow target. Nine *PF*/*PO* record pairs are included to represent four two-per-season pulses, four one-per-season pulses, and one annual pulse. In accordance with the environmental flow standards, the *PF* records are organized in order of increasing trigger magnitude so that smaller pulses are engaged simultaneously with larger pulses.

Table 18. Sample Input Records for Modeling High Flow Pulse Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-
**       1         2         3         4         5         6         7         8         9
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-
WRB2000E       0        20110301   8                            B2000E_PULSE
PF     0           35.70     120  13   2          11   2           2   4        B2000E _WINTER_S
PO             2
```

Pulse flow (*PF*) record with identifier B2000E_WINTER_S is used to model the winter “small seasonal” two-per-season high flow pulse. Pulse flow (*PF*) record field 3 option 0 tracks regulated flow at control point B2000E for defining pulse events. The values entered in fields 5, 6, and 7 for *TRIGGER*, *VOLUME*, and *DURATION* define the pulse event initiation and termination criteria. The winter small seasonal pulse event is initiated if the daily regulated flow equals or exceeds 35.70 acre-feet. The pulse is terminated when the cumulative pulse flow volume equals 120 acre-feet or when the pulse flow duration equals 13 days, whichever occurs first. Field 8 variable *FREQ* sets the maximum number of pulse events that are recognized per tracking period. The tracking period is limited to the winter season using the entries in fields 10 and 11. Field 14 option 2 limits the daily pulse targets to be less than or equal to the field 5 *TRIGGER* criterion. Thus, in accordance with the environmental flow standards, water right holders with a priority junior to March 1, 2011 may make diversions when stream flow levels exceed the high flow pulse trigger level. Field 15 option 4 sets the target as the maximum of the *PF* record target and the preceding target. Pulse options (*PO*) record field 4 option 2 is used to block pulse event initiation if another pulse event with a larger magnitude is engaged at the same control point.

2.4.1.5 Final Daily Instream Flow Target

Instream flow (*IF*) record with identifier IF-B2000E is an instream flow right modified by *TO* and *DO* records. Its purpose is to set the daily instream flow target for control point B2000E. Twenty-one target options (*TO*) records are used to select the maximum daily target established by the target setting water rights in Sections 2.4.1.3 and 2.4.1.4. Twenty of the twenty-one water rights referenced by the *TO* records correspond to subsistence and base flow targets for the four seasons. Fifteen of these water rights correspond to the spring, summer, and fall seasons, for which *WR* records are not included in Table 14. Daily options (*DO*) record field 3 option 16 applies the *TO* records as step 16 in the target building process. Instream flow (*IF*) record field 7 option 2 adopts the largest *IF* record target at control point B2000E.

2.4.2 Control Points Located on the Colorado River below Lake Travis

Control point J3000E (USGS Gage 08159200, Colorado River at Bastrop) is located on the Colorado River below Lake Travis. The environmental flow standards for this location consist of subsistence and base flows that vary monthly and according to hydrologic conditions, a two-per-season high flow pulse, and a one per 18-month high flow pulse, as seen in Table 19. Three hydrologic conditions are specified based on the combined reservoir storage in Lakes Travis and Buchanan, evaluated on the last day of the preceding season. The input records included in this section model all of the environmental flow requirements at control point J3000E.

Table 19. Environmental Flow Standards for Control Point J3000E

Season	Month	Hydrologic Condition	Subsistence (cfs)	Base (cfs)	Pulse	
					2 per season	
Winter	December	Severe	186	311	Trigger: (cfs)	3,000
		Dry	N/A	311	Duration: (days)	4
		Average	N/A	450		
	January	Severe	208	313		
		Dry	N/A	313		
		Average	N/A	433		
	February	Severe	274	317		
		Dry	N/A	317		
		Average	N/A	497		
Spring	March	Severe	274	274	Trigger: (cfs)	3,000
		Dry	N/A	274	Duration: (days)	4
		Average	N/A	497		
	April	Severe	184	287		
		Dry	N/A	287		
		Average	N/A	635		
	May	Severe	275	579		
		Dry	N/A	579		
		Average	N/A	824		
	June	Severe	202	418		
		Dry	N/A	418		
		Average	N/A	733		
Summer	July	Severe	137	347	Trigger: (cfs)	3,000
		Dry	N/A	347	Duration: (days)	4
		Average	N/A	610		
	August	Severe	123	194		
		Dry	N/A	194		
		Average	N/A	381		
Fall	September	Severe	123	236	Trigger: (cfs)	3,000
		Dry	N/A	236	Duration: (days)	4
		Average	N/A	423		
	October	Severe	127	245		
		Dry	N/A	245		
		Average	N/A	433		
	November	Severe	180	283		
		Dry	N/A	283		
		Average	N/A	424		
					1 per 18-month	
					Trigger: (cfs)	8,000
					Duration: (days)	2

The input records used for modeling the environmental flow standards for control point J3000E, as seen in Table 20, are categorized in four sections, as follows.

Section 2.4.2.1 - Daily subsistence and base flow targets are set. Three target setting water rights are used to set the subsistence flow targets for severe hydrologic conditions and the base flow targets for dry and average hydrologic conditions. Twelve target setting water rights are used to set the base flow targets for severe hydrologic conditions. Two target setting water rights are used to evaluate hydrologic conditions based on drought index (*DI*) records.

Section 2.4.2.2 - The daily high flow pulse target is set. A target setting water right adopts the maximum target set by a series of *PF* and *PO* records. A target of zero is set if no high flow pulse events are triggered.

Section 2.4.2.3 - The final daily instream flow target is set. An instream flow (*IF*) record adopts the maximum target set by the target setting water rights from Sections 2.4.2.1 and 2.4.2.2.

Section 2.4.2.4 - The combined reservoir storage for Lakes Travis and Buchanan is evaluated to determine if dry or average hydrologic conditions are applicable. Combined reservoir storage is evaluated using drought index *DI*/*IS*/*IP*/*IM* records.

Table 20. Input Records Used to Model Environmental Flow Standards at Control Point J3000E

```
**
** Use coefficients
**
UCJ3SSEV     186     208     274     274     184     275     202     137     123     123     127     180
UCJ3BDRY     311     313     317     274     287     579     418     347     194     236     245     283
UCJ3BAVG     450     433     497     497     635     824     733     610     381     423     433     424
UC   JAN       1       0       0       0       0       0       0       0       0       0       0       0
UC   FEB       0       1       0       0       0       0       0       0       0       0       0       0
UC   MAR       0       0       1       0       0       0       0       0       0       0       0       0
UC   APR       0       0       0       1       0       0       0       0       0       0       0       0
UC   MAY       0       0       0       0       1       0       0       0       0       0       0       0
UC   JUN       0       0       0       0       0       1       0       0       0       0       0       0
UC   JUL       0       0       0       0       0       0       1       0       0       0       0       0
UC   AUG       0       0       0       0       0       0       0       1       0       0       0       0
UC   SEP       0       0       0       0       0       0       0       0       1       0       0       0
UC   OCT       0       0       0       0       0       0       0       0       0       1       0       0
UC   NOV       0       0       0       0       0       0       0       0       0       0       1       0
UC   DEC       0       0       0       0       0       0       0       0       0       0       0       1
**
** Section 2.4.2.1 - Subsistence and base flow targets
**
WRJ3000E 4548.10  J3SSEV20110301   8                            J3000E_SUB
DW         2
WRJ3000E  620.83     JAN20110301   8                            J3000E_BASES_JAN
FS     1             0.0     1.0          620.83   1           0           1
DO                19
DW         2
WRJ3000E  628.76     FEB20110301   8                            J3000E_BASES_FEB
FS     1             0.0     1.0          628.76   1           0           1
DO                19
DW         2
WRJ3000E  543.47     MAR20110301   8                            J3000E_BASES_MAR
FS     1             0.0     1.0          543.47   1           0           1
DO                19
DW         2
WRJ3000E  569.26     APR20110301   8                            J3000E_BASES_APR
FS     1             0.0     1.0          569.26   1           0           1
DO                19
DW         2
WRJ3000E 1148.43     MAY20110301   8                            J3000E_BASES_MAY
FS     1             0.0     1.0         1148.43   1           0           1
DO                19
DW         2
WRJ3000E  829.09     JUN20110301   8                            J3000E_BASES_JUN
FS     1             0.0     1.0          829.09   1           0           1
DO                19
DW         2
WRJ3000E  688.26     JUL20110301   8                            J3000E_BASES_JUL
FS     1             0.0     1.0          688.26   1           0           1
DO                19
DW         2
WRJ3000E  384.79     AUG20110301   8                            J3000E_BASES_AUG
FS     1             0.0     1.0          384.79   1           0           1
DO                19
DW         2
WRJ3000E  468.10     SEP20110301   8                            J3000E_BASES_SEP
FS     1             0.0     1.0          468.10   1           0           1
DO                19
DW         2
WRJ3000E  485.95     OCT20110301   8                            J3000E_BASES_OCT
FS     1             0.0     1.0          485.95   1           0           1
DO                19
DW         2
```

Table 20 Continued.

```
WRJ3000E  561.32     NOV20110301   8                            J3000E_BASES_NOV
FS     1             0.0     1.0          561.32   1           0           1
DO                19
DW         2
WRJ3000E  616.86     DEC20110301   8                            J3000E_BASES_DEC
FS     1             0.0     1.0          616.86   1           0           1
DO                19
DW         2
**
WRJ3000E   99999               0   8                           8J3000E_TRGTD
WRJ3000E 7545.12  J3BDRY20110301   8                            J3000E_BASED
FS    10             1.0     0.0     1.0           1           0                J3000E_TRGTD
DO                19
DW         2
WRJ3000E   99999               0   8                           9J3000E_TRGTA
WRJ3000E12575.21  J3BAVG20110301   8                            J3000E_BASEA
FS    10             1.0     0.0     1.0           1           0                J3000E_TRGTA
DO                19
DW         2
**
** Section 2.4.2.2 - High flow pulse event target
WRJ3000E       0        20110301   8                            J3000E_PULSE
PF     0         5950.41           4   2          12   2           2   4                    J3000E_WINTER
PO             2
PF     0         5950.41           4   2           3   6           2   4                    J3000E_SPRING
PO             2
PF     0         5950.41           4   2           7   8           2   4                    J3000E_SUMMER
PO             2
PF     0         5950.41           4   2           9  11           2   4                    J3000E_FALL
PO             2
PF     0        15867.77           2   1     548                   2   4                    J3000E_1PER18MO
PO             2
**
** Section 2.4.2.3 - Final instream flow target
**
IFJ3000E                20110301   2            IF-J3000E
TO    13             MAX                                J3000E_SUB      CONT
TO    13             MAX                                J3000E_BASES_JANCONT
TO    13             MAX                                J3000E_BASES_FEBCONT
TO    13             MAX                                J3000E_BASES_MARCONT
TO    13             MAX                                J3000E_BASES_APRCONT
TO    13             MAX                                J3000E_BASES_MAYCONT
TO    13             MAX                                J3000E_BASES_JUNCONT
TO    13             MAX                                J3000E_BASES_JULCONT
TO    13             MAX                                J3000E_BASES_AUGCONT
TO    13             MAX                                J3000E_BASES_SEPCONT
TO    13             MAX                                J3000E_BASES_OCTCONT
TO    13             MAX                                J3000E_BASES_NOVCONT
TO    13             MAX                                J3000E_BASES_DECCONT
TO    13             MAX                                J3000E_BASED    CONT
TO    13             MAX                                J3000E_BASEA    CONT
TO    13             MAX                                J3000E_PULSE
DO        16
**
** Section 2.4.2.4 - Drought indices for determining hydrologic condition
**
DI     8       2  TRAVIS  BUCHAN
IS     4       0 1103699 1103700 1737460
IP             0       0     100     100
IM    -1  -2   3  -3  -3  -3   7  -7   9  -9  -9  12
DI     9       2  TRAVIS  BUCHAN
IS     4       0 1737459 1737460 9000000
IP             0       0     100     100
IM    -1  -2   3  -3  -3  -3   7  -7   9  -9  -9  12
```

2.4.2.1 Subsistence and Base Flow Targets

The water right (*WR*) record reproduced below with identifier J3000E_SUB, as seen in Table 21, is a type 8 target setting water right modified by *UC* and *DW* records. The purpose of this water right is to set a daily subsistence flow target. The *WR* record field 3 annual target *AMT* is set equal to the sum of the monthly subsistence flow standards converted from units of cubic feet per second to acre feet per day. Using the severe subsistence flow use coefficient *UC* record with identifier J3SSEV, a monthly target is set by multiplying the field 3 target *AMT* by the use coefficient monthly multiplier. The use coefficient monthly multiplier is determined by dividing the monthly coefficient for a given month by the sum of the twelve monthly coefficients. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and the *UC* record.

Table 21. Sample Input Records for Modeling Subsistence Flows

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!--
**       1         2         3         4         5         6         7
**345678901234567890123456789012345678901234567890123456789012345678901234
**-----!-------!-------!-------!-------!-------!-------!-------!-------!--
WRJ3000E 4548.10  J3SSEV20110301   8                            J30000_SUB
DW         2
```

Water right (*WR*) record with identifier J3000E_BASES_JAN, as seen in Table 22, is a type 8 target setting water right modified by *UC*, *FS*, *DO*, and *DW* records. Its purpose is to set a daily base flow target during severe hydrologic conditions in the month of January when regulated flow equals or exceeds the dry base flow level. The *WR* record field 3 target *AMT* is set equal to the severe base flow standard for the month of January converted from units of cubic feet per second to acre feet per day. The use coefficient (*UC*) record with identifier JAN multiplies the field 3 target *AMT* by 1.0 in the month of January and 0.0 in all other months. Flow switch (*FS*) record field 3 option 1 tracks regulated flow at the control point. If current-day regulated flow is less than the dry base flow level, then the *WR* record target *AMT* is multiplied by 0.0. Otherwise the target is multiplied by 1.0. Daily options (*DO*) record field 5 option 19 applies the *FS* record as step 19 in the target building process. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and *UC* record. Eleven similar target setting water rights are used to model severe base flow standards for the remaining months of the year, as seen in Table 20.

Table 22. Sample Input Records for Modeling Base Flow Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!
**       1         2         3         4         5         6         7         8
**345678901234567890123456789012345678901234567890123456789012345678901234567890
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!
WRJ3000E  620.83     JAN20110301   8                            J3000E_BASES_JAN
FS     1             0.0     1.0          620.83   1           0           1
DO                19
DW         2
```

Water right (*WR*) record with identifier J3000E_TRGTD, as seen in Table 23, is a type 8 target setting water right. Its purpose is to set a monthly non-zero target during dry hydrologic conditions. Water right (*WR*) record field 11 variable *DINDEX* is assigned a value of 8, corresponding to the drought index (*DI*) record with identifier 8. Using the drought index (*DI*) record and limits defined by *IS*/*IP* records, when the combined reservoir storage in Lakes Travis and Buchanan is within the limits for dry hydrologic conditions, the *WR* record target *AMT* is multiplied by 1.0. Otherwise the target is multiplied by 0.0. The monthly switch (*IM*) record is used to apply the hydrologic condition determined for one month to a specified number of following months. The hydrologic condition is determined for the starting month of each season and applied to the remaining months in the season. Job options (*JO*) record field 8 option 0 is used in the Colorado WAM. It uses beginning-of-period storage for calculating the drought index. Water right (*WR*) record field 5 is assigned a priority of 0. It is assumed that beginning-of-period storage evaluated at the beginning of the priority sequence at the beginning of the season is equivalent to the storage evaluated on the last day of the preceding season. Water right (*WR*) record with identifier J3000E_TRGTA and drought index (*DI*) record with identifier 9 (see Table 20) are similar records used to determine whether average hydrologic conditions are applicable.

Table 23. Sample Input Records for Determining the Hydrologic Condition

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!----
**       1         2         3         4         5         6         7
**34567890123456789012345678901234567890123456789012345678901234567890123456
**-----!-------!-------!-------!-------!-------!-------!-------!-------!----
WRJ3000E   99999               0   8                           8J3000E_TRGTD
**
DI     8       2  TRAVIS  BUCHAN
IS     4       0 1103699 1103700 1737460
IP             0       0     100     100
IM   -12 -12   3  -3  -3  -3   7  -7   9  -9  -9  12
```

Water right (*WR*) record with identifier J3000E_BASED, as seen in Table 24, is a type 8 target setting water right modified by *UC*, *FS*, *DO*, and *DW* records. Its purpose is to set the daily dry hydrologic conditions base flow target. The water right (*WR*) record field 3 target *AMT* is set equal to the sum of the dry base flow monthly targets converted from units of cubic feet per second to acre feet per day. The *WR* record target *AMT* is multiplied by the monthly multipliers specified by use coefficient (*UC*) record with identifier J3BDRY. Flow switch (*FS*) record field 3 option 10 is used to track the target set by water right J3000E_TRGTD. When the target is greater than 1.0 acre feet, the *WR* record target *AMT* is multiplied by 1.0. Otherwise the target is multiplied by 0.0. Daily options (*DO*) record field 5 option 19 applies the *FS* record as step 19 in the target building process. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and the *UC* record. Water right (*WR*) record with identifier J3000E_BASEA (see Table 20) is a similar target setting water right used to set the daily average hydrologic conditions base flow target.

Table 24. Sample Input Records for Modeling Base Flow Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-----
**       1         2         3         4         5         6         7         8         9
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-----
WRJ3000E 7545.12  J3BDRY20110301   8                            J3000E_BASED
FS    10             1.0     0.0     1.0           1           0                J3000E _TRGTD
DO                19
DW         2
```

2.4.2.2 High Flow Pulse Event Targets

Water right (*WR*) record with identifier J3000E_PULSE is a type 8 target setting water right modified by *PF* and *PO* records. Its purpose is to set the daily high flow pulse target. The setup used for modeling the high flow pulse standards for control point J3000E and other control points located on the Colorado River below Lake Travis is the same as the setup described previously (Section 2.4.1.4) for modeling high flow pulse standards at control points located on the Colorado River above Lake Travis and tributaries of the Colorado River.

2.4.2.3 Final Daily Instream Flow Target

Instream flow (*IF*) record with identifier IF-J3000E is an instream flow right modified by *TO* and *DO* records. Its purpose is to set the daily instream flow target at control point J3000E. The methodology used for setting the final daily instream flow target is the same as the methodology described previously in Section 2.4.1.5.

2.4.3 Omission of SB3 Water Right Permit Conditions

As described in Section 2.3.3, water right permit conditions are included in the environmental flow standards that preclude certain future water right permits from being subject to one or more of the high flow pulse requirements based on the permitted diversion rate or permitted on-channel storage capacity. As a result of the complexities associated with circumventing the priority sequence, the water right permit conditions were not incorporated in the set of input records used to model the environmental flow standards.

2.5 Overview of the Trinity River Basin and Trinity WAM

The Trinity River is approximately 400 miles in length with a drainage area of 18,000 square miles. The headwaters of the river originate north of the Dallas-Fort Worth Metropolitan area near the Texas-Oklahoma border and the river discharges to Galveston Bay east of Houston, as seen in Figure 4. Precipitation generally decreases moving from east to west across the basin. Average annual precipitation is 53 inches at the basin outlet at Galveston Bay and 29 inches at the northwestern tip of the basin. The major tributaries are the West Fork Trinity River, Elm Fork Trinity River, East Fork Trinity River, Cedar Creek, Chambers Creek, and Richland Creek. The 2010 population given for Region C of the 2012 Texas Water Plan, which encompasses the Dallas-Fort Worth metropolitan area, was 6.7 million.

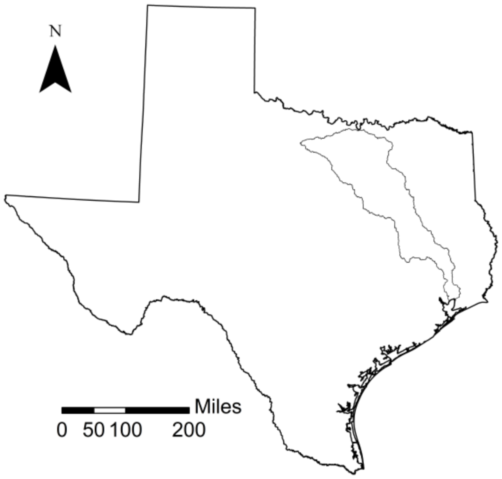

Figure 4. Trinity River Basin

A large portion of the water supply in the Trinity River basin is provided by surface water resources. The major water suppliers are the Trinity River Authority, Tarrant Regional Water District, Dallas Water Utilities, and North Texas Municipal Water District, which own 14 of the largest reservoirs in the basin. Eight multiple-use reservoirs are operated by the USACE Fort Worth District for flood control in addition to being used for water supply.

The original Trinity WAM dataset was completed in 2002 by Espey Consultants, as documented by a report (Espey Consultants, 2002). The dataset which was used to model the SB3 environmental instream flow requirements was the authorized use scenario Trinity WAM with draft revisions by TCEQ dated October 2012. The original Trinity WAM contained 552 water right records accounting for a total diversion of 5,322,610 acre-feet per year, with 58% used for municipal purposes, 35% used for industrial purposes, and 7% used for irrigation. The October 2012 Trinity WAM contains 1,061 water right records and 71 instream flow records. Conversion of the Trinity WAM to a daily time-step simulation involved several steps, including the disaggregation of flows from monthly to daily and the calibration of routing parameters, which are documented in the forthcoming report entitled *Application of Expanded WRAP Modeling Capabilities to the Trinity WAM* by Hoffpauir et al. The report also describes the records used to model SB3 instream flow standards and reservoir flood control operations. Subordination agreements that are represented in the October 2012 authorized use scenario Trinity WAM dataset were not included in the daily authorized use scenario Trinity WAM dataset used for the analyses included in this thesis. A methodology adequate to represent the subordination agreements within a daily time-step simulation is forthcoming and expected to be incorporated in the datasets accompanying the aforementioned report.

The Trinity WAM contains 40 primary control points. Locations and descriptive information for the primary control points are given in Figure 5 and Table 25, with the four control points at which environmental flows were modeled indicated in black. Net evaporation less precipitation depths are provided in the EVA file at the locations of 31 reservoirs and 19 quadrangles.

Table 25. Primary Control Points in the Trinity WAM

Control Point	USGS Gage No.	Location	Watershed Area (sq. miles)
8WTJA	08042800	West Fork Trinity River near Jacksboro	683
8BSBR	08044000	Big Sandy Creek near Bridgeport	333
8WTBO	08044500	West Fork Trinity River near Boyd	1,725
8CTAL	08046000	Clear Fork Trinity River near Aledo	251
8CTBE	08047000	Clear Fork Trinity River near Benbrook	431
8CTFW	08047500	Clear Fork Trinity River at Fort Worth	518
8WTFW	08048000	West Fork Trinity River at Fort Worth	2,615
8WTGP	**08049500**	**West Fork Trinity River at Grand Prairie**	**3,065**
8MCGP	08050100	Mountain Creek at Grand Prairie	298
8ELSA	08050500	Elm Fork Trinity River near Sanger	381
8IDPP	08051000	Isle Du Bois Creek near Pilot Point	266
8CLSA	08051500	Clear Creek near Sanger	295
8ELLE	08053000	Elm Fork Trinity River near Lewisville	1,673
8DNJU	08053500	Denton Creek near Justin	400
8DNGR	08055000	Denton Creek near Grapevine	705
8TRDA	**08057000**	**Trinity River at Dallas**	**6,106**
8WRDA	08057200	White Rock Creek at Greenville Ave	66
8ETMK	08059000	East Fork Trinity River near McKinney	190
8SGPR	08059500	Sister Grove Creek near Princeton	113
8ETLA	08061000	East Fork Trinity River near Lavon	773
8ETFO	08061750	East Fork Trinity River near Forney	1,118
8ETCR	08062000	East Fork Trinity River near Crandall	1,256
8TRRS	08062500	Trinity River near Rosser	8,146
8TRTR	08062700	Trinity River at Trinidad	8,538
8CEKE	08062800	Cedar Creek near Kemp	189
8KGKA	08062900	Kings Creek near Kaufman	233
8CEMA	08063000	Cedar Creek near Mabank	733
8RIDA	08063100	Richland Creek near Dawson	333
8RIRI	08063500	Richland Creek near Richland	734
8WABA	08063800	Waxahachie Creek near Bardwell	178
8CHCO	08064500	Chambers Creek near Corsicana	963
8RIFA	08064600	Richland Creek near Fairfield	1,957
8TEST	08064700	Tehuacana Creek near Streetman	142
8TROA	**08065000**	**Trinity River near Oakwood**	**12,833**
8TRCR	08065350	Trinity River near Crockett	13,911
8TRMI	08065500	Trinity River near Midway	14,450
8BEMA	08065800	Bedias Creek near Madisonville	321
8TRRI	08066000	Trinity River at Riverside	15,589
8TRRO	**08066500**	**Trinity River at Romayor**	**17,186**
8TRGB	N/A	Trinity River at Galveston Bay	17,949

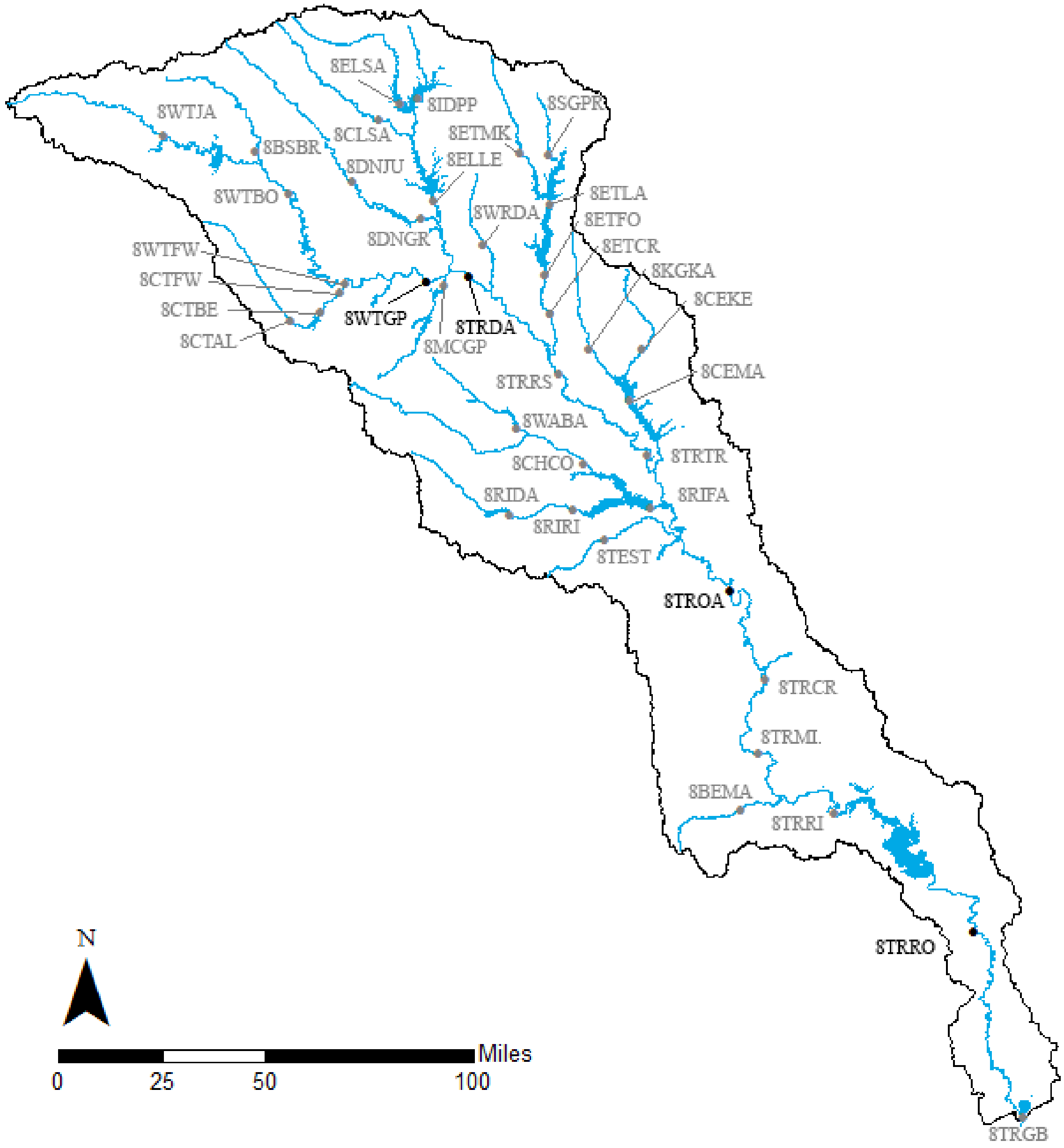

Figure 5. Map of Primary Control Points in the Trinity WAM

Figure 6 is a map showing the major tributaries and reservoirs in the basin. The numbers next to each reservoir correspond to the map identifiers in Table 26. The original dataset of naturalized flows and net evaporation-precipitation rates has a hydrologic period-of-analysis of 57 years from 1940 to 1996. An extended 73-year hydrologic period-of-analysis from 1940 to 2012, as documented by a report by Pauls et al. (2013), was implemented for the simulations included in this thesis.

Table 26. Major Reservoirs in the Trinity WAM

Map ID	Reservoir Name	WAM Identifier	Authorized Storage Capacity (ac-ft)
1	Lake Livingston	LIVSTN	1,750,000
2	Richland-Chambers Reservoir	RICHCH	1,135,000
3	Ray Roberts Lake	ROBDEN	799,600
4	Cedar Creek Reservoir	CEDAR	678,900
5	Lewisville Lake	LEWDE1	618,400
6	Lake Ray Hubbard	HUBBRD	490,000
7	Lavon Lake	LAVON0	456,500
8	Lake Bridgeport	BRIDGE	387,000
9	Eagle Mountain Lake	EGLMTN	210,000
10	Joe Pool Lake	JOPOOL	176,900
11	Grapevine Lake	GPVGP1	162,500
12	Benbrook Lake	BENBRK	88,250
13	Navarro Mills Lake	NAVARO	63,300
14	Bardwell Lake	BARDWL	54,900
15	Fairfield Lake	FAIRFD	50,600
16	Lake Arlington	ARLING	45,710
17	Lake Worth	WORTH	38,124
18	Lake Anahuac	ANAHUA	35,300
19	Lake Amon G. Carter	CARTER	28,589
20	Mountain Creek Lake	MTNCRK	22,840
21	White Rock Lake	WHITER	21,345
22	Houston County Lake	HOUCTY	19,500
23	Lake Weatherford	WTHRFD	19,470
24	North Lake	NORTH	17,100
25	Forest Grove Reservoir	FOREST	16,348
26	Lake Waxahachie	WAXAHC	13,500
27	Lost Creek Reservoir	LOSTCK	11,961
28	New Terrell City Lake	TERREL	8,712
29	Lake Halbert	HALBRT	7,357
30	Lake Kiowa	KIOWA	7,000
31	Trinidad Lake	TRINDD	6,200
32	Alvarado Park Lake	B5001	4,781

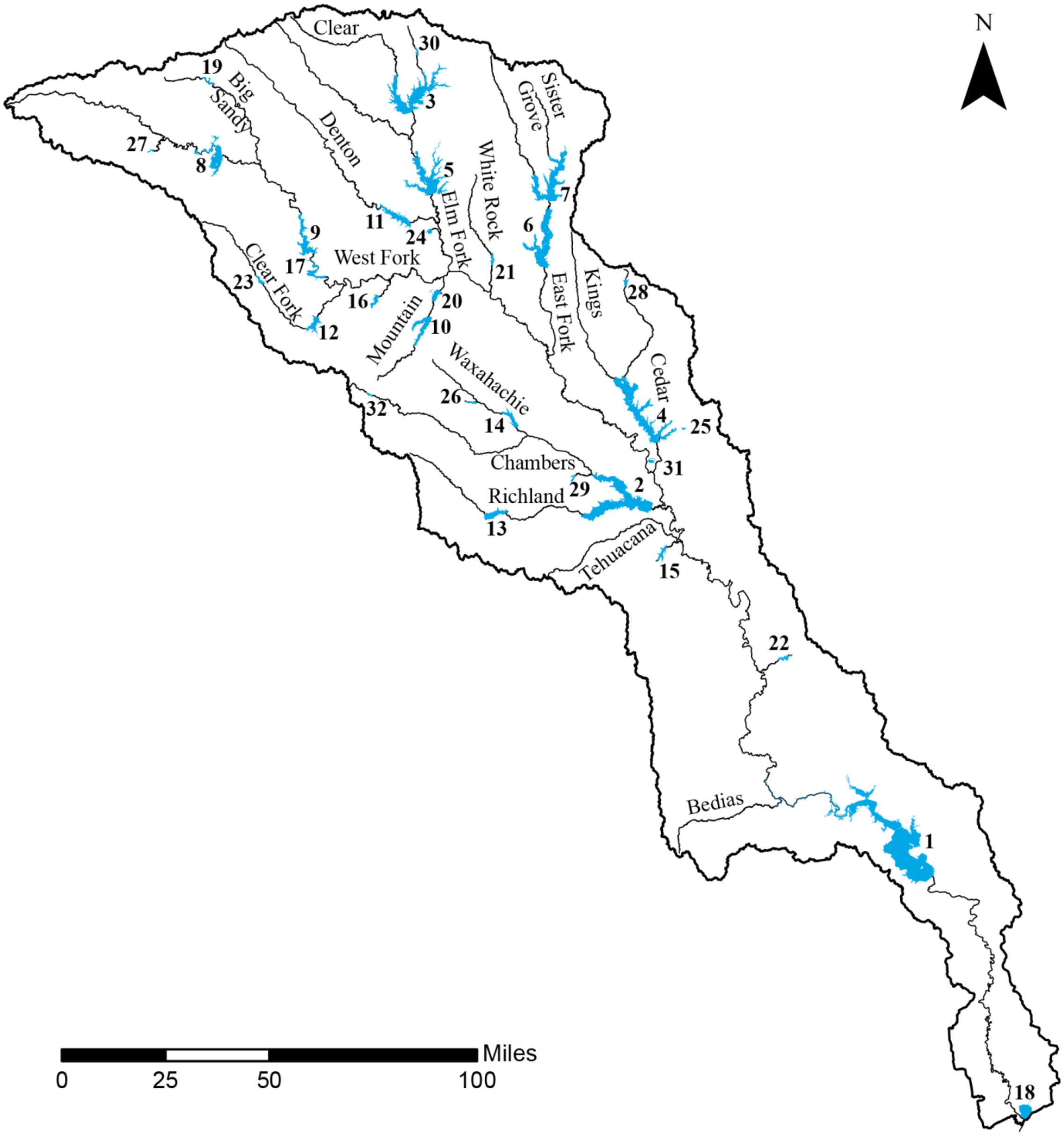

Figure 6. Major Tributaries and Largest Reservoirs in the Trinity River Basin

2.6 Environmental Flow Standards for the Trinity River Basin

The environmental flow standards for surface water for the Trinity and San Jacinto Rivers and Galveston Bay are documented in Texas Administrative Code Title 30, Part 1, Chapter 298, Subchapter B. Instream flow standards are established at six locations, including four sites in the Trinity River Basin and two sites in the San Jacinto River Basin. Bay and estuary freshwater inflow standards for Galveston Bay are also established for the Trinity and San Jacinto river outflows. Instream flow standards at four Trinity River Basin locations were incorporated into the daily Trinity WAM using the modeling techniques described in Section 2.7. The four locations, corresponding to the locations of Trinity WAM primary control points, are listed with descriptive information in Table 27. New control points were added immediately downstream of the primary control points in order to avoid over-writing any existing instream flow standards. The identifiers of the new control points are the same as the identifiers of the primary control points, with a letter "E" replacing the sixth character. The standards became effective May 15, 2011. The priority date used for water availability modeling is December 1, 2009, corresponding to the date that the BBEST report was submitted.

Table 27. Trinity WAM Control Point Locations for Instream Flow Standards

Control Point	USGS Gage No.	Location	Watershed Area	USGS Period-of-Record
			(sq. miles)	
8WTGPE	08049500	West Fork Trinity River near Grand Prairie	3,065	1925-present
8TRDAE	08057000	Trinity River at Dallas	6,106	1903-present
8TROAE	08065000	Trinity River near Oakwood	12,833	1923-present
8TRROE	08066500	Trinity River near Romayor	17,186	1924-present

The instream flow standards consist of seasonal subsistence flows, base flows, and high flow pulse events. Four seasons are defined according to the months listed in Table 28. For the purposes of tracking the frequency for which high flow pulse events are engaged, the six-month period from June through November is considered as a single season rather than two separate seasons.

Table 28. Months Included in Each Season

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

2.6.1 Subsistence and Base Flow Standards

If the flow at a control point is less than the applicable subsistence flow standard, then junior water right holders may not make diversions from the river. If the flow is greater than the subsistence flow standard and less than the applicable base flow standard, then junior water right holders may make diversions as long as the flow does not drop below the subsistence flow standard. The subsistence flow standards for the four control points in the Trinity River Basin are shown in Table 29.

Table 29. Subsistence Flow Standards (cfs)

Control Point	Winter	Spring	Summer	Fall
8WTGPE	19	25	23	21
8TRDAE	26	37	22	15
8TROAE	120	160	75	100
8TRROE	495	700	200	230

If the flow at a control point is greater than the applicable base flow standard and less than the applicable pulse flow trigger level, then junior water right holders may make diversions as long as the flow does not drop below the base flow standard. The base flow standards are shown in Table 30.

Table 30. Base Flow Standards (cfs)

Control Point	Winter	Spring	Summer	Fall
8WTGPE	45	45	35	35
8TRDAE	50	70	40	50
8TROAE	340	450	250	260
8TRROE	875	1,150	575	625

2.6.2 High Flow Pulse Standards

The high flow pulse standards are engaged when flow at a control point exceeds the applicable high flow pulse trigger level. Junior water right holders may not make diversions until either the applicable volume or duration time has passed since engagement of the trigger flow level. However, diversions can be made before the volume or duration criteria are met if the flow at the control point exceeds the high flow pulse trigger level, as long as diversions do not cause the flow to drop below the high flow pulse trigger level. Two pulses per season are specified for all four control points according to the criteria specified in Table 31. The tracking of high flow pulse events for each season is performed independently of preceding and subsequent seasons. As mentioned previously, the summer and fall seasons are combined as a single six-month season for the purposes of tracking high flow pulse events.

Table 31. High Flow Pulse Standards

Control Point	Criteria	Winter	Spring	Summer/Fall
8WTGPE	Trigger (cfs):	300	1,200	300
	Volume (ac-ft):	3,500	8,000	1,800
	Duration (days):	4	8	3
8TRDAE	Trigger (cfs):	700	4,000	1,000
	Volume (ac-ft):	3,500	40,000	8,500
	Duration (days):	3	9	5
8TROAE	Trigger (cfs):	3,000	7,000	2,500
	Volume (ac-ft):	18,000	130,000	23,000
	Duration (days):	5	11	5
8TRROE	Trigger (cfs):	8,000	10,000	4,000
	Volume (ac-ft):	80,000	150,000	60,000
	Duration (days):	7	9	5

2.6.3 Water Right Permit Conditions

For some water right permits issued after the effective date of the environmental flow standards, only a portion of the flow standards will apply, depending on the conditions of the new permit. Specifically, water right permits with an authorization to divert 10,000 acre-feet or less per year are not required to protect the high flow pulse requirements.

2.7 Modeling Environmental Flow Standards in the Trinity WAM

This section of the report documents the methodologies that were employed to model the environmental flow standards for the daily time-step Trinity WAM. The input records used to model the instream flow requirements for control point 8TRDAE, Trinity River at Dallas (USGS Gage 08057000), are included in this section for demonstration purposes. The same modeling methodology was used for all four control points in the Trinity WAM, as follows:

- Subsistence and base flow standards were modeled using target setting water right (*WR*) records in combination with flow switch (*FS*), target options (*TO*), daily data (*DW*), and daily options (*DO*) records.
- Pulse flow standards were modeled using a target setting water right (*WR*) record in combination with pulse flow (*PF*) records and pulse flow options (*PO*) records.
- The instream flow target was set using an instream flow (*IF*) record with a target equal to the maximum of the targets set by the target setting water right records.
- A priority number of 20091201 was used for all instream flow (*IF*) and water right (*WR*) records, corresponding to a priority date of December 1, 2009.

The environmental flow standards for control point 8TRDAE, Trinity River at Dallas, consist of seasonal subsistence flow, base flow, and high flow pulse requirements, as summarized in Table 32.

Table 32. Environmental Flow Standards for Control Point 8TRDAE

Season	Subsistence (cfs)	Base (cfs)	Pulse (2 per season)
Winter	26	50	Trigger (cfs): 700 Volume (ac-ft): 3,500 Duration (days): 3
Spring	37	70	Trigger (cfs): 4,000 Volume (ac-ft): 40,000 Duration (days): 9
Summer	22	40	Trigger (cfs): 1,000 Volume (ac-ft): 8,500 Duration (days): 5
Fall	15	50	

The input records used for modeling the environmental flow standards for control point 8TRDAE, as seen in Table 33, are categorized into three sections, as follows.

Section 2.7.1. Daily subsistence and base flow targets are set. Eight target setting water rights are implemented corresponding to subsistence and base flow targets for four seasons.

Section 2.7.2. The daily high flow pulse target is set using a target setting water right and a series of *PF* and *PO* records. A target of zero is set if no pulse events are triggered.

Section 2.7.3. The final daily instream flow target is set. An instream flow (*IF*) record adopts the maximum target set by the target setting water rights from Sections 2.7.1 and 2.7.2.

Table 33. Input Records for Environmental Flow Standards for Control Point 8TRDAE

```
**
** Use Coefficient Records Used to Identify Seasons
**
UCWINTER       1       1       0       0       0       0       0       0       0       0       0       1
UCSPRING       0       0       1       1       1       0       0       0       0       0       0       0
UCSUMMER       0       0       0       0       0       1       1       1       0       0       0       0
UC  FALL       0       0       0       0       0       0       0       0       1       1       1       0
**
** Section 2.7.1 - Subsistence and Base Flow Targets
**
WR8TRDAE   99999  WINTER20091201   8                            8TRDAE_SUB_WIN
TO    15   51.57     MIN
DO        16
WR8TRDAE  297.52  WINTER20091201   8                            8TRDAE_BASE_WIN
FS     1             0.0     1.0           99.17   1           0           1
DO                  19
DW          2
WR8TRDAE   99999  SPRING20091201   8                            8TRDAE_SUB_SPR
TO    15   73.39     MIN
DO        16
WR8TRDAE  416.53  SPRING20091201   8                            8TRDAE_BASE_SPR
FS     1             0.0     1.0          138.84   1           0           1
DO                  19
DW          2
WR8TRDAE   99999  SUMMER20091201   8                            8TRDAE_SUB_SMR
TO    15   43.64     MIN
DO        16
WR8TRDAE  238.02  SUMMER20091201   8                            8TRDAE_BASE_SMR
FS     1             0.0     1.0           79.34   1           0           1
DO                  19
DW          2
WR8TRDAE   99999    FALL20091201   8                            8TRDAE_SUB_FAL
TO    15   29.75     MIN
DO        16
WR8TRDAE  297.52    FALL20091201   8                            8TRDAE_BASE_FAL
FS     1             0.0     1.0           99.17   1           0           1
DO                  19
DW          2
WR8TRDAE       0        20091201   8                            8TRDAE_BASEFLOW
TO    13             MAX                                8TRDAE_SUB_WIN  CONT
TO    13             MAX                                8TRDAE_BASE_WIN CONT
TO    13             MAX                                8TRDAE_SUB_SPR  CONT
TO    13             MAX                                8TRDAE_BASE_SPR CONT
TO    13             MAX                                8TRDAE_SUB_SMR  CONT
TO    13             MAX                                8TRDAE_BASE_SMR CONT
TO    13             MAX                                8TRDAE_SUB_FAL  CONT
TO    13             MAX                                8TRDAE_BASE_FAL
DO        16
**
** Section 2.7.2 - Pulse Flow Targets
**
WR8TRDAE       0        20091201   8                            8TRDAE_PULSE
PF     0         1983.47    8500   5   2           6  11           2   4                    8TRDAE_SMRFAL
PO              2
PF     0         1388.43    3500   3   2          12   2           2   4                    8TRDAE_WINTER
PO              2
PF     0         7933.88   40000   9   2           3   5           2   4                    8TRDAE_SPRING
PO              2
**
** Section 2.7.3 - Final Instream Flow Target
**
IF8TRDAE                20091201   2            IF-8TRDAE
TO    13             MAX                                8TRDAE_BASEFLOW CONT
TO    13             MAX                                8TRDAE_PULSE
DO        16
```

2.7.1 Subsistence and Base Flow Targets

The water right (*WR*) record shown in Table 34 with identifier 8TRDAE_SUB_WIN is a type 8 target setting water right modified by *UC*, *TO*, and *DO* records.

Table 34. Sample Input Records for Modeling Subsistence Flow Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
**       1         2         3         4         5         6         7
**3456789012345678901234567890123456789012345678901234567890123456789012345678 9
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
WR8TRDAE   99999  WINTER20091201   8                            8TRDAE_SUB_WIN
TO    15   51.57     MIN
DO        16
```

Its purpose is to set the winter subsistence flow target. Target options (*TO*) record fields 2, 3, and 4 are used to set the water right target as the minimum of the target set in *WR* record field 3 and the Winter subsistence flow value (converted to units of acre-feet) in *TO* record field 3. Water right (*WR*) record field 3 is set to 99999 multiplied by the monthly use coefficient (*UC*) record with identifier WINTER. In January, February, and December, a positive target is set. For the remaining months of the year a target of 0.0 is set. Daily options (*DO*) record field 3 option 16 applies the *TO* record *TOTARGET* option as step 16 in the target building process. The same setup is used to set the spring, summer, and fall seasonal subsistence flow targets, corresponding to water right (*WR*) records with identifiers 8TRDAE_SUB_SPR, 8TRDAE_SUB_SMR, and 8TRDAE_SUB_FAL.

The water right (*WR*) record reproduced in Table 35 below with identifier 8TRDAE_BASE_WIN is a type 8 target setting water right modified by *UC*, *FS*, *DO*, and *DW* records.

Table 35. Sample Input Records for Modeling Base Flow Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
**       1         2         3         4         5         6         7
**34567890123456789012345678901234567890123456789012345678901234567890123456789
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
WR8TRDAE  297.52  WINTER20091201   8                            8TRDAE_BASE_WIN
FS     1             0.0     1.0           99.17   1           0           1
DO                19
DW         2
```

Its purpose is to set the winter base flow target. The value entered in water right (*WR*) record field 3 is equal to three times the base flow standard, in units of acre-feet. The target is modified by the use coefficient (*UC*) record with identifier WINTER. For the months of January, February, and December, the *WR* record target *AMT* is multiplied by 1/3. In all other months, the target *AMT* is multiplied by zero. The flow switch (*FS*) record is used to multiply the *WR* record target *AMT* by zero on days when the regulated flow is less than or equal to the winter base flow level. Daily options (*DO*) record field 5 option 19 applies the *FS* record as step 19 in the target building process. Daily data (*DW*) record field 3 option 2 sets a daily target using the *WR* record target and the *UC* record. The same methodology is used to model the spring, summer, and fall base flow requirements for water right (*WR*) records with identifiers 8TRDAE_BASE_SPR, 8TRDAE_BASE_SMR, and 8TRDAE_BASE_FAL.

2.7.2 High Flow Pulse Event Targets

The water right (*WR*) record shown in Table 36 below with identifier 8TRDAE_PULSE is a type 8 target setting water right modified by *PF* and *PO* records.

Table 36. Sample Input Records for Modeling High Flow Pulse Standards

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!--
**       1         2         3         4         5         6         7         8         9         1
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!-------!--
WR8TRDAE       0        20091201   8                            8TRDAE_PULSE
PF     0         1983.47    8500   5   2           6  11           2   4                    8TRDAE_SMRFAL
PO             2
```

Its purpose is to set the daily high flow pulse target. Pulse flow (*PF*) record with identifier 8TRDAE_SMRFAL is used to model the Summer/Fall seasonal pulse flow requirement. Pulse flow (*PF*) record field 3 option 0 specifies that regulated flow is used for defining pulse events. The values entered in fields 5, 6, and 7 for *TRIGGER*, *VOLUME*, and *DURATION* define the pulse event initiation and termination criteria. A Summer/Fall pulse event is initiated if the daily regulated flow equals or exceeds 1,983.47 acre-feet. The pulse is terminated when the cumulative pulse flow volume equals 8,500 acre-feet or when the pulse flow duration equals 5 days, whichever occurs first. Field 8 variable *FREQ* sets the maximum number of pulse events that are recognized per tracking period. The tracking period is limited to the Summer/Fall season using the entries in fields 10 and 11. Field 14 option 2 limits the daily pulse targets to be less than or equal to the field 5 *TRIGGER* criterion. Thus, in accordance with the environmental flow standards, water right holders with a priority junior to December 1, 2009 may make diversions when stream flow levels exceed the high flow pulse trigger level. Field 15 option 4 sets the target as the maximum of the *PF* record target and the preceding target. Pulse flow options (*PO*) record field 4 option 2 is used to block pulse event initiation if another pulse event with a larger magnitude is engaged at the same control point. The same methodology is used for the remaining two sets of *PF*/*PO* record pairs to model the winter and spring pulse flow requirements. All three *PF*/*PO* record pairs are evaluated simultaneously to set the *WR* record target.

2.7.3 Final Instream Flow Target

Instream flow (*IF*) record with identifier IF-8TRDAE, as seen in Table 37, is an instream flow right modified by *TO* and *DO* records. Its purpose is to set the daily instream flow target for control point 8TRDAE. Nine target options (*TO*) records are used to select the maximum daily target established by the target setting water rights in Sections 2.7.1 and 2.7.2. Daily options (*DO*) record field 3 option 16 applies the *TO* records as step 16 in the target building process. Instream flow (*IF*) record field 7 option 2 adopts the largest *IF* record target at control point 8TRDAE.

Table 37. Sample Input Records for Setting Daily Instream Flow Target

```
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
**       1         2         3         4         5         6         7
**34567890123456789012345678901234567890123456789012345678901234567890123456789
**-----!-------!-------!-------!-------!-------!-------!-------!-------!-------
IF8TRDAE                20091201   2            IF-8TRDAE
TO    13             MAX                                8TRDAE_BASEFLOW CONT
TO    13             MAX                                8TRDAE_PULSE
DO        16
```

2.7.4 Omission of SB3 Water Right Permit Conditions

The environmental flow standards specify that water right permits subject to the environmental flow standards with authorized yearly diversions of 10,000 acre-feet or less are not subject to the high flow pulse requirements. This provision was not incorporated in the modeling of instream flows as a result of the complexities associated with circumventing the priority sequence.

CHAPTER III

ATTAINMENT OF RECOMMENDED ENVIRONMENTAL FLOW STANDARDS

A variety of metrics were developed in order to characterize the engagement and attainment of various components of the environmental flow regimes for the Colorado and Trinity river basins. The attainment metrics are introduced and defined in Section 3.1. In Section 3.2, the metrics are used to evaluate SB3 environmental flow standards that were incorporated in daily time-step water availability models for the Colorado and Trinity river basins. Comparisons are made between alternate components of an environmental flow regime at a control point, alternate control points, and alternate river basin development scenarios.

3.1 Description of Attainment Metrics

As listed in Table 38, 28 metrics were developed in order to characterize the engagement and attainment of various components of the environmental flow regimes. The metrics were developed using spreadsheets and output from *SIMD* daily time-step simulations. The first 22 metrics listed in Table 38 with identifiers M1 through M12 represent general attainment metrics that are applicable to any flow conditions, including base flows and high flow pulse events. The 6 metrics listed in Table 38 with identifiers P1 through P6 can be evaluated for high flow pulse events only.

Table 38. Attainment Metrics

General Attainment Metrics

M1. Percentage of Time Instream Flow Target Was Engaged
M2. Engaged Volume Reliability
M3A. Engaged Period Reliability
M3B. Plot of Engaged Period Reliability vs. Allowable Deficit
M3C. Plot of Engaged Period Reliability vs. Allowable Percentage Deficit
M4A. Average Consecutive Number of Engaged Days
M4B. Exceedance Frequency Plot of Consecutive Number of Engaged Days
M5A. Average Consecutive Number of Engaged Days in Which Regulated Flow Equals or Exceeds the Instream Flow Target
M5B. Exceedance Frequency Plot of Consecutive Number of Engaged Days in Which Regulated Flow Equals or Exceeds the Instream Flow Target
M6A. Average Consecutive Number of Engaged Days in Which Regulated Flow is Less Than the Instream Flow Target
M6B. Exceedance Frequency Plot of Consecutive Number of Engaged Days in Which Regulated Flow is Less Than the Instream Flow Target
M7A. Average Consecutive Number of Days between Engagements
M7B. Exceedance Frequency Plot of Consecutive Number of Days between Engagements
M8. Histogram of the Cumulative Number of Engagements per Day-of-Year through the Period-of-Analysis
M9A. Average Vulnerability
M9B. Exceedance Frequency Plot of Vulnerability
M10A. Average Dimensionless Vulnerability
M10B. Exceedance Frequency Plot of Dimensionless Vulnerability
M11. Dimensionless Average Vulnerability
M12A. Expected Number of Days to Recover from Deficit
M12B. Plot of Resilience vs. Allowable Number of Days to Recovery

High Flow Pulse Attainment Metrics

P1. Target Number of Pulse Event Engagements
P2. Observed Number of Pulse Event Engagements
P3. Observed Number of Engaged Pulse Events That Satisfied Termination Criteria
P4. Percentage of Target Number of Pulse Events That Were Engaged
P5. Percentage of Years in Which All Pulse Flow Requirements Were Met
P6. Percentage of Engaged Pulse Events That Satisfied Volume Termination Criteria

3.1.1 General Attainment Metrics

The 22 metrics with identifiers M1 through M12 were developed using output from the SUB sub-monthly time-step simulation results file. Output from the *SIMD* simulation was recorded in the SUB file for a control point by listing the control point identifier on a *C2* record at the top of the DAT file just after the *JU* record. In order to develop the general attainment metrics, the regulated flow (REGFLOW) and instream flow target (IFTARGET) were evaluated for each day of the simulation at each control point of interest. A spreadsheet was designed so that metrics were only evaluated for IFTARGET values falling within a specified range of flow values and for flows occurring within a specified range of months. Creativity may be applied in setting the minimum IFTARGET, maximum IFTARGET, and set of months in which the target could occur in order to evaluate individual components of a flow regime, all of the flow components of a flow regime, or a specified subset of components of a flow regime.

In order to evaluate the Spring season, wet hydrologic conditions base flow at control point F1000E in the Colorado WAM, for example, the minimum and maximum IFTARGET values could both be set equal to 360 cfs, corresponding to the target flow, and the months 3, 4, 5, and 6 could be listed, corresponding to the Spring season. Using these parameters, the attainment metrics would only be evaluated for days in March, April, May, or June in which the IFTARGET was equal to 360 cfs.

Although the general attainment metrics may be used to evaluate flows corresponding to high flow pulse events, they are not immediately applicable for describing a specific high flow pulse event. For subsistence flows and base flows, the

IFTARGET is set to a single, specified value when the flow component is engaged. Thus, individual subsistence and base flow components may be evaluated by setting the minimum and maximum IFTARGET values equal to the specified target flow value. For high flow pulse events, however, a single high flow pulse event may be represented by multiple IFTARGET flow values. On the first day that the high flow pulse event is engaged, the IFTARGET is set equal to the trigger flow magnitude. On subsequent days, however, the IFTARGET may be set equal to the trigger magnitude or it may be set equal to a flow value less than the trigger magnitude based on the remaining event volume termination criterion. Additionally, smaller pulse events may be triggered before a large pulse event has met its volume criterion. This makes it difficult to identify flows corresponding to a specific high flow pulse event apart from the initial day in which it is triggered. It may still be useful, however, to evaluate all high flow pulse events within a specified range of flow values that occurred at a control point.

The general attainment metrics are defined as follows. Metric M1 is the percentage of time steps for which the IFTARGET falls within the ranges of flow values and months specified in the spreadsheet. The range of flow values is established by entering minimum and maximum flow values. The range of months is listed in numerical format, with multiple months separated by commas. The IFTARGET is engaged if it is greater than or equal the minimum flow value, less than or equal to the maximum flow value, and occurs within one of the listed months. The IFTARGET engagement is evaluated as a percentage of the total number of time steps for the period-of-analysis. If the month criterion were set to January, for example, the maximum possible value of M1 would be 8.33%.

Metric M2, the volume reliability, is the total sum of REGFLOW values divided by the total sum of IFTARGET values for engaged days.

Metric M3A, the period reliability, is the percentage of engaged days for which REGFLOW is greater than or equal to the IFTARGET. Metric M3B is a plot of the engaged period reliability evaluated for an array of IFTARGET values, in which the IFTARGET values are reduced by gradually increasing flow values, referred to as allowable deficits. Metric M3B is equal to the value of metric M3A for an allowable deficit equal to zero. Metric M3B is equal to 100% for an allowable deficit equal to the maximum deficit observed through the engaged period-of-analysis. A deficit is defined as the difference between the IFTARGET and REGFLOW if REGFLOW is less than the IFTARGET. Metric M3C is a plot of the engaged period reliability evaluated for an array of IFTARGET values, in which the IFTARGET values are reduced by gradually increasing flow values as a percentage of the IFTARGET, referred to as a gradually increasing allowable percentage deficit.

Metric M4A is the average of the consecutive number of engaged days. Metric M4B is an exceedance frequency plot of the consecutive number of engaged days.

Metric M5A is the average of the consecutive number of engaged days in which REGFLOW is greater than or equal to the IFTARGET. Metric M5B is an exceedance frequency plot of the consecutive number of engaged days in which REGFLOW is greater than or equal to the IFTARGET.

Metric M6A is the average of the consecutive number of engaged days in which REGFLOW is less than the IFTARGET. Metric M6B is an exceedance frequency plot of the consecutive number of engaged days in which REGFLOW is less than the IFTARGET.

Metric M7A is the average of the consecutive number of days between engagements of the IFTARGET. Metric M7B is an exceedance frequency plot of the consecutive number of days between engagements of the IFTARGET.

Metric M8 is a histogram of the cumulative number of IFTARGET engagements observed per calendar day-of-year through the period-of-analysis.

Vulnerability is another term for the deficit between REGFLOW and the IFTARGET. If the regulated flow equals or exceeds the instream flow target, the vulnerability is zero. Otherwise, vulnerability is computed as the IFTARGET minus REGFLOW. The vulnerability is computed for each engaged day of the simulation. Metric M9A is the average vulnerability. Metric M9B is an exceedance frequency plot of vulnerability for days in which a deficit was observed.

Dimensionless vulnerability is equal to vulnerability divided by the IFTARGET. Dimensionless vulnerability is computed for each engaged day of the simulation. Metric M10A is the average dimensionless vulnerability. Metric M10B is an exceedance frequency plot of dimensionless vulnerability for days in which a deficit was observed.

Metric M11, the dimensionless average vulnerability, is computed as the average vulnerability divided by the average engaged instream flow target. Metric M11 is differentiated from metric M10A in that days in which no deficits are observed are included in the computation of the average engaged instream flow target.

Resilience is the likelihood that once a deficit is observed, the system will recover (regulated flow will meet or exceed an instream flow target) within a specified number of time periods. Metric M12B is a plot of resilience versus allowable number of days to recovery. For each day of the simulation in which a deficit was observed, it was determined whether or not regulated flow equaled or exceeded the instream flow target in at least one of the allowable number of subsequent days. The resilience was computed as the number of days in which the system was able to recover from a deficit within the allowable number of days divided by the total number of days in which the system was in a deficit. The resilience was evaluated in this way for an array of allowable number of days to recovery. Metric M12A is the expected number of days to recover from a deficit. By treating the plot of M12B as a cumulative probability distribution function, the probability distribution function for allowable number of days to recovery was derived and used to compute the expected value for allowable number of days to recovery, termed the expected number of days to recovery.

3.1.2 High Flow Pulse Attainment Metrics

The six metrics with identifiers P1 through P6 were developed to characterize high flow pulse events using output from the SMM sub-monthly message file. The number of pulse events initiated per month and the number of pulse events that were terminated before achieving the event volume criterion were recorded in the SMM output file for each pulse flow record by entering a value of 2 in *PF* record field 16 for variable *PFSMM*. The six pulse flow specific metrics can be evaluated for individual high flow pulse event requirements specified by a single *PF* record or alternatively for all of the high flow pulse requirements at a control point.

Metric P1 is the target number of pulse event engagements. The target number of pulse event engagements per year is manually entered for each *PF* record in the spreadsheet. These values are multiplied by the number of years in the period-of-analysis to yield P1.

Metric P2 is the observed number of pulse event engagements. The number of pulse event engagements per month for each *PF* record is provided in tables in the SMM output file. This information is aggregated to yield total observed engagements for the full period-of-analysis for each control point.

Metric P3 is the observed number of pulse events engagements which satisfied the volume termination criteria. The number of pulse event engagements per month for each *PF* record that did not satisfy the termination criteria is provided in the SMM output file. These values are subtracted from the observed number of pulse engagements to yield the observed number of engagements which satisfied the volume termination criteria. These values are then aggregated over the period-of-analysis to yield metric P3.

Metric P4 is the percentage of the target number of pulse events that were engaged, computed as P2 divided by P1.

Metric P5 is the percentage of years in which all of the pulse flow requirements were completely met. For each year, the observed number of pulse event engagements was compared to the target number of pulse event engagements to determine whether all of the requirements were met for that year. For pulse events with frequency requirements exceeding one year, fractional target numbers of engagements were used. For the one per two year event, for example, a target engagement of 0.5 events per year was implemented.

Metric P6 is the percentage of engaged pulse events which satisfied the volume termination criteria, computed as P3 divided by P2.

3.2 Simulation Results

The attainment metrics were used to evaluate the results of three simulations. Two simulations were performed using the daily authorized use Colorado WAM for a 73-year period-of-analysis from 1940 to 2012. In the initial Colorado WAM simulation, the environmental flow requirements were modeled at 14 control points with a priority date of March 1, 2011, corresponding to the priority date specified in the Texas Administrative Code. In the second Colorado WAM simulation, the environmental flow requirements were simulated using a priority date of March 1, 1800, corresponding to the most senior priority in the basin. A third simulation was performed for the Trinity River basin for a 73-year period-of-analysis from 1940 to 2012 in which the environmental flow standards at four control points were modeled at a priority date of December 1, 2009, as specified in the Texas Administrative Code.

In Section 3.2.1, the attainment metrics were used to compare individual components of the environmental flow regime at control point B2000E based on results of the initial Colorado WAM simulation. In Section 3.2.2, the attainment metrics were used to make comparisons between alternate control points based on results of the initial

Colorado WAM simulation and the Trinity WAM simulation. Comparisons were made between 14 control points in the Colorado WAM and 4 control points in the Trinity WAM. In Section 3.2.3, the attainment metrics were used to compare the results of the two Colorado WAM simulations at control point F1000E.

Because the environmental flow standards were modeled within the authorized use scenario datasets, the attainment metrics and simulation results must be interpreted with caution. As described previously, return flows were not included in the authorized use scenario datasets and the permitted diversion amounts for each water right do not necessarily reflect the amount of water that is typically diverted by permit holders in reality.

3.2.1 Evaluation of Individual Environmental Flow Components at a Control Point

Alternate components of the SB3 environmental flow regime at control point B2000E using the attainment metrics and results of the initial Colorado WAM simulations. The SB3 environmental flow regime components and associated instream flow targets for control point B2000E are listed in Table 39.

The percentage of time for which instream flow targets were engaged (M1) and average consecutive number of days between engagements (M7A) are compared for each instream flow target at control point B2000E in Table 40.

Table 39. Instream Flow Targets and Corresponding Environmental Flow Regime Components for Control Point B2000E

IFTARGET (cfs)	Components of Environmental Flow Regime
1	All subsistence flows, severe and dry base flows for Summer and Fall
2	Severe and dry base flows for Winter and Spring
3	Average base flow for Summer
4	Average base flow for Fall and Winter
5	Average base flow for Spring
7	Wet base flow for Winter
8	Wet base flow for Summer
10	Wet base flow for Fall
12	Wet base flow for Spring
18	2 per season Winter pulse
42	1 per season Winter pulse
100	2 per season Summer and Fall pulses
330	1 per season Summer pulse
430	1 per season Fall pulse
600	2 per season Spring pulse
1,800	1 per season Spring pulse
3,000	Annual pulse

Table 40. Metric Comparison for All Instream Flow Targets at Control Point B2000E

IFTARGET (cfs)	M1	M7A (days)
1	5%	1,670
2	6%	2,168
3	7%	646
4	19%	378
5	13%	523
7	15%	494
8	8%	602
10	7%	607
12	16%	411
18	0.48%	279
42	0.26%	380
100	0.63%	179
330	0.18%	392
430	0.20%	359
600	0.28%	322
1,800	0.10%	1,194
3,000	0.15%	603
Variable	1.93%	

Summing percentages for metric M1 from Table 40, subsistence and base flow targets were engaged 95.8% of the time while pulse flow targets were engaged 4.2% of the time. For approximately half of the time that high flow pulse event targets were engaged, variable targets not listed in Table 39 were set in order to meet high flow pulse event volume termination criteria. As described in Section 2.3, the hydrologic conditions parameters for control points located on the Colorado River above Lake Travis and tributaries of the Colorado River were selected in order that severe, dry, average, and wet conditions occur approximately 5, 20, 50, and 25% of the time, respectively. Evaluating metric M1 for subsistence and base flows, it was observed that severe, dry, average, and wet conditions occurred approximately 5, 6, 39, and 46% of the time, respectively.

Figure 7 is an exceedance frequency plot of the consecutive number of days between engagements of each of the instream flow target values at control point B2000E, which are indicated in the legend at the right. As expected, the exceedance frequency curves for severe and dry hydrologic conditions subsistence and base flow targets, corresponding to target values of 1 and 2 cfs, had the greatest number of consecutive days between engagements. The exceedance frequency curve for the 1 per season Spring pulse event, corresponding to a target value of 1,800 cfs, was also relatively high compared to the other environmental flow components. The lowest exceedance frequency curve was the instream flow target of 100 cfs, corresponding to the 2 per season summer and 2 per season fall pulse events.

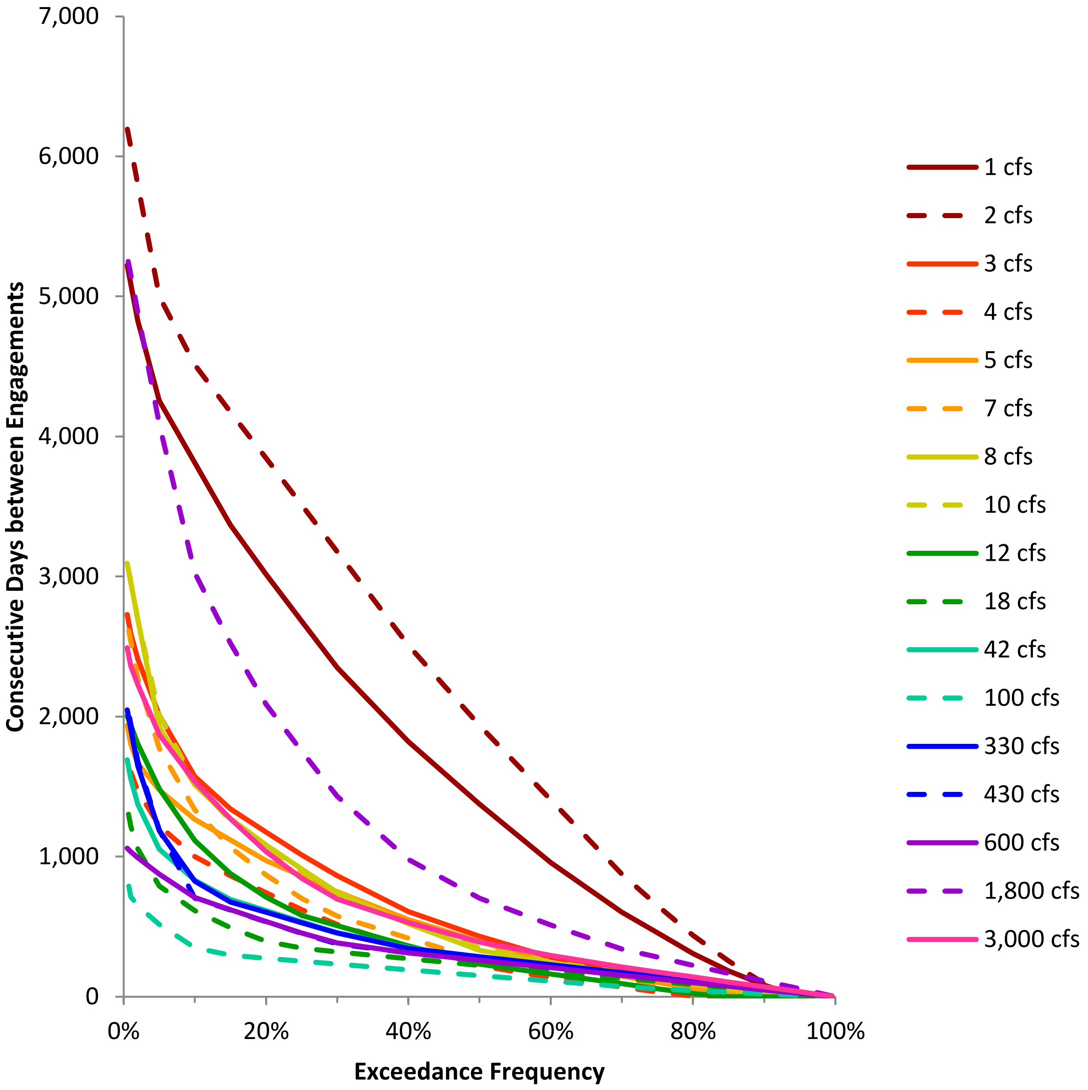

Figure 7. Exceedance Frequency Plot of Consecutive Number of Days between Engagements (M7B) for Instream Flow Targets in cfs at Control Point B2000E

Several metrics were evaluated for the various subsistence and base flow targets at control point B2000E, as seen in Table 41. The engaged volume reliability (M2) ranged from 359 to 2762%, with the lowest value corresponding to the wet base flow for winter and the highest value corresponding to the severe and dry base flows for winter and spring. The wet hydrologic conditions base flows generally had lower values of volume reliability compared to subsistence and base flows for other hydrologic conditions. The engaged period reliability (M3A) ranged from 39 to 56%. The average hydrologic conditions base flows generally had the greatest period reliabilities.

Table 41. Metric Comparison for Subsistence and Base Flow Targets at Control Point B2000E

IFTARGET (cfs)	M2	M3A	M4A (days)	M5A (days)	M6A (days)	M9A (cfs)	M10A
1	1661%	39%	2	0	1	1	93%
2	2762%	47%	4	1	1	2	89%
3	2688%	52%	2	0	0	3	86%
4	1612%	56%	8	2	2	3	78%
5	1724%	54%	6	1	1	4	77%
7	359%	41%	8	1	3	5	69%
8	1371%	51%	2	0	1	6	79%
10	1041%	49%	2	0	0	7	70%
12	966%	46%	6	1	1	9	74%

Figure 8 is an exceedance frequency plot of the consecutive number of days in which various subsistence and base flow targets were engaged (M4B). Targets were engaged for one day in a row or more a maximum of 20% of the time. Several targets were engaged for periods of 100 days or more, however this occurred a small fraction of the time. The average consecutive number of engaged days in which the regulated flow exceeded the instream flow target (M5A) and the average consecutive number of engaged days in which the regulated flow was less than the instream flow target (M6A) were both significantly less than the average consecutive number of days engaged (M4A) for all subsistence and base flow targets. This suggests that periods of consecutive target engagements were typically composed of both days in which the target was exceeded and days in which a deficit occurred, rather than periods in which the target was consistently exceeded or a deficit was consistently observed.

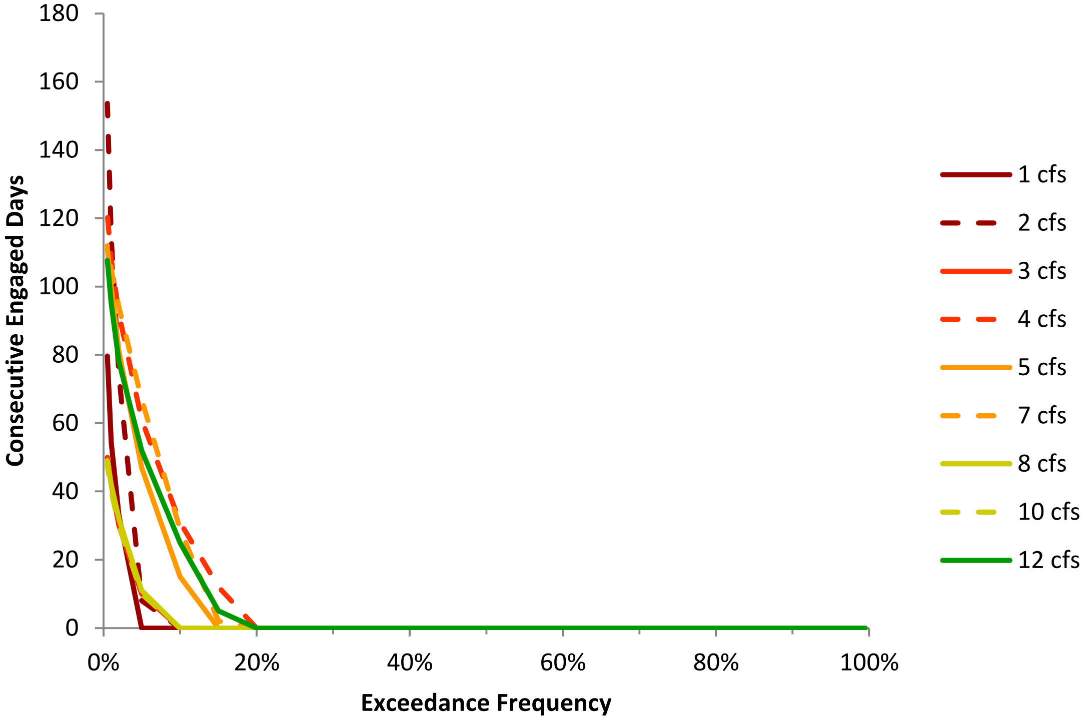

Figure 8. Exceedance Frequency Plot of Consecutive Number of Days Engaged (M4B) for Subsistence and Base Flow Targets in cfs at Control Point B2000E

Figure 9 and Figure 10 are exceedance frequency plots of the vulnerability (M9B) and dimensionless vulnerability (M10B) for each of the subsistence and base flow targets at control point B2000E. As expected, the vulnerability exceedance frequency curve moved further away from the origin for increasing values of the instream flow target. The vulnerability exceedance frequency curve was relatively flat for small values of the instream flow target and became more curved for higher values of the instream flow target.

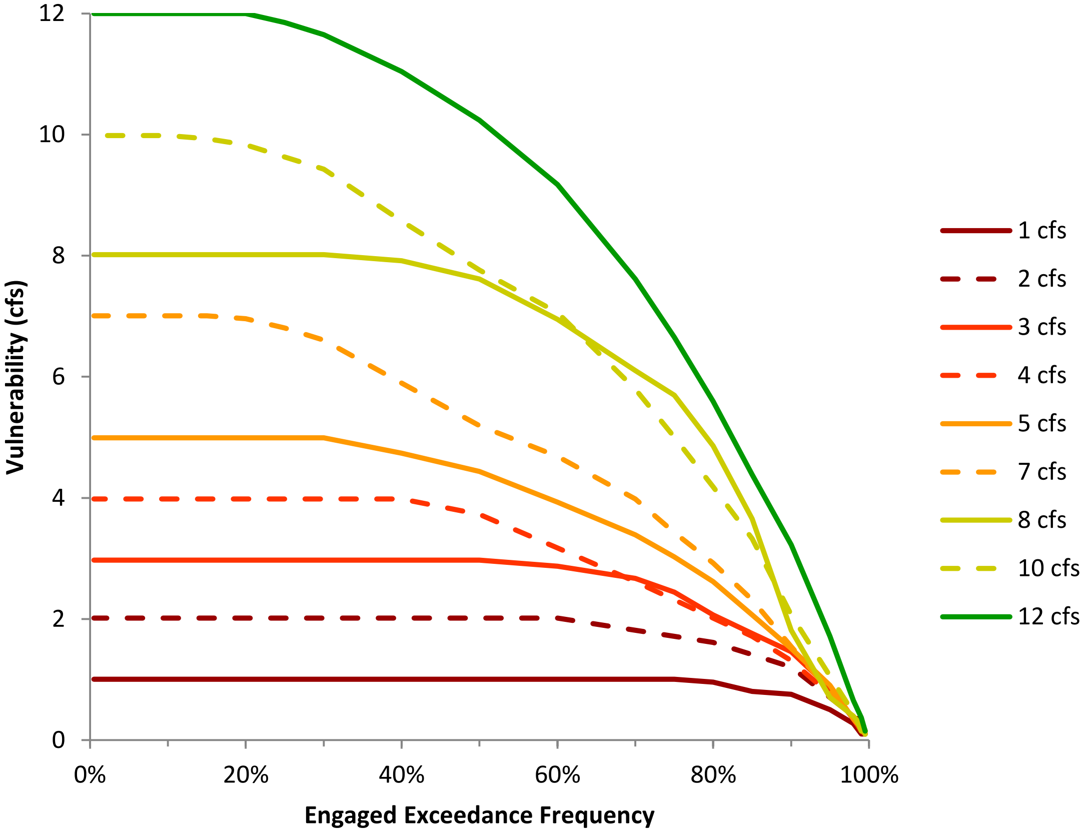

Figure 9. Engaged Exceedance Frequency Plot of Vulnerability (M9B) for Subsistence and Base Flow Targets in cfs at Control Point B2000E

As seen in Figure 10, the dimensionless vulnerability exceedance frequency curve generally moved closer to the origin for increasing values of the instream flow target, in which 100% vulnerability was observed a progressively smaller percentage of time. Average vulnerability (M9A) and average dimensionless vulnerability (M10A) for each of the subsistence and base flow targets are given in Table 41.

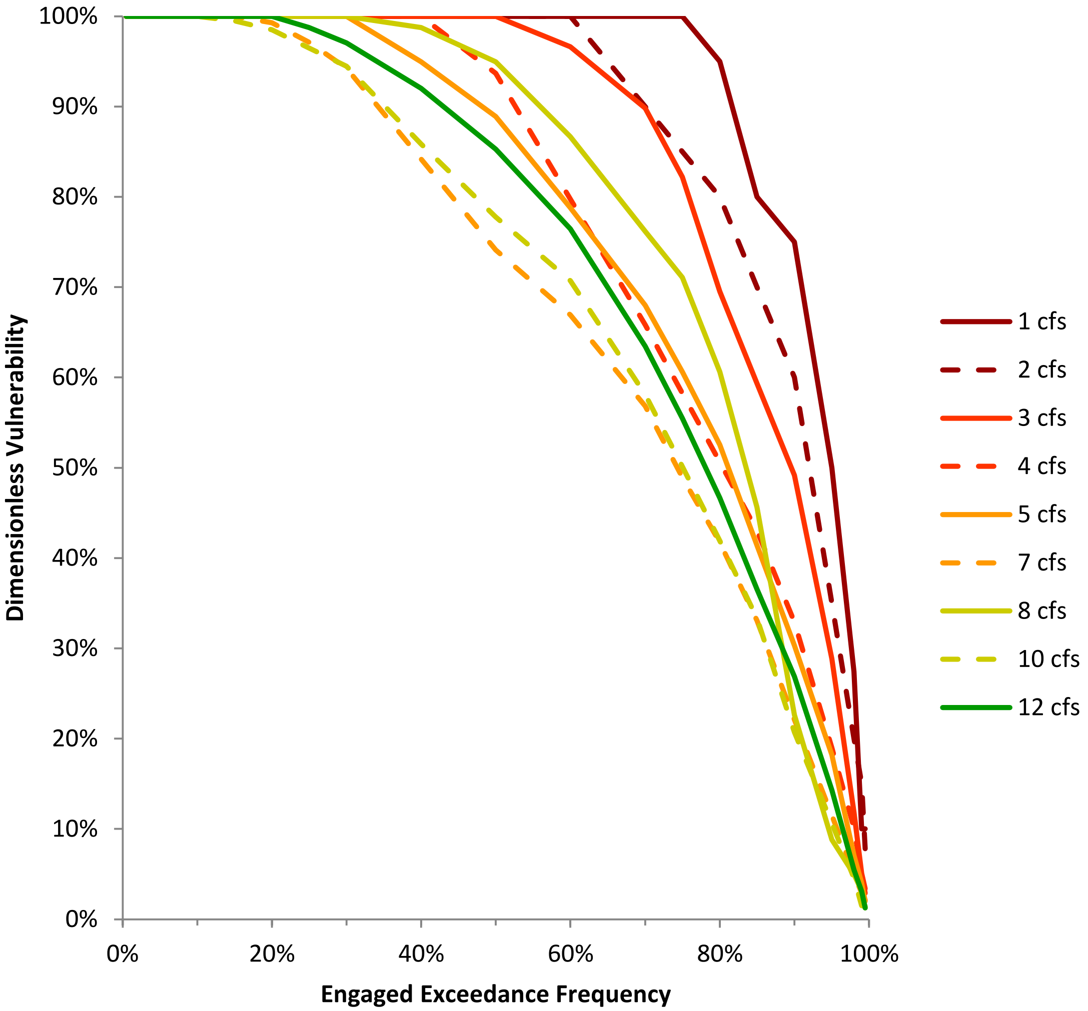

Figure 10. Engaged Exceedance Frequency Plot of Dimensionless Vulnerability (M10B) for Subsistence and Base Flow Targets in cfs at Control Point B2000E

The high flow pulse components of the environmental flow regime at control point B2000E are evaluated in Table 42. The percentage of the target number of pulse events that were engaged (P4) was greatest for the 2 per season high flow pulse events and least for the annual pulse event. Likewise, the percentage of years in which the pulse flow requirements were met completely (P5) was generally greatest for the 2 per season events and lowest for the annual event. The percentage of engaged pulse events that satisfied the volume termination criteria (P6) was consistently high for all pulse events. The lowest value of metric P6 was 91% for the Spring 1 per season event.

Table 42. Metric Comparison for High Flow Pulse Events at Control Point B2000E

Frequency	Season	P1	P2	P3	P4	P5	P6
2 per season	Winter	146	115	112	79%	68%	97%
	Spring	146	93	90	64%	58%	97%
	Summer	146	119	119	82%	77%	100%
	Fall	146	118	117	81%	78%	99%
1 per season	Winter	73	47	46	64%	58%	98%
	Spring	73	34	31	47%	47%	91%
	Summer	73	47	45	64%	64%	96%
	Fall	73	51	49	70%	70%	96%
Annual	N/A	73	37	35	51%	51%	95%

3.2.2 Comparison between Control Points

Using results of the Colorado WAM and Trinity WAM simulations, the attainment metrics were used to make comparisons between alternate control point locations, as described in Sections 3.2.2.1 and 3.2.2.2.

3.2.2.1 Comparison between Control Points in the Colorado WAM

The attainment metrics were used to make comparisons between each of the 14 control point locations in the Colorado WAM at which SB3 environmental flow standards were modeled based on results of the initial Colorado WAM simulation. The eight attainment metrics documented in Table 43 were developed based on all instream flow targets.

Table 43. Metric Comparison between Colorado WAM Control Points for All Instream Flow Targets

Control Point	M2	M3A	M5A	M6A	M9A	M10A	M11	M12A
			(days)	(days)	(cfs)			(days)
B2000E	494%	51%	14	16	5	77%	24%	28
C3000E	164%	47%	31	38	6	41%	38%	60
C1000E	286%	66%	23	4	15	60%	43%	12
D4000E	375%	55%	16	10	9	71%	28%	25
D3000E	561%	62%	37	13	1	80%	14%	44
E1000E	208%	60%	38	9	26	36%	27%	15
F2000E	483%	69%	18	4	6	80%	21%	12
F1000E	241%	66%	18	5	78	42%	28%	10
G1000E	221%	61%	43	13	47	36%	28%	44
H1000E	291%	57%	38	13	21	53%	31%	26
J5000E	350%	78%	92	9	7	64%	51%	5
J3000E	288%	80%	54	2	112	29%	21%	9
J1000E	214%	67%	25	5	272	38%	31%	21
K2000E	183%	52%	9	7	344	43%	40%	15

The volume reliability (M2) was greater than 100% at all 14 control points with a maximum of 561% at control point D3000E and minimum of 164% at control point C3000E. The period reliability (M3A) ranged from 47% at control point C3000E to 80%

at control point J3000E, with two control points exceeding 70% period reliability, six control points between 60 and 70%, and six control points less than 60%. Four of the six control points with period reliabilities less than 60% were located in the upper Colorado River basin and one was located on a smaller tributary of the Colorado River, indicating a possible correlation between drainage area and metric M3A. Figure 11 is a plot of engaged period reliability versus allowable deficit for each of the Colorado WAM control points. The shape of the curves for control points J3000E, J1000E, and K2000E, located on the main stem lower Colorado River, were similar to one another and different from the shape of the curves for the other control points. For these three control points, engaged period reliability did not significantly improve below an allowable deficit of 30 cfs.

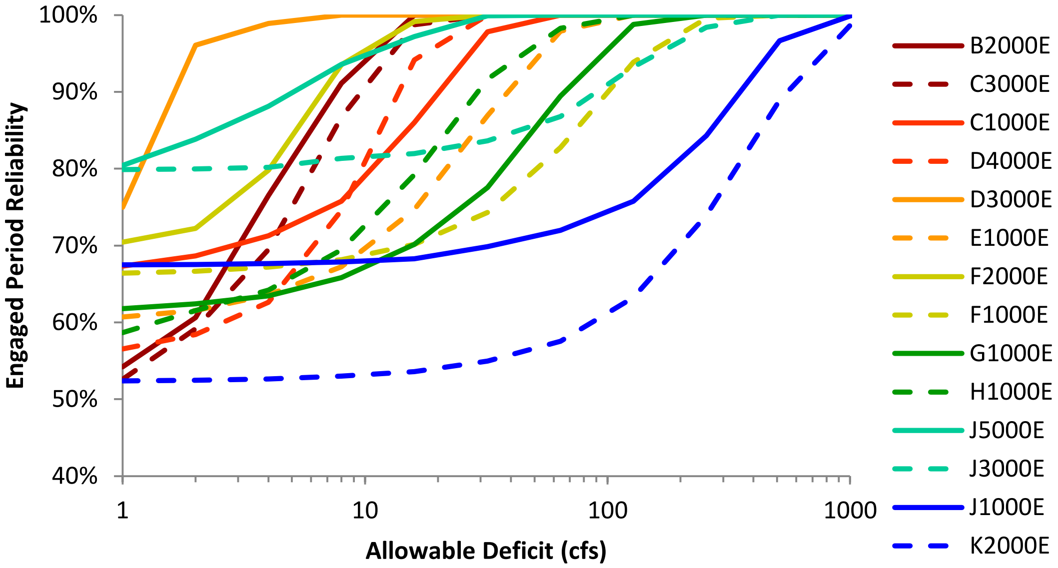

Figure 11. Comparison of Engaged Period Reliability vs. Allowable Deficit (M3B) between Colorado WAM Control Points for All Instream Flow Targets

Figure 12 is a plot of engaged period reliability versus allowable percentage deficit. For control points B2000E, D4000E, D3000E, and F2000E, the engaged period reliability steadily increased to approximately 80% for an allowable percentage deficit less than 100% and then immediately increased to 100% when the allowable deficit equaled 100%. This pattern suggests there were a significant number of days for which zero available flows were observed. Control points for which the curve approached 100% engaged period reliability more gradually indicated a smaller percentage of days with low or zero available flows.

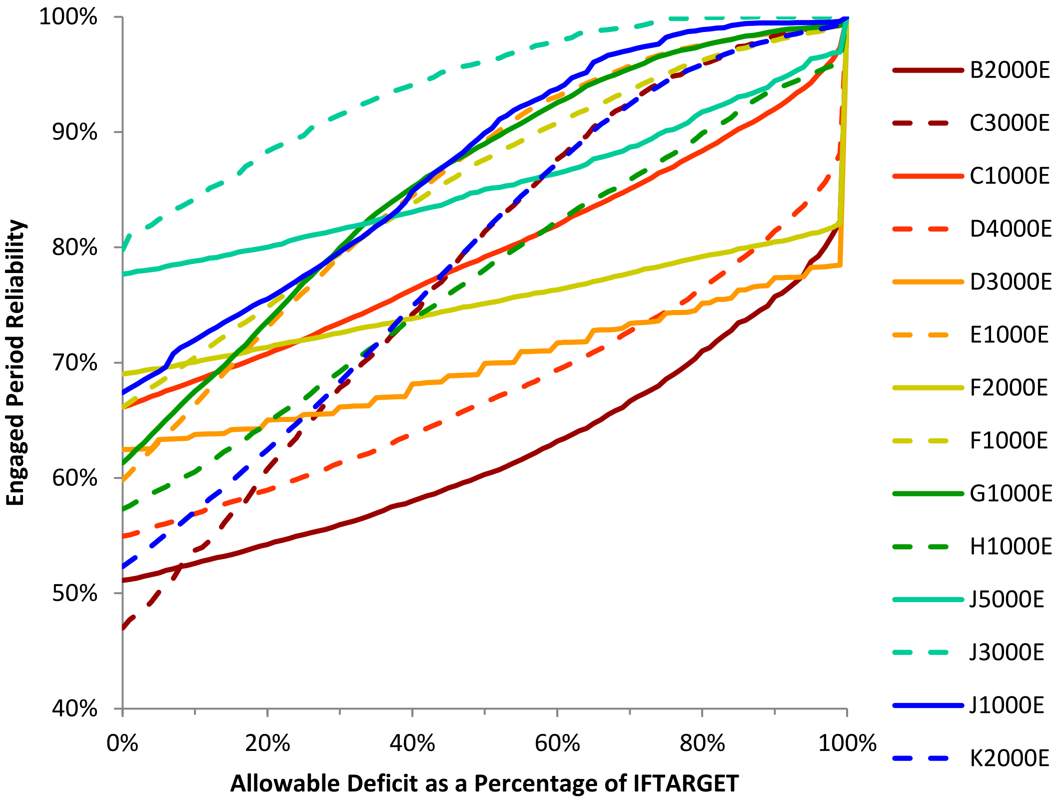

Figure 12. Comparison of Engaged Period Reliability vs. Allowable Percentage Deficit (M3C) between Colorado WAM Control Points for All Instream Flow Targets

The average number of consecutive days in which regulated flow exceeded the instream flow target (M5A) ranged from 9 days at control point K2000E to 92 days at control point J5000E. The average number of consecutive days in which the regulated flow was less than the instream flow target (M6A) ranged from 2 days at control point J3000E to 38 days at control point C3000E. Typically metric M6A was less than metric M5A, with the exception of control points B2000E, C3000E, and K2000E.

Figure 13 is an exceedance frequency plot of consecutive engaged days in which the instream flow target was met or exceeded (M5B). The number of consecutive engaged days in which the instream flow target was met or exceeded corresponding to a 0.5% exceedance probability ranged from approximately 100 days at control point K2000E to nearly 450 days at control point C1000E. Consecutive engaged days in which the instream flow target was met or exceeded occurred between 40 and 80% of the time for the 14 control points. The exceedance frequency curve was significantly greater for control point J5000E and least for control point K2000E relative to the other control points.

Figure 14 is an exceedance frequency plot of the consecutive number of engaged days in which a deficit occurred (M6B). The exceedance frequency curve was significantly further from the origin for control point C3000E compared to the other control points. For the other control points, the number of consecutive engaged days for which a deficit was observed corresponding to a 0.5% exceedance probability ranged from approximately 50 days to over 200 days, with consecutive engaged days in which deficits were observed occurring between 20 and 50% of the time.

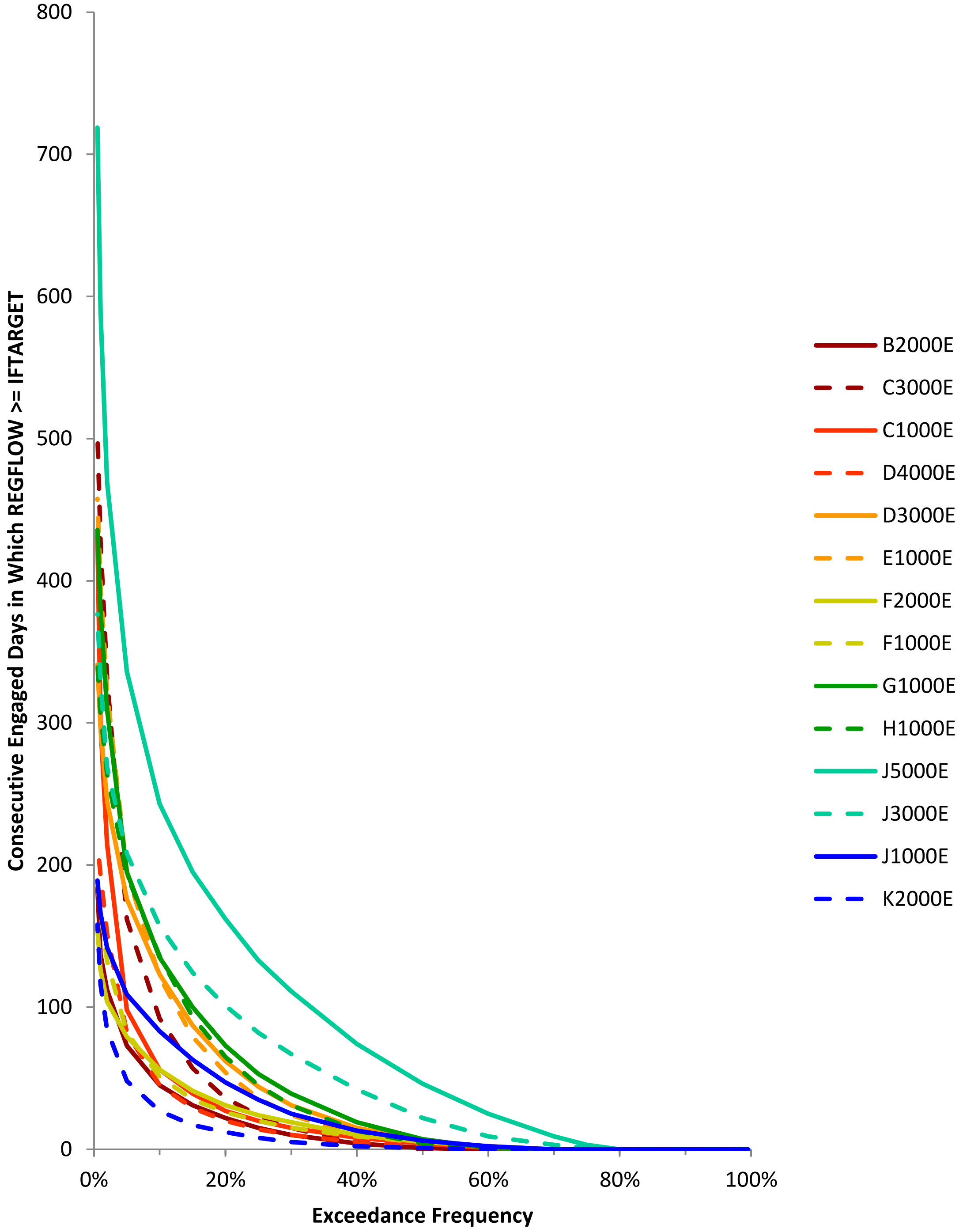

Figure 13. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW >= IFTARGET (M5B) for Colorado WAM Control Points for All Instream Flow Targets

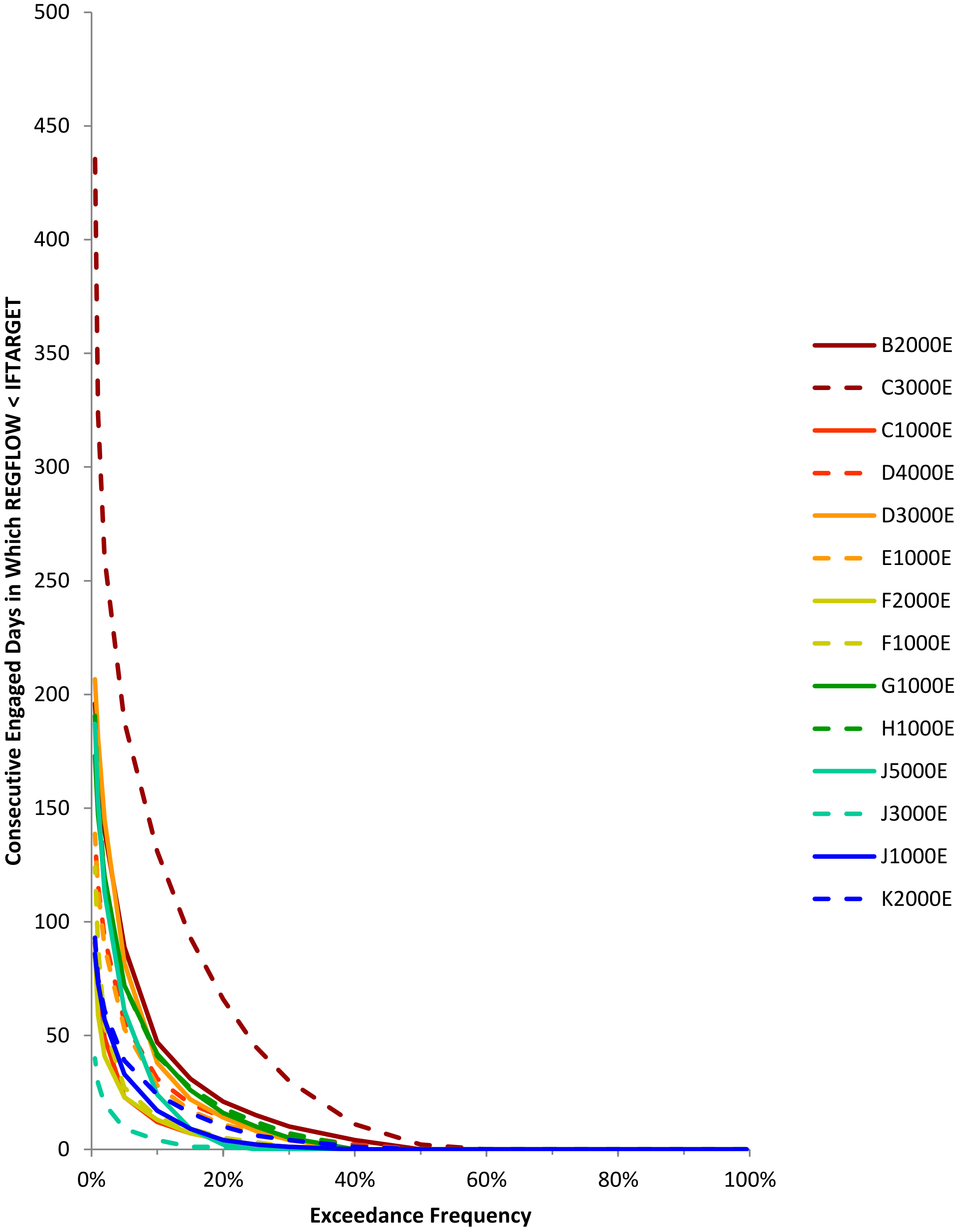

Figure 14. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW < IFTARGET (M6B) for Colorado WAM Control Points for All Instream Flow Targets

The average vulnerability (M9A) ranged from 1 cfs at control point D3000E to 344 cfs at control point K2000E. As expected, the average vulnerability increased with increasing drainage area, with greater values for control points on large tributaries and lower portions of the main stem Colorado River. Figure 15 is an engaged exceedance frequency plot of vulnerability (M9B). As expected, the curves moved farther from the origin with increasing drainage area as a result of increases in the instream flow targets and deficits.

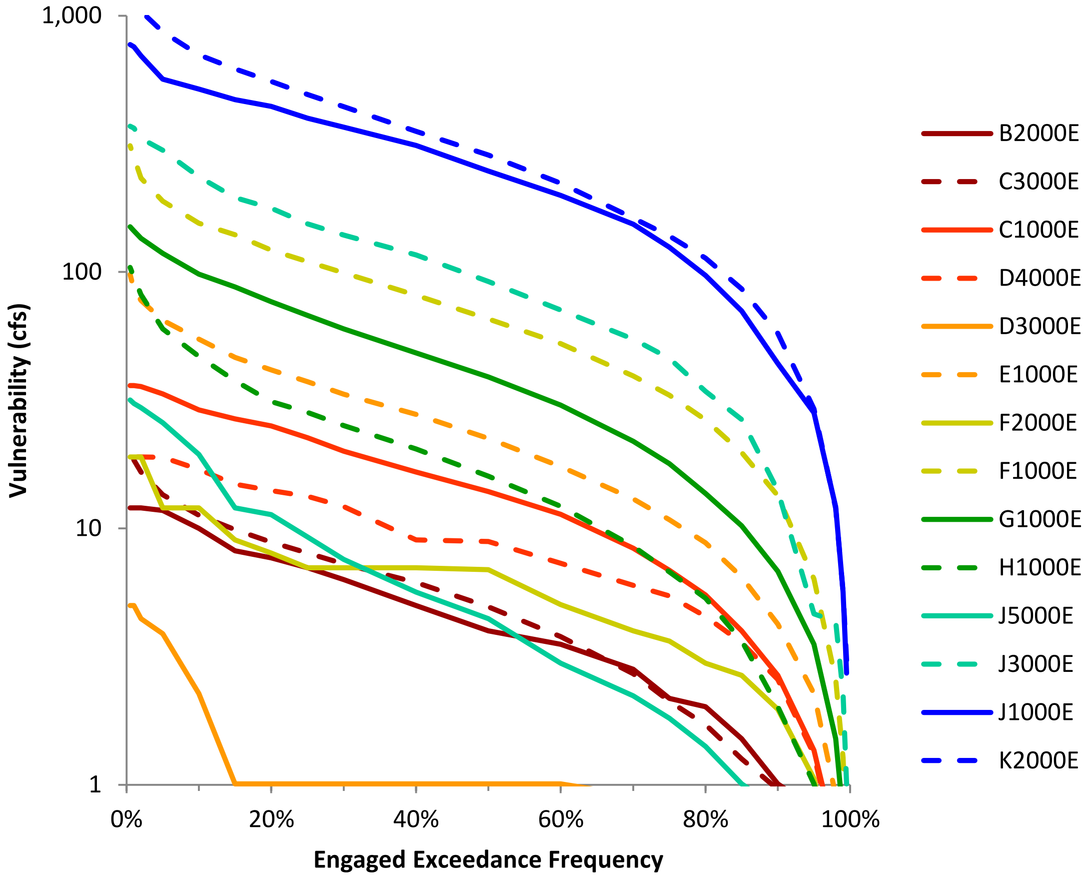

Figure 15. Engaged Exceedance Frequency Plot of Vulnerability (M9B) for Colorado WAM Control Points for All Instream Flow Targets

The average dimensionless vulnerability (M10A) ranged from 29% at control point J3000E to 80% at control point D3000E. The six highest values of average dimensionless vulnerability were observed at control points located in the upper Colorado River basin above O.H. Ivie Reservoir and tributaries of the Colorado River, suggesting possible correlation between contributing drainage area and dimensionless vulnerability. The dimensionless average vulnerability (M11) was consistently less than the average dimensionless vulnerability at all 14 control points. Metric M11 ranged from 14% at control point D3000E to 51% at control point J5000E. Interestingly, control point D3000E had the greatest average dimensionless vulnerability and least dimensionless average vulnerability among all 14 control points. As described earlier, the dimensionless average vulnerability was computed by dividing the average vulnerability by the average engaged instream flow target, which includes both days in which deficits were observed and days in which the instream flow target was met. In comparison, the average dimensionless vulnerability only includes days in which deficits were observed. As long as there were a sufficient number of days in which relatively large instream flow targets were met, the dimensionless average vulnerability should be less than the average dimensionless vulnerability. The high volume reliability and relatively large value of metric M5A compared to metric M6A at control point D3000E indicate that a significant number of instream flow targets were engaged and met compared to targets being engaged with deficits. This explains why control point D3000E had the greatest average dimensionless vulnerability and least dimensionless average vulnerability.

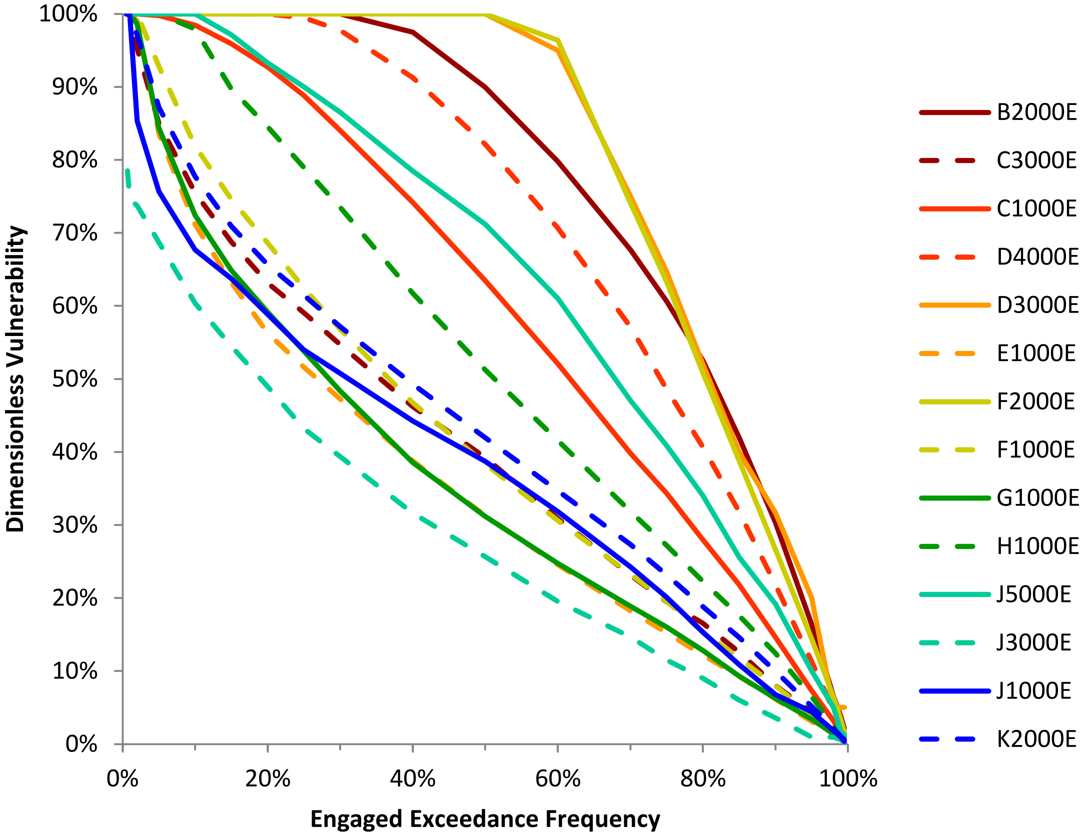

Figure 16. Engaged Exceedance Frequency Plot of Dimensionless Vulnerability (M10B) for Colorado WAM Control Points for All Instream Flow Targets

Figure 16 is an engaged exceedance frequency plot of dimensionless vulnerability (M10B). The percentage of time for which 100% vulnerability was observed was relatively small at most of the control points, with the exception of control points B2000E, D4000E, D3000E, and F2000E, which had values of 100% dimensionless vulnerability between 20 and 60% of the time. This supports the same conclusion as the plot of metric M3C that zero available flows were observed a relatively large percentage of time at these four control points in the upper Colorado

River basin. For control point J3000E, the dimensionless vulnerability corresponding to a 0.5% exceedance probability was 80%.

The expected number of days to recovery from a deficit (M12A) ranged from 5 days at control point J5000E to 60 days at control point C3000E. The six highest values of metric M12A occurred at control points located on the upper Colorado River above O.H. Ivie Reservoir or tributaries of the Colorado River. Figure 17 is a plot of resilience versus allowable number of days to recovery (M12B). The number of allowable days to recovery required to achieve 100% resilience ranged from approximately 25 days at control point J5000E to approximately 225 days at control point C3000E. For control points B2000E, D4000E, H1000E, and J1000E, the rate of increase of the resilience significantly lowered around 50 allowable days to recovery. The shift in rates at which the resilience increased was comparatively more gradual for control points C3000E, D3000E, and G1000E.

Control points J3000E, J1000E, and K2000E are located on the main stem Colorado River below Lake Travis. At these control points, metrics M6A, M9A, M10A, and M11 gradually increased moving from upstream to downstream while metrics M2, M3A, and M5A gradually decreased. This trend suggests that the magnitude of environmental instream flow targets increased more quickly than available flows moving from control point J3000E downstream. This observation is possibly explained by the senior appropriations made by rice farmers along this segment of the river.

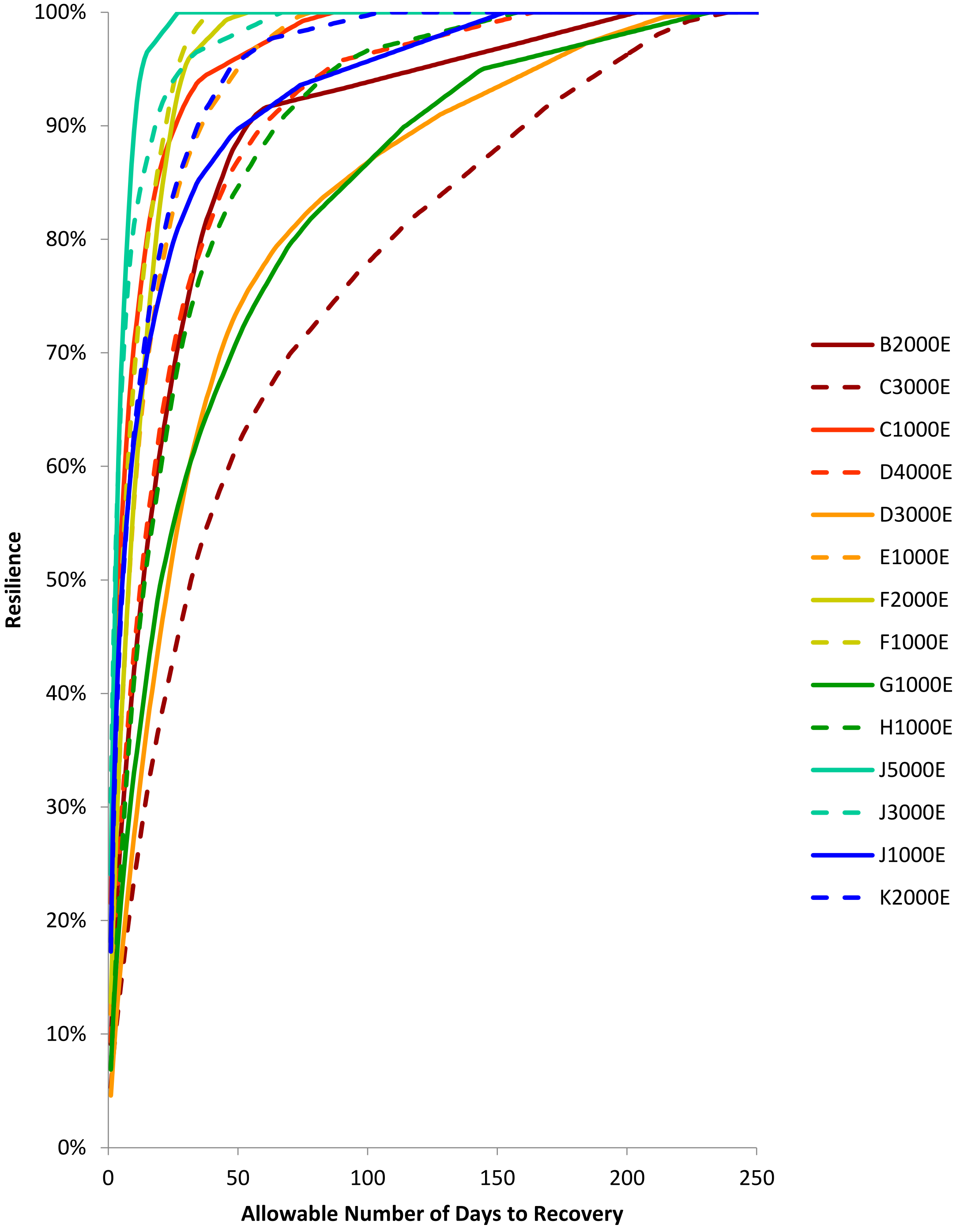

Figure 17. Comparison of Resilience vs. Allowable Number of Days to Recovery (M12B) between Colorado WAM Control Points for All Instream Flow Targets

The ten metrics compared in Table 44 were developed based on high flow pulse event instream flow targets only. The percentage of time for which high flow pulse event targets were engaged (M1) ranged from 2 to 6%, with the exception of control point C3000E, for which high flow pulse events were engaged 0.3% of the time. The low engagement percentage at control point C3000E was expected because only 2 high flow pulse events were specified for control point C3000E, compared to 13 high flow pulse events at most of the other control points.

Table 44. Metric Comparison between Colorado WAM Control Points for High Flow Pulse Event Targets

Control Point	M1	M2	M3A	M4A	M7A	P1	P2	P3	P4	P5	P6
				(days)	(days)						
B2000E	4%	207%	100%	0	83	949	661	644	70%	14%	97%
C3000E	0.3%	336%	100%	0	448	146	65	62	45%	32%	95%
C1000E	4%	194%	100%	0	62	949	732	692	77%	11%	95%
D4000E	4%	192%	100%	0	73	949	642	619	68%	11%	96%
D3000E	3%	288%	100%	0	72	949	652	594	69%	18%	91%
E1000E	3%	216%	100%	0	82	803	497	492	62%	7%	99%
F2000E	6%	189%	100%	0	54	949	763	695	80%	26%	91%
F1000E	4%	158%	100%	0	76	949	576	562	61%	7%	98%
G1000E	3%	221%	100%	0	112	803	442	432	55%	4%	98%
H1000E	2%	238%	100%	0	121	803	466	436	58%	12%	94%
J5000E	3%	155%	100%	0	159	584	313	294	54%	7%	94%
J3000E	5%	197%	100%	0	84	632.67	384	384	61%	5%	100%
J1000E	5%	204%	100%	0	76	669.17	442	442	66%	8%	100%
K2000E	5%	216%	100%	0	93	669.17	391	391	58%	8%	100%

The limited high flow pulse event requirements at control point C3000E were also made apparent by the relatively low number of target pulse event engagements for the simulation, given by metric P1, as well as the comparatively high average number of consecutive days between engagements, given by metric M7A.

The volume reliability (M2) was greater than 100% at all 14 control points, with a minimum of 158% at control point F1000E and maximum of 336% at control point C3000E. The period reliability (M3A) was 100% at all 14 control points.

The average number of consecutive days for which high flow pulse event targets were engaged (M4A) was approximately zero at all 14 control points. Figure 18 is an exceedance frequency plot of the consecutive number of days for which high flow pulse event targets were engaged (M4B). High flow pulse event targets were engaged on consecutive days a maximum of 5% of the time. As indicated by the plot, the number of consecutive days for which high flow pulse event targets were engaged corresponding to a 0.5% exceedance probability was at most 11 days.

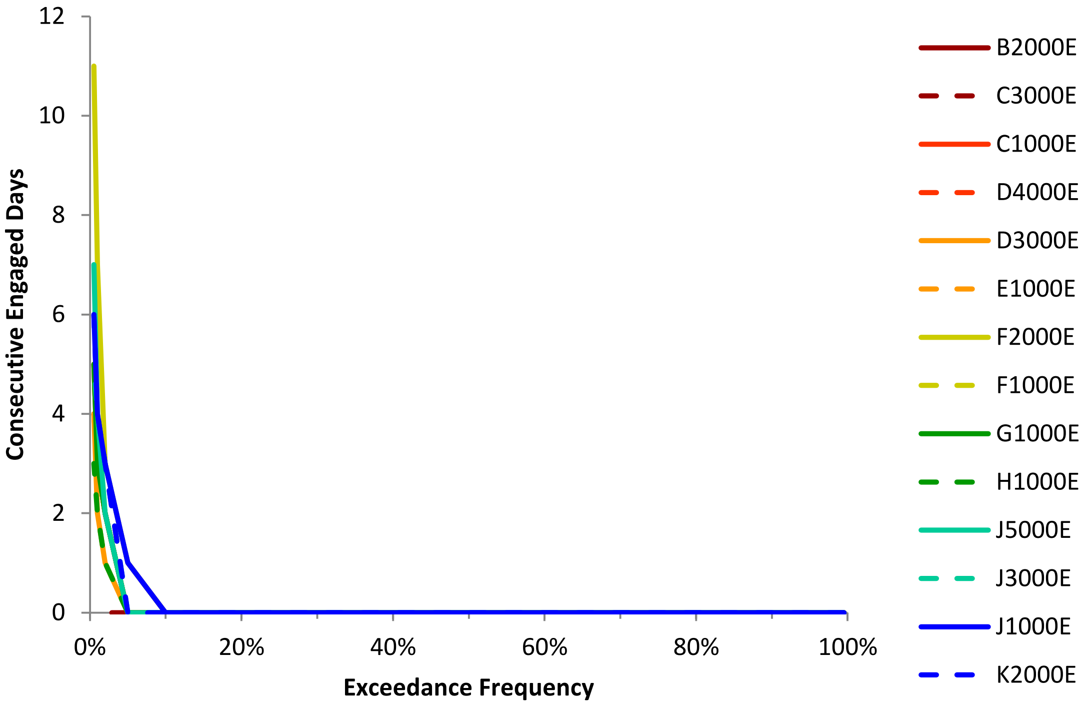

Figure 18. Exceedance Frequency Plot of Consecutive Engaged Days (M4B) for Colorado WAM Control Points for High Flow Pulse Event Targets

The average number of consecutive days between engagements (M7A) of high flow pulse events ranged from 54 days at control point F2000E to 448 days at control point C3000E. The value of metric M7A was less than 100 days at most of the control points, with the exception of control points G1000E, H1000E, J5000E, and C3000E, for which metric M7A had values of 112 days, 121 days, 159 days, and 448 days respectively. The high average value of consecutive days between engagements was expected at control point C3000E because of the relatively few number of engaged high flow pulse events, as described earlier. The number of engaged high flow pulse events was not necessarily a determining factor for the value of metric M7A, however. Figure 19 is an exceedance frequency plot of the consecutive number of days between engagements of high flow pulse events (M7B) at the Colorado WAM control points. The exceedance frequency curve was significantly greater at control point C3000E relative to the other control points, in correspondence with its comparatively large value of metric M7A. Excluding control point C3000E, the number of consecutive days between engagements of a high flow pulse event corresponding to a 0.5% exceedance probability ranged from approximately 300 days at control point F2000E to approximately 800 days at control point J5000E.

Metric P1 documented the target number of high flow pulse event engagements at each control point. The maximum value of metric P1 was 949, corresponding to the specification of 13 high flow pulse events per year for a period of 73 years. The values of metric P1 less than 949 at control points C3000E, E1000E, G1000E, H1000E, and J5000E indicate that fewer than 13 high flow pulse event per year were specified. The 2 per season, 1 per 18-month, and 1 per 2-year high flow pulse events specified at control points J1000E and K2000E correspond to 9.167 high flow pulse event targets per year and 669.17 high flow pulse events for the 73-year period-of-analysis. The 1 per 2-year event was not specified at control point J3000E.

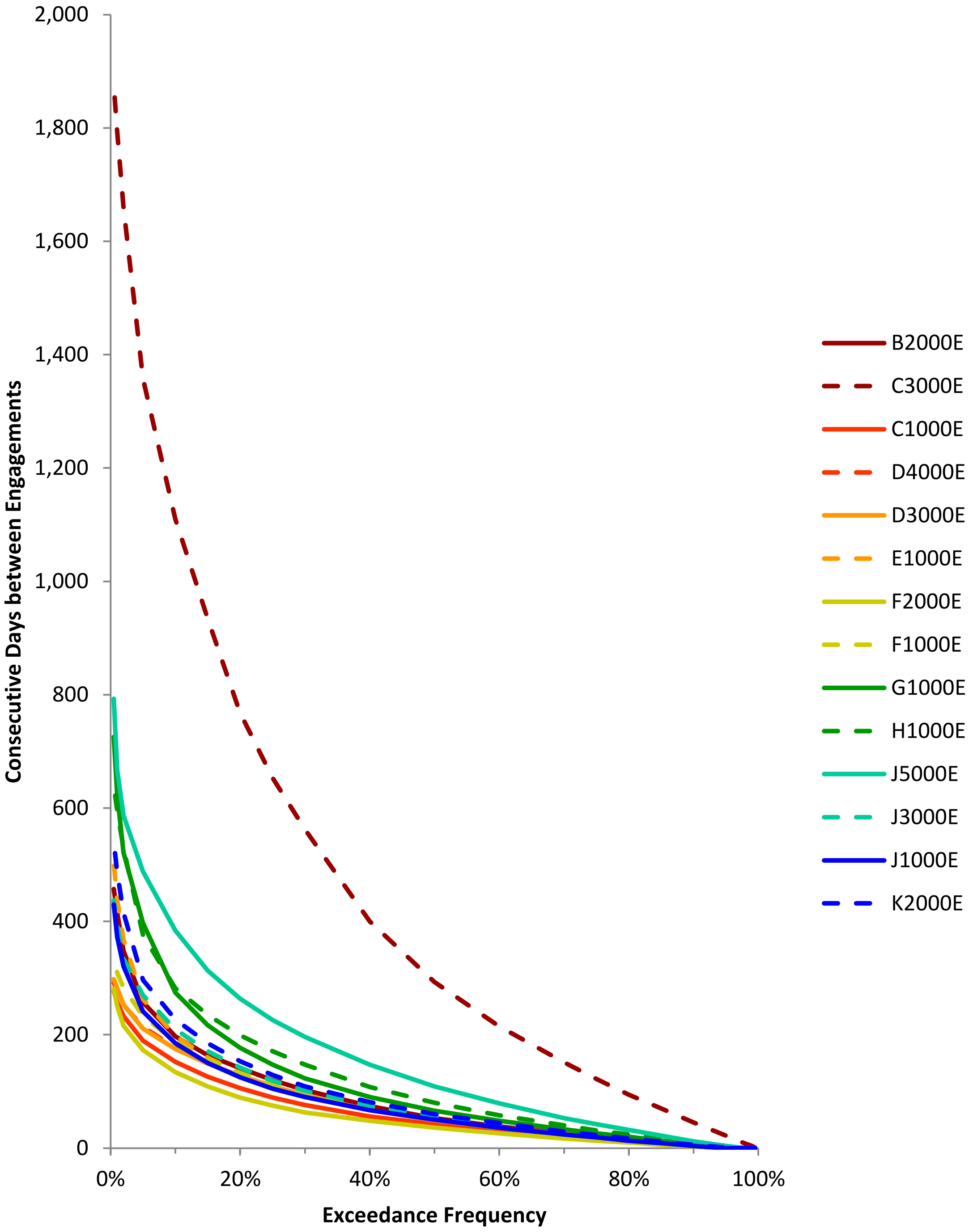

Figure 19. Exceedance Frequency Plot of Consecutive Days between Engagements (M7B) for Colorado WAM Control Points for High Flow Pulse Event Targets

Metrics P2 and P3 indicate the number of high flow pulse events that were engaged during the simulation and the number of high flow pulse events that were engaged and satisfied the pulse event volume termination criteria. The percentage of the target number of high flow pulse events that were engaged during the simulation (P4) ranged from 45% at control point C3000E to 80% at control point F2000E. The percentage of years in which all of the high flow pulse event targets were engaged (P5) ranged from 4% at control point G1000E to 32% at control point C3000E. The percentage of engaged pulse events that satisfied the volume termination criteria (P6) was relatively high at all control points, with a minimum of 91% and maximum of 100%.

3.2.2.2 Comparison between Control Points in the Trinity WAM

The environmental flow requirements were modeled at 4 control points within the daily authorized use scenario Trinity WAM dataset at a 20091201 priority number for a 73-year period-of-analysis.

The eight attainment metrics documented in Table 45 were developed based on all instream flow targets. The volume reliability (M2) was high at all four control points, with a minimum of 515% at control point 8TRROE and maximum of 943% at control point 8TRDAE. The period reliability (M3A) ranged from 50% at control point 8TROAE to 72% at control point 8WTGPE.

Table 45. Metric Comparison between Trinity WAM Control Points for All Instream Flow Targets

Control Point	M2	M3A	M5A	M6A	M9A	M10A	M11	M12A
			(days)	(days)	(cfs)			(days)
8WTGPE	882%	72%	37	11	16	69%	33%	14
8TRDAE	943%	51%	7	11	20	78%	22%	16
8TROAE	726%	50%	10	13	102	90%	26%	14
8TRROE	515%	59%	21	9	289	80%	33%	11

Figure 20 is a plot of engaged period reliability versus allowable deficit (M3B) for the Trinity WAM control points for all instream flow targets.

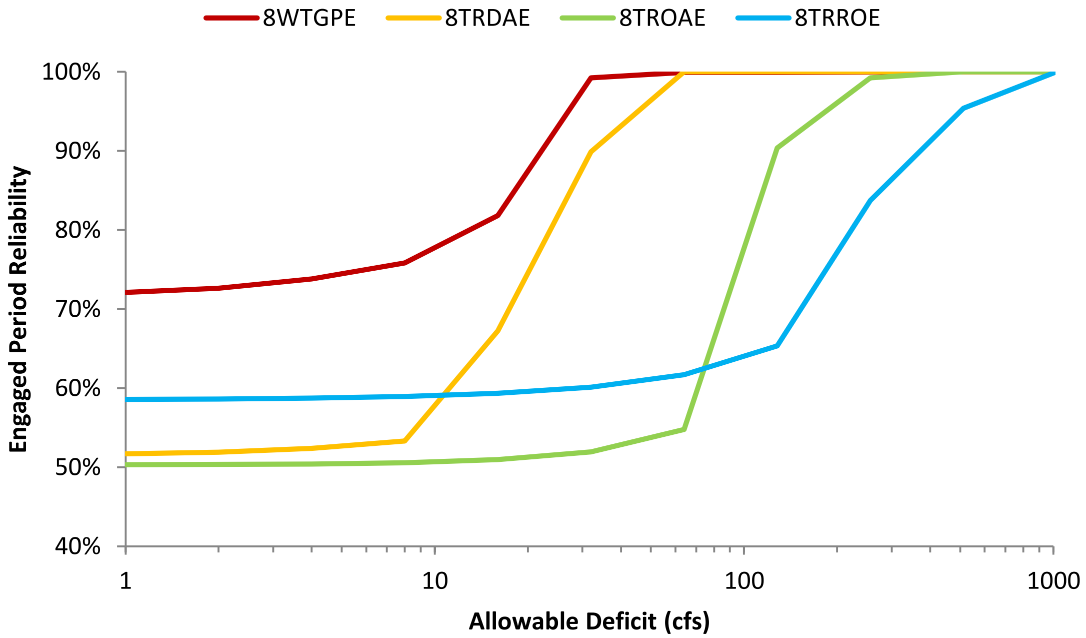

Figure 20. Comparison of Engaged Period Reliability versus Allowable Deficit (M3B) between Trinity WAM Control Points for All Instream Flow Targets

Although control point 8WTGPE had the smallest drainage area of the four control points, it had the greatest engaged period reliability for a range of allowable deficits. This suggests that the ratio of environmental flow requirements to drainage area was relatively low at control point 8WTGPE compared to the other control points. As expected, the allowable deficit required to observe significant improvements in the engaged period reliability increased moving from upstream to downstream. The allowable deficit required to observe a significant improvement in engaged period reliability at control point 8TROAE, for example, was approximately 70 cfs, whereas the required allowable deficit at control point 8TRROE was approximately 150 cfs.

Figure 21 is a plot of engaged period reliability versus allowable deficit as a percentage of the instream flow target (M3C) for all instream flow targets at the four control points. At control points 8WTGPE and 8TRROE, the engaged period reliability gradually improved until allowable deficits of 75 and 95%, respectively, after which significant improvement in the engaged period reliability was observed. For control points 8TRDAE and 8TROAE, the curves were relatively flat until significant improvement at allowable deficits of 70 and 95%, respectively. The large improvements in period reliability at high allowable percentage deficits indicate that a large proportion of the events that limited period reliability were characterized by proportionally low flows. The proportion of low flow events was particularly large at control points 8TRDAE and 8TRROE compared to the other control points. The allowable percentage deficit required to achieve significant improvement in the period reliability was particularly large at control points 8TROAE and 8TRROE.

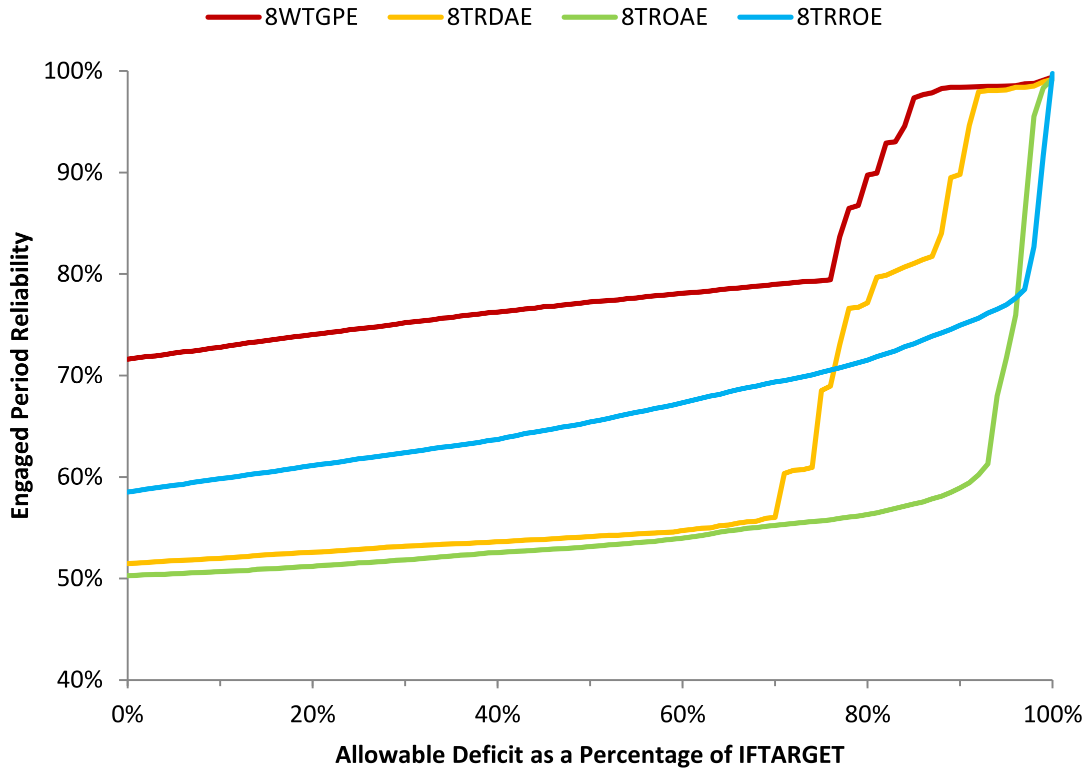

Figure 21. Comparison of Engaged Period Reliability versus Allowable Percentage Deficit (M3C) between Trinity WAM Control Points for All Instream Flow Targets

The average number of consecutive engaged days in which the regulated flow was greater than or equal to the instream flow target (M5A) ranged from 7 days at control point 8TRDAE to 37 days at control point 8WTGPE. With the exception of control point 8WTGPE, metric M5A appeared to increase gradually with increasing drainage area. Figure 22 is an exceedance frequency plot of consecutive engaged days in which the instream flow target was met or exceeded (M5B) for all instream flow targets at the four control points. The exceedance frequency curve was significantly greater for control point 8WTGPE than for the other control points. This observation reinforces the conclusion that the ratio of instream flow requirements to drainage area was relatively low for control point 8WTGPE compared to the other control points.

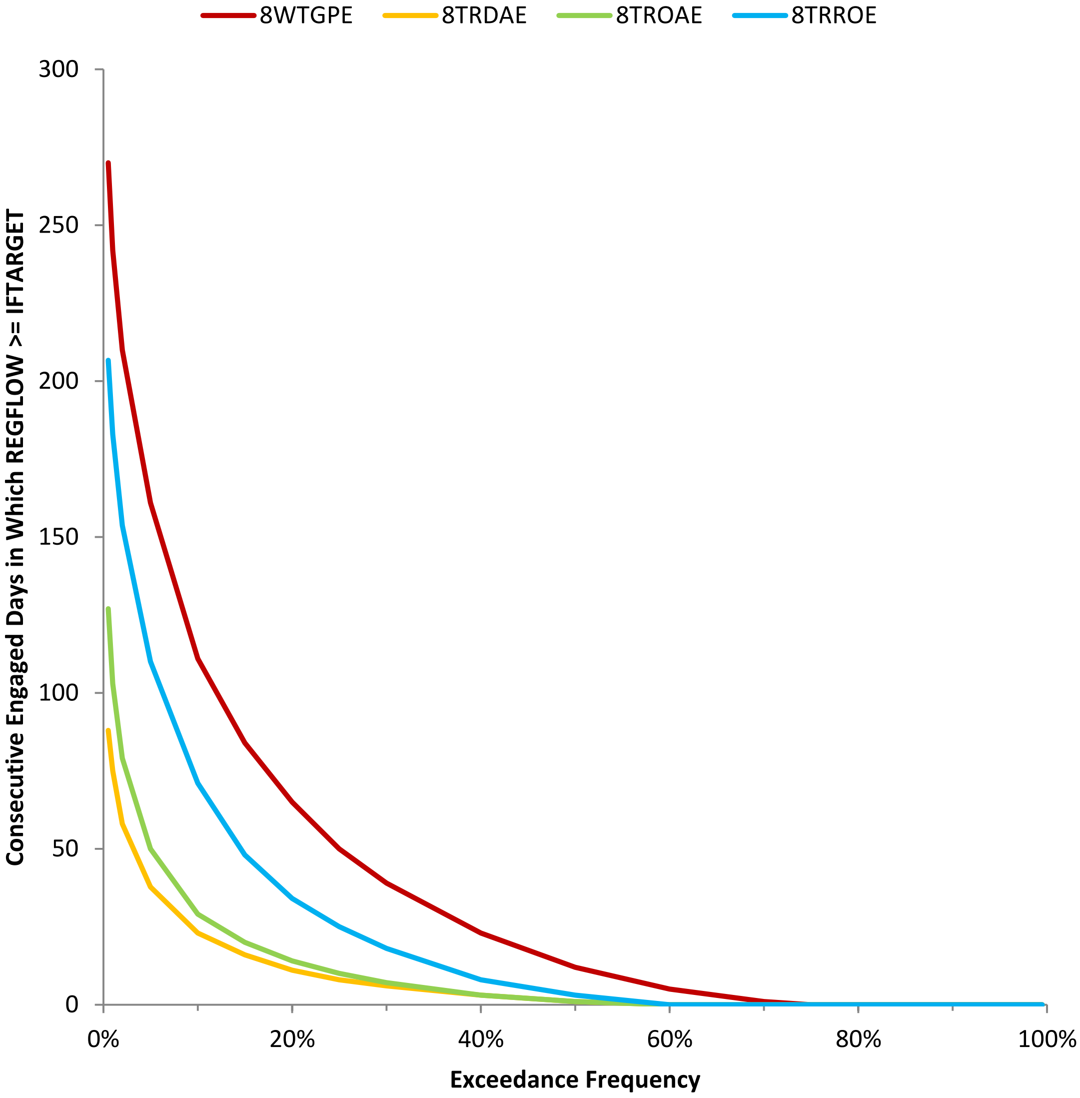

Figure 22. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW >= IFTARGET (M5B) for Trinity WAM Control Points for All Instream Flow Targets

The average number of consecutive engaged days in which a deficit was observed (M6A) ranged from 9 days at control point 8TRROE to 13 days at control point 8TROAE. There was not a clear relationship between drainage area and the value of metric M6A. Figure 23 is an exceedance frequency plot of consecutive engaged days for which a deficit was observed (M6B) for all instream flow targets at the four control points. In general, the exceedance frequency curves for all four control points were relatively similar to one another. Compared to the other control points, the curves for 8WTGPE and 8TROAE had relatively high values for the 0.5% exceedance probability.

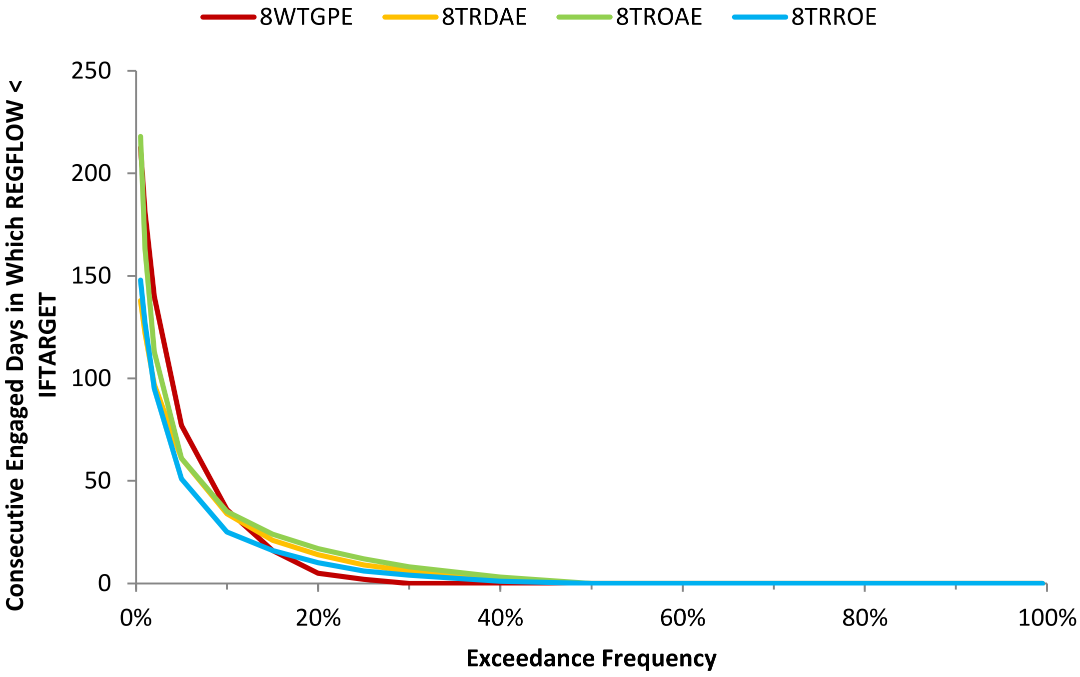

Figure 23. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW < IFTARGET (M6B) for Trinity WAM Control Points for All Instream Flow Targets

The average vulnerability (M9A) gradually increased with increasing drainage area, with a minimum of 16 cfs at control point 8WTGPE and maximum of 289 cfs at control point 8TRROE. Figure 24 is an exceedance frequency plot of vulnerability (M9B) for all instream flow targets at the four control points. The exceedance frequency curves for control points 8TROAE and 8TRROE were significantly greater compared to the other control points. The exceedance frequency curve for control point 8TRROE was characterized by two distinct areas in which the curve plateaued. These locations likely correspond to the fall subsistence flow target of 230 cfs and winter subsistence flow target of 495 cfs.

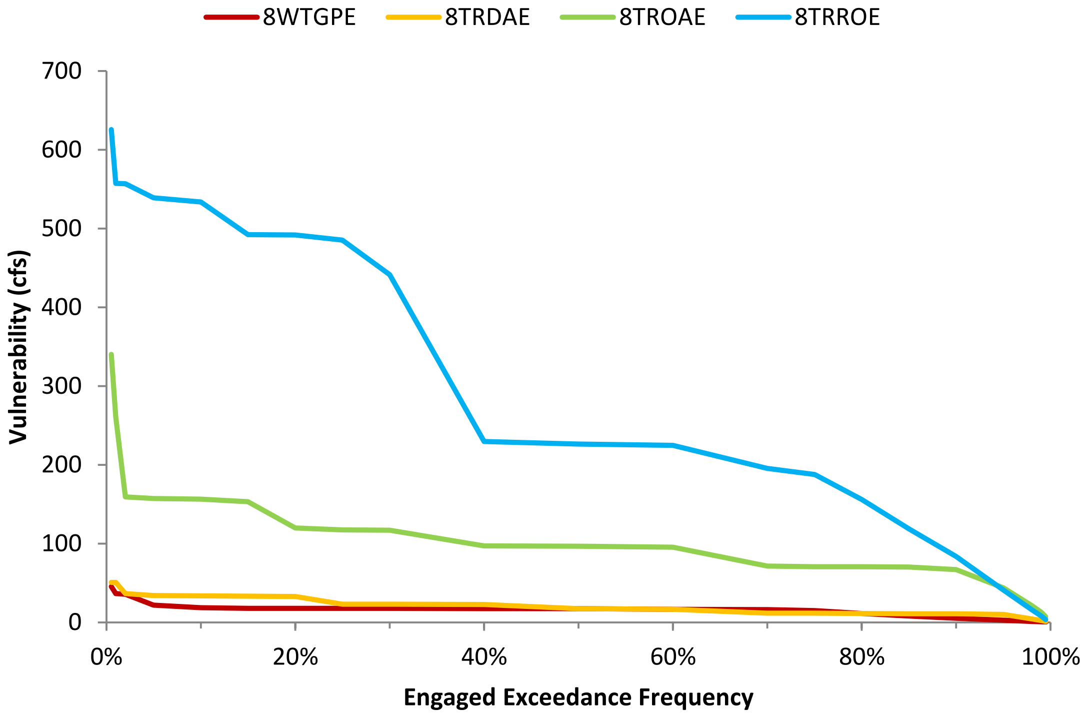

Figure 24. Engaged Exceedance Frequency Plot of Vulnerability (M9B) for Trinity WAM Control Points for All Instream Flow Targets

The average dimensionless vulnerability (M10A) increased moving from control point 8WTGPE downstream to control point 8TROAE but decreased between control points 8TROAE and 8TRROE. Metric M10A ranged from 69% at control point 8WTGPE to 90% at control point 8TROAE. The dimensionless average vulnerability (M11) was consistently lower than the average dimensionless vulnerability, ranging from 22% at control point 8TRDAE to 33% at control points 8TRROE and 8WTGPE. Figure 25 is an exceedance frequency plot of dimensionless vulnerability (M10B) for all instream flow targets at the four control points. The relative relationship of the curves to one another was similar to the relative relationship of the curves from the engaged period reliability versus allowable percentage deficit plot (M3C) of Figure 21.

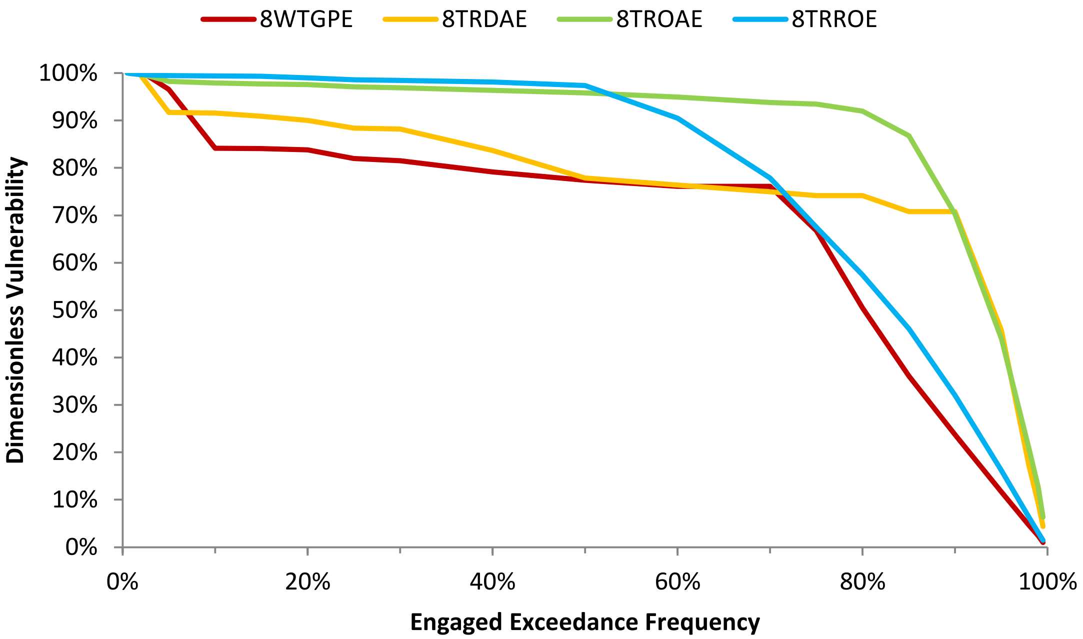

Figure 25. Engaged Exceedance Frequency Plot of Dimensionless Vulnerability (M10B) for Trinity WAM Control Points for All Instream Flow Targets

The expected number of allowable days to recovery (M12A) ranged from 11 days at control point 8TRROE to 16 days at control point 8TRDAE. As seen in Figure 26, the rate of improvement of the resilience changed suddenly for control point 8TRDAE around 30 allowable days to recovery. The rate of improvement of the resilience changed more gradually for the other control points. Control point 8TRDAE achieved 100% resilience around 140 allowable days to recovery while the other control points achieved 100% resilience around 70 allowable days to recovery.

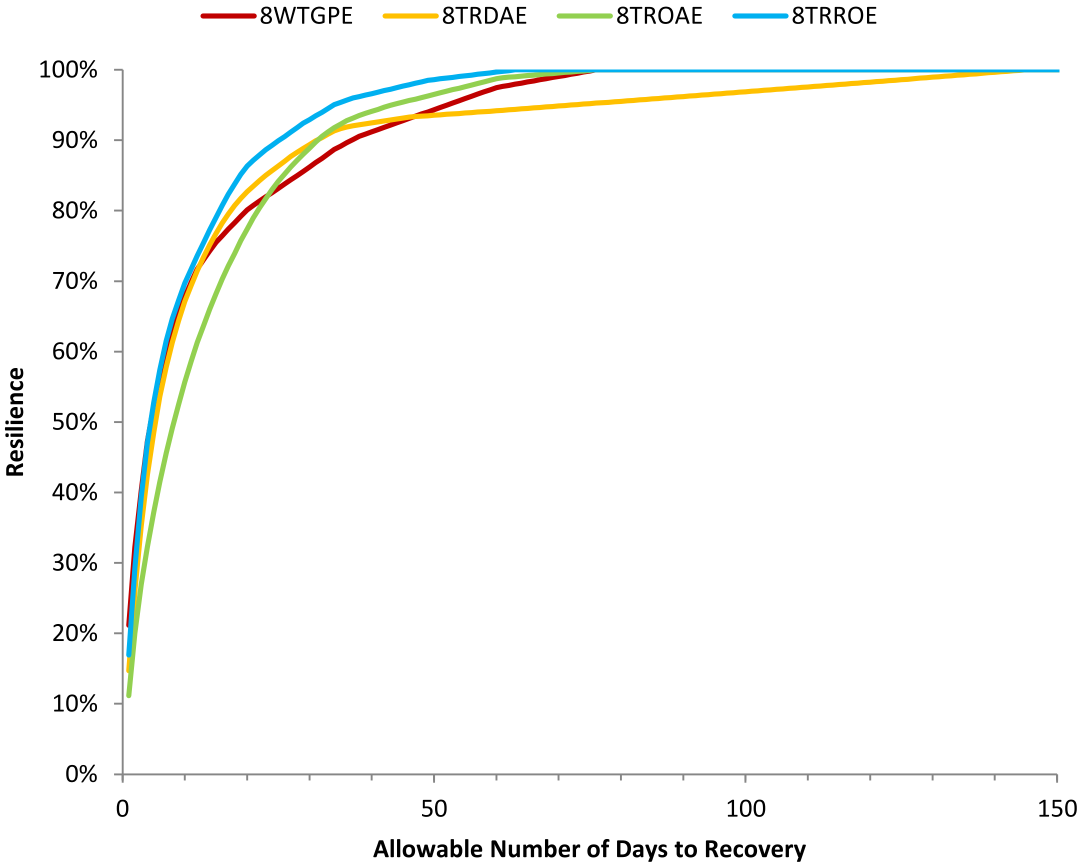

Figure 26. Comparison of Resilience versus Allowable Number of Days to Recovery (M12B) between Trinity WAM Control Points for All Instream Flow Targets

The eleven metrics documented in Table 46 were developed based on high flow pulse event targets at the four control points. The engagement percentage (M1) ranged from 3 to 5%, the engaged volume reliability (M2) ranged from 177 to 280%, and the engaged period reliability (M3A) ranged from 97 to 100%.

Table 46. Metric Comparison between Trinity WAM Control Points for High Flow Pulse Event Targets

Control Point	M1	M2	M3A	M4A	M7A	P1	P2	P3	P4	P5	P6
				(days)	(days)						
8WTGPE	4%	247%	97%	0	87	438	363	272	83%	44%	75%
8TRDAE	3%	280%	100%	0	78	438	369	266	84%	42%	72%
8TROAE	5%	209%	100%	0	83	438	366	287	84%	48%	78%
8TRROE	5%	177%	100%	0	122	438	323	237	74%	37%	73%

The average number of consecutive engaged days (M4A) was approximately zero at all four control points, summarizing the results of the exceedance frequency plot of consecutive engaged days (M4B) in Figure 27.

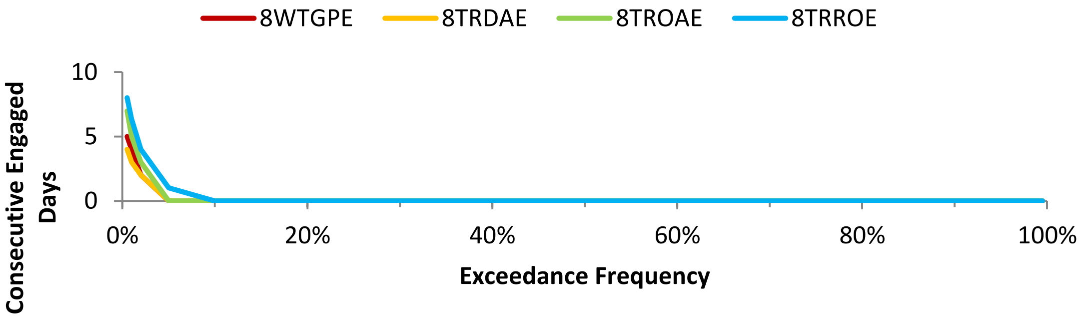

Figure 27. Exceedance Frequency Plot of Consecutive Engaged Days (M4B) for Trinity WAM Control Points for High Flow Pulse Event Targets

The average consecutive number of days between engagements (M7A) was significantly higher at control point 8TRROE, with a value of 122 days, compared to the other control points, which ranged from 78 to 87 days. Likewise, the exceedance frequency curve for consecutive days between engagement (M7B) for control point 8TRROE was significantly greater compared to the curves for the other control points, as seen in Figure 28.

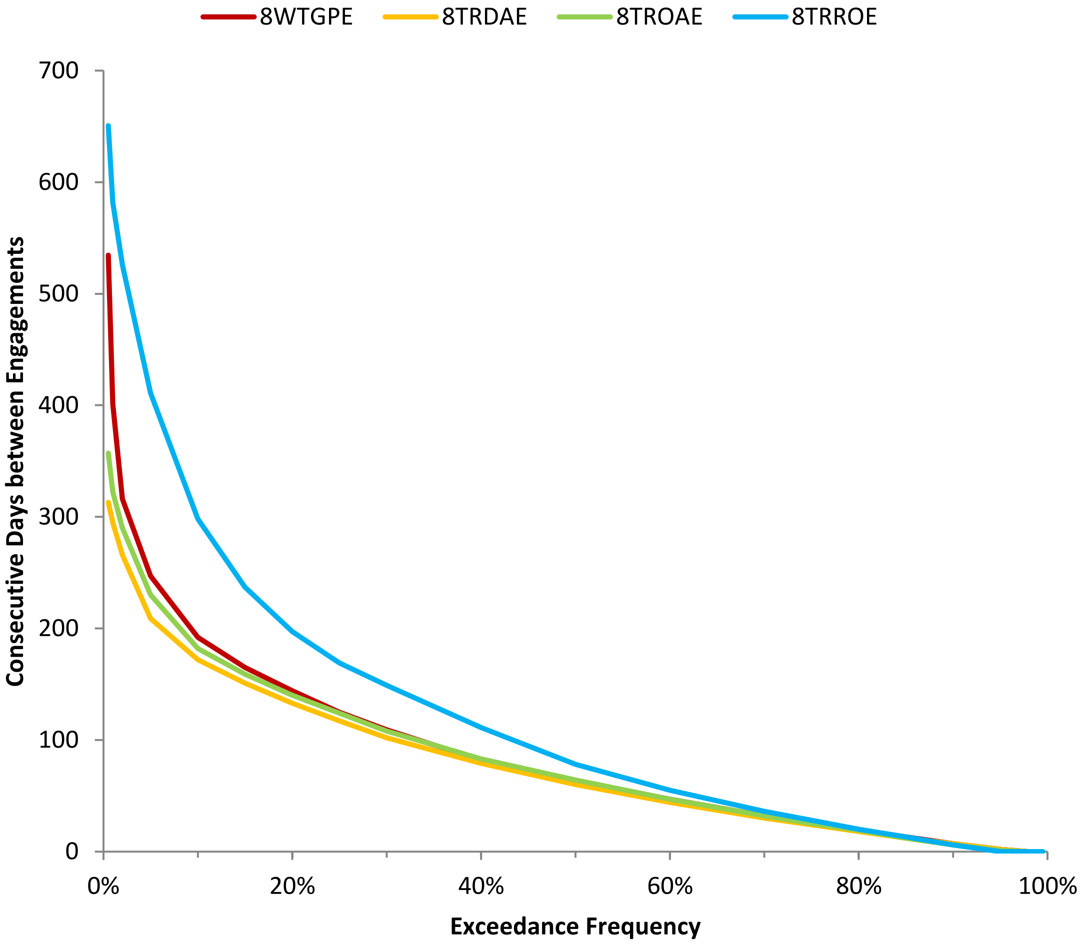

Figure 28. Exceedance Frequency Plot of Consecutive Days between Engagements (M7B) for Trinity WAM Control Points for High Flow Pulse Event Targets

The target number of high flow pulse event engagements (P1) was 438 at all four control points, corresponding to 6 high flow pulse event engagements per year for a period of 73 years. The observed number of high flow pulse event engagements (P2) from the simulation ranged from 323 to 369, corresponding to a range of engagement percentages (P4) between 74 and 84%. The percentage of years in which the high flow pulse event criteria were fully met (P5) ranged from 37 to 48%. The percentage of engaged high flow pulse events which satisfied the volume termination criteria (P6) ranged from 72 to 78%.

3.2.3 Comparison between Alternative Development Scenarios

The results of two Colorado WAM simulations were compared at control point F1000E to characterize the effects of alternative river basin development scenarios. The first development scenario (C1) consisted of the initial Colorado WAM simulation in which the environmental instream flow rights were modeled at a priority date of March 1, 2011, in accordance with provisions of the Texas Administrative Code. The second development scenario (C2) consisted of a Colorado WAM simulation in which the environmental instream flow rights were modeled at a priority date of March 1, 1800, senior to all other water rights in the basin. Any improvements in each metric between the first and second scenarios represent the maximum possible values of improvement for the current set of environmental flow standards at control point F1000E, given that the rights were simulated at the beginning of the priority sequence in the second simulation. Strategies for improving the attainment of the environmental flow standards at control point F1000E that involve adjustment or circumvention of the priority sequence can be expected to achieve values of improvement less than or equal to the values documented in this section.

Table 47 compares results of the alternative development scenarios at control point F1000E based on metrics evaluated for subsistence and base flow targets. Subsistence and base flow targets were engaged 96% of the time (M1) with approximately 290% volume reliability (M2) in both scenarios. The period reliability for subsistence and base flows (M3A) increased by 6% between the first and second scenarios.

Table 47. Metric Comparison between Alternate Development Scenarios at Control Point F1000E for Subsistence and Base Flow Targets

Scenario	M1	M2	M3A
C1-F1000E	96%	290%	65%
C2-F2000E	96%	292%	71%

Table 48 documents metrics computed for all instream flow targets at control point F1000E for each scenario. Between the first and second scenarios, the volume reliability (M2) remained approximately the same and the period reliability (M3A) increased by about 6%.

Table 48. Metric Comparison between Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

Scenario	M2	M3A	M5A (days)	M6A (days)	M9A (cfs)	M10A	M11	M12A (days)
C1-F1000E	241%	66%	18	5	78	42%	28%	10
C2-F1000E	231%	72%	22	4	61	33%	21%	9

Figure 29 is a plot of engaged period reliability versus allowable deficit (M3B) for both scenarios at control point F1000E. For a given level of engaged period reliability, the first scenario required a greater allowable deficit. The relative difference in allowable deficit decreased for increasing values of engaged period reliability. Both scenarios required large allowable deficits in order to achieve 100% period reliability.

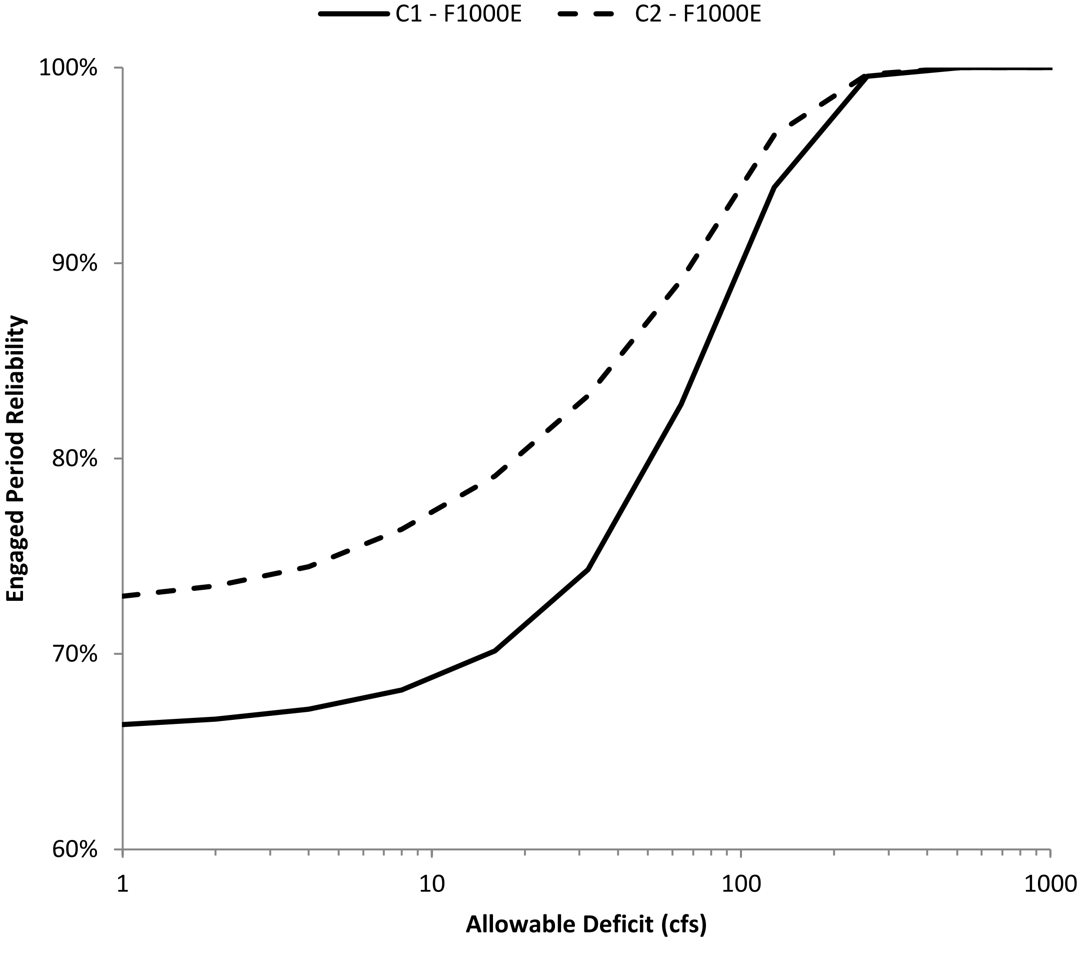

Figure 29. Comparison of Engaged Period Reliability vs. Allowable Deficit (M3B) between Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

Figure 30 is a plot of engaged period reliability versus allowable percentage deficit (M3C) for both scenarios at control point F1000E. The difference in allowable deficits was greatest around 80% engaged period reliability and gradually decreased for increasing values of engaged period reliability.

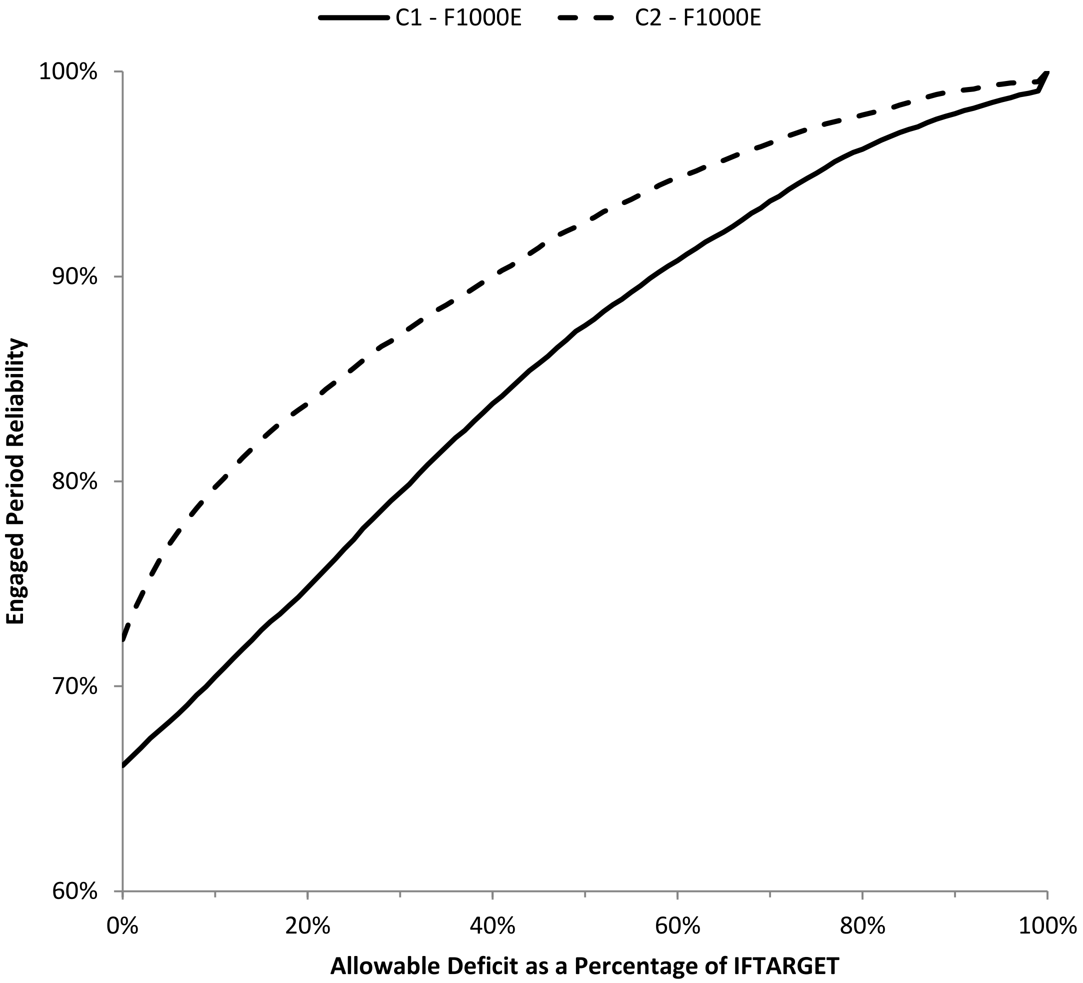

Figure 30. Comparison of Engaged Period Reliability vs. Allowable Percentage Deficit (M3C) between Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

The average consecutive number of engaged days in which the instream flow target was met or exceeded (M5A) increased from 18 to 22 days between the first and second scenarios. Figure 31 is an exceedance frequency plot of consecutive days engaged in which the regulated flow equaled or exceeded the instream flow target (M5B). Consecutive engaged days in which the instream flow target was met or exceeded were observed approximately 70% of the time in both scenarios.

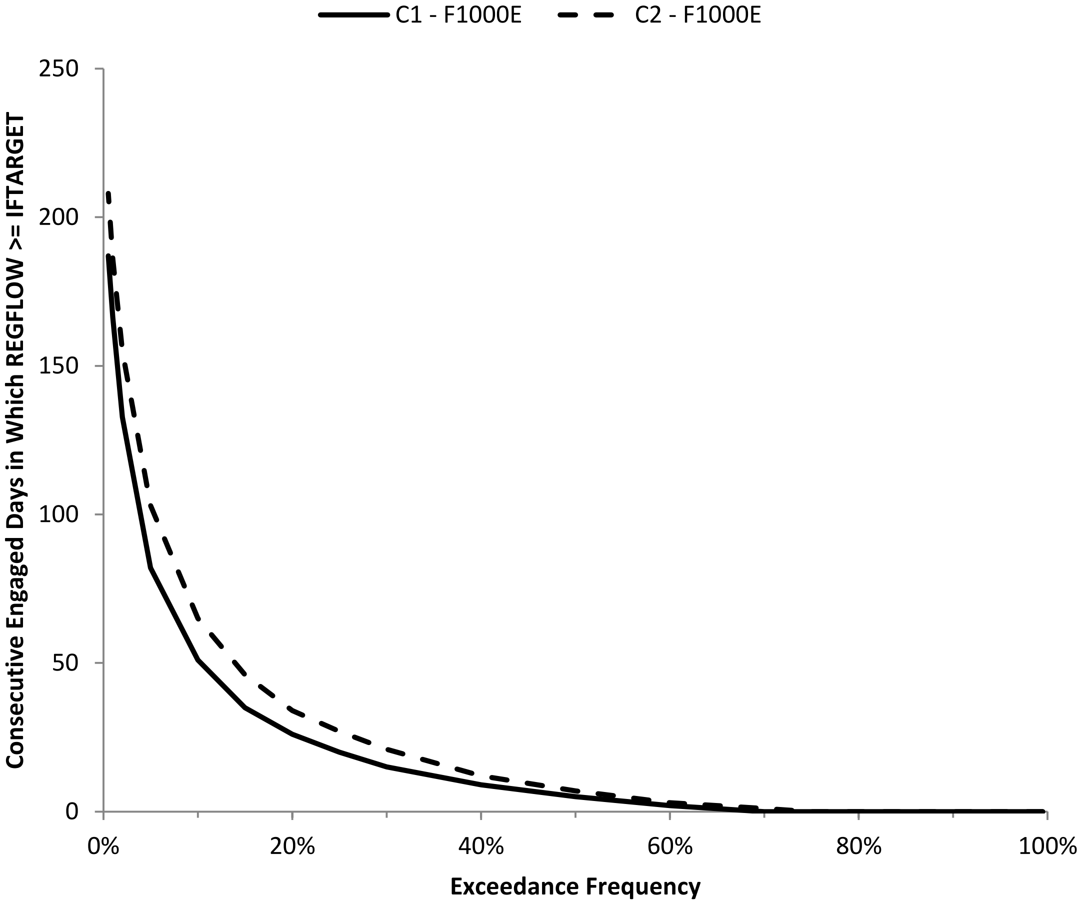

Figure 31. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW >= IFTARGET (M5B) for Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

The average consecutive number of engaged days in which a deficit was observed (M6A) decreased slightly from 5 to 4 days between the first and second scenarios. Figure 32 is an exceedance frequency plot of consecutive engaged days in which the regulated flow was less than the instream flow target (M6B). The curves for the first and second scenarios were very similar. The number of consecutive engaged days in which a deficit was observed corresponding to a 0.5% exceedance probability was approximately 120 days for both scenarios. Consecutive engaged days in which a deficit was observed occurred approximately 35% of the time in the first simulation and 30% of the time in the second simulation.

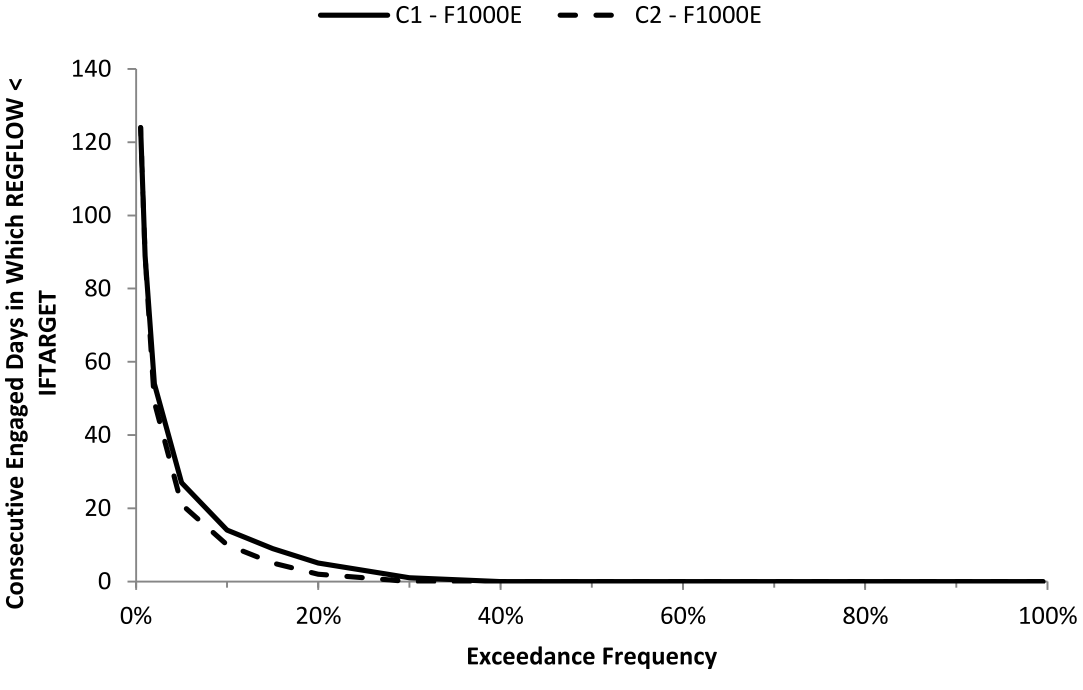

Figure 32. Exceedance Frequency Plot of Consecutive Engaged Days in Which REGFLOW < IFTARGET (M6B) for Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

The average vulnerability (M9A) at control point F1000E decreased between the first and second scenarios from 78 to 61 cfs, corresponding to a 9% decrease in the average dimensionless vulnerability (M10A) and 7% decrease in the dimensionless average vulnerability (M11).

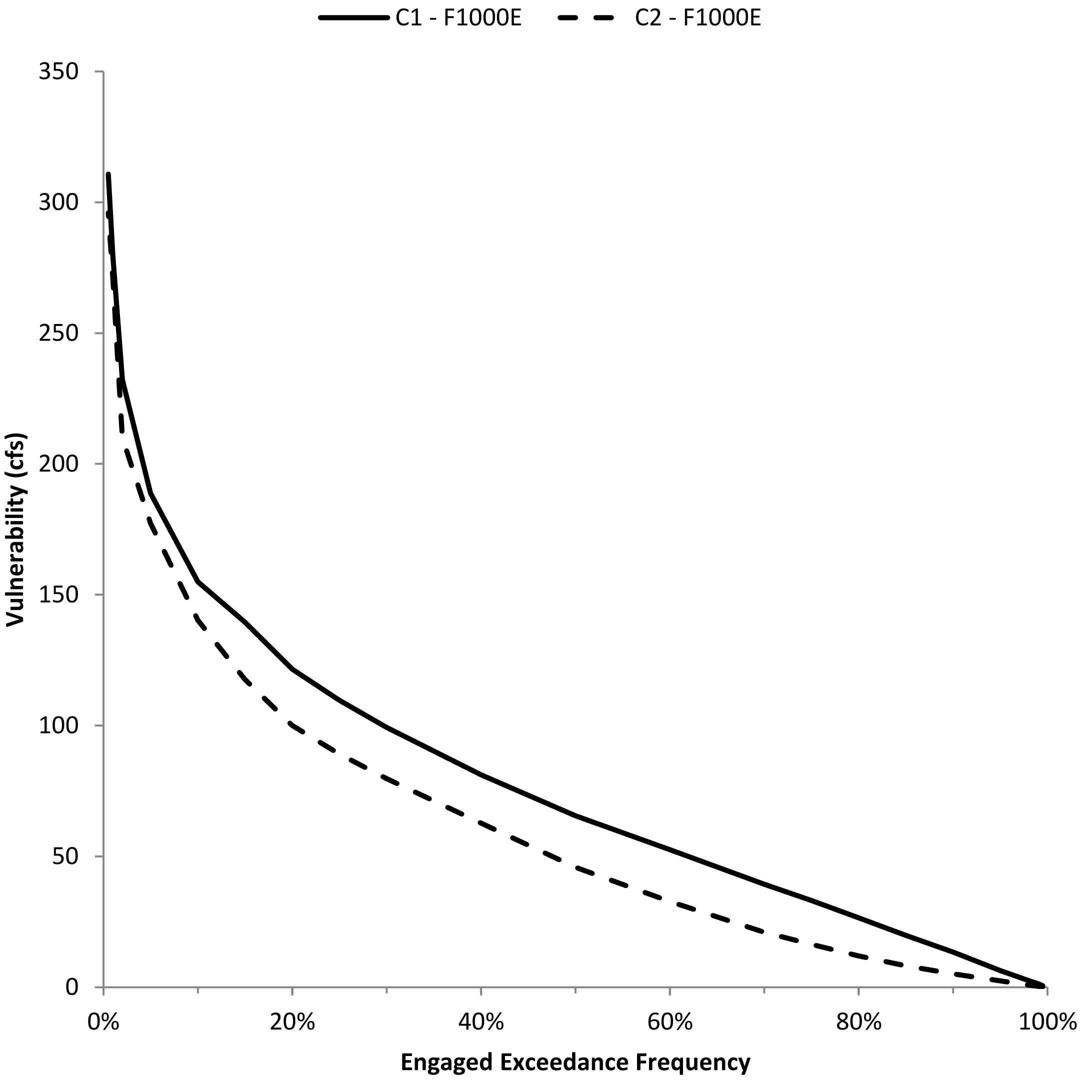

Figure 33. Engaged Exceedance Frequency Plot of Vulnerability (M9B) for Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

Figure 33 and Figure 34 are exceedance frequency plots of vulnerability (M9B) and dimensionless vulnerability (M10B). The vulnerability corresponding to a 0.5% exceedance probability was approximately 300 cfs for the first and second simulations. In both plots, the curve for the second scenario was closer to the origin than the curve for the first scenario, indicating a generally lower level of vulnerability in the second scenario.

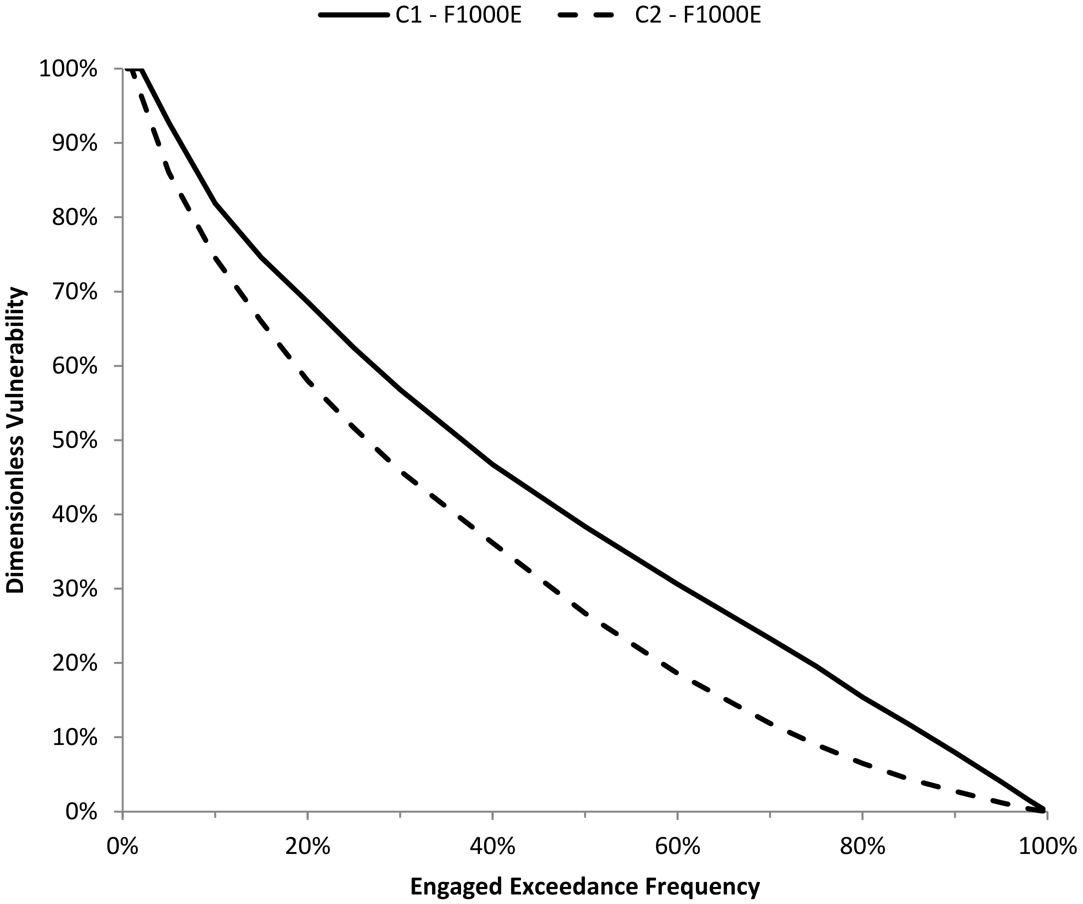

Figure 34. Engaged Exceedance Frequency Plot of Dimensionless Vulnerability (M10B) for Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

The expected number of days to recovery from a deficit (M12A) decreased slightly between the first and second scenarios from 10 to 9 days. Figure 35 is a plot of resilience versus allowable number of days to recovery (M12B). There was a slight improvement between the first and second scenarios, however both scenarios required approximately 40 allowable days of recovery to achieve 100% resilience.

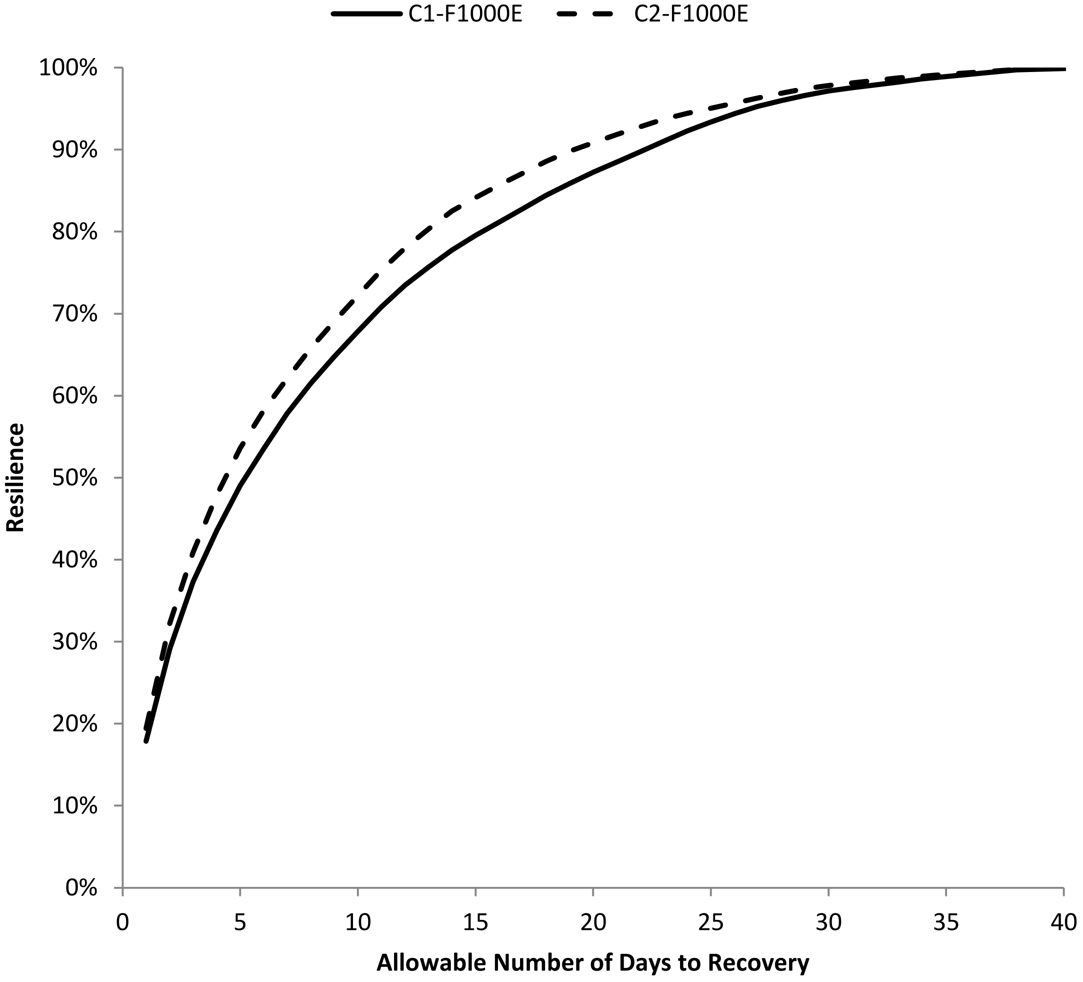

Figure 35. Comparison of Resilience vs. Allowable Number of Days to Recovery (M12B) between Alternate Development Scenarios at Control Point F1000E for All Instream Flow Targets

Table 49 compares results of the alternative development scenarios at control point F1000E based on metrics evaluated for high flow pulse event targets. The percentage of time for which high flow pulse events were engaged (M1) increased slightly between the first and second simulations, corresponding to the engagement of 29 additional high flow pulse events (P2), or a 3% increase in the target number of high flow pulse events that were engaged (P4). The volume reliability (M2) decreased by 11% and the period reliability (M3A) decreased by 5%. The percentage of years in which the target number of high flow pulse event engagements were met (P5) increased from 7 to 11%. The percentage of engaged high flow pulse events that satisfied the volume termination criteria (P6) increased slightly from approximately 98 to 99%.

Table 49. Metric Comparison between Alternate Development Scenarios at Control Point F1000E for High Flow Pulse Event Targets

Scenario	M1	M2	M3A	M7A (days)	P1	P2	P3	P4	P5	P6
C1-F1000E	4%	158%	100%	76	949	576	562	61%	7%	98%
C2-F1000E	4%	147%	95%	70	949	604	597	64%	11%	99%

The average consecutive number of days between engagements of high flow pulse events (M7A) decreased from 76 to 70 days between the first and second simulations. The relatively small change in metric M7A is reflected in the curves of Figure 36, which are relatively similar to one another. Figure 36 is an exceedance frequency plot of the consecutive number of days between engagements of high flow pulse events (M7B).

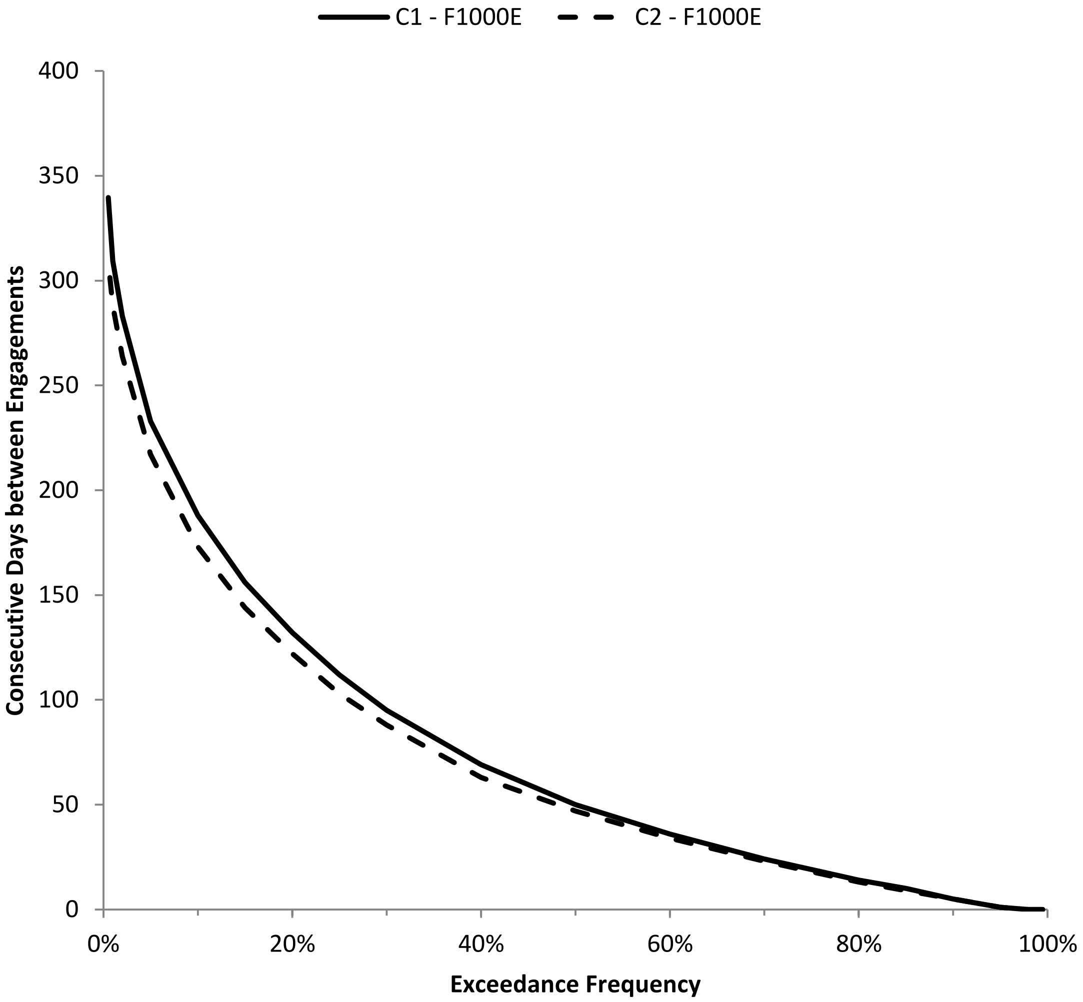

Figure 36. Exceedance Frequency Plot of Consecutive Days between Engagements (M7B) for Alternate Development Scenarios at Control Point F1000E for High Flow Pulse Event Targets

Figure 37 is a histogram of the cumulative number of high flow pulse event engagements per day-of-year that occurred through the period-of-analysis at control point F1000E for the initial Colorado WAM simulation. The spring, summer, fall, and winter seasons for control point F1000E began March 1, July 1, September 1, and November 1, corresponding to day-of-years 60, 180, 240, and 300, respectively. As seen in the histogram, high flow pulse events were typically engaged at the beginning of the summer, fall, and winter seasons. For the spring season, however, the engagement of high flow pulse events was more evenly distributed across the season, with a relatively higher proportion of engagements occurring in late April, May, and June.

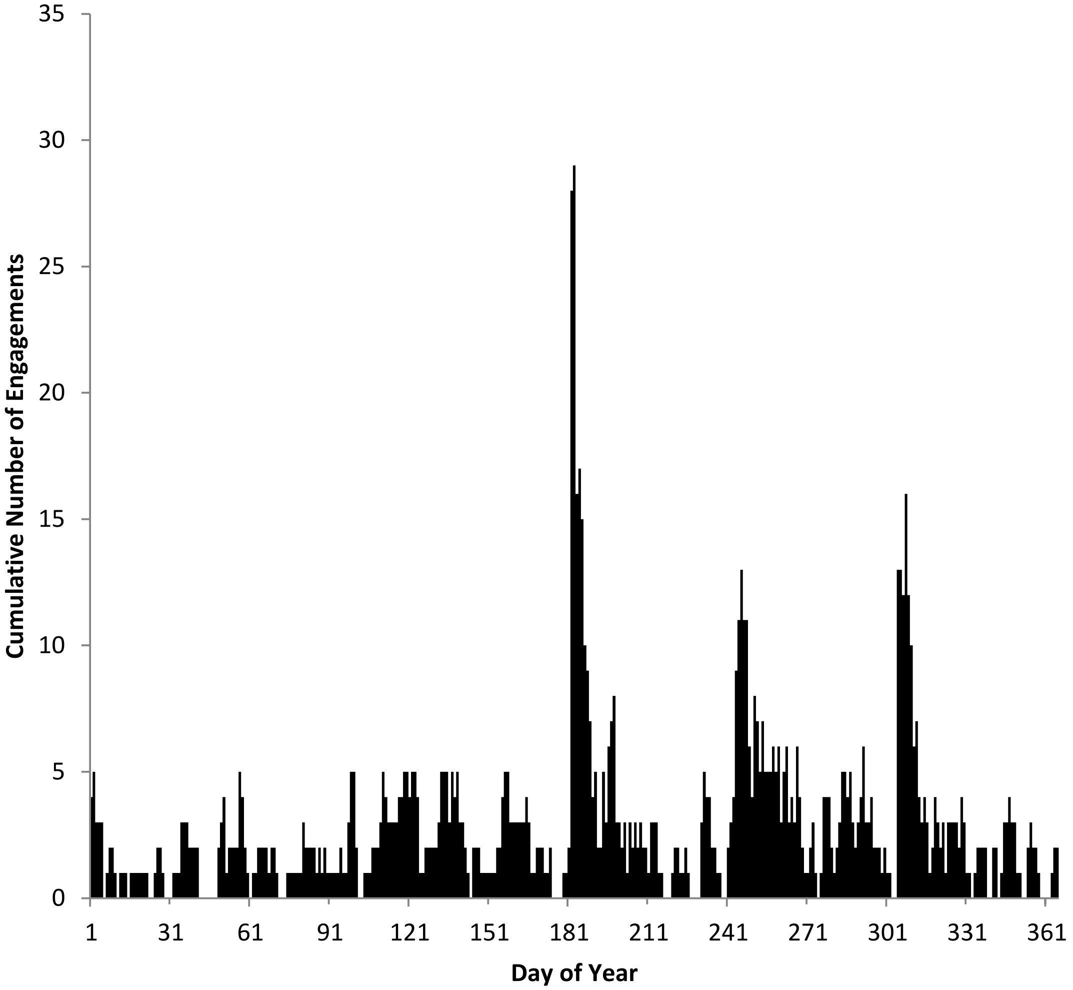

Figure 37. Histogram of the Cumulative Number of Engagements per Day-of-Year through the Period-of-Analysis (M8) at Control Point F1000E for the Initial Colorado WAM Simulation for High Flow Pulse Event Targets

CHAPTER IV

CONCLUSIONS

The Senate Bill 3 process of establishing environmental instream flow standards in Texas represents a unique, collaborative endeavor between scientists, stakeholders, and regulatory agencies. The initial set of instream flow standards has been established for selected priority river basins, however, additional work is necessary to incorporate the standards in the State's water rights permitting system. Two key challenges addressed by this thesis are the development of techniques for modelling environmental instream flows in daily time-step water availability models and the development of metrics to characterize the engagement and attainment of the modeled instream flows. The techniques developed in Chapter II to model environmental instream flows for the Colorado and Trinity river basins contribute to the body of knowledge available for modeling standards in other basins. The attainment metrics developed in Chapter III will assist scientists and decision-makers in the evaluation and revision of the standards and enable the development of risk assessment frameworks for evaluating tradeoffs between reliabilities for environmental flows and human water needs.

4.1 Environmental Flow Modeling Capabilities of the WRAP/WAM System

The environmental flow standards at 14 control point locations in the Colorado River basin and 4 control point locations in the Trinity River basin were modeled using recently added features of WRAP and daily time-step versions of the Colorado and Trinity WAMs. The recently added features of WRAP and overall flexibility of the modeling system allowed the environmental flow standards for the Colorado River basin and Trinity River basin to be effectively incorporated in the WAMs, with the exception of water right permit conditions that circumvented the priority sequence.

As evidenced by the descriptions in Sections 2.3 and 2.6, the environmental flow standards for the Colorado and Trinity river basins differed significantly in their level of complexity. Compared to the Trinity River basin, the environmental flow standards for the Colorado River basin were specified at a greater number of control points, required the computation of hydrologic conditions, and included a greater number of high flow pulse events. As such, the methodology used to model environmental flow standards in the Colorado River basin was significantly more complex than the methodology implemented for the Trinity River basin. The environmental flow standards for the Colorado River basin were modeled using approximately 2,700 input records, compared to approximately 270 input records for the Trinity River basin.

Compared to other generalized river/reservoir system models, WRAP appears to have the most flexible and comprehensive set of input records for modeling environmental instream flows. The recently added daily-time step features of WRAP, including specific records for modeling high flow pulse events, make it especially useful for incorporating environmental instream flow requirements.

4.2 Evaluation of Attainment Metrics

In total, 28 metrics were developed to characterize the engagement and attainment of environmental instream flow standards, including 22 general attainment metrics and 6 metrics specific to high flow pulse events. The metrics were developed using *WRAP-SIMD* output from the SUB and SMM files. The attainment metrics were used to perform several analyses, including the comparison of results between alternate components of the environmental flow regime at a control point, between alternate control point locations, and between alternate river basin development scenarios. The analyses were performed using the results of two Colorado WAM simulations and one Trinity WAM simulation. For the initial Colorado WAM simulation and the Trinity WAM simulation, the environmental flow requirements were modeled at the priority dates specified by the Texas Administrative Code. For the second Colorado WAM simulation, the environmental flow requirements were modeled at the most senior priority date in the basin. For all three simulations, daily time-step versions of the authorized use scenario datasets were implemented for an extended 73-year period-of-analysis.

The metrics were useful for evaluating the engagement and attainment of the environmental flow standards and for making comparisons. Output selection parameters offered flexibility in the environmental flow regime components that were assessed. Using the output selection parameters, both individual environmental flow regime components and the complete environmental flow regime were assessed. Alternate metrics were useful for describing alternate components of the environmental flow regime. For example, metrics M2, M3A, M3B, M3C, M5A, M5B, M6A, M6B, M9A, M9B, M10A, M10B, M11, M12A, and M12B were useful for describing all instream flow targets at a control point while metrics M1, M2, M3A, M4A, M4B, M7A, M7B, M8, P1, P2, P3, P4, P5, and P6 were useful for describing high flow pulse event targets.

REFERENCES

Black DC, Podger GM. 2012. Guidelines for modeling water sharing rules in eWater Source: Towards best practice model application. eWater Cooperative Research Centre, Bruce, ACT, Australia.

Butler RA. 2011. Modeling techniques to assess long-term reliability of environmental flows in basin scale planning. M.S. Thesis, Department of Civil, Environmental and Architectural Engineering, The University of Colorado, Boulder, Colorado.

Cardwell H, Jager HI, Sale MJ. 1996. Designing instream flows to satisfy fish and human water needs. *Journal of Water Resources Planning and Management*, ASCE, **122** : 356-363.

Center for Advanced Decision Support for Water and Environmental Systems. 2013. RiverWare Technical Documentation Version 6.3: Accounting. Center for Advanced Decision Support for Water and Environmental Systems, The University of Colorado, Boulder, Colorado.

Colorado Basin and Bay Area Stakeholder Committee. 2012. Draft Work Plan. Texas Commission on Environmental Quality, Austin, Texas.

Colorado Basin and Bay Expert Science Team. 2011. Environmental Flow Regime Recommendations Report. Texas Commission on Environmental Quality, Austin, Texas.

Espey Consultants, Incorporated. 2002. Final Report – Trinity River and Trinity-San Jacinto and Neches-Trinity Coastal Basins Water Availability Study. Prepared for the Texas Natural Resource Conservation Commission, Austin, Texas.

Gippel CJ, Stewardson MJ. 1995. Development of an environmental flow management strategy for the Thomson River, Victoria, Australia. *Regulated Rivers Research & Management* **10** : 121-135.

Gippel CJ, Cosier M, Markar S, Liu C. 2009. Balancing environmental flows needs and water supply reliability. *International Journal of Water Resources Development* **25**(2) : 331-353.

Harman C, Stewardson M. 2005. Optimizing dam release rules to meet environmental flow targets. *River Research and Applications* **21** : 113-129.

Hoffpauir RJ, Pauls MA, Wurbs RA. 2013. Application of Expanded WRAP Modeling Capabilities to the Colorado WAM. Prepared for the Texas Commission on Environmental Quality, Austin, Texas.

Hughes DA, Ziervogel G. 1998. The inclusion of operating rules in a daily reservoir simulation model to determine ecological reserve releases for river maintenance. *Water SA* **24**(4) : 293-302.

HydroLogics, Inc. 2009. User Manual for OASIS with OCL, Model Version 3.10.8, GUI Version 4.6.16. HydroLogics, Inc., Columbia, Maryland.

Labadie JW. 2010. MODSIM 8.1: River Basin Management Decision Support System User Manual and Documentation. Department of Civil and Environmental Engineering, Colorado State University, Ft. Collins, Colorado.

Meijer K. 2011. River Basin Simulation Model – A tool to support water resources planning and management. Deltares, Delft, Netherlands.

Palmer RN, Snyder RM. 1985. Effects of instream flow requirements on water supply reliability. *Water Resources Research* **21**(4) : 439-446.

Palmer SR. 2008. Averting a water supply crisis while protecting endangered species: Partnerships pay off for Tennessee's Duck River. EcoLogic from the Nature Conservancy, *Journal AWWA*, **100**(8) : 40-43.

Pauls MA, Hoffpauir RJ, Wurbs RA. 2013. Hydrologic Period-of-Analysis Extension for the Colorado River Basin and Brazos-Colorado Coastal Basin Water Availability Model. Prepared for the Texas Commission on Environmental Quality, Austin, Texas.

Pauls MA, Hoffpauir RJ, Wurbs RA. 2013. Hydrologic Period-of-Analysis Extension for the Trinity River Basin Water Availability Model. Prepared for the Texas Commission on Environmental Quality, Austin, Texas.

Pearsall SH, McCrodden BJ, Townsend PA. 2005. Adaptive management of flows in the Lower Roanoke River, North Carolina, USA. *Environmental Management* **3**(4) : 353-367.

Podger G, Beecham R. 2003. IQQM User Guide. Department of Infrastructure Planning and Natural Resources, Sydney South, NSW, Australia.

Podger G, Yang A, Brown A, Teng J, Power R, Seaton S. 2010. Proposed River Modelling Methods and Integrated River System Modelling Framework Design for use in Basin Plan Modelling. CSIRO: Water for a Healthy Country National Research Flagship.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: A paradigm for river conservation and restoration. *BioScience* **47**(11) : 769-784.

Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology* **55** : 194-205.

R. J. Brandes Company. 2001. Water Availability Modeling for Colorado and Brazos Colorado Water Availability Assessment – Final Report. Prepared for the Texas Natural Resource Conservation Commission, Austin, Texas.

Sale MJ, Brill Jr. ED, Herricks EE. 1982. An approach to optimizing reservoir operation for downstream aquatic resources. *Water Resources Research* **18**(4) : 705-712.

Sandoval-Solis S, McKinney DC. 2009. Hydrological feasibility of environmental flows in the Rio Grande/Bravo basin. World Environmental and Water Resources Congress, ASCE, 4927-4937.

Sandoval-Solis S, McKinney DC. 2014. Integrated water management for environmental flows in the Rio Grande. *Journal of Water Resources Planning and Management*, ASCE, **140**(3) : 355-364.

Science Advisory Committee. 2004. Science Advisory Committee Report on Water for Environmental Flows. Prepared for Commission on Water for Environmental Flows, Austin, Texas.

Science Advisory Committee. 2010. Consideration of Methods for Evaluating Interrelationships between Recommended SB-3 Environmental Flow Regimes and Proposed Water Supply Projects. Transmittal to Basin and Bay Area Stakeholder Committees and Basin and Bay Expert Science Teams, Report # SAC-2010-04.

Sieber J, Purkey D. 2011. Water Evaluation and Planning System (WEAP) User Guide. Stockholm Environmental Institute, Stockholm, Sweden.

Suen JP, Eheart JW. 2006. Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime. *Water Resources Research* **42**, W03417, 1-9.

Texas A&M University and United States Bureau of Reclamation. 1999. Model Description Form for MIKE BASIN. Hydrologic Modeling Inventory, USBR, Washington, D.C.

Texas A&M University and United States Bureau of Reclamation. 2007. Model Description Form for HYDROSS. Hydrologic Modeling Inventory, USBR, Washington, D.C.

Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Texas Water Development Board. 2008. Texas instream flow studies: Technical overview. *Report 369*, Texas Water Development Board, Austin, Texas.

Texas Water Development Board. 2010a. Assessing Instream Flow Recommendations in the Context of Water Availability Models for the Trinity and San Jacinto River Basins (Status Report). Texas Water Development Board, Austin, Texas.

Texas Water Development Board. 2010b. San Jacinto Basin Environmental Flow Analysis. Texas Water Development Board, Austin, Texas.

Tharme RE. 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19** : 397-441.

Trinity Basin and Bay Area Stakeholder Committee. 2012. Work Plan Report. Texas Commission on Environmental Quality, Austin, Texas.

United States Army Corps of Engineers – Hydrologic Engineering Center. 2007. HEC-ResSim Reservoir System Simulation User’s Manual Version 3.0. United States Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, California.

Vogel RM, Sieber J, Archfield SA, Smith MP, Apse CD, Huber-Lee A. 2007. Relations among storage, yield, and instream flow. *Water Resources Research* **43**, W05403, 1-12.

Wurbs RA, James WP. 2002. *Water Resources Engineering*. Prentice Hall: Upper Saddle River, New Jersey.

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

Wurbs RA. 2012. Reservoir/river system management models. Texas Water Resources Institute, *Texas Water Journal* **3**(1) : 26-40.

Wurbs RA. 2013. Water Rights Analysis Package (WRAP) modeling system users manual. *TR-256*, Texas Water Resources Institute, College Station, Texas.

Wurbs RA, Hoffpauir RJ. 2013. Water Rights Analysis Package (WRAP) daily modeling system. *TR-430*, Texas Water Resources Institute, College Station, Texas.

Wurbs RA, Hoffpauir RJ. 2013. Environmental flows in water availability modeling. *TR-440*, Texas Water Resources Institute, College Station, Texas.