APPLICATION OF INDICATORS OF HYDROLOGIC ALTERATION TO ECOLOGICAL HYDROLOGY IN TRINITY AND BRAZOS RIVER BASINS

A Thesis

by

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ABSTRACT

As the demand for water resources has been increasing all around the world, intense water appropriation has led to alterations of flow regimes over time. Changes in environmental flows have impaired beneficial functions of ecosystems. Thus, the protection of environmental instream flows to maintain healthy ecosystems has become more and more critical. The Texas Commission on Environmental Quality (TCEQ) has established environmental flow standards through a process established by the Texas Legislature in its 2007 Senate Bill 3 (SB3). The SB3 has expedited the process of developing methodologies and tools to analyze and quantify alterations in environmental flows. Furthermore, with the experts' participation, the establishment of SB3 has helped lawmakers to improve regulations, laws, and water management practices.

This thesis applies the Indicators of Hydrologic Alteration (IHA) software and the TCEQ Water Availability Modeling (WAM) System allied with Hydrologic Engineering Center Data Storage System (HEC-DSS) to analyze and quantify flow conditions at 13 gaging stations in the Trinity River Basin and 20 gaging stations in the Brazos River Basins. The thesis focuses on three types of flows: observed flow, WAM naturalized flow, and WAM simulated regulated flow. The thesis explores long-term alterations in different types of flow characteristics in research areas, develops meaningful frequency metrics, and evaluates capabilities of different methodologies. The results reveal the differences and similarities of alterations in long-term flow characteristics in Trinity and Brazos River Basins. In addition, this thesis proves that the application of IHA is meaningful. Also, the use of the WAM System is fundamental in this thesis.

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NOMENCLATURE

DSSVue	Data Storage System Visual Utility Engine
EFCs	Environmental Flow Components
HEC	Hydrologic Engineering Center
IHA	Indicators of Hydrological Alteration
NAT	Naturalized Flow
NWIS	National Water Information System
REG	Regulated Flow
RVA	Range of Variability Approach
SB3	Senate Bill 3
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

1.1 Assessing and Protecting Environmental Instream Flows

Population growth, economic development, and associated water resources development have altered the natural flow of rivers around the world. Providing reliable and affordable water supplies for growing populations while preserving the vitality of riverine ecosystems is a crucial challenge worldwide (O'Keefe 2012). The scientific literature related to flow characteristics necessary for a sound ecology is extensive (Tharme 2003, Acreman and Dunbar 2004, Poff and Zimmerman 2009).

Protecting instream flows in the river systems of Texas has been a concern for many years. However, efforts in establishing expanded environmental flow standards have greatly intensified pursuant to recent legislation (Wurbs 2015). The Texas Instream Flow Program (TIFP) created by the 2001 Senate Bill 2 is designed to both advance scientific knowledge and improve water management practices. However, the scientific and water management communities of Texas have recognized that many more future years will be required to realize the goals of the TIFP fully. Thus, the SB3 process was created by Senate Bill 3 in 2007 to expedite the establishment of environmental flow standards for priority river systems based on the best currently available information and expert opinion. The SB3 process anticipates future improvements to the flow standards as additional scientific knowledge and water management capabilities are developed.

Environmental flow standards have recently been established through the SB3 process for several major priority river systems in Texas, including the Trinity and Brazos, by the Texas Commission on Environmental Quality (TCEQ) based on recommendations of science teams and stakeholder committees. The flow standards are incorporated in the TCEQ Water Availability

Modeling (WAM) System, which is used for regional and statewide planning and administration of the water rights permit system (Wurbs and Hoffpauir 2013a). Applications for new water right permits or modifications to existing permits are subject to the environmental flow standards.

Environmental stream flow needs are defined regarding the magnitude, frequency, timing, duration, and spatial distribution of the flows required to sustain freshwater and estuarine ecosystems. Environmental flows include freshwater inflows to bays and estuaries as well as flow in inland stream systems. Environmental flow requirements were initially prescribed in Texas and elsewhere primarily as minimum flow limits. However, in Texas like elsewhere, the importance of considering all elements of a flow regime is now well recognized (Wurbs and Hoffpauir 2013). Environmental flow standards established through the SB3 process and incorporated into the TCEQ WAM System are defined regarding seasonally varying flow regimes with subsistence flows, base flows, in-bank high flow pulses, and overbank flooding events.

1.2 Modeling Systems Used in the Research

This thesis presents quantitative assessments of (1) long-term alterations in streamflow characteristics of the Trinity and Brazos Rivers and their tributaries and (2) capabilities for satisfying SB3 environmental flow standards in these two river systems. Comparative analyses of statistical metrics are performed for daily historical flows observed at gaging stations and sequences of daily naturalized and regulated flows for specified conditions of development generated with the Trinity and Brazos Water Availability Models (WAMs). The Indicators of Hydrologic Alteration (IHA) methodology and software (Nature Conservancy 2009) along with other tools are applied to perform statistical analyses of long sequences of daily observed and simulated flows.

The research combines two computer modeling systems: the TCEQ WAM System and the IHA software developed by the Nature Conservancy. The Hydrologic Engineering Center (HEC) Data Storage System (DSS) and Visual Utility Engine (HEC 2009) available from the HEC of the U.S. Army Corps of Engineers (USACE) are also used in the research to manage, analyze, and display flow data.

The TCEQ WAM System consists of the Water Rights Analysis Package (WRAP) developed at Texas A&M University (TAMU) and WRAP input datasets for all of the river basins of Texas (Wurbs 2005; Wurbs 2015). Monthly WAMs have been routinely applied since 2002. Motivated by the TIFP and SB3 environmental flow standards, the TCEQ has sponsored research at TAMU over the past several years that has included the development of a daily version of WRAP and six of the WAM datasets, including the Trinity and Brazos, which incorporate SB3 environmental flow standards.

WRAP is documented in detail by a set of manuals (Wurbs and Hoffpauir 2012). WRAP simulates specified scenarios of river system water resources development, allocation, management, and use of postulated repetitions of historical natural hydrology represented by sequences of naturalized streamflows and net reservoir evaporation fewer precipitation rates. The Trinity and Brazos WAMs have a daily time step and 1940-2015 hydrologic period-of-analysis. The authorized use scenario simulations are based on the premise that all water right permit holders store and use the full amounts of water authorized by their permits subject to streamflow availability.

WRAP is integrated with the USACE HEC-DSS and HEC-DSSVue. WRAP reads hydrology data from *DSS* files and stores simulation results in *DSS* files. Stream flows and other time series variables are plotted, manipulated, statistically analyzed, and displayed with HEC-DSSVue. Observed flows are downloaded directly from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website and stored in *DSS* files using HEC-DSSVue.

WRAP and HEC-DSSVue provide statistical frequency analysis as well as river/reservoir system simulation capabilities. However, the IHA software package provides more extensive statistical trend and frequency analysis capabilities focused specifically on parameters of particular significance to environmental flow issues. The IHA methodology and computer software were developed by the Nature Conservancy (Mathews and Richter 2007) and have been widely applied throughout the United States and the world (Mathews and Richter 2007). The IHA provide flexibility for developing a large set of statistical metrics for analyzing long sequences of daily stream flow rates or other daily time series variables relevant to ecosystem impact analyses. The IHA were adopted for the thesis research based on a literature review of available statistical analysis tools.

Stream flows in Texas are extremely variable with continuous fluctuations, seasonality, severe multiple-year droughts, and major floods that complicate analyses of long-term changes in flow characteristics. Conventional applications of the IHA are based on dividing a long historical record of observed daily stream flows into Pre-Impact and Post-Impact periods (Matthews and Richter 2007). Comparative statistics are computed for the ″before″ versus ″after″ observed flow sequences to assess the impacts of water resources development. This conventional strategy is included in the thesis research, but similar analyses are also performed for WAM simulated regulated versus naturalized flows. Period-of-record observed daily flows are non-stationary, reflecting continual population growth and associated river system development and increasing water use. The 1940-2015 daily WAM simulated flows represent homogeneous specifically-defined conditions of river system development. The alternative analyses with observed historical flows divided into two segments, and WAM naturalized versus authorized use scenario regulated flows provide different perspectives on changes in flow characteristics and capabilities for satisfying environmental flow requirements.

1.3 Research Scope and Objectives

The thesis research investigates stream flow characteristics of the Trinity and Brazos Rivers and their tributaries based on applying ecologically relevant statistical analyses methods to long sequences of observed and simulated daily flows. The research objectives are to:

1. Explore long-term alterations in streamflow characteristics that have occurred for the Trinity and Brazos Rivers and their tributaries.
2. Develop and analyze frequency metrics that meaningfully quantify the extent to which the SB3 environmental flow standards in the Trinity and Brazos River Basins can be expected to be satisfied.
3. Evaluate modeling and analysis capabilities for quantifying ecologically relevant streamflow characteristics and alterations thereof.

The thesis research consists of analyzing flows at 33 USGS gauging stations that include 23 sites with SB environmental flow standards plus ten other gauges with long periods-of-record. Statistical analyses are applied to observed daily flows available from the USGS NWIS website and daily flows synthesized with the Brazos and Trinity WAMs representing undeveloped natural conditions and the authorized use scenario of water resources development, allocation, management, and use. The research addresses the following questions regarding the flows of the Brazos and Trinity Rivers and their tributaries. What are the characteristics of the river flows? How have the flow characteristics changed over the past 100 years? To what extent will the recently established SB3 environmental flow standards be achieved? The research also provides a state-of-the-art assessment of modeling and analysis capabilities for addressing these types of questions.

CHAPTER II

ENVIRONMENTAL INSTREAM FLOW ASSESSMENT METHODS REPORTED IN THE LITERATURE

Anthropogenic alterations of natural hydrologic regimes are having growing impacts on the global ecosystem. Human activities have depleted or otherwise altered the river flows around the world. Simultaneously, it has caused the degradation of the natural hydrologic environment. The degradation of flow regimes had resulted in the loss of benefits, which should have been provided by healthy and functioning riverine systems.

Thereupon, the protection and restoration of environmental flows have been drawing more and more attention. The need for protecting stream flows has led to increasing requests for specialists to make recommendations about the amount and timing of appropriating water resources (Mathews and Richter 2007). Moreover, adverse impacts on river systems have stimulated the process of analyzing and quantifying flow characteristics for the purpose of setting up laws and regulations for protecting environmental instream flows (Mathews and Richter 2007).

Accordingly, numerous tools, methods, and simulation models have been developed, so as to analyze and quantify the degree to which river regimes have been altered attributed to human activities. As a result, environmental instream flow standards could be developed or modified to protect the five riverine components (hydrology, biology, geomorphology, water quality and connectivity) adequately.

2.1 Ecological Hydrology Assessment Methods

Mathews and Richter (2007) demonstrate that some of the methodologies use scientific expertise based on a variety of disciplines and sophisticated computational models and tools, and they are prone to be time-consuming and expensive. While, another realm of methods consists of “desktop” models and tools, such as the Tennant Method, Aquatic Base Flow Standard, and Flow Duration Curve methods, can be relatively cheaper and ready for use (Acreman and Dunbar 2004; Poff and Zimmerman 2010; Tharme 2003).

From 1958 to 1975, Donald Tennant systematically collected biological and hydrological data from rivers across the United States, comparing the river biological attributes with their hydrologic conditions. Based on his observations, he proposed some guidelines for protecting environmental flows, which became known as the Tennant Method, also known as the Montana Method. Tennant suggested that ten percent of the average annual flow (AAF) should be prescribed as a minimum instantaneous flow; 30 percent of AAF is designated to maintain suitable habitation; 60-100 percent of a river’s average flow need to be protected, to achieve “optimum” biological conditions. Moreover, 200 percent AAF is the “flushing flows”. Due to the simplicity, the Tennant Method became one of the most commonly applied approaches. On the other hand, the under the scrutiny of the Tennant Method has been a bit cynical concerning its scientific assumptions (Mann 2006; Richter et al. 1997).

The US Fish and Wildlife Service (USFWS) developed the Aquatic Base Flow Method (USFWS ABF). USFWS ABF assumes that the most critical circumstance of a flow regime is in August. This outstanding assumption is based on the fact that the metabolic stress to aquatic organisms in August is the highest due to high water temperatures, diminished living space, low dissolved oxygen, and low or diminished food supply (Richardson and Ridem 2005). The natural ecological-hydrological system serves as a baseline in this approach, so that, the appropriate protection of flow regimes could be identified. The USFWS ABF has been approved as a simple, time-tested, well proven minimum flow that protects the environment (Richardson and Ridem 2005)

USFWS has also developed the Instream Flow Incremental Methodology (IFIM), which adhere to the principle of incrementalism (Bovee 1982). An incremental approach allows a problem to be addressed, at least at first, from a common perspective. If a solution cannot be found, the problem should be slightly redefined until a solution can be found. The incremental approach is valuable when applied to problems with multiple aspects or solutions (Bovee 1982). IFIM has three major principles. The first one is that the implementation of an instream flow regime should be part of the water management system. Secondly, IFIM is designed to provide predictions about the impacts of different alternatives. Last but not the least, the objectives of this application must be rigorously defined. Considering the IFIM as a collection of computer models and analytical procedures, it can be utilized to predict changes in fish habitat caused by flow alterations. Also, IFIM is capable of evaluating different impacts such as changes in channel structures or alterations in waste loading from pollution sources (Bovee 1982; Bovee et al. 1998).

Hill et al. (1991) developed the approach based on four considerations: base flows, channel maintenance flows, riparian flows and valley maintenance streamflows. Hill et al. (1991) suggest a conceptual or theoretical method for evaluating both instream and out-of-stream flow requirements within a holistic streamflow management framework. Hill et al. (1991) combined well-known streamflow approaches into a unified methodology that recognizes flow requirements for fish, riparian habitat, floodplains, and channel morphology. It does address the range of flow variation, whereas, it ignores the duration of flows and the importance of daily and seasonal variations (Richter et al. 1997)

Arthington (1991) proposed a “holistic approach” in Australia, that is based on low flows, the first major wet season flood, medium-sized floods, and immense floods. Arthington et al. (1992) suggest using this approach that “rebuilds” a natural flow regime, where minimum monthly flow would be based on either a percentage exceedance for each month or a low flow that occurs “often” (Jowett 1997).

The Riverine Community Habitat Assessment & Restoration Concept (RCHARC) was developed in 1995 to integrate habitat enhancement into the stream restoration process (Peters et al. 1995). The RCHARC takes the spatial distribution and many other flow conditions into account. Especially, it considers the impact of human activities such as damming and channelization (Richter et al. 1997). Moreover, The RCHARC methodology has the potential to assess habitat quality for planned comparison reaches and indicate the level of success resulting from restoration (Richter et al. 1997).

Hydrologic Engineering Center (HEC) developed the Ecosystem Functions Model (HEC-EFM) to help study teams determine ecosystem responses to changes in the flow regime of a river or connected wetland. HEC-EFM analyses involve statistical analyses of relationships between hydrology and ecology, hydraulic modeling, and use of Geographic Information Systems (GIS) (Hickey et al. 2015; USACE 2013). Through this process, study teams define existing ecologic conditions, highlight promising restoration sites, and assess alternatives according to predicted ecosystem changes. HEC-EFM has many strengths, most notably is its capability of testing changes for many ecological relationships and management scenarios, linking ecology with established hydrologic, hydraulic, and GIS tools. Moreover, it can be applied quickly, inexpensively, and scientific expertise could be incorporated in the model (Hickey et al. 2015; USACE 2013).

The U.S. Geological Survey (USGS) developed the Hydro-ecological Integrity Assessment Process associated Hydrologic Assessment Tool (HIP/HAT). The HIP/HAT package uses a broad statistical template at a regional scale, and users can customize the stream classification system or list of stream type. The records of flow at many locations are essential without the influences of human activities and are assigned to one of the stream types (Hickey et al. 2015). During the computation phase, the statistical methods will be applied to decide which of the 171 statistics are crucial in characterizing each stream type. The results of analyses will provide a framework, which is helpful in developing environmental instream flow recommendations, assessing the degree of flow alterations, and making adjustments or changes in water management (Henriksen et al. 2006).

The River Analysis Package (RAP) was developed by the Australian Cooperative Research Centre for Catchment Hydrology in 2005. Different from HIP/HAT method, RAP enables users to define the ecologically relevant statistics for individual work. This function is carried by a tool called Eco Modeller. Eco Modeller provides users with a library of ecological response models, among which user-specified choices can be made. This approach analyzes the combinations of time series relevant to ecosystems statistically to compare water management alternatives. It is now used in some river basins in Australia (Hickey et al. 2015).

2.2 Models for the Protection of the Environmental Flows in Texas

2.2.1 Hydrology-based Environmental Flow Regime Method

In 2001, the Texas Legislature passed Senate Bill 2 (SB2), which established the Texas Instream Flow Program. One result of inaugurating the instream flow program was the determination of identifying instream flow needs to support a sound ecological environment (Opdyke et al. 2014).

In 2007, after the Texas Legislature passed SB3, a process for setting environmental flow standards has been established. SB3 requires science teams to develop “flow regime” recommendations. The Hydrology-based Environmental Flow Regime (HEFR) method was developed to summarize hydrologic data suitable for the SB3 effort and water rights permit conditions (Opdyke et al. 2014). This method combines a suite of user-specified hydrologic statistics with an implementation framework (Opdyke et al. 2014).

HEFR methodology adopts the concept of instream flow components identified by the National Research Council (NRC). NRC categorized instream flow into four components: subsistence flows, base flows, high-flow pulses, and overbank event (Opdyke et al. 2014). HEFR takes three general steps to complete analyses: a) selection of an appropriate flow gauge and period of record; b) hydrographic separation of the average daily flows into four flow components; and c) calculation of summary statistics. Meanwhile, several available options may handle the incorporation of ecological knowledge (SAC 2011). The Texas Environmental Flows Science Advisory Committee (SAC), a state-wide committee which was appointed to guide the science teams and to provide a critical review of their recommendation reports, stated that HEFR "might prove useful as a first step in developing instream flow recommendations."

2.2.2 Incorporating and Evaluating Environmental Instream Flows in a Priority Ordered Surface Water Allocation Model

In Texas, surface water is allocated to water permits holders following the doctrine of prior appropriation, which essentially stands for "first in time, first in right" (Pauls 2014). Individual water user diverts water for beneficial purposes (e.g., agricultural, industry, municipal, hydroelectric power generation, recreation, and mining) following the order of seniority (Pauls 2014).

Through the process of establishing and evaluating recommendations, environmental flow standards have been implemented into the state's prior-appropriation water rights permitting system by Pauls (2014). Pauls (2014) implements the environmental instream flow standards to the Colorado WAM and the Trinity WAM, using the WRAP with updated features. In water availability models, environmental instream flow standards are designated with junior water rights, which means, a large number of existing water rights have early priority dates, and consequently will be allowed to divert water before environmental flow standards get access to water. Meantime, the established environmental flow standards will have relatively senior water rights compare to the future water permits holders.

Pauls (2014) adds 14 new control points in the Colorado WAM and four new control points in the Trinity WAM to represent the environmental flow standards. Those control points are immediately downstream of the primary control points to avoid over-writing any existing instream flow standards. After modeling environmental flow standards in WAMs, and launching the SIMD daily time-step simulations, Pauls (2014) develops a variety of metrics for the sake of characterizing the engagement and attainment of five instream flow components in the Colorado WAM, and four elements in the Trinity WAM.

Pauls (2014) develops 28 attainment metrics in total, and they have been proved meaningful and efficient. The major attributions of these metrics include evaluating the engagement and attainment of the environmental flow standards and for making comparisons between alternative components at a control point, between alternate control point locations, and between alternate development scenarios, which are the “authorized scenario” (Run3) and the “current use scenario” (Run8).

In general, the attainment metrics can be used to inform scientists and decision-makers in the evaluation of alternative river basin development scenarios. Meanwhile, the attainment metrics can serve as the basis of risk assessment approaches for evaluating tradeoffs between environmental and human water needs (Pauls 2014).

Compared to Pauls (2014), likewise, this thesis uses the lately updated WAM features daily time-step simulation to generate WAM simulated naturalized flows and regulated flows of selected primary control points in the research areas. Successively, the frequency of metrics can be developed to quantify the extent to which the SB3 environmental flow standards in the Trinity and Brazos River Basins can be expected to be satisfied.

Whereas, this thesis does not insert any new control points in WAMs, nor simulate new attainment metrics. Instead, the thesis implements tools and metrics embedded in the IHA and the HEC-DSSVue software. The implementation of IHA program is a major distinction compared to Pauls (2014). The IHA software is employed in this thesis in order to analyze the alterations of observed historical daily flows so that the degree of hydrologic perturbations can be evaluated by separating one long period-of-record into two parts: Pre-Impact period and Post-Impact period, which will be interpreted in the following chapters. Moreover, the cooperation of WAM/WARP, the IHA program, and the HEC-DSSVue software enables this thesis to analyze and compare the changes between the WAM naturalized flows, and WAM simulated regulated flows. With the data being imported into the IHA software using the right format, the WAM naturalized flow is regarded as the Pre-Impact flow, while the simulated regulated flow is assigned as the Post-Impact flow. The rest of the analyses will resemble the ones conducted on the historical daily surface flow datasets.

2.2.3 Discussion

Opdyke et al. (2014) reckon that if we lived in a perfect world, then none of the hydrological statistics might be necessary. Given that we would have fuller understandings in flow regimes and its related ecological needs, for instance, the environmental flow demands, we could then put all our efforts along with resources into fulfilling those needs. Meanwhile, we would be able to balance the relationships between the environmental requirements and needs from human activities perfectly. Whereas, in the practical world, with limited understandings, technologies, and financial supports, in-depth studies can hardly be performed in every part of the states in a sophisticated fashion.

Although we have to admit that none of the methodologies or tools described in the previous sections can be considered perfect, the multi-disciplinary methods can be used to provide a good starting point. Thus, balancing the pros and cons of every possible model and employing one assisting another will most likely yield more comprehensive and strategic results. The urge to balance between maintaining a healthy ecological environment and sustaining civilized society has been motivating every party getting involved in this case. Therefore, the development and refining of low-cost and precise hydrological methodologies have been flourishing in recent decades. The fundamental reason for developing and applying the above programs is for researchers and analysts to quantify streamflows and give professional suggestions to decision-makers. Subsequently, lawmakers would be able to set up if not revise laws and regulations to provide legitimate protection for the ecological environment.

CHAPTER III

TRINITY RIVER BASIN

3.1 Basin Description

The Trinity River basin is the largest river basin in Texas that begins and ends within the state. It begins in the Four Forks region in the northern side of the basin. Just south of the Dallas Fort-Worth Metropolitan, the Clear Fork, West Fork, Elm Fork and East Fork merge to form the Main Stem of the Trinity River. The Trinity River is 715 miles long and drains nearly 18,000 square miles of Texas. The climate and land type vary greatly across the basin. The watershed's character transforms from rolling West Texas plains with 29 inches of annual precipitation, through the Central Texas prairies, into the East Texas piney woods, and into the Gulf Coastal Prairies, which receive 53 inches of annual rainfall (Wurbs and Zhang 2014).

Because of the scarcity of groundwater availability, residents of the Trinity River basin rely on surface waters to fulfill water demand (TRA 2012). The Trinity River provides water to over half of the population of Texas and serves two major population centers: Dallas Fort-Worth in the north and Houston to the south. Also, it is important to recognize that both major population centers drain into the Galveston Bay and estuary system, one of the most productive ecosystems and commercial fisheries in the United States. Figure 1 shows the geographical location of the Trinity River Basin in Texas.

A significant proportion of the population in the Trinity River Basin is located in the Dallas-Fort Worth metropolitan area in the upper basin. According to the 2012 State Water Plan, the residents of Dallas Fort-Worth area was approximately 6.7 million, which represented about one-fourth of the populaiton in Texas. The major regional water suppliers in the upper basin are Dallas Water Utilities (DWU), North Texas Municipal Water District (NTMWD), Tarrant

Regional Water District (TRWD), and Trinity River Authority (TRA). Major local water providers in the upper basin include the City of Denton, City of Grapevine, City of Weatherford, and Dallas County Park Cities Municipal Utilities District (DCPCMUD) (Wurbs and Zhang 2014). Figure 2 labels some of the major lakes, cities, and reservoirs in the Trinity River Basin.

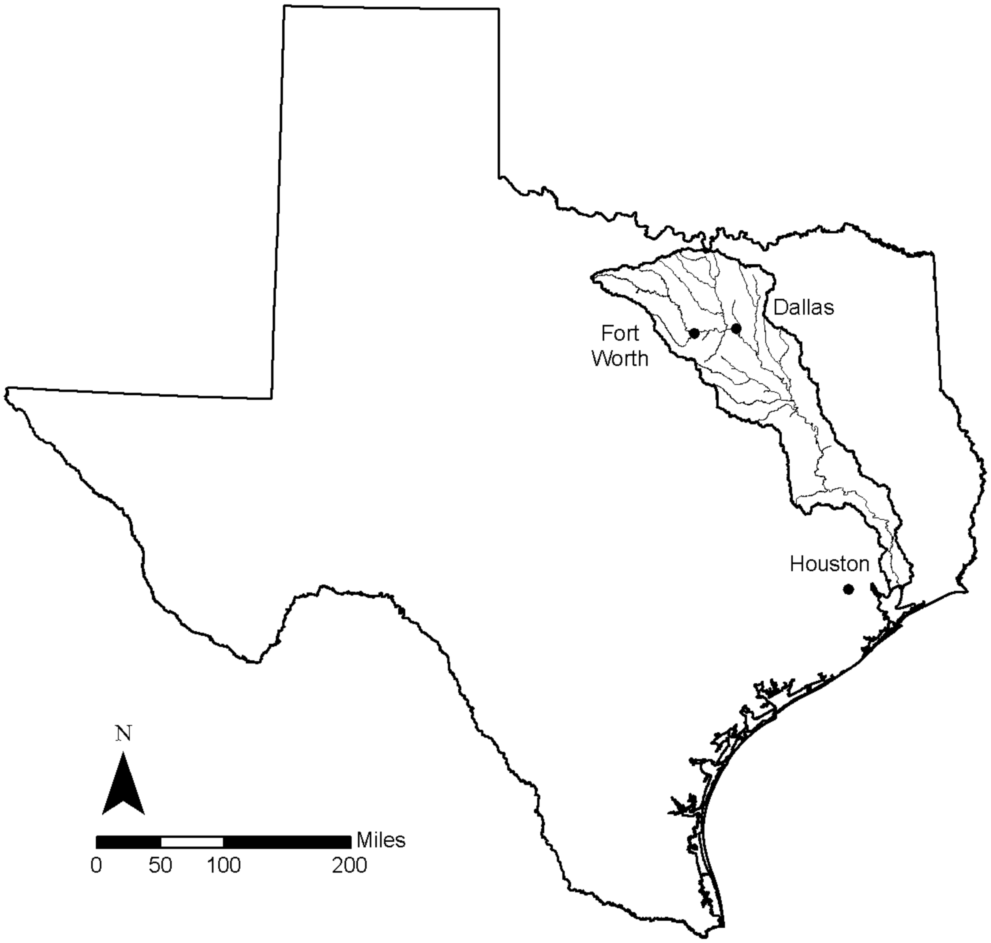


Figure 1. Trinity River Basin (Pauls 2014)

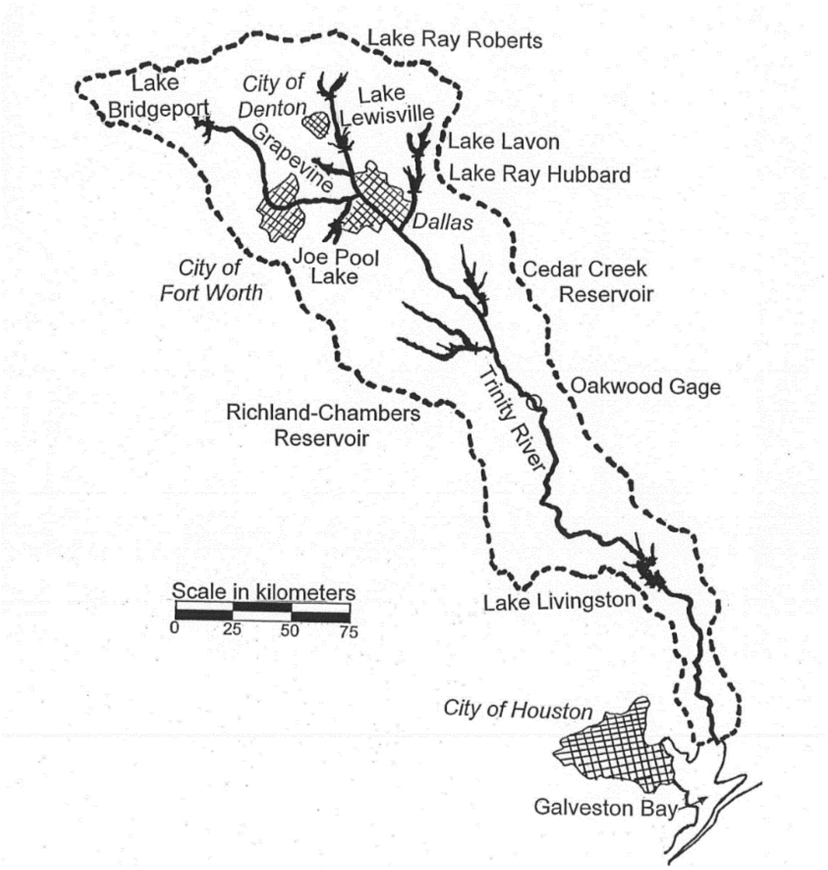


Figure 2. Trinity River Basin (Wurbs 2016)

3.2 Stream Gaging Stations

The Trinity WAM contains 40 primary control points. Locations and more descriptive information such as the WAM identifiers, USGS gage station numbers, and basin areas for the primary control points are tabulated in Table 1.

Table 2 presents the selected control points that are under-analyzed in this thesis, and their related information consists of the WAM identifiers, USGS gauge locations, period-of–analyses, days of missing data, and whether or not SB3 has been applied. Among these selected control points, four control points, to which SB3 have been implemented and are indicated in bold. Table 3 is the map of the primary control points in the Trinity WAM.

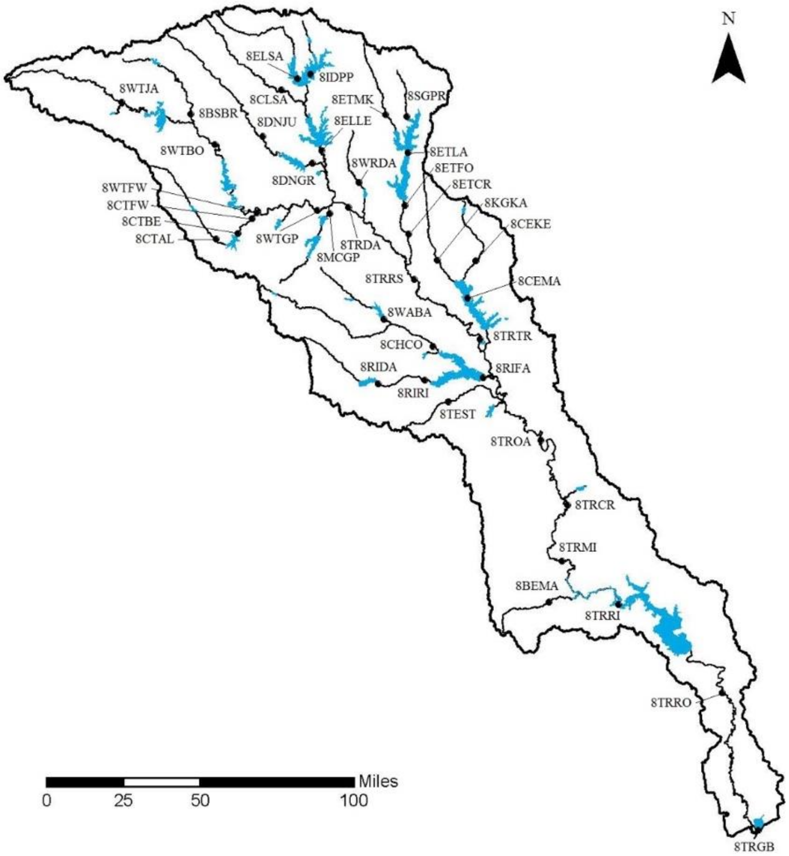


Figure 3. Map of Primary Control Points in the Trinity WAM (Wurbs 2016)

Table 1. Period-of-Record of Selected Control Points in the Trinity WAM

WAM CP	USGS Gage Location	Period of Record	Missing Days	SB3 IFS
8BSBR	Big Sandy Creek near Bridgeport	Oct 1936-present	3,288	-
8WTBO	West Fork Trinity River near Boyd	Jan 1947-present	0	-
8CTBE	Clear Fork Trinity River near Benbrook	Jul 1947-present	0	-
8CTFW	Clear Fork Trinity River at Fort Worth	Mar 1924-present	0	-
8WTGP	**West Fork Trinity River at Grand Prairie**	**Mar 1925-present**	**13**	**SB3**
8CLSA	Clear Creek near Sanger	Mar 1949-present	0	-
8ELLE	Elm Fork Trinity River near Lewisville	Mar 1949-present	0	-
8DNJU	Denton Creek near Justin	Oct 1949-present	0	-
8TRDA	**Trinity River at Dallas**	**Oct 1903-present**	**0**	**SB3**
8ETMK	East Fork Trinity River near McKinney	Sep 1949-present	12,496	-
8TRRS	Trinity River near Rosser	Aug 1924-present	4,807	-
8TROA	**Trinity River near Oakwood**	**Oct 1923-present**	**0**	**SB3**
8TRRO	**Trinity River at Romayor**	**May 1924-present**	**0**	**SB3**

Table 2. Primary Control Points in the Trinity WAM

WAM CP	USGS Gage	USGS Gage Location	Basin Area (mile^2)
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	no gage	Trinity River at Galveston Bay	17,949

3.3 Trinity Water Availability Model

3.3.1 Trinity WAM System Components

In the Trinity WAM, two scenarios have been developed. One is the Authorized Use Scenario (Run3), and the other is the Current Use Scenario (Run8). The number of system components, as recorded in the *SIM* message file, is tabulated in Table 3 for recently updated version of the Trinity WAM.

Table 3. Number of System Components in Trinity WAM Datasets

Latest Update of Datasets Water Use Scenario Filename	Oct 2012 Authorized Trin3	Oct 2012 Current Trin8	Oct 2014 Authorized Trin3
Total Number of Control Points	1,398	1,418	1,403
Number of Primary Control Points	40	40	40
Control Points with Evaporation-Precip Rates	50	50	50
Number of Reservoirs as Counted by SIM	697	700	697
Number of WR Record Water Rights	1,061	1,067	1,057
Number of Instream Flow IF Record Rights	71	89	71
Number of FD Records in DIS File	1,246	1,247	1,251

3.3.2 Major Reservoirs in the Trinity WAM

Eight out of the 14 largest reservoirs in the Trinity River Basin are owned and operated by the USACE Fort-Worth District (FDW) (Ray Roberts, Lewisville, Lavon, Joe Pool, Grapevine, Benbrook, Navarro Mills, and Bardwell). USACE are operating these eight multi-purpose reservoirs for flood control, and nonfederal sponsors hold contracts for their water supply storage capacity. The nonfederal water supply sponsors for the eight federal reservoirs include the TRA, TRWD, NTMWD, Dallas, Fort Worth, and other cities. The City of Dallas (DWU) owns Ray Hubbard Lake and White Rock Lake. The other major reservoirs are the property of various cities and electric power companies (Wurbs and Zhang 2014).

Table 4. Major Reservoirs in the Trinity River Basin (Storage Unit: ac-ft)

Map ID	Reservoir	WAM Identifier	WAM CP	Initial Impoundment	Authorized Storage
1	Lake Livingston	LIVSTN	B4248B	1969	1,750,000
2	Richland-Chambers Reservoir	RICHCH	B5035A	1987	1,135,000
3	Ray Roberts Lake	ROBDEN	B2335A	1987	799,600
4	Cedar Creek Reservoir	CEDAR	B4976A	1965	678,900
5	Lewisville Lake	LEWDE1	B2456A	1954	618,400
6	Lake Ray Hubbard	HUBBRD	B2462A	1968	490,000
7	Lavon Lake	LAVON0	B2410A	1953	456,500
8	Lake Bridgeport	BRIDGE	B3808A	1932	387,000
9	Eagle Mountain Lake	EGLMTN	B3809A	1934	210,000
10	Joe Pool Lake	JOPOOL	B3404A	1986	176,900
11	Grapevine Lake	GPVGP1	B2362A	1952	162,500
12	Benbrook Lake	BENBRK	B5157P	1952	88,250
13	Navarro Mills Lake	NAVARO	B4992A	1963	63,300
14	Bardwell Lake	BARDWL	B5021A	1965	54,900
15	Fairfield Lake	FAIRFD	B5040A	1969	50,600
16	Lake Arlington	ARLING	B3391A	1957	45,710
17	Lake Worth	WORTH	B3340A	1914	38,124
18	Lake Anahuac	ANAHUA	B4279C	1914	35,300
19	Lake Amon G. Carter	CARTER	B3320B	1956	28,589
20	Mountain Creek Lake	MTNCRK	B3408A	1937	22,840
21	White Rock Lake	WHITER	B2461A	1911	21,345
22	Houston County Lake	HOUCTY	B5097A	1966	19,500
23	Lake Weatherford	WTHRFD	B3356A	1957	19,470
24	North Lake	NORTH	B2365A	1957	17,100
25	Forest Grove Reservoir	FOREST	B4983A	1976	16,348
26	Lake Waxahachie	WAXAHC	B5018A	1956	13,500
27	Lost Creek Reservoir	LOSTCK	B3313B	1990	11,961
28	New Terrell City Lake	TERREL	B4972A	1955	8,712
29	Lake Halbert	HALBRT	B5030A	1921	7,357
30	Lake Kiowa	KIOWA	B2334A	1970	7,000
31	Trinidad Lake	TRINDD	B4970A	1925	6,200
32	Alvarado Park Lake	B5001	B5001A	1966	4,781

In October 2014, TCEQ updated the record of reservoirs in Trinity WAM under the Run3 scenario. The total number of reservoirs after the update is 697 and 32 major reservoirs have been listed in Table 4, as well as the descriptive information including names of the reservoirs, WAM identifiers, the WAM control points, initial impoundment years, and the authorized storages in acre-feet.

The reservoirs listed above have permitted storage capacities greater than 5,000 acre-feet. Amongst them, USACE FWD owns eight of the reservoirs. Figure 4 demonstrates the spatial locations of the largest reservoirs in the Trinity WAM on a map.

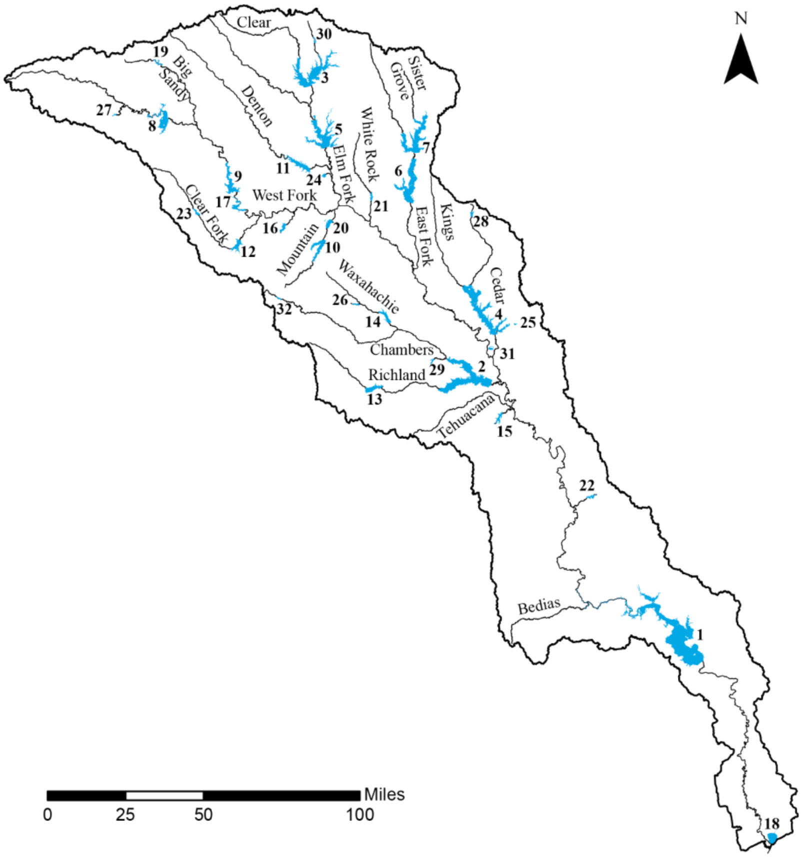


Figure 4. Largest Reservoirs in the Trinity River Basin (Wurbs 2016)

CHAPTER IV

BRAZOS RIVER BASIN

4.1 Basin Description

The Brazos Basin is the second largest river basin by area within Texas (TWDB 2011). The Brazos River Basin has encompassed a total area of 45,870 square miles, with about 43,160 square miles in Texas and the remainder in New Mexico. The extreme upper end of the Brazos River Basin in and near New Mexico is a flat, arid area that rarely contributes to stream flow. The Brazos River proper is formed at the confluence of the upper forks of the river, the Salt and Double Mountain, in Stonewall County. The Clear Fork joins the river just above Possum Kingdom Lake in Young County. In addition to the Salt Fork and Double Mountain Fork, there are five other principal tributaries along the Brazos River.

Principal tributaries to the Brazos Downstream of the Clear Fork are Yegua Creek, Bosque River, Little River and the Navasota River. Within these tributaries are 15 subtributaries, including the Leon River, a tributary of the Little River. The climate, hydrology, and geography of the basin vary widely across Texas from New Mexico to the Gulf of Mexico.

In its upper reaches, the Brazos River is a gypsum-salty intermittent stream. Toward the coast, it is a rolling river flanked by levees, agricultural fields, and hardwood bottoms. Like the terrain, the climate throughout the river basin ranges significantly, from temperate to subtropical. Mean annual precipitation varies from 19 inches in the upper basin which lies in the High Plains to 45 inches in the lower basin in the Gulf Coast region.

The most prevalent cities in the Brazos River basin are Lubbock, Graham, Waco, Temple, Belton, Georgetown, Round Rock, Bryan-College Station, Freeport and Galveston. The major metropolitan cities of Dallas-Fort Worth, Austin and Houston, lie just outside the watershed boundaries. In 2010 the population of the Brazos River Basin was about 2,440,000 people (Wurbs and Zhang 2014). Figure 5 shows the geographical location of the Brazos River Basin in Texas.

The Brazos River Authority water supply system includes 11 reservoirs scattered across the 42,000 square mile river basin. Three of the man-made lakes were built, and are owned and operated by the BRA while eight are owned and operated by the U.S. Army Corps of Engineers.

Figure 5. Brazos River Basin and San Jacinto-Brazos Coastal Basin (Wurbs and Hoffpauir 2013a)

4.2 Stream Gaging Stations

Table 5 tabulates the basic geographical information of 30 primary control points in the Brazos WAM. The table contains the WAM identifiers, the USGS gage identifiers, the locations by rivers and the nearest cities, the correlated counties, the drainage areas, period-of-analysis, days of missing data, and the SB3 application. Notice that, among 30 primary control points in the Brazos WAM, SB3 has been applied to 19 control points, which are indicated in bold.

Table 5. Period-of-Record of Selected Control Points in the Brazos WAM

WAM CP ID	USGS Gage ID	River and Nearest City	Period-of-Analysis		Days Missing	SB3 IFS	County	Drainage Area (mile^2)
			From	To				
DMAS09	**08080500**	**Double Mountain Fork Aspermont**	**1/1924**	**present**	**1,734**	**SB3**	Stonewall	1,891
SFAS06	**08082000**	**Salt Fork Brazos River Aspermont**	**1/1924**	**present**	**5,052**	**SB3**	Stonewall	2,504
BRSE11	**08082500**	**Brazos River near Seymour**	**12/1923**	**present**	**0**	**SB3**	Baylor	5,996
CFNU16	**08084000**	**Clear Fork Brazos near Nugent**	**3/1924**	**present**	**0**	**SB3**	Jones	2,236
CFFG18	**08085500**	**Clear Fork Brazos near Fort Griffin**	**2/1924**	**present**	**0**	**SB3**	Shackelford	4,031
BRSB23	**08088000**	**Brazos River near South Bend**	**10/1938**	**present**	**0**	**SB3**	Young	13,171
BRPP27	**08089000**	**Brazos River near Palo Pinto**	**2/1924**	**present**	**0**	**SB3**	Palo Pinto	14,309
BRGR30	**08091000**	**Brazos River near Glen Rose**	**10/1923**	**present**	**0**	**SB3**	Somervell	16,320
NBCL36	**08095000**	**North Bosque River near Clifton**	**10/1923**	**present**	**0**	**SB3**	Bosque	977
BRWA41	**08096500**	**Brazos River at Waco**	**10/1898**	**present**	**0**	**SB3**	Mclennan	20,065
−	08097500	Brazos River near Marlin	10/1938	9/1951	0	−	Falls	20,645
BRHB42	08098290	Brazos River near Highbank	10/1965	present	0	−	Falls	20,900
LEHM46	08100000	Leon River near Hamilton	1/1925	present	14,584	−	Hamilton	1,928
LEGT47	**08100500**	**Leon River near Gatesville**	**10/1950**	**present**	**0**	**SB3**	Coryell	2,379
LEBE49	08102500	Leon River near Belton	10/1923	present	0	−	Bell	3,579
LAKE50	**08103800**	**Lampasas River near Kempner**	**10/1962**	**present**	**0**	**SB3**	Lampasas	817
LRLR53	**08104500**	**Little River near Little River**	**10/1923**	**present**	**12,145**	**SB3**	Bell	5,266
LRCA58	**08106500**	**Little River near Cameron**	**11/1916**	**present**	**0**	**SB3**	Milam	7,100
−	08108700	Brazos River at SH 21 near Bryan	7/1993	present	0	−	Burleson	29,483
BRBR59	08109000	Brazos River near Bryan	9/1899	present	5,719	−	Brazos	29,949
YCSO62	**08110000**	**Yegua Creek near Somerville**	**5/1924**	**6/2014**	**6,210**	**SB3**	Burleson	1,011
DCLY63	08110100	Davidson Creek near Lyons	10/1962	present	0	−	Burleson	195
−	08110200	Brazos River at Washington	11/1965	3/1987	1,016	−	Washington	31,626
NAEA66	**08110500**	**Navasota River at Easterly**	**3/1924**	**present**	**0**	**SB3**	Leon	936
−	08110800	Navasota River Old Spanish Rd	4/1997	present	0	−	Robertson	1,287
NABR67	08111000	Navasota River near Bryan	1/1951	3/1997	801	−	Brazos	1,427
−	08111010	Navasota River College Station	5/1977	9/1985	0	−	Grimes	1,809
BRHE68	**08111500**	**Brazos River near Hempstead**	**10/1938**	**present**	**0**	**SB3**	Washington	34,374
BRRI70	**08114000**	**Brazos River near Richmond**	**11/03(10/99)**	**present**	**153**	**SB3**	Fort Bend	35,541
BRRO72	**08116650**	**Brazos River near Rosharon**	**4/1967**	**present**	**1,318**	**SB3**	Fort Bend	35,773

4.3 Brazos River Basin and Brazos WAM

4.3.1 Brazos WAM System Components

In the Brazos WAM, two scenarios are developed. One is the Authorized Use Scenario (Run3), and the other is the Current Use Scenario (Run8). The number of system components, as recorded in the *SIM* message file, is tabulated in Table 6 for recently updated versions of the Brazos WAM.

The Texas Commission on Environmental Quality (TCEQ) is revising Brazos WAM, and the updated Brazos WAM will exclude additional control points. Thus, the updated Brazos WAM will have fewer control points compared to August 2007 and September 2008 versions of the Brazos WAM. The 77 primary control points with *IN* records and the 67 control points with *EV* records are the same in all of the versions of the Brazos WAM datasets.

Table 6. Number of System Components in Brazos WAM Datasets

Latest Update of Datasets Water Use Scenario Filename	Aug 2007 Authorized Bwam3	Aug 2007 Current Bwam8	Sep 2008 Authorized Bwam3
Total Number Of Control Points	3,830	3,842	3,852
Number Of Primary Control Points	77	77	77
Control Points With Evaporation-Precip Rates	67	67	67
Number Of Reservoirs As Counted By SIM	670	678	719
Number Of Water Right WR Records	1,634	1,643	1,734
Number Of Instream Flow IF Records	122	122	145
Number Of FD Records In DIS File	3,138	3,141	3,157

4.3.2 Major Reservoirs in the Brazos WAM

In the updated version of the Brazos WAM, all the major reservoirs, which have storage capacities over 5,000 acre-feet, will remain the same. Meanwhile, the latest version will contain eight more small reservoirs compared to the August 2007 version.

The U.S. Army Corps of Engineers (USACE) Fort Worth District owns and operates a system of nine multi-purpose reservoirs. The Brazos River Authority (BRA) has contracted for the conservation storage capacity in the nine federal reservoirs and owns three other reservoirs. The City of Waco has water right permits for Lake Waco, and the BRA holds permits for the eleven other reservoirs of the twelve-reservoir USACE/BRA system.

Table 7 tabulates the largest reservoirs and their related information such as the names of reservoirs, the streams they are on, the years of initial impoundment, and the storage capacities in acre-feet.

Figure 6 shows the primary control points in the Brazos WAM to which SB3 has been applied, in company with the major reservoirs in the Brazos River Basin on a map.

Table 7. Largest Reservoirs in the Brazos River Basin

Reservoir	Stream	Initial Impoundment	Storage Capacity (ac-ft)		
			Conservation	Flood Control	Total
Brazos River Authority and U.S. Army Corps of Engineers					
Possum Kingdom	Brazos River	1941	724,739	−	724,739
Granbury	Brazos River	1969	155,000	−	155,000
Whitney	Brazos River	1951	636,100	1,363,400	1,999,500
Aquilla	Aquilla Creek	1983	52,400	93,600	146,000
Waco	Bosque River	1965	206,562	519,840	726,400
Proctor	Leon River	1963	59,400	314,800	374,200
Belton	Leon River	1954	457,600	640,000	1,097,600
Stillhouse Hollow	Lampasas River	1968	235,700	394,700	630,400
Georgetown	San Gabriel	1980	37,100	93,700	130,800
Granger	San Gabriel	1980	65,500	178,500	244,000
Somerville	Yequa Creek	1967	160,110	347,290	507,400
Limestone	Navasota River	1978	225,400	−	225,400
Allen′s Creek	Allen′s Creek	proposed	145,533	−	145,533
City of Lubbock					
Alan Henry	Double Mountain	1993	115,937	−	115,937
West Central Texas Municipal Water District					
Hubbard Creek	Hubbard Creek	1962	317,750	−	317,750
Texas Utilities Services (cooling water for Comanche Peak Power Plant)					
Squaw Creek	Squaw Creek	1977	151,500	−	151,500

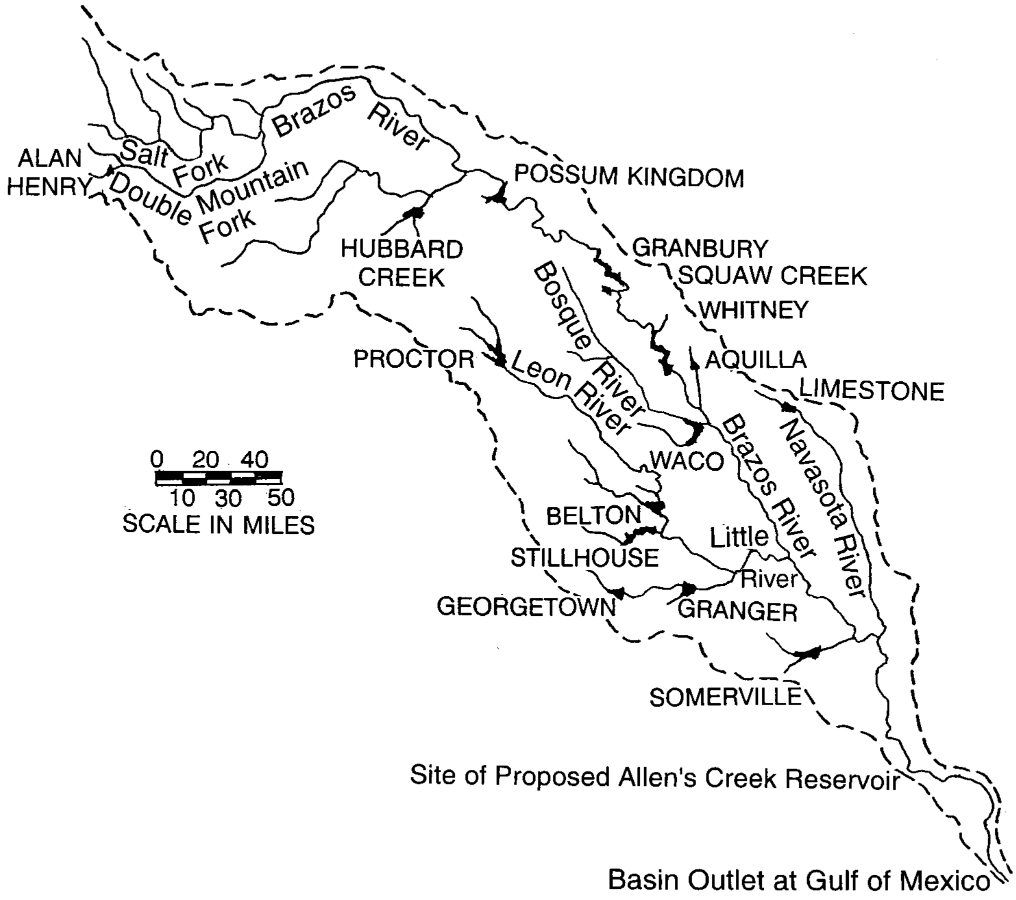


Figure 6. Selected USGS Gaging Station Locations and Major Reservoirs in the Brazos WAM (Wurbs and Hoffpauir 2013a)

CHAPTER V

IHA ANALYSES OF OBSERVED DAILY FLOWS

5.1 Indicators of Hydrologic Alteration (IHA) Methodology

Environmental flows are significant concerning protecting the processes and resilience of aquatic ecosystems, and in turn, the goods and services provided to humankind. Environmental flow regimes allow, to some extent, hydrologic alterations (Mathews and Richter 2007). On the other hand, it is well acknowledged that if environmental instream flows are altered too much, the function and structure of river regimes will change. The long-term alteration will have an influence on the physical, chemical, and biological properties of river systems (Kiesling 2003). For example, the alterations of magnitude, frequency and within-year variability potentially will modify the physical aspects of habitat (Kiesling 2003). The residence time of water would impact chemical properties, as well as the biological characteristics. As a result, altered riverine components are very likely to break a healthy aquatic system.

Therefore, establishing a comprehensive understanding of natural flows is crucial concerning setting up appropriate regulations and laws for the protection of environmental flows. Although river ecologists have realized that the full range of natural variation is important and rather complicated in maintaining a healthy ecosystem, insufficient scientific knowledge still remains a challenge in designing and implementing environmental flows standards. Water managers and decision-makers are looking for more scientific and reliable methods and tools that are practically applicable. Applying methods that provide the full range of variation assessment can be very expensive. With a limited budget, conducting assessments are prone to low-cost and readily methodologies (Mathews and Richter 2007). The IIHA software associated with ecological models provides includes formulations designed for water and land protection or restoration goals, as well as the development of focused research and monitoring program (Mathews and Richter 2007). In addition, the IHA was primarily developed to assist researchers to apply a rapid process to daily hydrologic records, and as long as the one has access to the internet can download the IHA software can be downloaded at no cost.

After being introduced to the world in 1996, the IHA program provided users with the "Range of Variability Approach" (RVA). Based on the RVA, 33 IHA parameters were developed to calculate the intra- and inter-annual variability in water conditions (Mathews and Richter 2007). While developing this original set of hydrological factors in the IHA, developers followed two primary principles to select the most related parameters. One of the criteria was the ecological relevance of parameters, and the other was their abilities to reflect the human-induced alterations in flow regimes (Mathews and Richter 2007). The RVA is designed to adapt to nature, where the ecological impacts on applying the anthropogenic management rules are monitored, and the results can be used to refine the environmental flow targets and regulations (Richter et al. 1997).

In 2005, 34 more parameters named "Environmental Flow Components" (EFCs) were implemented into the IHA program (Mathews and Richter 2007). The EFCs contains five components, and they are extremely low flows, low flows, high flow pulses, small floods and large floods. Similar to the IHA parameters, EFCs are ecological relevant and meaningful. They are developed to help water managers to attain targets at the desired magnitude, frequency, timing, duration and rate-of-change (Mathews and Richter 2007).

Many water managers, hydrologists, ecologists, researchers and decision-makers have used the IHA and EFCs parameters to analyze rivers, lakes, and groundwater basins globally (Nature Conservancy 2009). However, in some studies, researchers believe that only a few of the hydrologic indicators would adequately describe the degree of hydrologic alteration in an ideal world.

Gao et al. (2009) find that many of the IHA indicators overlapped and caused unnecessary problems when making environment flow management decisions. Those inter-correlated parameters in the IHA software were simplified by Gao et al. (2009). Gao et al. (2009) point out that it would be an informative redundancy if using all of the hydrologic parameters to describe the different flow components in river regimes. Thus, Gao et al. (2009) developed a set of independent and representative hydrologic indicators which characterize the hydrologic alteration caused by reservoirs and other forms of river regulation. Two sets of Pre-Impact and Post-Impact streamflow records are used: (1) based on artificial simulations of a wide range of reservoir release rules and (2) streamflow records for 189 gaging stations throughout the United States.

Yang et al. (2008) identify a small subset of hydrologic indicators that are the most representative of ecological flow regimes. They evaluated three approaches (genetic programming, principal component analysis, and autecology matrix) resulting the selection of six IHA parameters (Date of minimum, Rise Rate, Number of reversals, 3-day maximum, 7-day minimum and May flow) as the most ecologically relevant hydrologic indicators (ERHIs) (Gao et al. 2009). This thesis takes the suggestions from Gao et al. (2009) and evaluates the changes in the Trinity and Brazos River Basins using selected set of hydrological parameters instead of all 67 parameters in the IHA software.

5.1.1 Range of Variability Approach Algorithm

The RVA identifies annual river management targets based upon a comprehensive statistical characterization of ecologically relevant flow regime characteristics (Richter et al.

1996). Table 8 illustrates the hydrologic attributes used in the IHA program, the number of the hydrologic parameters in each attribute group, and their impact on the ecosystem.

Table 8. Summary of Hydrologic Attributes Utilized in the IHA and Their Characteristics

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month Subtotal 12 parameters	· Habitat availability for aquatic organisms · Soil moisture availability for plants · Availability of water for terrestrial animals · Availability of food/cover for fur-bearing mammals · Reliability of water supplies for terrestrial animals · Access by predators to nesting sites · Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year Subtotal 12 parameters	· Balance of competitive, ruderal, and stress-tolerant organisms · Creation of sites for plant colonization · Structuring of aquatic ecosystems by abiotic vs. biotic factors · Structuring of river channel morphology and physical habitat conditions · Soil moisture stress in plants · Dehydration in animals · Anaerobic stress in plants · Volume of nutrient exchanges between rivers and floodplains · Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments · Distribution of plant communities in lakes, ponds, floodplains · Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum Subtotal 2 parameters	· Compatibility with life cycles of organisms · Predictability/avoidability of stress for organisms · Access to special habitats during reproduction or to avoid predation · Spawning cues for migratory fish · Evolution of life history strategies, behavioral mechanisms

Table 8 Continued.

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days)	· Frequency and magnitude of soil moisture stress for plants · Frequency and duration of anaerobic stress for plants · Availability of floodplain habitats for aquatic organisms · Nutrient and organic matter exchanges between river and floodplain · Soil mineral availability · Access for water-birds to feeding, resting, reproduction sites · Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
	Subtotal 4 parameters	
5. Rate and frequency of water condition change	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals	· Drought stress on plants (falling levels) · Entrapment of organisms on islands, floodplains (rising levels) · Desiccation stress on low-mobility stream edge (varial zone) organisms
	Subtotal 3 parameters	
	Grand total 33 parameters	

Theoretically speaking, the IHA software is able to analyze any length of records. However, the selection of period-of-records has significant influence on the effectiveness and representativeness of hydrological indicators. It is crucial to specify the suitable period-of-records that best represent both natural, undisturbed conditions and human activities intervened circumstances. After collecting and importing appropriate period-of-records, the IHA parameters can be applied based on user-specified selections. The fundamental theory is that the river should be managed in such a way, which the annual value of each IHA parameter can fall within the range of natural variation for that parameter. Thus, the management target for any given parameter is expressed as a range of acceptable values. Moreover, the target should have both upper and lower boundaries. As to standard deviation, the users may choose ±1 as the dispersion, which also means the 25th and 75th percentile boundaries. Some researchers chose ±2 standard deviations, which can also be presented as a 20th and 80th percentile. Although it is a completely user-specified option, based on massiveness of statistical results and experiments, ± 1 is a more suitable option compared to ± 2 standard deviations, and it is the default setting in the software (Richter et al. 1997).

One of the distinguishing functions in the IHA software is its capability for analyzing alterations in a flow regime by separating one period-of-record into two time periods usually known as Pre-Impact and Post-Impact periods. When analyzing the differences between two time periods, RVA uses the Pre-Impact natural variation of IHA parameter values as a reference for defining the extent to which natural flow regimes have been altered and quantifies this alteration in a series of Hydrologic Alteration factors. In an RVA analysis, the full range of Pre-Impact data for each parameter is divided into three different categories. The boundaries between categories are based on either percentile values (for non-parametric analysis) or some standard deviations away from the mean (for parametric analysis), which are specified by users (Nature Conservancy 2009).

This thesis uses the default non-parametric analysis to characterize the changes in flow regimes; the default setting in the non-parametric RVA analysis is to place the category boundaries 17th percentiles from the median. This analysis yields an automatic delineation of three classes of equal size: the lowest category contains all values less than or equal to the 33rd percentile; the middle category contains all values falling in the range of the 34th to 67th percentiles, and the highest category contains all values greater than the 67th percentile. This method ensures that an equal number of Pre-Impact and Post-Impact values will fall into each category in most situations, which makes the results easier to understand and interpret. The program computes the frequency with which the Pre-Impact annual values of IHA parameters fell within each of the three categories. This expected frequency is equal to the number of values in the category during the Pre-Impact period multiplied by the ratio of Post-Impact years to Pre-Impact years. Finally, a Hydrologic Alteration factor is calculated for each of the three types as:

$$expected\ frequency = (numbers\ of\ values\ in\ the\ catagory\ in\ pre - period) \times \frac{post -\ years}{pre -\ years}$$

$$HA\ Factor = (observed\ frequency -\ expected\ frequency)\ /\ expected\ frequency$$

A positive Hydrologic Alteration value means that the frequency of values in the category has increased from the Pre-Impact to the Post-Impact period (with a maximum value of infinity); while a negative value means that, the frequency of values has decreased (with a minimum value of -1). For example, if a dam was able to store and attenuate all high flow events, then, for floods, the HA factor for the “high category” (highest third of all flows from Pre-Impact data) would be negative, while the “low category” (lowest third of all flows from Pre-Impact data) would be positive. Figure 7 shows the second example. In this example, there are fewer than expected October flows in the “high” category (the highest third of Pre-Impact flows): during the 48-year post-impact, one would expect 16-year records to fall into the “high” category, but only 11 do. Thus, the High HA factor is negative.

5.1.2 Environmental Flow Components Algorithm

Around the world, in order to characterize flow components, scientists have developed different types of methodologies to determining environmental flows. Indeed, the characterizations of flows differ from method to method, whereas, five components of flows are widely considered as ecologically relevant and meaningful. In the IHA software, those five types of flows are also included and referred as the EFCs. Table 9 describes the five EFC types the number of the hydrologic parameters of each EFC type and their related impact on ecosystem.

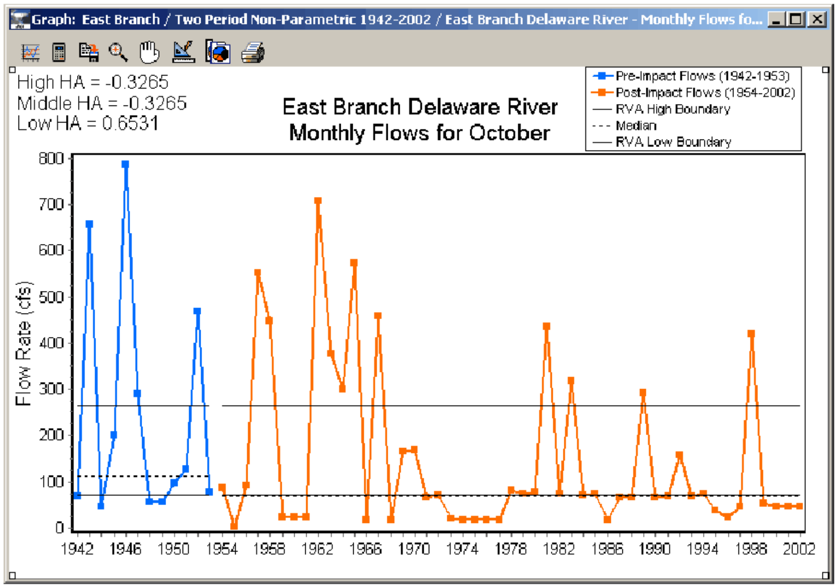


Figure 7. Example of HA Factors (Nature Conservancy 2009)

Table 9. Summary of Environmental Flow Component Parameters and Their Ecosystem Influences

EFC Types	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows	Mean or median values of low flows during each calendar month Subtotal 12 parameters	· Provide adequate habitat for aquatic organisms · Maintain suitable water temperatures, dissolved oxygen, and water chemistry · Maintain water table levels in floodplain, soil moisture for plants · Provide drinking water for terrestrial animals · Keep fish and amphibian egg suspended · Enable fish to move to feeding and spawning areas · Support hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event Duration (days) Peak flow (minimum flow during event) Timing (Julian date of peak flow) Subtotal 4 parameters	· Enable recruitment of certain floodplain plant species · Purge invasive introduced species from aquatic and riparian communities · Concentrate prey into limited areas to benefit predators

Table 9 Continued.

EFC Types	Hydrologic Parameters	Ecosystem Influences
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event Duration (days) Peak flow (maximum flow during event) Timing (Julian date of peak flow) Rise and fall rates	· Shape physical character of river channel, including pools, riffles · Determine size of streambed substrates (sand, gravel, cobble) · Prevent riparian vegetation from encroaching into channel · Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants · Aerate eggs in spawning gravels, prevent siltation · Maintain suitable salinity conditions in estuaries
	Subtotal 6 parameters	
4. Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: Duration (days) Peak flow (maximum flow during event) Timing (Julian date of peak flow) Rise and fall rates	· Applies to small and large floods: · Provide migration and spawning cues for fish · Trigger new phasee in life cycle (i.e. insects) · Enable fish to spawn in floodplain, provide nursery area for juvenile fish · Provide new feeding opportunities for fish, waterfowl · Recharge floodplain water table · Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances) · Control distribution and abundance of plants on floodplain · Deposit nutrients on floodplain · Applies to small and large floods: · Maintain balance of species in aquatic and riparian communities
	Subtotal 6 parameters	
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event Duration (days) Peak flow (maximum flow during event) Flush organism materials (food) and woody Timing (Julian date of peak flow) Rise and fall rates	· Create sites for recruitment of colonizing plants · Shape physical habitats of floodplain · Deposit gravel and cobbles in spawning areas · Flush organism materials (food) and woody debris (habitat structures) into channel · Purge invasive introduced species from aquatic and riparian communities · Disburse seeds and fruits of riparian plants · Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes)
	Subtotal 6 parameters	
	Grand total 34 parameters	

The EFCs algorithm designated the flow of each day to one of the 2-5 EFC types through three passes. During the first pass, daily flow records are allocated to one of the primary event types, low flows and high flows. During the second pass, the records that are assigned as high flows can be re-assigned to one of the three high flow classes, high flow pulses, small floods and large floods. However, it is a user-specified option; users can choose to check the number of high flow classes. During the third pass, the initial low flows can be re-assigned to the extremely low flow class if users want an extremely low flow class, if not, this pass is unnecessary. The following is a more detailed description of this algorithm (Nature Conservancy 2009).

First pass: Separation of data into the high flow and low flows.

If using the one parameter method, the days with flow rates that are greater than the high flow threshold (the default value is the 75th percentile of daily flows) will be assigned to the high flow class, and the ones smaller than this threshold will be apportioned to the low flow class. An alternative method is the four parameter method, also known as the calibration method.

(1) Initialization: The first day of the dataset needs to be initialized as either a high flow or low flow. If it is greater than the low flow threshold (the default value is the 50th percentile of daily flows), then it is classified as a high flow. Otherwise, it is a low flow. If it is a high flow, then if it is greater than the high flow threshold, it is computed as being on the ascending limb, otherwise on the descending limb.

(2) Proceeding sequentially through the rest of the daily values, the following rules are used to differentiate between low flows and high flows, and between the ascending and descending limbs of high flow events.

I. Following a low flow day, the next day is assigned to the ascending limb of a high flow event if the daily flow is greater than the high flow threshold, or if the flow exceeds the low flow threshold and the increase from the previous day are more than high flow start rate threshold (the default value is 25%). Otherwise, it continues as a low flow.

II. The ascending limb of a high flow event continues until daily flow decreases by more than the high flow end rate threshold (the default value is 10%)n, at which time the descending limb of the event is started.

III. During the descending limb of a high flow event, the ascending limb is restarted if daily flow increases by more than the high flow start rate threshold.

IV. During the descending limb of a high flow event, the event is ended if the rate of decrease of flow drops below the high flow end rate threshold (meaning that the change in flow is between $-1 \times$ high flow rate threshold and high flow start rate threshold), unless the flow is still greater than or equal to the high flow threshold, in which case the descending limb continues.

V. The event is always ended if the flow drops down to equal to or below the low flow threshold, regardless of whether the event is on the ascending or descending limb.

VI. After the high flow is ended, a low flow condition resumes.

Second pass: After all the initial high flow and low flow events are calculated, the high flow events are divided into two or three high flow classes. If the user only wants one high flow class, then this second pass is not necessary. If there are to be two high flow classes, then all events that have a peak flow of greater than or equal to either the small flood minimum peak flow (the default is the 2-year return interval) and large flood minimum peak flow (the default is the 10-year return interval) are assigned to the appropriate class, and all other events are assigned to the high flow pulse class. If there are to be three high flow classes, then all events that have a peak flow of greater than or equal to the large flood minimum peak flow are assigned to the large flood class, all remaining events that have a peak flow greater than or equal to the small flood minimum peak flow are assigned to the small flood class, and all others are assigned to the high flow pulse class.

Third pass: Days are assigned to the extremely low flow class. If the user does not want this class, then this pass is not necessary. All low flow days that have a flow of less than or equal to the extreme low flow threshold are assigned to the extreme low flow class. Some other important notes regarding the calculation of EFCs parameters are as follows.

For purposes of computing annual output statistics, extreme low flow, high flow pulse, small flood, and large flood events are assigned to the water year in which they peak, but their statistics will be computed using the entire length of the event, even if some of it is outside the water year. The peak of a high flow pulse, small flood, and large flood event is the day with the highest flow value, and the peak of an extreme low flow event is the day with the lowest flow value. If there are multiple peaks with the same flow value, the first one will be used. The timing of an event is the Julian date of the first peak.

In cases where a flow dataset has one or more water years of missing data, and the Advanced Calibration method is being used, the initialization procedure described above is rerun after each period of missing data. Note also that the occurrence of missing water years of data means that some EFC events may be truncated either at their beginning or end. The convention is to count any events in the statistics that are truncated by the end of a water year, but ignore events that are truncated by the beginning of a water year. In either of these situations, a warning is issued in the Message Report. Be aware that the truncated events that are counted may have errors in flow parameters such as peak flow, duration, timing, and rise and fall rates, because not all of the event is present in the flow data. Also, in the rare case that the peak of a high flow event occurs on the last day before a missing year, no fall rate from that event is used to compute annual statistics, since it cannot be calculated.

When using return intervals to identify small and large floods, the return interval is applied using the following procedure. First, a list is created of the maximum flood peaks (from the peaks of high flow pulse, small flood, and large flood events) in each year, and then this distribution is used to find the flow value that corresponds to each return interval. So for a 10-year return interval, the software finds the 90th percentile of all the annual maximum flood peaks, and for a 2-year return interval, the software finds the 50th percentile of all the annual maximum flood peaks. All events with peaks greater than the flow value that corresponds to the Large flood return interval are classified as large floods, and all events with peaks less than this value but greater than the flow value that corresponds to Small flood return interval are classified as small floods.

For two period analysis (or comparisons of two Hydro Data files), the return intervals for small and large floods and the flow level thresholds used to define extreme low flows and high flow pulses are based on data from the Pre-Impact period (or the Hydro Data file that represents Pre-Impact flows). For single period analysis, they are based on data for the entire period of analysis.

If desired, EFC parameters for high flow pulses, small floods, large floods, and extremely low flows can be calculated separately for two seasons. These seasons can cover two separate parts of the water year, and can overlap. Specifying two distinct seasons does not have any effect on the values of the seven calibration parameters described above or on the way the EFC algorithm assigns different days to various EFCs throughout the year. However, when the annual statistics are computed, only the events that peak during the appropriate season will be used in the calculation of statistics. As with events that overlap between water years, the statistics will take into account any parts of the event that are outside the specified season.

5.1.3 Flow Duration Curves Algorithm

Flow Duration Curves (FDCs) are computed using the following method.

Step 1: Sort (Rank) average daily discharges for the period of record from the largest value to the smallest value, involving a total of n values.

Step 2: Assign each discharge value a rank (M), starting with one for the largest daily discharge value.

Step 3: Calculate exceedance probability (P) as follows:

$$P = 100 \times [M/(n + 1)]$$

P = the probability that a given flow will be equaled or exceeded (% of time)

M = the ranked position on the listing (dimensionless)

n = the number of events for period-of-records (dimensionless)

5.2 Results for Sites on the Trinity River and Its Tributaries

As tabulated in Table 4, the initial impoundment of the major reservoirs in the Trinity WAM are before the 1970’s. Consequently, in this thesis, period-of-records are divided into two time periods. One is the Pre-Impact Period, which represents the stream flow conditions during the years before 1970, the other one is the Post-Impact Period, which shows the flow situations from the year 1970 to the latest USGS gage stations records. So that the impact of anthropogenic influences can be recognized, and quantified. In addition, the hydrologic circumstances before the 1970’s can be used as guidelines.

Table 10 demonstrates the output characteristics of graphs for the two-period analysis used in this thesis. It describes the the parameters that can be displayed in eah graph type and the additional display options each graph type provides

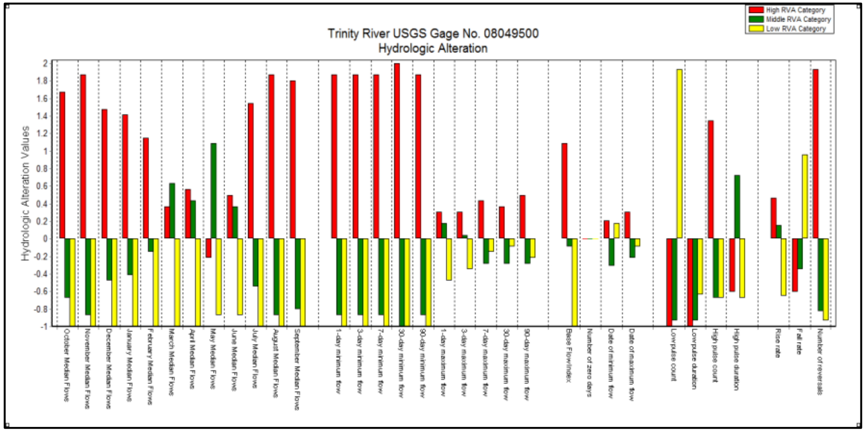
Table 10. Summary of IHA Output Characteristics of Graphs for Two-period Analysis.

Graph Type	Displayed Parameters	Additional Display Options
IHA Parameters Annual Data	33 standard parameters	· Mean or median lines · Variance lines (25th or 75th percentiles or mean plus or minus 1 SD) · RVA category boundaries, with or without Hydrologic Alteration values for each category
EFC Parameters Annual Data	34 standard parameters	· Mean or median lines · Variance lines (25th or 75th percentiles or mean ±1 SD)
Hydrologic Alteration	Hydrologic Alteration values for three RVA categories	· Can display values for all categories or just the category with the greatest alteration
Monthly Averages	Monthly average flow for Pre-Impact and Post-Impact periods	· Can show RVA category boundaries
Daily Data	All daily flow values	· Can show daily values with different colors depending on EFC type · Can display EFC calibration parameter values on graph
Flow Duration Curves	Annual and monthly flow duration curves, for each period	· Can display any number of FDCs on the same graph.

Figure 8(a)-(d) show the Hydrologic Alteration (HA) factors using the RVA analyses in IHA program. As discussed in section *5.1.1*, a positive HA factor represents an increase in flow rate compare Pre-Impact and Post-Impact periods. In contrast, if the HA factor is negative, it means a decrease in flow quantity.

In Figure 9(a)-(d) and Figure 10(a)-(d) 7-day minimum and maximum flows for the Pre-Impact period and Post-Impact period are shown for four gauge stations in the Trinity WAM to which SB3 has been applied. The following graphs contain the changes of flow rates in Pre-Impact and Post-Impact periods, 75th percentile flow line, median flow line, and 25th percentile flow line

a) USGS Gage No. 08049500 West Fork Trinity River at Grand Prairie



b) USGS Gage No. 08057000 Trinity River at Dallas

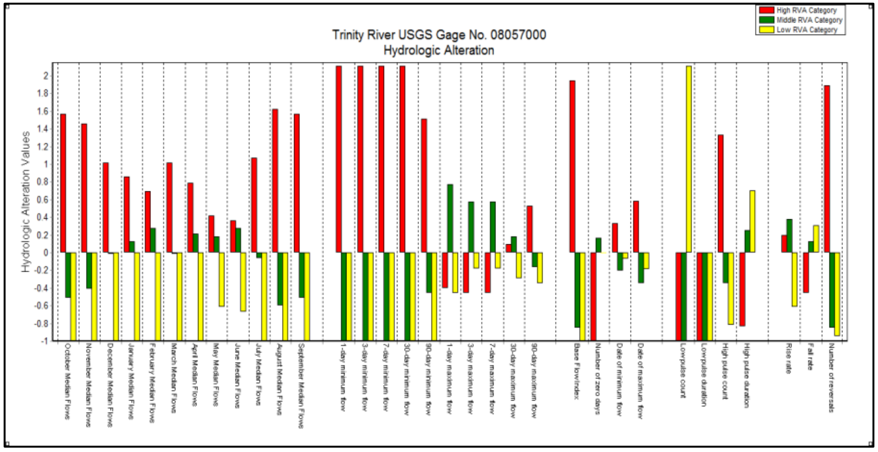
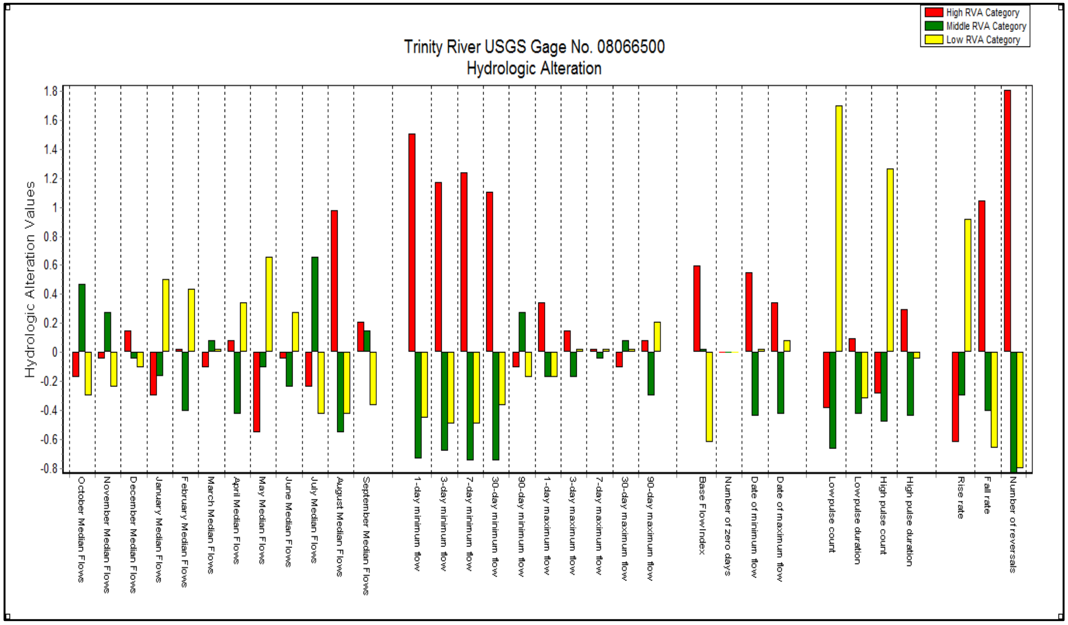


Figure 8. All Hydrologic Alteration Factors for Four Control Points in the Trinity River Basin.

c) USGS Gage No. 08065000 Trinity River near Oakwood



d) USGS Gage No. 08066500 Trinity River at Romayor

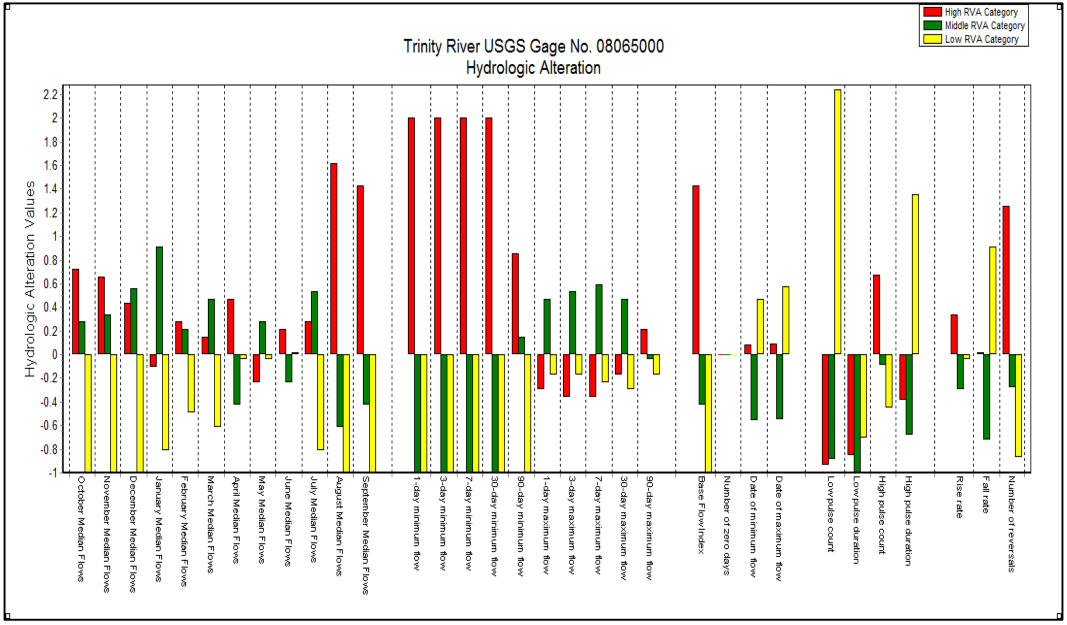
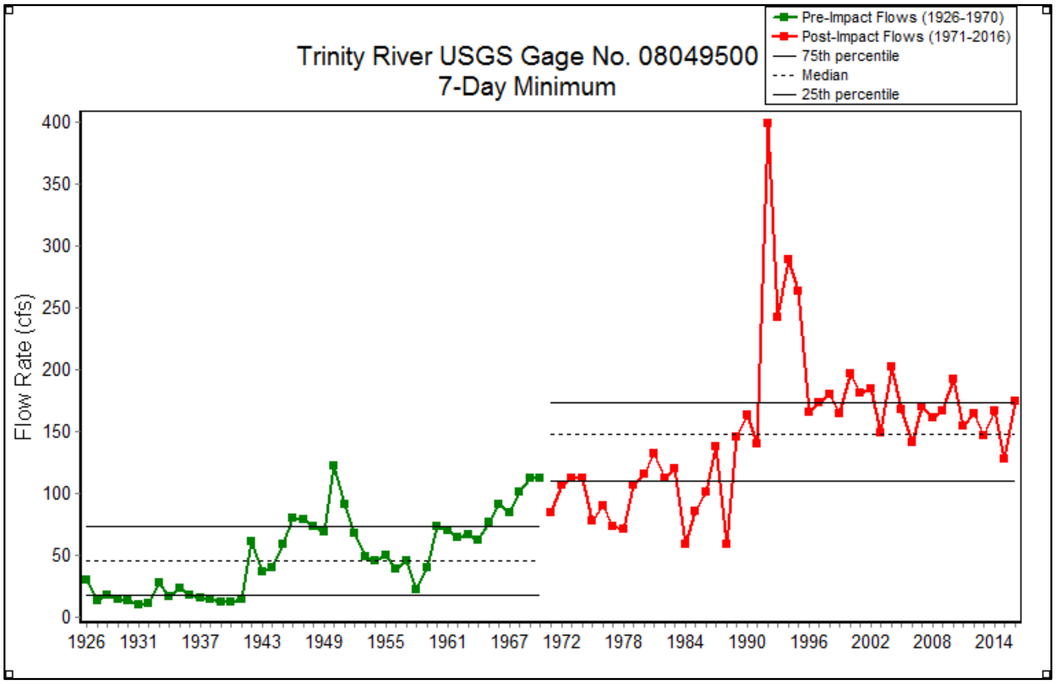


Figure 8 Continued.

a) USGS Gage No. 08049500 West Fork Trinity River at Grand Prairie



b) USGS Gage No. 08057000 Trinity River at Dallas

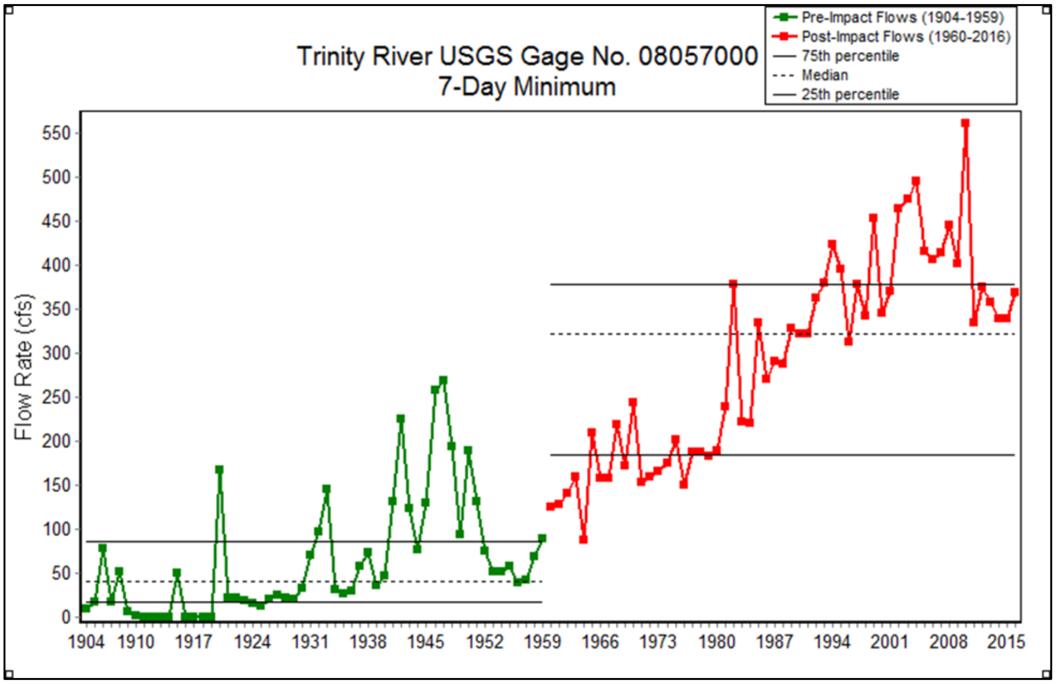
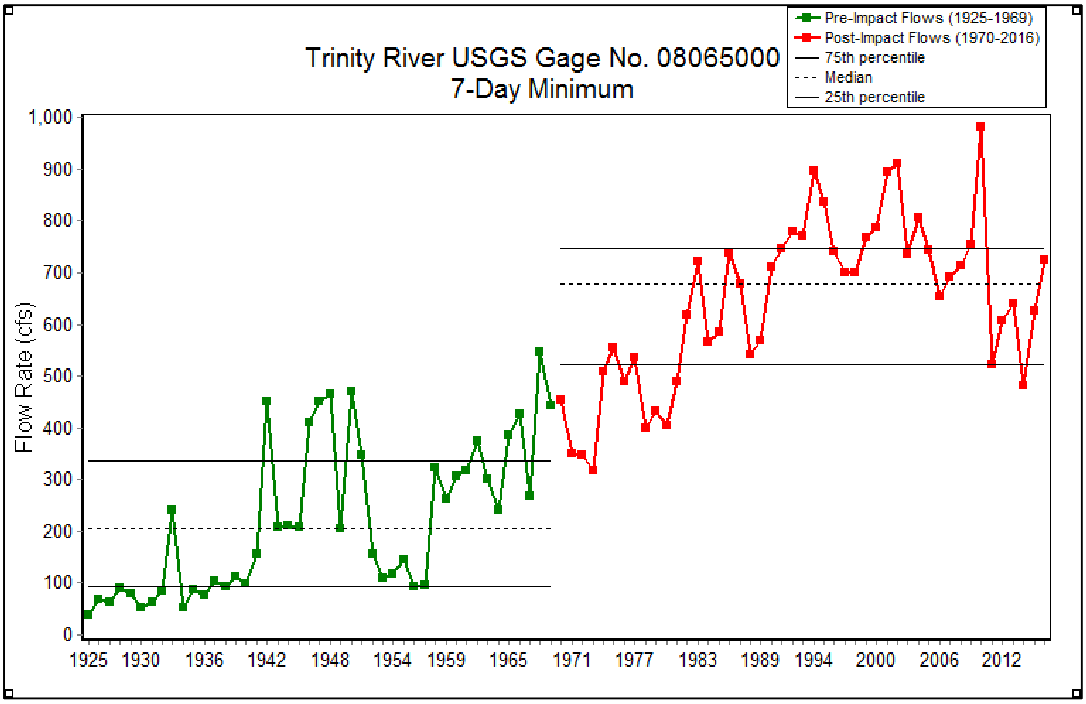


Figure 9. 7- day Minimum Flows for Four Control Points in the Trinity River Basin.

c) USGS Gage No. 08065000 Trinity River near Oakwood



d) USGS Gage No. 08066500 Trinity River at Romayor

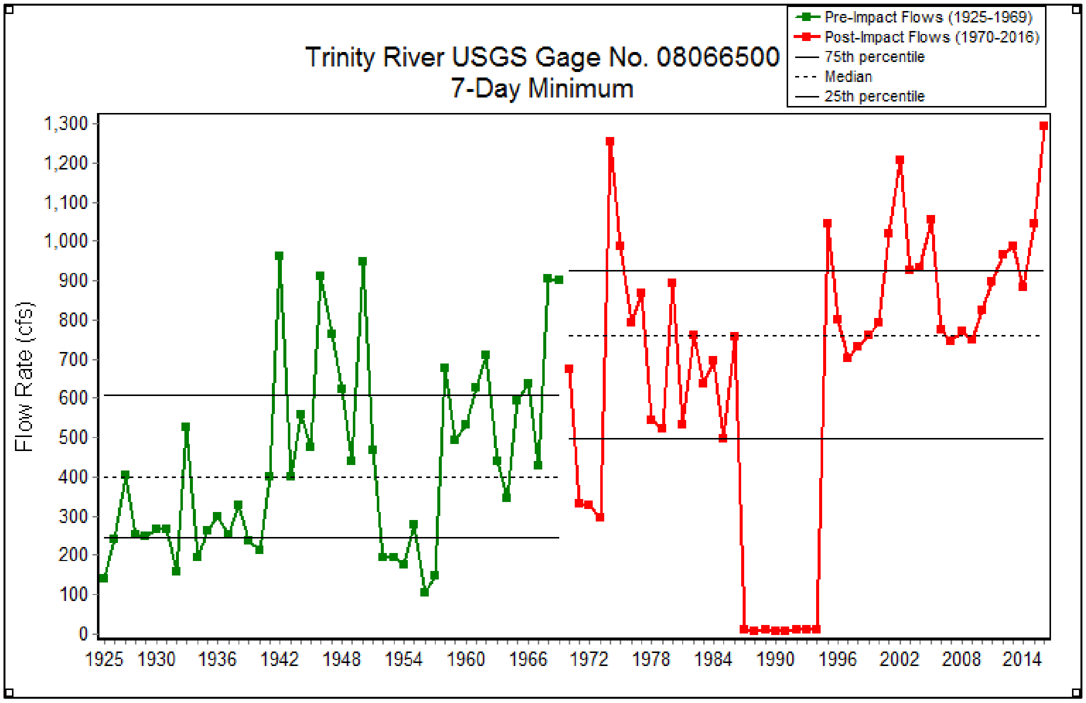
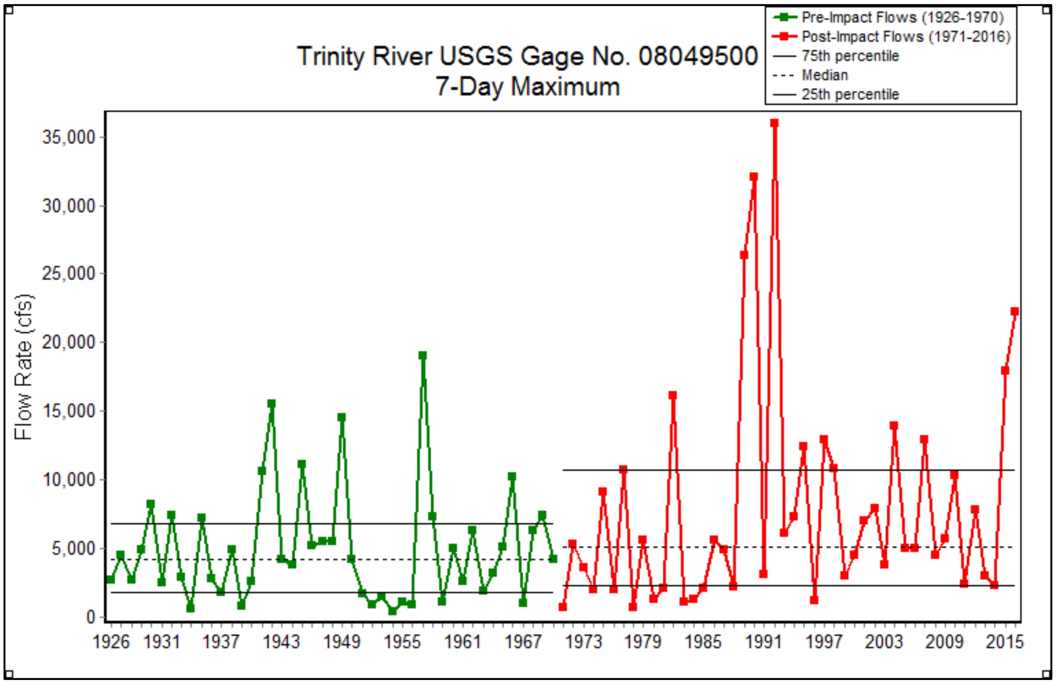


Figure 9 Continued.

a) USGS Gage No. 08049500 West Fork Trinity River at Grand Prairie



b) USGS Gage No. 08057000 Trinity River at Dallas

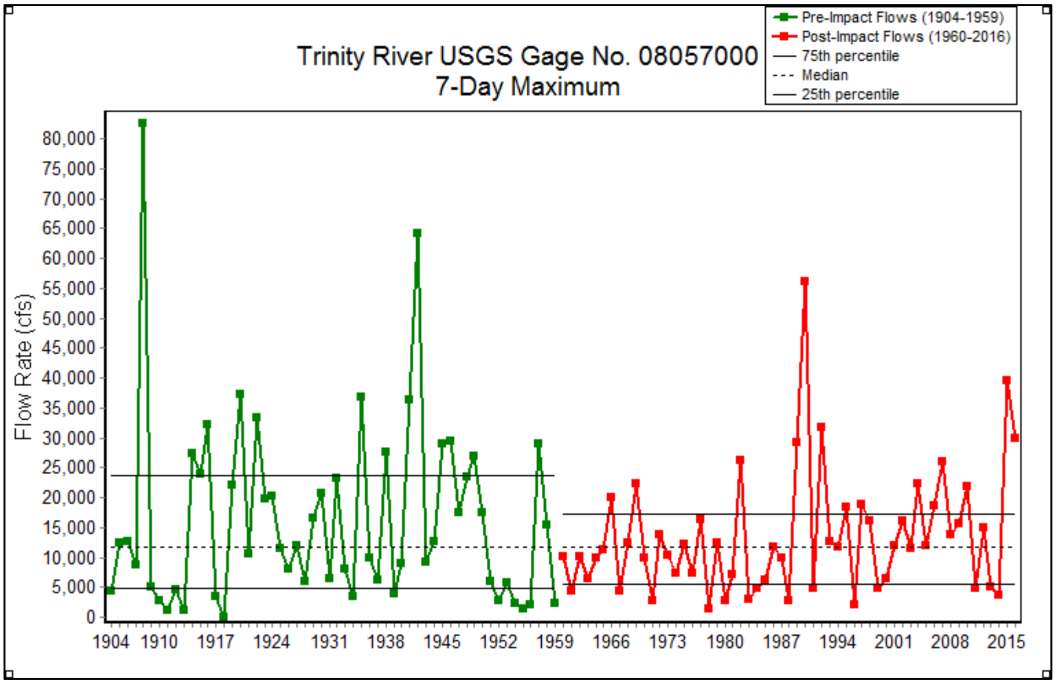
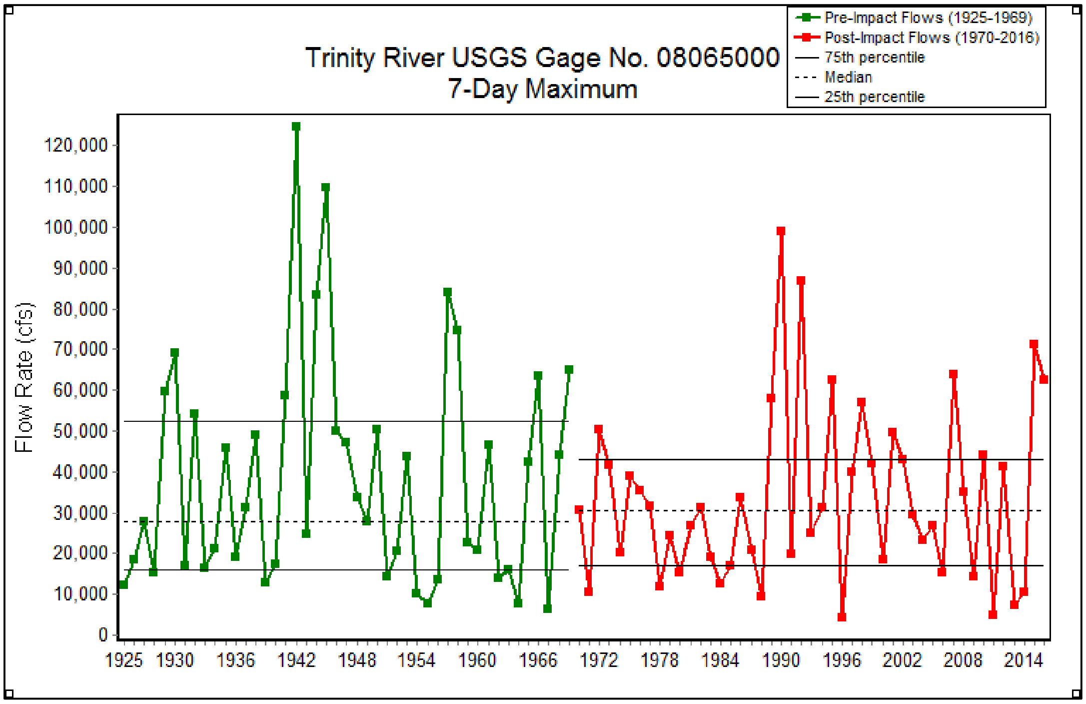


Figure 10. 7- day Maximum Flows (cfs) for Four Control Points in the Trinity River Basin.

c) USGS Gage No. 08065000 Trinity River near Oakwood



d) USGS Gage No. 08066500 Trinity River at Romayor

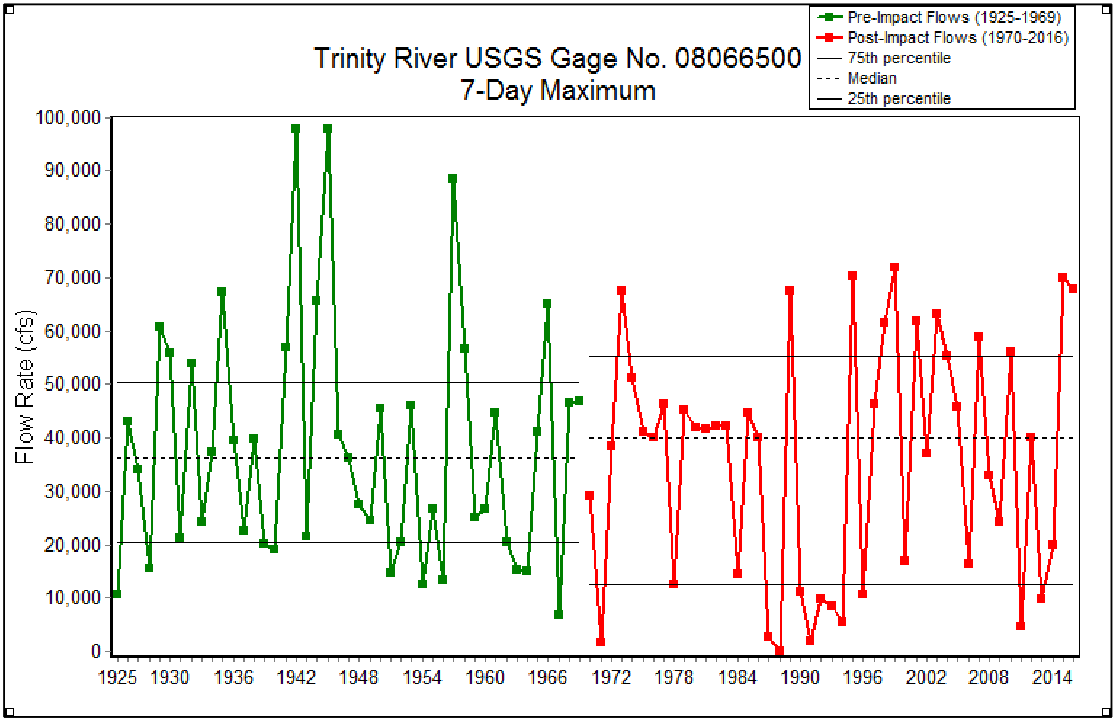
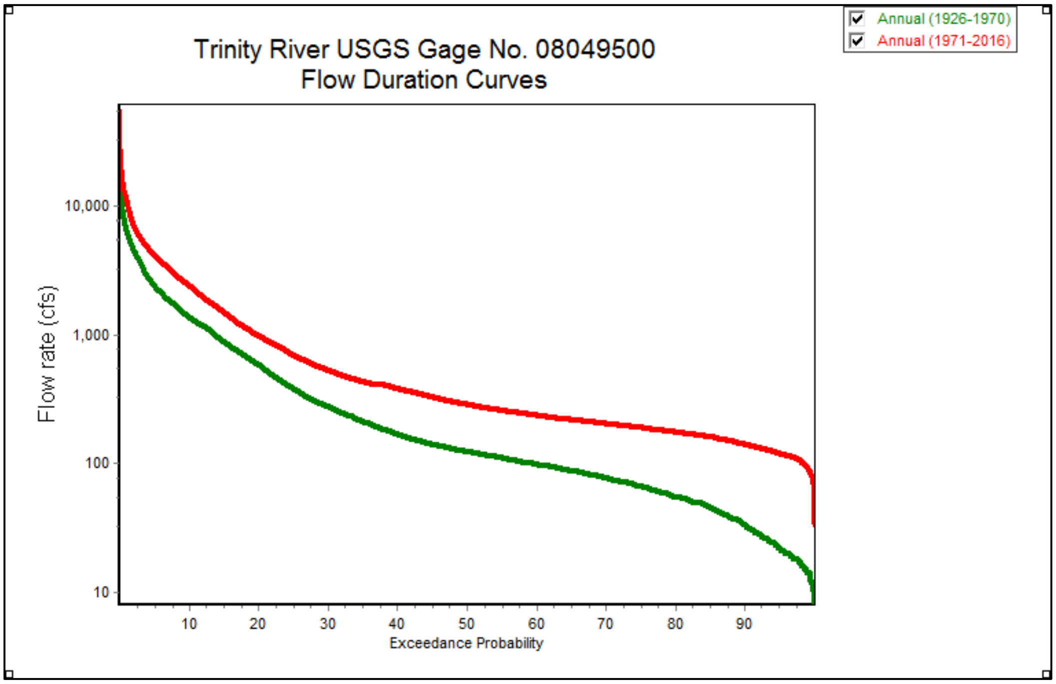


Figure 10 Continued.

a) USGS Gage No. 08049500 West Fork Trinity River at Grand Prairie



b) USGS Gage No. 08057000 Trinity River at Dallas

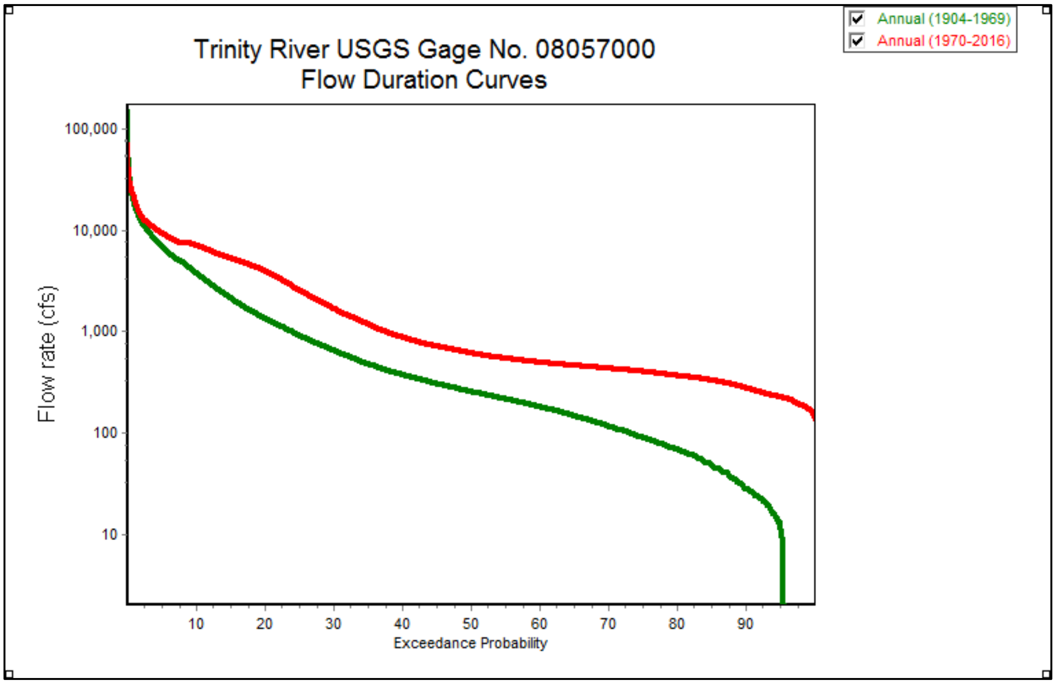
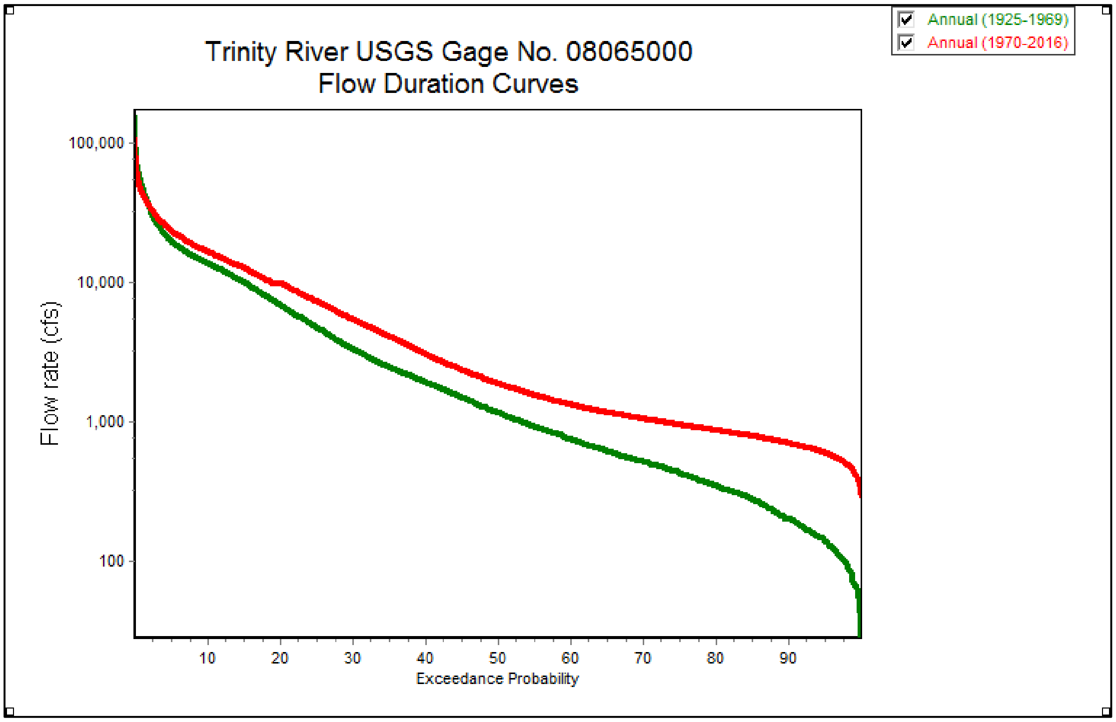


Figure 11. Flow Duration Curves for Four Control Points in the Trinity River Basin.

c) USGS Gage No. 08065000 Trinity River at Romayor



d) USGS Gage No. 08066500 Trinity River at Romayor

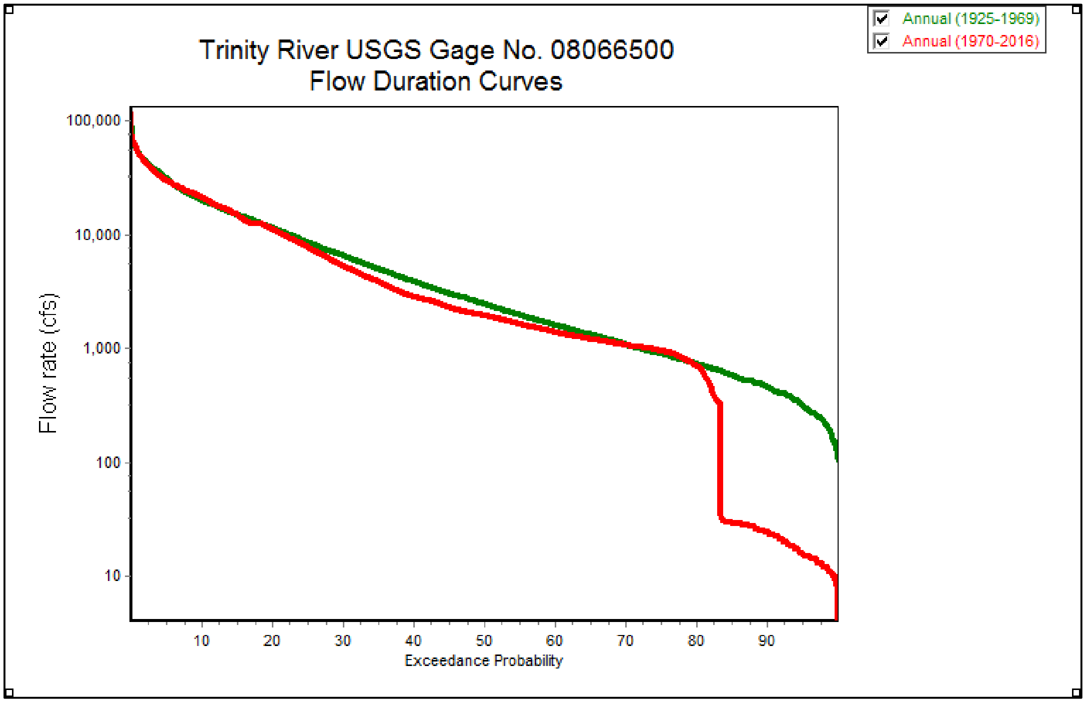


Figure 11 Continued.

Table 11. Frequency Metrics for Observed Daily Flows in the Trinity River Basin (Unit: cfs)

WAM ID / Exceedance Probability	8BSBR		8WTBO		8CTFW		8CTBE		**8WTGP**	
	Pre-Impact	Post-Impact	Pre-Impact	Post-Impact	Pre-Impact	Post-Impact	Pre-Impact	Post-Impact	**Pre-Impact**	**Post-Impact**
1%	1,630	1,570	3,080	4,860	1,850	3,200	1,480	1,920	**6,520**	**11,400**
2%	786	1,090	1,610	2,570	941	2,200	788	1,890	**4,640**	**7,090**
5%	215	425	822	937	343	1,340	285	903	**2,390**	**4,140**
10%	76	133	534	434	162	556	130	336	**1,360**	**2,420**
15%	40	61	361	318	99	288	67	133	**876**	**1,490**
20%	27	35	283	255	67	169	30	87	**581**	**974**
30%	15	16	188	188	30	62	18	48	**276**	**530**
40%	10	8	94	123	16	37	12	24	**162**	**380**
50%	5	4	40	78	8	26	5	15	**124**	**287**
60%	2	1	21	46	5	18	2	11	**96**	**236**
70%	0	0	11	26	2	14	1	8	**76**	**203**
75%	0	0	8	20	1	11	0	7	**64**	**189**
80%	0	0	5	15	0	10	0	5	**55**	**175**
85%	0	0	3	10	0	7	0	4	**46**	**160**
90%	0	0	1	7	0	5	0	2	**33**	**140**
95%	0	0	0	3	0	2	0	1	**22**	**119**
98%	0	0	0	0	0	0	0	1	**17**	**104**
99%	0	0	0	0	0	0	0	0	**14**	**91**

	8CLSA		8ELLE		8DNJU		**8TRDA**		8ETCR	
1%	1,380	2,550	5,000	6220	1,670	2,950	**19,200**	**19,100**	6,600	9,400
2%	746	1,590	4,500	5300	812	1,650	**12,700**	**13,100**	4,480	7,140
5%	240	692	3,530	4,550	292	554	**7,320**	**8,820**	2,490	4,910
10%	98	241	1,490	3,510	112	216	**3,570**	**6,640**	1,670	2,620
15%	61	135	460	2,480	67	129	**2,050**	**4,960**	1,040	2,120
20%	42	90	342	1,130	45	93	**1,320**	**3,570**	680	1,620
30%	21	52	253	464	23	45	**661**	**1,460**	223	524
40%	12	29	209	368	13	27	**376**	**770**	117	187
50%	8	16	171	310	7	17	**240**	**554**	62	129
60%	4	9	144	260	3	10	**145**	**460**	45	104
70%	0	5	119	219	0	4	**92**	**391**	33	88
75%	0	2	110	199	0	1	**73**	**354**	28	82
80%	0	0	98	177	0	0	**55**	**310**	22	75
85%	0	0	83	153	0	0	**40**	**263**	14	67
90%	0	0	71	125	0	0	**24**	**227**	7	59
95%	0	0	46	73	0	0	**0**	**190**	2	51
98%	0	0	27	36	0	0	**0**	**160**	0	44
99%	0	0	15	16	0	0	**0**	**144**	0	40

	8TRRS		**8TROA**		**8TRRO**	
1%	26,700	29,900	**48,000**	**42,900**	**53,400**	**52,400**
2%	17,600	23,200	**34,000**	**34,900**	**44,800**	**43,600**
5%	11,200	15,600	**19,600**	**23,300**	**31,500**	**29,900**
10%	7,440	11,800	**13,600**	**16,400**	**20,100**	**21,200**
15%	5,210	8,900	**9,970**	**12,600**	**15,000**	**14,900**
20%	3,400	6,620	**6,850**	**9,640**	**11,600**	**11,200**
30%	1,820	3,540	**3,320**	**5,370**	**6,530**	**5,320**
40%	1,050	1,960	**1,910**	**3,030**	**3,850**	**2,840**
50%	665	1,290	**1,150**	**1,870**	**2,460**	**1,950**
60%	493	950	**750**	**1,320**	**1,600**	**1,390**
70%	394	882	**511**	**1,050**	**1,090**	**1,070**

Table 11 Continued.

WAM ID Exceedance Probability	8TRRS		**8TROA**		**8TRRO**	
75%	347	827	**423**	**944**	**900**	**955**
80%	290	780	**345**	**865**	**725**	**708**
85%	224	724	**278**	**786**	**580**	**30**
90%	171	660	**198**	**698**	**455**	**24**
95%	137	564	**140**	**596**	**320**	**16**
98%	116	500	**96**	**493**	**230**	**12**
99%	102	449	**70**	**432**	**185**	**11**

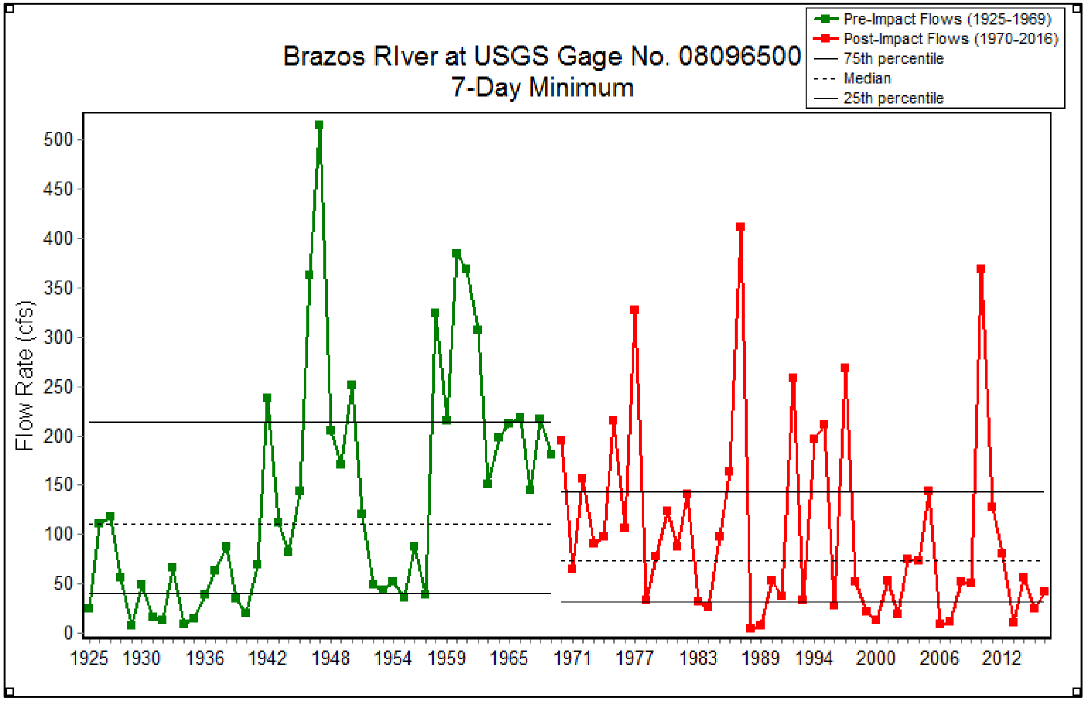
Table 11 organizes the frequency metrics of observed daily mean flows at 13 control points in the Trinity River Basin. The metrics are generated using the duration analysis tool in the IHA software. The table contains exceedance probabilities and their correlated observed daily mean flow rates in cubic feet per second. The frequency statistics of Pre-Impact and Post-Impact period-of-records are listed individually. Amongst the 13 control points, four control points with SB3 are indicated in bold.

5.3 Results for Sites on the Brazos River and Its Tributaries

Figure 12(a)-(d) and Figure 13(a)-(d) present the 7-day minimum and maximum flow rates at four gauge stations in the Brazos River Basin. They are USGS Gage 08096500 Brazos River at Waco, USGS Gage 08106500 Brazos River near Cameron, USGS Gage 08111500 Brazos River near Hempstead, and USGS Gage 08114000 Brazos River near Richmond.

Figure 14(a)-(r) show the flow duration curves of 19 control points to which the SB3 has been applied in the Brazos WAM. The flow duration curves display the annual mean flow rates of the Pre-Impact and Post-Impact periods at each gage station. Meanwhile, the flow duration curves compare the trends of Pre-Impact and Post-Impact periods.

a) USGS Gage 08096500 Brazos River at Waco



b) USGS Gage 08106500 Brazos River near Cameron

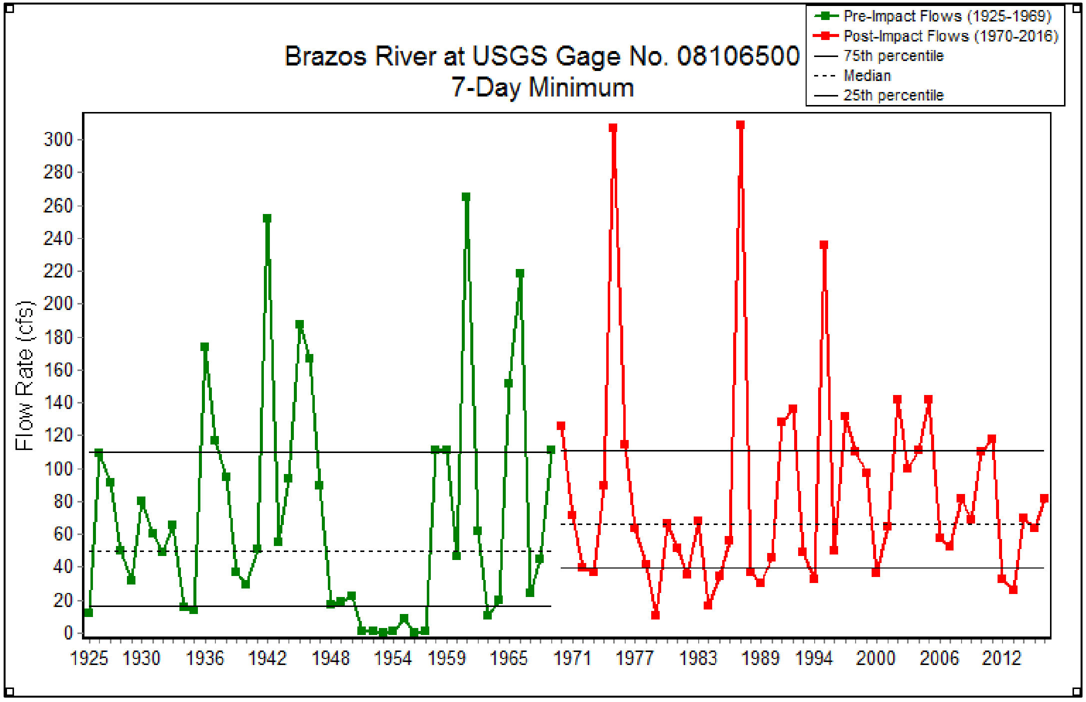
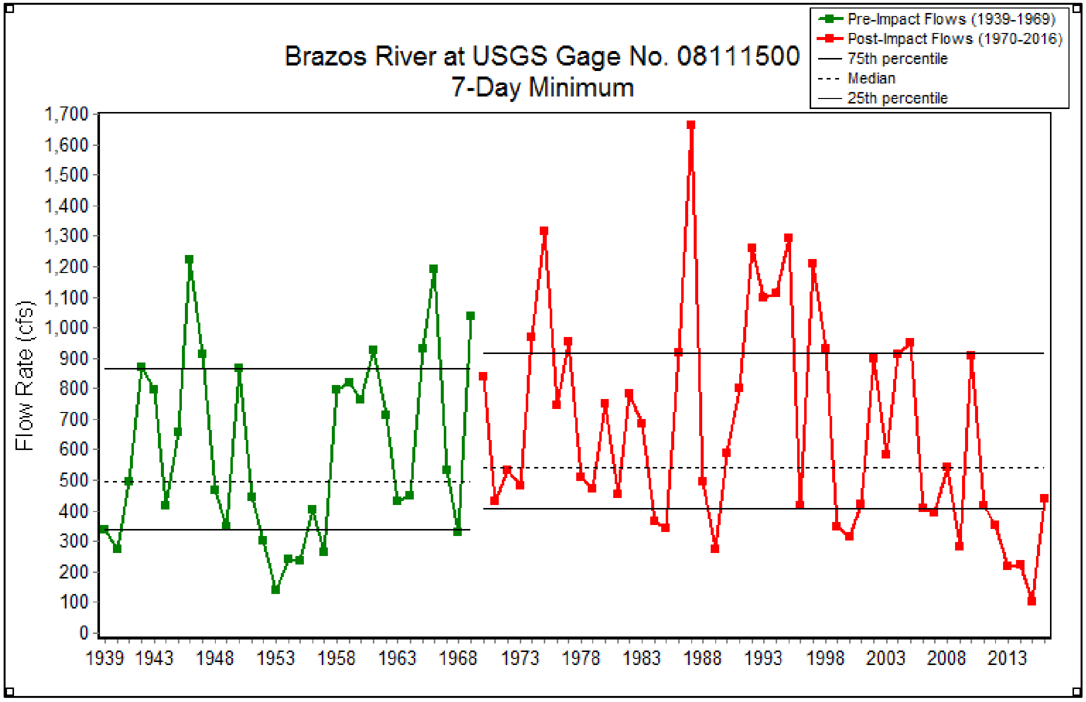


Figure 12. 7-day Minimum Flow Rates for Four Gage Stations in the Brazos River Basin.

c) USGS Gage 08111500 Brazos River near Hempstead



d) USGS Gage 08114000 Brazos River near Richmond

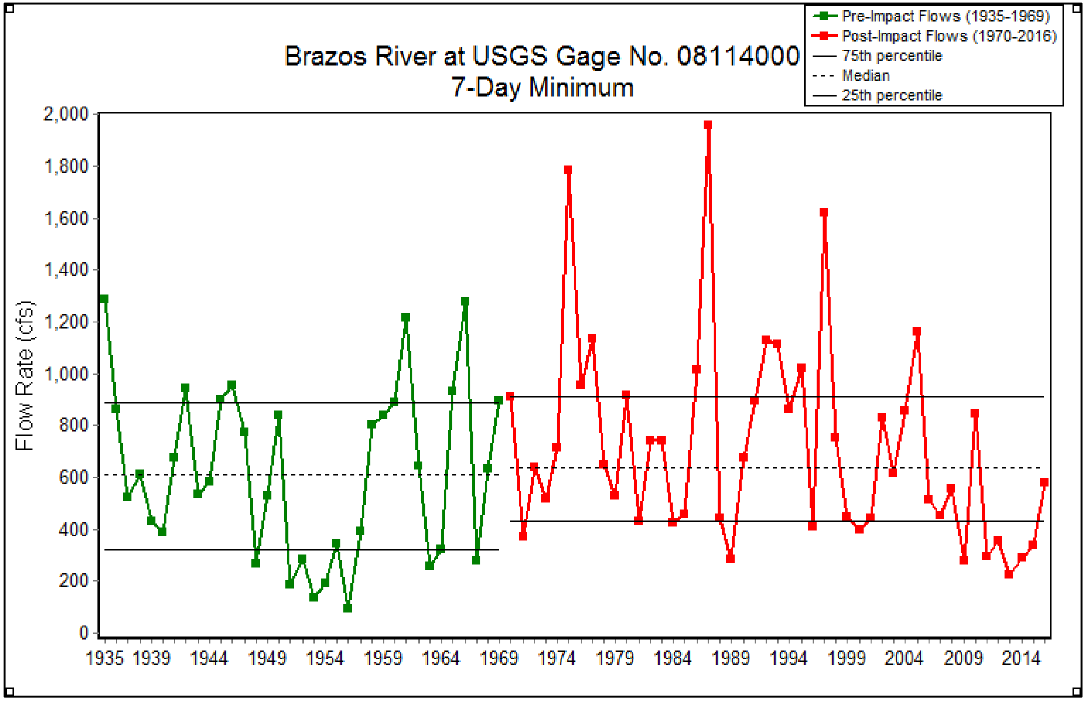
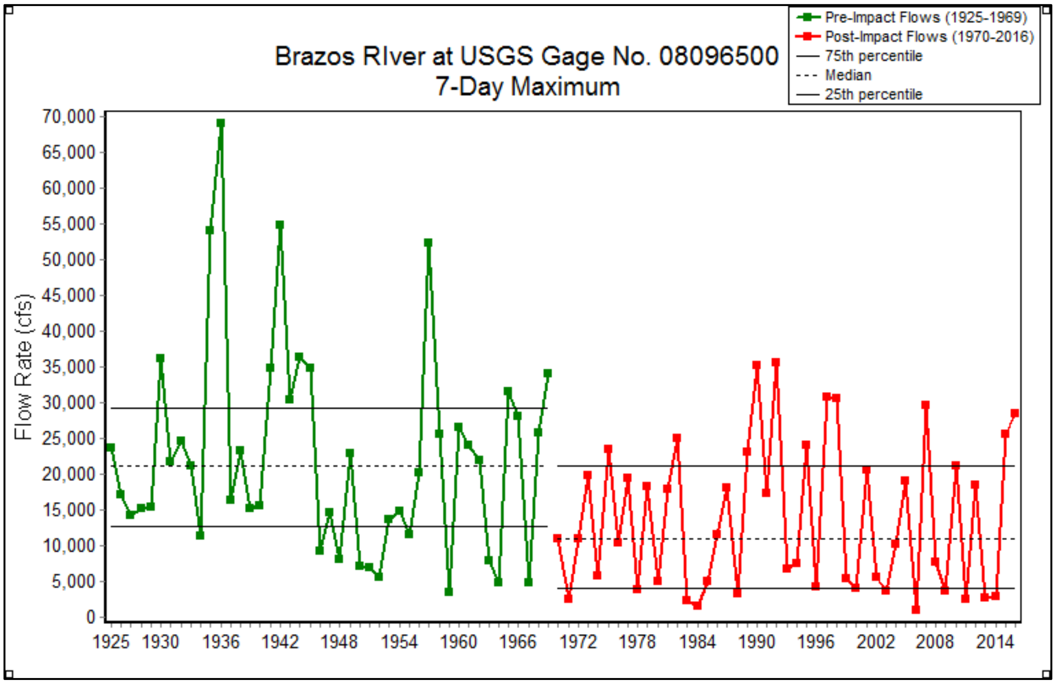


Figure 12 Continued.

a) USGS Gage 08096500 Brazos River at Waco



b) USGS Gage 08106500 Brazos River near Cameron

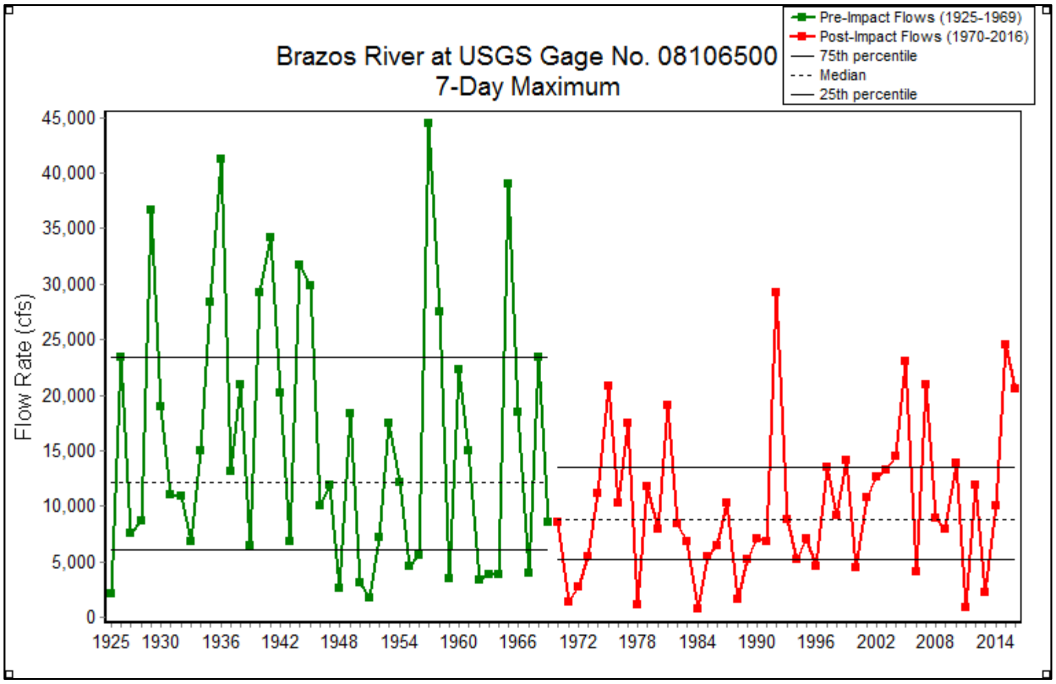
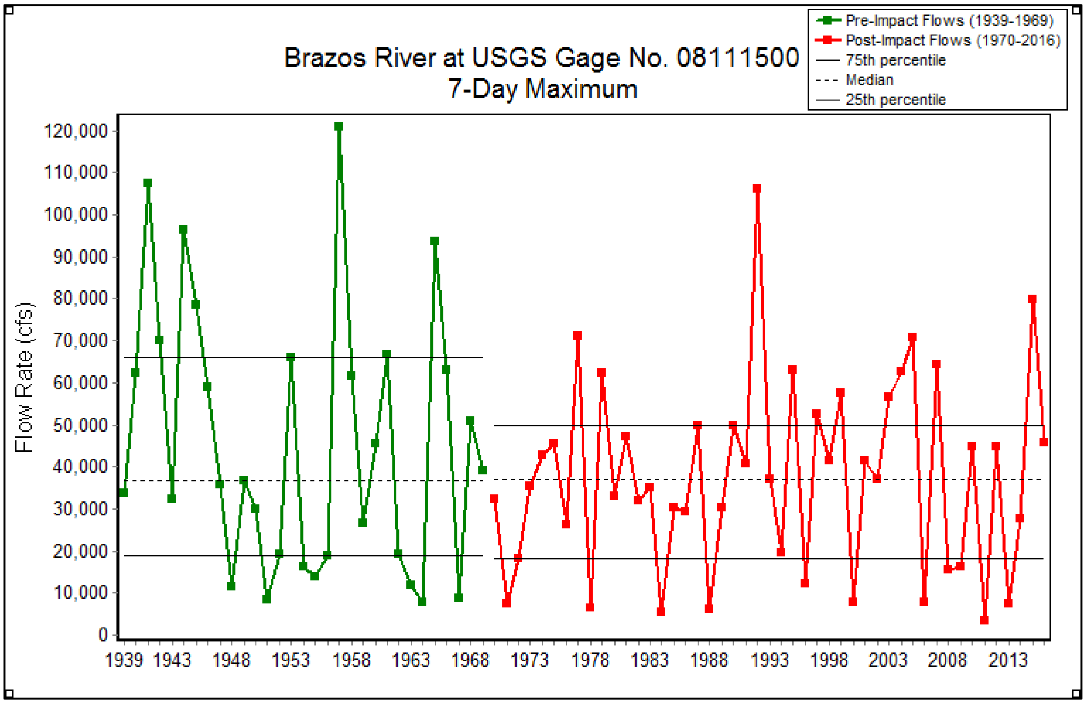


Figure 13. 7-day Maximum Flow Rates for Four Gage Stations in the Brazos River Basin.

c) USGS Gage 08111500 Brazos River near Hempstead



d) USGS Gage 08114000 Brazos River near Richmond

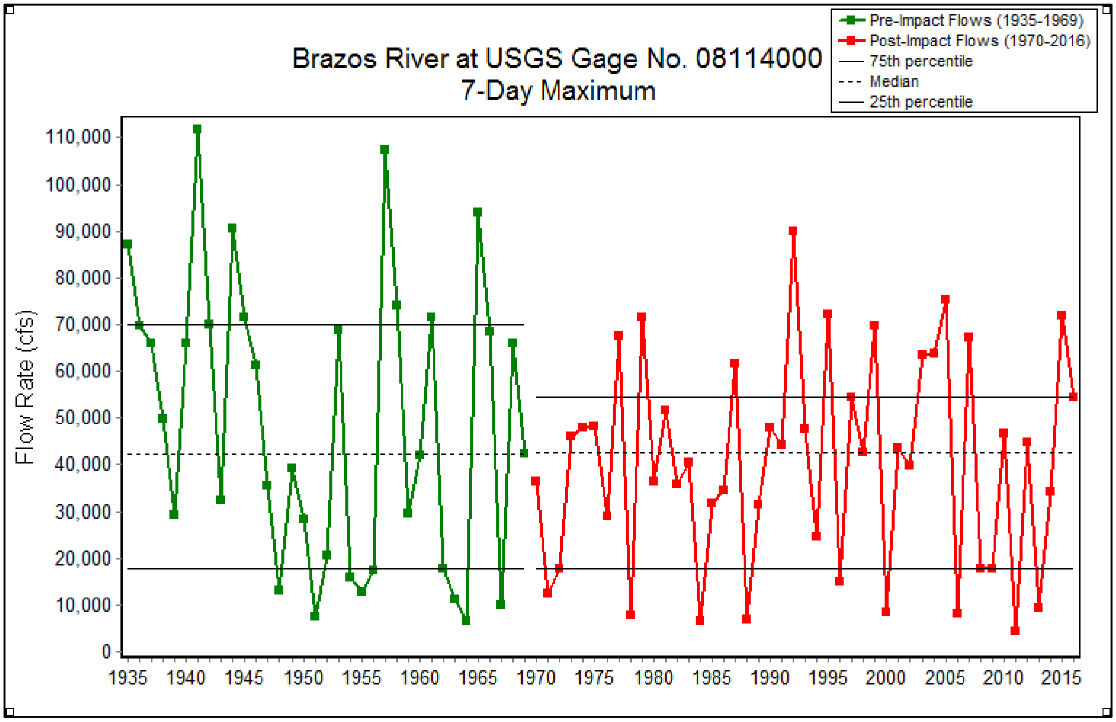
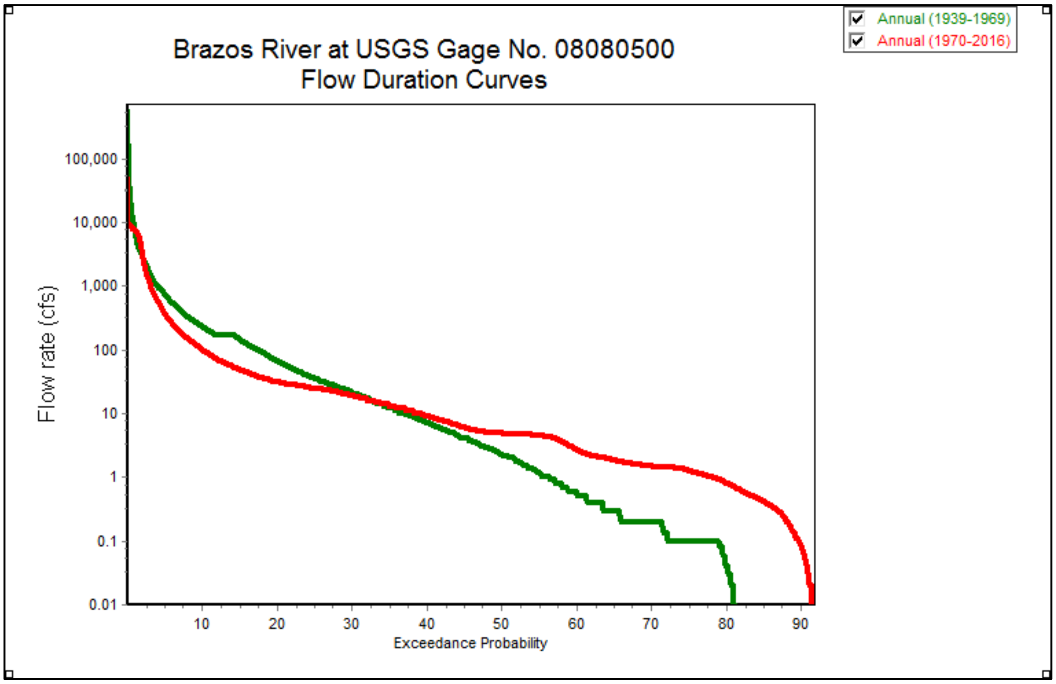


Figure 13 Continued.

a) USGS Gage No. 08080500 Double Mountain Fork near Aspermont



b) USGS Gage No. 08082000 Salt Fork Brazos River near Aspermont

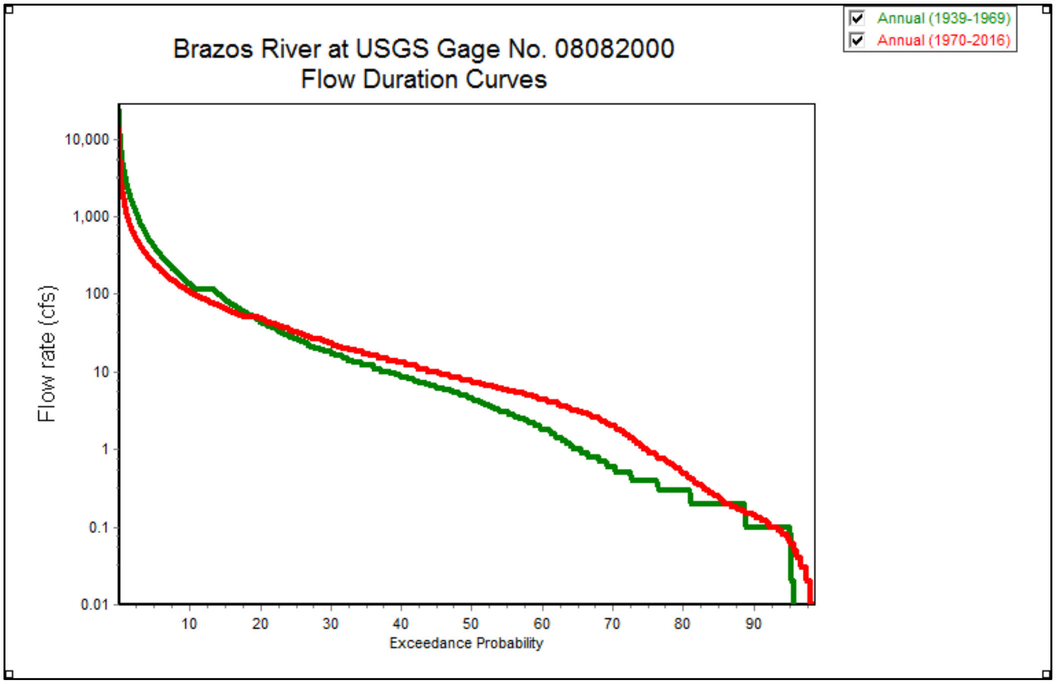
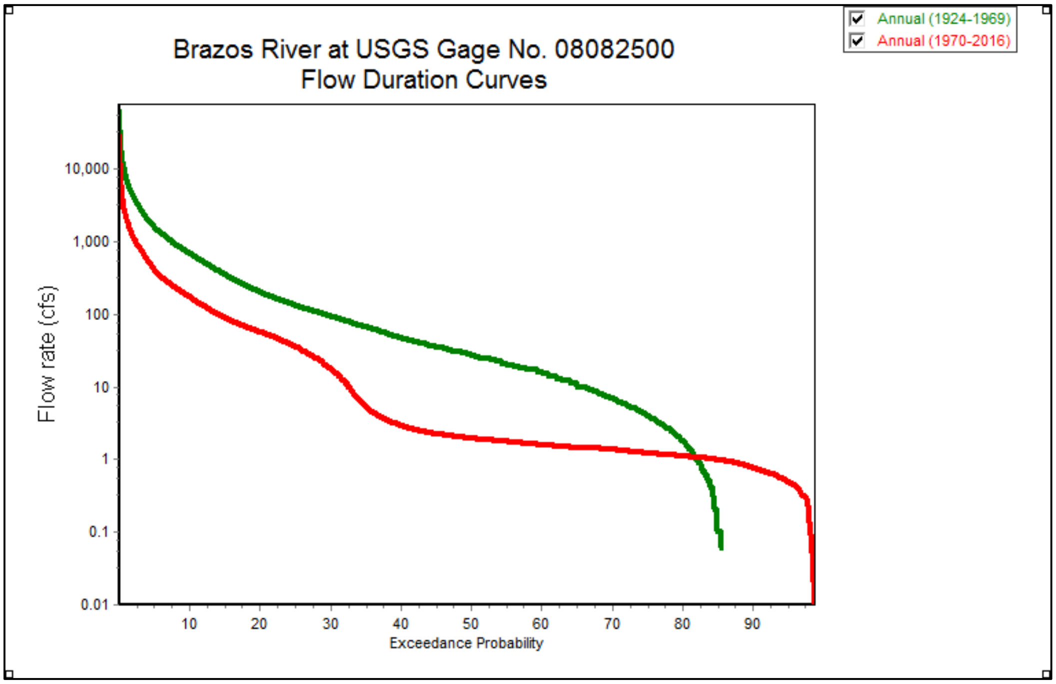


Figure 14. Flow Duration Curves for 19 Gaging Stations on the Brazos River Basin

c) USGS Gage No. 08082500 Brazos River near Seymour



d) USGS Gage No. 08084000 Clear Fork Brazos near Nugent

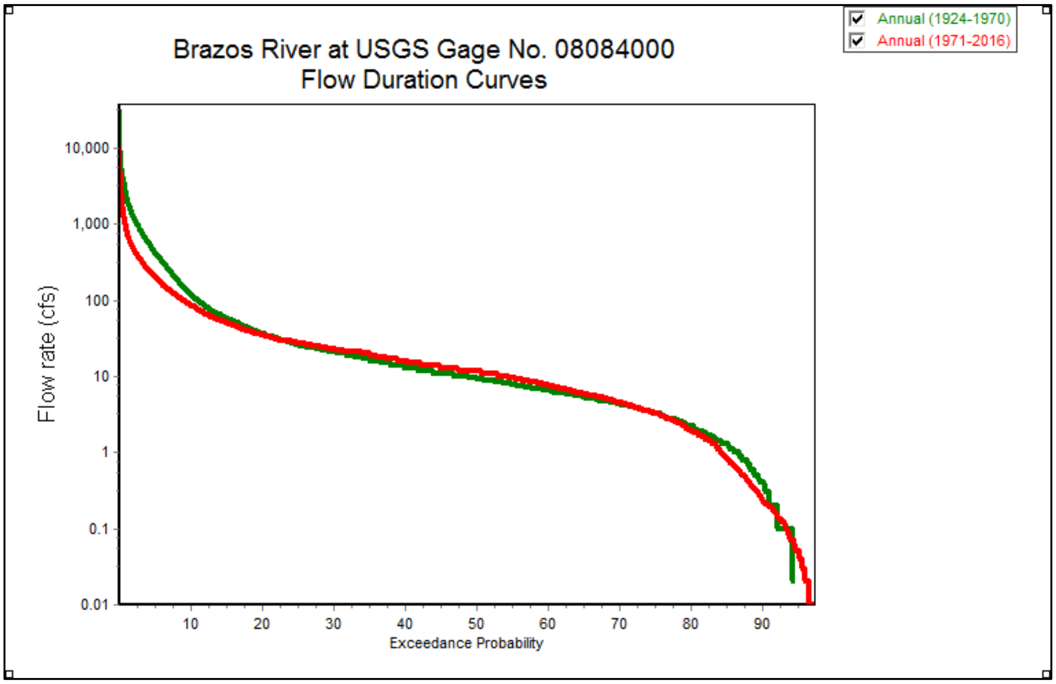
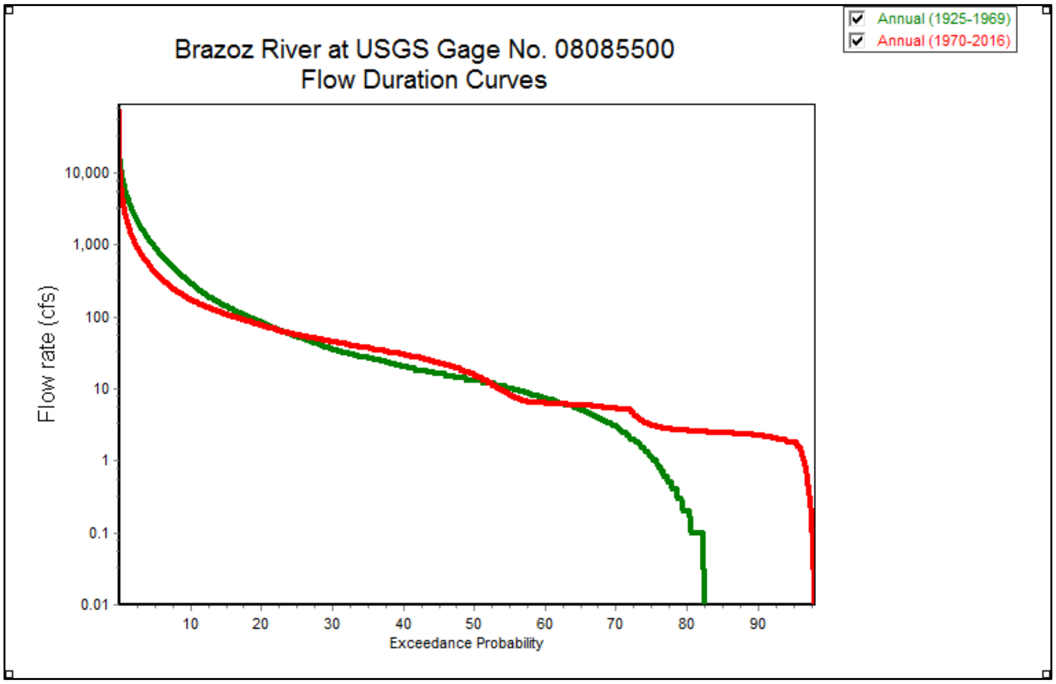


Figure 14 Continued.

e) USGS Gage No. 08085500 Clear Fork Brazos near Fort Griffin



f) USGS Gage No. 08088000 Brazos River near South Bend

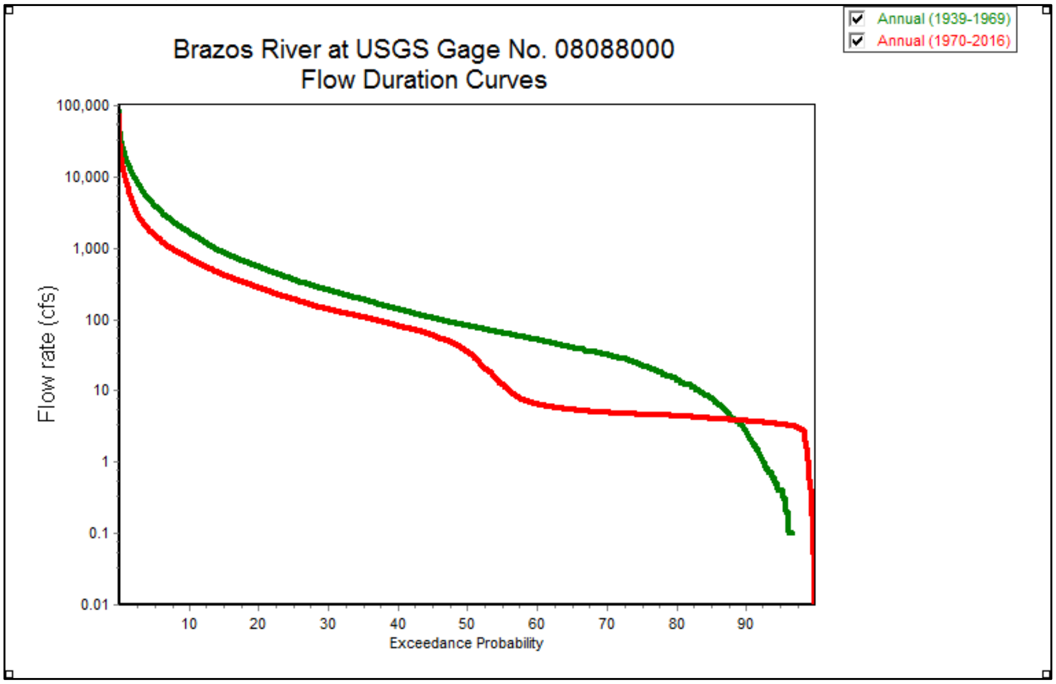
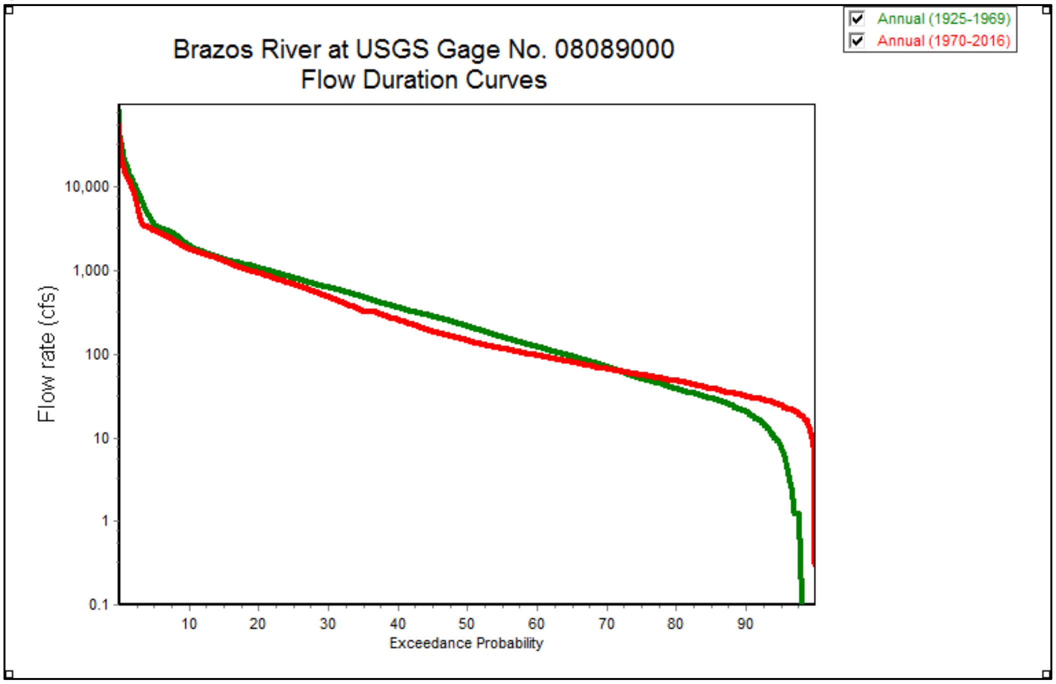


Figure 14 Continued.

g) USGS Gage No. 08089000 Brazos River near South Bend



h) USGS Gage No. 08091000 Brazos River near South Bend

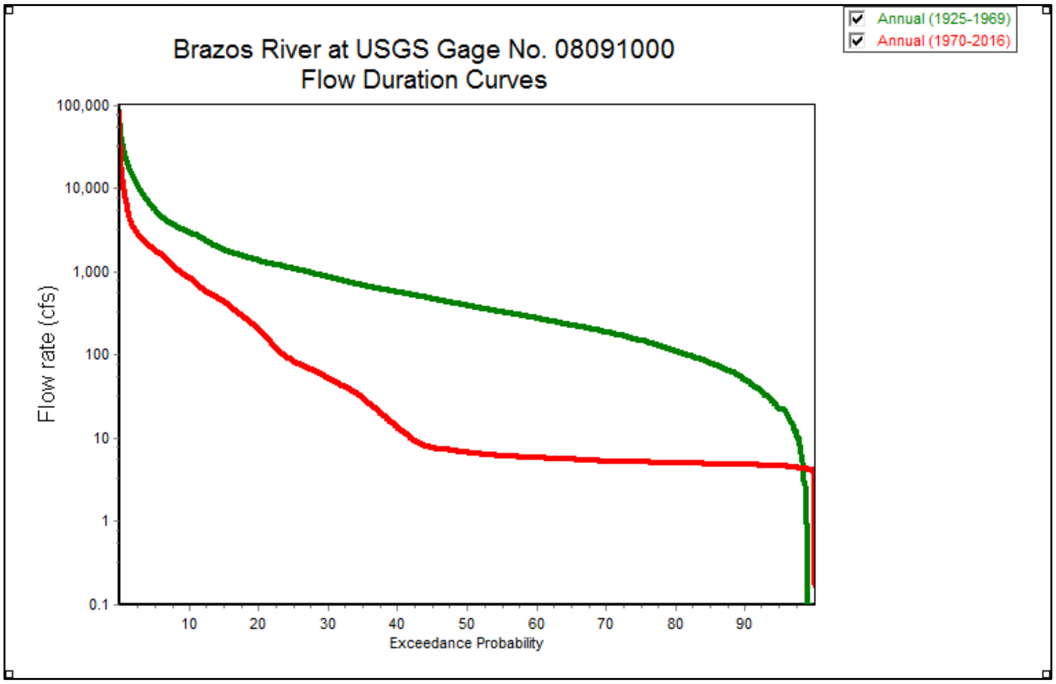
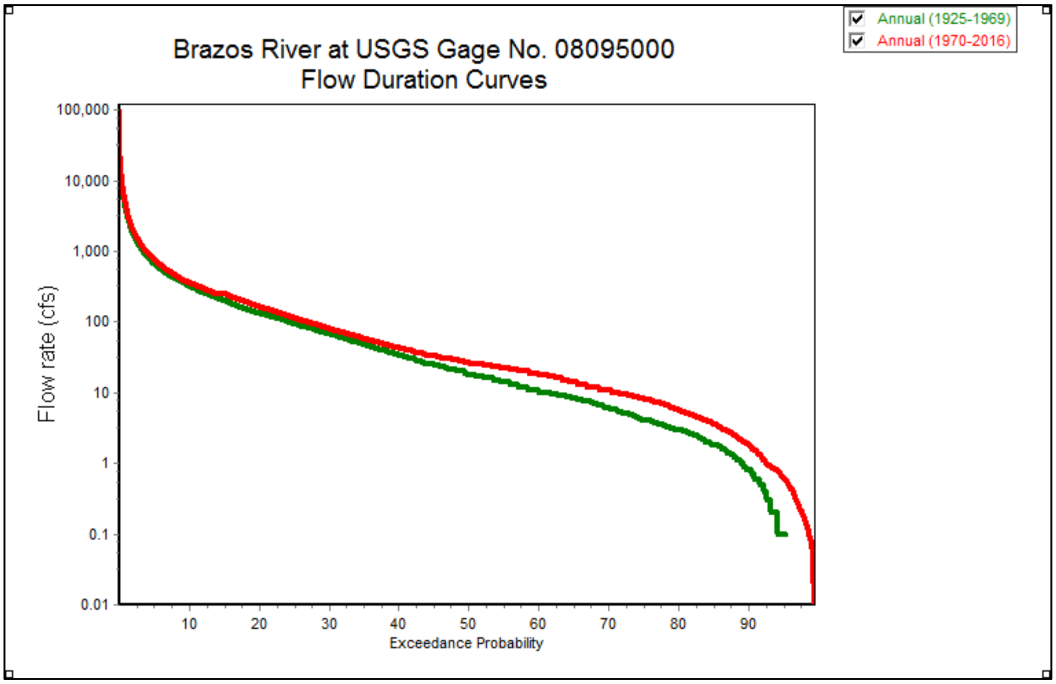


Figure 14 Continued.

i) USGS Gage No. 08095000



j) USGS Gage No. 08096500 Brazos River near Waco

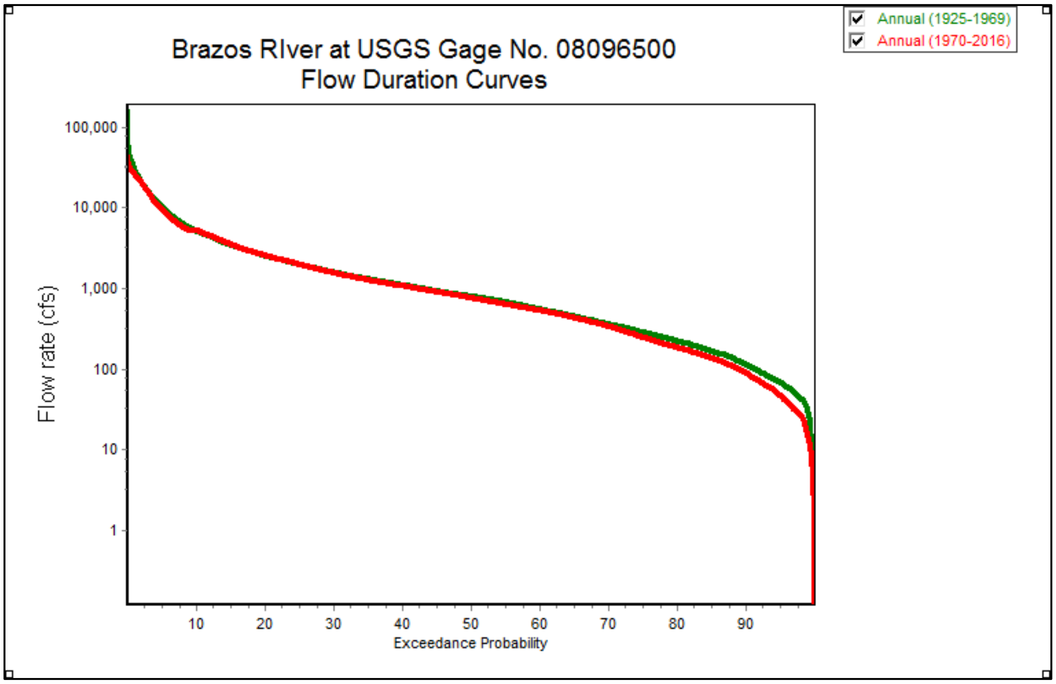
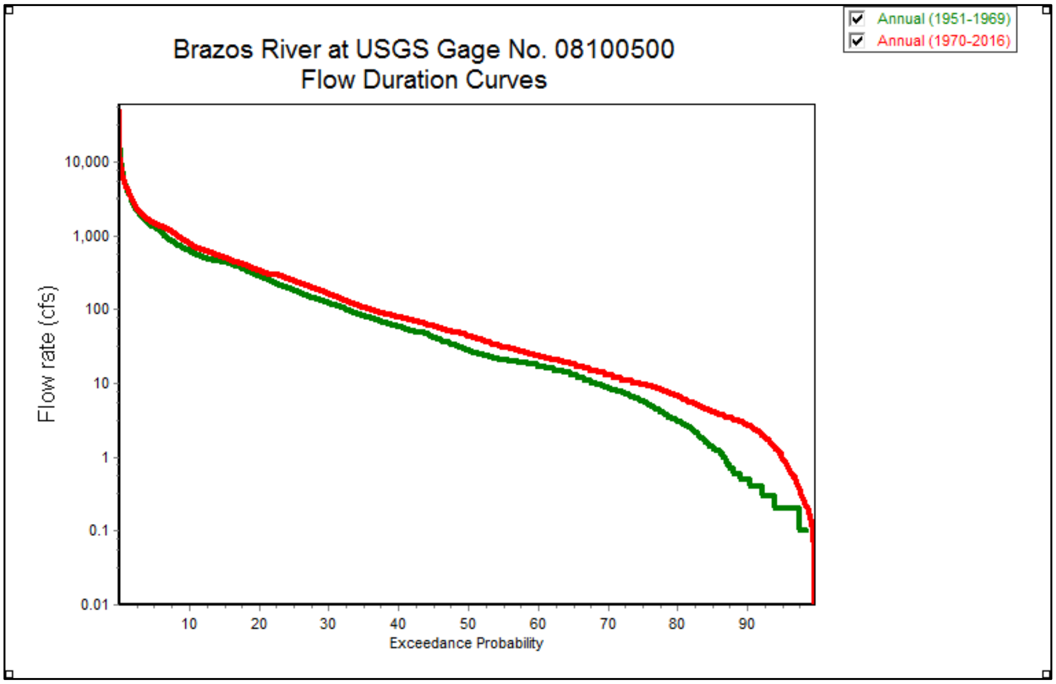


Figure 14 Continued.

k) USGS Gage No. 08100500 Leon River near Gatesville



l) USGS Gage No. 08103800 Lampasas River near Kempner

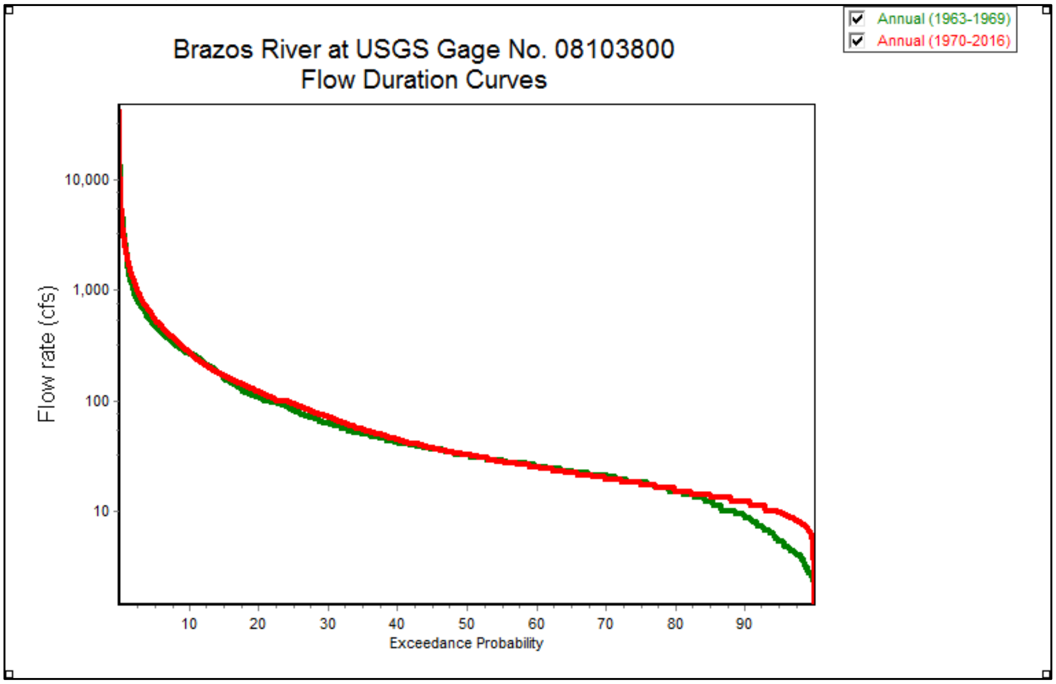
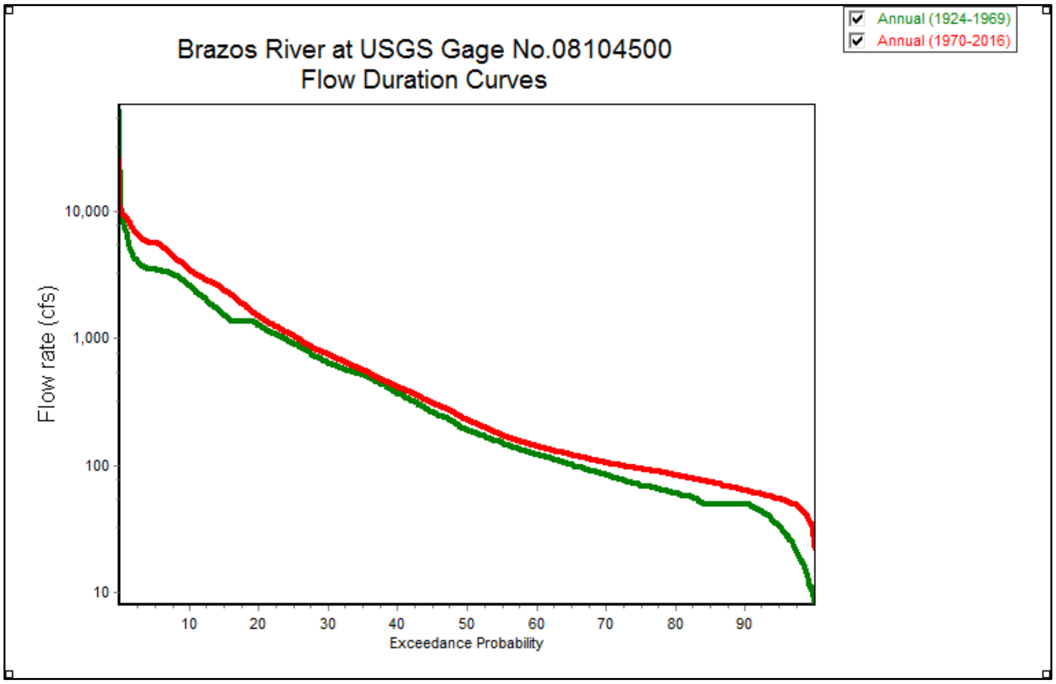


Figure 14 Continued.

m) USGS Gage No. 08104500 Little River near Little River



n) USGS Gage No. 08106500 Little River near Cameron

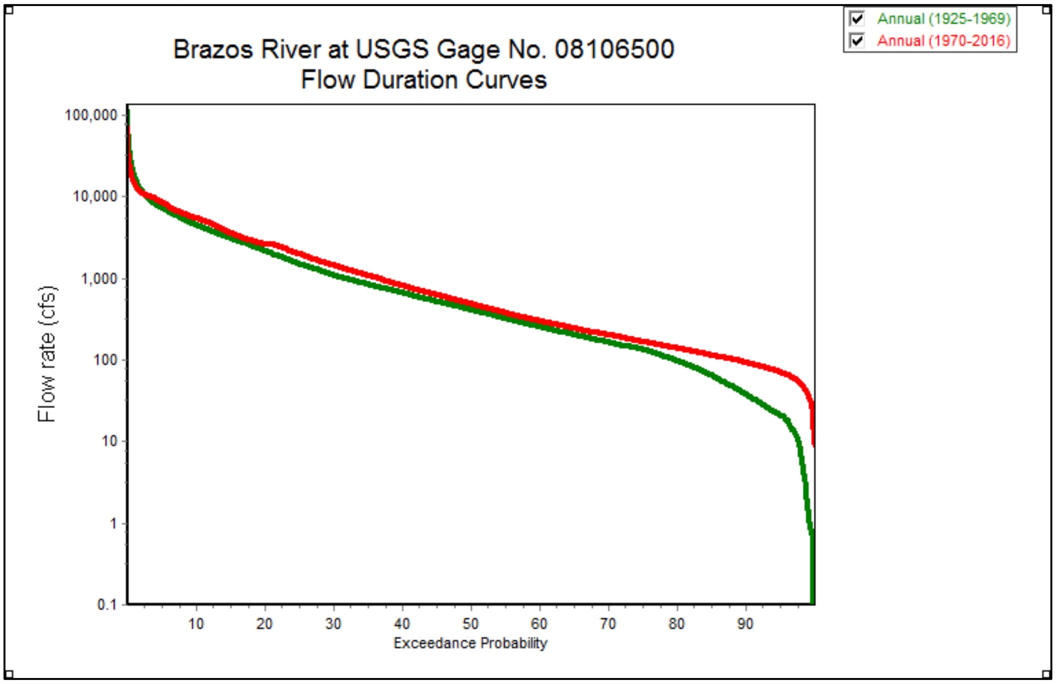
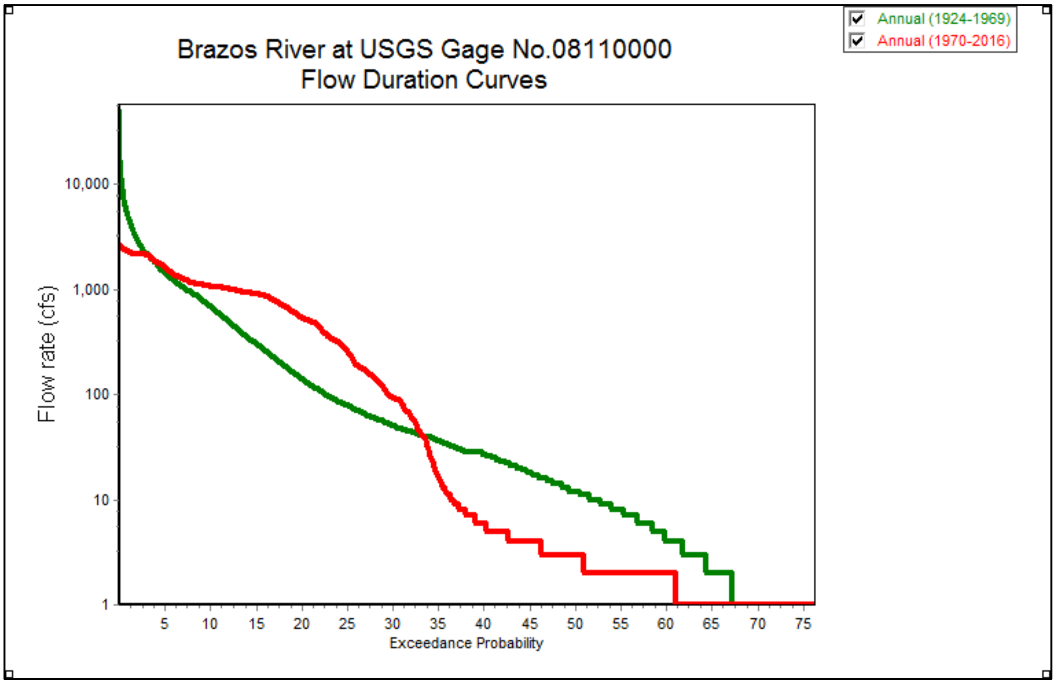


Figure 14 Continued.

o) USGS Gage No. 08110000 Yegua Creek near Somerville



p) USGS Gage No. 08110500 Navasota River at Easterly

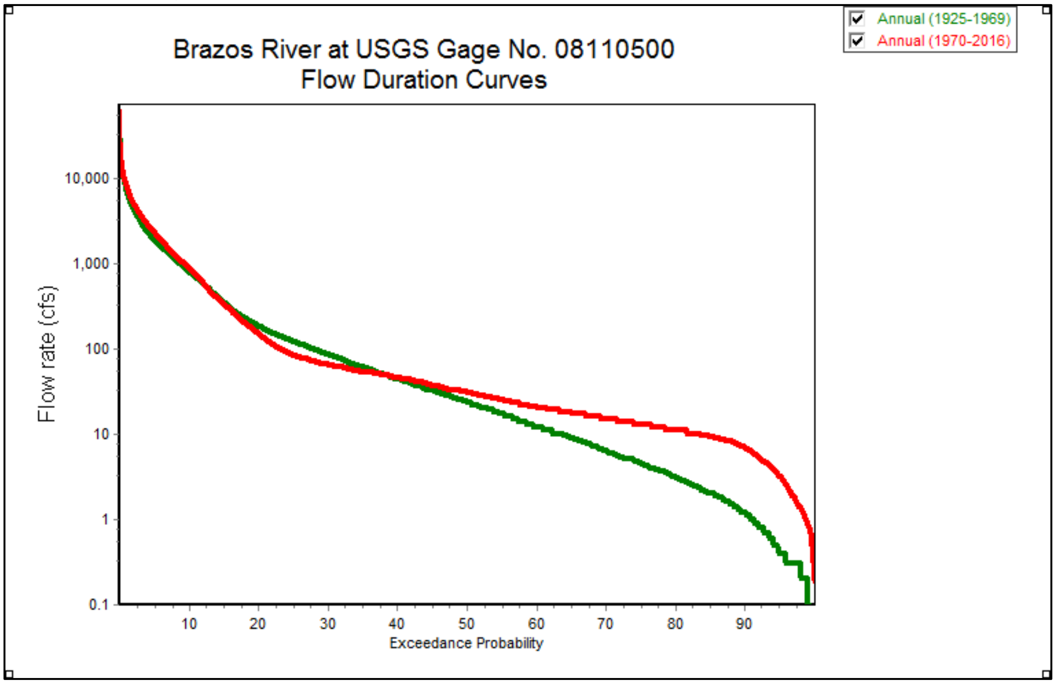
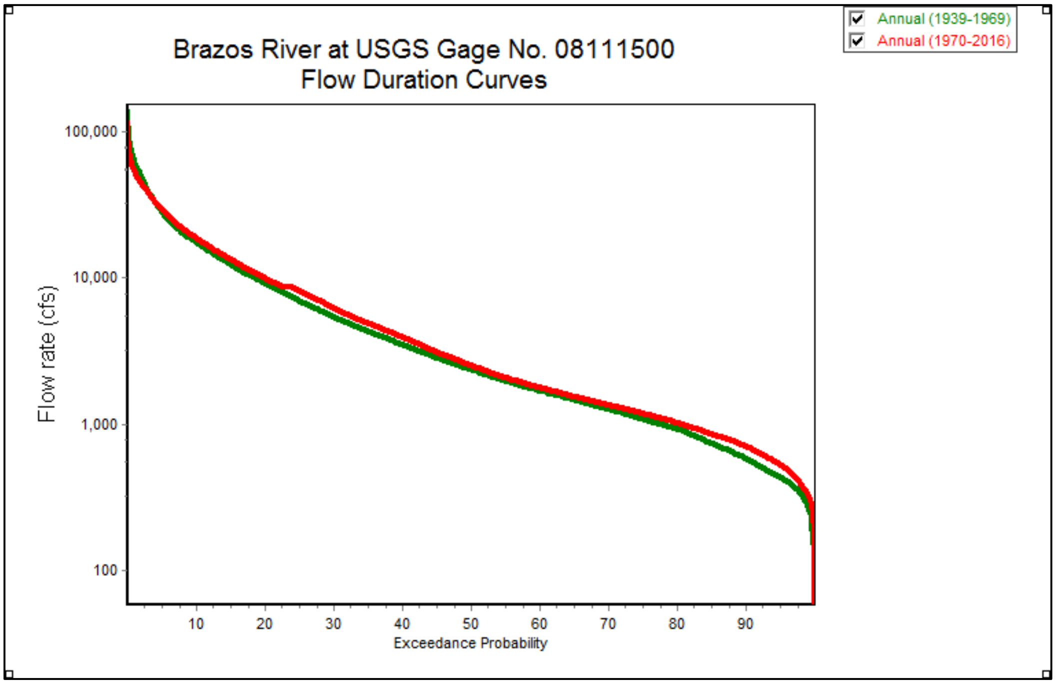


Figure 14 Continued.

q) USGS Gage No. 08111500 Brazos River near Hempstead



r) USGS Gage No. 08114000 Brazos River near Richmond

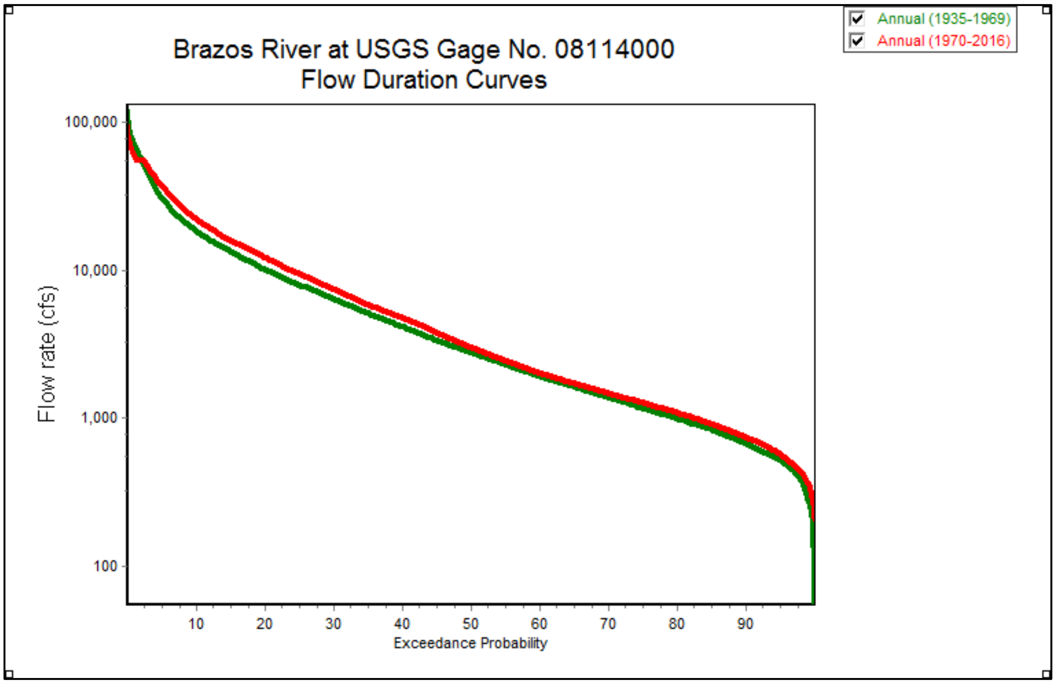


Figure 14 Continued.

s) USGS Gage No. 08116650 Brazos River near Rosharon

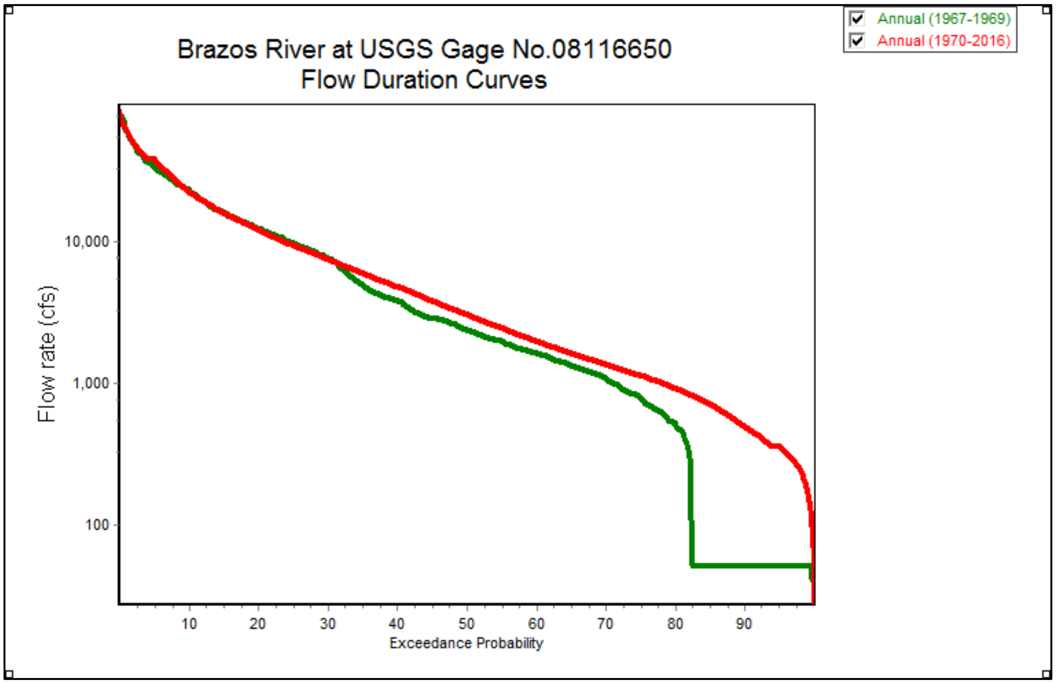


Figure 14 Continued.

Table 12. Frequency Metrics for Observed Daily Flow in the Brazos WAM (Unit: cfs)

WAM ID / Exceedance Probability	DMAS09		SFAS06		BRSE11		CFNU16		CFFG18	
	Pre-Impact	**Post-Impact**	**Pre-Impact**	**Post-Impact**	**Pre-Impact**	**Post-Impact**	**Pre-Impact**	**Post-Impact**	**Pre-Impact**	**Post-Impact**
1%	**6,720**	**7,600**	**2,410**	**1,220**	**7,310**	**2,040**	**2,240**	**826**	**5,000**	**2,320**
2%	**2,680**	**3,570**	**1,160**	**624**	**4,000**	**1,120**	**1,230**	**462**	**2,770**	**1,170**
5%	**705**	**369**	**358**	**245**	**1,570**	**406**	**421**	**204**	**926**	**423**
10%	**229**	**99**	**130**	**107**	**680**	**174**	**120**	**87**	**302**	**174**
15%	**141**	**45**	**79**	**65**	**350**	**89**	**58**	**51**	**140**	**109**
20%	**66**	**31**	**44**	**49**	**200**	**57**	**36**	**35**	**84**	**76**
30%	**23**	**18**	**19**	**23**	**93**	**18**	**21**	**23**	**36**	**45**
40%	**8**	**9**	**10**	**13**	**47**	**3**	**13**	**16**	**20**	**30**
50%	**3**	**5**	**5**	**7**	**28**	**2**	**9**	**12**	**13**	**15**
60%	**1**	**3**	**3**	**4**	**16**	**2**	**7**	**8**	**7**	**6**
70%	**0**	**1**	**1**	**2**	**7**	**1**	**4**	**5**	**3**	**5**
75%	**0**	**1**	**0**	**1**	**4**	**1**	**3**	**3**	**1**	**3**
80%	**0**	**1**	**0**	**0**	**2**	**1**	**2**	**2**	**0**	**3**
85%	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**2**
90%	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**2**
95%	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
98%	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
99%	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	BRSB23		**BRPP27**		**BRGR30**		**NBCL36**		**BRWA41**	
1%	**15,800**	**8,530**	**18,500**	**13,600**	**22,300**	**6,720**	**3,640**	**4,130**	**29,200**	**25,500**
2%	**9,480**	**3,820**	**11,500**	**9,200**	**13,400**	**3,380**	**1,720**	**1,920**	**20,600**	**20,800**
5%	**3,660**	**1,420**	**3,570**	**3,010**	**5,630**	**1,830**	**662**	**770**	**10,300**	**9,520**

Table 12 Continued.

WAM ID Exceedance Probability	**BRSB23**		**BRPP27**		**BRGR30**		**NBCL36**		**BRWA41**	
10%	1,520	628	2,000	1,820	2,960	841	324	357	5,090	5,200
15%	828	360	1,370	1,310	1,840	438	198	251	3,440	3,520
20%	544	225	1,070	936	1,360	201	133	164	3,440	2,560
30%	270	115	630	487	863	53	68	80	1,560	1,550
40%	154	62	362	258	569	13	34	43	1,090	1,070
50%	92	10	215	145	392	7	18	27	792	760
60%	58	5	122	96	275	6	11	18	548	530
70%	35	5	70	67	188	5	6	11	375	336
75%	26	5	51	57	149	5	4	8	284	246
80%	16	4	38	48	111	5	3	6	222	185
85%	9	4	30	39	79	5	2	4	167	136
90%	4	4	20	31	50	5	1	2	113	89
95%	0	3	8	24	22	5	0	1	67	47
98%	0	3	0	18	8	4	0	0	43	26
99%	0	2	0	14	1	4	0	0	29	15
	LEGT47		LEBE49		**LAKE50**		**LRLR53**		**LRCA58**	
1%	3,720	5,150	7200	5360	1,590	1,007	7,000	9,070	17,800	14,500
2%	2,140	3,350	5830	4870	916	1,510	4,440	7,230	12,000	11,200
5%	977	1,690	3300	3830	440	683	3,500	5,630	7,260	8,440
10%	512	1,070	1850	2140	235	328	2,600	3,530	4,480	5,440
15%	354	626	1080	1180	150	186	1,530	2,430	3,080	3,590
20%	222	431	719	688	105	130	1,280	1,500	2,150	2,590
30%	99	224	392	285	58	80	646	754	1,080	1,440
40%	48	98	207	89	40	49	366	417	660	810
50%	24	59	97	43	31	33	189	229	408	486
60%	15	32	44	29	24	25	121	142	252	298
70%	9	18	21	21	19	20	84	105	163	202
75%	6	13	14	17	17	18	69	94	134	167
80%	4	8	10	14	14	16	60	84	96	138
85%	2	4	6	11	13	14	50	74	64	114
90%	1	3	3	8	10	12	50	64	38	93
95%	0	1	0	4	8	10	33	54	21	71
98%	0	0	0	1	6	8	18	46	7	51
99%	0	0	0	0	4	8	14	39	2	38
	YCSO62		**NAEA66**		**BRHE68**		**BRRI70**		**BRRO72**	
1%	4,790	2,300	7,500	8,370	58,300	54,700	67,800	60,000	50,200	65,400
2%	2,860	2,170	4,300	5,050	45,700	45,400	51,700	54,300	41,300	56,000
5%	1,450	1,630	1,870	2,300	26,900	30,700	29,100	38,700	29,200	39,300
10%	692	1,070	796	872	17,000	19,300	17,600	23,100	18,300	26,600
15%	305	908	351	335	12,400	13,500	12,900	16,400	13,400	18,400
20%	141	540	184	150	9,440	9,780	9,890	12,700	10,400	13,800
30%	51	93	84	65	5,600	6,040	6,300	7,540	6,790	8,140
40%	27	6	44	45	3,610	3,810	4,140	4,750	4,310	5,060
50%	12	3	23	30	2,440	2,430	2,770	2,990	2,820	3,100
60%	4	2	12	21	1,740	1,720	1,900	2,010	1,860	1,990
70%	1	1	6	15	1,300	1,310	1,380	1,480	1,290	1,360
75%	0	1	5	13	1,120	1,150	1,160	1,280	1,090	1,120
80%	0	0	3	11	955	990	991	1,090	870	903
85%	0	0	2	9	790	827	845	908	657	695
90%	0	0	1	7	621	674	686	732	420	485
95%	0	0	0	3	449	505	530	554	268	342
98%	0	0	0	1	354	369	395	424	50	244
99%	0	0	0	1	288	318	303	359	50	182

Table 12 organizes the frequency metrics of observed daily mean flows at 20 control points in the Brazos River Basin. The metrics are generated using the duration analysis tool in the IHA software. The table contains exceedance probabilities and their correlated observed daily mean flow rates in cubic feet per second. The frequency statistics of Pre-Impact and Post-Impact period-of-records are listed individually. Amongst the 20 control points, 19 control points with SB3 are indicated in bold.

5.4 Discussion of Analysis Results

In this thesis, the selections of control points in the Trinity and Brazos River Basins are intended to cover each river basin in a reasonable manner. 13 gauges were selected to represent the hydrologic conditions in the Trinity River Basin, and 20 gauges have been chosen to display the hydrologic circumstances in the Brazos River Basin. Among selected control points, four control points in the Trinity WAM and 13 control points in the Brazos WAM have adopted SB3. The time periods of the USGS daily surface flow records range from 90 years to 50 years for 33 selected control points. In this thesis, selected IHA parameters and flow duration analysis have been applied to the daily observed flows at certain control points in both Trinity and Brazos River Basins.

Under the analysis of the Trinity River Basin, Figure 9 shows the 7-day minimum flow rates in the Trinity WAM. Under this comparison, 25th percentile,50th percentile, and 75th percentile have been considered as guidelines. In Figure 9 all indicators indicate clear increasing trends of daily streamflows rates over time.

Figure 10 shows the 7-day maximum flow rates at four control points in the Trinity WAM. The same as Figure 9, 25th, 50th, and 75th percentiles are used to evaluate the variations of gauge flows. The medians (50th percentile) of daily observed flow rates at four gage stations are sharing an increasing propensity, whereas, the changes in 25th and 75th percentiles vary from site to site.

Figure 11 shows the flow duration curves at four control points to which SB3 have been applied in the Trinity WAM. In Figure 12, green lines represent the flows of Pre-Impact period while the red lines represent flows during the Post-Impact period. Duration analysis reveals the alterations of annual daily historical flows. At control points 8WGTP, 8TRDA, and 8TROA, flow rates of Post-Impact periods have provided a clear increasing trend. At control point 8TRRO, the changes in flow rates of two periods are rather subtle.

Table 11 tabulates the frequency of metrics of 13 selected control points in the Trinity WAM. It has the selected frequencies and their related flow rates generated by the IHA program. They have confirmed the graphical results presented in Figure 12 and showed increasing flow rates at the majority of the control points in the Trinity River Basin. In the IHA software, the statistic results of duration analysis will be automatically generated every time the user runs the project. In the IHA software, there is no function designated to generate frequency metrics of seasonal flows. In this thesis, after running the analysis at one control point, frequency metric of each month will be generated and tabulated in the spread sheet. The frequency metric of each month begins from 0.1%, and ends at 99.99%. The increment of the flow duration analysis is not linear. With that being said, the selection of frequency must be accomplished manually, and the frequency may or may not be integer. If users are looking forward to generating frequency metrics for multiple WAMs using the IHA software, a lot of manual work have to be done. This work is fairly time-consuming and repetitive.

Under the analysis of the Brazos River Basin, the 7-day minimum and 7-day maximum flow rates are displayed in Figure 13 and 14. The 7-day minimum flow of Brazos River at Waco has decreased taking 25th, 50th, and 75th percentiles into consideration. At the control point near

Cameron, 25th and 50th percentiles of flow rates have slightly increased, while the 75th flow rate remains the same. The 7-day minimum flows of Brazos River near Hempstead and Richmond have essentially stayed the same. The changes in 7-day maximum of four selected control points in the Brazos River Basin are displayed on the Figure 13. USGS gage at Waco and Cameron present a relatively clear descending tendency, meanwhile, at control points near Hempstead and Richmond, 7-day maximum have stayed steady concerning 25th and median flow rates. At the same time the 75th percentile of flow rates has decreased in all control points.

Figure 14 provides the flow duration curves of 19 control points in the Brazos WAM. Table 12 presented above shows the numerical comparison between two period-of-records of observed daily mean flows associated with exceedance probabilities in the Brazos WAM. At four control points (8BRWA41, LRCA58, BRHE68, and BRRI70) flow duration curves have basically reamined the same druing the Pre-Impact and Post-Impact periods. Also, at some control points the changes are subtle but noticeable. While, at some control points, we can tell variations of two time-periods.

Different types of factors can impact the flow conditions and explain the changes in the daily observed flow rates. The population, which depends on the rivers and their tributaries, is one of the major influences. Dallas Fort-Worth area has 6.7 million people back in 2010, and the metropolitan area has not stopped growing. Brazos River Basin had approximately 2.4 million in 2010, which is about one-third of the population in Dallas Fort-Worth area. The population that depends on the water supply from Brazos River and its tributaries is considerably smaller than the population that is depending on the Trinity River Basin and its tributaries.

Considering the massive amount of water-users in the Trinity River Basin, water demands associated with population growth are expected to be increasing. Consequently, the flow rates of Trinity River and its tributary are supposed to decrease. However, according to the graphical and numerical results displayed previously, instead of witnessing decreasing trends of observed daily flow rates, at 11 control points, daily ovserved flow rates have increased over time, and at the rest of control points, flow rates have essentially remained the same. Different from the changes of gauged daily flows in the Trinity River Basin, the observed flows rates in Brazos River Basin have presented diversity of flow alterations at 20 selected control points during long period-of-records. Brazos River Basin has experienced a situation where observed surface water flow rates at certain control points have declined dramatically, while at some gaging stations, flow rates have essentially remained the same, and at the remaining sites, surface water flow rates increased during the long-term records.

Duration curves provide useful information for interpreting the alteration of annual average flow rates. Based on the observation of the graphical and tabular results given above, we are able to compare the changes among flow components at a certain control point, among multiple control points, and between the Trinity and the Brazos River Basin. Meanwhile, if observing daily surface flow in different ways, more flow characteristics could be revealed. IHA provides 33 IHA and 34 EFC parameters for users to choose from, depending on different purposes of investigations.

CHAPTER VI

ANALYSES OF WAM NATURALIZED AND REGULATED FLOWS

6.1 Modeling and Analysis Methodology

Present efforts in expanding the WRAP/WAM system are focusing on incorporating environmental flow standards (Wurbs and Zhang 2014). The modeling system has also provided the opportunity to perform the research presented in this thesis. Monthly WRAP modeling features applied in the studies reported in this thesis are documented by Wurbs (2009; 2013; 2008). Recently developed daily modeling capabilities designed for evaluating environmental flow standards are documented by Wurbs and Hoffpauir (2012; 2013b). Wurbs (2011) reviews the literature of modeling river and reservoir system management and compares WRAP with other similar modeling systems (Wurbs and Zhang 2014).

In the WAM, naturalized flows were developed by adjusting observed flows to eliminate the impact of human activities, based on the equation below.

Naturalized Flow=Historical Gaged Flow + Upstream Diversions – Upstream Return Flows+ Changes in Upstream Reservoir Storage + Upstream Reservoir Evaporation

The missing data were estimated by using the nearby gaging stations' historical data, and the methods are double mass curves, scatter plots and linear regression equations.

As to upstream diversions, WAM uses mixed methods for municipal, industrial, and agricultural water rights. The Texas Natural Resource Conservation Commission (TDRCC) provides the water use records of municipal water right, and those records were used to determine historical diversions. When encountering data gaps, water right holders were contacted individually, or estimations on a per capita basis were made based on population data. Industrial and agricultural related historical diversions were estimated by using historical water use patterns. If proper estimates cannot be made according to limited information, historical water use was set to be zero (Wurbs 2009).

According to the data provided by TNRCC, historical return flows data was available from1978 to 1996 only for municipal and industrial users. Records for the rest of the years were determined by collecting information from individual water users (Wurbs 2009).

Change in reservoir storage were decided using USGS data, alternative sources, or estimates of storage content changes (Wurbs 2009).

Reservoir evaporation=Net evaporation rate ×Average reservoir surface area

Net evaporation rate=Evaporation-Precipitation

Values of evaporation and precipitation for each reservoir were computed using the sum of weighted values from adjacent TWDB quadrangles.

Because of evaporation and seepage in stream channels, the adjustment of flows become rather difficult. Thus, modeling the downstream flows connected with the above circumstances can be somewhat rough (Wurbs 2009).

The WAM regulated flows conceptually should be representative of gaged flows during the years modeled by the Current Use Scenario root.*DAT* file, in other words, currently adopted environmental instream flow regulations and laws will be indicated by regulated flows (Wurbs 2009). Regulated flows represent the actual physical streamflow at a control point location after accounting for all of the water rights. Given all of the water right requirements and other premises reflected in the model, the regulated flows are the streamflow volumes in each computational time step that would be measured by a gaging station at the control point location.

In this thesis, WRAP is used with the assistance of HEC-DSSVue. HEC-DSSVue is capable of analyzing and quantifying river regimes. In this chapter, several basic capabilities of

HEC-DSSVue that are relevant to WRAP applications will be put into use, and they are listed as following.

- Importing observed stream flow data directly from USGS National Information System (NWIS) website to a root.*DSS* file.
- Time functions include (1) changing time intervals, (2) finding average values for specified time intervals.
- Statistical analyses, particularly duration analyses and duration curve plots using the Weibull plotting positions, percent of the time the value is equaled or exceeded.

$$E = 100 \times [M/(n+1)]$$

M = the rank position of the value

n = number of values.

- Tabular display, comparison, and editing of the time series data using either HEC-DSSVue tables or Microsoft Excel worksheets.

In this thesis, HEC-DSSVue is used to store and process the daily historical data. The relations between the WRAP/WAM and HEC-DSSVue have made it easier for users to make further calculations and conversions after simulating the naturalized and regulated flows via the WRAP. After running the Trinity WAM and the Brazos WAMs, the root.*DSS* files can be generated based on users' demands. Afterwards, the HEC-DSSVue will be used to open the root.*DSS* file. In the HEC-DSSVue, selected flow data can be tabulated either in HEC-DSSVue or MS Excel. IHA needs the daily hydrologic data to follow a generic two column format, where the first column contains the date and the second contains the flow value. However, the columns generated by the HEC-DSSVue are not fully satisfy the file formats required by the IHA software. Based on the format requirements in the IHA program, all naturalized and regulated flow data needs to be edited before imported into the IHA. In this thesis, the naturalized and regulated flows are imported separately for each of the four control points in the Trinity WAM and 19 control points in the Brazos WAM. According to the characteristics of the naturalized and regulated flows, the daily step naturalized flow is viewed as Pre-Impact period condition, while the regulated flow represents the Post-Impact scenario. The periods of records of these two types of flows are the same, which is from the year 1940 to the year 2015. After editing the formats of root.*DSS* files, every control point has one hydrologic data file for daily step naturalized flows and one for daily step regulated flows. This thesis analyzes both types of the dataset under one analysis project at each control point to quantify the alterations of flow charateristics over time.

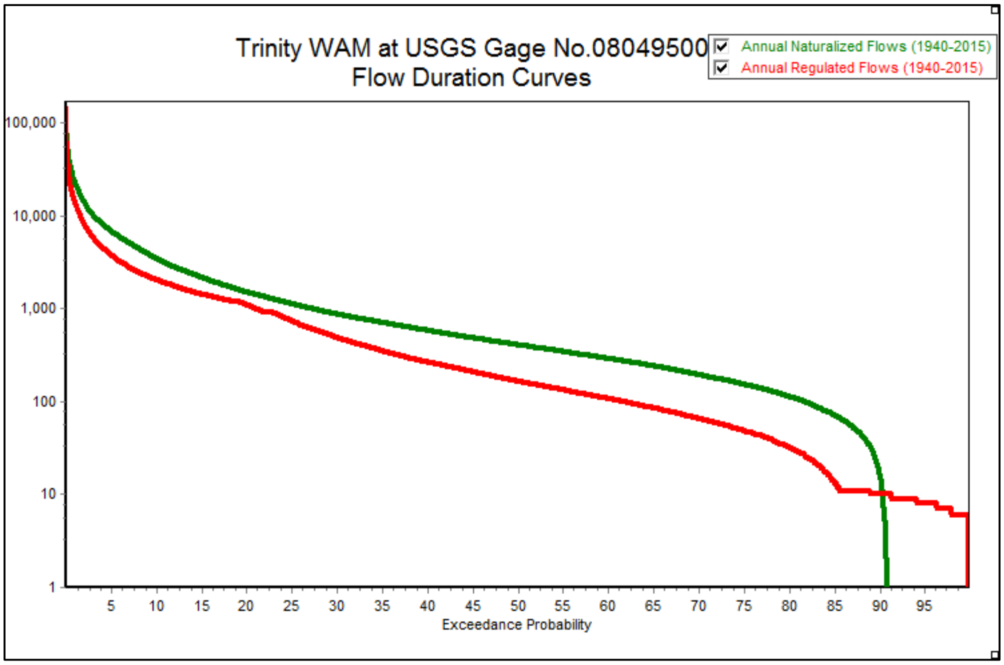
6.2 Results for Sites on the Trinity River and Its Tributaries

Figure 15 (a)-(d) display the flow duration curves of annul naturalized and regulated flows at each control points to which SB3 has been applied in the Trinity WAM. The green lines represent the annual naturalized flows, and the red lines represent the annual regulated flows. The unit of flow rates is cubic feet per second.

Figure 16 (a)-(d) present the monthly differences between the naturalized and regulated flows. The green lines represent the naturalized flows; the red lines are displaying the regulated flows. The comparison between two types of flows is conducted under the default setting. The beginning month of the analyzing year is October.

Table 13 presents the frequency metrics for annual naturalized and regulated flows in 13 selected control points in the Trinity WAM. The metrics are generated in the HEC-DSSVue using the duration analysis function which will be further discussed in the following chapters. The frequency metrics are listed separately for naturalized and regulated flows at each selected control points. Among the 13 selected control points, four gage stations, to which the SB3 has been applied, have been indicated in bold.

a) West Fork Trinity River at Grand Prairie



b) Trinity River at Dallas

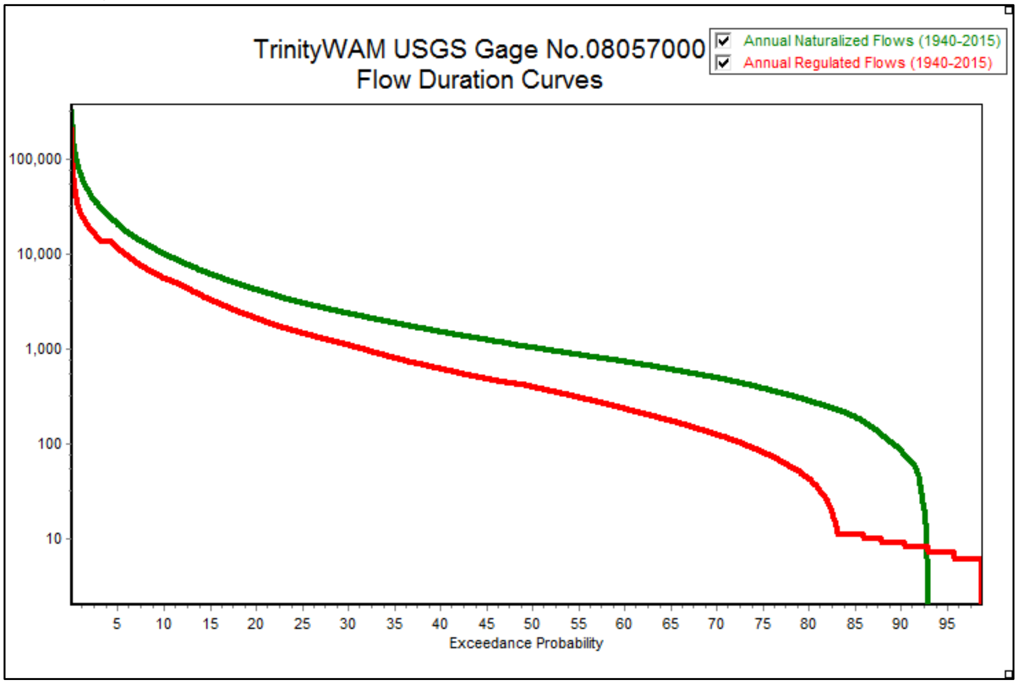
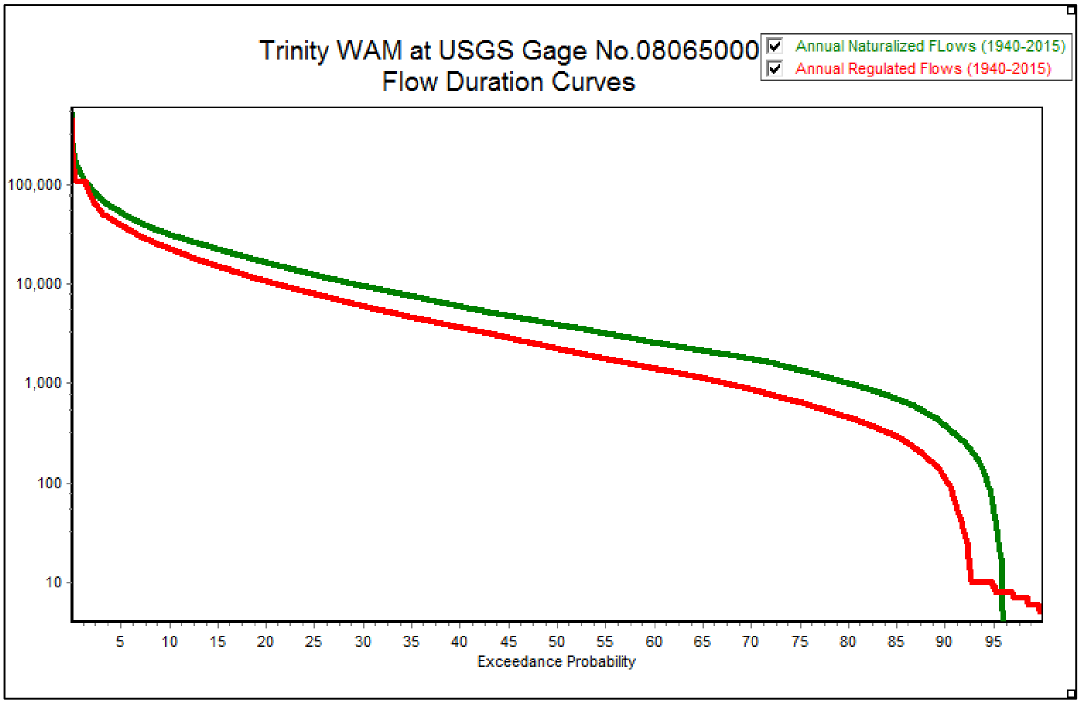


Figure 15. Flow Duration Curves for Naturalized and Regulated Flows at Four Control Points in the Trinity WAM.

c) Trinity River near Oakwood



d) Trinity River at Romayor

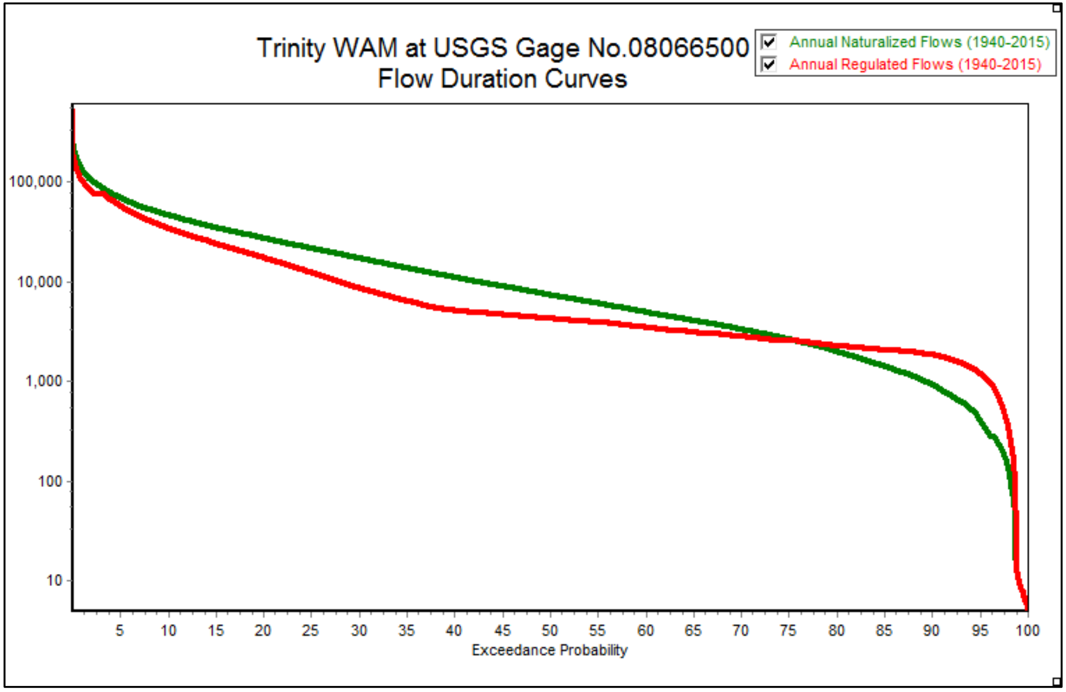
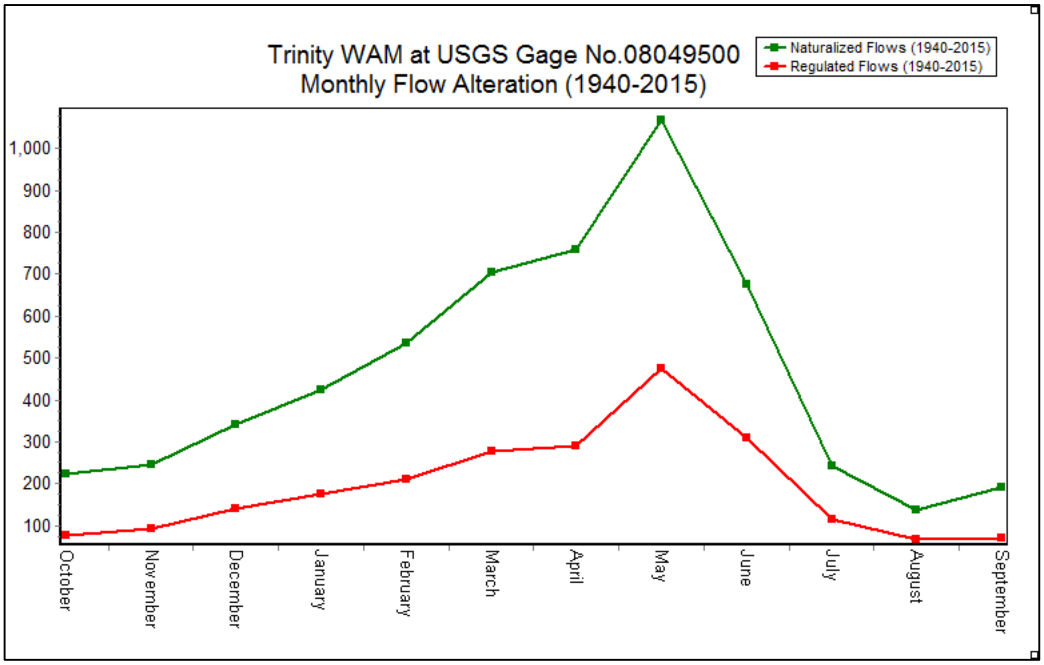


Figure 15 Continued.

a) West Fork at Grand Praire



b) Trinity River at Dallas

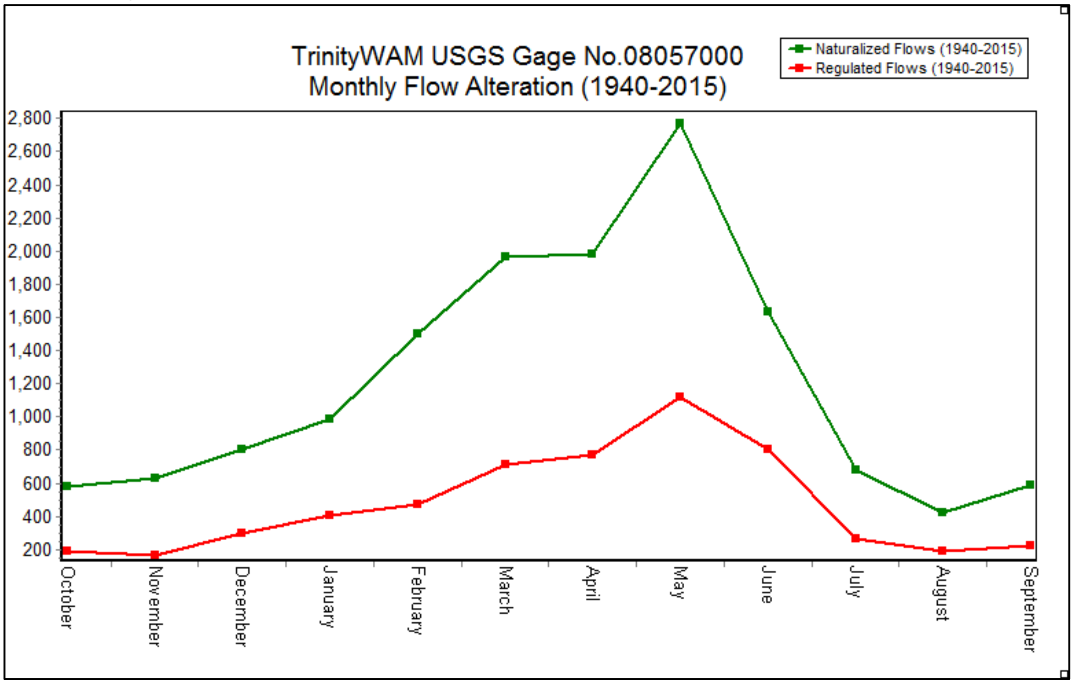
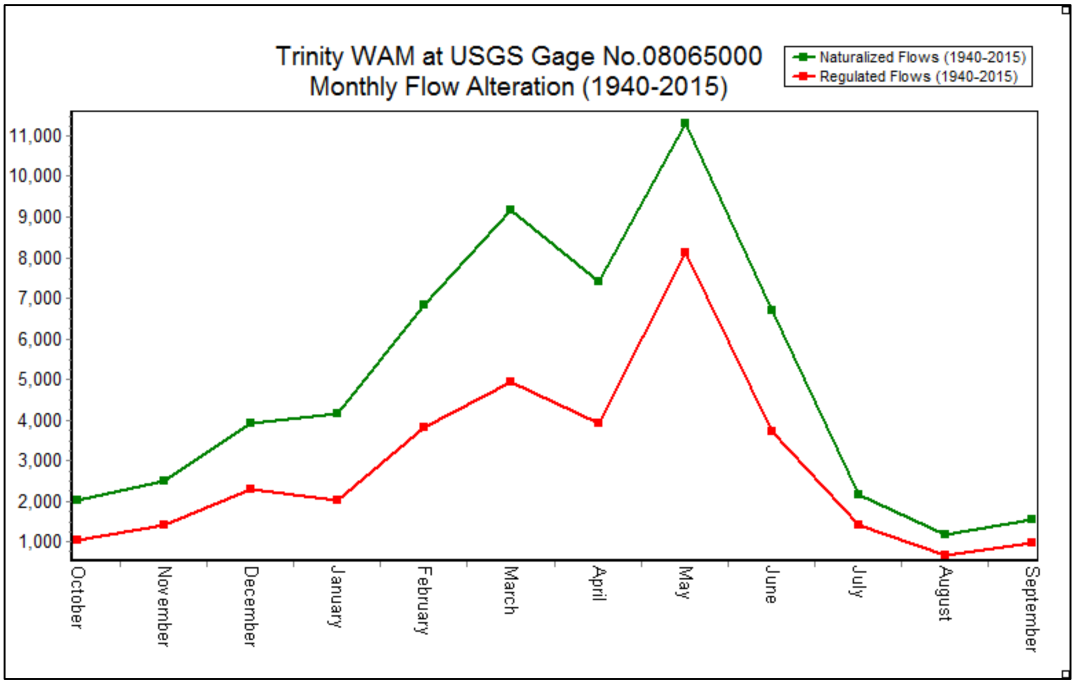


Figure 16. Monthly Flow Alterations of Naturalized and Regulated Flows at Four Control Points in the Trinity WAM.

c) Trinity River near Oakwood



d) Trinity River at Romayor

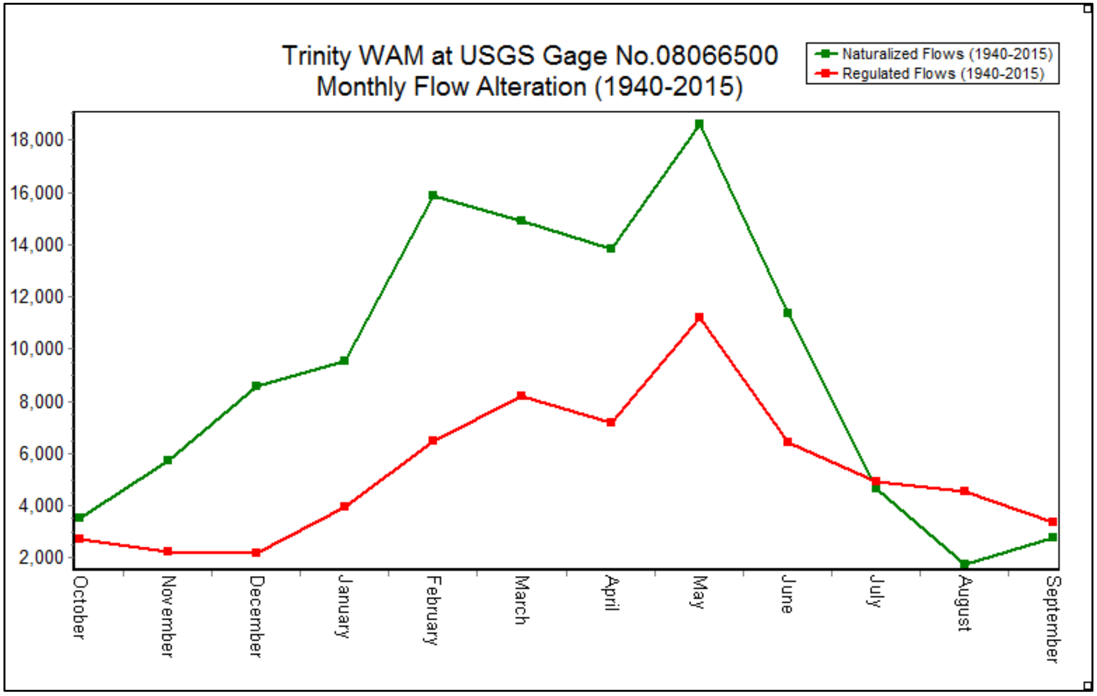


Figure 16 Continued.

Table 13. Frequency of Naturalized and Regulated Flows in the Trinity WAM (Unit: ac-ft/day**)**

WAM ID Exceedance Probability	8BSBR		8WTBO		8CTBE		8CTFW		8WTGP	
	NAT	REG	NAT	REG	NAT	REG	NAT	REG	NAT	REG
0.1%	13343	11151	34017	27381	18771	8018	22909	12279	62301	51339
0.5%	5336	4705	15852	11910	6541	2270	7948	3686	29599	20440
1.0%	3119	2861	10277	7598	3723	1420	4587	2104	18529	13457
2.0%	1596	1410	6311	4733	2121	1201	2796	1190	9985	7917
5.0%	494	450	2741	2034	872	1143	1218	1190	5080	3731
10.0%	179	164	1128	864	412	749	604	1190	2483	2020
15.0%	95	87	616	502	254	204	387	514	1512	1416
20.0%	60	56	407	336	177	100	274	248	1066	1095
30.0%	30	29	216	184	90	44	153	108	611	453
40.0%	17	16	128	109	50	23	88	61	402	254
50.0%	7	7	82	68	28	14	51	38	286	160
60.0%	2	2	50	39	12	11	31	26	201	104
70.0%	0	0	26	20	4	9	16	17	129	63
80.0%	0	0	7	3	0	8	5	11	66	31
85.0%	0	0	0	0	0	7	1	10	31	12
90.0%	0	0	0	0	0	6	0	8	0	10
95.0%	0	0	0	0	0	3	0	7	0	8
98.0%	0	0	0	0	0	2	0	6	0	6
99.0%	0	0	0	0	0	0	0	0	0	6
99.5%	0	0	0	0	0	0	0	0	0	6
99.9%	0	0	0	0	0	0	0	0	0	2
	8CLSA		8ELLE		8DNJU		8TRDA		8ETCR	
0.1%	13636	13636	110636	13849	16065	16065	181468	74405	64249	27895
0.5%	5696	5696	46821	6118	6986	6946	97980	36291	35608	15868
1.0%	3809	3809	28633	3541	4443	4400	67837	24737	25298	13181
2.0%	2321	2321	17242	1608	2281	2281	42558	17476	17132	10106
5.0%	813	813	7162	439	776	774	21002	9241	9295	5705
10.0%	307	307	3057	93	307	307	10163	4956	4663	3243
15.0%	179	179	1717	24	180	180	6217	2960	2921	2313
20.0%	121	121	1046	0	119	119	4224	1912	2019	1612
30.0%	65	65	491	0	63	63	2359	1022	1151	618
40.0%	36	36	267	0	38	38	1507	585	718	294
50.0%	22	22	138	0	22	22	1031	378	463	106
60.0%	12	12	62	0	12	12	732	224	269	29
70.0%	4	4	8	0	3	3	495	119	113	0
80.0%	0	0	0	0	0	0	286	40	21	0
85.0%	0	0	0	0	0	0	195	11	1	0
90.0%	0	0	0	0	0	0	90	9	0	0
95.0%	0	0	0	0	0	0	0	7	0	0
98.0%	0	0	0	0	0	0	0	6	0	0
99.0%	0	0	0	0	0	0	0	0	0	0
99.5%	0	0	0	0	0	0	0	0	0	0
99.9%	0	0	0	0	0	0	0	0	0	0

	8TRRS		8TROA		8TRRO	
0.1%	227563	104594	245527	165495	227662	171390
0.5%	123088	57468	158549	92003	172226	125048
1.0%	92272	39037	125418	69833	136768	99967
2.0%	62393	28941	91541	49277	105817	77642
10.0%	17627	10684	31782	20354	47360	31649
15.0%	11468	7284	22422	13830	35368	22389
20.0%	8098	5109	16429	9929	27671	16233
30.0%	4614	2777	9480	5654	17461	8159
40.0%	2970	1638	5928	3476	11207	5070
50.0%	1985	1012	3880	2137	7462	4230

Table 13 Continued.

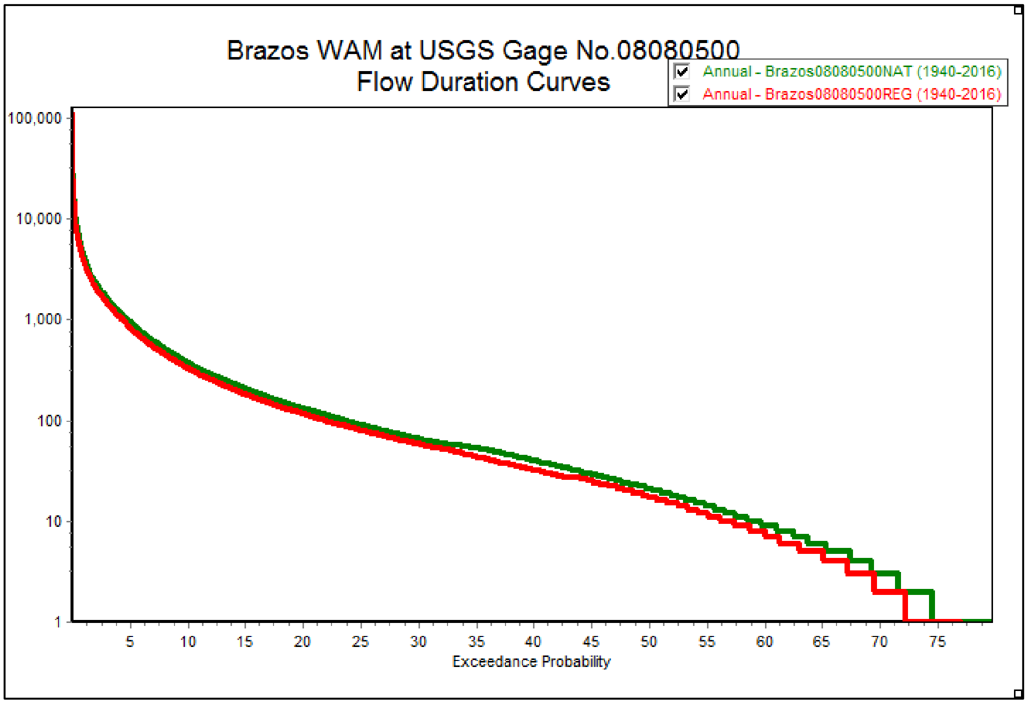
WAM ID Exceedance Probability	8TRRS		8TROA		8TRRO	
60.0%	1382	588	2581	1369	5042	3452
70.0%	882	325	1773	842	3384	2804
80.0%	460	141	1013	444	2037	2283
85.0%	303	57	711	282	1460	2081
90.0%	143	10	398	104	957	1856
95.0%	0	7	83	9	452	1187
98.0%	0	6	0	7	128	317
99.0%	0	6	0	6	0	10
99.5%	0	6	0	6	0	7
99.9%	0	6	0	5	0	6

6.3 Results for Sites on the Brazos River and Its Tributaries

Figure 17 (a)-(s) show the duration curves of annual naturalized and regulated flows in 19 control points in the Brazos WAM. The green lines are naturalized flows, and the red lines are regulated flows.

Figure 18 (a)-(s) present the monthly alterations in the naturalized and regulated flows at the selected control points. The selection of control points is based on the location. The first two USGS gage stations 08080500 and 08082000 are located in the upper basin. While the USGS gage stations 08089000 and 08091000 represent the middle Brazos River Basin. In addition, the last two gage stations 08106500 and 08116650 present the lower basin. The green lines represent the simulated naturalized flows; the red lines are displaying the regulated flows. The comparison between two types of flows is conducted under the default setting. The beginning month of the year is October.

a) Double Mountain Fork near Aspermont



b) Salt Fork Brazos River near Aspermont

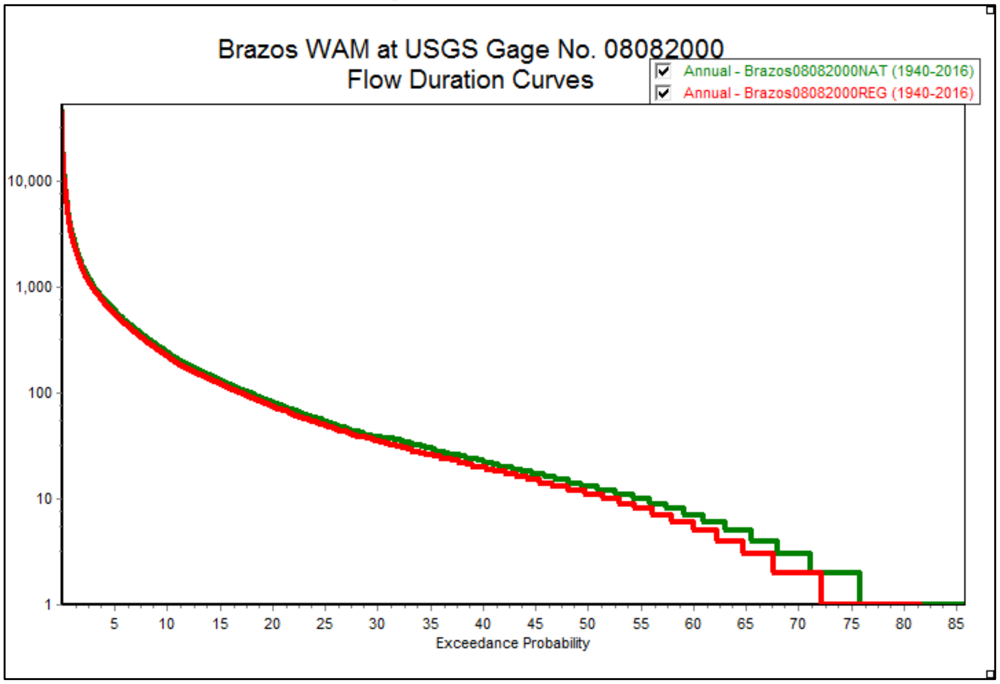
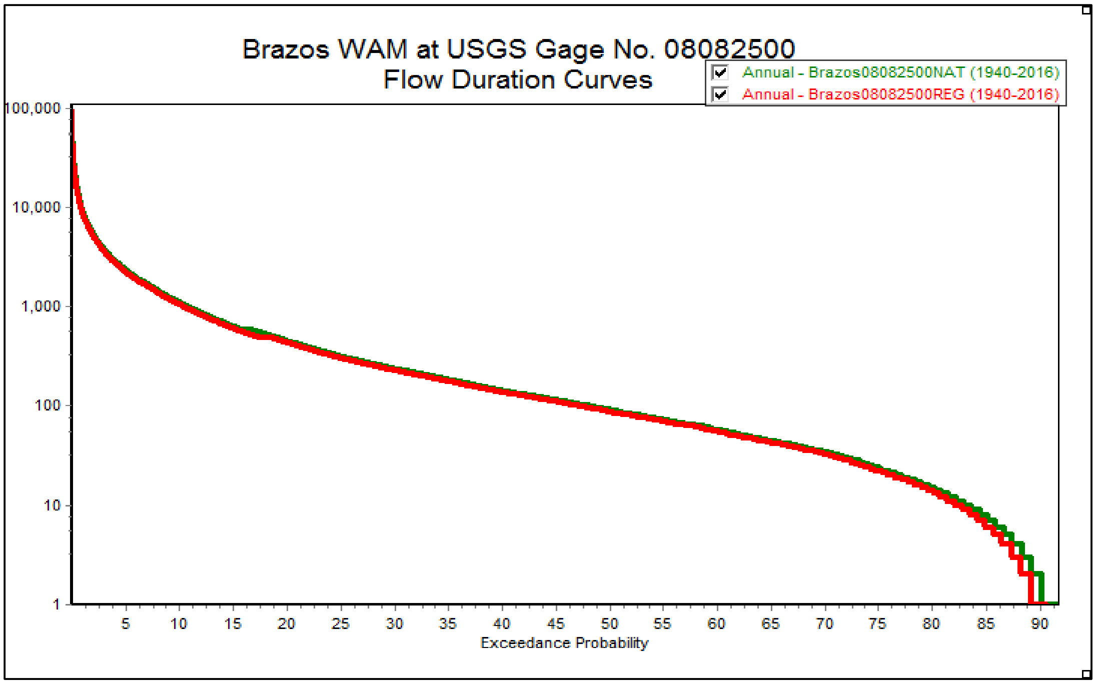


Figure 17. Flow Duration Curves for Naturalized and Regulated Flows in the Brazos WAM

c) Brazos River near Seymour



d) Clear Fork Brazos near Nugent

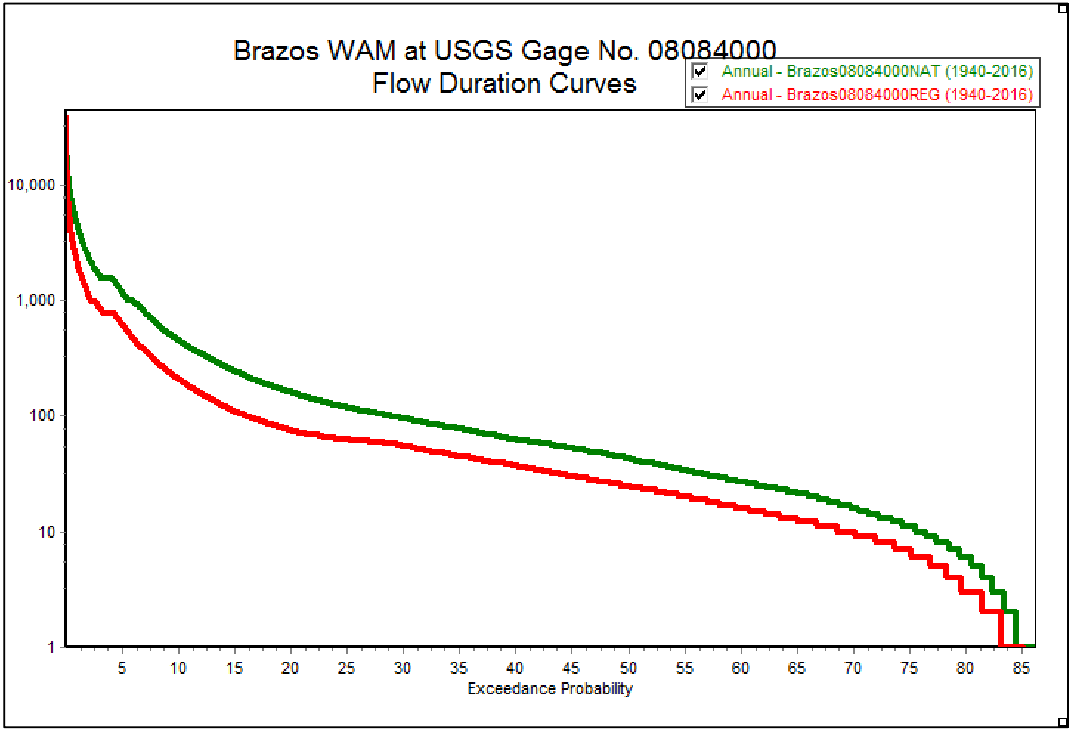
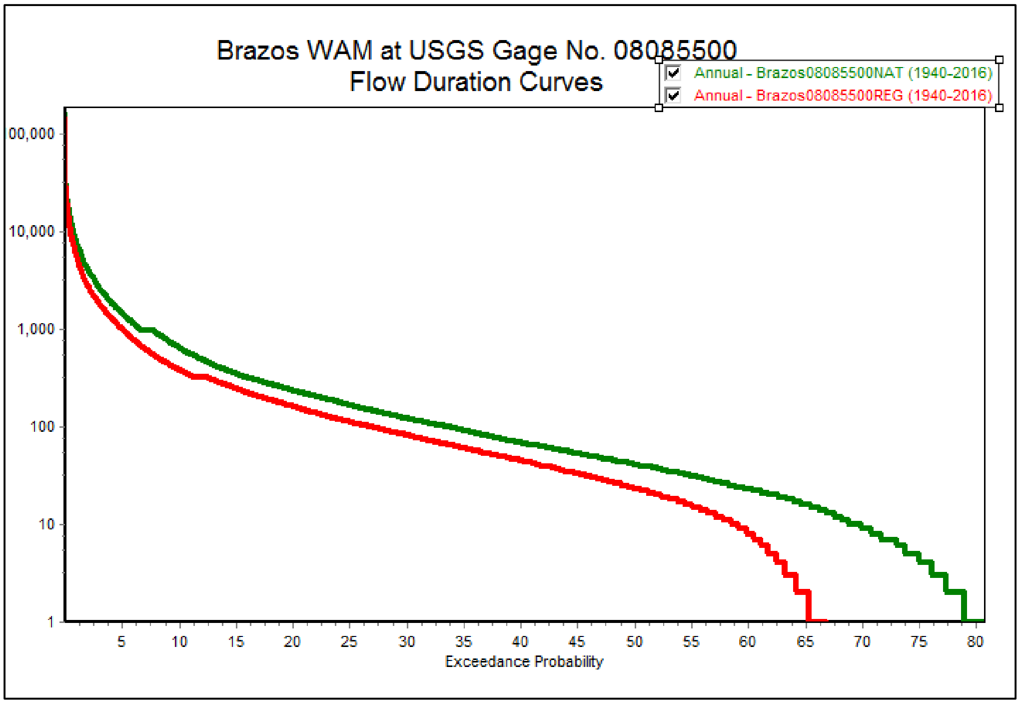


Figure 17 Continued.

e) Clear Fork Brazos near Fort Griffin



f) Brazos River near South Bend

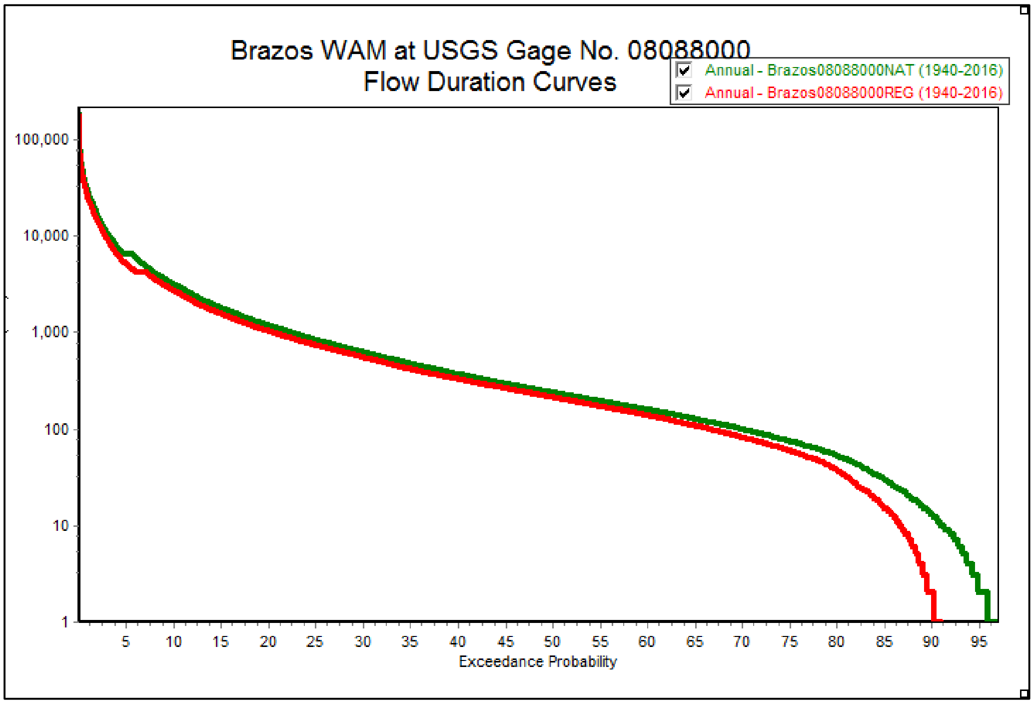
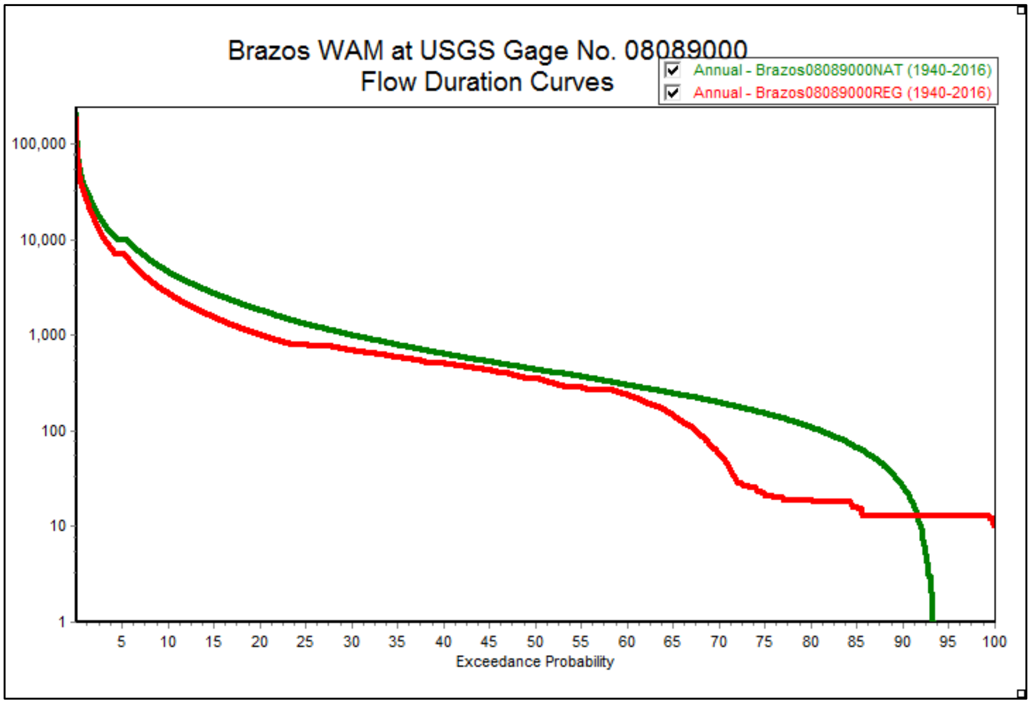


Figure 17 Continued.

g) Brazos River near Palo Pinto



h) Brazos River near Glen Rose

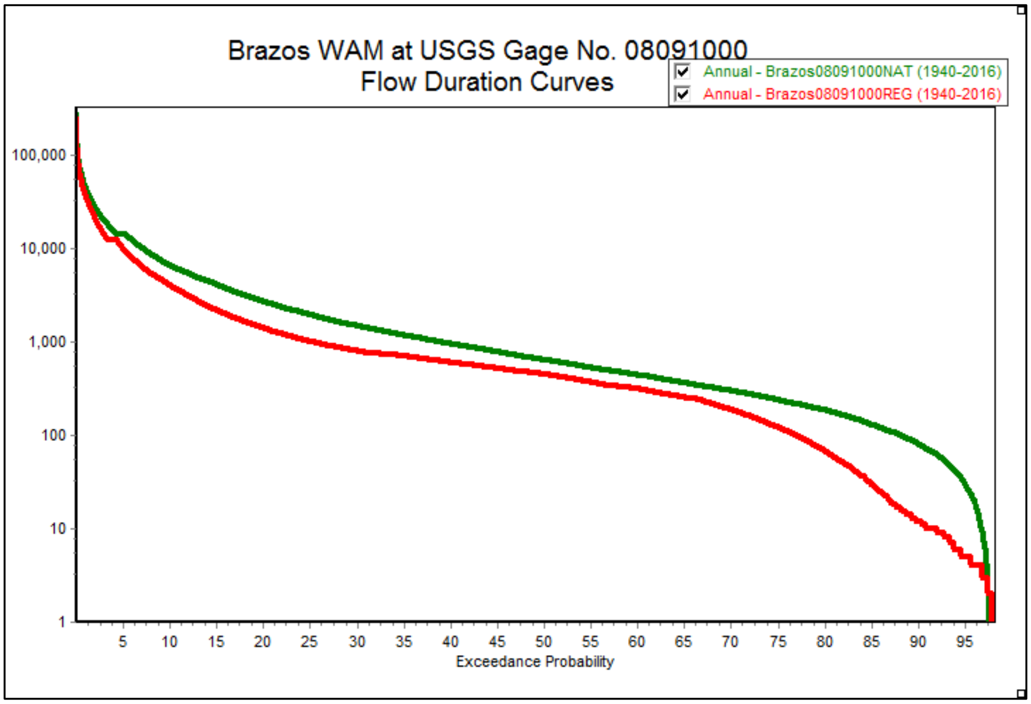
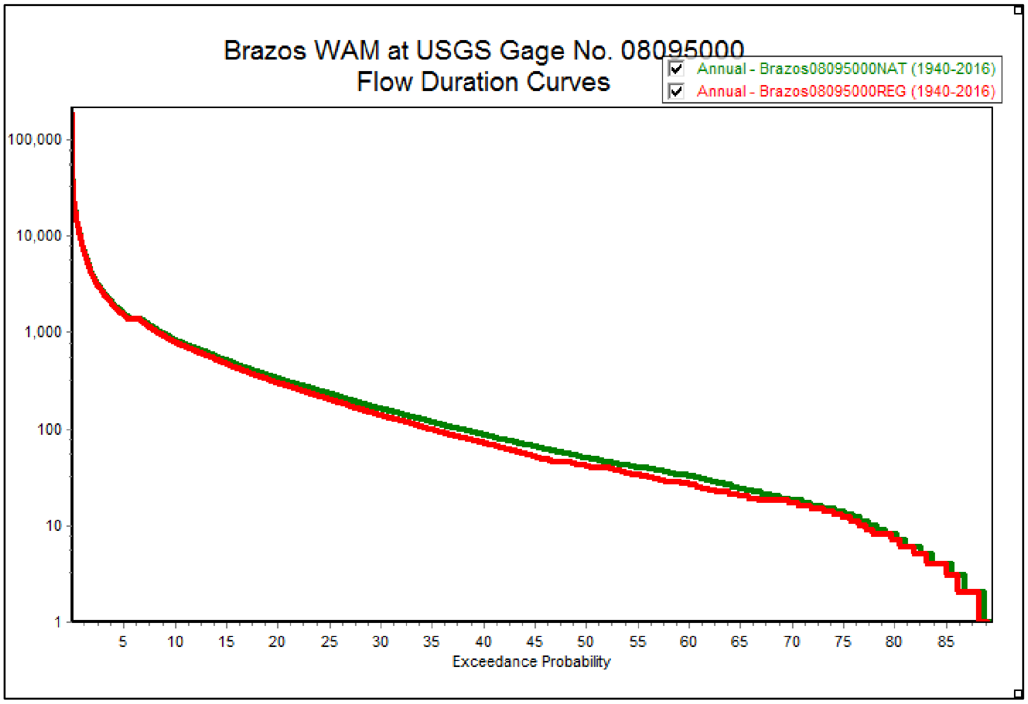


Figure 17 Continued.

i) North Bosque River near Clifton



j) Brazos River at Waco

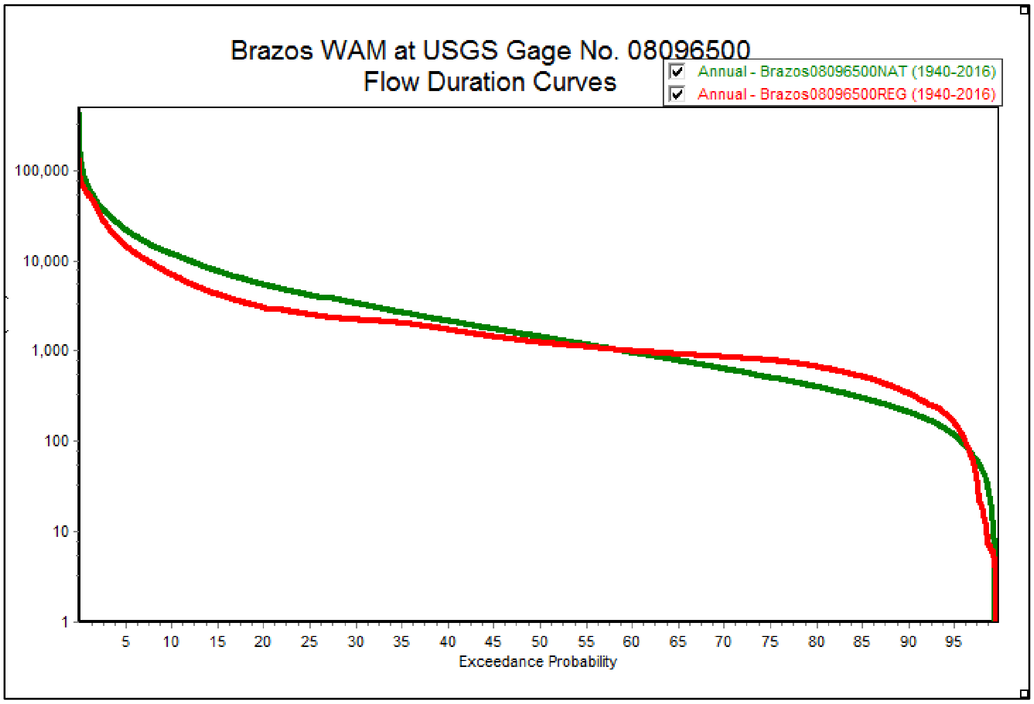
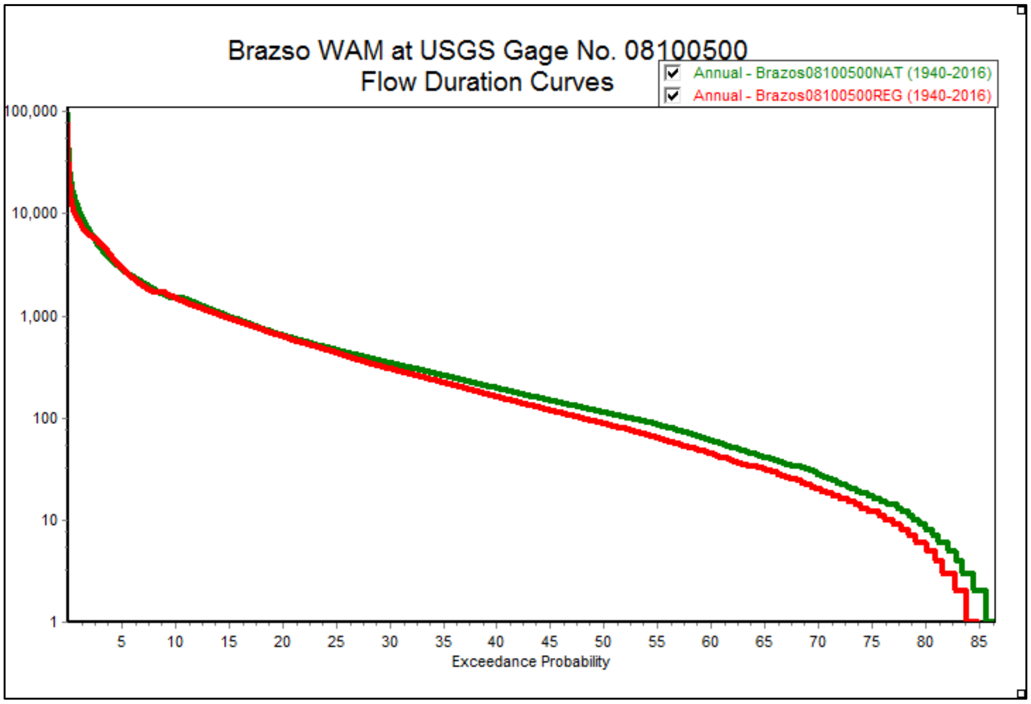


Figure 17 Continued.

k) Leon River near Gatesville



l) Lampasas River near Kempner

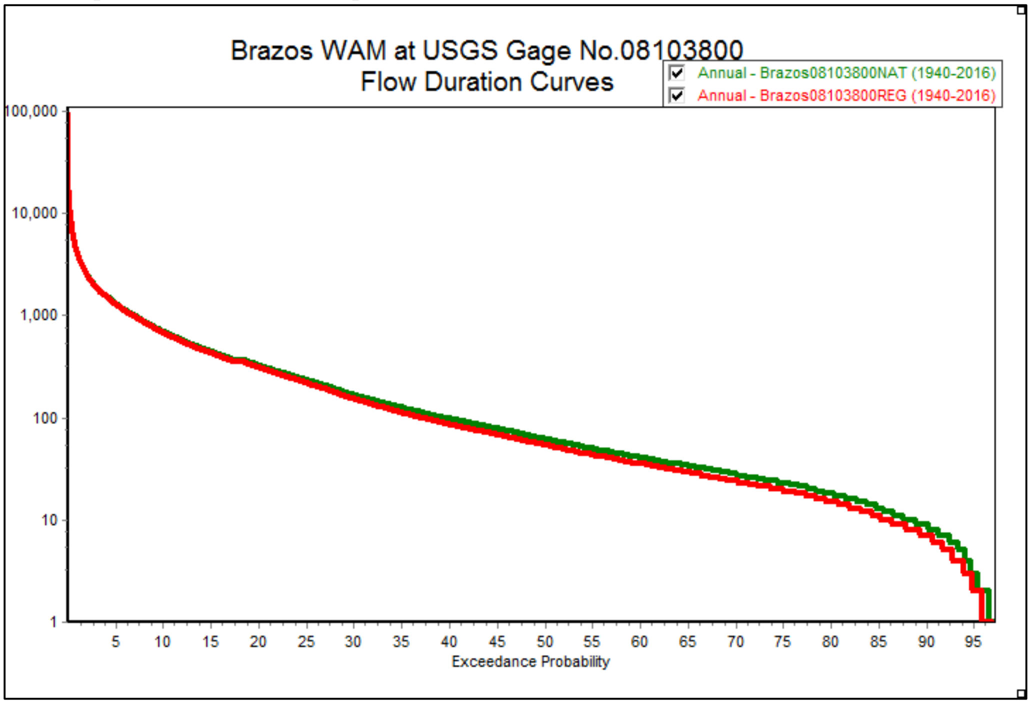
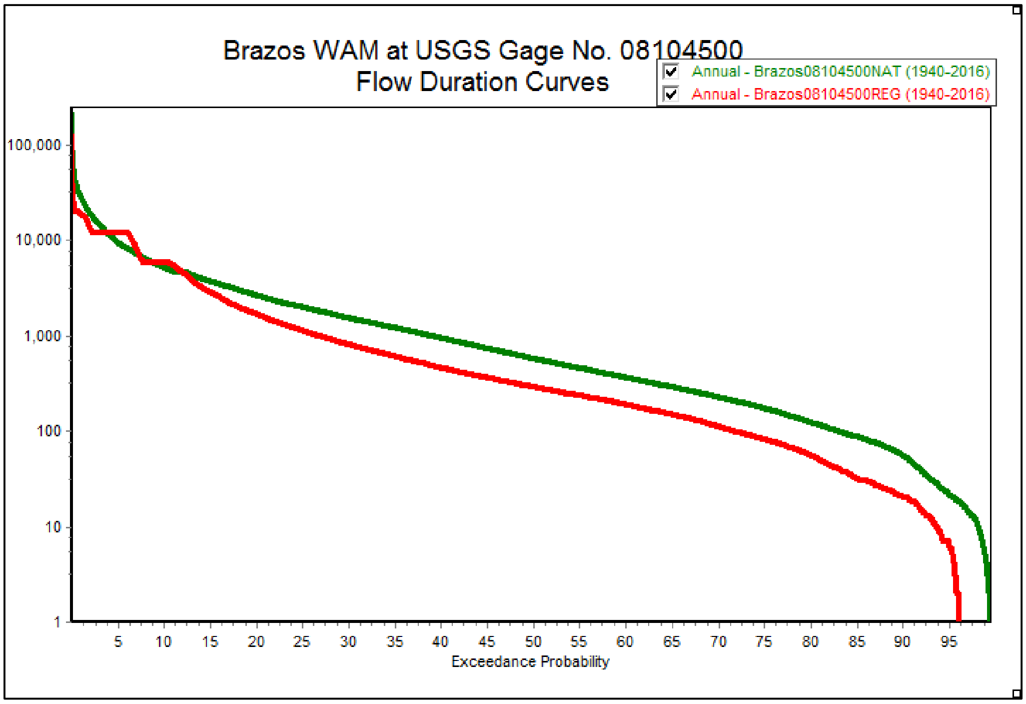


Figure 17 Continued.

m) Little River near Little River



n) Little River near Cameron

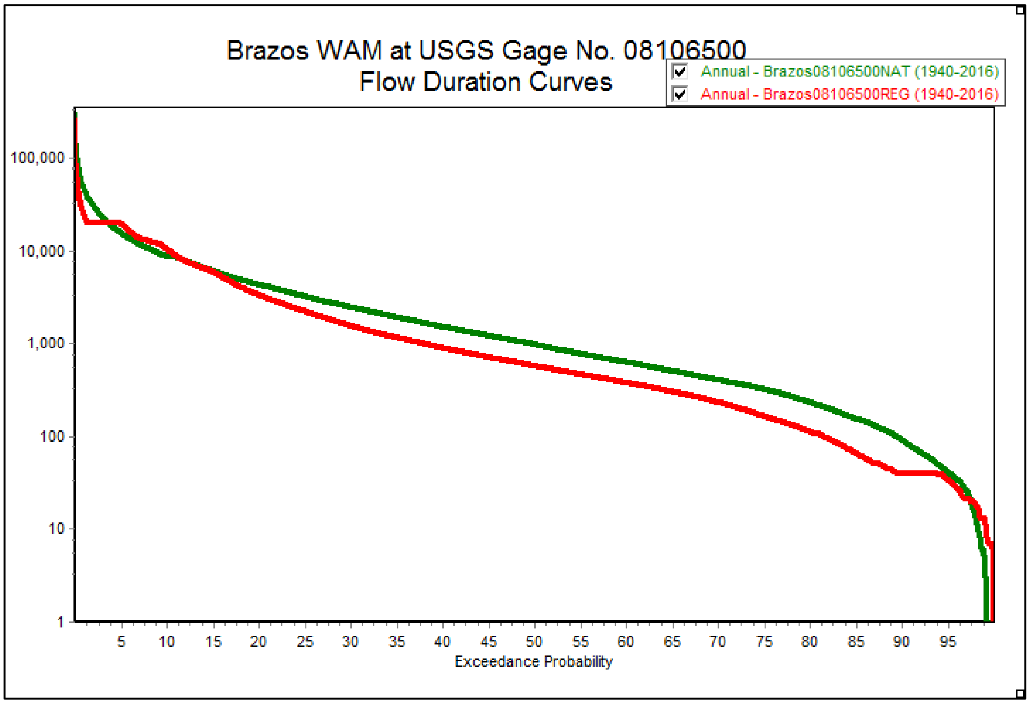
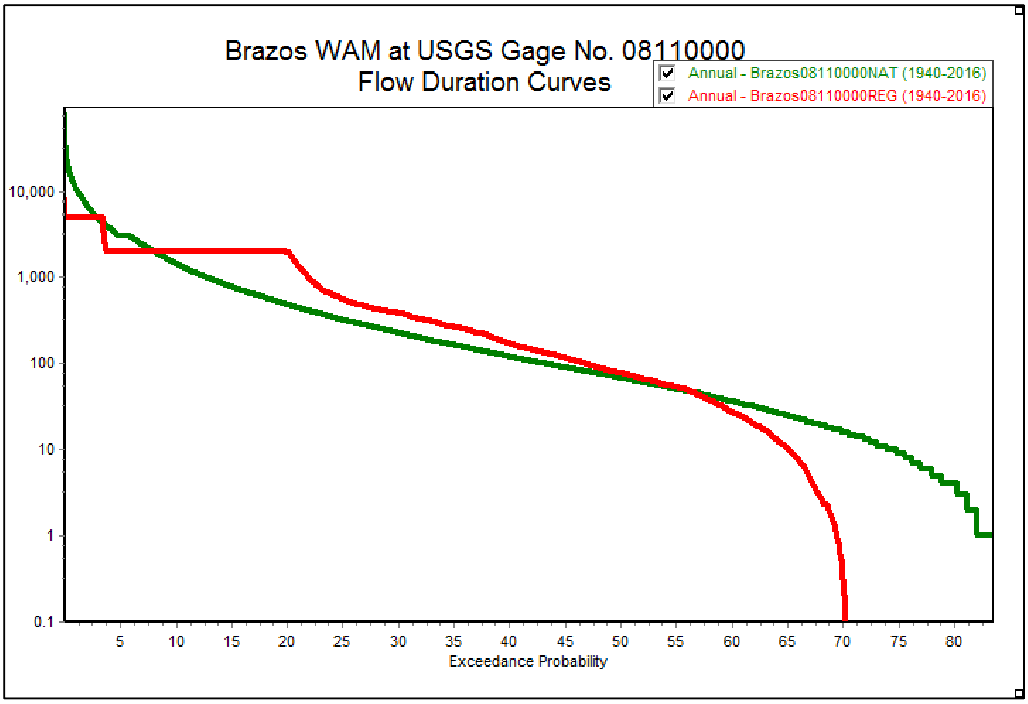


Figure 17 Continued.

o) Yegua Creek near Comerville



p) Navasota River at Easterly

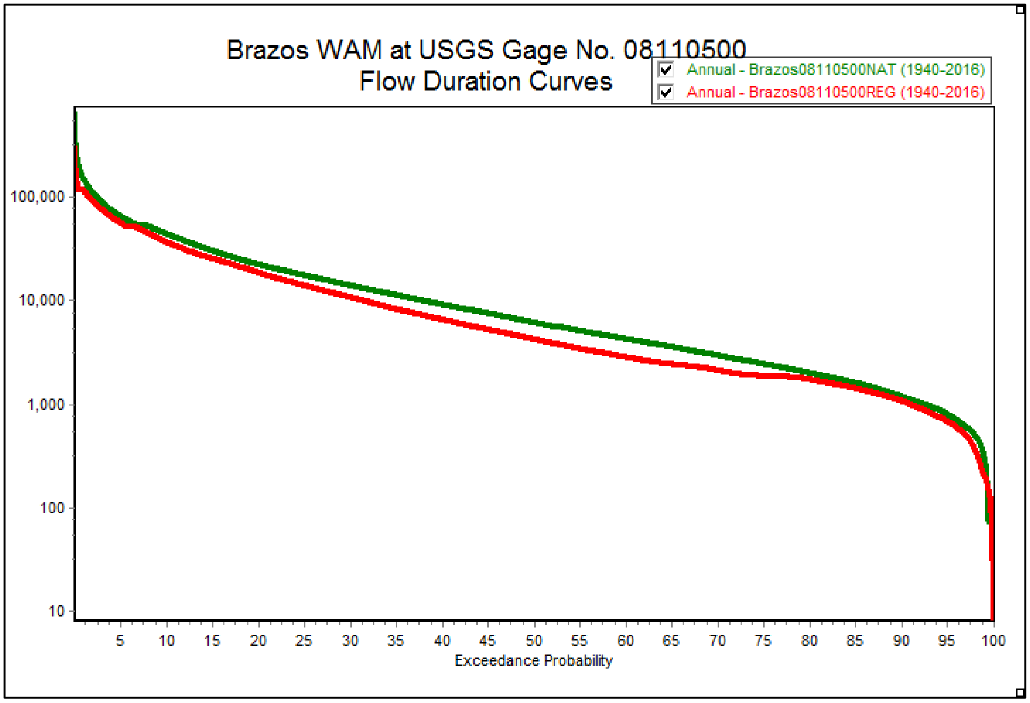
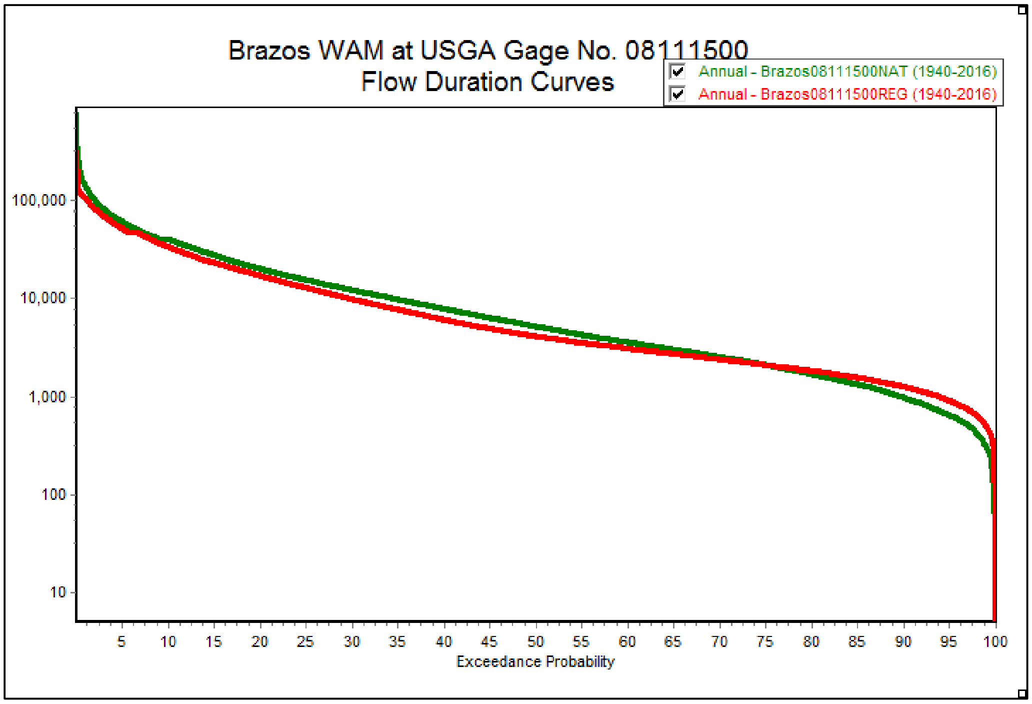


Figure 17 Continued.

q) Brazos River near Hempstead



r) Brazos River near Richmond

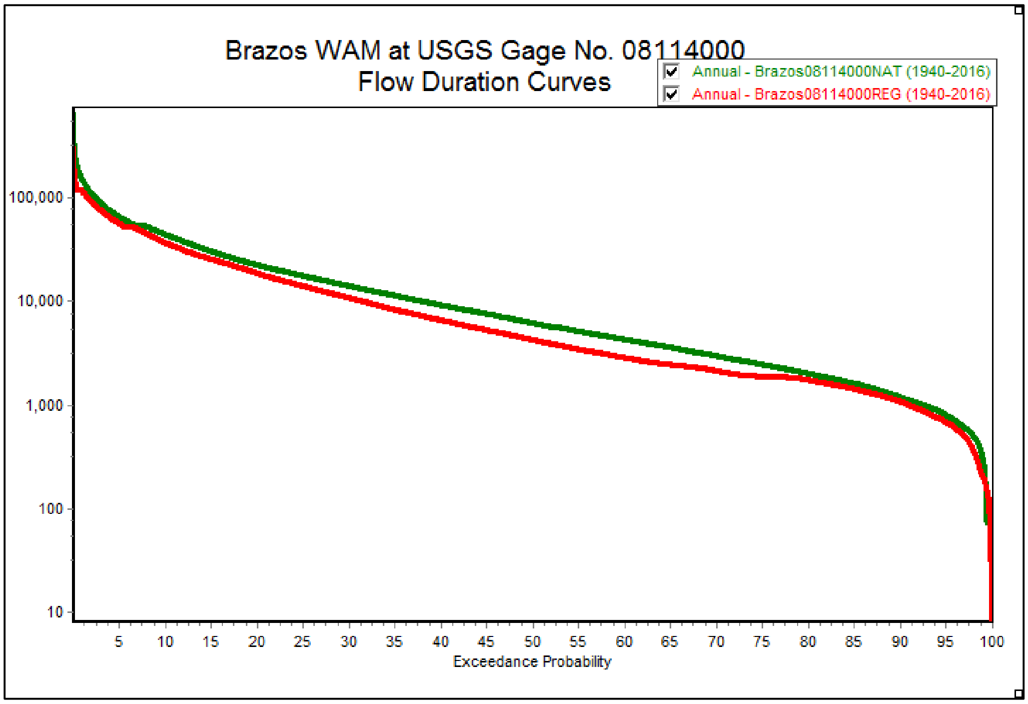


Figure 17 Continued.

s) Brazos River Near Rosharon

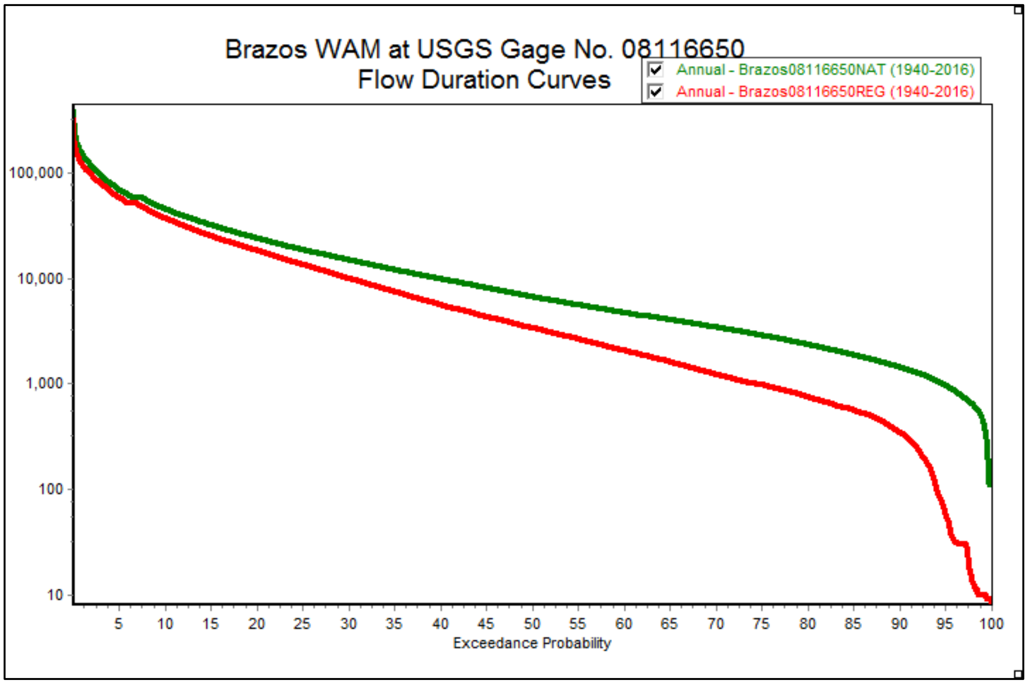


Figure 17 Continued.

a) Double Mountain Fork near Apermont

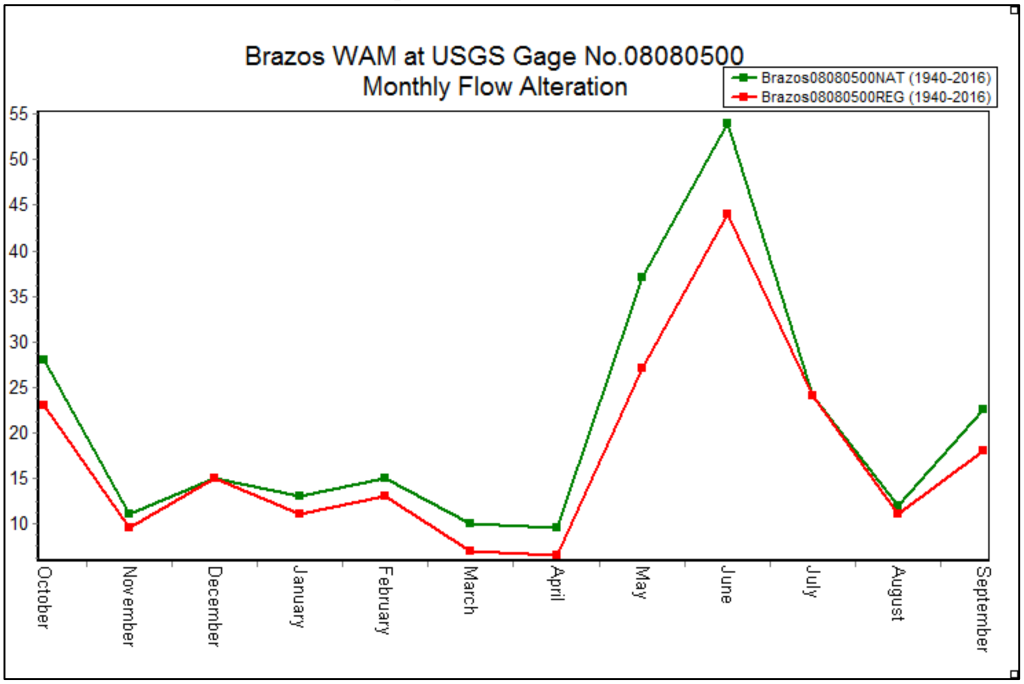
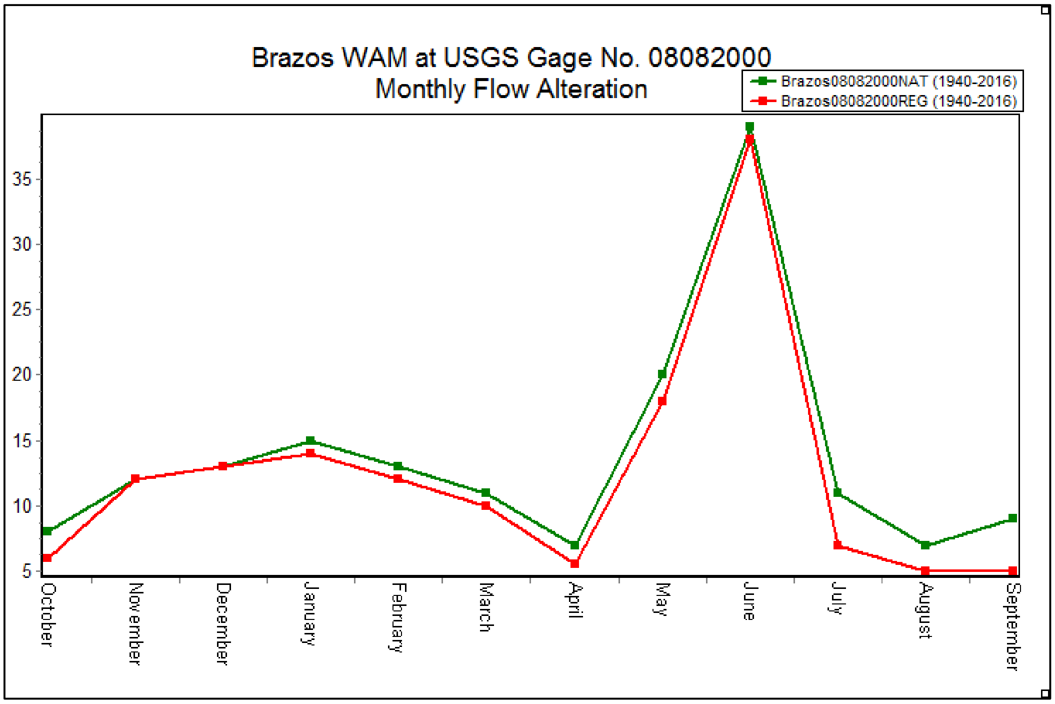


Figure 18. Monthly Flow Alteration of Selected Control Points in the Brazos River Basin

b) Salt Fork Brazos River near Aspermont



c) Brazos River near Palo Pinto

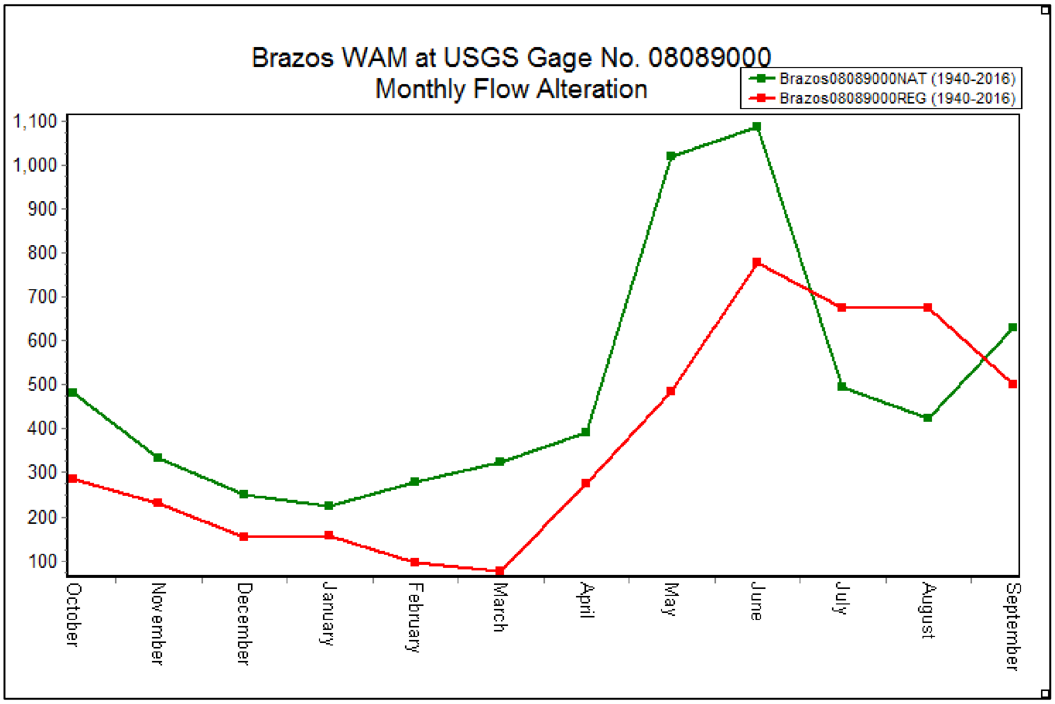
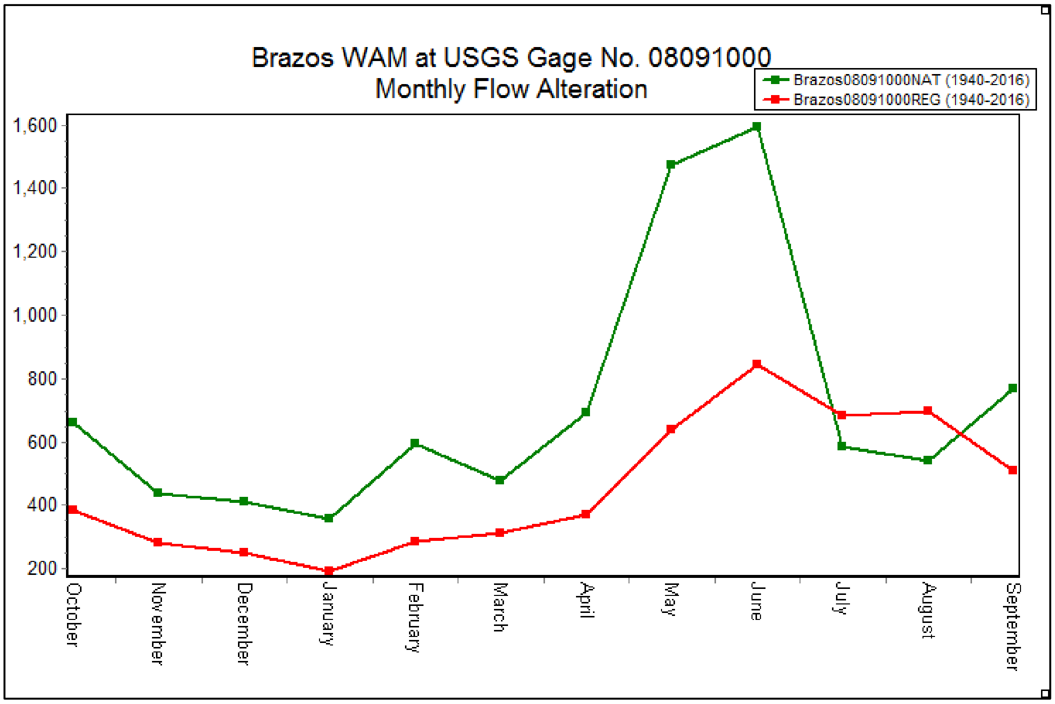


Figure 18 Continued.

d) Brazos River near Glen Rose



e) Little river near Cameron

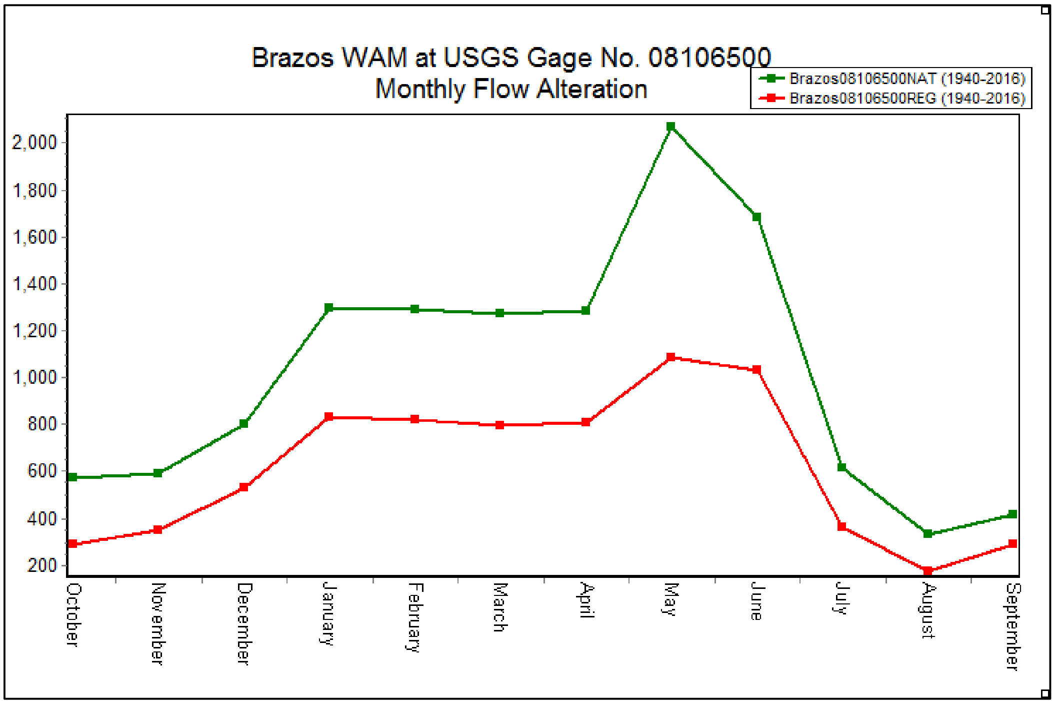


Figure 18 Continued.

f) Brazos River near Richmond

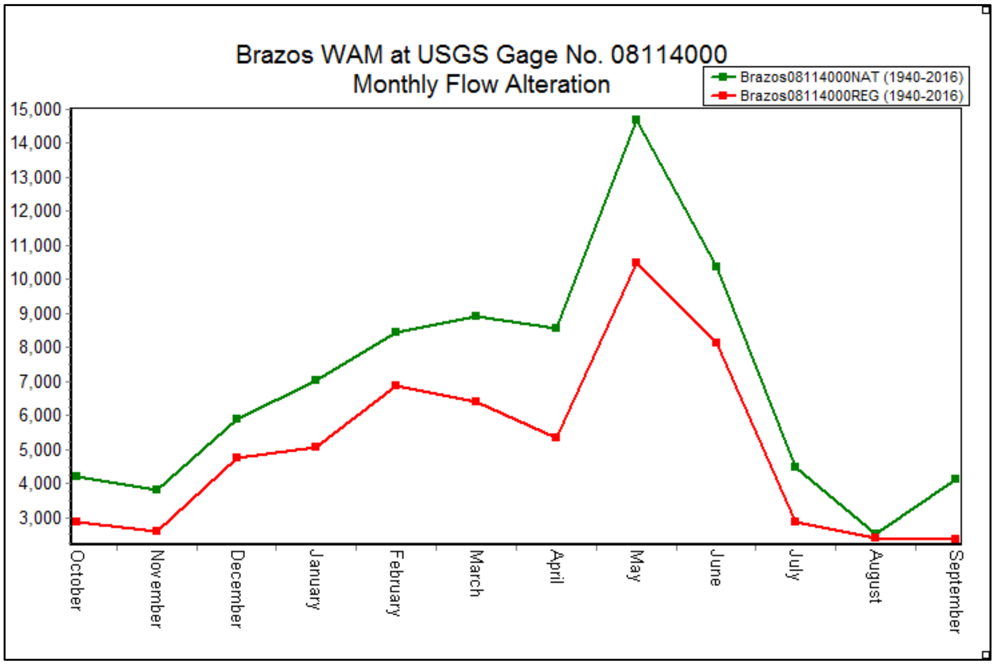


Figure 18 Continued.

Table 14 presents the frequency metrics for annual naturalized and regulated flows in 20 selected control points in the Brazos WAM. The metrics are generated in the HEC-DSSVue using the duration analysis function which will be further discussed in the following chapters. The frequency metrics are listed separately for naturalized and regulated flows at each selected control points. Among the 20 selected control points, 19 gage stations, to which the SB3 has been applied, have been indicated in bold.

Table 14. Frequency of Naturalized and Regulated Flows in the Brazos WAM (Unit: ac-ft/day)

WAM ID	**DMAS09**		**SFAS06**		**BRSE11**		**CFNU16**		**CFFG18**	
Exceedance Possibility	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**
0.10%	**22061**	**19258**	**17040**	**16351**	**39652**	**38641**	**15524**	**10908**	**29489**	**23973**
0.50%	**7764**	**6458**	**6023**	**5699**	**15581**	**14842**	**7153**	**3581**	**13058**	**9719**
1.00%	**4423**	**3869**	**3149**	**2859**	**9311**	**8727**	**4437**	**2125**	**7701**	**5623**
2.00%	**2372**	**2114**	**1557**	**1439**	**5395**	**5128**	**2387**	**1107**	**4127**	**2826**
5.00%	**970**	**843**	**617**	**566**	**2384**	**2255**	**917**	**433**	**1475**	**1016**
10.00%	**385**	**333**	**247**	**227**	**1107**	**1064**	**381**	**174**	**566**	**388**
15.00%	**212**	**184**	**134**	**124**	**636**	**610**	**218**	**99**	**326**	**229**

Table 14 Continued.

WAM ID	DMAS09		SFAS06		BRSE11		CFNU16		CFFG18	
Exceedance Possibility	NAT	REG	NAT	REG	NAT	REG	NAT	REG	NAT	REG
20.00%	134	118	83	76	424	408	148	71	224	153
30.00%	67	59	39	36	229	221	92	53	117	79
40.00%	39	33	22	20	139	134	61	36	67	44
50.00%	20	17	13	12	89	85	41	24	41	23
60.00%	9	7	7	6	57	54	27	16	23	8
70.00%	3	2	3	2	34	32	16	9	9	0
80.00%	0	0	1	1	15	14	6	3	1	0
85.00%	0	0	1	0	8	6	1	1	0	0
90.00%	0	0	0	0	2	1	0	0	0	0
95.00%	0	0	0	0	0	0	0	0	0	0
	BRSB23		BRPP27		BRGR30		NBCL36		BRWA41	
0.10%	73460	64283	99390	77249	122940	111124	34552	33768	144828	81619
0.50%	41334	36852	46396	38541	65865	55110	13742	13633	87257	62786
1.00%	27529	23707	34309	28022	45072	36286	8200	8099	63846	52469
2.00%	15962	13857	20802	15827	27819	21257	3915	3874	43917	36126
5.00%	5991	5173	8939	5746	12502	8025	1614	1527	22313	14757
10.00%	2858	2450	4101	2422	6012	3604	761	721	11993	7120
15.00%	1672	1454	2524	1407	3828	2030	475	437	7719	4278
20.00%	1121	980	1721	948	2574	1329	314	283	5492	3053
30.00%	605	535	962	675	1447	783	156	132	3268	2192
40.00%	360	316	621	493	942	598	84	69	2096	1684
50.00%	232	207	428	339	636	446	50	41	1412	1224
60.00%	155	135	292	225	439	308	32	26	948	993
70.00%	97	80	192	52	295	182	18	17	630	857
80.00%	52	36	105	18	184	65	8	7	395	672
85.00%	29	15	65	15	128	29	4	3	296	523
90.00%	13	2	25	13	79	12	0	0	207	344
95.00%	2	0	0	13	29	5	0	0	114	157
	LEGT47		LEBE49		LAKE50		LRLR53		LRCA58	
0.10%	35274	25927	54413	26332	80404	35937	80404	35937	130942	81558
0.50%	16088	11358	24495	16966	38694	19835	38694	19835	64954	36517
1.00%	11062	8585	18334	12569	28711	19028	28711	19028	46321	24243
2.00%	6900	6235	12479	10600	19379	13547	19379	13547	30716	19835
5.00%	2919	2980	6017	5517	9728	11901	9728	11901	15911	16537
10.00%	1468	1363	3318	2683	5259	5640	5259	5640	8755	9079
15.00%	918	884	2132	1281	3528	2609	3528	2609	5732	5384
20.00%	610	592	1501	790	2530	1582	2530	1582	4171	3148
30.00%	333	292	846	406	1488	782	1488	782	2400	1495
40.00%	190	156	492	250	922	451	922	451	1484	878
50.00%	110	86	299	189	565	286	565	286	963	568
60.00%	59	44	171	154	361	188	361	188	624	375
70.00%	28	20	87	131	226	111	226	111	406	232
80.00%	8	5	34	104	124	56	124	56	232	112
85.00%	2	0	13	94	86	33	86	33	154	64
90.00%	0	0	0	72	55	20	55	20	89	40
95.00%	0	0	0	32	22	6	22	6	41	33
	YCSO62		NAEA66		BRHE668		BRRI70		BRRO72	
0.10%	28655	4958	42078	38466	324139	189849	309837	181117	274095	185991
0.50%	15475	4958	20848	18379	174239	117237	184471	119010	178570	140697
1.00%	10663	4958	14870	12580	137447	103053	146027	112947	146509	117965
2.00%	6875	4958	9191	7659	101609	82514	109938	90514	114852	94969
5.00%	2992	1983	4270	3162	60633	51372	65325	56331	69099	58106
10.00%	1272	1983	1837	1071	37112	31000	40908	33902	41926	34330
15.00%	710	1983	940	498	25791	21728	28677	24216	30118	23665
20.00%	453	1509	544	272	19080	16129	21436	17704	22888	17419
30.00%	216	372	234	104	11725	9443	13554	10394	14445	9566
40.00%	116	162	119	58	7594	5872	8947	6392	9575	5412
50.00%	67	76	66	39	5044	4008	6024	4089	6529	3271
60.00%	36	26	39	30	3476	3002	4168	2781	4658	1994
70.00%	16	0	23	27	2473	2349	2897	2081	3361	1188
80.00%	4	0	11	22	1646	1798	1973	1699	2313	731

Table 14 Continued.

WAM ID	**YCSO62**		**NAEA66**		**BRHE668**		**BRRI70**		**BRRO72**	
Exceedance Possibility	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**	**NAT**	**REG**
85.00%	**0**	**0**	**7**	**19**	**1299**	**1530**	**1581**	**1394**	**1836**	**547**
90.00%	**0**	**0**	**3**	**16**	**956**	**1235**	**1166**	**1058**	**1412**	**336**
95.00%	**0**	**0**	**0**	**14**	**632**	**886**	**788**	**669**	**946**	**54**

6.4 Discussion of Analysis Results and Modeling

6.4.1 Discussion of Analysis Results

According to figure 15, regulated flow rates at four control points in the Trinity WAM are smaller than the naturalized flows. If using the concept of time periods, flow rates in Post-Impact periods are lower than the ones in a Pre-Impact period. Human-induced hydrological changes are having a great impact on water resources since the 1950s. The constructions of varieties of water conservancies such as dams, reservoirs, channels, and culverts thrived in the 1960s. Given that naturalized flows are flows from which the impact of human activities has been removed, it makes sense that Pre-Impact flow rates are greater than Post-Impact ones.

In figure 16, we can interpret the flow alterations based on the monthly flow rates. In USGS Gage No. 08049500 West Fork at Grand Prairie and 08057000 Trinity River at Dallas, naturalized flow rates are greater than the regulated flows in every month. The largest difference between naturalized flows and regulated flows appears in the month of May, which is the end of the spring. The smallest difference happens in the month of August, which is the end of summer. Similar to the previous two control points, at gage station 08065000 Trinity River near Oakwood, naturalized flows are larger than the regulated flows, the most significant difference happens in the month of March, which is the middle month of spring. Meantime, the smallest difference appears in the month of August, which is in summer. In the USGS gage station No. 08066500 Trinity River at Romayor, Naturalized flows are greater than regulated flows during a month of October, November, December, January, February, March, April, May, and June. Also, the largest difference happens in the month of February which is the end of winter. Whereas, during the month of July, August, and September, regulated flows are greater than naturalized flows. In July, the difference appears to be the smallest, which is the middle month of summer. Based on the monthly alteration analysis, we could get a general idea about how human-induced alterations have been impacting on hydrological situations over time. The water conservancies are helping increasing the flow rates during the seasons, which are lack of water resources. Meanwhile, dams and reservoirs lower the possibility of flooding events during the wet seasons. However, more detailed investigations should be conducted to certify this scenario. After all, precipitation is not evenly distributed over the state. In addition, the dry season and wet season of different parts of Texas do not happen around the same time. That explained the results that the alterations vary from location to location.

In Table 14, frequency metrics of annual naturalized and regulated flows of each selected control point are listed individually in two columns. It is generated in the HEC-DSSVue software by using Math Function-Statistics-Duration Analysis-Plotting Points-Standard (23 Points). Whereas, for presentation purposes, the tables presented in this thesis do not include 23 points. The numbers enumerated in the table reflects the difference between annual naturalized and regulated flows. Further analysis and interpretations can be made based on individual needs. Comparing the analysis results of observed flows with the alterations in naturalized and regulated flows, we could notice that the trend of historical daily observed surface flows in the Trinity River is different from the tendency of the simulated flows. Considering naturalized flow as the Pre-Impact situation, and regulated flow as the Post-Impact period of time, the simulated Post-Impact flow rates are lower than the simulated Pre-Impact situation at the four selected control points. Meanwhile, the comparison between two periods of observed flows is showing very subtle alterations at several gage stations, and slight increasing trend at some other stations.

The different tendencies of observed flows and simulated flows brings up the conflict that based on the simulated flows, the flow rates in the Trinity River Basin are decreasing, whereas, the observed flows are having an increasing trend.

One assumption involves treated water. Water treatment process consists of collecting water that has already been used by people in their homes or businesses (wastewater), purifying this water to a level suitable for its intended use at a wastewater treatment plant (also called a water reclamation plant), and using it again for beneficial purposes within the community (TWDB 2011). Therefore, the discharge of treated water for during the dry seasons may account for the increasing of the flow rates.

In 2010, U.S. Dallas–Fort Worth metropolitan area had 6.7 million people, which made this area the eighth-largest metropolitan area in the United States. With this large amount of population, the human-induced alterations on natural flows are noteworthy. Cities like Dallas and Fort Worth draw water from the river’s headwaters and discharge their treated wastewater downstream. During summertime and other times when the river’s natural flow is reduced, the river consists almost entirely of treated wastewater as it flows away from Dallas and Fort Worth.

Houston is located on the south-eastern side of downstream Trinity River, and this river is the main source for Houston. After a two-week southward journey, during which natural processes eliminate some trace organic contaminants, the water collects in Lake Livingston—one of Houston’s main drinking water reservoirs. There it mixes with rainwater and other water in the reservoir until it is drawn into a drinking water treatment plant and distributed through Houston’s taps. Over the course of a year, about half the lake’s water is made up of treated wastewater from Dallas and Fort Worth. After treatment, the potable water from the Trinity River meets Environmental Protection Agency drinking water standards.

Another hypothesis could be the replacement of groundwater. Groundwater is a precious resource in Texas. According to the Texas Water Development Board, water from aquifers or groundwater provides over 55% of the state's water supply. A vast majority of the groundwater (almost 80%) is used to irrigate crops. Cities such as San Antonio, El Paso, Houston and Amarillo also depend, to varying degrees, on groundwater to supply homes, businesses, and industries. Many Texas residents in unincorporated areas also rely on groundwater from individual wells. After withdrawing groundwater, the amount of water may be used then released on the surface and would inevitably be measured as surface water. In this case, the number of observed surface flow rate would increase, but truly, it is due to the replacement of water resources.

In figure 17, the differences between naturalized and regulated flows are barely noticeable at USGS gage station 08080500, 08082000, 08082500, 08089500, 08103800. At gage stations, 08088000, 08096500, 08100500, 08110500, 08111500, 08114000, the differences, in general, are not significant but do exist in several exceedance probabilities. In the rest of the control points, the differences are rather apparent.

Figure 18 presents the monthly alterations between naturalized and regulated flows in the Brazos River. The tendency of changes is related to the locations of control points. In the upper basin, the monthly alteration between naturalized and regulated flows is not significant. As to the middle basin, the regulated flows are smaller than the naturalized flows from September to June. Also, the important differences appear in May and June. The regulated flows exceed the naturalized flows in the months of July and August. At the lower basin gages, the regulated flows are smaller than the naturalized flows throughout the year, and the noteworthy differences happen in April, May, and June.

Table 15 tabulates the naturalized and regulated flow individually for each selected control point. Comparing the numbers of flow rates, the significant difference between naturalized and regulated flows appears in the middle and lower Brazos Basin. The control points located in the upper basin show no clear alterations between naturalized and regulated flows. In the Brazos River Basin, he trends of observed surface flows and the tendency of the alterations between naturalized and regulated flows basically remain the same.

In the Brazos River Basin, it is noticeable that the alterations of observed flow and the changes between naturalized and regulated flows are similar, and neither of the flow duration curves is showing any substantial differences. However, it is clear that there is a slightly increasing tendency of observed flows at the most of the gage stations. Meanwhile, the regulated flows are smaller than the naturalized flows in general. Figure 19 shows the location water reuse plants in Texas.

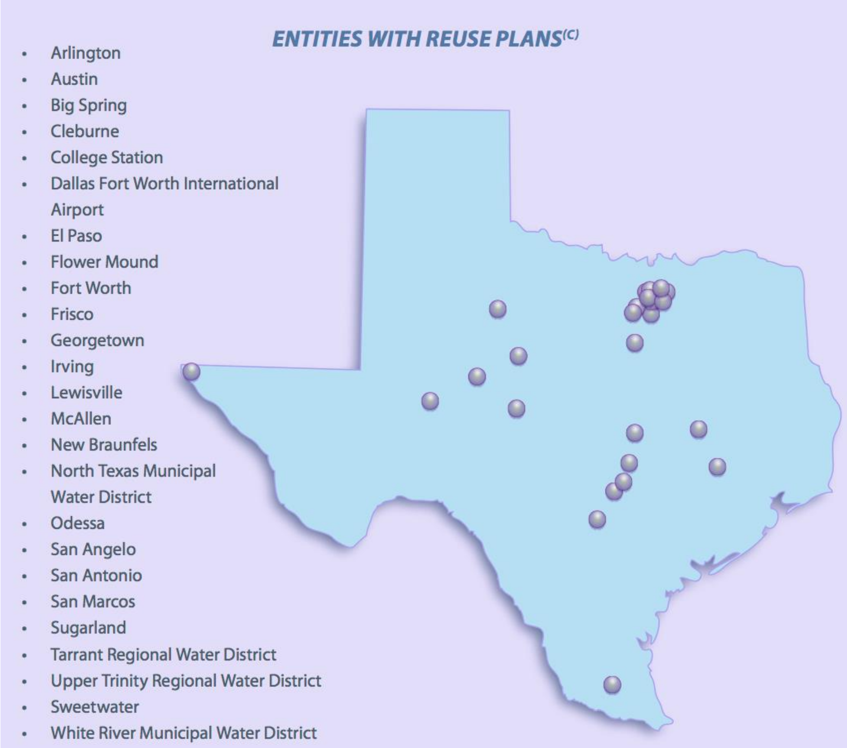


Figure 19. Water Reuse Plants in Texas (TWDB 2011)

6.4.2 Discussion of Modeling

In this part of the discussion, comparisons among the IHA software, the WRAP/WAM, and the HEC-DSSVue. The features of each program will be stressed.

The WAM System developed and maintained by the TCEQ includes the generalized WRAP simulation model and WRAP input datasets for all of the river basins of Texas. The application of the WRAP/WAM systems is the foundation of the analyses conducted in this chapter. The use of WRAP/WAM simulation requires sophisticated knowledge of inputting datasets and hydraulic engineering. The users must be trained, in order to program and apply this simulation model well to selected basins. A simulation is performed with *SIM* using input files describing water resources development, allocation, and management (*DAT* file) and hydrology (*FLO, EVA, DIS* files) provided by the model user. Once the users are capable of utilizing the system, the desired output can be generated fast and conveniently. WRAP can produce organized simulation result in root. *TOU* file, main simulation result in root. *DSS* file read by HEC-DSSVue, and root. *YRO* file, which is the yield-reliability analysis output file. The organized table contains Time Series Tables, Reliability and Frequency Tables, and Summary and Water Budget Tables. The details of utilizing WRAP/WAM can be found in the Fundamentals of Water Availability Modeling with WRAP (Wurbs, 2013).

In this thesis, the application of WRAP/WAM is focusing on generating the Trinity and Brazos *DSS*. files, which contain the naturalized and regulated flows’ datasets for each control points in the Trinity and Brazos WAM. The execution time for Brazos and Trinity WAM can vary from one computer to another. Runtimes for the six daily WAMs with the datasets are posted at the WRAP website, and also reported in the Daily Water Availability Models (Wurbs, 2005). As the first step scientific process, WRAP/WAM, is irreplaceable by neither HEC-DSSVue nor IHA. The competencies of WAM regarding generating naturalized, regulated, unregulated, unappropriated flows are distinguishing. Meanwhile, WRAP appears to have the most flexible and comprehensive set of input records for modeling environmental instream flows. Especially after the updates on daily time step features of WRAP in both Trinity and Brazos WAMs, including specific records for modeling high flow pulse events, make it particularly useful for incorporating environmental instream flow requirements. In this thesis the application of HEC-DSSVue is rather substantial and makes a significant contribution to the thesis after generating the root.*DSS* files by running the Trinity and Brazos WAMs.

Compared to WRAP/WAM, IHA software does not require users to master programming or have sophisticated academic knowledge. The whole platform is friendly to users, who has no computer science or advanced hydraulic engineering background. Whereas, users are asked to work under the basic Windows environment, and master using MS Excel, Textbook, and Word. The application of MS software is a main affiliation to both the IHA and DSSVue software.

When analyzing observed surface flows in the Trinity and Brazos River Basins, ways of importing data into IHA and HEC-DSSVue are unalike. In HEC-DSSVue, users can import observed flow data directly from the USGS NWIS website. While, in the IHA program, analysts need to download observed flow data files from the website. On the other hand, using HEC-DSSVue to download USGS gaged data can be problematic when associated datasets are incomplete. And users will have to obtain gaged data manually from the USGS NWIS websites. Other than that, users can create time series flow data manually following the requirements and import into either HEC-DSSVue or IHA.

On the other hand, IHA software consists of 74 parameters. 33 parameters fall into the IHA group, and 34 parameters are in the EFCs category. Consequently, IHA enables users to apply various of analyses of every set of data. Program users are allowed to conduct various of analyses. In general, IHA provides many potentials and aspects for users to interpret the changes of flows. Nevertheless, there are some drawbacks of applying the IHA. Water managers may feel overwhelmed when first introduced to these 67 parameters (Mathews and Richter 2007). Besides, this approach would not be the ideal method to analyze river systems, which are wildly impacted due to climate changes within a short period-of-time. Moreover, RVA flow targets are not attained until the end of the year. So if the water managers look forward to getting a higher certainty or taking endangered species into consideration, RVA would be less useful (Mathews and Richter 2007).

IHA program and HEC-DSSVue are different applying variety of analyses. During the process of duration analysis, IHA program is capable of generating one long-time record analysis or two period-of-records comparison using user-specified algorithm. Whereas, HEC-DSSVue cannot separate one long period series into two. Visual-wise, after using the FDC function in IHA, related graphs and tables will be created simultaneously. In HEC-DSSVue, graphs and tables are generated based on users' preferences and needs. Noticeably, in HEC-DSSVue, users are offered multiple options before plotting and tabulating. Users can choose have all data points, standard (23 points) or user defined points. This is rather convenient as to developing frequency of metrics, considering that standard (23 points) option will be illustrative enough. However, in IHA, whenever the FDCs tables have generated along with the graphs, users will have to select certain exceedance possibilities and related flow rated one by one. This approach used in the thesis may have impaired the validity of the results. Due to the embedded functions of the IHA software, it is not possible for users to generate the frequency metrics with selected exceedance probabilities. Under this circumstance, users will have to manually select desired exceedance probabilities along with their associated flow rates. It almost inevitably brings up the problems. One of the problems will be overload amount of labor. This thesis introduces the frequency metrics for two river basins and 33 control points in total. The work of manually searching for exceedance probability is not considerably overwhelming, whereas, if a research requires frequency metrics of a lot of datasets, the work time would be greatly prolonged. The other problem is the inaccuracy of the manually selected numbers. As described in the previous chapters, the algorithm of flow duration analysis does not follow a linear pattern. As a result, one has to choose the most relevant exceedance probabilities arbitrarily. Therefore, the level of accuracy of the final results can be challenged.

It is self-evident that neither HEC-DSSVue nor IHA program is comprehensive enough to cover every function. While it is reasonably obvious that employing WRAP/WAM with HEC-DSSVue is quite powerful concerning simulating naturalized and regulated stream flows as well as processing them. Every time after researcher successfully run the WAM, the accompanying *DSS* file can be created if researchers activate the option. Then, users can open the DSS file in HEC-DSSVue and obtain further results. Whereas, if one wants to use IHA to analyze any kind of flow, flow related data will have to be created, imported and analyzed individually. More implementation of IHA software is in the following chapter, meantime, further evaluation will be made.

CHAPTER VII

CAPABILITIES FOR MEETING SB3 ENVIRONMENTAL FLOW STANDARDS

7.1 Senate Bill 3 Environmental Flow Standards

In 2007, TCEQ established the Environmental flow standards consist of a set of flow metrics and rules that vary seasonally or by hydrologic condition and by location that govern decisions to curtail junior rights to divert and/or store streamflows. Environmental flow requirements or standards are defined in terms of flow regimes which describe the magnitude, frequency, duration, timing, and rate of change of streamflows required to maintain a sound ecology (Wurbs and Hoffpauir 2012).

In the past, environmental flow requirements typically have been specified as a minimum instream flow target that may vary by month and location. However, the TIFP and SB 3 strategy is based on flow regimes with multiple components. Scientists recognize that various characteristics of flow variability are important determinants of aquatic community structure and stability. Ecosystems are adapted to hydrologic patterns reflecting flow variability for a full range of flows, not just low flows.

The SB 3 process has adopted a framework recommended by studies performed pursuant to the SB 2 TIFP that defines an instream flow regime that includes four components: subsistence flows, base flows, within-bank high flow pulses, and overbank high pulse flows. The magnitude, frequency, duration, timing, and rate of change of streamflows are considered for each component (Wurbs and Hoffpauir 2012).

7.2 Modeling and Analysis Methodology in 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. The standards entered into force May 15, 2011. Instream flow standards at four Trinity River Basin locations were incorporated into the daily Trinity WAM.

Four seasons are defined according to the months listed in Table 15. For the purposes of tracking the frequency for which high flow pulse events are engaging, the six-month period from June through November is considered as a single season rather than two separate seasons.

Table 15. Months Included in Each Season

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

7.2.1 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 16.

Table 16. Subsistence Flow Standards (Unit: cfs)

Control point	Winter	Spring	Summer	Fall
8WTGP	19	25	23	21
8TRDA	26	37	22	15
8TROA	120	160	75	100
8TRRO	495	700	200	230

If the flow at a control point is greater than the applicable base flows 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 17.

Table 17. Base Flow Standards (Unit: cfs)

Control point	Winter	Spring	Summer	Fall
8WTGP	45	45	35	35
8TRDA	50	70	40	50
8TROA	340	450	250	260
8TRRO	875	1,150	575	625

7.2.2 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 done 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 18. The tracking of high flow pulse events for each season is performed independently of preceding and subsequent seasons. As mentioned, the summer and fall seasons are combined as a single six-month season for the purposes of tracking high flow pulse events.

Table 18. High Flow Pulse Standards

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

7.3 Modeling and Analysis Methodology in the Brazos River Basin

The Brazos BBEST selected four seasons are tabulated in Table 20, and each season has three months. The BBEST concluded, and the BBASC agrees, that this seasonal separation will ensure that the BBASC's instream flow recommendations reflect observed, natural, intra-annual variability in flow conditions.

Table 19. Months Included in Each Season

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

7.3.1 Subsistence and Base Flow Standards

The BBEST selected the following methodology and parameters (based on IHA methodology) to separate flows into subsistence, base, pulse and overbank flows:

- **Subsistence Flow Limit:** flows below this value are subsistence flows. Consistent with the BBEST, the BBASC uses the 5th percentile of all flows as the subsistence flow limit.

- **Minimum Flow for Pulse Flows:** flows below this limit cannot be a pulse or overbank flows. They are subsistence or base flows.
- **Maximum Flow for Base Flows:** flows above the 75th percentile cannot be base or subsistence flows. They are a pulse or overbank flows. Flows between the minimum flow for pulse flows and the maximum flow for base flows can be classified as either base/subsistence flows or pulse/overbank flows. Flows remain at the classification of the previous day unless certain criteria are met, as follows:
- **Percent Increase that Changes Base Flow to Pulse Flow (Applies for Flows between the Maximum and Minimum):** A base or subsistence flow changes to a pulse flow under the following conditions: if the previous day's flow is base or subsistence flow and if the current day's flow is the maximum flow for base flows and the minimum flow for pulse flows, then the day is classified as a pulse if the flow increases by more than 25 percent. If the increase is less than this value (or if there is a decrease), the flow remains a base or subsistence flow, like the previous day's flow.
- **Percent Decrease Below Which Pulse Flow Changes to Base Flow (Applies for Flows between the Maximum and Minimum):** A pulse flow changes to a base flow or subsistence flow under the following conditions: if the previous day's flow is a pulse or overbank flow and if the current day's flow is between the maximum base flow and minimum pulse flow, then the day is classified as a base flow or subsistence flow if the flow decreases less than five percent. If the increase is greater than this value or if the flow increases, the flow remains a pulse/overbank flow, like the previous day's flow.

7.3.2 Environmental Flow Standards at Selected Gage Station in the Brazos River Basin

Table 20 (a)-(r) tabulate the environmental flow standards at 18 gage stations in the Brazos River Basin. Each table presents three important types of flow standards in different seasons.

Table 20. Environmental Flow Standards at Each Gage Station in the Brazos River Basin

a) USGS Gage 8080500 Brazos River near Rosharon

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	1 cfs 4 cfs 15 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	1 cfs 3 cfs 8 cfs	Pulse(s) 1 Qp:280 Volume 1,270 Duration 10	Pulse(s) 2 Qp:280 Volume 1,270 Duration 10	Pulse(s) 1 Qp:570 Volume 2,600 Duration 12
Summer	1 cfs	Dry Average Wet	1 cfs 2 cfs 7 cfs	Pulse(s) 1 Qp:230 Volume 990 Duration 9	Pulse(s) 2 Qp:230 Volume 990 Duration 9	Pulse(s) 1 Qp:480 Volume 2,160 Duration 12

b) USGS Gage 8082000 Salt Fork Brazos River near Aspermont

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	1 cfs 4 cfs 9 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	1 cfs 2 cfs 5 cfs	Pulse(s) 1 Qp:160 Volume 720 Duration 10	Pulse(s) 2 Qp:160 Volume 720 Duration 10	Pulse(s) 1 Qp:300 Volume 1,350 Duration 11
Summer	1 cfs	Dry Average Wet	1 cfs 1 cfs 2 cfs	Pulse(s) 1 Qp:140 Volume 560 Duration 8	Pulse(s) 2 Qp:140 Volume 560 Duration 8	Pulse(s) 1 Qp:26- Volume 1,090 Duration 10

Table 20 Continued.

c) USGS Gage 8082500 Brazos River at Seymour

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	10 cfs 25 cfs 46 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	7 cfs 19 cfs 35 cfs	Pulse(s) 1 Qp:560 Volume 2,960 Duration 10	Pulse(s) 2 Qp:560 Volume 2,960 Duration 10	Pulse(s) 1 Qp: 1,040 Volume 5,870 Duration 12
Summer	1 cfs	Dry Average Wet	4 cfs 13 cfs 32 cfs	Pulse(s) 1 Qp:370 Volume 1,870 Duration 8	Pulse(s) 2 Qp:370 Volume 1,870 Duration 8	Pulse(s) 1 Qp:800 Volume 4,290 Duration 11

d) USGS Gage 8084000 Clear Fork Brazos River at Nugent

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	5 cfs 8 cfs 13 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	3 cfs 6 cfs 12 cfs	Pulse(s) 1 Qp:180 Volume 860 Duration 9	Pulse(s) 2 Qp:180 Volume 860 Duration 9	Pulse(s) 1 Qp:590 Volume 2,800 Duration 12
Summer	1 cfs	Dry Average Wet	1 cfs 4 cfs 9 cfs	Pulse(s) 1 Qp:100 Volume 460 Duration 8	Pulse(s) 2 Qp:100 Volume 460 Duration 8	Pulse(s) 1 Qp:390 Volume 1,890 Duration 12

e) USGS Gage 8085500 Clear Fork Brazos River at Fort Griffin

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	8 cfs 17 cfs 34 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	4 cfs 13 cfs 27 cfs	Pulse(s) 1 Qp:110 Volume 620 Duration 10	Pulse(s) 2 Qp:360 Volume 2,120 Duration 12	Pulse(s) 1 Qp: 1,230 Volume 7,310 Duration 15
Summer	1 cfs	Dry Average Wet	1 cfs 5 cfs 20 cfs	Pulse(s) 1 Qp:110 Volume 620 Duration 10	Pulse(s) 2 Qp:110 Volume 620 Duration 10	Pulse(s) 1 Qp:700 Volume 4,110 Duration 16

Table 20 Continued.

f) USGS Gage 8088000 Brazos River near South Bend

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	36 cfs 73 cfs 120 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	29 cfs 60 cfs 100 cfs	Pulse(s) 1 Qp: 1,260 Volume 7,280 Duration 10	Pulse(s) 2 Qp: 1,260 Volume 7,280 Duration 10	Pulse(s) 1 Qp: 2,480 Volume 15,700 Duration 13
Summer	1 cfs	Dry Average Wet	16 cfs 46 cfs 95 cfs	Pulse(s) 1 Qp:580 Volume 3,140 Duration 8	Pulse(s) 2 Qp:580 Volume 3,140 Duration 8	Pulse(s) 1 Qp: 1,180 Volume 7,050 Duration 11

g) USGS Gage 08089000 Brazos River near Palo Pinto

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season		Wet Hydrological Conditions Pulse per Season	
Winter	17 cfs	Dry Average Wet	49 cfs 61 cfs 100 cfs	Pulse(s) 2 Qp:850 Volume 3,690 Duration 5	Pulse(s) 4 Qp:850 Vol. 3,690 Duration 5	Pulse(s) 2 Qp: 1,390 Vol. 7,180 Duration 7	Pulse(s) 4 Qp:850 Vol. 3,690 Duration 5	Pulse(s) 3 Qp: 1,390 Vol. 7,180 Duration 7
Spring	17 cfs	Dry Average Wet	39 cfs 75 cfs 120 cfs	Pulse(s) 2 Qp: 1,400 Volume 6,600 Duration 6	Pulse(s) 4 Qp: 1,400 Vol. 6,600 Duration 6	Pulse(s) 2 Qp: 3,370 Vol. 20,200 Duration 10	Pulse(s) 4 Qp: 1,400 Vol. 6,600 Duration 6	Pulse(s) 3 Qp: 3,370 Vol. 20,200 Duration 10
Summer	17 cfs	Dry Average Wet	40 cfs 72 cfs 120 cfs	Pulse(s) 2 Qp: 1,230 Volume 5,920 Duration 6	Pulse(s) 4 Qp: 1,230 Vol. 5,920 Duration 6	Pulse(s) 2 Qp: 2,260 Vol. 13,000 Duration 9	Pulse(s) 4 Qp: 1,230 Vol. 5,920 Duration 6	Pulse(s) 3 Qp: 2,260 Vol. 13,000 Duration 9

h) USGS Gage 8091000 Brazos River near Glen Rose

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season		Wet Hydrological Conditions Pulse per Season	
Winter	17 cfs	Dry Average Wet	42 cfs 77 cfs 160 cfs	Pulse(s) 2 Qp:930 Volume 5,400 Duration 8	Pulse(s) 4 Qp:930 Vol. 5,400 Duration 8	Pulse(s) 2 Qp: 1,700 Vol. 10,800 Duration 10	Pulse(s) 4 Qp:930 Vol. 5,400 Duration 8	Pulse(s) 3 Qp: 1,700 Vol. 10,800 Duration 10
Spring	17 cfs	Dry Average Wet	47 cfs 92 cfs 170 cfs	Pulse(s) 2 Qp: 2,350 Volume 14,300 Duration 10	Pulse(s) 4 Qp: 2,350 Vol. 14,300 Duration 10	Pulse(s) 2 Qp: 6,480 Vol. 46,700 Duration 14	Pulse(s) 4 Qp: 2,350 Vol. 14,300 Duration 10	Pulse(s) 3 Qp: 6,480 Vol. 46,700 Duration 14
Summer	17 cfs	Dry Average Wet	37 cfs 70 cfs 160 cfs	Pulse(s) 2 Qp: 1,320 Volume 7,830 Duration 8	Pulse(s) 4 Qp: 1,320 Vol. 5,920 Duration 6	Pulse(s) 2 Qp: 3,090 Vol. 21,200 Duration 12	Pulse(s) 4 Qp: 1,230 Vol. 5,920 Duration 6	Pulse(s) 3 Qp: 3,090 Vol. 21,200 Duration 12

Table 20 Continued.

i) USGS Gage 8095000 North Bosque River near Clifton

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	5 cfs 23 cfs 25 cfs	Not Recommended	Not Recommended	Not Recommended
Spring	1 cfs	Dry Average Wet	7 cfs 16 cfs 33 cfs	Pulse(s) 1 Qp: 710 Volume 3,490 Duration 12	Pulse(s) 2 Qp: 710 Volume 3,490 Duration 12	Pulse(s) 3 Qp: 710 Volume 3,490 Duration 12
Summer	1 cfs	Dry Average Wet	3 cfs 8 cfs 17 cfs	Not Recommended	Not Recommended	Pulse(s) 2 Qp: 130 Volume 500 Duration 6

j) USGS Gage 8096500 Brazos River at Waco

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	56 cfs	Dry Average Wet	120 cfs 210 cfs 480 cfs	Pulse(s) 1 Qp: 2,320 Volume 12,400 Duration 7	Pulse(s) 3 Qp : 2,320 Volume 12,400 Duration 7	Pulse(s) 2 Qp: 4,180 Volume 25,700 Duration 9
Spring	56 cfs	Dry Average Wet	1,250 cfs 2,570 cfs 4,740 cfs	Pulse(s) 1 Qp: 5,330 Volume 32,700 Duration 10	Pulse(s) 3 Qp: 5,330 Volume 32,700 Duration 10	Pulse(s) 2 Qp: 14,200 Volume 102,000 Duration 14
Summer	56 cfs	Dry Average Wet	930 cfs 1,420 cfs 2,630 cfs	Pulse(s) 1 Qp: 980 Volume 10,500 Duration 7	Pulse(s) 3 Qp: 1,980 Volume 10,500 Duration 7	Pulse(s) 2 Qp: 4,160 Volume 26,400 Duration 10

k) USGS Gage 8100500 Leon River at Gatesville

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	9 cfs 20 cfs 52 cfs	Not Recommended	Not Recommended	Pulse(s) 2 Qp: 100 Volume 540 Duration 6
Spring	1 cfs	Dry Average Wet	10 cfs 24 cfs 54 cfs	Pulse(s) 1 Qp: 340 Volume 1,910 Duration 10	Pulse(s) 3 Qp: 340 Volume 1,910 Duration 10	Pulse(s) 2 Qp: 830 Volume 4,050 Duration 13
Summer	1 cfs	Dry Average Wet	4 cfs 12 cfs 27 cfs	Pulse(s) 1 Qp: 58 Volume 220 Duration 4	Pulse(s) 3 Qp: 58 Volume 220 Duration 4	Pulse(s) 2 Qp: 140 Volume 600 Duration 6

Table 20 Continued.

l) USGS Gage 8103800 Lampasas River near Kempner

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	10 cfs	Dry	18 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	27 cfs	Qp:78	Qp:78	Qp:190
		Wet	39 cfs	Volume 430	Volume 430	Volume 1,150
				Duration 8	Duration 8	Duration 11
Spring	10 cfs	Dry	21 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	29 cfs	Qp:780	Qp:780	Qp: 1,310
		Wet	43 cfs	Volume 4,020	Volume 4,020	Volume 6,680
				Duration 13	Duration 13	Duration 16
Summer	10 cfs	Dry	16 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	23 cfs	Qp:77	Qp:77	Qp:190
		Wet	32 cfs	Volume 270	Volume 270	Volume 680
				Duration 4	Duration 4	Duration 6

m) USGS Gage 8104500 Little River at Little River

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	55 cfs	Dry	82 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	110 cfs	Qp:520	Qp:520	Qp: 1,600
		Wet	190 cfs	Volume 2,350	Volume 2,350	Volume 11,800
				Duration 5	Duration 5	Duration 11
Spring	55 cfs	Dry	95 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	150 cfs	Qp: 1,420	Qp:780	Qp: 3,290
		Wet	340 cfs	Volume 9,760	Volume 4,020	Volume 21,200
				Duration 10	Duration 13	Duration 17
Summer	55 cfs	Dry	84 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	120 cfs	Qp:430	Qp:430	Qp: 1,060
		Wet	200 cfs	Volume 1,560	Volume 1,560	Volume 5,890
				Duration 4	Duration 4	Duration 8

n) USGS Gage 8106500 Little River near Cameron

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	32 cfs	Dry	110 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	190 cfs	Qp: 1,080	Qp: 1,080	Qp: 2,140
		Wet	450 cfs	Volume 6,680	Volume 6,680	Volume 14,900
				Duration 8	Duration 8	Duration 10
Spring	32 cfs	Dry	140 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	310 cfs	Qp: 1,420	Qp:780	Qp: 4,790
		Wet	760 cfs	Volume 9,760	Volume 4,020	Volume 38,400
				Duration 10	Duration 13	Duration 14
Summer	32 cfs	Dry	97 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	160 cfs	Qp:560	Qp:560	Qp: 990
		Wet	330 cfs	Volume 2,860	Volume 2,860	Volume 5,550
				Duration 6	Duration 6	Duration 8

Table 20 Continued.

o) USGS Gage 8110500 Navasota River near Easterly

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	1 cfs	Dry Average Wet	9 cfs 14 cfs 23 cfs	Pulse(s) 1 Qp: 260 Volume 1,610 Duration 9	Pulse(s) 3 Qp: 260 Volume 1,610 Duration 9	Pulse(s) 2 Qp: 800 Volume 5,440 Duration 2
Spring	1 cfs	Dry Average Wet	10 cfs 19 cfs 29 cfs	Pulse(s) 1 Qp: 72 Volume 4,590 Duration 11	Pulse(s) 3 Qp: 72 Volume 4,590 Duration 11	Pulse(s) 2 Qp: 1,340 Volume 8,990 Duration 13
Summer	1 cfs	Dry Average Wet	3 cfs 8 cfs 16 cfs	Not Recommended	Not Recommended	Pulse(s) 2 Qp: 140 Volume 600 Duration 6

p) USGS Gage 8111500 Brazos River near Hempstead

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	510 cfs	Dry Average Wet	920 cfs 1,440 cfs 2,890 cfs	Pulse(s) 1 Qp: 5,720 Volume 49,800 Duration 10	Pulse(s) 3 Qp: 8,530 Volume 85,000 Duration 13	Pulse(s) 2 Qp: 11,200 Volume 125,000 Duration 15
Spring	510 cfs	Dry Average Wet	1,130 cfs 1,900 cfs 3,440 cfs	Pulse(s) 1 Qp: 8,530 Volume 85,000 Duration 13	Pulse(s) 3 Qp: 8,530 Volume 85,000 Duration 13	Pulse(s) 2 Qp: 16,800 Volume 219,000 Duration 19
Summer	510 cfs	Dry Average Wet	950 cfs 1,330 cfs 2,050 cfs	Pulse(s) 1 Qp: 2,620 Volume 17,000 Duration 7	Pulse(s) 3 Qp: 2,620 Volume 17,000 Duration 7	Pulse(s) 2 Qp: 5,090 Volume 40,900 Duration 9

q) USGS Gage 8114000 Brazos River at Richmond

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	550 cfs	Dry Average Wet	990 cfs 1,650 cfs 3,310 cfs	Pulse(s) 1 Qp: 6,140 Volume 60,600 Duration 11	Pulse(s) 3 Qp: 6,140 Volume 60,600 Duration 11	Pulse(s) 2 Qp: 12,400 Volume 150,000 Duration 15
Spring	550 cfs	Dry Average Wet	1,190 cfs 2,140 cfs 3,980 cfs	Pulse(s) 1 Qp: 8,930 Volume 94,000 Duration 13	Pulse(s) 3 Qp: 8,930 Volume 94,000 Duration 13	Pulse(s) 2 Qp: 16,300 Volume 215,000 Duration 19
Summer	550 cfs	Dry Average Wet	930 cfs 1,330 cfs 2,190 cfs	Pulse(s) 1 Qp: 2,460 Volume 16,400 Duration 6	Pulse(s) 3 Qp: 2,460 Volume 16,400 Duration 6	Pulse(s) 2 Qp: 5,430 Volume 46,300 Duration 10

Table 20 Continued.
r) USGS Gage 8116650 Brazos River near Rosharon

Season	Subsistence	Hydrological Conditions	Base	Dry Hydrological Conditions Pulse per Season	Average Hydrological Conditions Pulse per Season	Wet Hydrological Conditions Pulse per Season
Winter	430 cfs	Dry	1,140 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	2,090 cfs	Qp: 9,090	Qp : 9,090	Qp: 13,600
		Wet	4,700 cfs	Volume 94,700	Volume 94,700	Volume 16,800
				Duration 12	Duration 12	Duration 16
Spring	430 cfs	Dry	150 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	270 cfs	Qp: 6,580	Qp: 6,580	Qp: 14,200
		Wet	690 cfs	Volume 58,500	Volume 58,500	Volume 184,000
				Duration 10	Duration 10	Duration 18
Summer	430 cfs	Dry	140 cfs	Pulse(s) 1	Pulse(s) 3	Pulse(s) 2
		Average	250 cfs	Qp: 2,490	Qp: 2,490	Qp: 4,980
		Wet	590 cfs	Volume 14,900	Volume 14,900	Volume 39,100
				Duration 6	Duration 6	Duration 9

*Hydrological conditions based on the Palmer Index, 25%ile Dry, 50%ile Average, 75%ile Wet
*50% Rule applies for Dry Conditions Base Flow
*Over-bank flows not adopted
*Qp is in Cubic Feet per Second
*Volume is in ac-ft
*Duration is in Days

7.4 Analysis Results

7.4.1 Analysis Results on Sites of the Trinity River and Its Tributary

In the IHA software, there is no function designated to produce frequency metrics of seasonal flows. In this thesis, after running the analysis at one control point, frequency metric of each month will be generated and tabulated in the spreadsheet. According to the SB3 standards, the average flow rate of three months will be used to represent the seasonal flow. During the processing of datasets, the use of MS Excel and Word are quite critical.

Table 21 tabulates the frequency metrics of seasonal flows at four control points, to which the SB3 has applied in the Trinity WAM. Figure 19 is the HEC-DSSVue generated percent exceedance curves for simulated regulated flows at four selected control points in the Trinity WAM.

Table 21. Frequency Metrics of Regulated Seasonal Flows in the Trinity WAM (Unit: ac-ft/day)

WAM ID	8WTGP				8TRDA			
Season / Frequency	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1%	9,035	22,744	11,486	12,458	18,134	36,672	23,417	18,533
2%	5,362	12,733	7,373	6,846	13,334	23,565	16,490	14,163
5%	2,642	6,684	3,465	3,154	7,721	14,488	10,395	5,578
10%	1,603	3,291	2,046	1,489	3,875	9,114	5,799	2,692
20%	718	1,754	1,044	481	1,525	4,051	2,574	916
30%	368	1,088	567	214	794	2,163	1,274	455
40%	242	658	343	123	507	1,291	746	281
50%	166	381	163	79	362	829	446	157
60%	112	243	89	54	227	517	245	78
70%	74	160	50	34	127	311	128	17
80%	46	105	25	8	59	172	51	8
90%	13	57	9	8	12	29	10	8
95%	6	18	9	7	6	7	10	6
100%	0	0	0	0	0	0	0	0
WAM ID	8TROA				8TRRO			
1%	95,063	110,529	106,437	73,933	93,255	121,615	84,189	83,089
2%	65,368	98,890	46,722	34,901	77,539	97,598	61,241	50,182
5%	37,768	54,124	23,532	18,922	58,810	74,112	33,205	24,853
10%	21,921	34,761	14,365	9,791	38,528	50,934	19,828	12,594
20%	11,106	18,949	8,478	4,411	22,131	29,960	12,054	5,030
30%	6,590	11,983	5,143	2,471	12,238	19,438	8,404	3,352
40%	4,060	7,954	3,143	1,532	6,881	13,177	6,237	2,900
50%	2,643	5,368	2,026	1,014	4,048	8,179	4,850	2,724
60%	1,710	3,584	1,291	636	2,589	4,614	4,358	2,576
70%	1,056	2,101	692	341	2,117	2,854	4,065	2,532
80%	570	1,253	339	97	1,858	2,397	3,767	2,151
90%	569	1,251	338	96	964	2,189	3,536	1,025
95%	170	626	93	7	661	1,451	2,625	101
100%	0	192	9	7	0	0	0	0

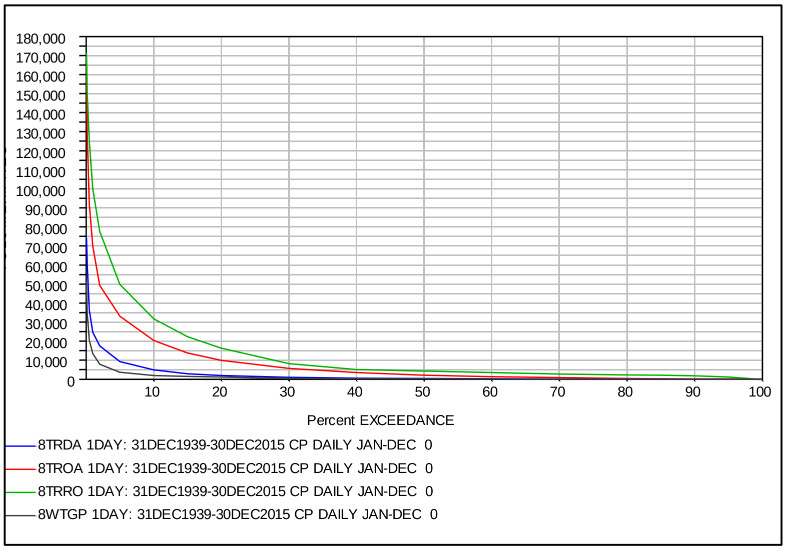


Figure 20. Percent Exceedance of Regulated Flows in the Trinity WAM.

7.4.2 Analysis Results on Sites of the Brazos River and Its Tributary

Seasonal flows are calculated and organized in the MS Excel. It is noticeable that the selection of months is different from the one in the Trinity River Basin. In the Brazos River Basin, the season of Winter starts from January. Nevertheless, the season of Winter in the Trinity River Basin starts from December. Table 22 presents the frequency metrics of seasonal flows at 19 control points, to which the SB3 has applied, in the Brazos River Basin.

Figure 20 is the HEC-DSSVue generated percent exceedance curves for simulated regulated flows at 19 selected control points in the Brazos WAM.

Table 22. Frequency Metrics of Seasonal Regulated Flows in the Brazos WAM (Unit: ac-ft/day)

WAM ID	DMAS09				SFAS06			
Season / Frequency	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1%	758	3,972	5,113	4,407	459	3,207	4,463	3,729
2%	434	2,403	3,297	2,432	319	1,558	2,529	1,926
5%	173	842	1,538	950	121	645	1,054	652
10%	101	338	710	418	62	267	472	290
20%	54	132	265	172	35	90	161	107
30%	37	60	115	81	25	41	75	43
40%	24	30	58	41	18	21	35	19
50%	13	15	29	17	13	11	15	8
60%	7	7	14	5	8	6	6	3
70%	3	2	5	1	4	3	2	1
80%	0	0	0	0	1	1	1	0
90%	0	0	0	0	0	0	0	0
95%	0	0	0	0	0	0	0	0
100%	0	0	0	0	0	0	0	0
WAM ID	BRSE11				CFNU16			
1%	1,789	9,633	11,478	10,788	941	2,970	2,375	2,608
2%	1,114	5,414	6,991	6,005	813	1,625	1,463	1,512
5%	527	2,582	3,779	2,465	249	650	703	667
10%	296	1,230	1,876	1,234	90	270	309	239
20%	175	514	811	520	59	95	116	82
30%	124	259	458	278	41	59	64	55
40%	124	259	458	277	28	46	39	35
50%	94	149	270	161	20	33	23	23
60%	68	99	154	95	14	22	13	13
70%	48	62	86	47	10	14	6	6
80%	34	35	41	23	5	7	3	1
90%	17	18	14	5	0	0	0	0
95%	0	0	0	0	0	0	0	0
100%	0	0	0	0	0	0	0	0

Table 22 Continued.

WAM ID	CFFG18				BRSB23			
1%	1,832	7,391	5,945	5,279	6,509	24,907	23,868	23,004
2%	900	4,028	3,729	3,015	4,279	16,405	16,681	14,633
5%	333	1,471	1,414	1,112	1,602	8,167	7,544	6,279
10%	164	599	702	427	800	3,736	3,864	2,892
20%	82	218	275	155	397	1,471	1,801	1,211
30%	52	121	142	70	272	694	981	670
40%	33	69	74	34	208	405	595	362
50%	19	36	36	11	158	253	373	208
60%	7	18	12	0	116	161	227	117
70%	0	5	4	0	74	94	128	58
80%	0	0	0	0	33	41	53	14
90%	0	0	0	0	1	5	6	0
95%	0	0	0	0	0	0	0	0
100%	0	0	0	0	0	0	0	0
WAM ID	BRPP27				BRGR30			
1%	9,632	31,826	25,995	23,965	17,515	46,978	34,457	33,635
2%	5,645	19,054	18,034	14,907	9,189	30,202	21,983	20,238
5%	2,221	8,900	9,085	6,549	3,892	13,725	11,198	9,083
10%	980	3,641	4,231	3,205	1,618	6,322	5,741	3,986
20%	438	1,248	1,935	1,098	695	2,153	2,409	1,435
30%	327	722	1,083	529	424	1,093	1,326	738
40%	252	460	852	368	323	676	934	496
50%	138	288	711	334	232	446	743	380
60%	47	139	626	262	145	302	643	320
70%	16	52	463	180	67	167	513	250
80%	15	16	123	70	23	56	228	137
90%	13	13	17	18	6	9	18	21
95%	13	13	13	13	0	0	0	0
100%	0	0	0	0	0	0	0	0
WAM ID	NBCL36				BRWA41			
1%	6,879	12,631	5,499	4,855	38,562	54,480	44,597	36,437
2%	3,445	7,105	3,025	2,544	18,705	39,929	32,425	21,952
5%	1,628	2,643	1,049	1,053	7,718	25,862	19,826	9,689
10%	764	1,364	549	462	3,667	12,053	9,932	4,687
20%	323	635	232	151	2,029	5,171	4,412	2,147
30%	165	319	116	71	1,329	3,074	2,973	1,411
40%	68	171	68	40	1,055	2,080	2,404	1,109
50%	31	98	40	26	918	1,549	2,098	978
60%	26	59	26	14	835	1,170	1,866	878
70%	20	39	16	6	651	960	1,569	697
80%	9	23	9	3	368	786	1,114	431
90%	0	10	2	0	149	457	641	212
95%	0	0	0	0	83	148	366	26
100%	0	0	0	0	0	0	0	0
WAM ID	LEGT47				LEBE49			
1%	6,985	11,583	7,032	7,642	4,110	5,360	4,252	1,467
2%	5,080	7,833	5,493	3,811	2,460	3,340	2,438	948
5%	2,169	4,705	2,905	1,619	1,301	1,857	969	502
10%	1,181	2,584	1,714	857	660	1,173	529	279
20%	495	1,082	745	349	301	604	252	111

Table 22 Continued.

30%	262	589	349	163	150	362	155	69
40%	154	318	157	85	81	221	99	46
50%	87	183	73	42	50	120	64	30
60%	41	112	36	20	35	72	42	21
70%	20	64	18	7	26	46	25	14
80%	7	32	8	0	17	26	13	7
90%	1	7	1	0	9	12	4	1
95%	0	0	0	0	6	6	0	0
100%	0	0	0	0	0	0	0	0
WAM ID	LAKE50				LRLR53			
1%	4,110	5,360	4,252	1,467	13,961	20,602	18,530	14,800
2%	2,460	3,340	2,438	948	11,901	18,493	14,546	10,913
5%	1,301	1,857	969	502	9,382	11,901	9,178	4,908
10%	660	1,173	529	279	4,149	9,256	6,280	1,737
20%	301	604	252	111	2,641	6,584	3,148	1,090
30%	150	362	155	69	1,655	3,982	2,403	707
40%	81	221	99	46	679	1,895	897	371
50%	50	120	64	30	369	1,029	555	246
60%	35	72	42	21	240	652	347	161
70%	26	46	25	14	154	433	209	93
80%	17	26	13	7	87	285	132	52
90%	9	12	4	1	34	161	74	26
95%	6	6	0	0	9	55	22	9
100%	0	0	0	0	0	18	3	0
WAM ID	LRCA58				YCSO62			
1%	23,538	26,733	22,373	26,152	4,959	4,959	4,959	4,959
2%	19,835	20,571	19,835	19,835	4,118	4,959	3,967	3,967
5%	17,554	19,693	14,300	11,281	2,009	1,984	3,967	1,984
10%	9,125	13,341	11,091	4,706	1,984	1,984	1,501	1,181
20%	3,460	7,141	3,504	1,500	1,984	1,984	1,383	365
30%	1,800	3,529	1,508	736	620	715	426	121
40%	1,046	1,837	860	445	263	364	198	61
50%	638	1,089	565	300	150	202	71	15
60%	417	727	382	171	41	86	22	0
70%	259	502	239	91	6	41	3	0
80%	120	311	129	43	0	0	0	0
90%	41	128	48	25	0	0	0	0
95%	0	4	11	0	0	0	0	0
100%	0	0	0	0	0	0	0	0
WAM ID	NAEA66				BRHE68			
1%	113,351	107,638	80,040	101,383	101,965	106,845	75,178	89,981
2%	89,673	92,230	70,391	82,148	78,797	86,568	62,431	69,871
5%	52,098	66,925	49,439	41,434	47,195	61,755	44,788	35,795
10%	33,537	48,595	33,522	23,408	29,088	46,208	30,686	19,091
20%	24,480	37,441	26,442	15,026	16,486	27,034	17,487	9,240
30%	19,115	28,460	18,960	10,539	10,562	16,794	9,617	5,165
40%	12,288	17,052	10,253	5,871	6,668	10,990	6,259	3,574
50%	8,112	11,177	6,192	3,858	4,447	7,234	4,571	2,618
60%	5,304	7,433	4,295	2,587	2,948	5,015	3,468	2,084
70%	3,276	4,684	3,026	1,951	2,164	3,400	2,702	1,680
80%	2,104	2,975	2,212	1,724	1,592	2,438	2,063	1,284

Table 22 Continued.

90%	1,755	2,063	1,625	1,267	965	1,694	1,505	776
95%	969	1,300	953	675	719	1,209	1,064	535
100%	49	101	9	31	185	262	318	5
WAM ID	BRRI70				BRRO72			
1%	113,351	107,638	80,040	101,383	116,271	116,065	89,258	105,724
2%	89,673	92,230	70,391	82,148	84,596	97,682	74,245	82,762
5%	52,098	66,925	49,439	41,434	52,751	69,857	49,527	43,377
10%	33,537	48,595	33,522	23,408	52,555	69,524	49,433	43,299
20%	19,115	28,460	18,960	10,539	34,065	49,067	33,377	22,710
30%	12,288	17,052	10,253	5,871	19,015	28,318	18,227	9,569
40%	8,112	11,177	6,192	3,858	12,378	16,970	9,586	5,292
50%	5,304	7,433	4,295	2,587	7,583	10,353	5,313	3,302
60%	3,276	4,684	3,026	1,951	4,594	5,852	3,138	2,154
70%	2,104	2,975	2,212	1,724	2,697	3,426	1,973	1,385
80%	1,755	2,063	1,625	1,267	1,605	1,818	1,035	915
90%	964	1,297	949	672	873	910	574	578
95%	725	665	477	343	322	384	156	185
100%	49	101	9	31	8.5	10	8	8

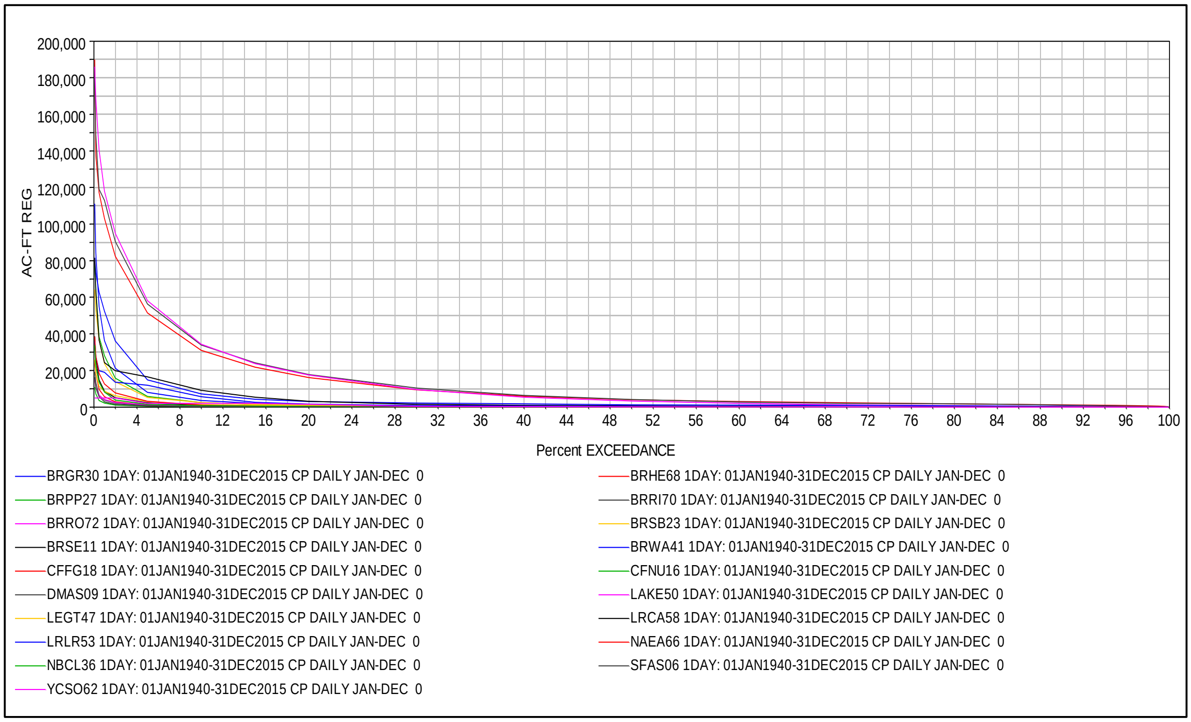


Figure 21. Percent Exceedance of Regulated Flows in the Brazos WAM.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The thesis research consists of analyzing flows at 33 USGS gauging stations, which include 23 sites with SB3 environmental flow standards plus ten other gauges with long periods-of-records. The analyses conducted on long-term observed flows in the Trinity and Brazos River Basins are documented in Chapter V. In the Trinity River Basin, the long-term observed 7-day minimum flows in the majority of the sites have significantly increased. Meanwhile, the observed 7-day maximum flows have moderately declined. According to the flow duration analyses, the overall flow rates in the Trinity River Basin have a growing tendency. In the Brazos River and its tributary, the long-term 7-day minimum flows have an unimportant rising trend. As to observed 7-day maximum flows, the declining tendency could be spotted in several selected sites, while in others, the changes are rather subtle. What’s more, the flow duration analyses show that the long-term observed flow rates in the Brazos River Basin remain steady in the majority of the gaging stations while some of the stations are sharing a declining tendency, and a few sites have experienced obvious turbulence of flow rates over time.

Compared to the situations in the Brazos River and its tributary, the changes are relatively more evident in the Trinity River Basin. However, the alterations of long-term flows differ from site to site in each river basin. In the Trinity River Basin, the significant increasing trend appears in the upper, middle, and most of gaging sites in the lower basin. In the Brazos River Basin, based on the flow duration curves, significant fluctuations have happened in a few stations, at the same time, the alterations are pretty negligible in most of the gaging stations. In fact, when interpreting changes in flow characteristics, the propensity of flows cannot be just explained as increasing or decreasing. For instance, the IHA program default sets 25th, 50th and

75th percentiles as flow variation indexes. However, if one uses different indexes and baselines, the tendency of flows may have different explanations.

Chapter VI has recorded the comparisons between WAM naturalized and simulated regulated flows in the Trinity and Brazos River Basins; we could notice the conflict between observed flows and WAM simulated flows in the Trinity River Basin. The observed long-term flows have an increasing tendency, whereas, naturalized and simulated regulated flows have shown this declining trend over time. One assumption to the conflict could be a result of water reuse. Surface water resource is withdrawn and distributed to municipal, industrial and agricultural purposes, afterward, waste water would be delivered to the water treatment plants and released downstream after it reaches certain standards. Houston locates on the eastern side of downstream Trinity River, nowadays, the majority of water used in Houston is waste water from the treatment plants in Dallas Fort-Worth area. The other one could be the relocating of the groundwater. After withdrawing groundwater, a certain amount of water may be used then released into the surface water bodies and may be measured as surface water. In this case, the number of observed surface flow rate would increase, but truly, it might be due to the replacement of groundwater. Simultaneously, in the Brazos River Basin, the alterations of WAM simulated flows and observed long-term flows are homogenous. On one hand the decreasing of surface flow could be a result of growing population and economics. One the other hand, the changes of flows are impaired by various of factors, and it is hard to conclude that flow alterations are merely hydrological phenomena.

In this thesis, the recently added features of WRAP and overall flexibility of the modeling system allowed the environmental flow standards for the Trinity and Brazos River Basins to be effectively incorporated in the WAMs. The Trinity and Brazos WAMs have a daily time step and 1940-2015 hydrologic period-of-analysis. The authorized use scenario simulations are based on the premise that all water right permit holders store and use the full amounts of water authorized by their permits subject to streamflow availability. The cooperation of WRAP/WAM and HEC-DSSVue provides researchers flow duration analyses to long-term flow datasets. Also, it enables users to quantify the flow characteristics conveniently using selected exceedance probabilities. In general, WRAP/WAM have a considerably comprehensive set of input records for analyzing historical flows and modeling environmental instream flows. Meanwhile, the application of the IHA software, to some extent, expands the aspects of analyzing and quantifying the alteration of flows. The IHA program is designed to assess the degree of hydrologic alteration attributed to human influence with an ecosystem. It emphasizes on the ecologically significant features of surface and ground water. Thus, the parameters in this program provide extensive analyses on the hydrologic perturbations as the results of human influence on wetland, aquatic, and riparian ecosystems. After running the projects, the program presents not only statistic results but a variety of graphical ones. Whereas, just like every modeling approach, there are still drawbacks of applying the IHA program, which are discussed in Chapter VI. This thesis applies the WRAP/WAM, IHA, and the HEC-DSSVue to analyze and quantify the flow conditions in two river basins. However, the results are still not fully comprehensive. According to the literature review of various of models and approaches in Chapter II, more applications, for instance, the HEC-EFM, HEC Statistical Software Package (SSP) could be used to expand and affiliate this research. Along with the advancing of technology and academic acknowledgment, the methodology of investigations would most likely be more refined and versatile. Further research may need to be conducted in the future if stakeholders and decision-makers are looking for more in-depth studies concerning flow alterations. Consequently, further revises and suggestions on environmental flow standards can be made.

REFERENCES

Acreman, M.C. and Dunbar, M.J., 2004. Defining Environmental River Flow Requirements. Hydrology and Earth System Sciences Discussions European Geosciences Union, 8(5), pp.861-876. Wallingford, United Kingdom.

Arthington, A.H., 1991. Ecological and Genetic Impacts of Introduced and Translocated Freshwater Fishes in Australia. Canadian Journal of Fisheries and Aquatic Sciences, 48(S1), pp.33-43. Armidale, Australia.

Arthington, A.H., King, J.M., O'keeffe, J.H., Bunn, S.E., Day, J.A., Pusey, B.J., Bluhdorn, D.R. and Tharme, R., 1992. Development of an Holistic Approach for Assessing Environmental Flow Requirements of Riverine Ecosystems. In Proceedings of An International Seminar and Workshop on Water Allocation for the Environment (Vol. 69, p. 76). The Centre for Water Policy Research, University of New England: Armidale, Australia.

Bovee, K.D., 1982. A Guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology. IFIP No. 12 (No. 82/26) US Fish and Wildlife Service. Washington, D.C, United States.

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B. and Taylor, J., 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology (No. USGS/BRD/ITR--1998-0004). Geological Survey Biologicalresources Div. Virginia, United States.

Gao, Y., Vogel, R.M., Kroll, C.N., Poff, N.L. and Olden, J.D., 2009. Development of Representative Indicators of Hydrologic Alteration. Journal of Hydrology, 374(1), pp.136-147. Medford, Massachusetts.

Hickey, J.T., Huff, R. and Dunn, C.N., 2015. Using Habitat to Quantify Ecological Effects of Restoration and Water Management Alternatives. Environmental Modelling & Software, Vol. 70, pp.16-31. Davis, California.

Hill, M.T., Platts, W.S. and Beschta, R.L., 1991. Ecological and Geomorphological Concepts for Instream And Out-Of-Channel Flow Requirements. Rivers, 2(3), pp.198-210. Boise, Idaho.

Jowett, I.G., 1997. Instream Flow Methods: A Comparison of Approaches. Regulated Rivers: Research & Management, 13(2), pp.115-127. Hamilton, New Zealand.

Kiesling, R.L., 2003. Applying Indicators of Hydrologic Alteration to Texas Streams: Overview of Methods with Examples from the Trinity River Basin U.S. Geological Survey Fact Sheet FS-128-03. 6p. Austin, Texas.

Mann, J.L., 2006. Instream Flow Methodologies: An Evaluation of the Tennant Method for Higher Gradient Streams in the National Forest System Lands in the Western US Master of Science Thesis. Colorado State University. Fort Collins, United States.

Mathews, R. and Richter, B.D., 2007. Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting, JAWRA Journal of the American Water Resources Association, 43: 1400–1413, Middleburg, United States.

Nature Conservancy., 2009. IHA Software Version 7.1 User's Manual, The Nature Conservancy, Virginia, United States.

Opdyke, D.R., Oborny, E.L., Vaugh, S.K. and Mayes, K.B., 2014. Texas Environmental Flow Standards and the Hydrology-Based Environmental Flow Regime Methodology. Hydrological Sciences Journal, 59(3-4), pp.820-830. Austin, Texas.

Pauls, M.A., 2014. Incorporating and Evaluating Environmental Instream Flows in a Priority Order Based Surface Water Allocation Model, Texas A&M University, College Station, Texas.

Peters, M.R., Abt, S.R., Watson, C.C., Fischenich, C. and Nestler, J.M., 1995. Assessment of Restored Rwerine Habitat Using RCHARC. JAWRA Journal of the American Water Resources Association, 31: 745–752, Middleburg, Virginia.

Poff, N.L. and Zimmerman, J.K., 2010. Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. Freshwater Biology, 55(1), pp.194-205. Fort Collins, Colorado.

Richardson, A.R. and Ridem, P.E., 2005. Modified Aquatic Base Flow (RI-ABF) for Rhode Island. Rhode Island DEM Office of Water Resources, Providence, United States.

Richter, B., Baumgartner, J., Wigington, R. and Braun, D., 1997. How Much Water Does a River Need? Freshwater Biology, 37(1), pp.231-249. Hayden, Colorado.

Tharme, R.E., 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(5-6), pp.397-441. Cape Town, South Africa.

US Army Corps of Engineers., 2013. HEC-EFM Ecosystem Functions Model. Quick Start Guide Version 3.0, Hydrologic Engineering Center, Davis, United States.

Wurbs, R.A., 2005. Texas Water Availability Modeling System. Journal of Water Resources Planning and Management, 131(4), pp.270-279. College Station, Texas.

Wurbs, R., 2009. Water Rights Analysis Package Modeling System Reference Manual. Texas Water Resources Institute, College Station, Texas.

Wurbs, R., and Hoffpauir, R., 2012. Water Rights Analysis Package (WRAP) Daily Modeling System. Texas Water Resources Institute, College Station, Texas.

Wurbs, R., and Hoffpauir, R., 2013a. Environmental flows in water availability modeling. Texas Water Resources Institute, College Station, Texas.

Wurbs, R., and Hoffpauir, R., 2013b. Water rights analysis package daily modeling system. TR-430, Texas Water Resources Institute, College Station, Texas.

Wurbs, R., and Zhang, Y., 2014. River system hydrology in Texas. Texas Water Resources Institute, College Station, Texas.

Wurbs, R.A., 2015. Institutional and Hydrologic Water Availability in Texas. Water Resources Management, 29(2), pp.217-231. College Station, Texas

Yang, Y.C.E., Cai, X. and Herricks, E.E., 2008. Identification of Hydrologic Indicators Related to Fish Diversity and Abundance: A Data Mining Approach for Fish Community Analysis. Water Resources Research, 44(4). Urbana, Illinois.