CRWR Online Report 06-11

Assessment of Hydrologic Alteration Software

by

Eric S. Hersh, B. S.

Graduate Research Assistant

and

David R. Maidment, PhD

Principal Investigator

October 2006

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • The University of Texas at Austin
J.J. Pickle Research Campus • Austin, TX 78712-4497

Executive Summary

The purpose of this project was to assess the applicability of hydrologic analysis tools such as The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) and US Geological Survey's (USGS's) Hydrologic Assessment Tool (HAT) for use in the Texas Instream Flow Program (TIFP) and to evaluate the flow regime in six priority subbasins: Lower Sabine, Middle Trinity, Middle and Lower Brazos, Lower Guadalupe, and Lower San Antonio.

As general methods of streamflow hydrograph characterization, both IHA and HAT offer many useful functions that illuminate the nature of streamflow patterns through time at a stream gaging site. In their current versions, however, neither IHA nor HAT is directly suitable for use in the TIFP; both would require modifications to successfully be implemented to define flow component statistics and wet, dry, and normal years. IHA, as its name implies, is best suited to assess hydrologic alteration and to quantify the effects of dam construction and other such water management development projects on the flow regime via two-period analyses and the Range of Variability Approach. HAT, as its name implies, is focused on characterizing streamflow, particularly in the context of a regional analysis of factors that influence streamflow properties.

If the task of choosing between the two programs is framed as which tool better characterizes streamflow hydrographs in general, then there is little difference between these two software packages. But if the task of choosing between them is framed more narrowly as which program will best support the four-level flow characterization (subsistence flow, base flow, high flow pulses, and overbank flows) as for the Texas Instream Flow Program, then the HAT program is a better choice than IHA as it allows for more flexibility in the determination of flow component thresholds and has a greater capacity for regionalization, as described below. Note that the indices calculated in IHA and HAT can all be calculated using independent software such as Microsoft Excel, Matlab, or SAS, oftentimes allowing for greater flexibility.

Using daily flow information available from USGS gaging stations, IHA, HAT, and other tools were used to evaluate the flow regime at 24 selected gages within the 6 TIFP priority subbasins for a period-of-record averaging 68 years. The study has demonstrated that there are pronounced

regional patterns in the seasonality of the streamflow hydrograph, with little seasonal variation in central Texas grading to a strongly seasonal variation in East Texas. The degree of spatial variability in the seasonal pattern of streamflow in East Texas is significantly greater than spatial variation in precipitation alone can explain.

When considered over a long time scale, the seasonal variation in the flow regime of various percentile levels of flow follows a consistent pattern, such that if the median flow goes down then both high and low flow percentiles reduce proportionately to some extent, and vice versa when the median flow increases. Although this pattern holds true across a sample of priority gages studied, the high and low portions of the flow regime also each exhibit their own secondary patterns of seasonality. For the hydrologic conditions present in Texas, the median flow is the most robust streamflow characteristic that is available (i.e., it is most consistently estimated with a given number of data values), and it can reasonably be estimated both from daily and from monthly streamflow data.

Components of the TIFP flow component model may be better delineated using alternatives to IHA or HAT, such as by using the Standard Institute of Hydrology Method for base flow separation using the United States Bureau of Reclamation's BFI computer program. The overbank flow component has a specific, physically-based flow threshold for any given stream cross-section based on the stream slope, roughness, and channel capacity. Looking at additional published gage data (in addition to discharge) provides additional insight into the delineation of this flow component that discharge data alone can not provide, and can be used to estimate the incipient point of overbank flooding.

From this study we conclude that a Texas-customized version of HAT (as part of the Hydroecological Integrity Assessment Process, or HIP) is suitable and preferable to IHA for application in the Texas Instream Flow Program. Further work is necessary as part of the TIFP guidance or within the subbasin studies to define the specific role of hydrologic assessment tools, particularly with respect to flow component delineation and the definition of wet, dry, and normal years.

Table of Contents

List of Figures

List of Tables

List of Acronyms

7Q2	Seven-day average, two-year recurrence interval discharge
CCEFN	Consensus Criteria for Environmental Flow Needs
CFS	Cubic feet per second
CRWR	Center for Research in Water Resources
EFC	Environmental Flow Components
ESRI	Environmental Systems Research Institute
HAT	Hydrologic Assessment Tool
HIP	Hydroecological Integrity Assessment Process
HIT	Hydrologic Index Tool
IHA	Indicators of Hydrologic Alteration
NATHAT	National Hydrologic Assessment Tool
NJHAT	New Jersey Hydrologic Assessment Tool
NJSCT	New Jersey Stream Classification Tool
NWIS	National Water Information System
PCA	Principle Components Analysis
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RVA	Range of Variability Approach
SB2	Senate Bill 2
SCT	Stream Classification Tool
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
TXHAT	Texas Hydrologic Assessment Tool
USGS	United States Geological Survey
VBA	Visual Basic for Applications
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

Acknowledgements

The authors would like to thank the Texas Water Development Board (TWDB) for funding and supporting this research under TWDB Project #2005-483-029, and the Texas Commission on Environmental Quality (TCEQ) and Texas Parks and Wildlife Department (TPWD) for their valuable input. In particular, the assistance of Jordan Furnans and Mark Wentzel of the TWDB, Wendy Gordon of the TCEQ, and Kevin Mayes of the TPWD is appreciated.

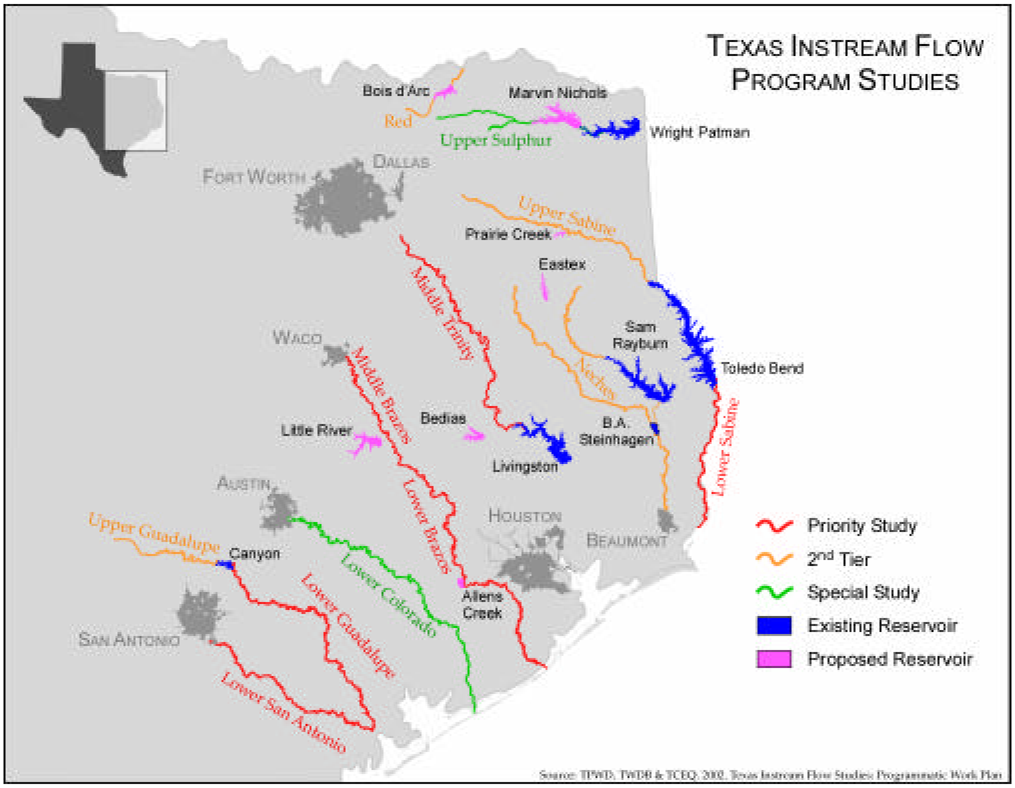
I. Texas Instream Flow Program

Background

History and Goals

The 77th session of the Texas Legislature passed Senate Bill 2 (SB2) in 2001, directing the Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board (hereinafter referred to as "the agencies") to "…jointly establish and continuously maintain an instream flow data collection and evaluation program…" and to "…conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state rivers and streams necessary to support a sound ecological environment." The Texas Instream Flow Program (TIFP) was developed by the agencies in response (Senate Bill 2, TIFP 2006).

Six subbasins were identified by the agencies for TIFP priority study based on potential water development projects, water rights permitting issues, and other factors: Lower Sabine River, Middle Trinity River, Middle and Lower Brazos River, Lower Guadalupe River, and Lower San Antonio River (Figure 1). Basin-specific instream flow studies are scheduled to be completed for each priority basin by December 31, 2010 (TIFP 2002).



Source: TPWD, TWDB & TCEQ. 2002. Texas Instream Flow Studies: Programmatic Work Plan

Figure 1. TIFP priority studies (TIFP 2002).

Disciplines

Instream flow science is both multidisciplinary, relying on multiple different scientific fields, and interdisciplinary, relying on the interconnectedness of these various fields. The TIFP will include analyses of hydrology and hydraulics, geomorphology and physical processes, water quality, and biology, and the connectivity between and among the four primary disciplines. The integration of sometimes disparate findings from these disciplines is one of the most challenging and one of the most important steps of developing instream flow recommendations.

Environmental flows encompass instream flows, and the terms are often used interchangeably. Despite the terminology, "instream flows" is typically used to describe the entire spectrum of the flow regime including overbank flows, which are technically not "instream." The term "instream" flow requirement is used to distinguish these flow requirements from legal prescriptions on water withdrawals – those taking the water out of the stream.

Hydrology

Recent work has come to recognize streamflow as the “master variable” controlling riverine physical, biological, and chemical processes (Poff et al. 1997, Annear et al. 2004). In other words, flow is often the driving force in the complex web of fluvial processes. This is because the quantity and timing of flow are critical to the function, health, and ecological integrity of riverine systems as they affect nearly every other process that occurs within the system. Streambank erosion, habitat availability, and dissolved oxygen concentrations are examples of physical, biological, and chemical components that all are highly impacted by the amount of flow in a river as flow affects the stream power, water depth, habitat connectivity, water temperature, reaeration, and numerous other factors that regulate in this example. As such, an understanding of the linkages between the flow regime and the natural processes that occur in the river is essential to developing environmental flow recommendations to preserve those natural processes to the maximum extent practicable. Within TIFP, evaluations of the hydrology and hydraulics are to be conducted along with evaluations of the other three disciplines immediately following the Study Design element for the sub-basin studies (Figure 2).

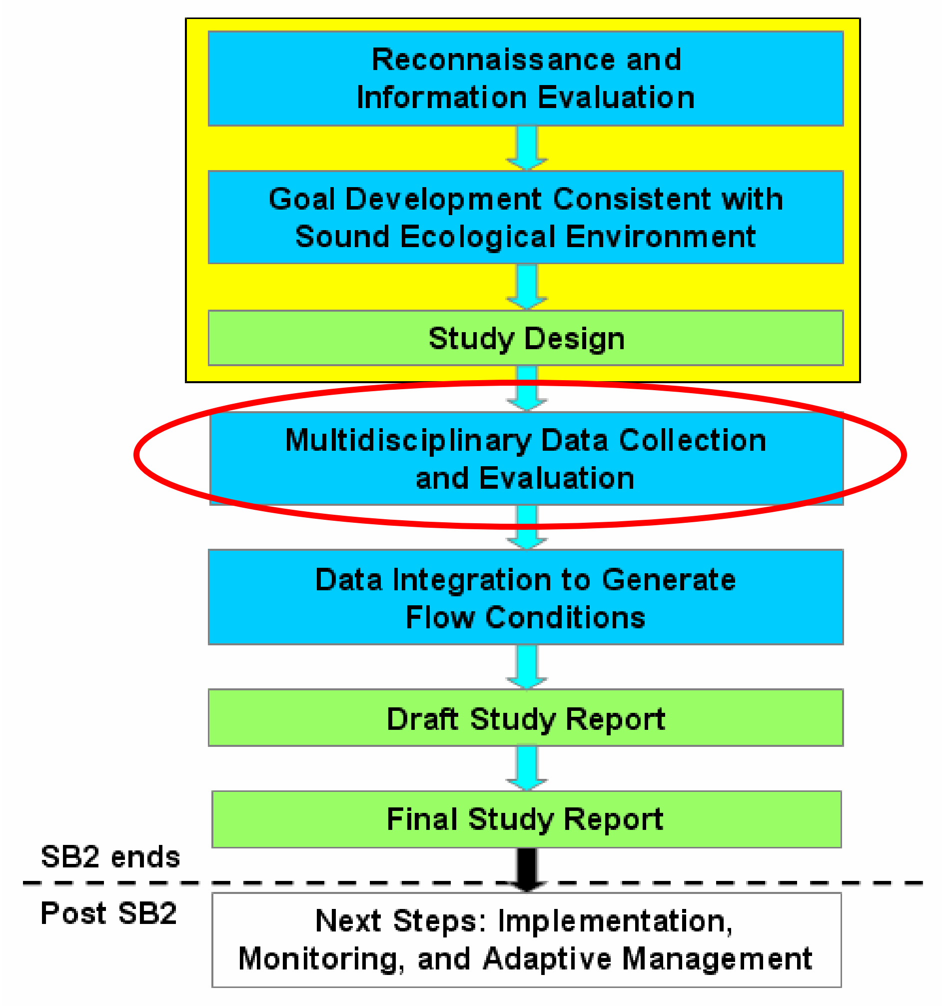


Figure 2. TIFP sub-basin study flowchart (TIFP 2006).

Instream Flow Regime

The Natural Flow Regime

In the 1950s, instream flow methods were developed that identified a minimum flow value practitioners believed to be protective of aquatic resources. However, scientific thinking on the topic of instream flows has progressed over the last half-century to the point of recognizing that the temporal variability of flow across hours, days, months, seasons, years, and even decades is critical in sustaining biodiversity and ecosystem integrity (Poff et al. 1997, Richter et al. 1997). This variability is represented by consideration of the natural flow regime, which is the full range of magnitude, timing, and variability of streamflows that have occurred historically or that could reasonably be expected to occur naturally within a given reach. The natural flow regime is characterized by five components: magnitude, frequency, duration, timing, and rate of change of hydrologic conditions, and a large body of research demonstrates that protecting or recreating the natural range of flow variation in a river system serves to protect or recreate a healthy river (Arthington et al. 1991, Sparks 1995, Stanford et al. 1996. Richter et al. 1997).

Flow Components

The National Research Council of the National Academy of Sciences performed a scientific peer review of the TIFP in which, among other recommendations, they put forth a conceptual model to characterize the natural flow regime into four flow components: subsistence flow, base flow, high flow pulses, and overbank flows (NRC 2005). According to the NRC (2005) document *The Science of Instream Flows: A Review of the Texas Instream Flow Program,*

> Subsistence flow is the minimum streamflow needed during critical drought periods to maintain tolerable water quality conditions and to provide minimal aquatic habitat space for the survival of aquatic organisms. Base flow is the 'normal' flow conditions found in a river in between storms, and base flows provide adequate habitat for the support of diverse, native aquatic communities and maintain ground water levels to support riparian vegetation. High flow pulses are short-duration, high flows within the stream channel that occur during or immediately following a storm event; they flush fine sediment deposits and waste products, restore normal water quality following prolonged low flows, and provide longitudinal connectivity for species movement along the river. Lastly, overbank flow is an infrequent, high flow event that breaches riverbanks. Overbank flows can drastically restructure the channel and floodplain, recharge groundwater tables, deliver nutrients to riparian vegetation, and connect the channel with floodplain habitats that provide additional food for aquatic organisms.

An example daily streamflow hydrograph from the NRC report for the Guadalupe River at Victoria, Texas (USGS Gage No. 08176500) for water year 2000 is presented in Figure 3 with flow components identified.

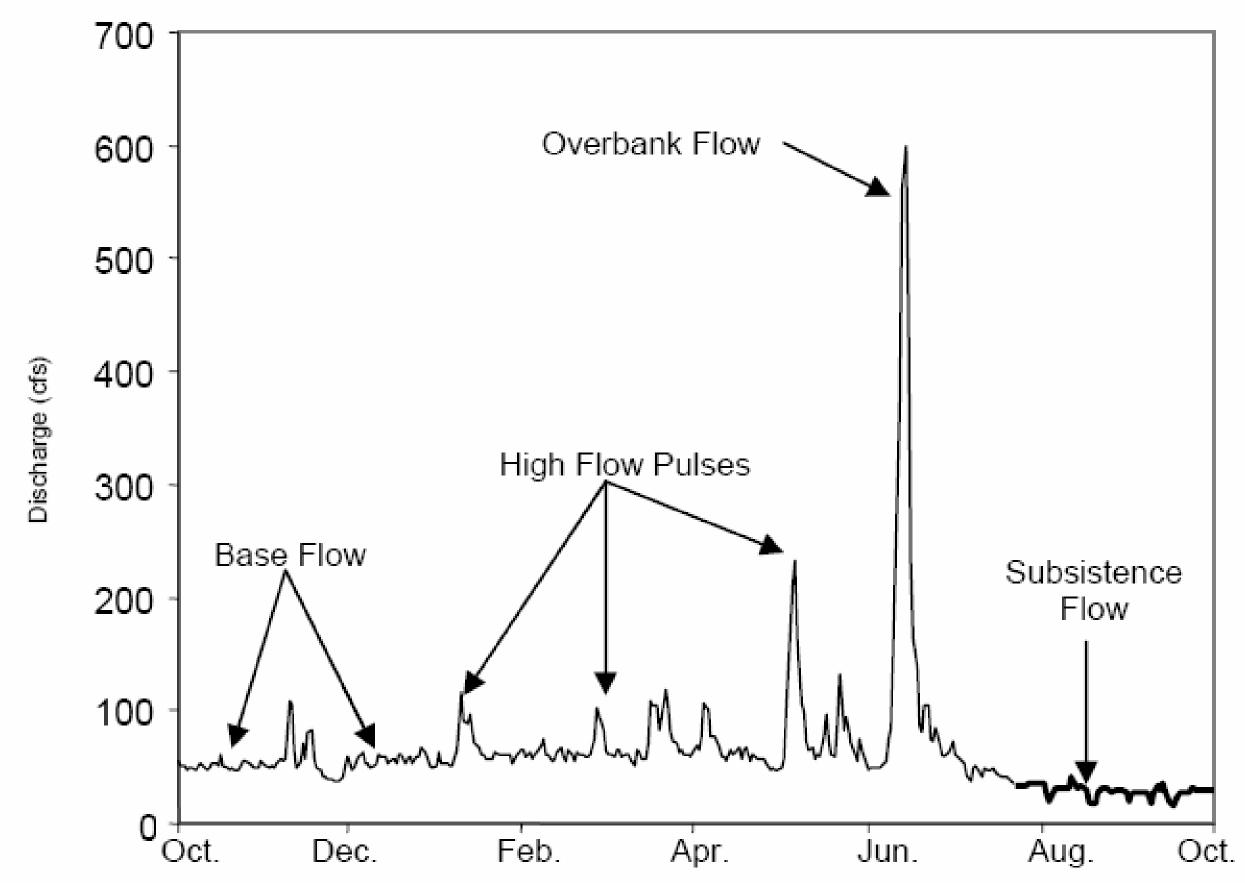
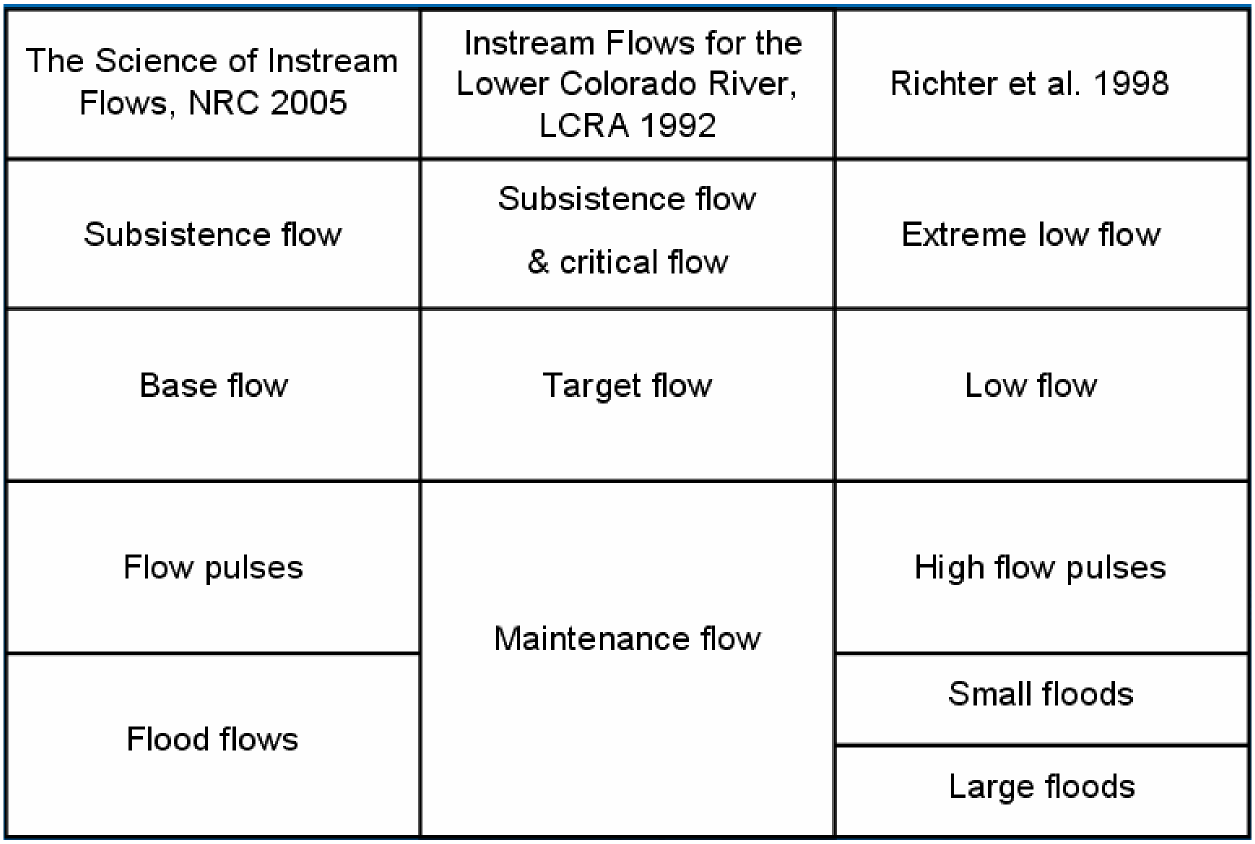


Figure 3. Example daily streamflow hydrograph depicting flow components (from NRC 2005).

Although the TIFP has adopted the conceptual model and terminology for flow components from the NRC report, previous iterations of this model had been presented (Richter et al. 1998), including one within the State of Texas (Mosier and Ray 1992) (Table 1).

Table 1. Comparison of conceptual models for flow components.



The Science of Instream Flows, NRC 2005	Instream Flows for the Lower Colorado River, LCRA 1992	Richter et al. 1998
Subsistence flow	Subsistence flow & critical flow	Extreme low flow
Base flow	Target flow	Low flow
Flow pulses	Maintenance flow	High flow pulses
Flood flows		Small floods
		Large floods

As discussed above, each of the four components of the natural flow regime controls and affects different purposes, functions, and processes of the riverine ecosystem, evident in each of the four TIFP disciplines (Table 2). Many of the flow pattern influences are specific to certain species, communities, regions, and rivers, and sound instream flow policy lies within the successful integration of these spatial, temporal, and interdisciplinary factors. Within the TIFP, the specific characteristics and their relative ecological significance will be identified as part of each sub-basin study, and specific flows may be recommended that provide specific ecological benefits (TIFP 2006).

It is important to note that hydrology occurs in four dimensions of space and time. Flow must be considered longitudinally (down a river's length), laterally (between river channel and floodplain), vertically (surface water-groundwater interactions), and through the course of time.

Table 2. Common characteristics for each flow component for each discipline (TIFP 2006).

Component	Hydrology	Geomorphology	Biology	Water Quality
Subsistence Flows	Infrequent, low flows	Increased deposition of fine & organic particles	Restricted aquatic habitat Limited connectivity	Elevated temperature Reduced levels of dissolved oxygen
Base Flows	Normal flow conditions with variability	Maintain soil moisture & groundwater table Maintain diversity of habitats	Suitable aquatic habitat Connectivity along channel corridor	Suitable in-channel water quality
High Flow Pulses	In-channel, short duration, high flows	Maintain channel & substrate characteristics Prevent encroachment of riparian vegetation	Recruitment events for organisms Connectivity to near-channel water bodies	Restore in-channel water quality after prolonged low-flow
Overbank Flows	Infrequent, high flows that exceed normal channel	Floodplain maintenance Lateral channel movement New habitat construction Flush organic material into channel Deposit nutrients in floodplain	Life phase cues for Organisms Riparian recruitment & maintenance Connectivity with floodplain	Restore water quality in floodplain water bodies

Hydrologic Characteristics

The range and variability of a flow regime is commonly characterized by the magnitude, frequency, duration, timing, and rate of change of hydrologic events (Karr 1991, Richter et al. 1996, Poff et al. 1997). Magnitude is a measure of the flow volume associated with a particular hydrologic event; frequency describes how often events occur within a specific time period; duration is how long an event occurred (above a certain flow rate threshold); timing is when the events occur within a specific time period; and rate of change is how rapidly the hydrograph rises and falls (Figure 4).

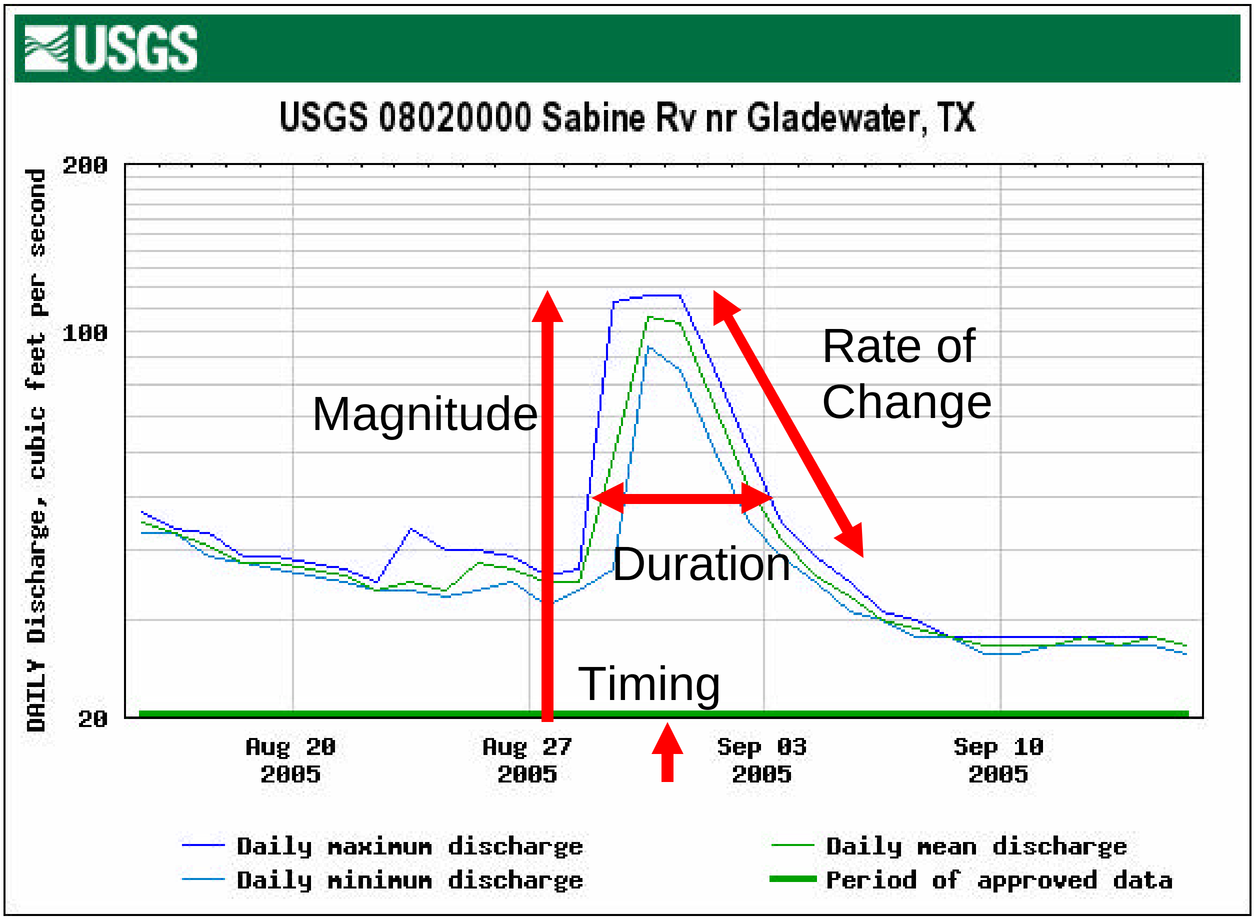


Figure 4. Hydrograph depicting hydrologic event characteristics (not shown: frequency).

II. Instream Flow Models

Categories

The science of quantifying environmental flow needs has progressed remarkably in the last half century, and hundreds of methods and models have emerged that seek to answer the question of how much water a river needs (Richter et al. 1997, Tharme 2003). Based on available data and resources and desired goals and confidence level, scientists have developed and applied methodologies from four broad categories (Table 3).

Table 3. Environmental flow model types.

- **Hydrologic (Desktop) Models**
    - Simple, cheap, inexpensive
    - Use flow as an indicator for ecological and biological functions
- Examples:
    - Indicators of Hydrologic Alteration (IHA), The Nature Conservancy, 1997
    - Hydrologic Assessment Tool (HAT), USGS, 2006
    - Tennant Method (a.k.a. Montana Method), U.S. Fish and Wildlife Service, 1976
    - Lyons' Method, Texas Parks and Wildlife Dept., 1979

- **Hydraulic Models**
    - Correlate flow with available habitat area based on river channel geometry
    - Physical proxy for *in-stream* ecology and biology, i.e., does not account for overbank processes
- Examples:
    - Wetted Perimeter Method, Montana Dept. of Fish, Wildlife, and Parks, 1970s
    - R2-Cross Method, Colorado Div. of Wildlife, 1980s

- **Habitat Models**
    - Complex, data intensive
    - Use target species population data with hydraulic data to determine optimal habitat
    - Mainly used for economically valuable or endangered species
    - Has proven legal credibility in the United States
- Examples:
    - Instream Flow Incremental Methodology (IFIM), U.S. FWS, 1970s. Includes Physical Habitat Simulation Model (PHABSIM)

- **Holistic Models**
    - Very complex, resource and data intensive
    - Comprehensive ecosystem assessment
    - Based on multidisciplinary scientific consensus
- Examples:
    - Building Block Methodology (BBM), South Africa Dept. of Water Affairs and Forestry and Univ. of Cape Town, 1990s. Top-down approach.
    - Downstream Response to Imposed Flow Transformation (DRIFT), above plus Southern Waters Ecological Research and Consulting, 1990s

Model Development

IHA

According to The Nature Conservancy's Sustainable Waters Program website (TNC 2006):

> The Indicators of Hydrologic Alteration (IHA) is a software program that provides useful information for those trying to understand the hydrologic impacts of human activities or trying to develop environmental flow recommendations for water managers. More than 1,000 water resource managers, hydrologists, ecologists, researchers and policy makers from around the world have used this program to assess how rivers, lakes, and groundwater basins have been affected by human activities over time, or to evaluate future water management scenarios.

IHA was originally developed as a result of work done by Brian Richter and others from 1996 through 1998, and is intended to model "what the fish feels" (Richter et al. 1996, Richter et al. 1997, Poff et al. 1997, Richter et al. 1998). In this study, IHA version 7.0.0 Beta 4.10 was used.

HAT

The Hydrologic Assessment Tool (HAT) is a primary component of the USGS Hydroecological Integrity Assessment Process (HIP) software. HIP was developed in 2004 to 2006 by a team led by James Henriksen of the USGS Fort Collins [Colorado] Science Center along with the New Jersey Water Science Center and the New Jersey Department of Environmental Protection. The current HIP software suite is composed of four components:

1. **Hydrologic Index Tool (HIT)**, version 1.0. HIT is a generic tool (i.e., not developed for any particular geographic region) to calculate the 171 statistical hydrologic indices presented in Olden and Poff (2003) based solely on the input of USGS streamflow data for any gaged site.
2. **National Hydrologic Assessment Tool (NATHAT)**, version 3.0. Commonly referred to in this document as "HAT," NATHAT is a nationwide customization of HIT based on the six stream classifications of Olden and Poff (2003). The six stream classes were pared down from ten original classes developed by Poff (1996) based on a study of 420 gages across the contiguous United States (Figure 5). Although NATHAT performs the full complement of 171 statistical routines, the default graphical presentation of results is limited to the ten non-redundant, critical indices identified by Olden and Poff (2003) for each of their six national stream classes.

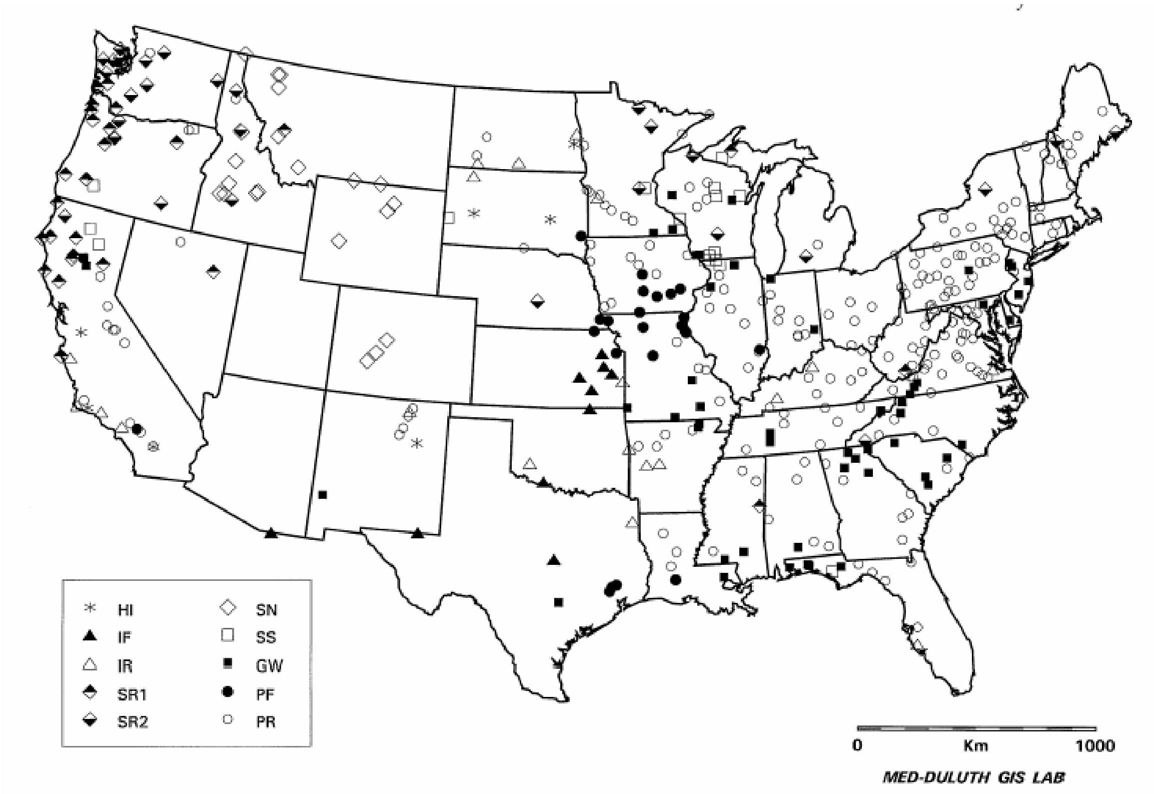


Figure 5. Location and stream classification of the 420 gages of Olden and Poff (2003).

3. **New Jersey Stream Classification Tool (NJSCT)**, version 1.0. NJSCT is a New Jersey-specific tool to partition that state's gaged streams into four stream classes, termed A, B, C, and D, by their relative degree of skewness of daily flows (high versus low) and by the relative frequency of low flow events (high versus low). The USGS currently has no plans to develop a national stream classification tool on this basis.
4. **New Jersey Hydrologic Assessment Tool (NJHAT)**, version 3.0. NJHAT is a New Jersey-specific regionalization of NATHAT incorporating the results of the NJSCT and the identification of ten primary flow indices for each of the State's four stream classes.

The analyses presented in this report were predominantly performed using a 2005 beta-released version of NATHAT, version 2.15. HIP was officially released to the public in June 2006. Currently, New Jersey is the only state to have completed the Hydroecological Integrity Assessment Process. The Missouri Department of Conservation is in the midst of the process with USGS as is the Commonwealth of Massachusetts, and the TCEQ is set to embark on the process as well in 2006-2007 (Henriksen personal communication 2006, Henriksen et al 2006).

Input Data Requirements and Sources

Note on Model Documentation

This document is not intended to be a user's manual for the IHA and HAT programs; refer to The Nature Conservancy (2006a) and Henriksen et al (2006) for that purpose. Use of the tools will be described only where an important distinction exists that affects the functionality and/or suitability of the program for use in the TIFP.

IHA

IHA requires an input file of daily streamflow data; in the United States, these data are typically obtained from the USGS National Water Information System (NWIS). To adequately capture annual and interannual variations in the flow regime, 20 or more years of continuous daily flow data are recommended (Richter et al. 1997). Currently, there are NWIS records for 957 stream gaging sites in the State of Texas, of which 406 have 20 or more years of daily flow data.

If data are missing from the input files, IHA performs a linear interpolation across the missing data gap. If a particular year in the input flow record has no data values, the entire year will be excluded from analysis. The IHA program will issue a warning message if there is a consecutive block of missing data greater than a user-defined length, defaulted as 10 days; a warning message is also issued to identify water years with more than 30 missing daily values.

HAT

HAT requires the same input file of daily streamflow as IHA, and the above-discussed issue of record length remains applicable. If data are missing from the input files, HAT will not interpolate data gaps and will not use missing flow value days in the statistical calculations; however, all years within the user-specified period of record will be used in the analyses. In both IHA and HAT, data gaps of significant length will cause the programs to return peculiar results. The number of missing flow values that might invalidate or otherwise cast excessive doubt on the flow statistics returned by the program results is debatable, but the user must be aware of the effect of missing data when performing analyses. HAT also requires a file of annual instantaneous peak flow data that is also commonly available from NWIS. If peak data are not available, the analysis can still be performed to generate all but eight indices (Table 4).

Table 4. HAT indices requiring the input of peak flow data.

Index	Definition
FH11	Flood frequency
DH22	Flood interval
DH23	Flood duration
DH24	Flood-free days
TA3	Seasonal predictability of flooding
TH3	Seasonal predictability of non-flooding
TL3	Seasonal predictability of low flow
TL4	Seasonal predictability of non-low flow

Detailed definitions and calculation instructions for these indices along with an explanation of the index naming convention can be found in Appendix C – HAT Parameters. Of these eight indices, the first six are based on the definition of a flood as a flow event exceeding a 1.67-year recurrence interval, calculated by assuming the peak flow values are a sample from a lognormal distribution of flows; the last two are based on the same principle, but use a 5-year recurrence interval for low flow calculations (Poff 1996). The 1.67-year flood is used as an assumption of bankfull flow (Dunne and Leopold 1978).

Model Use and Application

Temporal Scale

Both IHA and HAT include indices calculated across multiple time scales ranging from daily to annual and intra-annual statistics. This range of time scales is important to adequately capture the timing, duration, frequency, and rate of change aspects of a flow regime. Both IHA and HAT include tools to define analyses based on either one or two specific time periods that are not necessarily the period of record. This is a powerful feature of the tools in that they can be used to isolate and characterize the flow regime for particular time periods of interest, including: before and after water development project implementation, before and after major water withdrawals or transfers, and specific droughts or wet periods, among others. IHA allows for batch processing of multiple data sets at once, a feature that HAT does not currently support.

External Verification

For both programs, flow statistics are calculated such that independent external verification is possible. Henriksen (2006) includes a discussion of HAT verification results performed by USGS and Colorado State University using commercially-available software including: MATLAB, SAS, and Microsoft Excel. Calculations of the 33 IHA indices (not including the 34 Environmental Flow Components (EFCs)) were replicated using Microsoft Excel in unpublished work by Joe Trungale (2006) of Trungale Engineering and Science for a sample Texas streamflow gage.

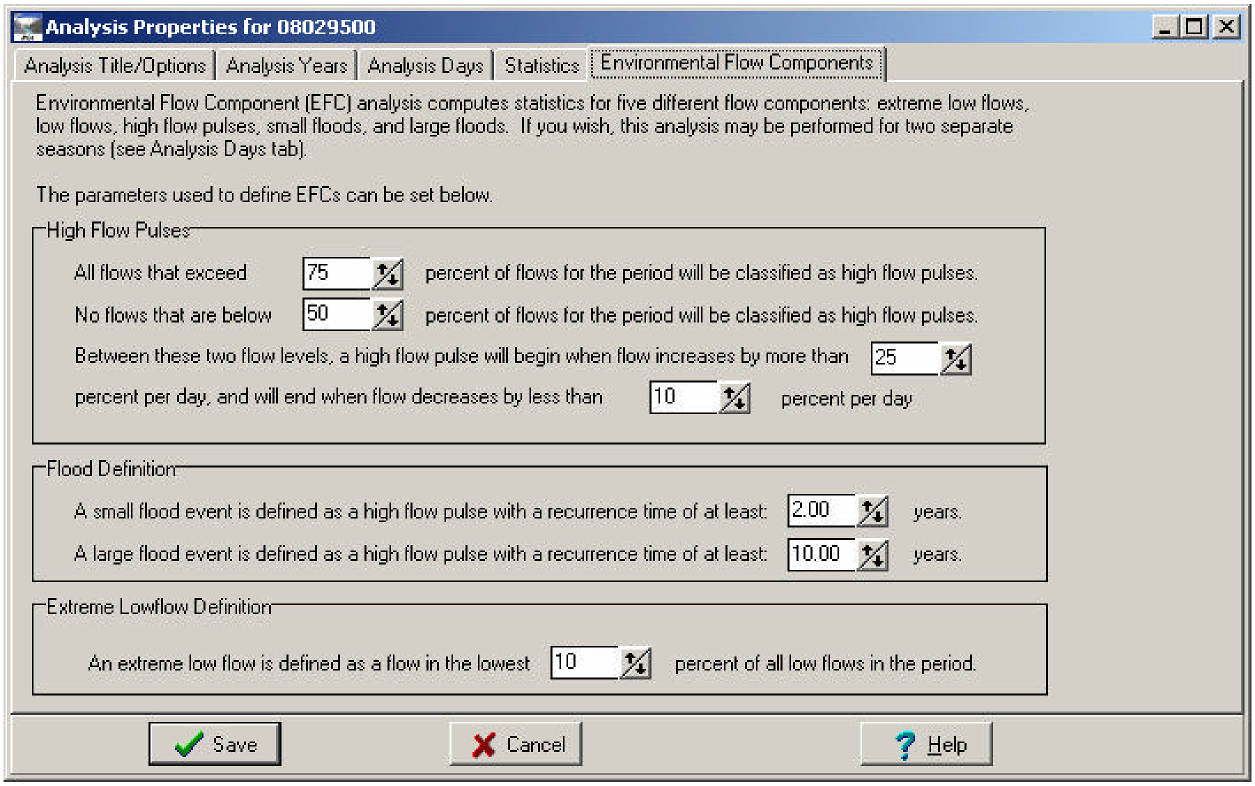
Statistical Definitions

Both IHA and HAT allow the user to choose between parametric (characterized by a normal distribution around the mean with a standard deviation) and non-parametric statistics (no *a priori* frequency distribution, characterized by the median and percentiles). 'For most [hydrologic] situations non-parametric statistics are a better choice, because of the skewed (non-normal) nature of many hydrologic datasets…but for certain situations, such as flood frequency or average monthly flow volumes, parametric statistics may be preferable." (The Nature Conservancy 2006a).

Environmental Flow Component Definitions

The four flow component conceptual model recommended in the NRC Report and subsequently adopted into the TIFP Technical Overview bears strong resemblance to the IHA Environmental Flow Component (EFC) model as the lead IHA developer, Brian Richter of The Nature Conservancy, served on the NRC committee. The stated goal of delineating the hydrograph in this manner is linking specific flow events with their ecological purposes so that the benefits of each flow component are preserved or recreated (The Nature Conservancy 2006a). One difficulty of this flow component model is that the specific linkages, particularly biological, must be understood in a particular sub-basin so that the appropriate flow components may be incorporated into the environmental flow prescription. In the absence of detailed understanding and exhaustive data on various riverine systems, a first-pass approach may be used in conjunction with a program of adaptive management, where indicators of system health are monitored for a period of time following instream flow implementation and the flow criteria reevaluated as needed. Nonetheless, it behooves the tri-agencies and stakeholders to make the 'first-pass' at flow component delineation as ecologically-significant as possible by optimizing the flow thresholds based on realistic, physically-based principles.

The IHA EFC parameters (Appendix B) are broken down into five categories: extreme low flow, low flow, high flow pulses, small floods, and large floods. The software incorporates default parameters for the delineation of the EFCs as well as an interface for some user modification of the defaults (Figure 6).



Environmental Flow Component (EFC) analysis computes statistics for five different flow components: extreme low flows, low flows, high flow pulses, small floods, and large floods. If you wish, this analysis may be performed for two separate seasons (see Analysis Days tab).

The parameters used to define EFCs can be set below.

High Flow Pulses

All flows that exceed 75 percent of flows for the period will be classified as high flow pulses.

No flows that are below 50 percent of flows for the period will be classified as high flow pulses.

Between these two flow levels, a high flow pulse will begin when flow increases by more than 25 percent per day, and will end when flow decreases by less than 10 percent per day

Flood Definition

A small flood event is defined as a high flow pulse with a recurrence time of at least: 2.00 years.

A large flood event is defined as a high flow pulse with a recurrence time of at least: 10.00 years.

Extreme Lowflow Definition

An extreme low flow is defined as a flow in the lowest 10 percent of all low flows in the period.

Figure 6. IHA EFC definitions screen, displaying default thresholds.

Under the IHA EFC model, all daily flows fall within one of the five categories and a complex algorithm parses the hydrograph accordingly based on the delineation thresholds being employed (Figure 7). The program logic is to separate flow into base flows and flow pulse periods (i.e. partition in time) using a base flow separation method, then take the pulses and classify them by the rate of change of flow (from percent difference from previous day) and take the base flows and classify them by the magnitude (from recurrence intervals). The thresholds include: flow magnitude (e.g.: 10th percentile and median), recurrence intervals (e.g.: 2-year event), and rate of change (e.g.: 25 percent flow increase from previous day). The default threshold values were recently reformulated based on the scientific judgment of the software developers from their extensive collective experience to be “ecologically-responsive” to model “what a fish feels,” but not all the consequences of this reformulation on flow characterization have been worked out as of yet (Richter personal communication 2006).

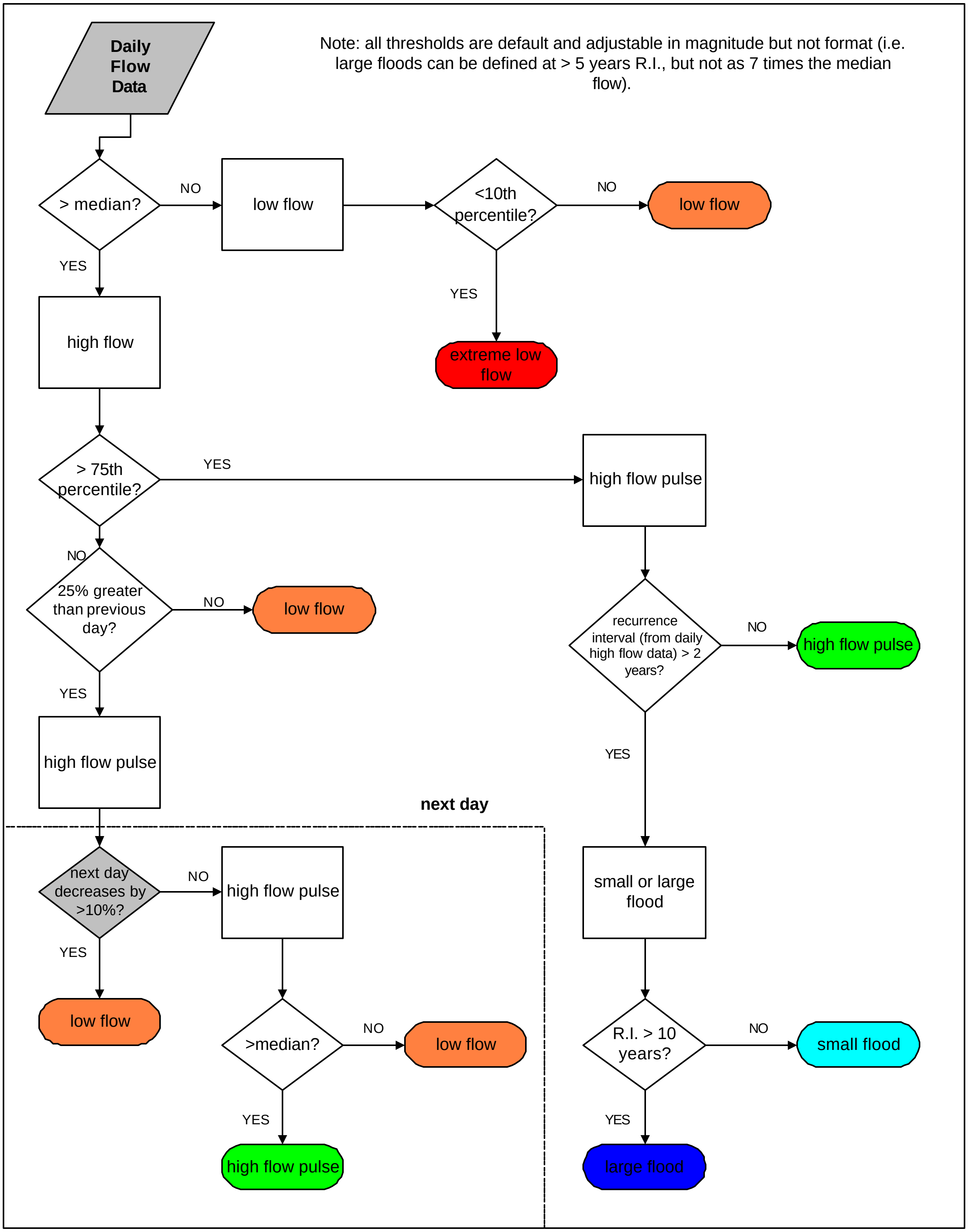


Figure 7. IHA Environmental Flow Component algorithm flow chart.

The software allows for the user to change the magnitude of each threshold but not the type of threshold employed. For example, small floods can be adjusted from the 2-year recurrence interval to a 1.5-year or 3-year event but not pegged to the 80th percentile of all daily flows or three times the median flow. In addition, the algorithm methodology with respect to the rate of flow onset or recession often defines daily streamflows with smaller absolute magnitude than other recent days being considered as high flow pulses, whereas the 'higher flows' are considered low flows (Figure 8). The default rate of change parameters can be tweaked to minimize this occurrence, but this anomaly likely results in a flow characterization too complex for effective regulation and the communication of said regulation. A quantitative comparison of cases where the IHA EFCs overlap is presented in Figure 9. Likewise, this increased level of complexity of flow component delineation does not mesh well with the goal for flow prescriptions presented in the TIFP Technical Overview (2006).

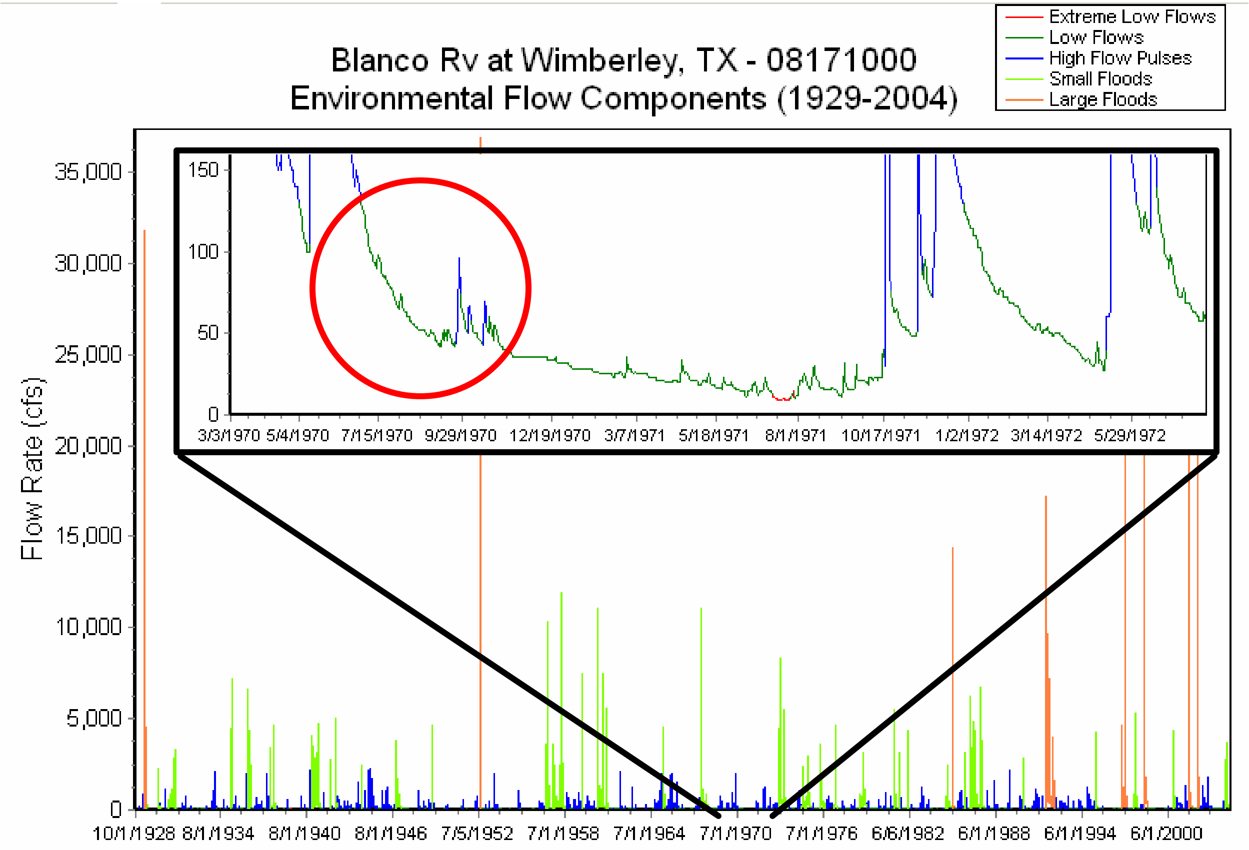


Figure 8. Daily Environmental Flow Components for USGS Gage No. 08171000, Blanco Rv at Wimberley, TX, with a close-up view of a case where low flows (dark green) are of greater magnitude than high flow pulse events (blue).

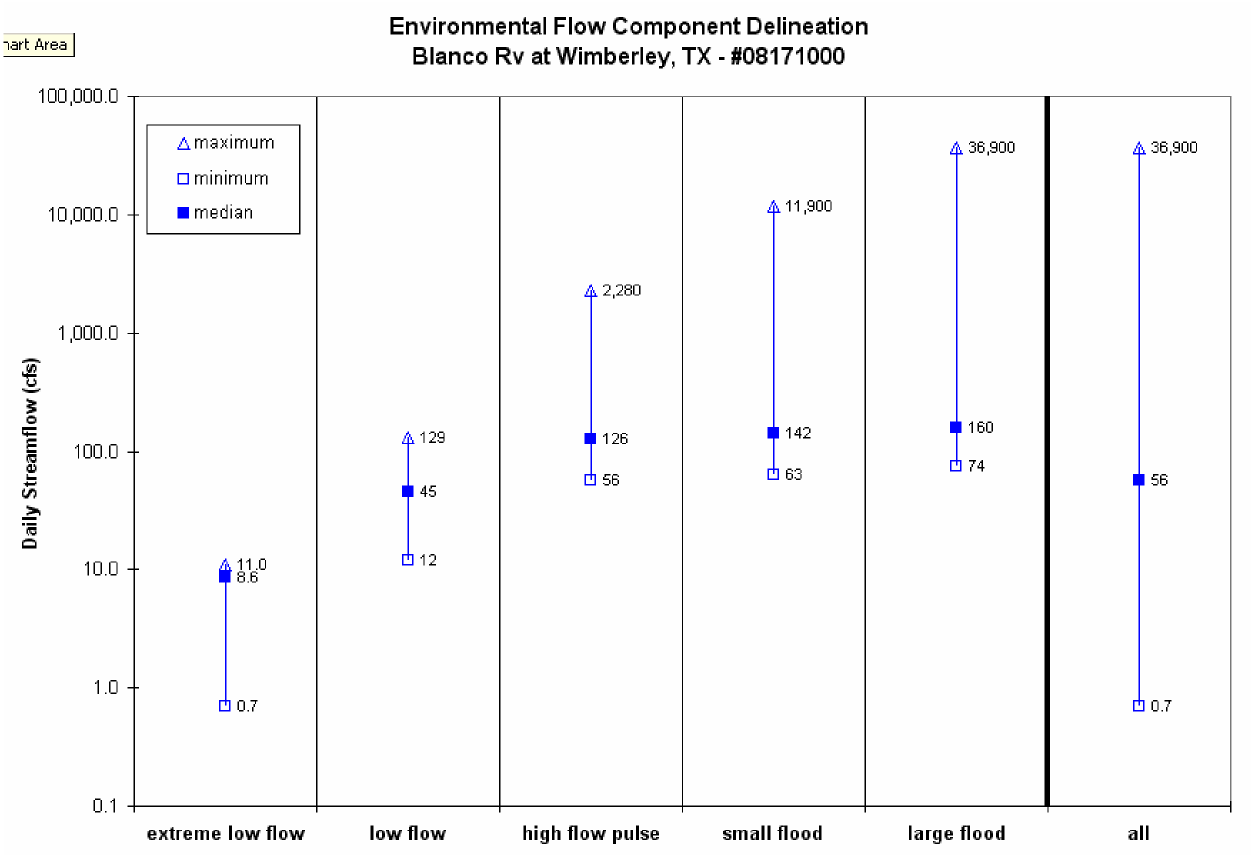
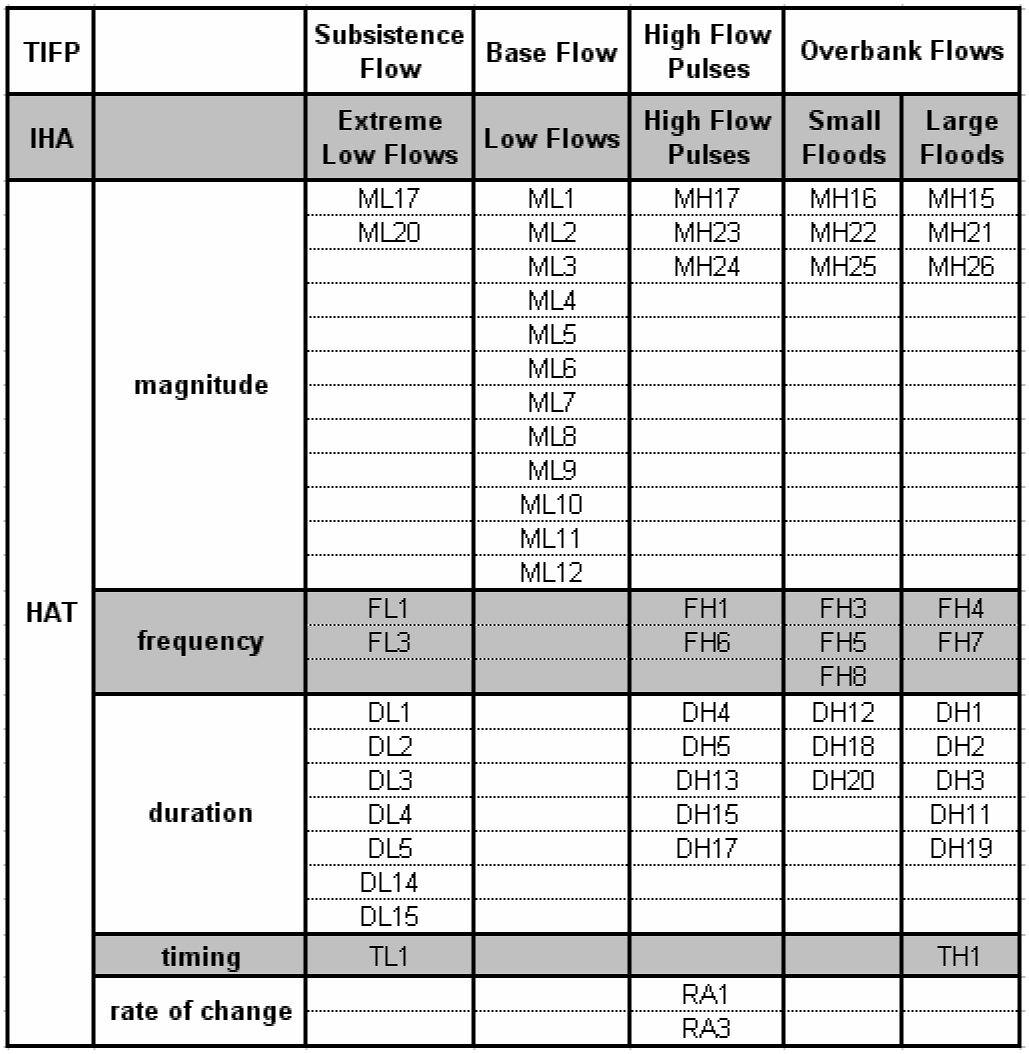


Figure 9. Quantitative comparison of IHA EFCs for USGS Gage No. 08171000, Blanco Rv at Wimberley, TX for the period of record.

The hydrologic stream classification of NATHAT includes six stream types that arose from the hydrogeographic classification scheme of Poff (1996): (1) harsh intermittent, (2) intermittent flashy or runoff, (3) snowmelt, (4) snow and rain, (5) superstable or stable groundwater, and (6) perennial flashy or runoff. The stream types are based on Pearson correlation coefficients for 13 variables on 420 streams nationwide. HAT includes flow indices based on: percentiles, multipliers of the median flow, and recurrence intervals, among others (Appendix C). None of the statistics are internally adjustable with respect to flow component thresholds, but HAT also does not define Environmental Flow Components (i.e., "what the fish feels") as IHA does, so no specific indices or thresholds are tied to any particular flow component. In other words, it is up to the user to explore the results produced by HAT (often using statistical tools) to select appropriate indices for flow component delineation or otherwise for hydrograph characterization. One example of this selection process is the multivariate statistics Principal Component Analysis

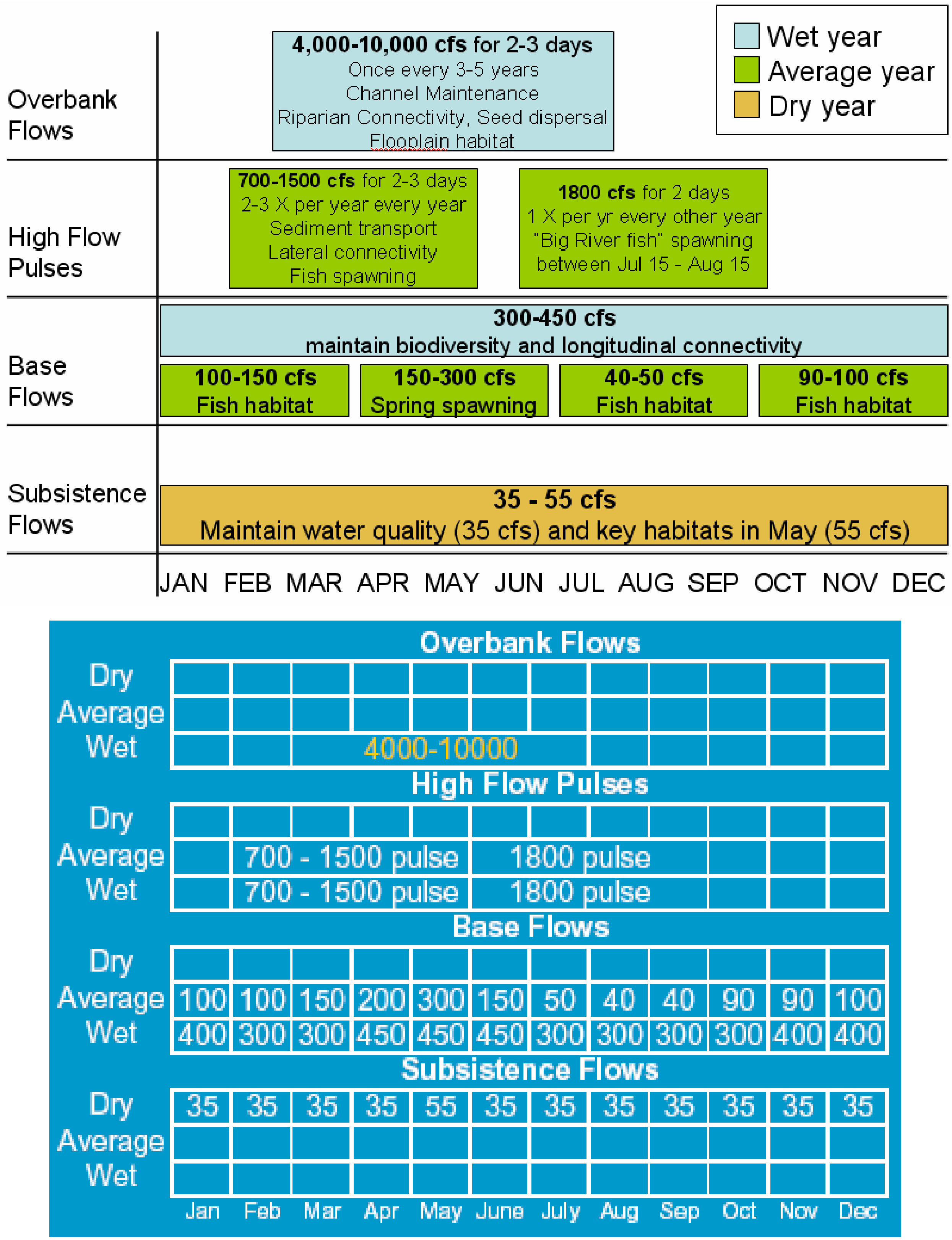
(PCA) that was employed by USGS and NJDEP to determine a subset of non-redundant indices for the NJSCT and NJHAT. A number of the 171 HAT indices describe streamflow in a manner that closely parallels the TIFP flow component model (Table 5).

Table 5. HAT indices useful for the delineation of the TIFP flow components (refer to Appendix C for explanation of indices).



TIFP		Subsistence Flow	Base Flow	High Flow Pulses	Overbank Flows	
IHA		Extreme Low Flows	Low Flows	High Flow Pulses	Small Floods	Large Floods
HAT	magnitude	ML17	ML1	MH17	MH16	MH15
		ML20	ML2	MH23	MH22	MH21
			ML3	MH24	MH25	MH26
			ML4			
			ML5			
			ML6			
			ML7			
			ML8			
			ML9			
			ML10			
			ML11			
			ML12			
	frequency	FL1		FH1	FH3	FH4
		FL3		FH6	FH5	FH7
					FH8	
	duration	DL1		DH4	DH12	DH1
		DL2		DH5	DH18	DH2
		DL3		DH13	DH20	DH3
		DL4		DH15		DH11
		DL5		DH17		DH19
		DL14				
		DL15				
	timing	TL1				TH1
	rate of change			RA1		
				RA3		

The intended outcome for SB2 is an instream flow prescription that integrates the results of the multi-disciplinary studies, broken down by month, by flow component, and by hydrologic conditions (i.e. wet, dry, normal years) (Figure 10). Each 'building block' depicted in Figure 10a is intended to provide the flow conditions necessary to provide the associated ecosystem function (e.g. channel maintenance, seed dispersal, fish spawning, etc). Although a number of hydrologic



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Overbank Flows												
Dry												
Average												
Wet			4000-10000									
High Flow Pulses												
Dry												
Average		700 - 1500 pulse				1800 pulse						
Wet		700 - 1500 pulse				1800 pulse						
Base Flows												
Dry												
Average	100	100	150	200	300	150	50	40	40	90	90	100
Wet	400	300	300	450	450	450	300	300	300	300	400	400
Subsistence Flows												
Dry	35	35	35	35	55	35	35	35	35	35	35	35
Average												
Wet												

Figure 10. (a) Example instream flow prescription to be developed under SB2 depicting integration of the flow components, and (b) tabular representation of (a) (TIFP 2006).

indices in NATHAT can be used to delineation the TIFP flow components (Table 5), HAT is not explicitly designed in accordance with the flow component model of IHA and subsequently incorporated into TIFP based on the NRC recommendations (NRC 2005). As such, modifications would need to be made to HAT to increase its suitability for use in the TIFP that would focus on assessing the appropriate hydrologic indices to delineation each of the four flow components. The indices presented in Table 5 could be evaluated for application for Texas rivers, modified or amended as needed, and the NATHAT software could be revised to present analyses and results grouped by flow component.

In IHA, all of the flow magnitude indices are absolute and expressed as the volumetric flow rate in units of length cubed per time, often cubic feet per second (cfs) or cubic meters per second (cms). IHA allows for the normalization of some flow statistics by the contributory drainage area. In HAT, some of the indices are expressed in similar fashion, whereas others are normalized by another flow, often the median daily streamflow, resulting in a dimensionless ratio. These ratios give an indication of the range of the flow regime and the occurrence of various flows within that regime, yet are decoupled from the watershed size and characteristics. This allows for an isolated characterization of the hydrograph shape and pattern and also for an equivalent comparison of these dimensionless ratios across disparate drainage basins or regions of the State, a feature highly valuable for TIFP. Although IHA allows for normalization by drainage area, varying impacts of factors such as land use, land cover, soils, surficial geology, and local climatology cause varying hydrologic responses that are not necessarily explained by the sheer area of flow contribution. By normalizing by another flow at the same gage, the indices in HAT account for (and thus remove) many of the impacts of the physical and climatological factors associated with flow generation.

Model Output

IHA

IHA tabular output is displayed on-screen in Microsoft Spreadsheet format and can easily be exported to spreadsheet software such as Microsoft Excel. The output includes tabbed pages for:

(1) annual summary statistics, (2) (non-) parametric IHA summary scorecard, (3) linear regression, for identifying trends in the data, (4) IHA percentile data, (5) EFC daily flow characterization, and (6) messages and warnings regarding the results generated. The output is also available as text (.txt) files.

IHA graphical output includes numerous plotting options for various indices with various presentation styles. The plots are displayed individually on-screen and can be exported or captured to image software (such as Microsoft Paint) or saved in various graphics file types (e.g. .jpg). The current version of IHA appears to have a software bug for certain operating systems that affects the quality of exported images (Figure 11a). Screen-capture tools can be used as a workaround to this problem, but the exporting bug should be addressed in future versions of IHA (Figure 11b).

HAT

HAT tabular output is saved in comma-separated value (.csv) files that can also be read into standard spreadsheet software. The single output table consists of the median value of each of the 171 statistical indices across all years of the period analyzed along with the lower and upper limits of that particular value, where applicable. The defaults for the limits are the 25th and 75th percentiles of the results, but the percentiles can be user-defined. Some of the indices do not have limits associated with them. For example, TL1, the median Julian day of the annual minimum flow across all years, is a single, finite numeric value, has no distribution of results, and thus has no related percentiles.

Additional tables and graphs of the ten default 'non-redundant' indices for the selected stream type are available within the HAT program; the ten default indices for the six stream types are based on the hydrogeographic classification scheme of Poff (1996). In lieu of the ten default indices, the user has two alternatives. First, the ten default indices can be user-selected from menus of 18 to 30 indices (number based on stream type), with one index representing each of the following categories: (1) magnitude of flow events under average flow conditions, (2) magnitude of flow events under low flow conditions, (3) magnitude of flow events under high

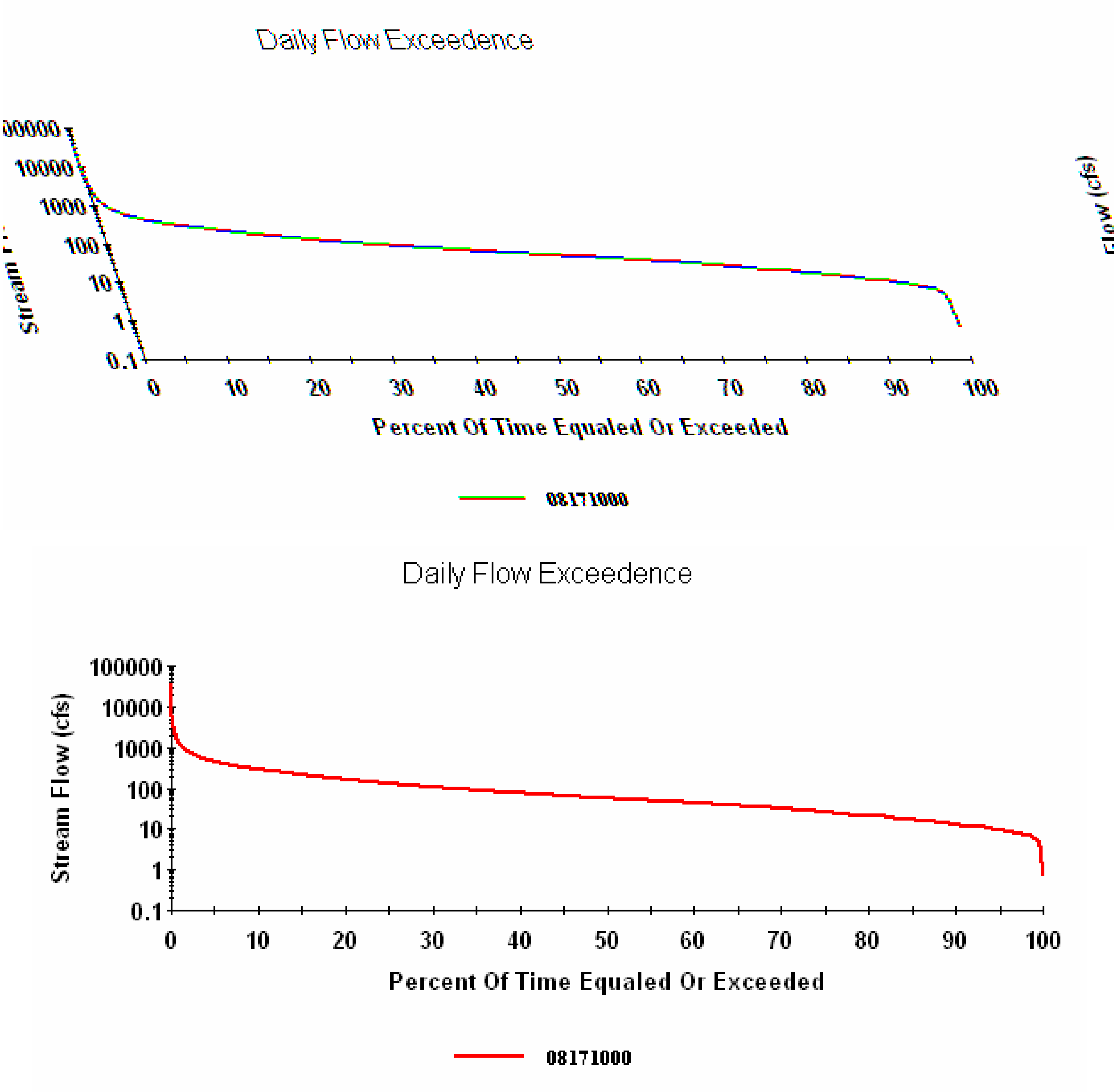
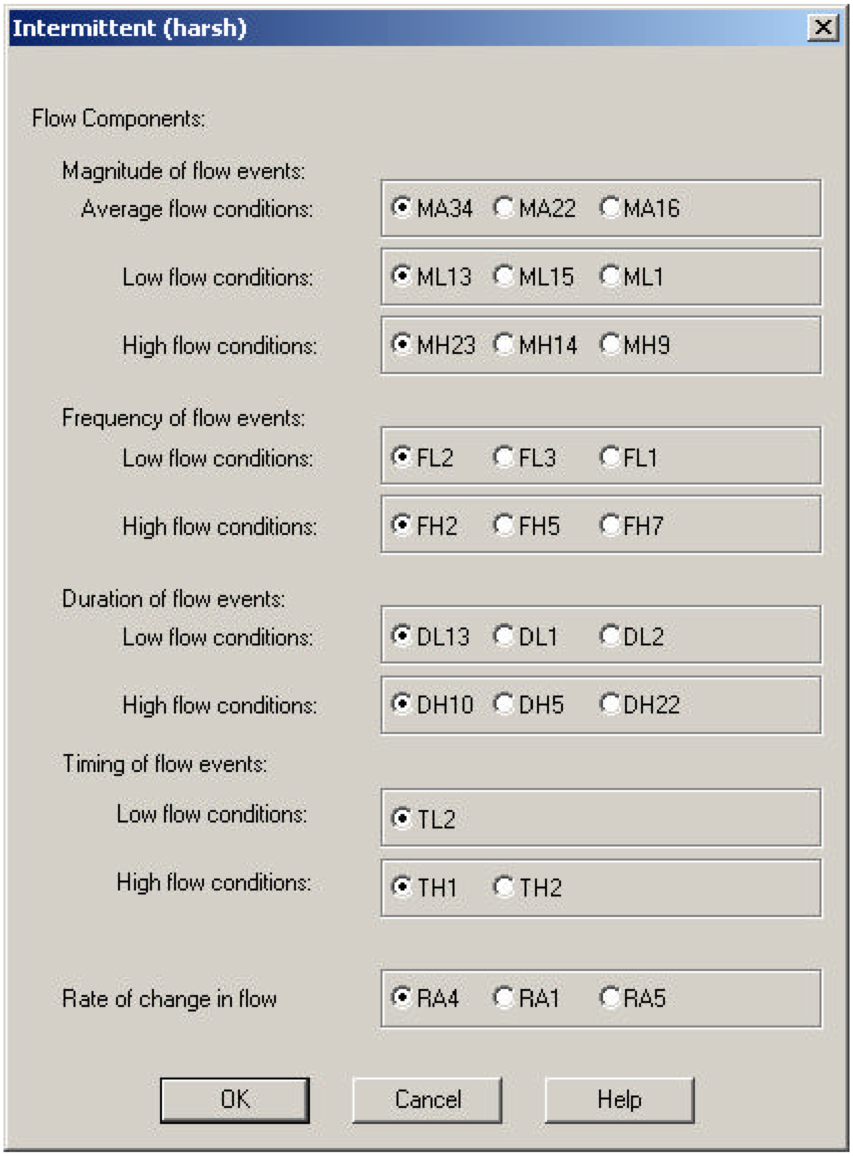


Figure 11. (a) Example of graphics capture bug present in version 3.0 of NATHAT; (b) same plot as viewed on-screen in the NATHAT software and captured for comparison here using screen-capture tools.

flow conditions, (4) frequency of flow events under low flow conditions, (5) frequency of flow events under high flow conditions, (6) duration of flow events under low flow conditions, (7) duration of flow events under high flow conditions, (8) timing of flow events under low flow conditions, (9) timing of flow events under high flow conditions, and (10) rate of change in flow (Table 6, Figure 12).

Table 6. Ten default hydrologic indices for each stream type in NATHAT.

Stream Type	Magnitude	Frequency	Duration	Timing	Rate of Change
Intermittent (harsh)	MA34, ML13, MH23	FL2, FH3	DL13, DH10	TL2, TH1	RA4
Intermittent (flashy or runoff)	MA37, ML16, MH23	FL2, FH3	DL18, DH13	TL1, TH3	RA9
Perennial (snowmelt)	MA29, ML13, MH1	FL3, FH8	DL5, DH19	TL1, TH1	RA1
Perennial (snow and rain)	MA3, ML13, MH17	FL3, FH3	DL6, DH12	TL1, TH1	RA9
Perennial (superstable/ stable groundwater)	MA3, ML18, MH17	FL3, FH3	DL9, DH11	TL2, TH1	RA9
Perennial (flashy or runoff)	MA26, ML17, MH23	FL3, FH4	DL10, DH13	TL1, TH3	RA9



Intermittent (harsh)

Flow Components:

Magnitude of flow events:
Average flow conditions: ● MA34 ○ MA22 ○ MA16
Low flow conditions: ● ML13 ○ ML15 ○ ML1
High flow conditions: ● MH23 ○ MH14 ○ MH9

Frequency of flow events:
Low flow conditions: ● FL2 ○ FL3 ○ FL1
High flow conditions: ● FH2 ○ FH5 ○ FH7

Duration of flow events:
Low flow conditions: ● DL13 ○ DL1 ○ DL2
High flow conditions: ● DH10 ○ DH5 ○ DH22

Timing of flow events:
Low flow conditions: ● TL2
High flow conditions: ● TH1 ○ TH2

Rate of change in flow ● RA4 ○ RA1 ○ RA5

Figure 12. Example NATHAT default hydrologic index selection menu depicting selection options for one of the six stream types.

The selection of ten replacement indices may be saved in the NATHAT software as the program default. Second, up to twelve indices of the entire list of 171 can be selected for graphical presentation, but this selection can not be saved within the software. Output presented within the program can be exported similarly to IHA.

III. Model Application in the Texas Instream Flow Program

Hydrologic Study Needs

Hydrologic and hydraulic analyses are an integral part of all of the steps of the TIFP sub-basin studies, and a robust hydrologic statistics tool is essential for many of the study steps. For the purposes of the flow regime, there is a need to calculate subsistence flow, base flow, high flow pulse, and overbank flow (flood) frequency statistics and to define wet, dry, and normal years. During the Reconnaissance and Information Evaluation step recommended in TIFP (2006), there is a need to calculate historic and current flow statistics and to identify existing features (e.g., tributaries) and existing and proposed alterations (diversions, impoundments, land uses, etc) affecting hydrologic character. During the Data Integration to Generate Flow Recommendations step, there is a need to: (1) calculate the occurrence of various flow rates during historical and current conditions, (2) determine annual variability of hydrologic characteristics, including description of wet, normal and dry years, (3) develop hydrologic time series to evaluate habitat suitability of a proposed flow regime, (4) calculate variability a of proposed flow regime and compare with historic/current conditions, and (5) evaluate how proposed flow regimes would impact current operating conditions (TIFP 2006).

Temporal Resolution

A focus of current environmental flow science is on the importance of flow events that operate on a relatively small (i.e., daily) time step. This represents a paradigm shift from historical methods applied in Texas such as the Lyons Method (Bounds and Lyons 1979) that uses daily gaged flow data as input but the resulting flow prescriptions are presented on a monthly basis. Likewise, the Consensus Criteria for Environmental Flow Needs (CCEFN) (TCEQ 2004) are developed using monthly flow data from the Water Rights Analysis Package (WRAP) Water Availability Models (WAM) (Wurbs 2003, TCEQ 2006).

Both IHA and HAT require the input of daily flow data, and both models generate statistical indices that represent a broad spectrum of time scales: daily, weekly, monthly, seasonal, annual, and inter-annual. This point is critical in that neither model can ingest the monthly naturalized flows derived from the Water Availability Models, nor can they ingest any other flow data that is measured or modeled on a monthly time step. If the Texas Instream Flow Program is to use monthly flow data, neither program is applicable. Thus, daily flow data must be available at the site of interest or must be reconstructed from monthly flow data. It is possible to synthesize a daily flow record via apportionment of modeled monthly flows, but this transformation inherently introduces uncertainty into the input data.

If the IHA and HAT models were modified to require the input of monthly flow data instead of daily, some of the statistical indices of the two tools would be impossible to calculate and others would have less relevance due to the decreased temporal resolution. In general, indices of flow magnitude would be largely preserved but indices of flow frequency, duration, timing, and rate of change would be largely destroyed. This is because hydrologic events that are driven by runoff occur on a time scale much smaller than one month, so any signal generated by individual flow events within a month would be muted when viewed over the entire month.

Additional Potential Enhancements

Calculation of Medians

Measures of central tendency are critical to hydrologic analysis and various calculation methods were explored in detail in this study; a discussion of these methods can be found in the following chapter. From this work, however, arose a concern over the methodology IHA and HAT use to calculate the monthly median flow.

As depicted in Figure 13a, the two software tools first calculate the median for all daily flows within one month of one year (here, January 1940), repeat this process for every January, then calculate the median of all the January values to get the long-term median flow for the month of January across the entire time period of analysis. Given the typical large positive skew in the distribution of streamflow data, particularly for streams in Texas, calculating the median of a median likely results in a downward bias. More accurate methods for calculating the long-term daily median and the long-term monthly median are shown in Figure 13b and Figure 13c; these methods are considered 'more accurate' because they eliminate the likely downward bias that results from the multi-step calculation process of Figure 13a. The concern discussed above is a moot point if parametric statistics are being calculated, as the mean of a mean preserves the true measure of central tendency. The method shown in Figure 13b was employed in this study to calculate median daily flows, as discussed in the Measures of Central Tendency section.

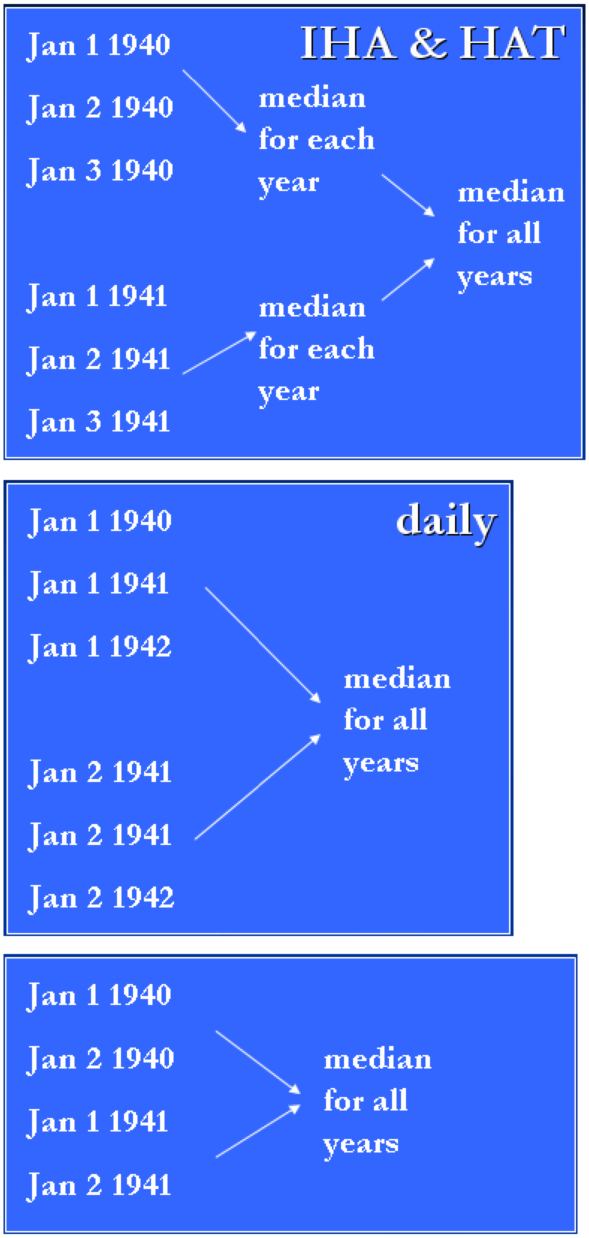


Figure 13. Various procedures for the calculation of median streamflows: (a) method employed in IHA, (b) alternative method for daily medians, and (c) alternative method for monthly medians.

Environmental Flow Component Thresholds

As previously discussed, the default IHA EFC flow thresholds that define the five flow components (extreme flow, low flow, high flow pulses, small floods, and large floods) arose from the judgment of the ecologists and hydrologists that is based on and field-truthed over time at multiple rivers and regions across the United States and the world. Oftentimes, the EFCs and environmental flow prescriptions are tailored for specific applications such as the protection or restoration of a particular species, habitat, or life cycle cue. A large body of research (see discussion in Poff et al (1997)) has established the ecological significance of certain flow components for certain species for certain purposes in certain regions of the world. However, TIFP faces a different and broader challenge. Rather than a specific, narrow goal, the language of SB2 calls for the "support of a sound ecological environment," a much more holistic viewpoint that has been interpreted to account for all endemic species over all of their lifecycles for all habitat types across all regions of the State.

Given the diversity of species, habitats, and other conditions within the large State of Texas, the difficulty of establishing suitable flow component thresholds becomes obvious. Thus, the default EFC delineations in IHA may not be representative nor suitable for widespread application in Texas, and additional field studies and sampling would be required to truly ascertain the ecological significance of various components of the flow regime.

As such, there is a need to establish the ecological significance of the EFC thresholds for Texas, or redefine the thresholds accordingly. It would be ideal to customize the thresholds to suitable Texas flow component delineations, such as recurrence intervals, percentiles, or fixed flow rates at specific points, like the streamflow required to reach the incipient point of overbank flooding at a particular cross section of interest. The development of such basin- or reach-specific thresholds is likely to be highly resource intensive, and this work is likely to be developed on a study-specific case as deemed necessary and beneficial.

HAT Display Indices

The choice of non-redundant indices in NATHAT is based on the six stream classifications and associated analyses from Poff (1996). Regardless of selected stream classification, the model calculates all 171 indices and returns the results in spreadsheet format. A user-defined selection of up to twelve alternative indices is possible for graphical display, but there is no current capability in the program to save the suite of manually-selected indices. The addition of this functionality would likely be simple to accomplish and would streamline the creation of graphical output.

IV. Flow Regime Evaluation

Data Sources and Metadata

One goal of this study was to evaluate hydrologic flow regimes using hydrologic assessment tools such as IHA and HAT. A cohort of 24 USGS streamflow gages were selected for study by the TWDB in conjunction with the Center for Research in Water Resources (CRWR) with four gages located within each of the six TIFP priority study subbasins: Lower Sabine, Middle Trinity, Middle and Lower Brazos, Lower Guadalupe, and Lower San Antonio. A list of the study gages is presented in Table 7. The flow data obtained from the USGS NWIS and analyzed in this study is presented in electronic format in Appendix D. A general locus map of the study gages may be found in Figure 14, and specific locus maps of the study gages by subbasin may be found in Figure 15 through Figure 18. These 24 gages were selected because they: (1) are believed to be representative of hydrologic conditions in the main stems and tributaries of the priority subbasins; (2) each have 20 or more years of continuous daily mean streamflow data and instantaneous peak streamflow data; and (3) encompass contributory drainage areas and time periods where streamflow is both minimally and highly altered by water development projects. The 24 gages have contributory drainage areas ranging from 42.8 to 35,773 square miles with a mean of 8,618 square miles and continuous periods of record ranging from 20 to 87 years with a mean of 64 years, typically through Water Year 2004.

Table 7. Selected USGS gages for flow regime evaluation.

Site Number	Site Name	Period of Record (Years)	Contributory Drainage Area (mi^2)
08020000	Sabine Rv nr Gladewater, TX	72	2,791
08028500	Sabine Rv nr Bon Wier, TX	81	8,229
08029500	Big Cow Ck nr Newton, TX	52	128
08030500	Sabine Rv nr Ruliff, TX	80	9,329
08062500	Trinity Rv nr Rosser, TX	65	8,147
08062700	Trinity Rv at Trinidad, TX	40	8,538
08065000	Trinity Rv nr Oakwood, TX	81	12,833
08066500	Trinity Rv at Romayor, TX	80	17,186
08093100	Brazos Rv nr Aquilla, TX	66	17,678
08098290	Brazos Rv nr Highbank, TX	39	20,870
08100500	Leon Rv at Gatesville, TX	54	2,342
08106500	Little Rv nr Cameron, TX	87	7,065
08110500	Navasota Rv nr Easterly, TX	80	968
08111500	Brazos Rv nr Hempstead, TX	66	34,314
08115000	Big Ck nr Needville, TX	52	42.8
08116650	Brazos Rv nr Rosharon, TX	20	35,773
08168500	Guadalupe Rv abv Comal Rv at New Braunfels, TX	76	1,518
08171000	Blanco Rv at Wimberley, TX	76	355
08175800	Guadalupe Rv at Cuero, TX	39	4,934
08176500	Guadalupe Rv at Victoria, TX	69	5,198
08181800	San Antonio Rv nr Elmendorf, TX	42	1,743
08183500	San Antonio Rv nr Falls City, TX	79	2,113
08186000	Cibolo Ck nr Falls City, TX	74	827
08188500	San Antonio Rv at Goliad, TX	65	3,921

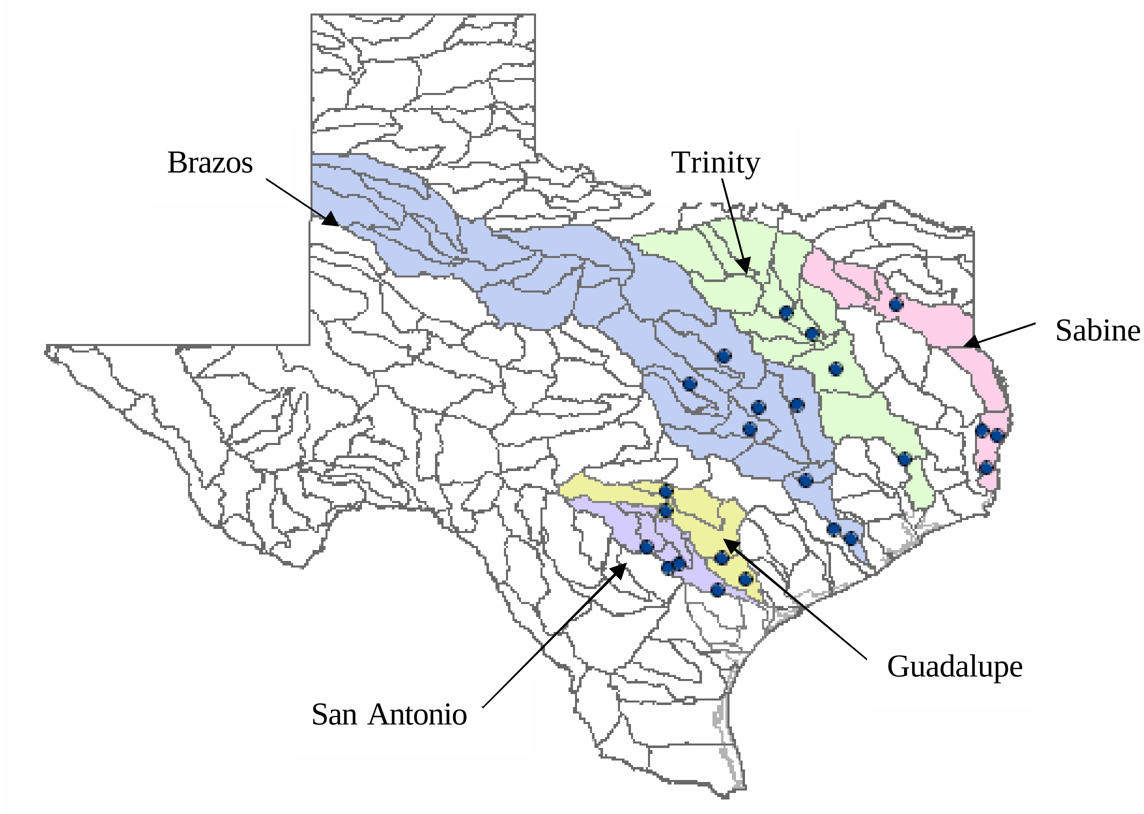


Figure 14. Locus map of 24 study gages in the State of Texas.

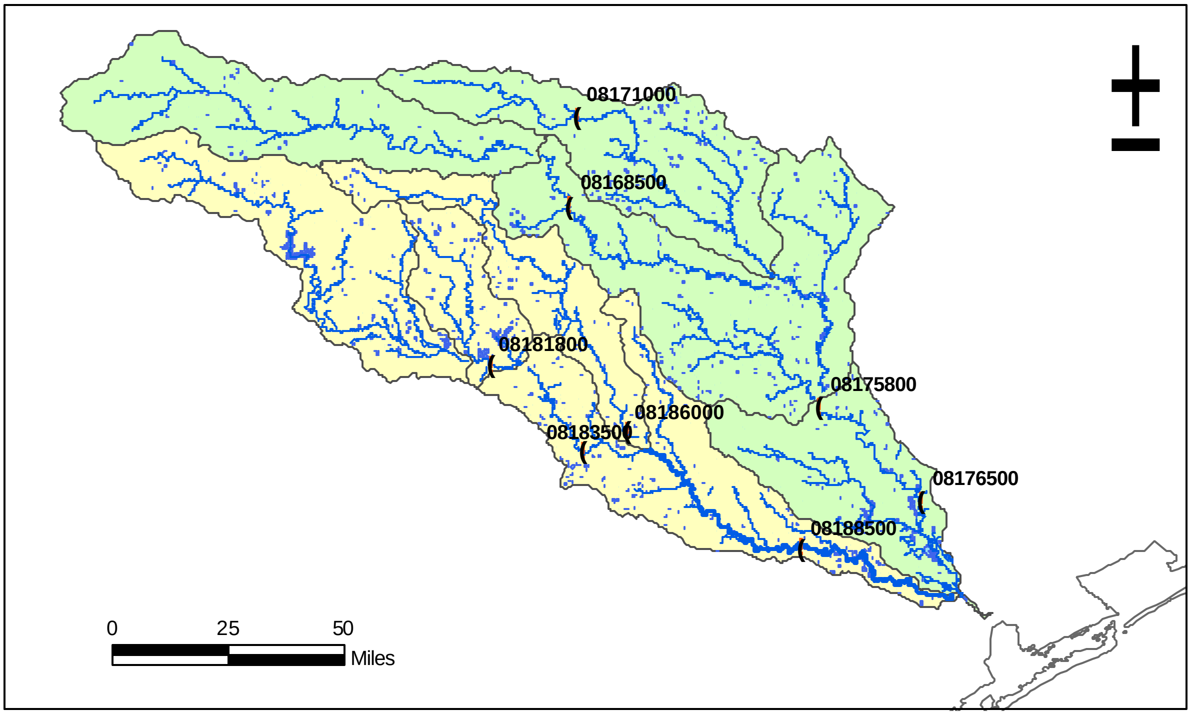


Figure 15. Map of study gages in the Lower Guadalupe and Lower San Antonio River subbasins.

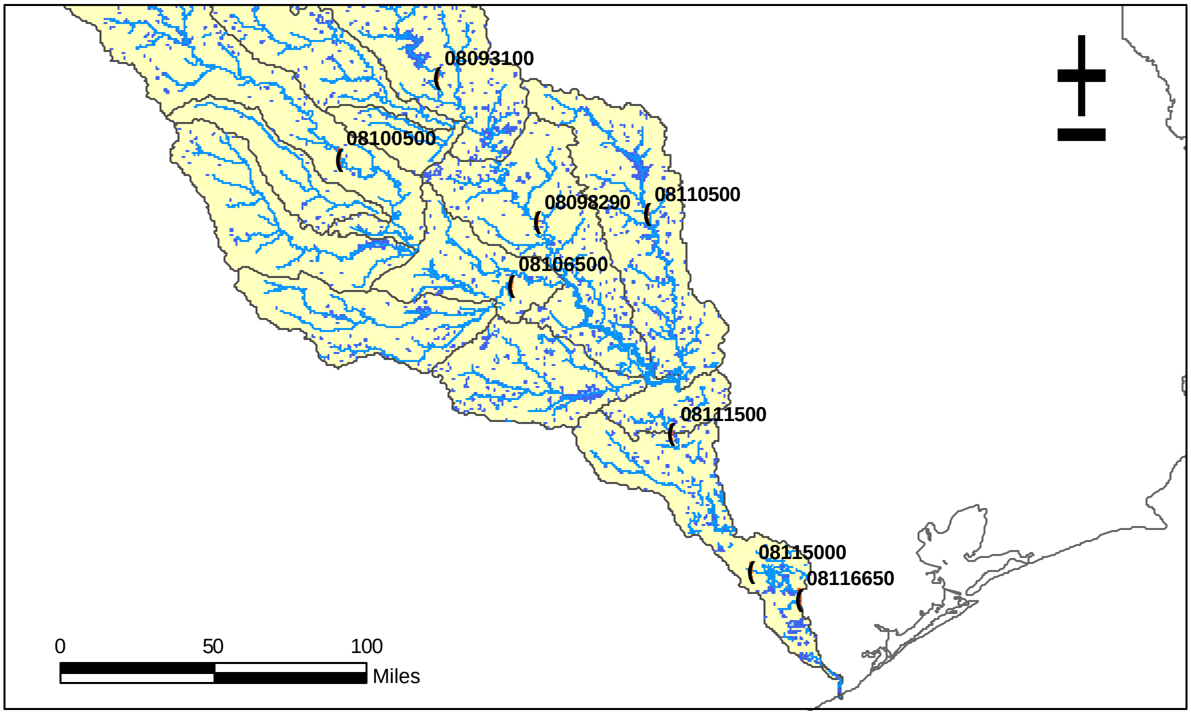


Figure 16. Map of study gages in the Middle and Lower Brazos River subbasins.

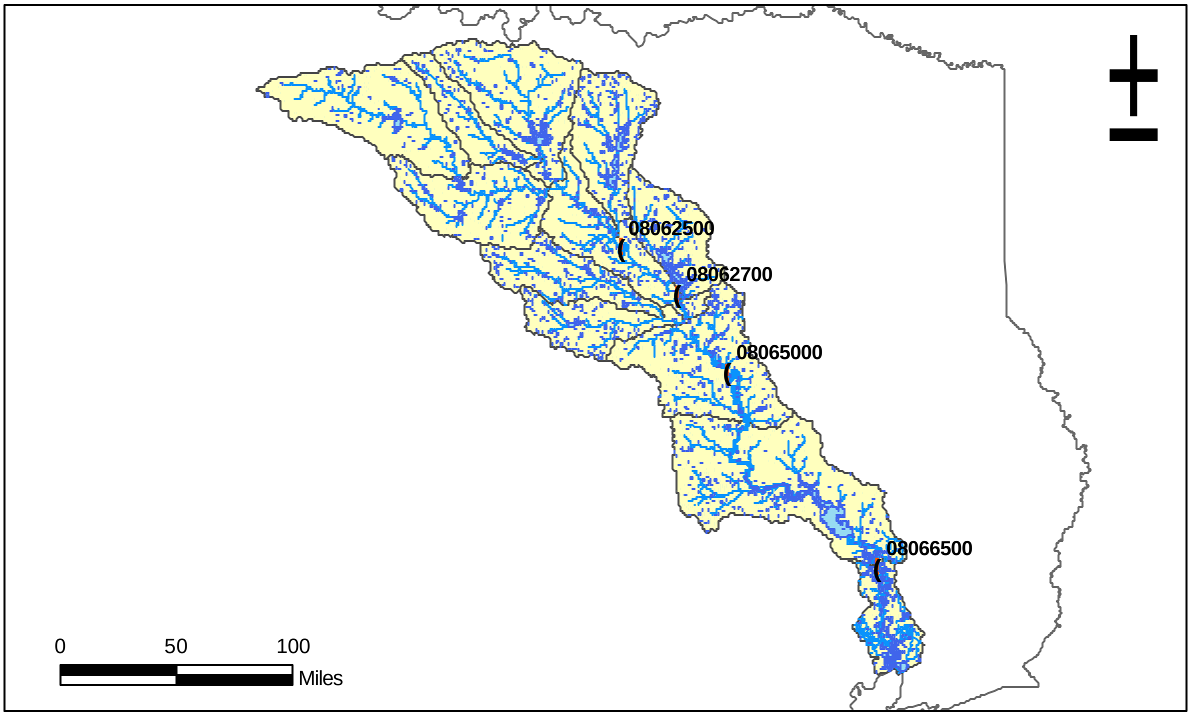


Figure 17. Map of study gages in the Middle Trinity River subbasin.

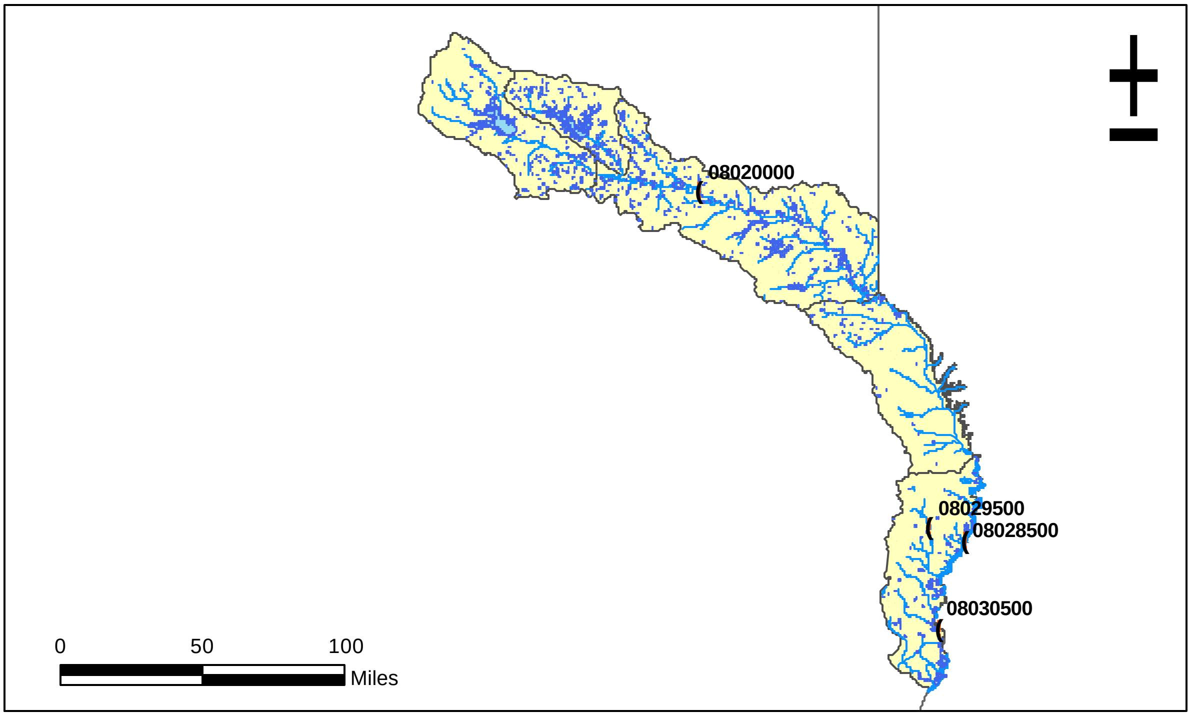


Figure 18. Map of study gages in the Lower Sabine River subbasin.

In addition to streamflow, the flow regime assessment performed included an analysis of precipitation. Data for this analysis were obtained from digital climate maps created by using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) by Oregon State University's PRISM Group for the period 1961 through 1990 (PRISM 2006). Electronic copies of the data and maps of the data in raster format are included in Appendix D.

In an analysis of systematic methodologies to delineate flow components this study also made use of published USGS stream gage measurement data (Appendix D). In particular, a time series of the field-measured (as opposed to gaged) streamflow and the measured active width of flow at the time of streamflow measurement was used to identify the river channel and overbank morphology.

Methodology

Both IHA and NATHAT were used to analyze the flow regime at each of the 24 gages; the results of these analyses in included in Appendix D. The initial period-of-record results were examined for spatial and temporal trends and patterns and a number of intriguing results were revisited using IHA, HAT, an external tool, or more commonly, multiple tools for comparison purposes. External analyses were performed using Microsoft Excel spreadsheets, customized Microsoft Visual Basic for Applications programs, Environmental Systems Research Institute (ESRI) ArcGIS ArcMap version 9.1, and Minitab statistical software package version 14.1. These tools were employed in instances where they provided greater flexibility for analyses or where their specific capabilities were more valuable in addressing specific issues than IHA, HAT or both. Individual case methodologies are discussed in the sections below.

Problem Definition

IHA includes 67 statistical routines and HAT includes 171. Both tools include capabilities to view the hydrograph for each stream gage analyzed, a prudent starting point for any flow regime evaluation. However, in the case of an engineer or scientist tasked with evaluating the flow regime of a river and armed with one or both of these tools and little other information and data, the user can quickly become overwhelmed by the sheer number and diverse meaning and purpose of the various hydrologic indices. Furthermore, the user's ability to identify spatial and temporal trends and patterns is only as good as their understanding of the particular indices of interest or the particular goal of their assessment.

For example, which flow characteristics are of primary import: magnitude, duration, frequency, timing, and/or rate of change? Is the user concerned with seasonal, annual, or inter-annual variation? Is the purpose of the analysis to assess the impacts of change or define acceptable limits of change? Are generalized long-term patterns or the evaluation of individual flood events more important? As the problem at hand becomes better defined, the capabilities of IHA and HAT best suited to solving of that problem become better defined as well. In the absence of a narrowly-defined problem for this study, external tools were sometimes relied upon to identify macro-scale trends and patterns across space and time.

Impact and Extent of Flow Regulation

A major capability of the tools, particularly IHA, is the ability to assess hydrologic alteration, and this is typically how IHA has been employed to-date (Nature Conservancy 2006); HAT is too new to have an understanding of its typical usage Thus, an analysis of hydrologic alteration became a logical starting point in this study and served both as a means of evaluating and comparing the two tools and as a means of understanding how water development projects such as dams, major diversions, and return flows have impacted flow regimes at the study gages.

Of the 24 gages, 19 are now considered by the USGS to be highly impacted due to upstream flow regulation, meaning that runoff from greater than ten percent of their contributory drainage area is affected by regulation (Figure 19) (USGS 2004). Eight major dams impound reservoirs that impact a number of the rivers studied (Table 8).

Besides all providing water supply capabilities, the reservoirs variously support hydropower, irrigation, recreation, and flood control. As such, individual operating rules of each dam serve as the primary measure of when, how, and to what extent the downstream flow regime is altered. For example, the construction of a water supply or flood control dam is commonly associated with a decreased magnitude of peak flows. Figure 20 illustrates this case for the Lower Guadalupe River above the Comal River at New Braunfels, Texas following the development of Canyon Lake. Also, irrigation reservoirs or wastewater treatment plant return flows from a major city may cause artificially elevated summertime low flows, as is evident in the Middle Trinity River downstream of the Dallas-Fort Worth Metroplex (Figure 21). The temporal analysis capabilities of both IHA and HAT are useful for illustrating the extent and quantifying the magnitude of such flow regulation. In addition, both programs can analyze historic gaged streamflow data to assess actual historic change, and both can accept modeled streamflow data (in a compatible file format) to assess proposed future change.

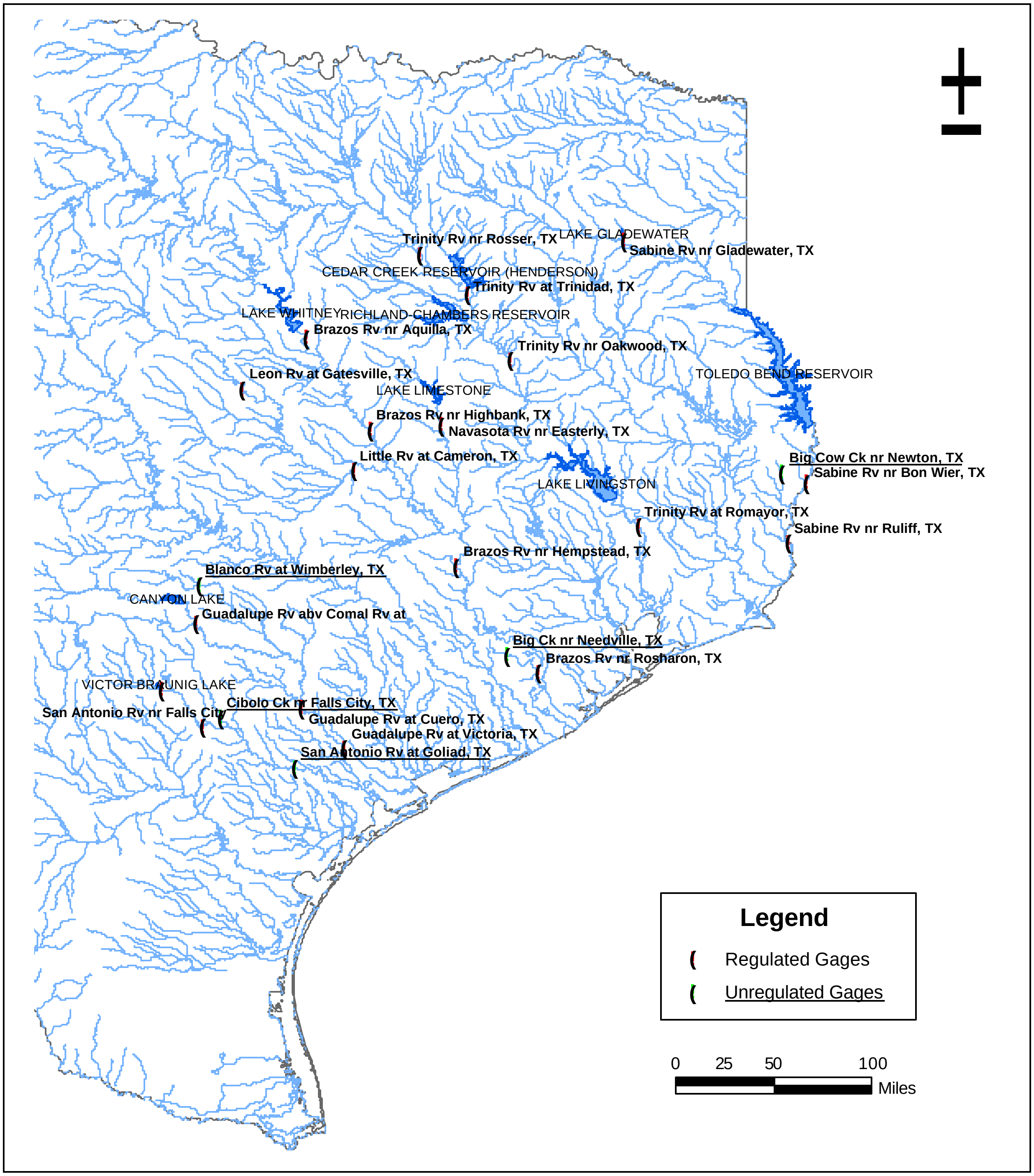


Figure 19. **Flow regulation at study gages, where regulated gages are defined as those where runoff from greater than ten percent of their contributory drainage area is affected by regulation.**

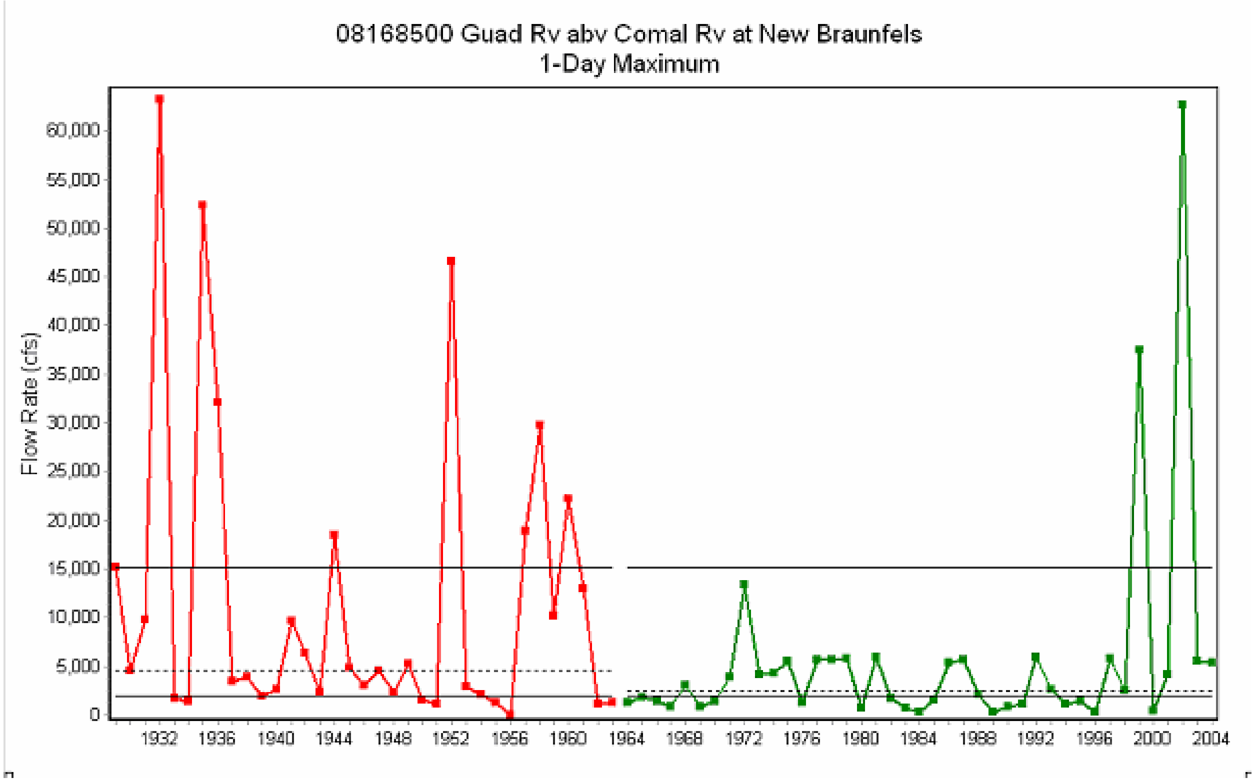


Figure 20. Time trend of maximum 1-day flow in Lower Guadalupe River downstream of Canyon Dam, which began impounding water in 1964.

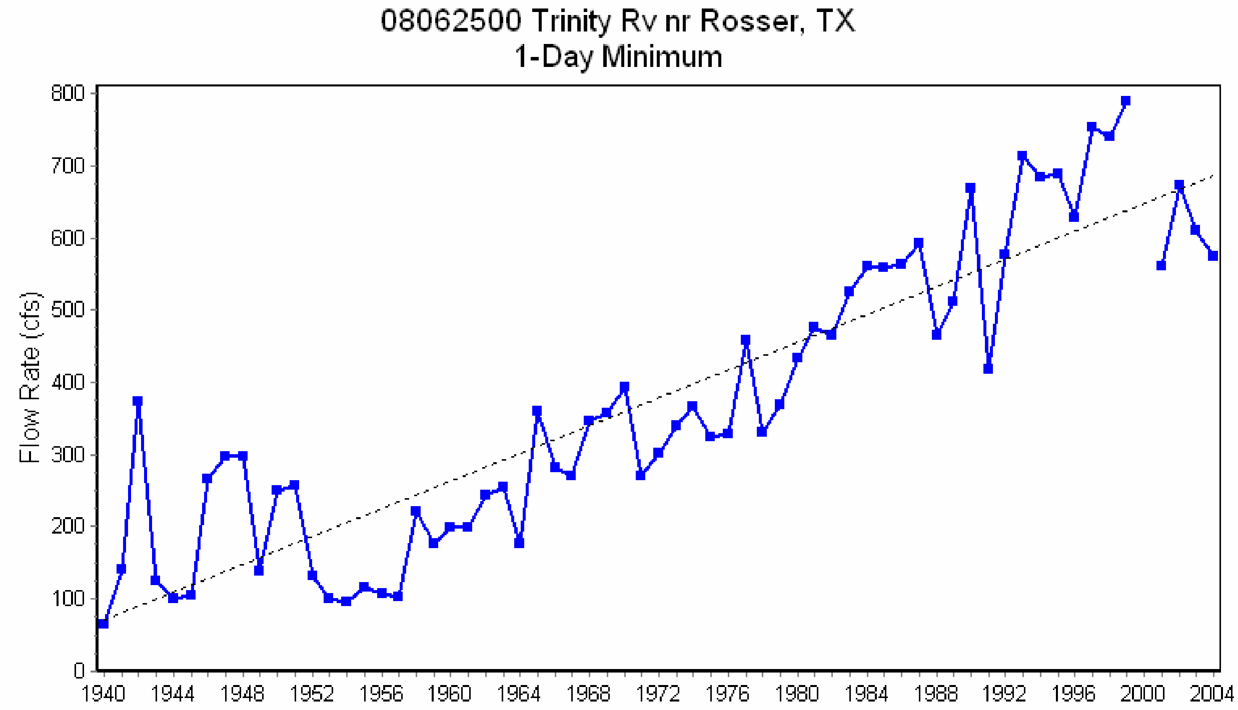


Figure 21. Time trend of minimum 1-day flow in the Middle Trinity River downstream of Dallas-Fort Worth.

Table 8. Major dams and reservoirs regulating flow at the study gages.

Reservoir Name	Dam Name	Owner	Purpose	River	D/S Gage	Date Impound	Normal Height (ft)	Normal Storage (ac-ft)	Cons Height (ft)	Cons Storage (ac-ft)	Flood Height (ft)	Flood Storage (ac-ft)	Max Height (ft)	Length (ft)	DA (mi2)
Lake Gladewater	Gladewater Dam	City of Gladewater	WS	Glade Creek	08020000, 08028500, 08030500	8/1952	36	6,950	36	6,950	N/A	N/A	48	1,203	35
Cedar Creek Reservoir (Trinity)	Joe B. Hogsett Dam	Tarrant Regional Water District	WS, R	Trinity River	08065000	7/1965	53	N/A	73	679,200	N/A	N/A	91	17,539	1,007
Lake Whitney	Whitney Dam	Army Corps of Eng. Fort Worth District	FC, WS, HP	Brazos River	08093100, 08092890?	12/1951	49	4,270	108	679,200	146	1,999,500	159	17,695	17,656
Toledo Bend Reservoir	Toledo Bend Dam	Sabine River Auth. of TX & LA	WS, HP, R	Sabine River	08028500, 08030500	10/1966	72	1,161,800	99	4,477,000	102	5,102,000	112	11,200	7,178
Lake Livingston	Livingston Dam	Trinity River Authority	WS	Trinity River	08066500	10/1968	54	N/A	86	1,750,000	89	N/A	100	14,400	16,616
Canyon Lake	Canyon Dam	Army Corps of Eng. Fort Worth District	FC, WS	Guad. River	08168500	6/1964	125	N/A	159	386,200	193	737,444	224	6,830	1,432
Richland-Chambers Reservoir	Richland-Chambers Dam	Tarrant Regional Water District	WS, R	Richland Creek	08065000	11/1987	N/A	N/A	83	1,135,000	86	N/A	96	31,000	1,957
Lake Limestone	Sterling C. Roberston Dam	Brazos River Authority	WS, I, R	Navosta River	08110500	10/1978	54.6	325,670	48	225,400	61	458,603	65	9,100	675

Purpose: Water Supply, Recreation, Flood Control, Hydropower, Irrigation

Measures of Central Tendency

For each of the 24 study gages, the long-term daily median flow for each calendar day was calculated across the period of record (average = 68 years) of continuous daily flow data. The calculation was performed using a Visual Basic for Applications (VBA) macro in Microsoft Excel (Appendix D). External to IHA and HAT, this analysis was performed as part of the flow regime assessment as a means to evaluate the long-term seasonal patterns of streamflow within each subbasin by filtering out the effects of individual flow events and thus the variability and flashiness associated with the daily time series hydrograph. As such, the following figures are useful for visualizing the underlying patterns of daily streamflow but are not suitable for the development of environmental flow prescriptions, as they do not include any of the shorter duration variability that has been recognized to be so critical to ecosystem preservation. Figure 22 through Figure 27 are plotted by subbasin with streamflow depicted on equivalent logarithmic scales on the ordinate and calendar day depicted on the abscissa.

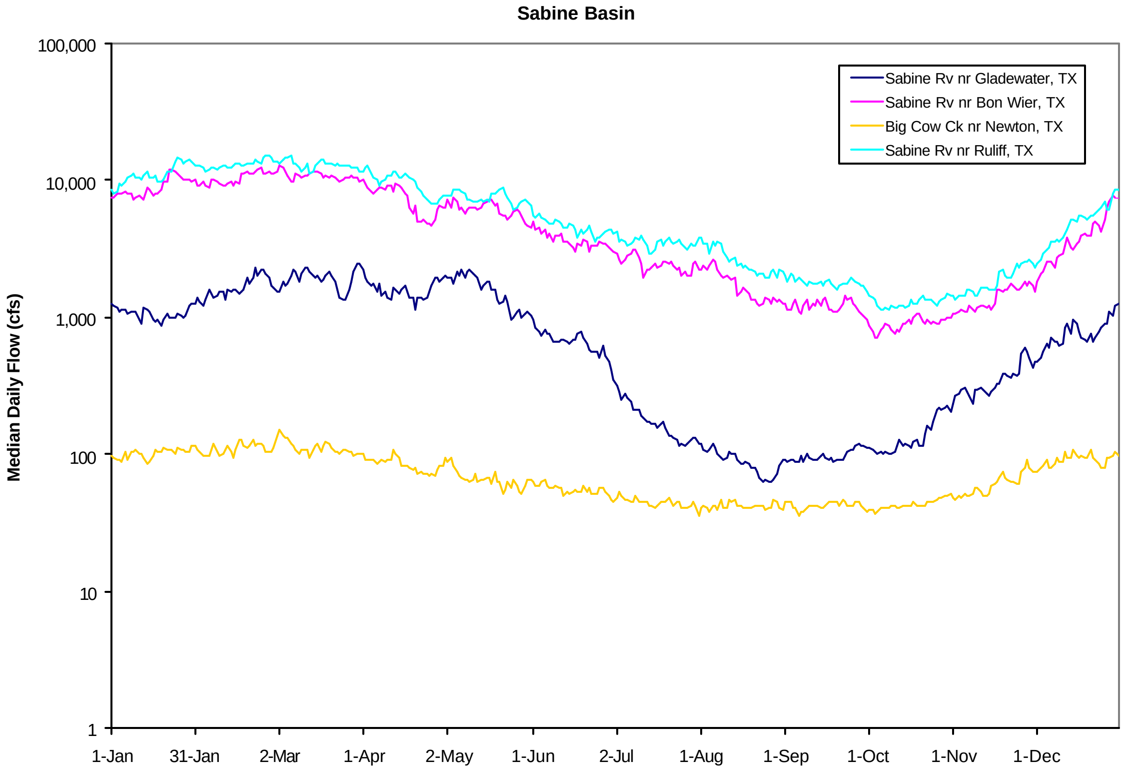


Figure 22. Median daily streamflow in the Lower Sabine River subbasin.

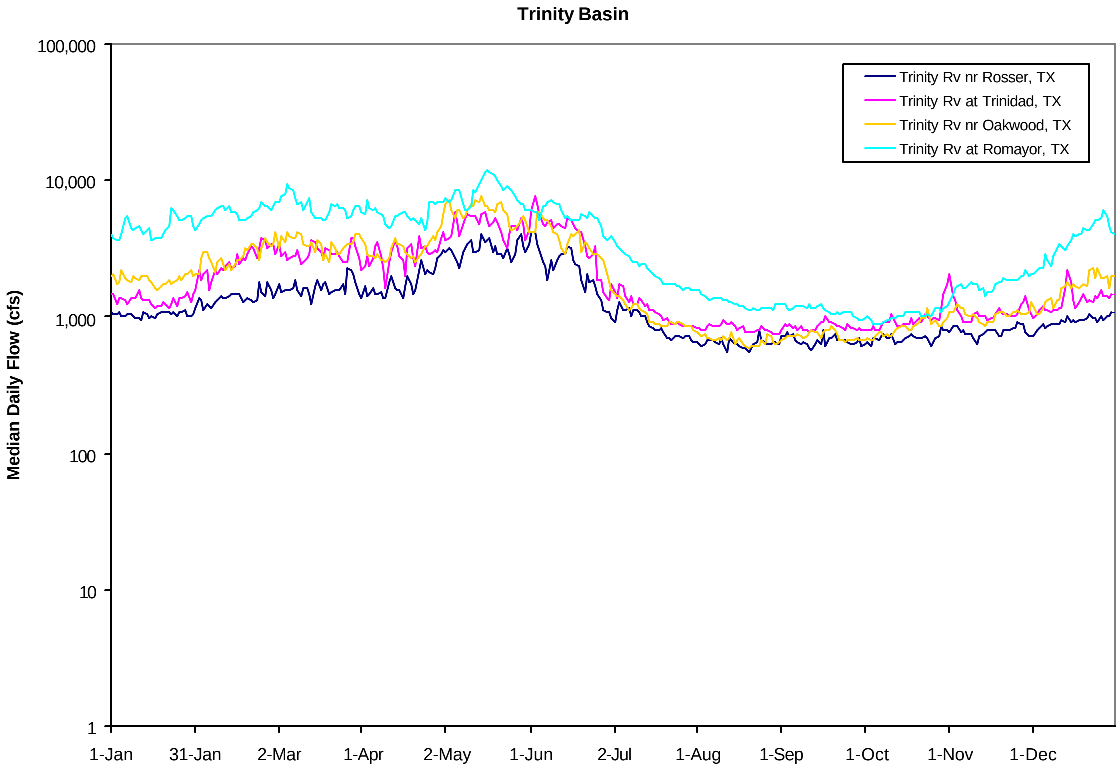


Figure 23. Median daily streamflow in the Middle Trinity River subbasin.

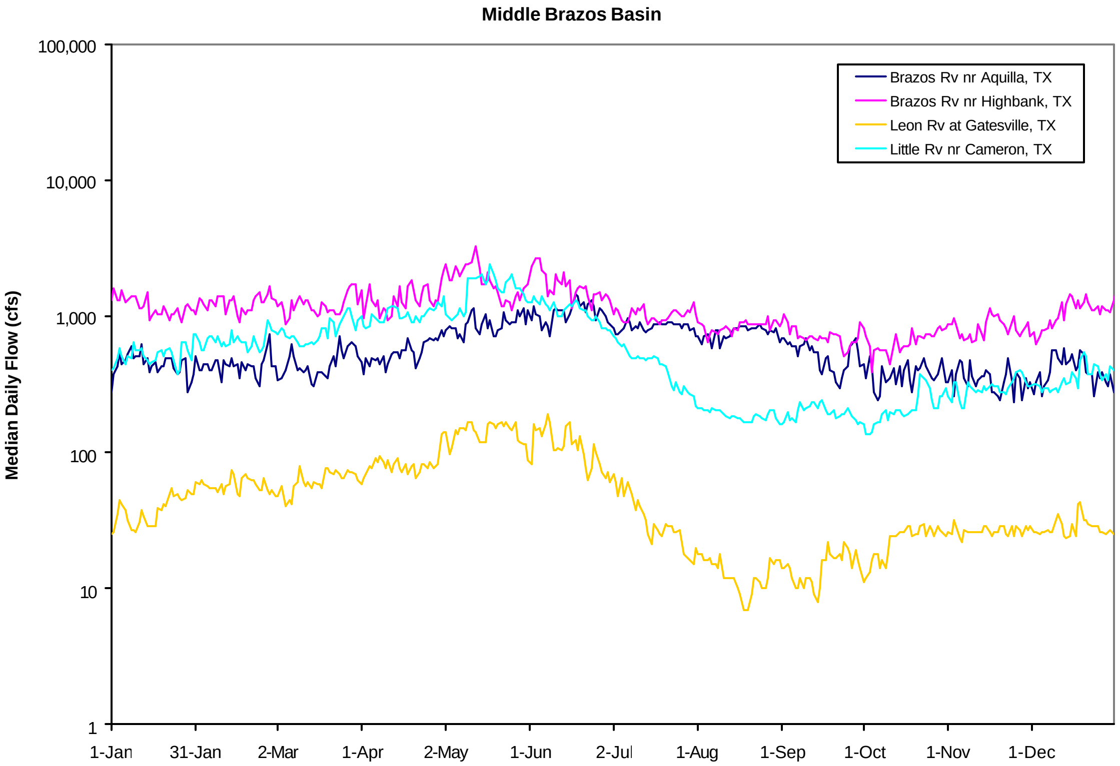


Figure 24. Median daily streamflow in the Middle Brazos River subbasin.

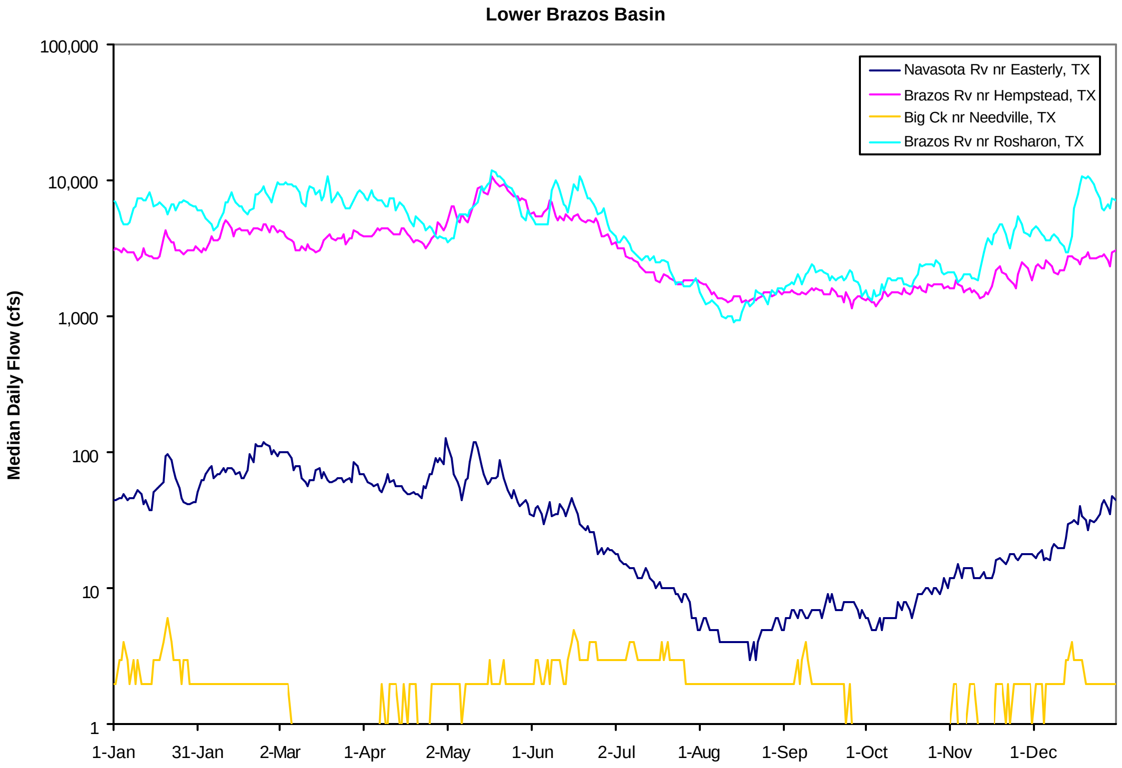


Figure 25. Median daily streamflow in the Lower Brazos River subbasin. Note: Due to the logarithmic scale, flows shown along the abscissa are 1 cfs or less, and not necessarily 0 cfs.

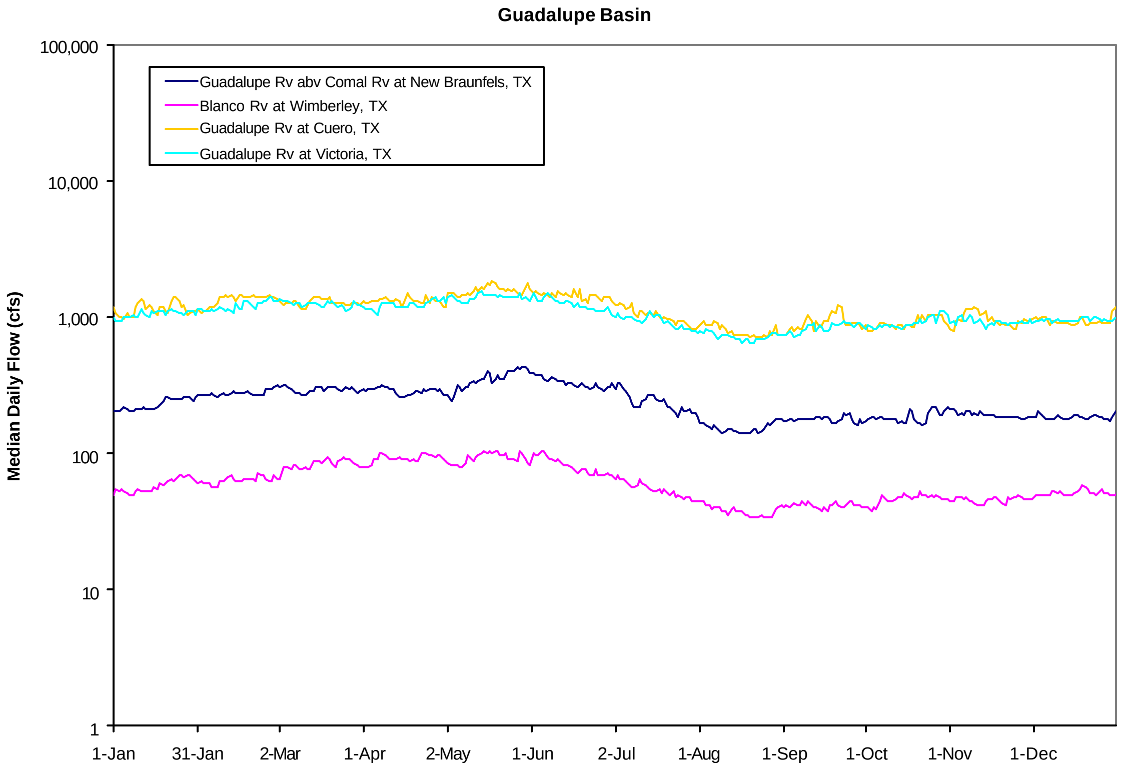


Figure 26. Median daily streamflow in the Lower Guadalupe River subbasin.

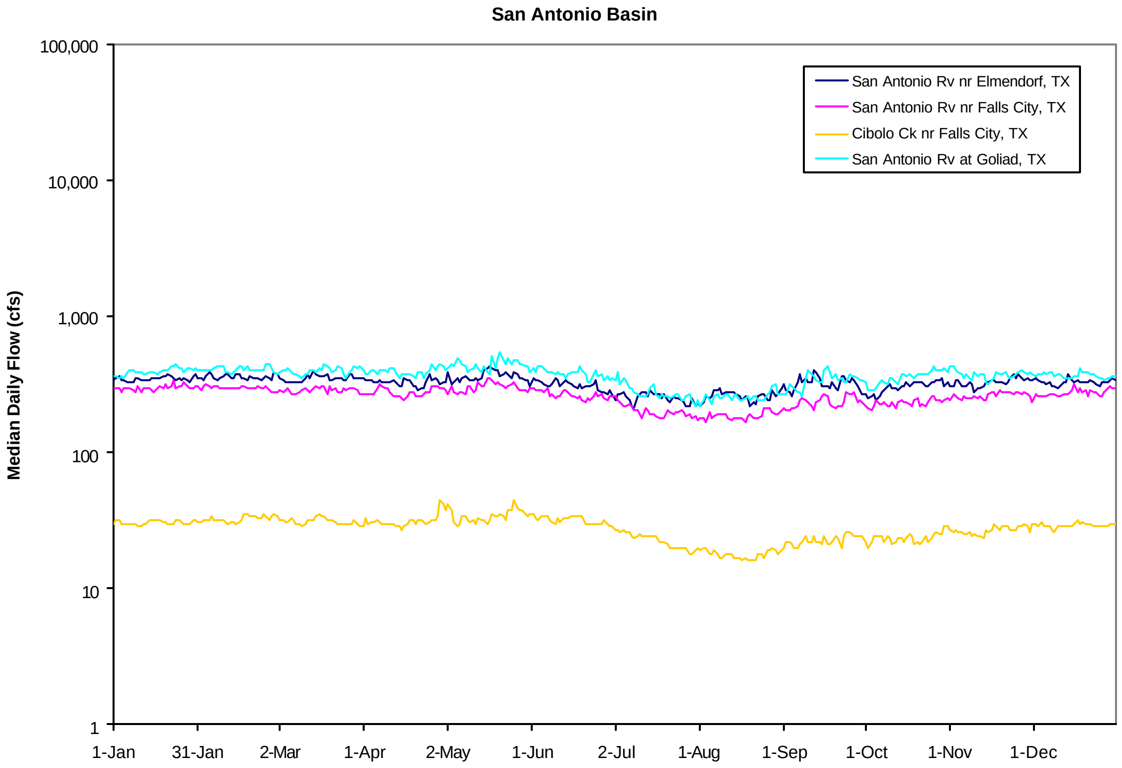


Figure 27. Median daily streamflow in the Lower San Antonio River subbasin.

As can be seen from the graphs, many of the hydrographs within each subbasin follow a similar pattern to other streams within that subbasin, irrespective of the contributory drainage area to each gage. The streamflows generally follow a sinusoidal pattern, with a spring peak (May-June) and a fall trough (August-September) when viewed on a semi-log plot, with the signal being stronger to the east (e.g. Lower Sabine and Middle Trinity) and muted to the west (e.g. Lower Guadalupe and Lower San Antonio) along the Texas Gulf Coast, thus demonstrating that there are pronounced regional patterns in the seasonality of the streamflow hydrograph within the State of Texas. Because of the semi-log plotting style, the seasonal pattern is not a true sinusoid in time and streamflow.

The hydrographs depicted above were developed from flow data that typically encompasses time periods of both relatively unaltered and highly altered hydrologic conditions as the periods of record for many of the study gages bracket the construction of numerous major dams, the rapid growth of multiple urban areas, and the creation of many other communities. Consideration of the long-term seasonal patterns would prove beneficial to the TIFP in the development of instream flow requirements as the patterns reflect the underlying seasonality of flow in many of the rivers of interest. In addition, the signals expressed here also provide clues regarding the likely streamflow pattern based on a stream's geographic location within the State.

Given the importance of measures of central tendency to an evaluation of flow regimes, this project incorporated a study comparing means and medians and also comparing monthly median flows to daily median flows (Table 9). Based on an analysis of the period of record data for the 24 study gages, the long-term daily median streamflow can be reasonably approximated by the long-term monthly median streamflow, with an average error of 1.3 percent and error values ranging from 0 to 7 percent. There is no difference in the calculation of the long-term mean daily flow from either daily or monthly mean flow data. The mean daily flow for each of the 24 gages was higher than the median daily flow, an indication of the large positive skew of daily streamflow data, with a typical difference of 56 percent and difference ranging from 25 to 95 percent. This study shows that there is minimal loss in accuracy when measures of central tendency are calculated based on a monthly time step as opposed to a daily time step.

Precipitation and Streamflow

In conjunction with the analysis of long-term seasonal streamflow patterns discussed above, a parallel analysis of long-term precipitation patterns was conducted. This analysis was performed using Spatial Analyst tools within ESRI ArcGIS version 9.1 and PRISM data for the period 1961 through 1990; note that the time period of this analysis does not match exactly with the periods of record for each of the 24 study gages, but is assumed to be a reasonable approximation of long-term conditions based on the considerable length of the time period being analyzed. In this case, the long-term streamflow was aggregated into monthly medians instead of daily to more closely match the monthly precipitation estimates, and the streamflow was also normalized by the contributory drainage area to arrive at a unit monthly median flow represented in inches of flow depth across the drainage area, thus directly comparable to inches of precipitation depth. The results of this analysis are presented in Figure 28 through Figure 31 for four of the priority subbasins.

Table 9. Comparison of measures of central tendency by proportionally-weighted months.

gage number	period of record (yr)	mean daily median (cfs)	mean weighted monthly median (cfs)	percent difference	abs value percent difference	mean daily mean	mean weighted monthly mean	percent difference	percent difference (mean daily median to mean daily mean)
8020000	72	848	836	1%	1%	1918	1918	0.0%	56%
8028500	81	4919	4798	2%	2%	6996	6996	0.0%	30%
8029500	52	71	70	1%	1%	132	132	0.0%	46%
8030500	80	6276	6255	0%	0%	8398	8398	0.0%	25%
8062500	65	1336	1313	2%	2%	3206	3206	0.0%	58%
8062700	40	2067	2065	0%	0%	4452	4452	0.0%	54%
8065000	81	2258	2236	1%	1%	5259	5259	0.0%	57%
8066500	80	3984	3959	1%	1%	7905	7905	0.0%	50%
8093100	66	593	597	-1%	1%	1541	1541	0.0%	62%
8098290	39	1147	1127	2%	2%	2775	2775	0.0%	59%
8100500	54	53	52	2%	2%	304	304	0.0%	83%
8106500	87	619	612	1%	1%	1751	1751	0.0%	65%
8110500	80	37	34	7%	7%	425	425	0.0%	91%
8111500	66	3191	3212	-1%	1%	6914	6914	0.0%	54%
8115000	52	2.0	2	3%	3%	37	37	0.0%	95%
8116650	20	4828	4653	4%	4%	8813	8813	0.0%	45%
8168500	76	242	240	1%	1%	488	488	0.0%	50%
8171000	76	62	62	1%	1%	144	144	0.0%	57%
8175800	39	1137	1127	1%	1%	2148	2148	0.0%	47%
8176500	69	1053	1050	0%	0%	1963	1963	0.0%	46%
8181800	42	321	321	0%	0%	592	592	0.0%	46%
8183500	79	259	257	1%	1%	488	488	0.0%	47%
8186000	74	28	28	0%	0%	139	139	0.0%	80%
8188500	65	366	364	0%	0%	808	808	0.0%	55%
average	**64**				**1.3%**			**0.0%**	**56%**

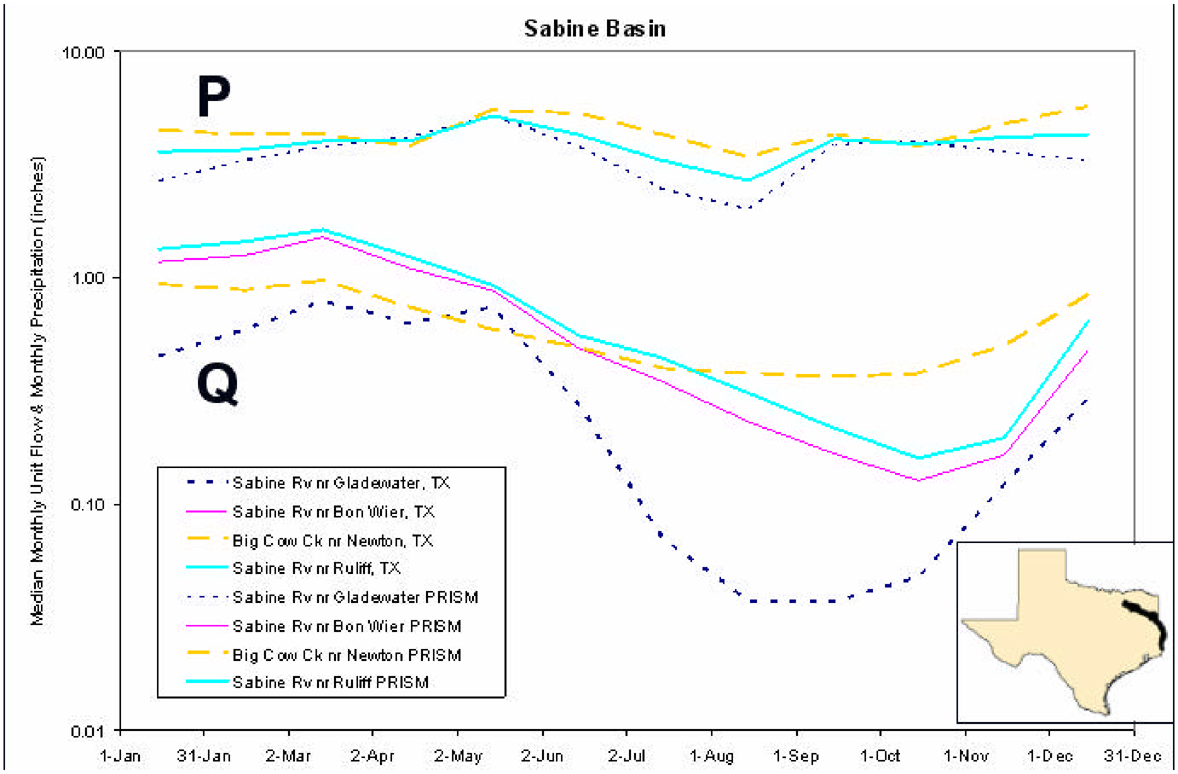


Figure 28. Streamflow and precipitation patterns for the Lower Sabine River basin.

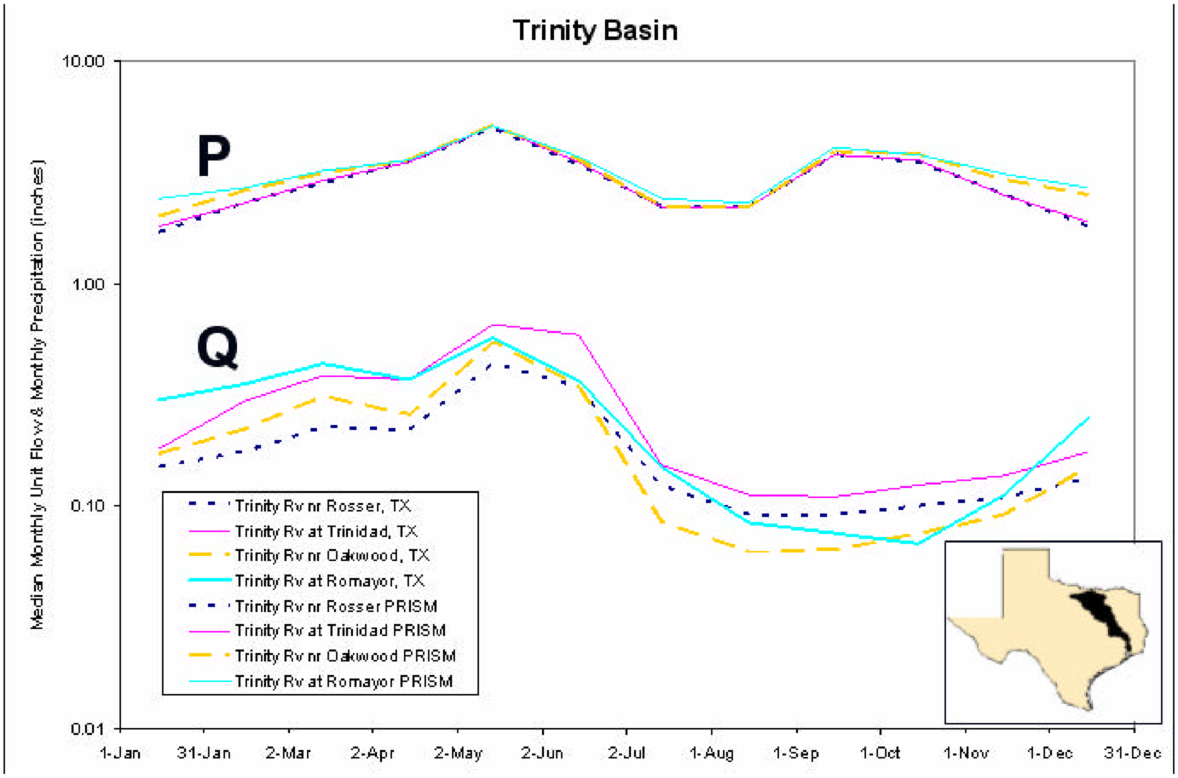


Figure 29. Streamflow and precipitation patterns for the Middle Trinity River basin.

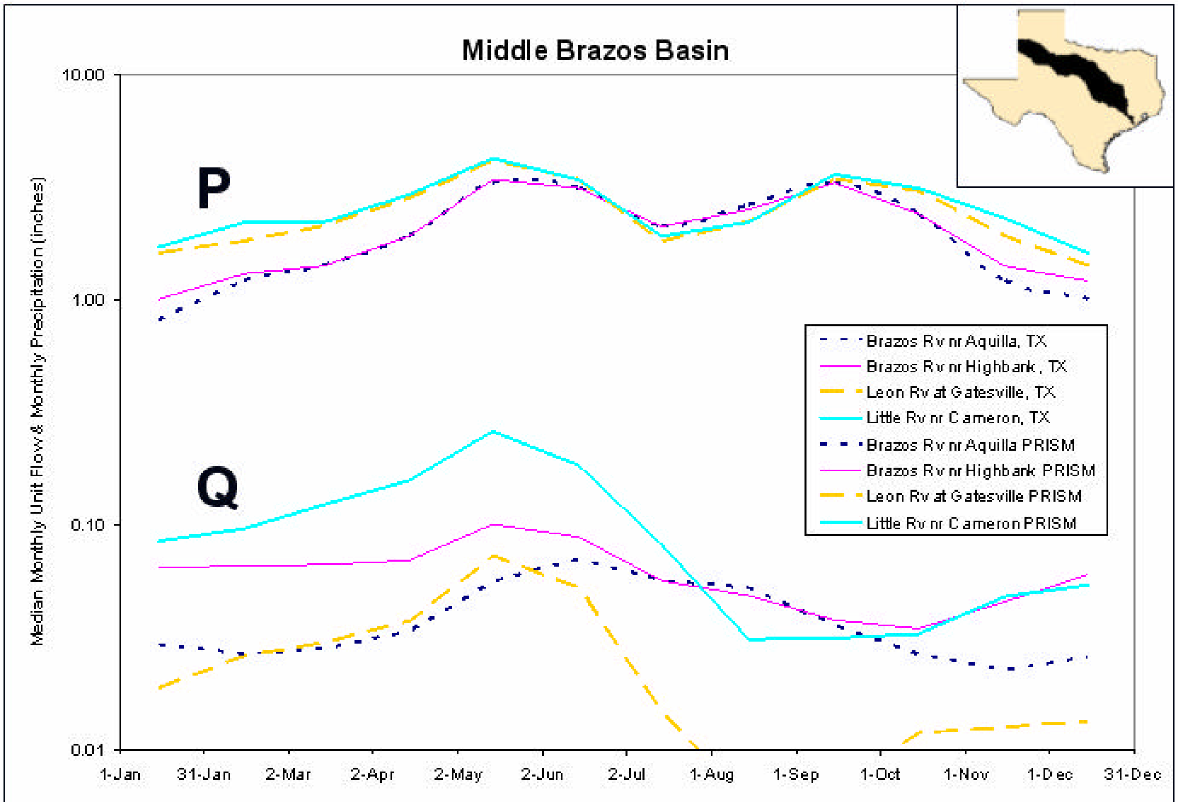


Figure 30. Streamflow and precipitation patterns for the Middle Brazos River basin.

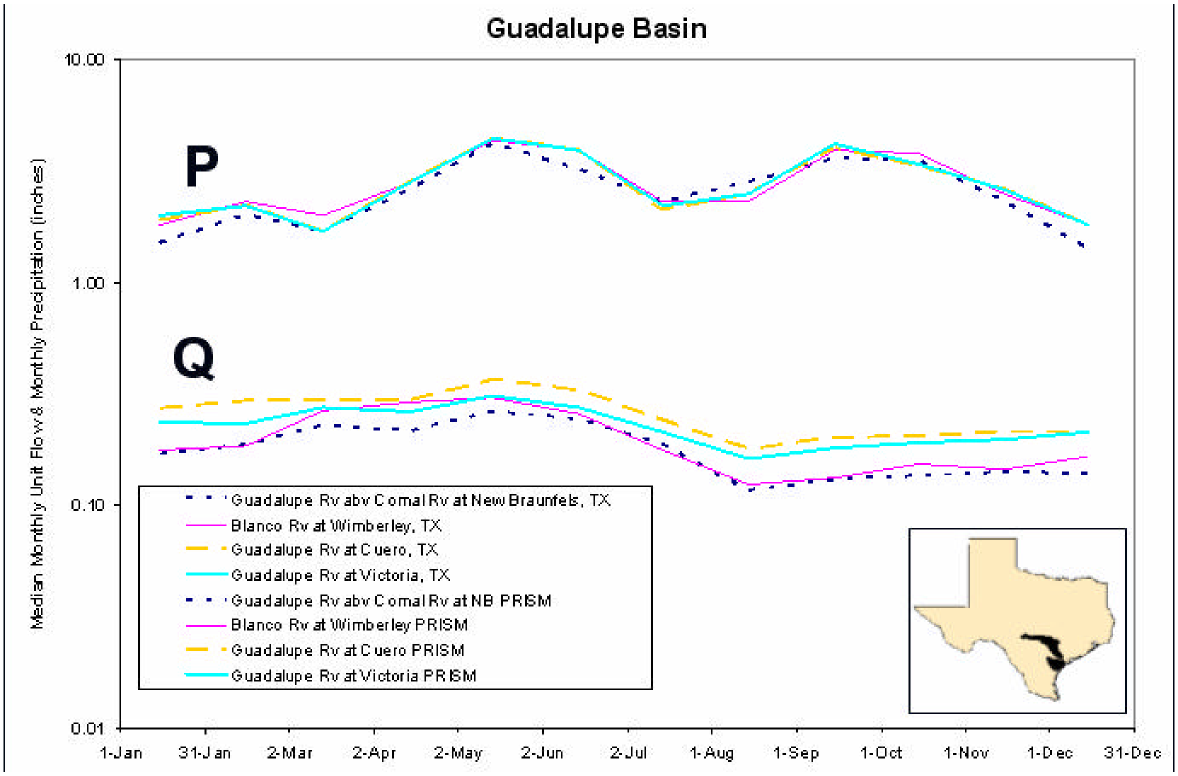


Figure 31. Streamflow and precipitation patterns for the Lower Guadalupe River basin.

Based on the above graphs for a 30-year period of record, the precipitation signal is bimodal, irrespective of geography, with spring (i.e. May to June) and fall (i.e. September to October) peaks. The precipitation gradient from East to Central Texas is expressed in the magnitude of precipitation (more to the east) but doesn't change the timing of spring and fall peaks. Also, there appears to be a correlation between the spring peaks in streamflow and precipitation whereby the increased precipitation accounts for increased runoff in the waterways. However, there does not appear to be a similar correlation for the fall peak in precipitation; multiple factors might explain this discrepancy, but for the purposes of this study is it important to note that the spatial variability of the seasonality in long-term streamflow patterns cannot be explained by spatial variability long-term patterns in precipitation alone.

Seven-Day Two-Year Low Flow (7Q2)

The seven-day average, two-year recurrence interval low flow discharge (7Q2) is an important flow statistic in the State of Texas due to its statutory designation in the Texas Surface Water Quality Standards (TCEQ 2000) as the defining low-flow condition variable to determine the 'critical low flow,' the flow below which some water quality standards no longer apply and the flow at which the impacts of permitted discharges are analyzed. Here, the 7Q2 values were calculated for each of the 24 study gages based on the entire period of record using IHA and verified with Microsoft Excel (Table 10). Neither IHA nor HAT explicitly has the capability to calculate the 7Q2. IHA calculates the seven-day minimum flows for each year (7Q1), and the user can then externally calculate the median of these values to obtain the 7Q2. ML17, the 'base flow' index in HAT, is the average of the seven-day minimum flow (7Q1) divided by the median (or mean) annual flow for that year; the user can externally modify ML17 to obtain the 7Q2. Note that the official TCEQ Surface Water Quality Standards values for the 7Q2 are calculated from a sliding, limited time period that does not necessarily include the entire period of record of gaged flow data.

Table 10. Seven-day average, two-year recurrence interval low flow discharge (7Q2).

Site Number	Site Name	Contributory Drainage Area (mi^2)	7Q2 (cfs)
8020000	Sabine Rv nr Gladewater, TX	2,791	38.4
8028500	Sabine Rv nr Bon Wier, TX	8,229	457.9
8029500	Big Cow Ck nr Newton, TX	128	26.8
8030500	Sabine Rv nr Ruliff, TX	9,329	788.6
8062500	Trinity Rv nr Rosser, TX	8,147	370.1
8062700	Trinity Rv at Trinidad, TX	8,538	615.6
8065000	Trinity Rv nr Oakwood, TX	12,833	384.7
8066500	Trinity Rv at Romayor, TX	17,186	552.4
8093100	Brazos Rv nr Aquilla, TX	17,678	42.8
8098290	Brazos Rv nr Highbank, TX	20,870	179.0
8100500	Leon Rv at Gatesville, TX	2,342	2.0
8106500	Little Rv nr Cameron, TX	7,065	54.7
8110500	Navasota Rv nr Easterly, TX	968	1.2
8111500	Brazos Rv nr Hempstead, TX	34,314	620.6
8115000	Big Ck nr Needville, TX	42.8	0.4
8116650	Brazos Rv nr Rosharon, TX	35,773	573.1
8168500	Guadalupe Rv abv Comal Rv at New Braunfels, TX	1,518	76.9
8171000	Blanco Rv at Wimberley, TX	355	18.9
8175800	Guadalupe Rv at Cuero, TX	4,934	489.4
8176500	Guadalupe Rv at Victoria, TX	5,198	530.6
8181800	San Antonio Rv nr Elmendorf, TX	1,743	141.9
8183500	San Antonio Rv nr Falls City, TX	2,113	110.0
8186000	Cibolo Ck nr Falls City, TX	827	9.9
8188500	San Antonio Rv at Goliad, TX	3,921	164.6

Range of Flow Regime

Similar to the analysis of long-term seasonal patterns of the daily median flow, additional analyses were performed for various other magnitudes of flow, including the 5th, 25th, 75th, and 95th percentile flows across the period of record. Additional VBA macros were developed for each of these analyses (Appendix D), and the output was then aggregated into modified box and whisker plots whereby the four flow magnitudes discussed above were plotted alongside the median flow on a monthly basis; results for selected study gages are presented in Figure 32 to Figure 35. When considered over a long time scale, the seasonal variation in the flow regime of various percentile levels of flow follows a consistent pattern, such that if the median flow goes down then both high and low flow percentiles reduce proportionately to some extent, and vice versa when the median flow increases. This means that the high and low flows within a particular flow regime are pegged to the median flow to some degree.

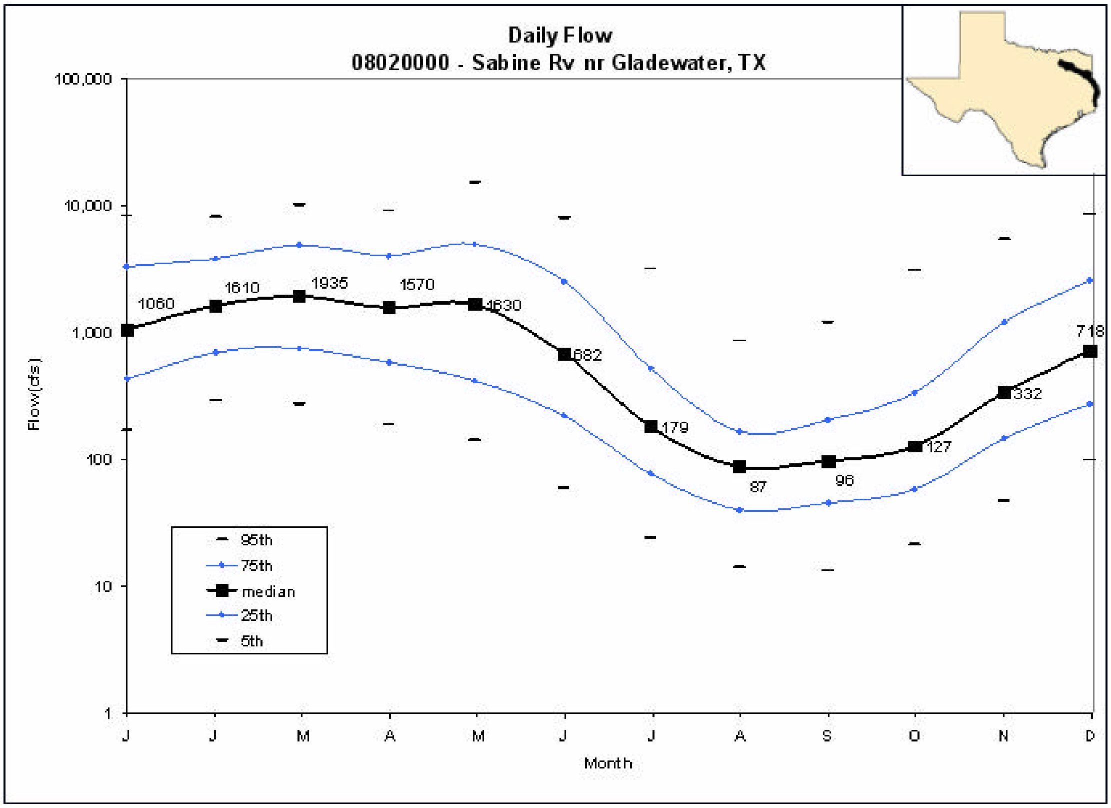


Figure 32. Modified box and whisker plot for USGS Gage No. 0802000, Sabine Rv nr Gladewater, TX.

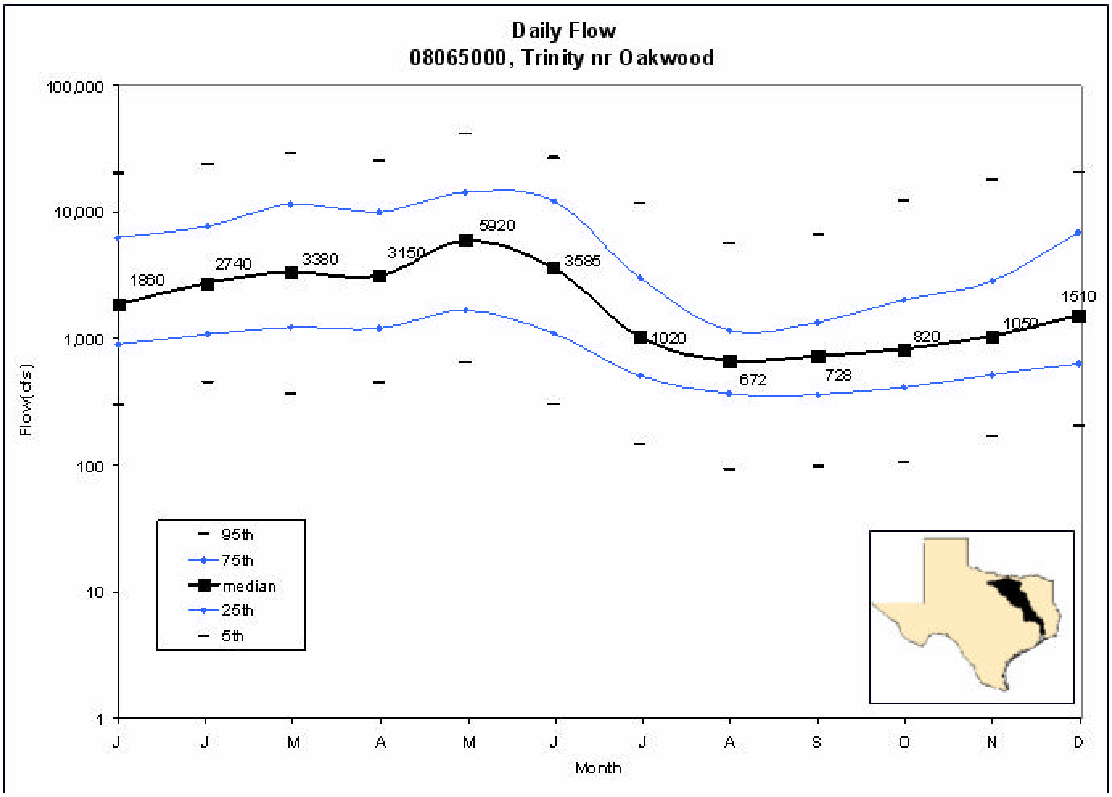


Figure 33. Modified box and whisker plot for USGS Gage No. 08065000, Trinity Rv nr Oakwood, TX.

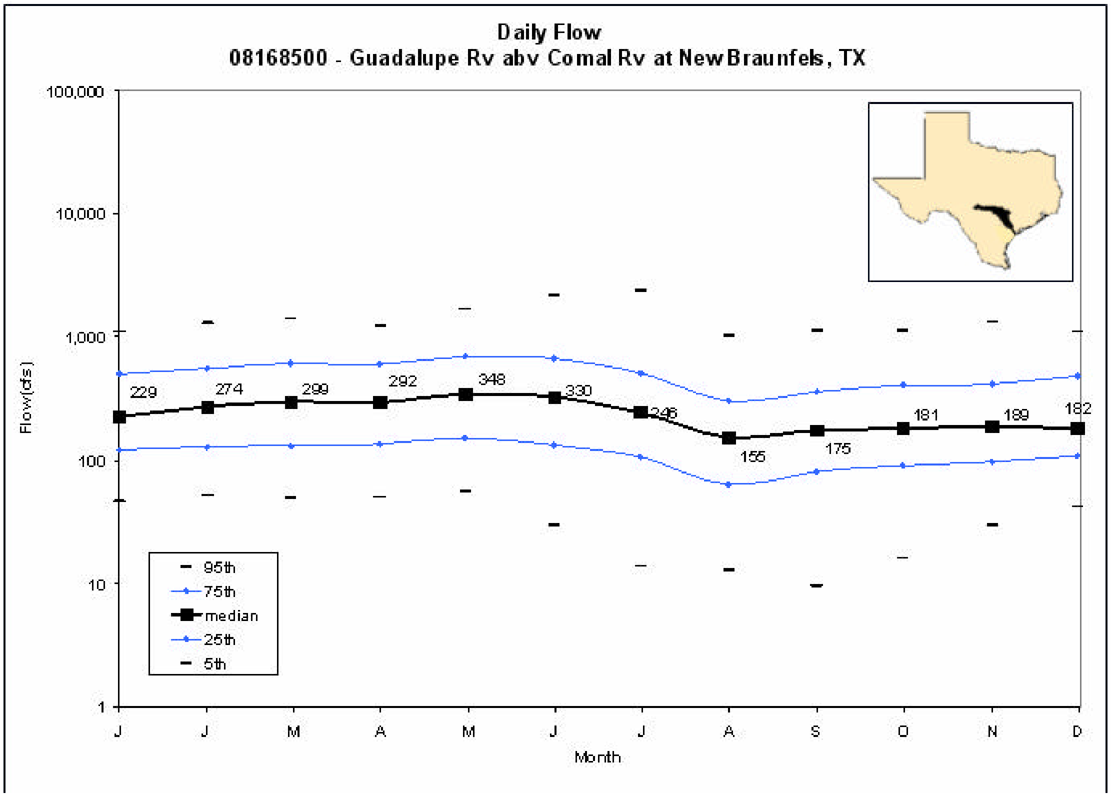


Figure 34. Modified box and whisker plot for USGS Gage No. 08168500, Guadalupe Rv abv Comal Rv at New Braunfels, TX.

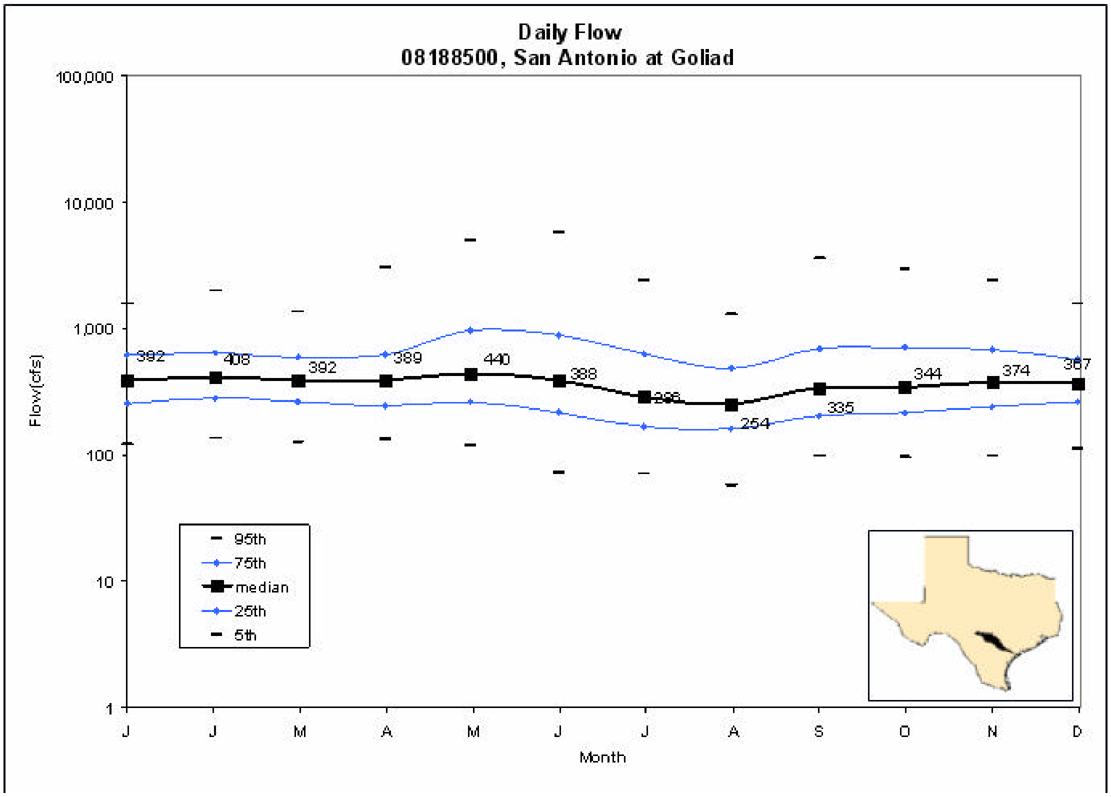


Figure 35. Modified box and whisker plot for USGS Gage No. 08188500, San Antonio Rv at Goliad, TX.

If the pattern of flow regime variation as a function of the median flow was able to completely explain the seasonal variation of the entire flow spectrum, then the filtering of the seasonal pattern of the median flow signal from the entire flow regime would result in a series of parallel lines representing the various high and low flows flanking the median. As can be seen in Figure 36, this explanation is partly true in this test case, particularly for the 25th and 75th percentile flows, but secondary factors are also contributing to the statistical variation of the atypical flows.

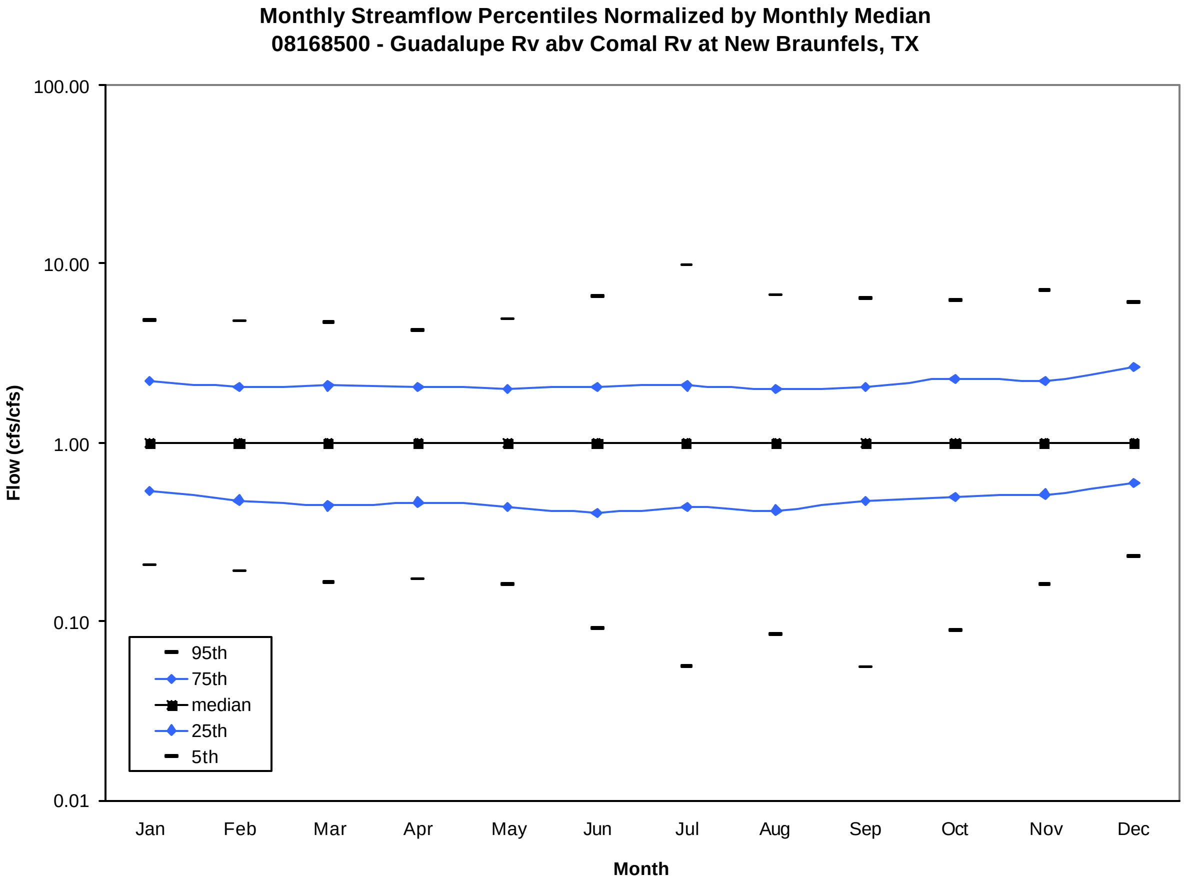


Figure 36. Modified box and whisker plot for USGS Gage No. 08168500, Guadalupe Rv abv Comal Rv at New Braunfels, TX, normalized by dividing by the median flow.

To explain some of the secondary variations still exhibited following the filtering of flow values by the median, an alternative step was performed that entailed subtracting the median flow and then dividing by the interquartile range, which is the 75th percentile flow minus the 25th percentile flow. The result of this test for two gages is presented in Figure 37 and Figure 38.

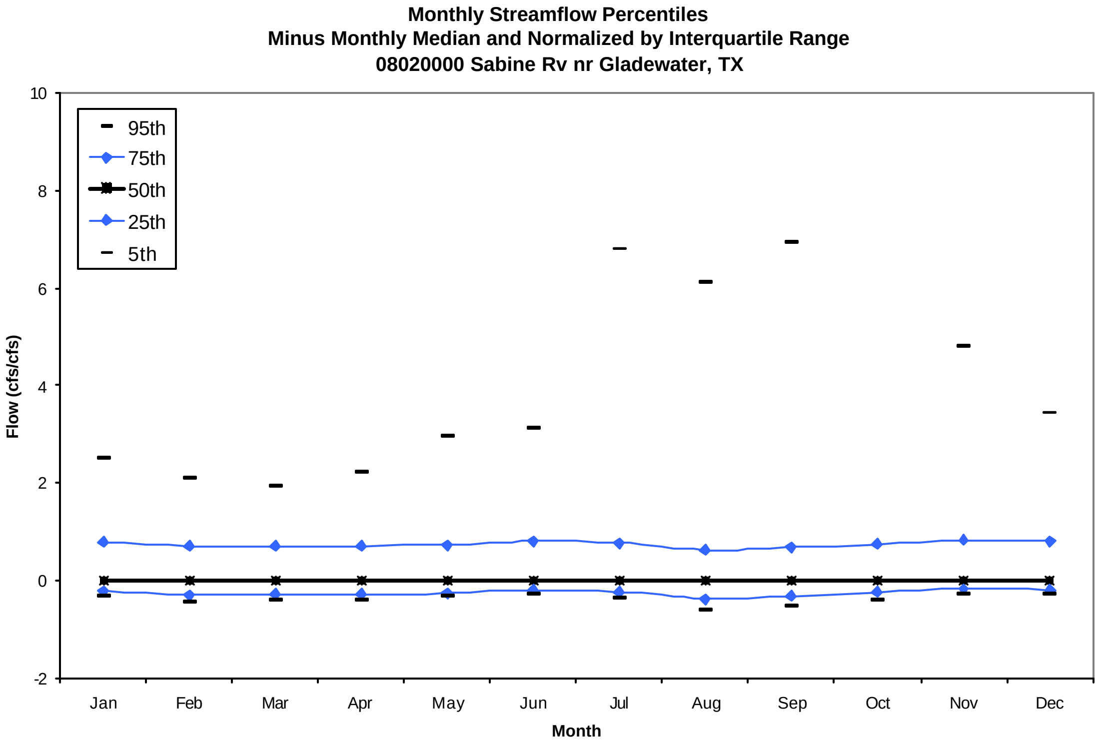


Figure 37. Modified box and whisker plot for USGS Gage No. 0802000, Sabine Rv nr Gladewater, TX, minus the monthly median and normalized by the interquartile range.

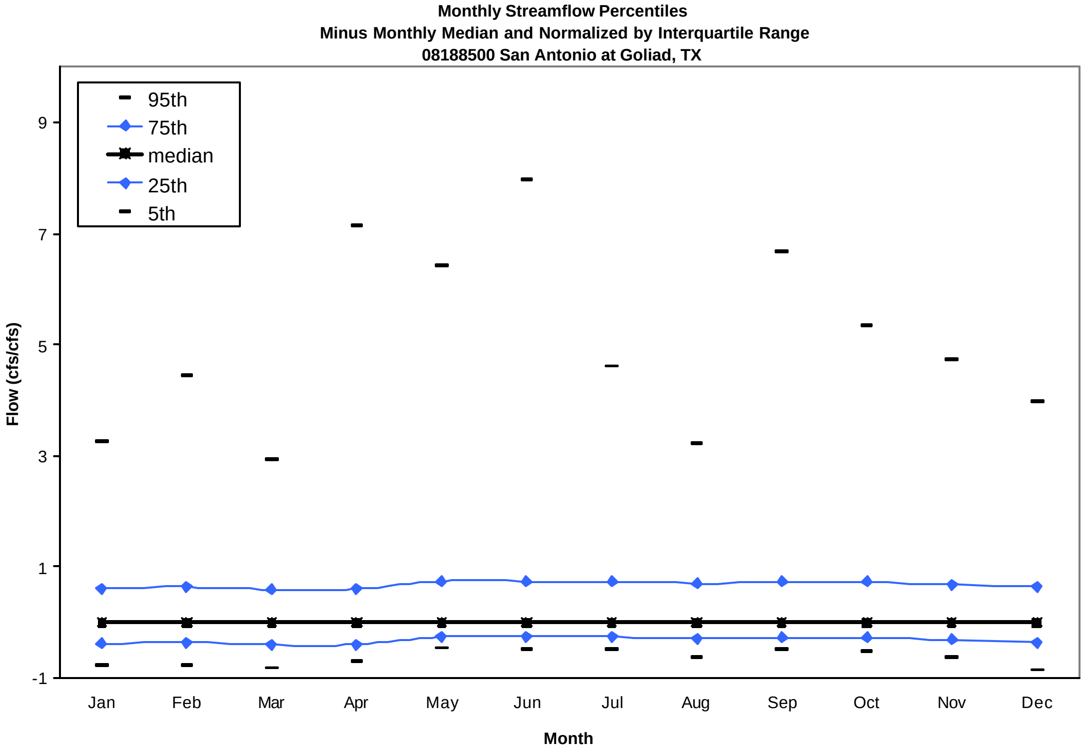


Figure 38. Modified box and whisker plot for USGS Gage No. 08188500, San Antonio Rv at Goliad, TX, minus the monthly median and normalized by the interquartile range.

From a subset of the study gages, it is evident that the last normalization step was able to account for a large majority of the seasonal variation for the 5th, 25th, and 75th percentile flows, as each of these flows is depicted in the above plots as a nearly straight line parallel to the median. However, the occurrence of 95th percentile streamflows is not explained at all by this statistical technique and is thus likely a factor of the skewness of higher order statistical moments that affect the distribution of extreme flood events.

Base flow

Base flow is the part of the stream discharge that is not attributable to direct runoff from precipitation or snowmelt and is usually sustained by throughflow and groundwater flow; base flow can be thought of as the typical flow condition of a river in the absence of a rain event. The concept of base flow is not new to the environmental flow component model, nor is the task of calculating base flow statistics a new one to the field on hydrology. As such, there are multiple existing hydrograph-separation techniques that could be suitable for the determination of the base flow component of the TIFP flow regime model.

One of these techniques, the Standard Institute of Hydrology Method, was applied to a subset of the study gages using the United States Bureau of Reclamation's BFI computer program (Institute of Hydrology 1980, USBR 2004). An example of the results of this analysis is presented in Figure 39. An adoption or incorporation of the principles of base flow separation or the comparison of results from this technique of hydrograph analysis would be beneficial to the TIFP as a means to better define and evaluate the base flow component of the four flow component model. Furthermore, the BFI program has seen widespread use and is becoming the standard base flow separation tool in the United States.

Overbank Flow

At the opposite end of the flow spectrum lies overbank flows, those streamflows where the water level surpasses the height of the channel banks and results in flow over the floodplain. Unlike the other flow components, overbank flows have a finite, physically-defined lower bound. Given the channel slope, roughness, and cross-sectional area, it is easy to determine the flow volume required to overtop the banks and cause flooding, and all flows up to this threshold will be entirely contained with the stream channel. Also, bankfull flow is a common metric within the field of geomorphology (Leopold et al 1964).

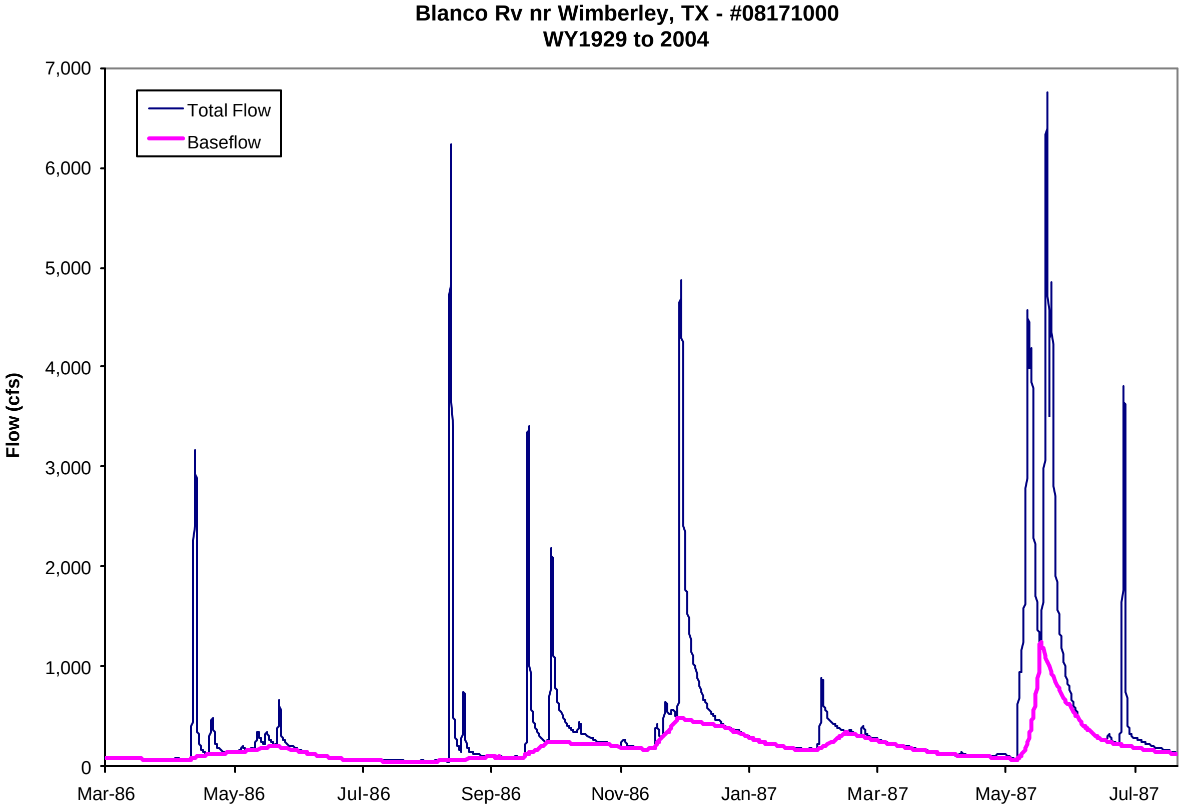


Figure 39. Base flow separation using the BFI program for USGS Gage No. 08171000, Blanco Rv nr Wimberley, TX.

Methods to ascertain the incipient point of overbank flooding were evaluated as part of this study. It was found that looking at additional published gage measurement data (in addition to discharge) from the USGS provides additional insight into the delineation of the overbank flow component that discharge data alone can not provide.

The USGS maintains an extensive nationwide network of real-time streamflow gaging stations across the United States; these stations measure real-time stage and that information is combined with an established rating curve to estimate the volumetric streamflow. The rating curves are continually calibrated and verified by USGS employees who visit the gage sites to measure the stream velocity and the flow cross-sectional area. Records of these site calibration visits are available on the USGS website and the pertinent data for the 24 study gages is included in Appendix D.

By plotting the discharge versus the measured active flow width and identifying the discharge range where the flow width increases significantly, it is possible to estimate the streamflow corresponding to the incipient point of overbank flooding. Examples of this technique are shown in Figure 40 and Figure 41.

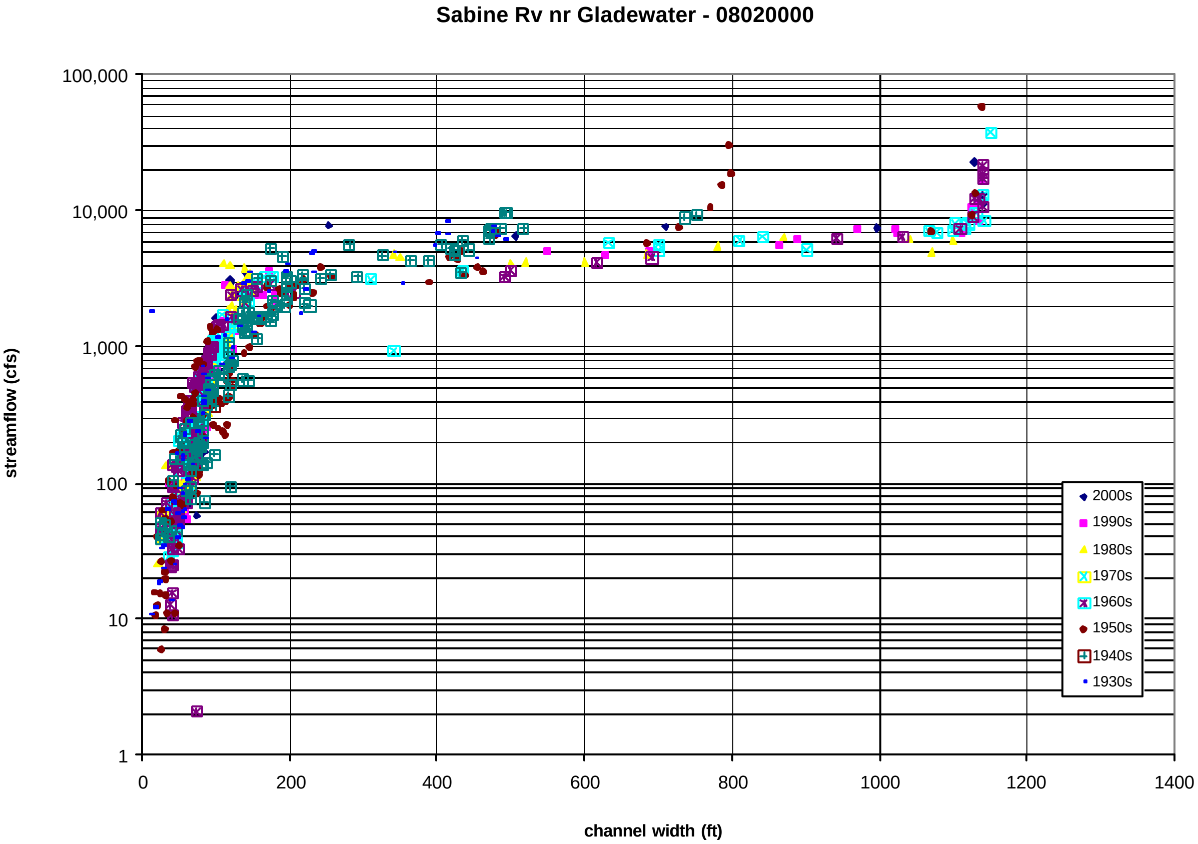


Figure 40. Discharge versus wetted channel width for USGS Gage No. 0802000, Sabine Rv nr Gladewater, TX, plotted by decade.

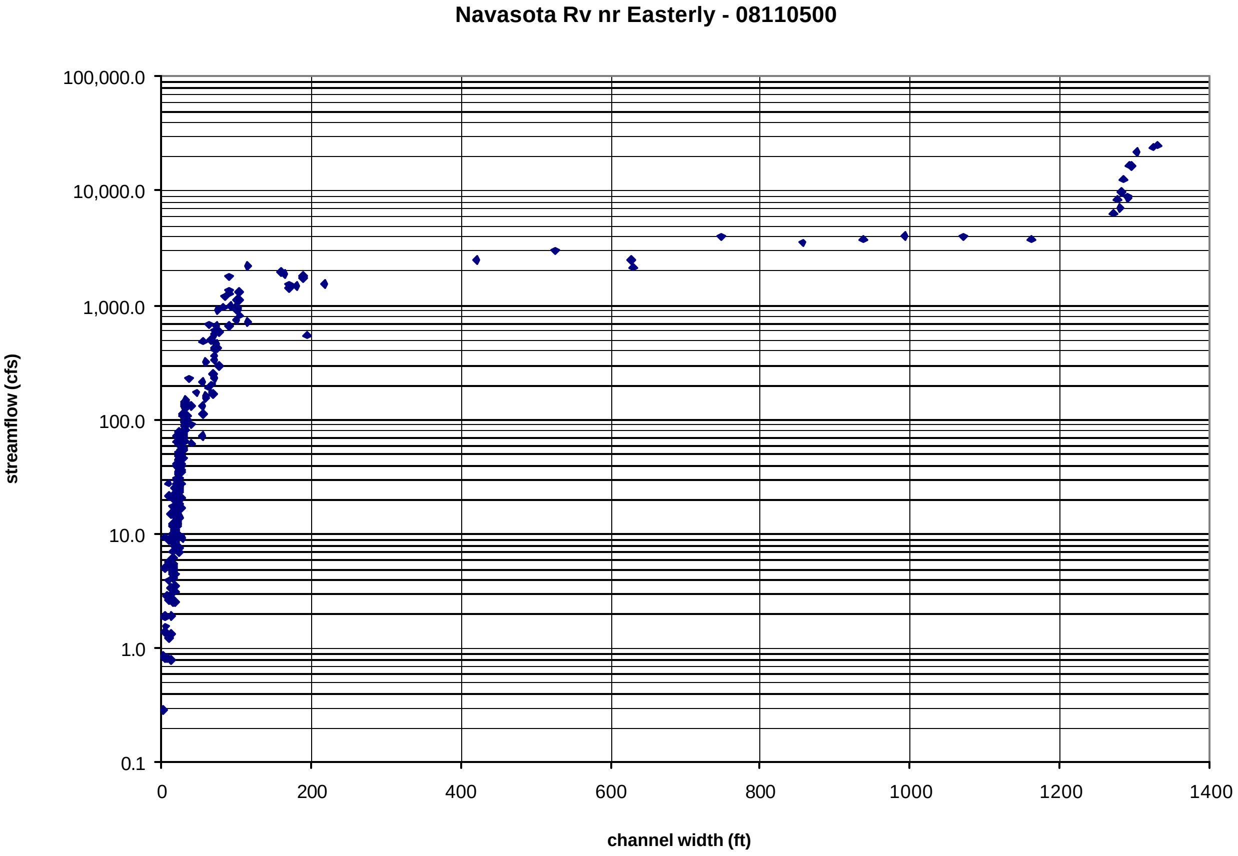


Figure 41. Discharge versus wetted channel width for USGS Gage No. 08110500, Navasota Rv nr Easterly, TX.

This technique is currently under development and subsequent refinements may increase its effectiveness and value as an analytical methodology for the estimation of overbank flows, particularly the development of a methodology to quantitatively determine a break in slope. A limitation of this method is that the gaging stations are often sited at altered river cross sections, such as at bridges or culverts, or the gage itself causes alteration of the river, such as via the installation of a weir. Thus, the streamflow required to cause overbank flooding at the gage site may not be representative of that required at the broader reach or river. Nonetheless, techniques for the evaluation of overbank flows based on geomorphic conditions may prove valuable in the understanding of the overbank flow component and for the development of statistical thresholds for defining overbank flows.

V. Conclusions and Recommendations

As general methods of streamflow hydrograph characterization, both IHA and HAT offer many useful functions that illuminate the nature of streamflow patterns through time at a stream gaging site. Both are simple to learn and to use, require the same readily-available input data, and are based on a consistent theory of hydrograph characterization that incorporates the magnitude, duration, timing, frequency, and rate of change of various hydrologic events. As such, the use of either analysis package to support the range of natural flow variability in making instream flow determinations represents a vast improvement over the old paradigm of a flat-line, minimum-flow approach to environmental flow prescriptions. Statistics generated by each program have many similarities, chiefly among them the inclusion of the 33 indicators of hydrologic alteration in the 171 HAT indices. In their current versions, however, neither IHA nor HAT is directly suitable for use in the TIFP; both would require modifications to be able to define flow component statistics for wet, dry, and normal years.

IHA, as its name implies, is best suited to assess hydrologic alteration and to quantify the effects of dam construction and other such water management development projects on the flow regime via two-period analyses and the Range of Variability Approach. HAT, as its name implies, is focused on characterizing streamflow, particularly in the context of a regional analysis of factors that influence streamflow properties. The USGS Hydroecological Integrity Assessment Protocol provides for the customization of NATHAT to specific regions for optimal results via the development of region-specific, hydrologically-defined stream classifications. The stream classifications and corresponding indices derived from a national dataset within NATHAT are likely neither ecologically significant nor relevant for application in the State of Texas. Both tools currently include temporal comparison tools (i.e., both tools can be used to compare results for the same stream gage over different periods of time), though neither tool currently includes spatial comparison tools (e.g., upstream versus downstream analysis of a specific reach or water withdrawal point).

If the task of choosing between the two programs is framed as the question of which tool better characterizes streamflow hydrographs in general, then there is little difference between these two packages. But if the task of choosing between them is framed more narrowly as the question of which program will best support the four-level flow characterization (subsistence flow, base flow, high flow pulses, and overbank flows) of the Texas Instream Flow Program, then the HAT program is a better choice than IHA as it allows for more flexibility in the determination of flow component thresholds and greater capacity for regionalization. Note that the indices calculated in IHA and HAT can all be calculated using independent software such as Microsoft Excel, Matlab, or SAS, oftentimes allowing for greater flexibility.

It would be of great benefit to stakeholders and those performing the subbasin studies if TIFP were to provide guidance and suggest methodologies to determine thresholds with ecological and/or biological significance of the four flow components. This guidance will help to define how a hydrologic assessment tool will be used to calculate statistics for the entire range of the flow regime. Guidance on the definition of wet, dry, and normal years would be similarly valuable.

The IHA Environmental Flow Component algorithm subdivides the daily streamflow hydrograph into a set of discrete flow regimes based on the magnitude and rate of change of the discharge. At any time, the flow must be in one of the five specified flow regimes (extreme low flow, low flow, high flow pulses, small floods, and large floods, which are analogous to the four TIFP flow components when small and large floods are considered in aggregate). The decision tree that makes the distinction between flow components is complex and at times the criteria that characterize the magnitude of flow and those that characterize the rate of change of flow get combined in ways that are hard to justify or understand. For example, it is possible for high flow pulses to have a lower daily discharge than surrounding periods of low flow due to the rate of hydrograph recession. As such, it will likely be hard to apply and explain this algorithm to a general audience and ever more difficult to codify into water allocation permits. We have concluded that the procedure within IHA for identifying high flow pulses on the basis of percent change in flow leads to illogical results where high flow pulses can have lower peak discharges than surrounding periods of low flow. We have discussed these issues with Brian Richter, the developer of IHA, and have found that he concurs and has indicated that he will address this issue in a future version of IHA, along with changing the name of the IHA “low flow” component to “base flow” to more accurately describe this component of the hydrograph and also to ensure semantic consistency with the NRC recommendations and thus the TIFP flow component model (Richter personal communication 2006).

HAT determines a set of streamflow indicators that characterize the flow hydrograph without requiring it to be partitioned into a discrete number of flow regimes. This is a more flexible approach that does not require the complex flow process used by IHA, but also does not internally incorporate the flow component model of IHA and TIFP. As discussed above, HIP provides for regionalization via the application of multivariate statistical analyses to a large population of HAT results to identify a subset of non-redundant indices that best characterize the flow regime. Based on preliminary exploratory analyses at a limited number of streamflow gages in the six priority subbasins, HAT can generate streamflow characteristics that will meet the TIFP criteria and that correlate well with similarly derived characteristics by other hydrologic methods such as for the determination of base flow. Unlike IHA, HAT makes use of non-dimensional indices, many of which are normalized by the median daily streamflow. These indices have great potential to be applied regionally as they are not direct measures of magnitude and thus are somewhat decoupled from contributory drainage area. The seven-day, two-year low flow (7Q2) is an important regulatory threshold in the Texas Surface Water Quality Standards; Neither IHA nor HAT currently has the ability to explicitly calculate the 7Q2, but it can be derived easily from indices within each of the programs.

The study of streamflow time series at the 24 selected gages within the 6 TIFP priority subbasins for a period-of-record averaging 68 years has demonstrated that there are pronounced regional patterns in the seasonality of the streamflow hydrograph, with little seasonal variation in central Texas (e.g., Lower San Antonio and Lower Guadalupe subbasins) grading to a strongly seasonal variation in East Texas (e.g., Lower Sabine and Middle Trinity subbasins). The degree of spatial variability in the seasonal pattern of streamflow in East Texas is significantly greater than spatial variation in precipitation alone can explain. In general, the long-term average daily hydrographs in East Texas exhibited a sinusoidal pattern with a spring peak (i.e., May to June) and a fall trough (i.e., August to September) when viewed on a semi-log plot. For a 30-year period of record, precipitation is bimodal, irrespective of geography, with spring (i.e., May to June) and fall (i.e., September to October) peaks; the precipitation gradient from East to Central Texas is expressed in the magnitude of precipitation (more to the east) but not in the timing.

When considered over a long time scale, the seasonal variation in the flow regime of various percentile levels of flow follows a consistent pattern, such that if the median flow goes down then both high and low flow percentiles reduce proportionately to some extent, and vice versa when the median flow increases. Although this pattern holds true across a sample of priority gages studied, the high and low portions of the flow regime also each exhibit their own secondary patterns of seasonality. This suggests that if the seasonal variation of the flow regime is normalized by dividing by the median flow, then some of the statistical variation of percentiles of low and high flow ratios throughout the year may be explained. Also, it will likely be easier to characterize the seasonal variation of within-bank high flow pulses and flood flows as ratios to the seasonal variation of median flow rather than via rate of change of flow (i.e., hydrograph onset and recession) arguments. As previously discussed, HAT makes use of such ratios to the median flow as indices of regional streamflow characteristics but IHA does not.

For the hydrologic conditions present in Texas, the median flow is the most robust streamflow characteristic that is available (i.e., it is most consistently estimated with a given number of data values), and it can reasonably be estimated both from daily and from monthly streamflow data. This means that either gaged flows or WAM-derived naturalized flows can be used to recommend median flows. This is not so for definitions of instream flow pulses using rate of change arguments where daily data (perhaps even hourly data on small watersheds) are required. The time scales selected for evaluation and implementation in the TIFP are critical to the success of environmental flow prescriptions as various riverine physical, chemical, and biological processes operate on highly variable time scales.

The overbank flow component has a specific, physically-based flow threshold for any given stream cross-section based on the stream slope, roughness, and channel capacity. Looking at additional published gage data (in addition to discharge) provides additional insight into the delineation of this flow component that discharge data alone can not provide. For example, flood flows out of the stream banks can be characterized by plotting the discharge versus the measured active flow width in the records available at all USGS streamflow gage sites and identifying the discharge range where the flow width increases significantly, thus likely indicating the incipient point of overbank flooding. The social, political, and economic issues of prescribing flood events for ecological purposes are real and complex; work done as part of this study has focused simply on promising analytical methodologies to identify the portion of the historic flow regime that is overbank.

From this study we conclude that a Texas-customized version of HAT (as part of the HIP) is suitable and preferable to IHA for application in the Texas Instream Flow Program. Further work is necessary as part of the TIFP guidance or within the subbasin studies to define the specific role of hydrologic assessment tools, particularly with respect to flow component delineation and the definition of wet, dry, and normal years. Regardless of the tool selected, the consideration of the variability of the natural flow regime and the development of instream flow prescriptions accordingly represents a leap forward in the science and policy of instream flow and in the ability to protect and/or restore a “sound ecological environment.”

Appendix A – Scope of Work

The purpose of this project is to assess the applicability of hydrologic analysis tools such as The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) and US Geological Survey's Hydrologic Assessment Tool (HAT) for use in the Texas Instream Flow Program. Additionally, the Principal Investigator may recommend improvements or changes to these software tools that would make them more useful to the Texas Instream Flow Program.

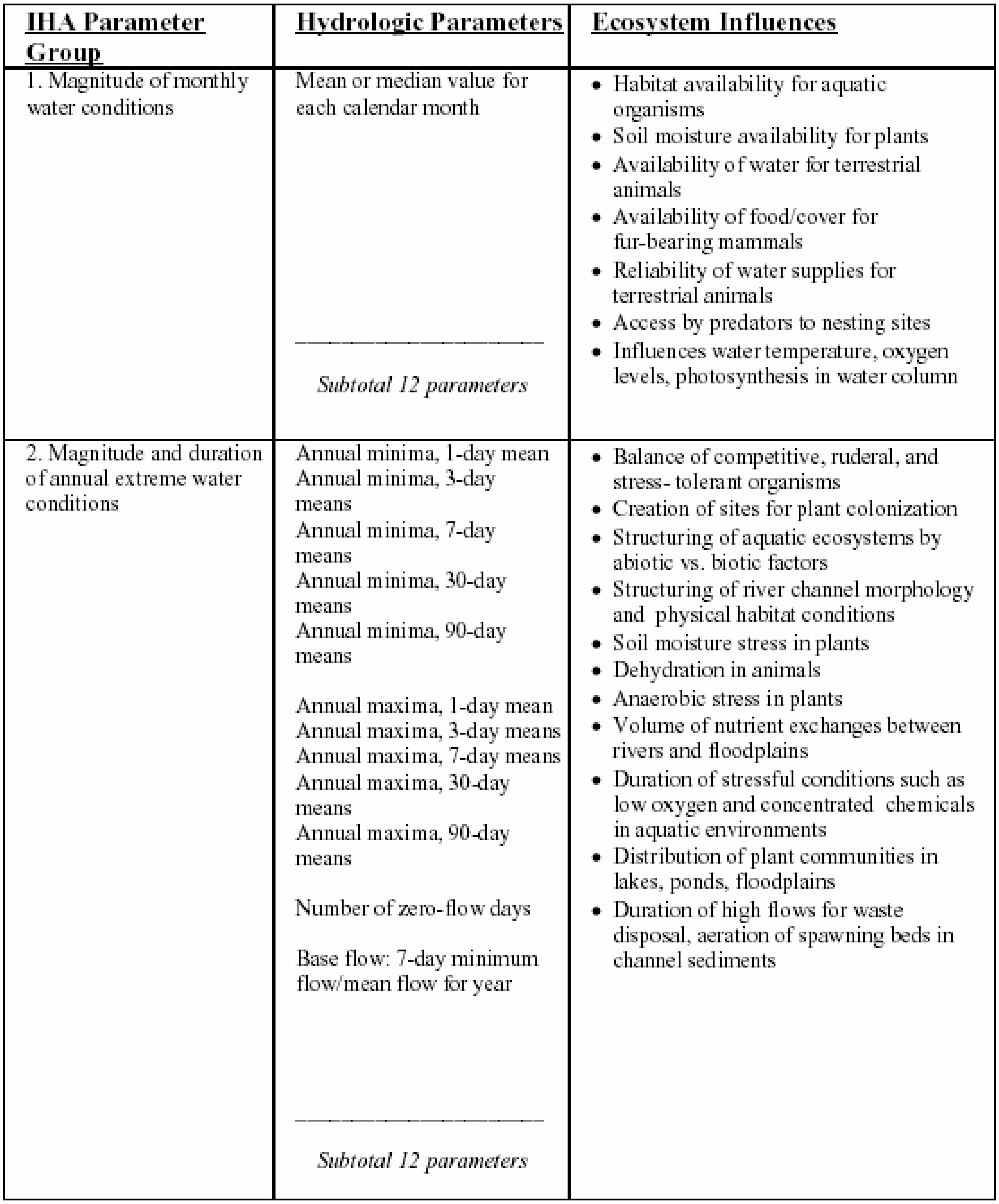
Both IHA and HAT software are designed to help users analyze flow regimes and easily identify the hydrologic impacts of human activities in a time series of flows. They are intended to provide users with tools to characterize and compare hydrologic regimes in ecologically-meaningful terms. Parameters are based on five fundamental characteristics of hydrologic flow regimes: magnitude, timing, frequency, duration, and rate of change. Different time periods in the flow record can be separated for analyzing the impact of such activities as reservoir construction and operation, major water rights, or long-term changes in climate. The software may also prove helpful for identifying subsistence and base flows, high flow pulses, and overbanking flows. While IHA includes 67 statistical routines, HAT incorporates the 171 hydrologic indices of Olden and Poff (2003). HAT offers the added utility of guiding users to tailor the selection of hydrologic indices based on the type of hydrologic regime (i.e., stable, groundwater-fed stream versus intermittent, flashy stream). HAT has been customized and adopted by the state of New Jersey for use in its instream flow program. Similar customization is underway for use by other states and Canada (Henriksen 2006).

Using daily flow information available from USGS gaging stations, Dr. Maidment and his research staff will use IHA and HAT to evaluate the flow regime of at least four reaches in each of six sub-basins currently under investigation by the state agencies: Guadalupe, Lower Sabine, middle and lower Brazos, Trinity, and San Antonio rivers. Reaches will be selected in coordination with state agencies and should include mainstem and tributary segments, as well as regulated and non-impacted sites.

At the culmination of this exercise, Center for Research in Water Resources (CRWR) staff will have assessed the appropriateness of these software packages for use in the Texas Instream Flow Program, determined whether HAT or IHA is more suitable for Texas' purposes, and recommended any changes or enhancements that might make the software more effective for Texas studies. Subject to time and resource availability and the ability to obtain program source code, the contractor may modify IHA and/or HAT software as recommended and provide training for state agency staff.

Appendix B – IHA Parameters

(from Nature Conservancy 2005)



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: 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
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) *Subtotal 4 parameters*	• 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 waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	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 *Subtotal 3 parameters* **Grand total 33 parameters**	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

EFC Type	**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 eggs 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

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 *Subtotal 6 parameters*	• 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
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 *Subtotal 6 parameters*	Applies to small and large floods: • Provide migration and spawning cues for fish • Trigger new phase 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

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) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters* **Grand total 34 parameters**	Applies to small and large floods: • Maintain balance of species in aquatic and riparian communities • Create sites for recruitment of colonizing plants • Shape physical habitats of floodplain • Deposit gravel and cobbles in spawning areas • Flush organis 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) • Provide plant seedlings with prolonged access to soil moisture

Appendix C – HAT Parameters

(from Henriksen 2006)

Explanation – The following information is for the 171 hydrologic indices is from Olden and Poff (2003). The USGS revised a limited number of the formula and (or) definitions when deemed appropriate. A USGS Scientific Investigations Report in preparation will document these changes. The Olden and Poff (2003) article contains 12 additional references from which the indices were derived. Two of these articles are referenced here because they provide examples and additional explanation for complex indices.

The alphanumeric code preceding each definition refers to the category of the flow regime (magnitude, frequency, duration, timing, and rate of change) and type of flow event (A, average, L, low, and H, high) the hydrologic index was developed to describe. Indices are numbered successively within each category. For example, MA1 is the first index describing magnitude of the average flow condition.

MA# - Magnitude, average flow event
ML# -Magnitude, low flow event
MH# - Magnitude, high flow event
FL# - Frequency, low flow event
FH# - Frequency, high flow event
DL# - Duration, low flow event
DH# - Duration, high flow event
TA# - Timing, average flow event
TL# -Timing, low flow event
TH# -Timing, high flow event
RA# - Rate of change, average event

Following each definition, in parentheses, are (1) the units of the index, and (2) the type of data, temporal or spatial data, from which the upper and lower percentiles limits (for example, 75/25) are derived. Temporal data are from a multiyear daily flow record from a single stream gage. For example, index MA1- mean for the entire flow record - uses 365 mean daily flow values for each year in the flow record to calculate the mean for the entire flow record. Consequently, there are 365 values for each year to calculate upper and lower percentile limits. However, formulas for 60 of the indices do not produce a range of values from which percentile limits can be calculated. MA5 (skewness), for example, the mean for the entire flow record divided by the median for the entire record results in a single value, and thus, upper and lower percentile limits cannot be calculated.

Exceedance and percentile are used in the calculation for a number of indices. Note the difference - a 90 percent exceedance means that 90 percent of the values are equal to or greater than the 90 percent exceedance value, while a 90th percentile means that 10 percent of the values are equal to or greater than the 90th percentile value.

MA1	Mean of the daily mean flow values for the entire flow record (cubic feet per second – temporal).
MA2	Median of the daily mean flow values for the entire flow record (cubic feet per second – temporal).
MA3	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows. Compute the mean of the annual coefficients of variation (percent - temporal).
MA4	Standard deviation of the percentiles of the logs of the entire flow record divided by the mean of percentiles of the logs. Compute the log10 of the daily flows for the entire record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the logs of the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute the standard

	deviation and mean for the percentile values. Divide the standard deviation by the mean (percent - spatial).
MA5	The skewness of the entire flow record is computed as the mean for the entire flow record (MA1) divided by the median (MA2) for the entire flow record (dimensionless - spatial).
MA6	Range in daily flows is the ratio of the 10 percent to 90 percent exceedance values for the entire flow record. Compute the 5 percent to 95 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 10 percent exceedance value by the 90 percent value (dimensionless – spatial).
MA7	Range in daily flows is computed like MA6 except using the 20 percent and 80 percent exceedance values. Divide the 20 percent exceedance value by the 80 percent value (dimensionless - spatial).
MA8	Range in daily flows is computed like MA6 except using the 25 percent and 75 percent exceedance values. Divide the 25 percent exceedance value by the 75 percent value (dimensionless – spatial).
MA9	Spread in daily flows is the ratio of the difference between the 90th and 10th percentile of the logs of the flow data to the log of the median of the entire flow record. Compute the log10 of the daily flows for the entire record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the logs of the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute MA9 as (90th – 10th) /log10(MA2) (dimensionless – spatial).
MA10	Spread in daily flows is computed like MA9 except using the 20th and 80th percentiles (dimensionless – spatial).
MA11	Spread in daily flows is computed like MA9 except using the 25th and 75th percentiles (dimensionless – spatial).
MA12-23	Means (or medians - Use Preference option) of monthly flow values. Compute the means for each month over the entire flow record. For example, MA12 is the mean of all January flow values over the entire record (cubic feet per second – temporal).
MA24-35	Variability (coefficient of variation) of monthly flow values. Compute the standard deviation for each month in each year over the entire flow record. Divide the standard deviation by the mean for each month. Average (or median - Use Preference option) these values for each month across all years (percent – temporal).
MA36	Variability across monthly flows. Compute the minimum, maximum, and mean flows for each month in the entire flow record. MA36 is the maximum monthly flow minus the minimum monthly flow divided by the median monthly flow (dimensionless – spatial).
MA37	Variability across monthly flows. Compute the first (25th percentile) and the third (75th percentile) quartiles (every month in the flow record). MA37 is the third quartile minus the first quartile divided by the median of the monthly means (dimensionless – spatial).
MA38	Variability across monthly flows. Compute the 10th and 90th percentiles for the monthly means (every month in the flow record). MA38 is the 90th percentile minus the 10th percentile divided by the median of the monthly means (dimensionless – spatial).
MA39	Variability across monthly flows. Compute the standard deviation for the monthly means. MA39 is the standard deviation times 100 divided by the mean of the monthly means (percent – spatial).
MA40	Skewness in the monthly flows. MA40 is the mean of the monthly flow means minus the median of the monthly means divided by the median of the monthly means (dimensionless – spatial).

MA41	Annual runoff. Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area (cubic feet per second/square mile – temporal).
MA42	Variability across annual flows. MA42 is the maximum annual flow minus the minimum annual flow divided by the median annual flow (dimensionless – spatial).
MA43	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA43 is the third quartile minus the first quartile divided by the median of the annual means (dimensionless –spatial).
MA44	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA44 is the 90th percentile minus the 10th percentile divided by the median of the annual means (dimensionless – spatial).
MA45	Skewness in the annual flows. MA45 is the mean of the annual flow means minus the median of the annual means divided by the median of the annual means (dimensionless – spatial).
ML1-12	Mean (or median - Use Preference option) minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. For example, ML1 is the mean of the minimums of all January flow values over the entire record (cubic feet per second – temporal).
ML13	Variability (coefficient of variation) across minimum monthly flow values. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years (percent – spatial).
ML14	Compute the minimum annual flow for each year. ML14 is the mean of the ratios of minimum annual flows to the median flow for each year (dimensionless – temporal).
ML15	Low flow index. ML15 is the mean of the ratios of minimum annual flows to the mean flow for each year (dimensionless – temporal).
ML16	Median of annual minimum flows. ML16 is the median of the ratios of minimum annual flows to the median flow for each year (dimensionless – temporal).
ML17	Base flow. Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios (dimensionless – temporal).
ML18	Variability in base flow. Compute the standard deviation for the ratios of 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios (percent – spatial).
ML19	Base flow. Compute the ratios of the minimum annual flow to mean annual flow for each year. ML19 is the mean (or median - Use Preference option) of these ratios times 100 (dimensionless – temporal).
ML20	Base flow. Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow (dimensionless – spatial).
ML21	Variability across annual minimum flows. Compute the mean and standard deviation for the annual minimum flows. ML21 is the standard deviation times 100 divided by the mean (percent – spatial).

ML22	Specific mean annual minimum flow. ML22 is the mean (or median - Use Preference option) of the annual minimum flows divided by the drainage area (cubic feet per second/square mile – temporal).
MH1-12	Mean (or median - Use Preference option) maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. For example, MH1 is the mean of the maximums of all January flow values over the entire record (cubic feet per second – temporal).
MH13	Variability (coefficient of variation) across maximum monthly flow values. Compute the mean and standard deviation for the maximum monthly flows over the entire flow record. MH13 is the standard deviation times 100 divided by the mean maximum monthly flow for all years (percent – spatial).
MH14	Median of annual maximum flows. Compute the annual maximum flows from monthly maximum flows. Compute the ratio of annual maximum flow to median annual flow for each year. MH14 is the median of these ratios (dimensionless – temporal).
MH15	High flow discharge index. Compute the 1 percent exceedance value for the entire data record. MH15 is the 1 percent exceedance value divided by the median flow for the entire record (dimensionless – spatial).
MH16	High flow discharge index. Compute the 10 percent exceedance value for the entire data record. MH16 is the 10 percent exceedance value divided by the median flow for the entire record (dimensionless – spatial).
MH17	High flow discharge index. Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record (dimensionless – spatial).
MH18	Variability across annual maximum flows. Compute the logs (log10) of the maximum annual flows. Find the standard deviation and mean for these values. MH18 is the standard deviation times 100 divided by the mean (percent – spatial).
MH19	Skewness in annual maximum flows. Use the equation: $MH19 = \frac{N2 \text{ x } sum(qm3) - 3N \text{ x } sum(qm) \text{ x } sum(qm2) + 2 \text{ x } (sum(qm))3}{N \text{ x } (N-1) \text{ x } (N-2) \text{ x } stddev3}$ where: N = Number of years qm = Log10(annual maximum flows) stddev = Standard deviation of the annual maximum flows. (dimensionless – spatial).
MH20	Specific mean annual maximum flow. MH20 is the mean (or median - Use Preference option) of the annual maximum flows divided by the drainage area (cubic feet per second/square mile – temporal).
MH21	High flow volume index. Compute the average volume for flow events above a threshold equal to the median flow for the entire record. MH21 is the average volume divided by the median flow for the entire record (days – temporal).
MH22	High flow volume. Compute the average volume for flow events above a threshold equal to three times the median flow for the entire record. MH22 is the average volume divided by the median flow for the entire record (days - temporal).
MH23	High flow volume. Compute the average volume for flow events above a threshold equal to seven times the median flow for the entire record. MH23 is the average volume divided by the median flow for the entire record (days - temporal).
MH24	High peak flow. Compute the average peak flow value for flow events above a threshold equal to the median flow for the entire record. MH24 is the average peak flow divided by the median flow for the entire record (dimensionless – temporal).

MH25	High peak flow. Compute the average peak-flow value for flow events above a threshold equal to three times the median flow for the entire record. MH25 is the average peak flow divided by the median flow for the entire record (dimensionless – temporal).
MH26	High peak flow. Compute the average peak flow value for flow events above a threshold equal to seven times the median flow for the entire record. MH26 is the average peak flow divided by the median flow for the entire record (dimensionless – temporal).
MH27	High peak flow. Compute the average peak flow value for flow events above a threshold equal to 75th percentile value for the entire flow record. MH27 is the average peak flow divided by the median flow for the entire record (dimensionless – temporal).
FL1	Low flood pulse count. Compute the average number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FL2	Variability in low pulse count. Compute the standard deviation in the annual pulse counts for FL1. FL2 is 100 times the standard deviation divided by the mean pulse count (percent – spatial).
FL3	Frequency of low pulse spells. Compute the average number of flow events with flows below a threshold equal to 5 percent of the mean flow value for the entire flow record. FL3 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH1	High flood pulse count. Compute the average number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH2	Variability in high pulse count. Compute the standard deviation in the annual pulse counts for FH1. FH2 is 100 times the standard deviation divided by the mean pulse count (number of events/year – spatial).
FH3	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years (number of days/year – temporal).
FH4	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to seven times the median flow for the entire record. FH4 is the mean (or median - Use Preference option) of the annual number of days for all years (number of days/year – temporal).
FH5	Flood frequency. Compute the average number of flow events with flows above a threshold equal to the median flow value for the entire flow record. FH5 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH6	Flood frequency. Compute the average number of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. FH6 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH7	Flood frequency. Compute the average number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH6 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH8	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 25 percent exceedance value for the entire flow record. FH8 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
FH9	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 75 percent exceedance value for the entire flow record. FH9 is the average (or median - Use Preference option) number of events (number of events/year – temporal).

FH10	Flood frequency. Compute the average number of flow events with flows above a threshold equal to median of the annual minima for the entire flow record. FH10 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
Note -	1.67-year flood threshold (Poff, 1996) - For indices FH11, DH22, DH23, DH24, TA3, and TH3 compute the log10 of the peak annual flows. Compute the log10 of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 1.67 year recurrence interval (60th percentile) as input to the regression equation, predict the log10 of the average daily flow. The threshold is 10 to the log10 (average daily flow) power (cubic feet/second).
FH11	Flood frequency. Compute the average number of flow events with flows above a threshold equal to flow corresponding to a 1.67-year recurrence interval. FH11 is the average (or median - Use Preference option) number of events (number of events/year – temporal).
DL1	Annual minimum daily flow. Compute the minimum 1-day average flow for each year. DL1 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DL2	Annual minimum of 3-day moving average flow. Compute the minimum of a 3-day moving average flow for each year. DL2 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DL3	Annual minimum of 7-day moving average flow. Compute the minimum of a 7-day moving average flow for each year. DL3 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DL4	Annual minimum of 30-day moving average flow. Compute the minimum of a 30day moving average flow for each year. DL4 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DL5	Annual minimum of 90-day moving average flow. Compute the minimum of a 90day moving average flow for each year. DL5 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DL6	Variability of annual minimum daily average flow. Compute the standard deviation for the minimum daily average flow. DL6 is 100 times the standard deviation divided by the mean (percent – spatial).
DL7	Variability of annual minimum of 3-day moving average flow. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean (percent - spatial).
DL8	Variability of annual minimum of 7-day moving average flow. Compute the standard deviation for the minimum 7-day moving averages. DL8 is 100 times the standard deviation divided by the mean (percent - spatial).
DL9	Variability of annual minimum of 30-day moving average flow. Compute the standard deviation for the minimum 30-day moving averages. DL9 is 100 times the standard deviation divided by the mean (percent - spatial).
DL10	Variability of annual minimum of 90-day moving average flow. Compute the standard deviation for the minimum 90-day moving averages. DL10 is 100 times the standard deviation divided by the mean (percent - spatial).
DL11	Annual minimum daily flow divided by the median for the entire record. Compute the minimum daily flow for each year. DL11 is the mean of these values divided by the median for the entire record (dimensionless – temporal).
DL12	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record (dimensionless – temporal).

DL13	Annual minimum of 30-day moving average flow divided by the median for the entire record. Compute the minimum of a 30-day moving average flow for each year. DL13 is the mean of these values divided by the median for the entire record (dimensionless – temporal).
DL14	Low exceedance flows. Compute the 75 percent exceedance value for the entire flow record. DL14 is the exceedance value divided by the median for the entire record (dimensionless – spatial).
DL15	Low exceedance flows. Compute the 90 percent exceedance value for the entire flow record. DL14 is the exceedance value divided by the median for the entire record (dimensionless – spatial).
DL16	Low flow pulse duration. Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations (number of days – temporal).
DL17	Variability in low pulse duration. Compute the standard deviation for the yearly average low pulse durations. DL17 is 100 times the standard deviation divided by the mean of the yearly average low pulse durations (percent – spatial).
DL18	Number of zero-flow days. Count the number of zero-flow days for the entire flow record. DL18 is the mean (or median - Use Preference option) annual number of zero flow days (number of days/year – temporal).
DL19	Variability in the number of zero-flow days. Compute the standard deviation for the annual number of zero-flow days. DL19 is 100 times the standard deviation divided by the mean annual number of zero-flow days (percent – spatial).
DL20	Number of zero-flow months. While computing the mean monthly flow values, count the number of months in which there was no flow over the entire flow record (percent – spatial).
DH1	Annual maximum daily flow. Compute the maximum of a 1-day moving average flow for each year. DH1 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DH2	Annual maximum of 3-day moving average flows. Compute the maximum of a 3day moving average flow for each year. DH2 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DH3	Annual maximum of 7-day moving average flows. Compute the maximum of a 7day moving average flow for each year. DH3 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DH4	Annual maximum of 30-day moving average flows. Compute the maximum of 30day moving average flows. Compute the maximum of a 30-day moving average flow for each year. DH4 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DH5	Annual maximum of 90-day moving average flows. Compute the maximum of a 90day moving average flow for each year. DH5 is the mean (or median - Use Preference option) of these values (cubic feet per second – temporal).
DH6	Variability of annual maximum daily flows. Compute the standard deviation for the maximum 1-day moving averages. DH6 is 100 times the standard deviation divided by the mean (percent – spatial).
DH7	Variability of annual maximum of 3-day moving average flows. Compute the standard deviation for the maximum 3-day moving averages. DH7 is 100 times the standard deviation divided by the mean (percent – spatial).
DH8	Variability of annual maximum of 7-day moving average flows. Compute the standard deviation for the maximum 7-day moving averages. DH8 is 100 times the standard deviation divided by the mean (percent – spatial).

DH9	Variability of annual maximum of 30-day moving average flows. Compute the standard deviation for the maximum 30-day moving averages. DH9 is 100 times the standard deviation divided by the mean (percent – spatial).
DH10	Variability of annual maximum of 90-day moving average flows. Compute the standard deviation for the maximum 90-day moving averages. DH10 is 100 times the standard deviation divided by the mean (percent – spatial).
DH11	Annual maximum of 1-day moving average flows divided by the median for the entire record. Compute the maximum of a 1-day moving average flow for each year. DL11 is the mean of these values divided by the median for the entire record (dimensionless – temporal).
DH12	Annual maximum of 7-day moving average flows divided by the median for the entire record. Compute the maximum daily average flow for each year. DL12 is the mean of these values divided by the median for the entire record (dimensionless – temporal).
DH13	Annual maximum of 30-day moving average flows divided by the median for the entire record. Compute the maximum of a 30-day moving average flow for each year. DL13 is the mean of these values divided by the median for the entire record (dimensionless – temporal).
DH14	Flood duration. Compute the mean of the mean monthly flow values. Find the 95th percentile for the mean monthly flows. DH14 is the 95th percentile value divided by the mean of the monthly means (dimensionless – spatial).
DH15	High flow pulse duration. Compute the average duration for flow events with flows above a threshold equal to the 75th percentile value for each year in the flow record. DH15 is the median of the yearly average durations (days/year – temporal).
DH16	Variability in high flow pulse duration. Compute the standard deviation for the yearly average high pulse durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations (percent – spatial).
DH17	High flow duration. Compute the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the average (or median - Use Preference option) duration of the events (days – temporal).
DH18	High flow duration. Compute the average duration of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. DH18 is the average (or median - Use Preference option) duration of the events (days – temporal).
DH19	High flow duration. Compute the average duration of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. DH19 is the average (or median - Use Preference option) duration of the events (days – temporal).
DH20	High flow duration. Compute the 75th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 75th percentile value for the median annual flows. DH20 is the average (or median - Use Preference option) duration of the events (days – temporal).
DH21	High flow duration. Compute the 25th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 25th percentile value for the entire set of flows. DH21 is the average (or median - Use Preference option) duration of the events (days – temporal).
DH22	Flood interval. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the median number of days between flood events for each year. DH22 is the mean (or median - Use Preference option) of the yearly median number of days between flood events (days – temporal).
DH23	Flood duration. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the number of days each year that the flow remains above the flood threshold.

	DH23 is the mean (or median - Use Preference option) of the number of flood days for years in which floods occur (days – temporal).
DH24	Flood-free days. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Compute the maximum number of days that the flow is below the threshold for each year. DH24 is the mean (or median - Use Preference option) of the maximum yearly no-flood days (days – temporal).
TA1	Constancy. Constancy is computed via the formulation of Colwell (see example in Colwell, 1974). A matrix of values is compiled where the rows are 11 flow categories and the columns are 365 (no February 29th) days of the year. The cell values are the number of times that a flow falls into a category on each day. The categories are: log(flow) < .1 x log(mean flow), .1 x log(mean flow) <= log(flow) < .25 x log(mean flow) .25 x log(mean flow) <= log(flow) < .5 x log(mean flow) .5 x log(mean flow) <= log(flow) < .75 x log(mean flow) .75 x log(mean flow) <= log(flow) < 1.0 x log(mean flow) 1.0 x log(mean flow) <= log(flow) < 1.25 x log(mean flow) 1.25 x log(mean flow) <= log(flow) < 1.5 x log(mean flow) 1.5 x log(mean flow) <= log(flow) < 1.75 x log(mean flow) 1.75 x log(mean flow) <= log(flow) < 2.0 x log(mean flow) 2.0 x log(mean flow) <= log(flow) < 2.25 x log(mean flow) log(flow) >= 2.25 x log(mean flow) The row totals, column totals, and grand total are computed. Using the equations for Shannon information theory parameters, constancy is computed as: $1 - \frac{\text{(uncertainty with respect to state)}}{\text{log (number of state)}}$ (dimensionless – spatial).
TA2	Predictability. Predictability is computed from the same matrix as constancy (see example in Colwell, 1974). It is computed as: 1-(uncertainty with respect to interaction of time and state - uncertainty with respect to time $1 - \frac{\text{(uncertainty with respect to interaction of time and state - uncertainty with respect to time)}}{\text{log (number of state)}}$ (dimensionless – spatial).
TA3	Seasonal predictability of flooding. Divide years up into 2-month periods (that is, Oct-Nov, Dec-Jan, and so forth). Count the number of flood days (flow events with flows > 1.67-year flood) in each period over the entire flow record. TA3 is the maximum number of flood days in any one period divided by the total number of flood days (dimensionless – temporal).
TL1	Julian date of annual minimum. Determine the Julian date that the minimum flow occurs for each water year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day – spatial).
TL2	Variability in Julian date of annual minima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian day – spatial).
Note -	5-year flood threshold (Poff, 1996) – For TL3 and TH3, compute the log10 of the peak annual flows. Compute the log10 of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 5-year recurrence interval (20th percentile) as input to the regression equation, predict the log10 of the average daily flow. The threshold is 10 to the log10 (average daily flow) power (cubic feet per second).

TL3	Seasonal predictability of low flow. Divide years up into 2-month periods (that is, Oct-Nov, Dec-Jan, and so forth). Count the number of low flow events (flow events with flows <= 5 year flood threshold) in each period over the entire flow record. TL3 is the maximum number of low flow events in any one period divided by the total number of low flow events (dimensionless – spatial).
TL4	Seasonal predictability of non-low flow. Compute the number of days that flow is above the 5-year flood threshold as the ratio of number of days to 365 or 366 (leap year) for each year. TL4 is the maximum of the yearly ratios (dimensionless – spatial).
TH1	Julian date of annual maximum. Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day – spatial).
TH2	Variability in Julian date of annual maxima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian days - spatial).
TH3	Seasonal predictability of nonflooding. Computed as the maximum proportion of a 365-day year that the flow is less than the 1.67-year flood threshold and also occurs in all years. Accumulate nonflood days that span all years. TH3 is maximum length of those flood-free periods divided by 365 (dimensionless – spatial).
RA1	Rise rate. Compute the change in flow for days in which the change is positive for the entire flow record. RA1 is the mean (or median - Use Preference option) of these values (cubic feet per second/day – temporal).
RA2	Variability in rise rate. Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean (percent – spatial).
RA3	Fall rate. Compute the change in flow for days in which the change is negative for the entire flow record. RA3 is the mean (or median – Use Preference option) of these values (cubic feet per second/day – temporal).
RA4	Variability in fall rate. Compute the standard deviation for the negative flow changes. RA4 is 100 times the standard deviation divided by the mean (percent – spatial).
RA5	Number of day rises. Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record (dimensionless – spatial).
RA6	Change of flow. Compute the log10 of the flows for the entire flow record. Compute the change in log of flow for days in which the change is positive for the entire flow record. RA6 is the median of these values (cubic feet per second – temporal).
RA7	Change of flow. Compute the log10 of the flows for the entire flow record. Compute the change in log of flow for days in which the change is negative for the entire flow record. RA7 is the median of these log values (cubic feet per second/day – temporal).
RA8	Number of reversals. Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values (days - temporal).
RA9	Variability in reversals. Compute the standard deviation for the yearly reversal values. RA9 is 100 times the standard deviation divided by the mean (percent – spatial).

Appendix D – Electronic Files

IHA and HAT Output for 24 Priority Gages

Study Data

Study Maps, Models and Programs

References

77th Texas Legislature. (2001). “Senate Bill 2.”

Acreman, M., and Dunbar, M. J. (2004). "Defining environmental river flow requirements - a review." Hydrology and Earth System Sciences, 8(5), 861-876.

Anderson, A. A., Hubbs, C., Winemiller, K. O., and Edwards, R. J. (1995). "Texas Fresh-Water Fish Assemblages Following 3 Decades of Environmental-Change." Southwestern Naturalist, 40(3), 314-321.

Annear, T., Chisholm, I., Beecher, H., Locke, A., et al. (2004). *Instream Flows for Riverine Resource Stewardship: Revised edition.* Instream Flow Council: Cheyenne, Wyoming.

Arthington A.H., King J.M., O’Keefe J.H., Bunn S.E., Day J.A., Pusey B.J., Bluhdorn D.R., and Thame R. (1991). “Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems.” In Pigram J.J., Hooper B.A., eds. *Water allocation for the environment: proceedings of an international seminar and workshop*. University of New England Armidale (Australia): The Centre for Water Policy Research.

Austin, B. (2005). The Texas Instream Flow Program. Presentation at the Environmental Flows Conference, Texas State University, San Marcos, October 31.

Bounds R. and Lyons B. (1979). *Existing Reservoir and Stream Management: Statewide Minimum Streamflow Recommendations*. Austin, TX: Texas Parks and Wildlife Department.

Bovee K., Lamb B., Bartholow J., Stalnaker C., Taylor J., and Henriksen J. (1998). *Stream habitat analysis using the Instream Flow Incremental Methodology.* U.S. Geological Survey Information and Technical Report USGS/BRD-1998-0004. Fort Collins, CO: USGS Biological Resources Division.

Bunn, S. E., and Arthington, A. H. (2002). "Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity." Environmental Management, 30(4), 492-507.

Clausen B, Iversen H.L., and Ovesen N.B. (2000). “Ecological flow indices for Danish streams.” In *Nordic Hydrological Conference*, Nilsson T (ed.). Uppsala, Sweden; 3-10.

Clausen, B., and Biggs, B. J. F. (1997). "Relationships between benthic biota and hydrological indices in New Zealand streams." Freshwater Biology, 38(2), 327-342.

Clausen, B., and Biggs, B. J. F. (2000). "Flow variables for ecological studies in temperate streams: groupings based on covariance." Journal of Hydrology, 237(3-4), 184-197.

Colwell R.K. (1974). “Predictability, constancy, and contingency of periodic phenomena.” Ecology, 55, 1148-1153.

Dunne T., and Leopold L.B. (1978). *Water in Environmental Planning*. W.H. Freeman and Company, New York.

Dyson M., Bergkamp G. and Scanlon J., Ed. (2003). *Flow: The Essentials of Environmental Flow*. International Union for Conservation of Nature and Natural Resources (IUCN): Gland, Switzerland.

Espegren G.D. (1998). *Evaluation of the Standards and Methods Used for Quantifying Instream Flows in Colorado. Final Report*. ColoradoWater Conservation Board: Denver, CO.

Henriksen J. (2005). Personal communication.

Henriksen J. A., Heasley J., Kennen J.G., and Niewsand S. (2006). *Users' manual for the hydroecological integrity assessment process software (including the New Jersey Assessment Tools)*. U.S. Geological Survey, Biological Resources Discipline, Open File Report 2006-1093. http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html

Hughes J.M.R., and James B. (1989). "A hydrological regionalization of streams in Victoria, Australia, with implication for stream ecology." Australian Journal of Marine and Freshwater Research, 40, 303-326.

Hughes D. A., and Hannart P. (2003). "A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa." Journal of Hydrology, 270(3-4), 167-181.

Institute of Hydrology. (1980). *Low flow studies: Wallingford, Oxon, United Kingdom*. Report Nos. 1 and 3.

Johnson I. W., and Law F. M. (1995). "Computer-Models For Quantifying The Hydro-Ecology Of British Rivers." Journal of The Chartered Institution Of Water and Environmental Management, 9(3), 290-297.

Jowett I. G. (1997). "Instream flow methods: A comparison of approaches." Regulated Rivers-Research & Management, 13(2), 115-127.

Kaiser R. A., and Binion S. (1998). "Untying the gordian knot: Negotiated strategies for protecting instream flows in Texas." Natural Resources Journal, 38(1), 157-196.

Karim K.G., Maureen, E., and Goulter, I.C. (1995). Review of determination of instream flow requirements with special application to Australia. *Water Resources Bulletin*. Volume 31, No. 6, pp. 1063-1077.

Karr J.R. (1991). "Biological integrity: a long neglected aspect of water resource management." Ecological Applications, 1, 66-84.

Kiesling R. (2003). “Applying Indicators of Hydrologic Alteration to Texas Streams- Overview of Methods with Examples from the Trinity River Basin.” U.S. Geologic Survey, Fact Sheet 128-03.

Lamb B. L. (1995). "Criteria For Evaluating State Instream-Flow Programs - Deciding What Works." Journal of Water Resources Planning and Management, 121(3), 270-274.

LBJ School of Public Affairs. (1978). *Preserving Texas’ Natural Heritage*. Research Project Report 31.

Leopold L.B., Wolman M. G., and Miller J. P. (1964). *Fluvial Processes in Geomorphology*. W. H. Freeman and Company, San Francisco.

Maidment D., Montagna P., Sansom A., Ward G., Winemiller K. (2005). Scientific Principles for Definition of Environmental Flows. Statement for Environmental Flows Conference, Texas State University, San Marcos, October 31.

Merwade V.M. (2004). “Geospatial Description of River Channels in Three Dimensions.” Dissertation, The University of Texas at Austin.

Metsi Consultants. (2000). *Consulting Services for the Establishment and Monitoring of the Instream Flow Requirements for River Courses Downstream of LHWP (Lesotho Highlands Water Project) dams. Final Report: summary of main findings*. Report No. 648-F-02. (Authors: King J, Sabet H, Brown C, Hirst S.) Lesotho Highlands Development Authority Contract 648: Maseru, Lesotho.

Mosier D. and Ray R.. 1992. *Instream Flows for the Lower Colorado River: Reconciling Traditional Beneficial Uses with the Ecological Requirements of the Native Aquatic Community.* Austin, TX: Lower Colorado River Authority.

National Research Council Committee (2005). *The Science of Instream Flows: A Review of the Texas Instream Flow Program*. Committee on Review of Methods for Establishing Instream Flows for Texas Rivers, National Research Council. The National Academies Press, Washington, D.C.

Nilsson, C., and Svedmark, M. (2002). "Basic principles and ecological consequences of changing water regimes: Riparian plant communities." Environmental Management, 30(4), 468-480.

Olden, J.D., and Poff, N.L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications,* 19, 101-121.

Pittman, E.G.R. (March 16, 2004). Letter to: The Honorable Kenneth Armbrister, Texas Senate, and The Honorable Robert R. Puente, Texas House of Representatives, RE: Environmental Flows.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K.L., Richter, B. D., Sparks, R. E., and Stromberg, J. C. (1997). The natural flow regime. *Bioscience*, 47(11), 769-784.

Poff, N. L., and Ward, J. V. (1989). "Implications of Streamflow Variability And Predictability For Lotic Community Structure - A Regional-Analysis Of Streamflow Patterns." Canadian Journal Of Fisheries And Aquatic Sciences, 46(10), 1805-1818.

Poff, N.L. (1996). A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology*, 36, 71-91.

Postel, S. and Richter, B. (2003). *Rivers for Life: Managing Water for People and Nature*. Island Press: Washington, D.C.

PRISM Group, Oregon State University, http://www.prismclimate.org, created January 2006.

Puckridge, J. T., Sheldon, F., Walker, K. F., and Boulton, A. J. (1998). "Flow variability and the ecology of large rivers." Marine and Freshwater Research, 49(1), 55-72.

Resh V.H., Brown A.V., Covich A.P., Gurtz M.E., Li H.W., Minshall G.W., Reice S.R., Sheldon A.L., Wallace J.B., and Wissmar R. (1988). “The role of disturbance in stream ecology.” Journal of the North American Benthological Society, (7), 433-455.

Richards R.P. (1989). “Measures of flow variability for Great Lakes tributaries.” Environmental Monitoring and Assessment, 12, 361-377.

Richards R.P. (1990). “Measures of flow variability and a new flow-based classification of Great Lakes tributaries.” Journal of Great Lakes Research, 16, 53-70.

Richter B. (2006). Personal communication.

Richter, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, 10(4), 1163-1174.

Richter, B. D., Baumgartner, J. V., Wigington, R., and Braun, D. P. (1997). How much water does a river need? Freshwater Biology, 37(1), 231-249.

Richter, B. D., Mathews, R., and Wigington, R. (2003). Ecologically sustainable water management: Managing river flows for ecological integrity. Ecological Applications, 13(1), 206-224.

Richter, B.D., J.V. Baumgartner, D.P. Braun, and J. Powell. (1998). A Spatial Assessment of Hydrologic Alteration Within a River Network. Regulated Rivers 14:329-340.

Shiau, J. T., and Wu, F. C. (2004). Feasible diversion and instream flow release using range of variability approach. Journal Of Water Resources Planning And Management-ASCE, 130(5), 395-404.

Sparks R.E. (1995). "Need for ecosystem management of large rivers and their floodplains." Bioscience, 45, 168-182.

Stalnaker C.B., Lamb B.L., Henriksen J., Bovee K.D., and Bartholow J. (1994). *The Instream Flow Incremental Methodology: A Primer for IFIM.* National Ecology Research Center, Internal Publication. National Biological Survey: Fort Collins, CO.

Stalnaker C.B., Lamb B.L., Henriksen J., Bovee K.D., and Bartholow, J. (1995). The Instream Flow Incremental Methodology-A primer for IFIM. National Biological Service, U. S. Department of the Interior. Biological Report 29.

Stanford J.A., Ward J.V., Liss W.J., Frissell C.A., Williams R.N., Lichatowich J.A., and Coutant C.C. (1996). "A general protocol for restoration of regulated rivers." Regulated Rivers: Research & Management ,12, 391-414.

Teasley, R.L. (2005). "Modeling the Forgotten River Segment of the Rio Grande/Bravo Basin." Thesis, The University of Texas at Austin.

Tennant, D.L. (1976), Instream Flow Regiments for Fish, Wildlife, Recreation, and Related Environmental Resources" in Orsborn, J.F. and C.H. Allman (Editors). Proceedings of the Symposium and Specialty Conference on Instream Flow Needs II. American Fisheries Society, Bethesda, MD, pages 359-373.

Texas Commission on Environmental Quality. (2000). "Surface Water Quality Standards." Chapter 307 of the Texas Administrative Code.

Texas Commission on Environmental Quality. (2004). "Consensus Criteria for Environmental Flow Needs."

Texas Commission on Environmental Quality. (2006). "Water availability models". http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html

Texas Instream Flow Program. (2002). *Texas Instream Flow Studies: Programmatic Work Plan.*

Texas Instream Flow Program. (2006). *Draft Texas Instream Flow Studies: Technical Overview.*

Texas Instream Flow Program. (June 15, 2006). Stakeholder Technical Workshop. University of Texas at San Antonio.

Tharme R.E., and King J.M. (1998). "Development of the Building Block Methodology for Instream Flow Assessments, and Supporting Research on the Effects of Different Magnitude Flows on Riverine Ecosystems." Water Research Commission Report No. 576/1/98.

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), 397-441.

The Nature Conservancy. (2006). "IHA Applications Database."

The Nature Conservancy. (2006a). "Indicators of Hydrologic Alteration – Version 7 User's Manual."

The Nature Conservancy. (2006b). "Sustainable Waters Program website." http://www.nature.org/initiatives/freshwater/

Trungale J.F. (2006). "IHA Test." Unpublished data.

Trungale J.F., Mayes K.B., Moss R.E., and Kleinsasser L.J. (2003). *Draft Report: Using Water Availability Models to Assess Alterations in Instream Flows*. Resource Protection Division, Texas Parks and Wildlife Department, Austin, Texas.

United States Bureau of Reclamation. (2004). "BFI: A Computer Program for Determining an Index to Base Flow." Department of the Interior.

United States Geological Survey (2002). *Water Resources Data – Texas, Water Year 2001: Vols. 1, 2, 3, and 5*. USGS: Austin.

Ward G.H. (2000). "Texas Water at the Century's turn — perspectives, reflections and a comfort bag." In *Water for Texas: 2000 and Beyond*.

Whiting, P.J. (2002). "Streamflow necessary for environmental maintenance." Annual Review Earth. Planet. Sci., 30,181-206.

Wood P.J., Agnew M.D., and Petts G.E. (2000). "Flow variations and macroinvertebrate community responses in a small groundwater-dominated stream in south-east England." Hydrological Processes, 14, 3133-3147.

Wurbs R.A. (2003). "Water Rights Analysis Package (WRAP) Modeling System Users Manual" Texas Water Resources Institute, TR-256.