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Decision Support for Active Water Management

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Decision Support for Active Water Management

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Dedication

I would like to dedicate this thesis to my family, and to the memory of my grandfather.

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I would like to thank my adviser, Dr. Maidment, for his support and guidance through this research and writing process. I would also like to thank the rest of the Maidment research group, especially Dr. Tim Whitaker, Dr. Eric Hersh, and Fernando Salas, for teaching me, answering endless questions, and helping me find my way.

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Abstract

Decision Support for Active Water Management

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The University of Texas at Austin, 2013

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Active water management uses real-time information to continually respond and adjust to water management needs and situations. To support active water management, the Texas Commission on Environmental Quality (TCEQ) needs tools to access and understand data and to apply that understanding to operational decisions. The work described herein addresses two objectives in providing decision-support for the TCEQ: (1) methods for including environmental pulse flow regulations in water rights documents, and (2) improved ease of access to information needed for TCEQ watermaster operations, particularly in times of drought.

A Pulse Scaling Method for calculating the trigger flow rate, volume, and duration of flow pulses, using known characteristics at a reference location A, that are appropriate at a target location B (with unknown characteristics) was developed from three key relationships found in the written environmental flow regulations for fifteen locations in the Trinity, San Jacinto, Sabine, and Neches basins. Applying the method

and analyzing the results shows that the predictions are statistically consistent with original regulations.

A Common Operating Picture is a layered web-map allowing simultaneous access to one or more spatially-related datasets that TCEQ watermaster staff need to consider in decision-making. By its very nature as a dynamic map with associated time series, the Common Operating Picture presents data as information in a way that can support water resource management and decision-making. The project is currently in the pilot stage, with a number of data sources included and an interface available, but with additional work planned and further testing needed before larger-scale implementation.

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Chapter 1: Introduction

One of the primary water management agencies in the state of Texas is the Texas Commission on Environmental Quality (TCEQ). The mission of the TCEQ is to "[protect] our state's human and natural resources consistent with sustainable economic development," and the agency's philosophy in supporting that mission states (in part), that they will:

- "base decisions on the law, common sense, good science, and fiscal responsibility;
- ensure that regulations are necessary, effective, and current;
- apply regulations clearly and consistently;
- ensure consistent, just, and timely enforcement when environmental laws are violated; and
- ensure meaningful public participation in the decision-making process." (About the TCEQ 2013)

TCEQ requires up-to-date decision support in order to efficiently and effectively fulfill its stated mission.

The division of TCEQ relevant to this work, the Water Availability Division, engages in an extensive list of tasks to help achieve the agency's goals in relation to water bodies and water use in Texas. A few of these tasks include:

- Issuing new and amended water rights[1],
- Canceling water rights,
- Ensuring compliance with water rights,
- Regulating reservoirs and diversions[2],
- Assessing drought contingency plans.

[1] A "water right" is a legal permit to withdraw water from a Texas waterbody.
[2] A "diversion" is a withdrawal of water from a waterbody.

The decisions involved in the accomplishment of these tasks require considerable information on past, current, and potential future conditions of water resources in the state, as well as on the past, current, and planned or desired activity of water users. Such decisions are made both by staff who work on the permitting process and by staff who work with the various Texas Watermasters. Watermasters manage the water resources in a few basins in the state; they go beyond the general edicts of water permits to make daily decisions about who may and may not withdraw water from each water body under their jurisdiction. Thus various TCEQ staff must make more general decisions about water rights as well as very specific decisions about diversions, with similar types of information needed for both management activities, though sometimes on different scales or in different degrees of detail.

To help staff at TCEQ easily access this necessary information, the Center for Research in Water Resources (CRWR) at the University of Texas at Austin has partnered with the agency since 1998 to provide various aspects of decision support. The work discussed herein was completed under the auspices of that ongoing work partnership; the goals of the work were set to meet the specific decision support needs of TCEQ, both for water permitting- and water diversion-related decisions.

OBJECTIVES

The work described herein addresses two overall decision-support objectives:

1. Methods for including environmental pulse flow regulations in water rights documents,
2. Improved ease of access to information needed for Watermaster operations, particularly in times of drought.

Objective 1: Environmental Pulse Flow Regulations

The first objective of this work was set to assist the staff who write new and amended water permit documents. According to recent legislation, new or amended water rights in the state of Texas must include provisions for ensuring certain flow levels in streams for the maintenance of ecological health. These provisions are based on scientific and stakeholder committee recommendations, and some work was needed to translate portions of the recommendations into applicable and enforceable rules that can be included in any water rights document.

More specifically, TCEQ has followed "an aggressive schedule for determining environmental flow standards adequate to support a sound ecological environment in the State's river basins and bay systems" since Texas Senate Bill 3 was adopted in 2007; these standards include standards for pulse flows, which are short duration, high flow events, typically following rainstorms (Senate Bill 3 Science Advisory Committee 2009). These standards must be established and codified so that they can be included in legal water rights permitting documents, which dictate when and to what extent a user may withdraw water from a given point in a stream. Codification is necessary so that these standards can be enforced along with the other terms of the permits.

Environmental flow regimes for the rivers in Texas are currently being established, one basin at a time, by an approximately 18-month process for each that includes an extensive scientific study of the basin followed by a stakeholder analysis and discussion. Because this process is time-consuming and costly, it can only be completed at a few points in each river basin; however, environmental flow regimes are needed throughout each basin at any point at which TCEQ may need to write a permit for a water user. For example, in the Trinity basin, which has a drainage area of about 46,000 km^2, regulations have been written at only four points, as shown in Figure 1.

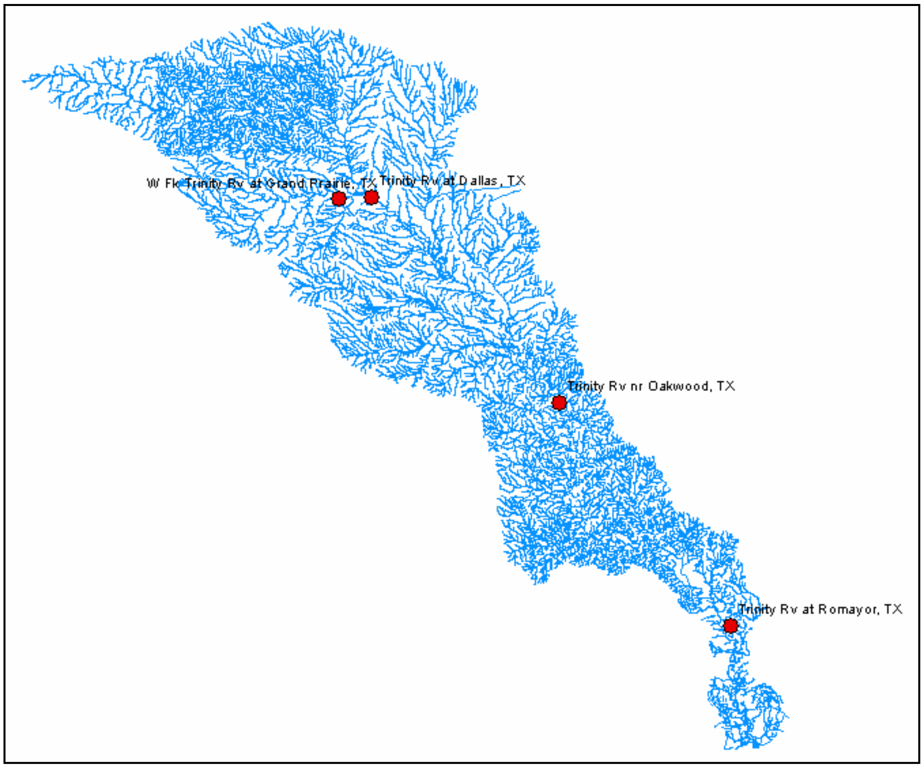

Figure 1. Trinity River Basin in Texas, with Four Environmental Flow Regulation Points

Since stream sizes and flow levels vary widely across a river system, the trigger flow rate, volume, and duration of a typical pulse event in one location are not the same as the characteristics of a typical pulse event in all other locations. For instance, a high flow event in a stream with mean annual flow of 1000 cubic feet per second (cfs) may be characterized quite differently than a high flow event in a stream with mean annual flow of 50 cfs. Therefore, the first objective of this work was to provide a straightforward way of scaling the characteristics of pulse flow that are used for regulatory purposes between a primary location, where these characteristics are established in existing legal documents, and a secondary location, where they are required for new or amended permitting documents, and to evaluate the success of the recommended method.

The secondary objectives of this task include that the recommended method must:

- Be scientifically based,
- Be straightforward, simple, and quick to apply,
- Give results consistent with existing regulations documents,
- Be applicable at any point in a regulated basin,
- Be consistent with TCEQ best practices.

Objective 2: Information Access for Watermaster Operations

The second objective of this work was set to assist staff working with the South Texas Watermaster, who must make daily decisions about diversions in the basins in their jurisdiction. Each time a water user with an existing water right (in the included basins) wishes to withdraw water from a stream, the user must contact the watermaster office and obtain approval to withdraw a certain amount of water over a certain period of time. During wet conditions, the Watermaster may approve most requests for withdrawals; during drought conditions, the staff face difficult decisions about which withdrawals to allow and which to deny. These decisions are based on information in the legal rights documents, such as priority date[3], as well as on current conditions, expected future conditions (based on precipitation and temperature predictions), and other approved and pending withdrawal requests.

The current system for approving or denying requests to withdraw water relies on staff making professional judgments based on considerable experience, because the information needed is scattered and synthesis is left up to each employee on a case-by-case basis. To facilitate this decision-making process, the watermaster office desires an

[3] Texas water rights are based on a "first in time, first in right" system, in which users with older permits have higher priority when water is allocated; e.g. a user with a water right dating to 1950 will be allocated water before a user with a water right dating to 1980 (What Your Water Right Means 2012).

information system that will present much of the necessary information in one easy-to-use interface so that staff can find what they need more quickly, and make more consistent judgments.

The information used in these decisions comes from a variety of sources, including two separate internal TCEQ databases along with a number of other agencies. A successful solution needs to combine these disparate data sources in a single interface, and that interface must be easily accessible by various different employees working in different locations, each of whom might need to consider a slightly different set of information depending on the situation. Thus, the secondary objectives of this task included that the designed decision support system must:

- Be accessible by users inside and outside of the Watermaster's physical office,
- Combine in a single interface information from both relevant TCEQ databases as well as other relevant data sources,
- Allow for customized views including only the information relevant to each decision,
- Not require users to have advanced knowledge of a specific software system,
- Be consistent with TCEQ best practices.

RESEARCH QUESTIONS

The objectives listed above gave rise to a set of larger questions that underlay and drove the research process:

1. What does it mean to define and quantify a flow pulse?

2. What does it mean to “preserve” a flow pulse as it moves through a river network system?
3. How can rigorous science and emerging or recently available technologies be used to support the decision-making needs of a governmental agency?

Chapter 2: Literature Review

Active Water Management

Extensive literature is available on water resource management, integrated water resource management, adaptive water management, and other similar terms, but there does not seem to be an extensive literature as yet on the subject of "active water management." The term does appear occasionally in papers, when an author wishes to specify that the management of water is not passive. However, the phrase "active water management" can be taken to mean more than simply "not passive;" as TCEQ Commissioner Carlos Rubinstein explained in a spring 2013 personal communication, "Active Water Management in my mind is monitoring water use, particularly diversions of raw water using on the ground information and data. Active Water Management requires constant and near real-time communication that encompasses an understanding of real time water flows in a stream, how to best utilize those flows, protect priority diversions and monitoring actual use. This communication and data exchange can occur by either on the ground verification of diversion, metered diversions or a combination of both. Active Water Management in most cases also would benefit from pre-diversion authorization and post diversion reporting." This definition implies that monitoring is necessary so that policies and actions can be adjusted and adapted as necessary to address problems found, and that being constantly aware of both current and planned activity (e.g. "pre-diversion authorization") allows managers and policy-makers to anticipate problems before they arise. The activities mentioned also require integration of data sources, and potentially including information outside the strict realm of hydrology to encompass other areas that might impact water use (e.g. "how best to use these flows"). Much literature on water resource management does touch on these ideas, only without applying the name "active water management."

The term "integrated water resource management," or IWRM, came into use in the 1990s to describe "a management tool that recognizes the interrelatedness of resource uses with each other and within the broader social and economic systems which influence the state and use of water resources" (Creighton 1999). Around the same time it was also noted that "IWRM is well understood as a concept [but] it lacks a very precise definition" (Schilling n.d.), but by 2013 it has become well accepted as a holistic framework for including diverse and potentially conflicting variables in water resources management (Leidel et al 2013; Lenton and Muller 2009; Podimata and Yannopoulos 2013). It is a popular framework, and a flexible one: it simply stresses, as the name implies, that many pieces must be integrated into the water management puzzle. IWRM does not prescribe any specific methods or priorities, simply a set of considerations; some other conceptions of water management begin to introduce specific considerations that should be included.

In 2008, Martínez-Santos et al noted that "adaptive water management is already widely discussed in the literature," citing three papers, the earliest of which was published as long ago as 1999. Indeed, it is not difficult to find literature discussing, evaluating, or advocating for adaptive management. Bruch (2009) offers the following definition of the term:

> "Adaptive management – including adaptive water management – is an ongoing, iterative approach that seeks to 'learn by doing.' This includes:
>
> - The development and adoption of a provisional legal, policy, and institutional framework
> - Ongoing monitoring and collection of information
> - Periodic assessment of the collected information (to determine the effectiveness of the laws and institutions)
> - Modification of the legal and institutional frameworks as appropriate
> - Continuing the management cycle of monitoring, assessment, and revision.

Not all papers adopt exactly this definition, but they do generally agree that adaptive management includes ongoing "cycle[s] of monitoring, assessment, and revision."

"Anticipatory water management" is a less-commonly used phrase but it does appear in existing literature. It is typically used in reference to extreme events, such as floods: for example, van Andel (2008) defines it as "the operation and management of water systems on the basis of forecasts of extreme events." However, it can be more broadly viewed as water management approached in the manner of adaptive governance, which Quay (2010) defines as "a flexible framework that uses a wide range of possible futures to prepare for change and to guide current decisions toward maximizing future alternatives or minimizing future threats." This definition clearly encompasses the idea of preparing for floods, which falls in the category of "minimizing future threats," but also broadens the outlook to include "maximizing future alternatives," which could include a wide range of other planning activities. The key element of anticipatory management, then, is careful inclusion of the future in current management activities; this is very similar to many definitions of "sustainability," which might also be considered an important aspect of "active water management."

The literal meaning of "active" in "active water management" can perhaps be best understood by contrasting it against passive water management. The phrase "passive water management" is itself not well defined in the literature, but from context it is found to typically refer to water management technologies or strategies that can be deployed and then largely ignored except for perhaps basic maintenance or eventual replacement, such as levees and weirs (O'Neal et al 2008; Kuhn et al 1999; Koob et al 2001; Wills and Dorshow 2012). Therefore "active water management" would mean management measures that require action on the part of managers or operators.

When this definition is taken together with the other components described above, "active water management" becomes a type of water management that incorporates many interrelated variables, institutes provisional frameworks and measures that are revised through a continuous cycle of monitoring and assessment, considers the future as well as the present, and employs technologies and strategies that may require ongoing action for best efficiency and effectiveness. Active water management uses real-time information to continually respond and adjust to the situation at the current moment.

ENVIRONMENTAL FLOWS

Water in streams and rivers is used not only by humans, but by a whole host of organisms. If human users withdraw most of the water from any stream, little will be left for use by those other organisms: a certain level of flow is necessary to maintain healthy stream ecology. In addition, many scientists believe that setting a simple minimum flow level is not sufficient, as "the integrity of flowing water systems depends largely on their natural dynamic character" (Poff et al 1997). These varying flow needs of a river can be quantified (using many methods, to greater or lesser degrees of accuracy), and a collection of these requirements is called, collectively, "environmental flows" or an "environmental flow regime." Environmental flow regimes include several categories of flows typically called subsistence flows (for very dry conditions), base flows, and high flow pulses, as well as floods or overbank events in some regimes, which describe the necessary flows for different stream conditions and the requirement for infrequent high-flow events (Senate Bill 3 Science Advisory Committee 2009). Each type of flow can potentially be described using five components: magnitude, frequency, duration, timing, and rate of change (also known as flashiness) (Poff et al 1997). Table 1 shows a sample environmental flow regime and Figure 2 shows an example of the hydrograph that would result if the flow at a point in a river was always exactly equal to its environmental flow (only base flows and pulse flows are illustrated). Figure 3 shows an illustration of a single environmental flow pulse.

Table 1. Example Environmental Flow Regime, per TCEQ Regulation Documents

USGS Gage 08019500, Big Sandy Creek near Big Sandy			
Season	**Subsistence**	**Base**	**Pulse**
Winter	20 cfs	73 cfs	1 per season Trigger: 358 cfs Volume: 5,932 af Duration: 10 days
Spring	9 cfs	33 cfs	2 per season Trigger: 313 cfs Volume: 5,062 af Duration: 13 days
Summer	8 cfs	15 cfs	1 per season Trigger: 50 cfs Volume: 671 af Duration: 6 days
Fall	8 cfs	22 cfs	2 per season Trigger: 130 cfs Volume: 2,189 af Duration: 9 days
cfs = cubic feet per second , af = acre-feet			

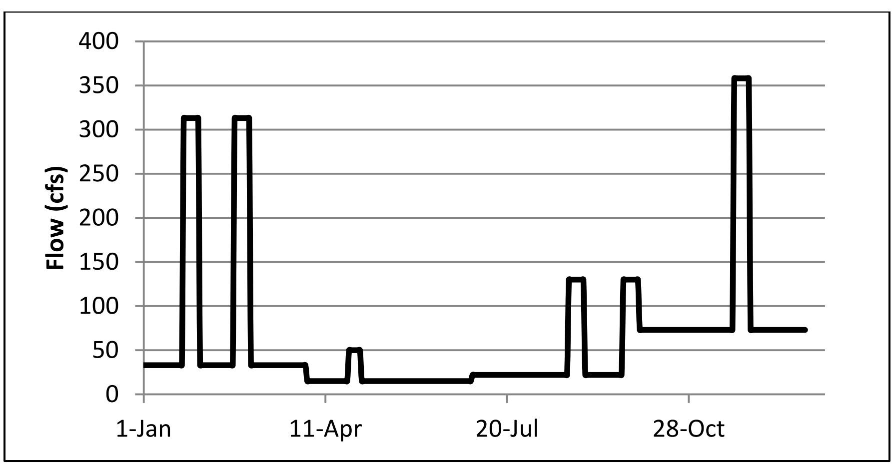

Figure 2. Example Hydrograph with Base and Pulse Environmental Flows

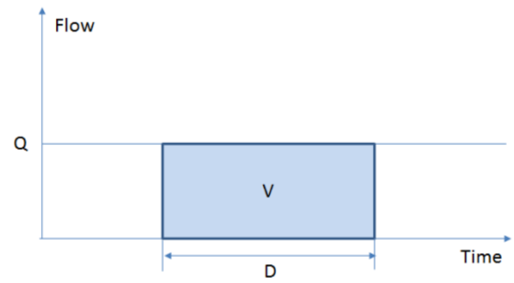

Figure 3. Illustration of a Single Environmental Flow Pulse

The research described herein focuses on high flow pulses, or "pulse flows." Pulse flows are defined as "relatively short-duration, high flows within the stream channel that occur during or immediately following a storm event" (Texas Administrative Code §298.1 2011). Their importance in maintenance of stream health has been investigated by researchers such as Robyn Watts, from Charles Sturt University in Australia, who has found that "water 'pulses' trigger a release of organic matter into the river and within hours you get a bacterial response which plays a vital role in the river's food web. This in turn triggers organisms that feed on the bacteria and that flows [on to] other groups in the web" (Ward 2011). Pulse flows also play a role in physically forming river channels and keeping vegetation from encroaching into river channels (Richter et al 2006); they transport sediments differently than moderate and low flows do, which affects habitats of riverine species, and the timing of pulse flows "provides environmental cues for initiating life cycle transitions in fish, such as spawning, egg hatching, rearing…or migration upstream or downstream" (Poff et al 1997).

Environmental flows thus serve a wide variety of purposes; quantifying them can be difficult both because there are so many purposes that might be addressed and because the specific flow needs associated with each purpose can themselves be quite difficult to fully and accurately quantify. In 2003, Tharme found 207 distinct methodologies being used in 44 countries around the world to attempt to determine environmental flow regimes adequate for meeting some of the myriad needs of stream ecosystems. These methods fall primarily into four categories: hydrological, hydraulic rating, habitat simulation, and holistic (Tharme 2003; Arthington et al 2006; Alcazar and Palau 2010). The most commonly used methods are hydrological, also sometimes called "fixed-percentage or look-up table methodologies," which typically involve the use of simple indices based on hydrologic data such as flow exceedence percentiles or a percentage of total or mean annual base flow (Tharme 2003; Acreman and Dunbar 2004; Arthington et al 2006). These methods can be applied quickly once look-up tables have been generated, but the results are generally not considered the most ecologically sound; in fact, Acreman and Dunbar (2004) call these methods "purely based on hydrological convenience, perhaps with retrospective ecological justification." Hydraulic methods are perhaps even more simplified, to the point that by 2003 they were becoming less-commonly used on their own, though still used as components of holistic methods (Tharme 2003). Habitat modeling methods are often ad hoc and focused on one or a few specific target species; holistic methods are growing in popularity, but the more comprehensive the method, the more time- and data-intensive it tends to be (Tharme 2003).

However, the work herein is not strictly about assessing environmental flow regimes; rather, it is about working with existing regimes written into regulation documents according to recent Texas legislation, which are written for specific locations but need to be widely applied. For this purpose, it is important to understand the methods instituted by the relevant legislation, and how those and other methods might be used to address the specific need at hand.

In 1997, the Texas Legislature passed Senate Bill 1 (SB1), which "[amended] the Water Code to implement a comprehensive drought and water conservation, development, and management plan for Texas" (Texas Legislature Online SB1 1997). The bill also allocated funds for the creation of water availability models, which have been used since then by the Texas Commission on Environmental Quality (TCEQ) in making water permitting decisions (Texas Legislature Online SB1 1997). In addition, SB1 addresses the need for maintenance of instream flows, also known as environmental flows (Texas Legislature Online SB1 1997). In 2007, Senate Bill 3 (SB3) instituted a procedure for determining specific environmental flow needs in water bodies in Texas and charged TCEQ with "determining the environmental flow standards that are necessary to support the ecological environment of each river basin and bay system in the state…[and] creating a process for reducing the amount of water available under a water rights permit in order to protect environmental flows" (Texas Legislature Online SB3 2007). These provisions allow TCEQ to formally include environmental flow needs in their permitting process; the water availability modeling process had not previously included specific required instream flow amounts, so instream flows had been recognized as important but not included in water permits.

The procedure established by Texas Senate Bill 3 for determining environmental flows is an approximately 18-month process that includes an extensive scientific study of the given basin followed by a stakeholder analysis and discussion. The scientific study is carried out by an appointed Basin and Bay Expert Science Team (BBEST) and uses "the best science available" (Texas Water Code §11.02362 2013) to generate recommendations at specific locations based on the needs of the ecosystem. The BBEST members are appointed by the Basin and Bay Area Stakeholder Committee (BBASC), which consists of stakeholders representing agricultural, municipal, recreational, and industrial water users as well as other interest groups; the BBASC considers the recommendations of the BBEST in conjunction with the needs of all other users (as represented by the stakeholders on the committee), and generates a second set of recommendations that takes into account both ecological and human needs (Texas Water Code §11.02362 2013). Guiding and commenting on these committees' processes are an Environmental Flows Advisory Group, made up of legislators, and a Science Advisory Committee (SAC), which includes between five and nine "persons who will provide an objective perspective and diverse technical expertise in hydrology, geology, water quality, computer modeling, and other technical areas pertinent to the evaluation of environmental flows" (Texas Water Code §11.02361 2013).

In both a 2009 report and a very similar 2011 report, the SAC discussed possible methods for generating environmental flow regimes. These reports give preference to hydrologic methods, while noting their limitations, because "hydrologic data typically provide the most convenient, initial understanding of riverine systems" (Senate Bill 3 Science Advisory Committee 2011). The 2011 report goes on to quote the National Research Council (2005) in saying that "hydrologic desktop methods can be very useful in obtaining a ballpark estimate of instream flow needs in rivers for which detailed instream flow studies have not yet been conducted," which is relevant in fulfilling the requirements of SB3 because BBESTs are directed to work with "the best science available," and do not have the time or resources to conduct extensive on-site field studies (Texas Water Code §11.02362 2013). Given the repeated caveat that the recommendations resulting from hydrologic methods should be monitored and verified through an adaptive management approach, the SAC endorses the software used by all BBESTs to date in generating environmental flow regimes: the Hydrology-Based Environmental Flow Regime (HEFR), which is based in part on an algorithm used by the Indicators of Hydrologic Alteration (IHA) (Senate Bill 3 Science Advisory Committee 2011).

HEFR uses a statistical approach to create a flow regime matrix consistent with other methods in use in Texas (the Texas Instream Flow Program) (Senate Bill 3 Science Advisory Committee 2011). In other words, the output of HEFR is an environmental flow regime that can be used as a starting point from which, when other considerations (available knowledge on biology, geomorphology, etc.) are included, an implementable environmental flow regime can be developed. What is crucial to note, though, is that the literature overwhelmingly advises that hydrologic methods alone not be considered sufficient to achieve the goals of environmental flows; when hydrologic methods are the primary methods used in developing the environmental flow regimes that are implemented, adaptive management must be employed to validate that those regimes result in the desired ecological health. Validation and potential adjustment through adaptive management is all the more important because the environmental flow regimes recommended for implementation are based not only on the findings of the BBESTs but on the further adjustments of the BBASC so that the final regimes will meet the needs of human users as well as the needs of ecosystems.

The recommendations of the BBASC, which incorporate the recommendations of the BBEST, are delivered to TCEQ; after a period for public comment, the TCEQ writes environmental flow regulations based on those recommendations, which are included in water permitting documents and thus legally enforceable. Because the process of determining environmental flows is time-consuming and costly, it can only be completed at a few points in each river basin; however, environmental flow regimes are needed throughout each basin at any point at which TCEQ may need to write or amend a permit for a water user. The regimes at all possible points should have the same consequences, namely that ecological health is balanced with sufficient supplies for human uses; however, because the originally implemented regimes (in regulation documents) are not the outputs of a single tool or clearly delineated process but instead are the product of complex processes involving many considerations, it is difficult to predict exactly what the consequences of the original regimes will be, much less how to duplicate those consequences with regimes at other locations. Thus any process developed for modifying existing environmental flow regimes for application at other points of interest must be subject to the same adaptive management process as the original regimes themselves, and a period of adjustment must be expected in order for regimes to be developed that adequately achieve the desired outcomes.

DECISION SUPPORT SYSTEMS AND MAPPING

Liew (2007), in the Journal of Knowledge Management Practice, addresses the lack of adequate definitions of the words data, information, and knowledge and offers these definitions to fill the gap:

> **Data** are recorded (captured and stored) symbols and signal readings…The main purpose of data is to record activities or situation, to attempt to capture the true picture or real event.
> **Information** is a message that contains relevant meaning, implication, or input for decision and/or action. Information comes from both current (communication) and historical (processed data or 'reconstructed picture') sources. In essence, the purpose of information is to aid in making decisions and/or solving problems or realizing an opportunity.
> **Knowledge** is the (1) cognition or recognition (know-what), (2) capacity to act (know-how), and (3) understanding (know-why) that resides or is contained within the mind or in the brain. The purpose of knowledge is to better our lives.

The relationship between these ideas is neatly illustrated in a graphic by Jack Dangermond – founder of geographic information science (GIS) software-maker ESRI, a company predicated on the common need to turn data into information by displaying them spatially – shown in Figure 4. Data can be collected by observation or generated through modeling, but they must in some way be synthesized or interpreted in order to become information; it is only with information that decisions can be made. Going beyond information to knowledge allows for such activities as large-scale planning that can, for example, improve water access for all users across a region.

Figure 4. Progression from Data to Understanding

Source: Jack Dangermond, Environmental Systems Research Institute

In order to carry out the types of management discussed previously in this literature review, water resource managers need access not only to data, but to information. GIS – geographic *information* systems – inherently participate in the process of generating information from data: such systems have been conceived of at least since the 1960s, when – without reference to desktop computing possibilities that did not yet exist – a GIS was expected simply "to make spatially oriented information available in a useable form" (Dacey and Marble 1965). Moreover, when data come from different sources and are tied to different types of natural features and phenomena – such as flow rates in streams, amounts of precipitation, or counts of bacteria – "GIS serves as the key to integrate these layers of geospatial information, and to provide a framework for water resources management and enhanced environmental management" (Dangermond and Maidment 2010).

Though GIS has existed for decades, it has taken on new forms along with the advent and growth of the Internet. Web-based GIS now allows for not only access to static maps, but dynamic creation, modification, and sharing of maps, in systems such as ArcGIS Online, which promises that a user can "Create interactive maps and apps and share them with the rest of your organization. Realize new opportunities and gain insight into your data. Do this quickly and easily with nothing to install or setup" (ArcGIS Online n.d.). Through these types of online systems, data with a spatial component can be easily accessed and manipulated by anyone, not only a small set of technical experts.

ArcGIS Online and similar web-based GIS systems are currently being used for projects in public health, municipal waste disposal, forest fire prevention, pavement maintenance, and watershed management, along with many other projects and decision support systems (Li et al 2013; Eisen and Eisen 2012; Rada et al 2013; Wen Yu et al 2013; Peng and Jiang 2012; Sun 2013). Within the water resources sphere, many current efforts are aimed at creating nearly or truly real-time, integrative systems that allow access to data from many sources via a single, cohesive, map-based, online interface. Leinert et al (2011) have published several papers on their work on a Swiss system that incorporates "availability of real-time and historical data, spatial referencing and visualization of data in maps, high cartographic quality…interactive methods to adapt map content and layout, [and] integration of multiple flood-relevant variables." Their primary goal is support for flood response activity, which was also the goal of the Global Flood Working Group (supported by the Global Disaster Alert and Coordination System) that led to their 2013 draft report on a Global Integrated Flood Map pilot project. Indeed, flood and other emergency management have recently been common motivations for these types of real-time, web-based, map-interface systems (Karnatak et al 2012; Chang et al 2012; Huat et al 2012; Cheng et al 2012; Cannata et al 2013).

Many additional efforts are aimed not only at handling emergency situations but at general water management needs (Deeprasertkul and Chitradon 2012; Verma et al 2012; Brooking and Hunter 2013). The number of projects with similar goals reflects the fundamental problem that "environmental science is often fragmented: data is collected using mismatched formats and conventions, and models are misaligned and run in isolation" (Elkhatib et al 2013). Yet, as previously discussed, water managers and decision makers need information based on this data to effectively and efficiently manage and make decisions. Though some progress has been made since this was published in 2011, it is still largely true that,

> [of] existing hydrological information systems…some contain maps and diagrams generated using data that have been averaged over a certain time period…other systems include a wealth of high-value, real-time and forecast data, but the information is not primarily visualized in maps, but rather in graphs and diagrams…other systems use maps as the primary interface to data, but visualizations and interactivity are limited to a small number of parameters…other systems focus on the historical descriptions of events and do not include spatial data. (Leinert et al 2011)

Even within the context of newly-developed, integrated, interactive, web-based GIS systems, there are challenges that must be met. One key challenge is the integration of geospatial data and time series data (Dangermond and Maidment 2010). There are also technical challenges related to automation of data acquisition and processing, integration of real-time data in existing models, computing and visualizing speed issues that go along with serving data over the Internet, and various others. Some technologies have been developed that assist the current efforts, such as services-based architectures and the

XML-based data format WaterML, but more work is needed before these systems are comprehensive and reliable enough to move beyond pilot stage to full implementations.

Chapter 3: Environmental Pulse Flow Regulations

Current environmental flow regulations in Texas include standards for subsistence flows (for dry periods), base flows, and pulse flows. Pulse flows are short duration, high flow events, which can be characterized with three key components, as shown in Figure 5: a trigger flow rate (Q, cfs) that signifies the beginning of a pulse event as distinct from normal flow, a duration (D, days) giving the length of time the pulse event lasts before flow returns to a normal level, and a volume (V, acre-ft) of water that flows past a chosen point during the pulse event. In the existing environmental flow regulations, once a pulse event begins, the diverter may not reduce the river flow below the trigger flow rate. The pulse event is considered complete when either a specified pulse volume has passed the target location or a specified duration has elapsed, whichever criterion is met first. These environmental pulse trigger flow rates, volumes, and durations are defined for each location for each season and correspond to the enforcement of the regulations: the trigger flow rate indicates when a permit-holder must stop diverting water, and the duration and volume are alternate indicators of when a permit-holder may begin diverting water again. Thus for these regulations to be applied, all three components are necessary.

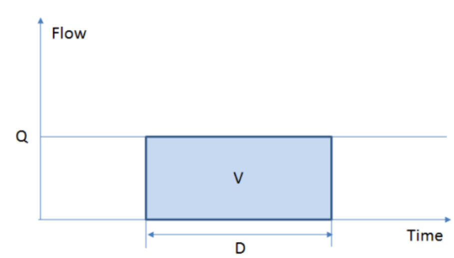

Figure 5. Illustration of the Components of a Regulated Environmental Flow Pulse

Since stream sizes and flow levels vary widely across a river system, what is considered a typical pulse event in one location is not the same as a typical pulse event in all other locations. For instance, a high flow event in a stream with mean annual flow of 1000 cubic feet per second (cfs) may be characterized quite differently than a high flow event in a stream with mean annual flow of 50 cfs. Therefore, it is not obvious how to take a regulation written at one point in a basin and apply it at another point in the basin. The objective of this work was thus to provide a straightforward way of scaling the defining characteristics of pulse flow between a primary location where these characteristics are established in existing legal documents and a secondary location where the characteristics are required for new or amended permitting documents, and to evaluate the success of the recommended method.

PRELIMINARY WORK

In the early stages of this work, historical flow records were studied for better understanding of pulse behavior and possible methods of translating pulse characteristics to new points. Three approaches were explored that did not fulfill all of the needs of the Texas Commission on Environmental Quality (TCEQ): creating a new complete environmental flow matrix at each point of interest, generating a scaling ratio by comparing volumes of pulses at known locations and points of interest, and routing pulses upstream and downstream from known locations to points of interest.

Creating a new environmental flow matrix at each point of interest essentially replicates some parts of the process that is used to generate environmental flow regimes at points in regulation documents, in a few steps using a few tools instead of over 18 months and involving two committees. This scaled-down process would begin with gage or model flow values at the point of interest (upstream on a tributary), then flows would be processed with the IHA and HEFR tools[4] to produce environmental flow matrices,

[4] See the literature review for more information on IHA and HEFR.

which could give the characteristics of a pulse at the upstream location. A trial run of the process was completed and documented; the results were promising but the process did not meet the needs of the TCEQ because using the IHA and HEFR tools requires considerably more time than a TCEQ water manager can afford to spend on every permitting decision, thus this approach did not fulfill all of the objectives of the project.

Comparing volumes of pulses (as delineated by the IHA tool) at Trinity River at Dallas to volumes of corresponding pulses at a single upstream location was done to create a ratio factor (upstream pulse volume/downstream pulse volume). The process was repeated for three pairs of points, but no consistent ratio could be calculated for any pair of points, and some ratios were found to be greater than 1, which does not make physical sense when comparing an upstream location with significantly smaller mean annual flow than the downstream location. It was found that this approach required much more simplified data than result from the very complex natural process of pulse flows, and so it was determined that this was not a fruitful approach to the problem.

The third approach incorporated the Muskingum-Cunge method, which is a well-established variant of kinematic wave routing that has been shown to be applicable when the effects of pressure and acceleration are negligible – typically the case except in very large flood waves in very wide rivers. The approach combined this routing with the idea of applying a ratio that could scale either the trigger flow rate or the volume of a pulse from a known location to another point of interest. The essence of this approach was to take a pulse at the known regulation point and route it upstream or downstream to the point of interest, then to scale the routed pulse using the ratio of mean annual flows at the two points as a scale factor. An example of the results of this method can be seen in Figure 6. As seen in this figure, the results of the method were adequate but not excellent at this point in the research. The Musking-Cunge routing method is successful at routing pulses downstream, in the direction of natural flow, but not at routing pulses upstream, opposite the direction of natural flow. Research was begun on how to “route backwards,” but while it was underway it was also determined that this method, like the first approach, would be too time-consuming for TCEQ staff to employ it on a regular basis and this line of research was set aside.

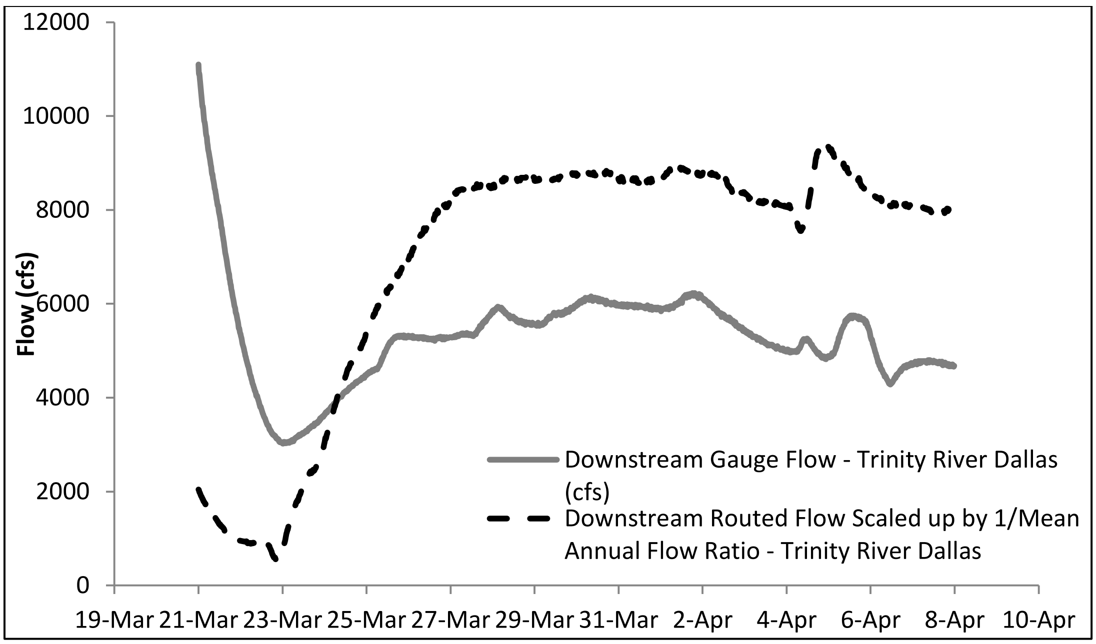

Figure 6. Example of a Flow Pulse, Routed to a Downstream Location and Scaled, Compared to the Measured Flow Pulse at the Downstream Location

METHODS

As explained above, pulse flows can be characterized with three key components: a trigger flow rate (Q, cfs), a duration (D, days), and a volume (V, acre-ft), defined for each location for each season. The trigger flow rate indicates when a permit-holder must stop diverting water, and the duration and volume are alternate indicators of when a permit-holder may begin diverting water again; more specifically, a user may divert water during a pulse event but may not divert so much that the flow in the stream drops below the trigger flow rate; in other words, once the stream reaches the trigger flow rate, the flow in the river must remain at or above that flow rate until either the required volume or required duration has passed. This stipulation that diversion may occur to a certain point means that the pulses mandated by environmental flow regulations are not necessarily like natural pulses that see increasing flow rate until a peak is reached, at which point the flow rate decreases until it returns to a normal level; these natural pulses can be visualized as peaks in hydrographs (see Figure 7), whereas the pulses mandated by regulations are more likely to be approximately rectangular in shape (see Figure 8), because the flow above "the top of the rectangle," i.e. the trigger flow rate, can be diverted. In other words, the pulse peak is truncated by diversions made until the limit (the trigger flow rate) is met.

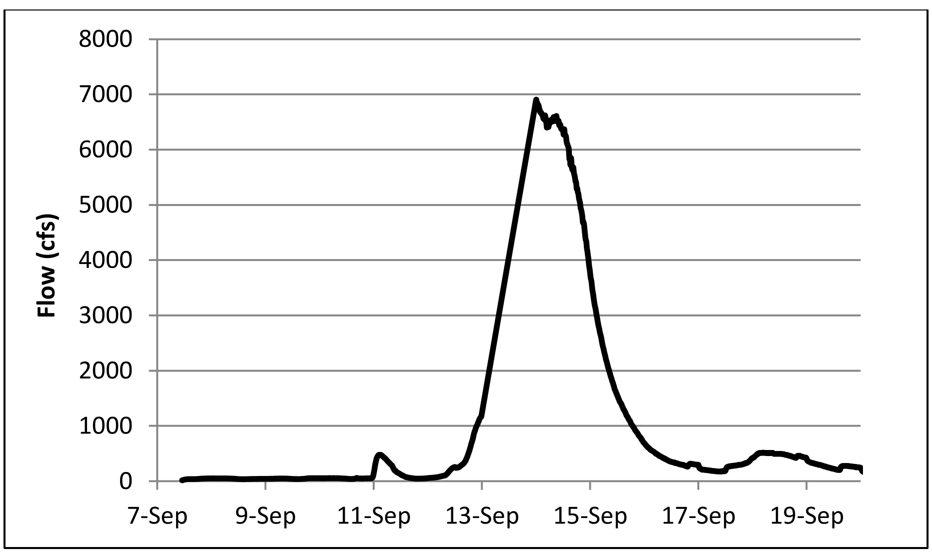

Figure 7. Example of a Naturally Occurring Flow Pulse, Which Forms a Peak

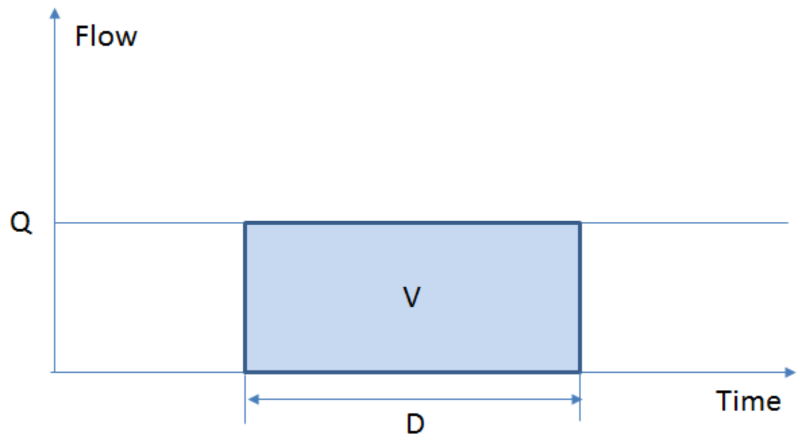

Figure 8. Environmental Flow Pulse per Regulations, with a Truncated Peak

The characteristics of pulse flows specified in Texas Administrative Code §§ 298.225, 298.280 (2011) for fifteen measurement locations in the Trinity, San Jacinto, Sabine and Neches basins were included in this study; these locations are shown in Figure 9.[5] At each location, there are pulses defined for the winter, spring, summer, and fall seasons. The method used throughout the analysis was to pair one of these fifteen points with some other point within the same basin; the characteristics of a regulated flow pulse in each season are known at the first point, called point A, and are not known but are desired at the second point, called point B. It follows that the pulse flow characteristics at each of these locations are denoted as:

- Trigger flow rate: Q_a and Q_b,
- Pulse volume: V_a and V_b,
- Pulse duration: D_a and D_b,

[5] The location Sabine River near Gladewater, 08020000, was not included in this analysis although it does have published environmental flow regulations. The regulations in the fall season fail to fit the relationships found among all of the other data, so it was concluded that there may be an error in the written regulation. It was thus excluded from the analysis.

and any ratio is denoted with a subscript of the denominator followed by the numerator, i.e. flow at point B divided by flow at point A – or the ratio of flow at B relative to point A – is designated R_{ab}.

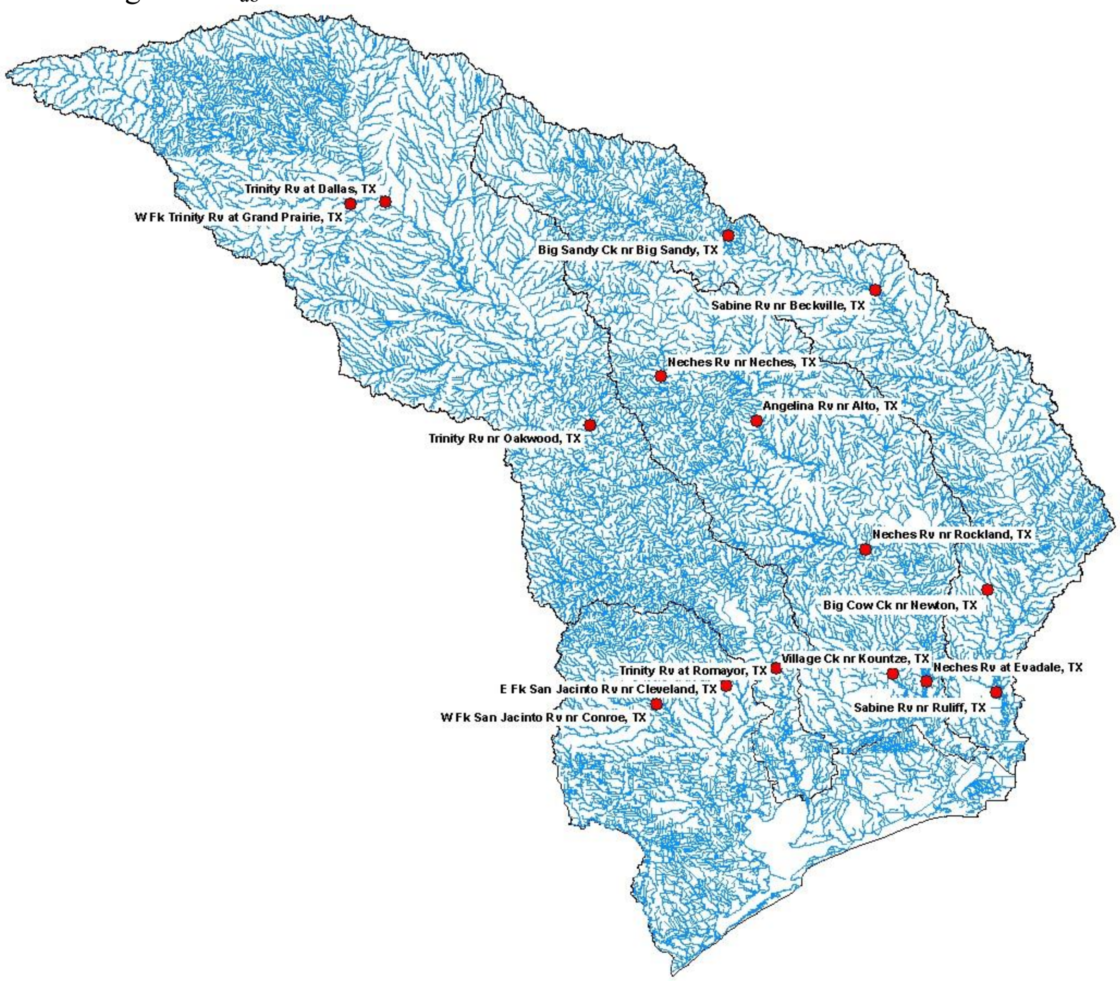

Figure 9. Four Basins - Trinity, San Jacinto, Sabine, and Neches - Named in Existing TCEQ Environmental Flow Regulations, with Fifteen Regulation Points

The goal of the analysis was to develop a consistent procedure for using the pulse characteristics known at point A to determine the pulse characteristics at point B. This procedure was developed by examining the pulse flow characteristics described in the documented regulations for the fifteen points shown above and identifying relationships between those characteristics. The key relationships discovered in the data – discussed in detail in the following sections – are:

- Mean Annual Flow Ratio: The trigger flow at point A is scaled to give a trigger flow at point B using the ratio of the naturalized mean annual flows, R_{ab}, at the corresponding stream reaches on the NHDPlus version 2.1 dataset.
- Pulse Ratio: The pulse volumes at points A and B are related such that the pulse ratio, $\frac{QD}{V}$, is the same at both locations.
- Duration Ratio: The duration at point A is scaled to give a duration at point B using the ratio $(R_{ab})^e$, where $e = 0.105$ is a duration exponent obtained from a power law relationship between pulse volumes and trigger flows in a given basin. The scaled duration is rounded to an integer number of days (or hours when appropriate).

These three key relationships taken together lead directly to a three-step procedure for using pulse flow regulations written for point A to calculate pulse flow regulations for point B.

Mean Annual Flow Ratio

The mean annual flow (MAF) values used in this study were taken from the United States Geological Survey (USGS) measured flows at gages and from the NHDPlus version 2.1 dataset, which is a product developed by USGS and the Environmental Protection Agency as "an integrated suite of application-ready geospatial data sets that incorporate many of the best features of the National Hydrography Dataset (NHD), the National Elevation Dataset, and the Watershed Boundary Dataset (WBD)."

NHDPlus includes flowlines (stream reaches) for all of the United States at the 1:100,000 scale, along with various attributes for these flowlines (NHDPlus Home n.d.).[6]

The existence of such a dataset that is consistent for water bodies across the country facilitates work involving flowlines (streams) that lack recorded measurements. For example, one of the attributes associated with flowlines in NHDPlus is mean annual flow, which gives consistent estimated mean annual flow data for all flowlines in the dataset.

In 2012, version 2.1 of NHDPlus was released across the U.S. This version calculates mean annual flows according to the Enhanced RunOff Method, which is an improvement over the much simpler model used for mean annual flows in NHDPlus version 1 (NHDPlus Home n.d.). NHDPlus version 2.1 provides several estimates for mean annual flow based on the results of the multiple calculation steps in the enhanced runoff method. During this study, the option of using the gage-adjusted mean annual flow (Q0001E) was examined and compared to using the naturalized mean annual flow (Q0001C). It was found that the gage-adjusted flow is sometimes lower for the reach downstream of a stream gage than for the reach upstream of the gage because of error correction at gage locations; even if the flow below the gage is more representative of the flow actually occurring in the river at that location, the discontinuity of flow at a gage location that this creates is unrealistic and problematic. Since the method being developed here requires a consistent relationship among flows going both upstream and downstream, it was decided to employ the naturalized mean annual flows in the NHDPlus dataset, namely Q0001C.

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[6] TCEQ regularly uses naturalized streamflow values from the Water Availability Model (WAM); these flow values were not available for including in this paper, but future work will repeat analysis and testing using WAM flows.

At each location named in the regulations there are values of the trigger flows for each of the four seasons. The average of those four trigger flows for each location was compared with mean annual flow for each site for the period of record, and the ratio of the average trigger flow to the mean annual flow was calculated. The average of these ratios was found to be 0.97 when USGS gaged flows were used and 1.16 when NHDPlus naturalized mean annual flow values were used, which suggests that as an overall tendency the average of the trigger flows is in the range of the mean annual flow. Average trigger flow versus mean annual flow was then plotted using both USGS flows and NHDPlus flows, as shown in Figure 10 and Figure 11. Comparison of the two figures suggests that the average of the trigger flows scales better with the NHDPlus naturalized mean annual flow than it does with the USGS gaged mean annual flow; in fact the line that best fits the NHDPlus data is very nearly 1-to-1 (y = 1.1129x) while the line that best fits the USGS data has a coefficient of 0.5787 (both trend lines have similar R^2 values), so the rest of the analysis was completed using mean annual flow values from NHDPlus.

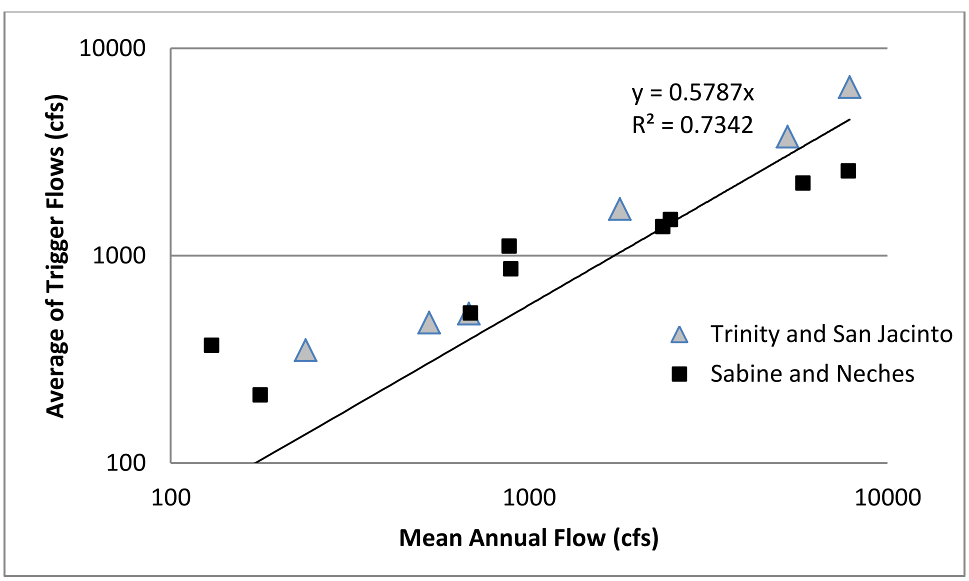

Figure 10. Average Pulse Trigger Flow Rate vs. Mean Annual Flow (from USGS)

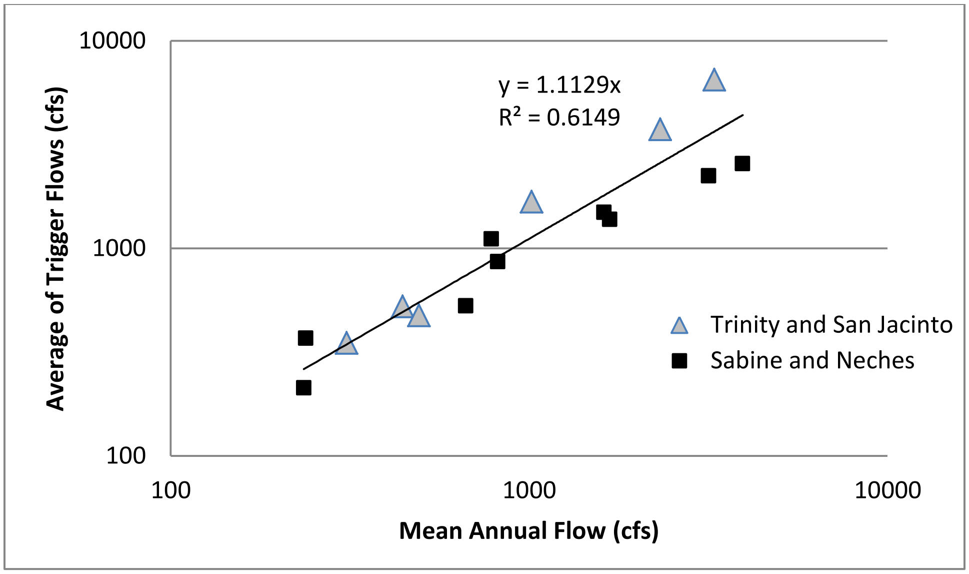

Figure 11. Average Pulse Trigger Flow Rate vs. Mean Annual Flow (from NHDPlus)

Given this similarity between the average trigger flow rate values and the mean annual flow values, and the fact the mean annual flow values are easy to find at any location on the river network from the NHDPlus dataset, the ratio of the mean annual flows at two points should be approximately the same as the ratio between the trigger flow rates. In other words, if Q_a and Q_b are the trigger flows for two locations in a particular season, and MAF_a and MAF_b are the corresponding mean annual flows at those locations, as estimated using the NHDPlus version 2.1 data for mean annual flows on stream reaches, then:

$$\frac{Q_b}{Q_a} = \frac{MAF_b}{MAF_a} = R_{ab} \tag{1}$$

where R_{ab} is the ratio of the mean annual flow estimates at the two locations.

Pulse Ratio

In fluid mechanics, there is a technique called "dimensional analysis" wherein large groups of variables are reduced to smaller numbers of dimensionless ratios so as to identify relationships within groups of observed data. In this case, only one dimensionless ratio is involved: the combination of variables $\frac{QD}{V}$ is dimensionless because Q has the dimension $[{}^{L^3}/_{T}]$, D has the dimension [T], and V has the dimension $[L^3]$.

This ratio is called here the pulse ratio because it summarizes the characteristics of a particular pulse. The value of the pulse ratio, k, is given (after correction for units) by:

$$k = \frac{QD}{V} \tag{2}$$

A remarkable degree of cohesion was observed among these pulse ratios in the existing environmental flow pulse regulations. The pulse ratio average was found to be 1.21, which means that on average the product of the trigger flow and the pulse duration is approximately 20% larger than the pulse volume, or that the pulse duration is on average approximately 20% longer than needed to pass the pulse volume if the stream discharge holds steady at the trigger flow. There are significant discrepancies, however, in values of the pulse ratio from this average value in particular seasons and at particular locations; those discrepancies are preserved in the proposed method.

Duration Ratio

The relationship between pulse volumes (acre-ft) and trigger flows (cfs) in each season were found to be consistent within the group of study locations, with no visible tendency for the relationship to differ by season. A graph of volume versus trigger flow for all seasons in all basins is shown in Figure 12, and a power law relationship fitted to the sixty data points (four seasons at fifteen sites) yields the equation:

$$V = 5.9533Q^{1.1054} \tag{3}$$

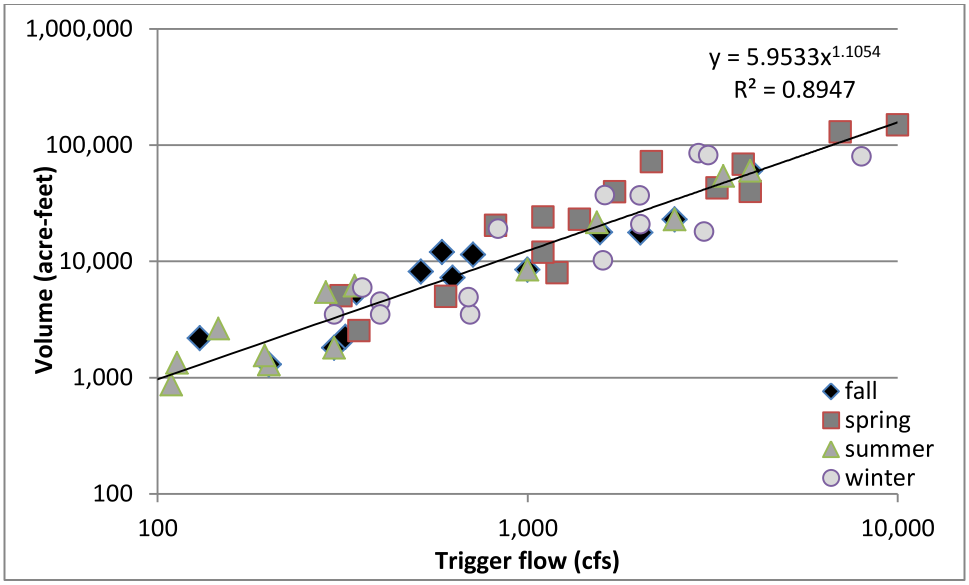

Figure 12. Pulse Volume vs. Pulse Trigger Flow Rate for All Locations in All Seasons

The relationship between the trigger flow and pulse volume can be generalized from Equation (3) as:

$$V = cQ^d \tag{4}$$

From Equation (2), the pulse volume can be written as a function of the pulse ratio, the trigger flow and the pulse duration as:

$$V = \frac{QD}{k} \tag{5}$$

If Equations (4) and (5) are combined:

$$\frac{QD}{k} = cQ^d \tag{6}$$

or

$$D = kcQ^{d-1} \tag{7}$$

and the ratio D_b/D_a can be found as:

$$\frac{D_b}{D_a} = \frac{kcQ_b^{d-1}}{kcQ_a^{d-1}} = \frac{Q_b^{d-1}}{Q_a^{d-1}} = (R_{ab})^{d-1} \tag{8}$$

where R_{ab} is the ratio of the mean annual flows, as given in Equation (1). It follows from Equation (8) that the duration at location B is calculated as:

$$D_b = D_a(R_{ab})^e \tag{9}$$

The value of the duration exponent, e, for the basins studied is 0.105, calculated from the exponent in Equation (3):

$$e = d - 1 = 1.105 - 1 = 0.105 \tag{10}$$

The significance of this value can be interpreted in the following way. Suppose an environmental pulse is desired for an upstream location on a tributary (point B) that has half as much flow as point A, where regulations are known (i.e. $R_{ab} = 0.5$). Then in the Trinity, San Jacinto, Sabine, or Neches basins, the durations at the two locations would be scaled by $0.5^{0.105} = 0.93$, which means that the durations at the upstream location would be approximately 93% of those at the reference location. Conversely, if the site is downstream on a main stem river where the ratio of the mean annual flows is 1.5, then the durations would be scaled by $1.5^{0.105} = 1.04$, so the durations would be slightly longer than those at the reference location for which the regulation has been published.

The "Pulse Scaling Method"

The Pulse Scaling Method is a direct mathematical result of the above relationships, and allows for the calculation of environmental pulse flow regulations at a point of interest (point B) using existing environmental pulse flow regulations at another location (point A). The Pulse Scaling Method can be summarized as follows:

<u>Given</u>:

A set of flow pulse characteristics for a particular season and a particular reference location – Q_a, V_a, and D_a – a ratio of the mean annual flows, R_{ab}, for the reference and target location, and a duration exponent, e.

<u>Step 1: Trigger Flow</u>:

The desired trigger flow at location B is given by:

$$Q_b = R_{ab} Q_a \tag{11}$$

Step 2: Pulse Duration:

A tentative duration at location B is calculated as:

$$D_b{}' = D_a (R_{ab})^e \tag{12}$$

This calculation yields a non-integer value for the duration in days. This value is rounded to the nearest integer to find the value of D_b. (If $D_b' < 1$, it is rounded to the nearest whole number of hours and reported in hours.)

Step 3: Pulse Volume:

The required pulse volume is computed as:

$$V_b = V_a R_{ab} \frac{D_b}{D_a} \tag{13}$$

which has the effect of preserving the value of the pulse ratio between the reference and target locations.

Example of Applying the Pulse Scaling Method

The Elm Fork of the Trinity River near Carrollton is a point at which environmental flow regulations have not been written; they must be calculated. The calculations are done using the Trinity River at Dallas as the primary point, as it is the closest point for which regulations have been written (see Table 2):

Table 2. Environmental Flow Regulations for the Trinity River at Dallas as Written in TCEQ Regulation Documents

Season	Trigger Flow (cfs)	Volume (acre-ft)	Duration (days)
Spring	4,000	40,000	9
Summer	1,000	8,500	5
Fall	1,000	8,500	5
Winter	700	3,500	3

Prepare the Inputs:

The Trinity River at Dallas is called point A and the Elm Form of the Trinity River near Carrollton is called point B. The spring season's pulse characteristics are used for the initial example calculations:

- Q_a = 4000 cfs,
- V_a = 40,000 acre-ft,
- D_a = 9 days.

The naturalized mean annual flow at each point is found from the NHDPlus v2.1 dataset flowline attribute Q0001C.

$$Mean\ Annual\ Flow_a = 1016.812\ cfs$$

$$Mean\ Annual\ Flow_b = 690.233\ cfs$$

Divide the flow at B by the flow at A to obtain the ratio.

$$R_{ab} = \frac{Mean\ Annual\ Flow_b}{Mean\ Annual\ Flow_a} = \frac{690.233}{1016.812} = 0.6788$$

The duration exponent e = 0.105 as these points are within the Trinity basin, for which this exponent has been found to be valid.

Step 1: Calculate the Pulse Trigger Flow at Point B:

According to Equation 11, multiply the trigger flow at point A by the ratio R_{ab} to find the trigger flow at point B.

$$Q_b = R_{ab}Q_a = 0.6788 \times 4000\ cfs = \mathbf{2715\ cfs}$$

Step 2: Calculate the Pulse Duration at Point B:

According to Equation 12, multiply the duration at point A by the ratio $R_{ab}^{0.105}$ to find the tentative duration at point B.

$$D_b' = R_{ab}^{0.105}D_a = 0.6788^{0.105} \times 9\ days = 8.64\ days$$

Round the tentative duration to the nearest whole number to find the final duration at point B.

$D_b = \mathbf{9\ days}$

Note: If the tentative duration is less than 1 day, the duration should be rounded to a whole number of hours, not days, and reported in hours.

<u>Step 3: Calculate the Pulse Volume at Point B</u>:

Divide the duration at point B by the duration at point A to find the duration ratio.

$\frac{D_b}{D_a} = \frac{9\ days}{9\ days} = 1.0$

According to Equation 13, multiply the volume at point A by both the flow ratio and the duration ratio to find the volume at point B.

$V_b = R_{ab} \frac{D_b}{D_a} V_a = 0.6788 \times 1.0 \times 40000\ acre - ft = \mathbf{27152\ acre - ft}$

<u>Repeat for All Seasons</u>:

The process is repeated to find the trigger flow, duration, and volume for the three remaining seasons. Note that the mean annual flow ratio R_{ab} is constant throughout the year and does not need to be recalculated for each season.

Summer:

$Q_b = R_{ab} Q_a = 0.6788 \times 1000\ cfs = \mathbf{679\ cfs}$

$D_b' = R_{ab}^{0.105} D_a = 0.6788^{0.105} \times 5\ days = 4.80\ days$

$D_b = \mathbf{5\ days}$

$\frac{D_b}{D_a} = \frac{5\ days}{5\ days} = 1.0$

$V_b = R_{ab} \frac{D_b}{D_a} V_a = 0.6788 \times 1.0 \times 8500\ acre - ft = \mathbf{5770\ acre - ft}$

Fall:

$Q_b = R_{ab} Q_a = 0.6788 \times 1000\ cfs = \mathbf{679\ cfs}$

$D_b' = R_{ab}^{0.105} D_a = 0.6788^{0.105} \times 5\ days = 4.80\ days$

$D_b = \mathbf{5\ days}$

$\frac{D_b}{D_a} = \frac{5\ days}{5\ days} = 1.0$

$V_b = R_{ab} \frac{D_b}{D_a} V_a = 0.6788 \times 1.0 \times 8500\ acre - ft = \mathbf{5770\ acre - ft}$

Winter:

$Q_b = R_{ab} Q_a = 0.6788 \times 700\ cfs = \mathbf{475\ cfs}$

$D_b{}' = R_{ab}{}^{0.11} D_a = 0.6788^{0.105} \times 3\ days = 2.88\ days$

$D_b = \mathbf{3\ days}$

$\frac{D_b}{D_a} = \frac{3\ days}{3\ days} = 1.0$

$V_b = R_{ab} \frac{D_b}{D_a} V_a = 0.6788 \times 1.0 \times 3500\ acre - ft = \mathbf{2376\ acre - ft}$

<u>Tabulate Complete Pulse Flow Regulations for Point B</u>:

Calculated in reference to the pulse flow regulations written for the Trinity River at Dallas (see Table 3), a corresponding pulse flow regulation for point B, the Elm Fork of the Trinity River near Carrollton, is now complete (see Table 4).

Table 3. Environmental Flow Regulations for the Trinity River at Dallas as Written in TCEQ Regulation Documents, the Basis for Calculated Values in Table 4

Season	Trigger Flow (cfs)	Volume (acre-ft)	Duration (days)
Spring	4,000	40,000	9
Summer	1,000	8,500	5
Fall	1,000	8,500	5
Winter	700	3,500	3

Table 4. Environmental Flow Regulations for the Elm Fork of the Trinity River near Carrollton, Calculated Using the Pulse Scaling Method

Season	Trigger Flow (cfs)	Volume (acre-ft)	Duration (days)
Spring	2,715	27,152	9
Summer	679	5,770	5
Fall	679	5,770	5
Winter	475	2,376	3

ANALYSIS

The Pulse Scaling Method was tested by making primary-secondary point pairings from the fifteen locations for which environmental flow regulations have been published; i.e. one point with published regulations was chosen as the A point and another point also with published regulations was chosen as the B point. Physically proximal (judged based on looking at a map – see Figure 13) gages were paired together, with the requirement that they be within the same basin. When two gages were near each other and very far from all other gages, a single pairing was chosen with one gage as the primary location and the other gage as the secondary location. When three gages were found in proximity to each other, two pairings were formed from the three gages such that no pairing used the same two points as another. In other words, the pairing of Dallas as point A/Grand Prairie as point B would not be used alongside the pairing of Grand Prairie as point A/Dallas as point B; one of these would be considered redundant.

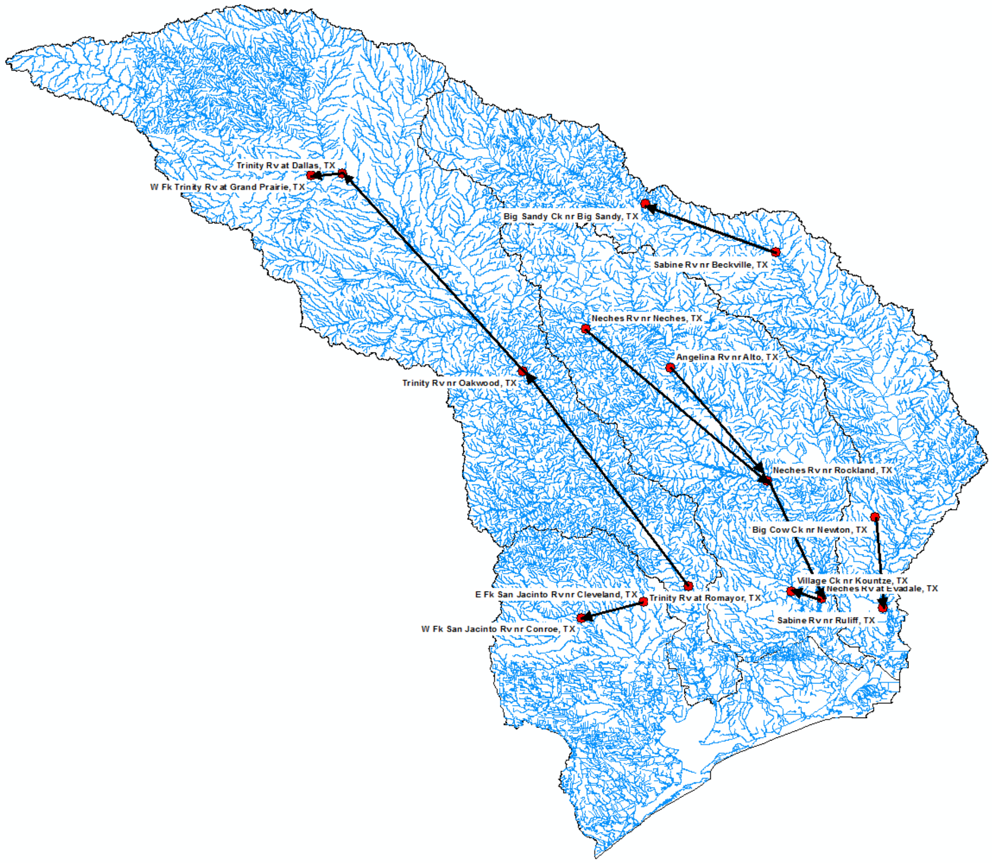

Figure 13. Map of Pairings of Regulation Points for Use in Tests of the Pulse Scaling Method - Each Arrow Points from the A Point Toward the B Point

In some instances the decision of which point would be the primary point and which would be the secondary point was based on the resulting R_{ab} value: a range of R_{ab} values was desired to examine the limits of appropriate values. (The Rab values of the final pairings range from 0.0603 to 6.8777.) In the interest of creating the most possible pairings from the available locations and a range of R_{ab} values, physical proximity was not the sole criterion in choosing which gages would be grouped to form a primary-secondary pair. However, all pairs are based primarily on physical proximity. The list of paired points can be seen in Table 5.

Table 5. Pairing of Regulation Points for Use in Tests of the Pulse Scaling Method (Fifteen Points Arranged into Ten Pairings)

Primary Point (A)	Secondary Point (B)
Trinity River at Dallas, 08057000	West Fork Trinity River near Grand Prairie, 08049500
Trinity River near Oakwood, 08065000	Trinity River at Dallas, 08057000
Trinity River at Romayor, 08066500	Trinity River near Oakwood, 08065000
East Fork San Jacinto River near Cleveland, 08070000	West Fork San Jacinto River near Conroe, 08068000
Sabine River near Beckville, 08022040	Big Sandy Creek near Big Sandy, 08019500
Big Cow Creek near Newton, 08029500	Sabine River near Ruliff, 08030500
Neches River at Neches, 08032000	Neches River near Rockland, 08033500
Angelina River near Alto, 08036500	Neches River near Rockland, 08033500
Neches River near Rockland, 08033500	Neches River at Evadale, 08041000
Neches River at Evadale, 08041000	Village Creek near Kountze, 08041500

Using the Pulse Scaling Method, pulse flow characteristics were calculated for the secondary point (the B point) in each of these ten pairings; the characteristics calculated for each secondary location were then compared to the characteristics written in the regulations for the same location. For example: the Pulse Scaling Method was applied using the written pulse regulations at the Trinity River at Dallas as the reference set of characteristics (point A) to find the characteristics for the West Fork Trinity River near Grand Prairie (point B); the resulting calculated characteristics for the Grand Prairie location were then compared to the characteristics written in published pulse regulations for that same Grand Prairie location. To quantify the comparison, the percent different between the calculated characteristics and the characteristics written in the regulations for the same location was calculated:

$$percent\ difference = \frac{value_{calculated} - value_{written\ regs}}{value_{written\ regs}} \times 100$$

Table 6 shows the percent difference between the calculated characteristic and the characteristic written in the regulations, averaged over all seasons for all test points that had $R_{ab} < 3$, eight of the ten test pairings. In all eight cases, the written regulations were reproduced by the method to within 10% on average. The mean annual flow ratio was then restricted to $0.5 < R_{ab} < 3$ and the same metric was calculated using only the five pairings that had Rab within this range; Table 7 shows the results of these calculations. Restricting the mean annual flow ratio to $0.5 < R_{ab} < 3$ gives the best results for the mean and median percent difference for both trigger flow rates and durations, and very good results for the mean and median percent difference for volumes.

Table 6. Percent Difference Between Flow Pulse Characteristic as Written in TCEQ Regulation Documents and Characteristic as Calculated Using the Pulse Scaling Method for Eight Pairings with $0 < R_{ab} < 3$ Over All Seasons

Characteristic	**Mean % Difference Between Calculated and Written**	**Median % Difference Between Calculated and Written**
Trigger Flow	-7.35%	-20.87%
Volume	-3.68%	-18.25%
Duration	-8.47%	-8.08%

Table 7. Percent Difference Between Flow Pulse Characteristic as Written in TCEQ Regulation Documents and Characteristic as Calculated Using the Pulse Scaling Method for Five Pairings with 0.5 < Rab < 3 Over All Seasons

Characteristic	**Mean % Difference Between Calculated and Written**	**Median % Difference Between Calculated and Written**
Trigger Flow	1.78%	-17.73%
Volume	6.32%	-18.59%
Duration	-6.63%	-4.49%

The comparison of characteristics calculated using the Pulse Scaling Method with characteristics written in regulations documents for the same locations led to several recommendations, given here and discussed in detail below:

- If the mean annual flow ratio $R_{ab} > 3$ or $R_{ab} < 0.5$, a more appropriate primary/secondary point pairing should be found.
- The duration exponent e = 0.105 gives good results for all points across basins.
- Naturalized mean annual flow values from NHDPlus version 2.1 (attribute Q0001C) should be used rather than gage-adjusted mean annual flow values.
- If the tentative duration $D_b{}' < 1$, the duration should be rounded to the nearest hour and reported in hours.

Regulations written at a point with a small mean annual flow are not appropriate bases for regulations at a secondary point with a much larger mean annual flow. When mean annual flow at point B is more than three times the mean annual flow at point A ($R_{ab} > 3$), the calculated pulse characteristics start to scale in an unreasonable way. This criterion indicates that if the flow at the secondary point (point B) is significantly larger than the flow at the primary point (point A), the pairing of points is inappropriate and a different primary point (point A) should be chosen. Scaling downward – the primary point (point A) having the larger flow and the secondary point (point B) having the smaller flow – seems to work reasonably well for all flow magnitudes but the best results are obtained when $R_{ab} > 0.5$.

The Pulse Scaling Method can be used with duration exponent e = 0.105 for all basins with good results. Regulation volume was plotted versus trigger flow for all fifteen regulation points in four basins, and the resulting relationship was $V = CQ^{1.105}$ (where C was a constant) as shown in Figure 14. The test calculations for all ten pairings were done using 0.105 as the duration exponent; when the characteristics calculated at each secondary point were compared to the characteristics written in the regulations for the same location, the results were very good, as explained above and shown in Table 6 and Table 7.

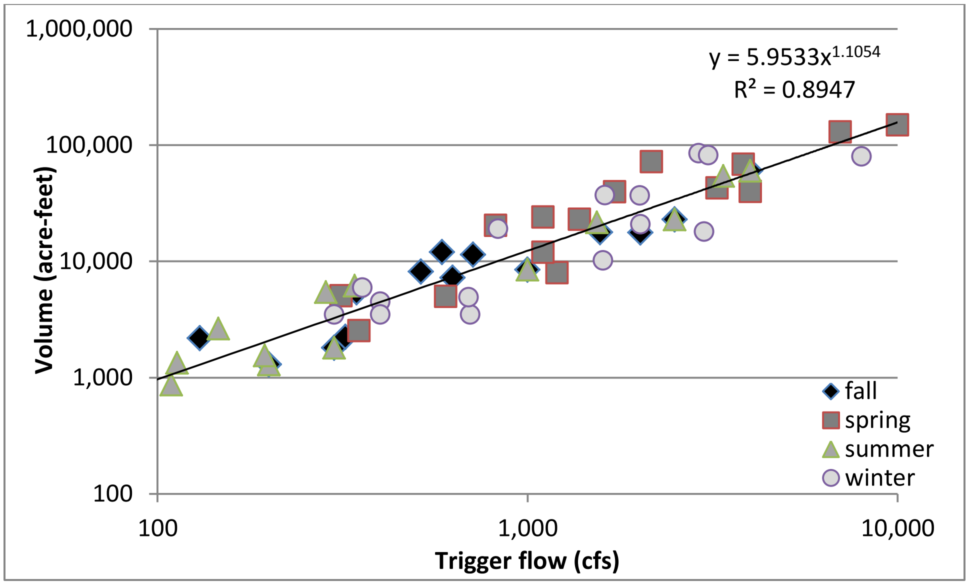

Figure 14. Pulse Volume vs. Pulse Trigger Flow Rate for All Locations in All Seasons

Two of the pairings in this test – the Angelina River near Alto with the Neches River near Rockland, and the Neches River near Rockland with the Neches River at Evadale – had slightly larger percent difference values in certain seasons than was generally seen for the other pairings; the reason for this is that in each case the location with the larger mean annual flow nevertheless had smaller values for some of the pulse characteristics, namely the volume. The expectation is that the location with larger flow would also require a larger pulse volume to be passed; the violation of this expectation led to the slightly larger percent difference values for those locations in those seasons. The average result was still very good, even with these two anomalous parings included. In practice, because calculated characteristics will not be compared with characteristics created by a stakeholder committee for the same point, this will not be an issue.

The relationship between D_b/D_a and R_{ab} was explored as a possible alternative relationship that could be utilized in the Pulse Scaling Method. However, it was found that the best-fit relationship varied somewhat depending on the choice of point-pairings; because the relationship was not constant, it was not deemed an appropriate basis for the method. Instead, the relationships used in the development of the method are dependent only on the existing pulse flow regulations, not on any particular arrangement of the data points within that set.

It was also noticed in the analysis that using naturalized mean annual flow values from the NHDPlus version 2.1 dataset gives better (smaller average percent difference) and more consistent results than are obtained using gage-adjusted flows from the same dataset. The naturalized mean annual flow values are found in attribute Q0001C in the NHDPlus Version 2.1 dataset.

Finally, according to the proposed method, durations are found by calculating a value and then rounding it to the nearest whole number, so that the duration is always a whole number of days. When the calculated value is less than 1, it should be rounded to a whole number of hours and reported in hours. However, TCEQ currently reports all durations in regulations documents in whole-day amounts, so subsequent testing of the Pulse Scaling Method (discussed below) rounded all durations to whole numbers of days. It will be up to TCEQ to decide whether to report all durations in whole numbers of days or to report durations less than one day in hours.

This analysis was repeated using location pairings with the A and B locations in different basins: the pulse characteristics were calculated at the B points using the Pulse Scaling Method with the characteristics at the A points as inputs, and the calculated characteristics were compared to the characteristics written in the regulations for the same locations, exactly as above. However, the percent difference metric (see Table 8) shows that the method does not succeed when the points are in different basins, even when the mean annual flow ratio is restricted to $0.5 < R_{ab} < 3$. What is interesting to note is that the duration predictions are much more successful than the trigger flow or volume predictions, which suggests that pulse durations are more dependent on geographically regional events, whereas trigger flows and volumes may be more dependent on basin-related characteristics. Further research is needed to understand these results, and will be included in future work.

Table 8. Percent Difference Between Flow Pulse Characteristic as Written in TCEQ Regulation Documents and Characteristic as Calculated Using the Pulse Scaling Method for Inter-Basin Pairings with 0.5 < Rab < 3 Over All Seasons

Characteristic	**Mean % Difference Between Calculated and Written**	**Median % Difference Between Calculated and Written**
Trigger Flow	147.67%	4.57%
Volume	287.92%	37.55%
Duration	2.10%	4.61%

RESULTS

The Pulse Scaling Method was analyzed, as discussed above, using ten pairings made from fifteen locations in four river basins, so there were ten B points included in the analysis. The pulse flow portions of these regulations include trigger flow rate, volume, and duration, for each point for each season. Each component was analyzed separately, giving three datasets with forty points in each. The characteristics for these B points taken from the regulations documents are herein referred to as the "regulation datasets," while the characteristics for these B points calculated using the Pulse Scaling Method are referred to as the "prediction datasets." Thus there are six datasets in total: trigger flow rate, volume, and duration as written in regulations documents for each B point in each season, and trigger flow, volume, and duration as calculated using the method for each B point in each season. The regulation and prediction datasets for each characteristic – trigger flow rate, volume, or duration – were directly compared using statistical tests and the results illustrate the success of the method in accurately reproducing pulse flow characteristics.

The statistical tests used to compare the datasets were the rank sum test and the paired t-test. Both tests were performed at the 5% significance level. In the paired t-tests, the difference was taken between the regulation value for a characteristic component at one location in one season and the corresponding prediction value for the same component at the same location in the same season.

Both of the chosen tests demonstrate similarity or difference between two data samples. The hypothesis of the rank sum test is that the two samples being compared have identical distributions. This hypothesis is rejected if the calculated test statistic is larger than the critical value found from the standard normal table for the chosen significance level. The hypothesis of the paired t-test is that when the differences are calculated between each pair of values from the two samples, those differences are normally distributed. This hypothesis is rejected if the calculated test statistic is larger than the critical value taken from the t table for the chosen significance level and the given degrees of freedom. See Table 9 for results of the rank sum tests and Table 10 for results of the paired t-tests. The tests were also repeated on the values grouped by season; see Table 11 and Table 12 for results.

Table 9. Results of Rank Sum Tests

Characteristic	**Z_{rs}**	**Critical Value $\alpha = 5\%$**	**Hypothesis: Identical Distributions Reject if Z_{rs} > Critical Value**
Trigger Flow Rate	0.419	1.65	Do not reject
Volume	0.630	1.65	Do not reject
Duration	0.423	1.65	Do not reject

Table 10. Results of Paired T-Tests

Characteristic	**t_p**	**Critical Value $\alpha = 5\%$**	**Hypothesis: Normal Distribution of Differences Reject if t_p > Critical Value**
Trigger Flow Rate	-0.001	2.021	Do not reject
Volume	0.275	2.021	Do not reject
Duration	0.699	2.021	Do not reject

Table 11. Results of Rank Sum Tests for Each Season

Characteristic	**Z_{rs}**	**Critical Value $\alpha = 5\%$**	**Hypothesis: Identical Distributions Reject if Z_{rs} > Critical Value**
Trigger Flow Rate			
Winter	0.567	1.65	Do not reject
Spring	0.0378	1.65	Do not reject
Summer	0.0378	1.65	Do not reject
Fall	0.265	1.65	Do not reject
Volume			
Winter	0.340	1.65	Do not reject
Spring	0.340	1.65	Do not reject
Summer	0.265	1.65	Do not reject
Fall	0.265	1.65	Do not reject
Duration			
Winter	0.680	1.65	Do not reject
Spring	0.113	1.65	Do not reject
Summer	0.151	1.65	Do not reject
Fall	0.832	1.65	Do not reject

Table 12. Results of Paired T-Tests for Each Season

Characteristic	t_p	Critical Value $\alpha = 5\%$	Hypothesis: Normal Distribution of Differences Reject if t_p > Critical Value
Trigger Flow Rate			
Winter	1.017	2.021	Do not reject
Spring	3.119	2.021	Reject
Summer	2.405	2.021	Reject
Fall	0.375	2.021	Do not reject
Volume			
Winter	0.245	2.021	Do not reject
Spring	1.177	2.021	Do not reject
Summer	2.928	2.021	Reject
Fall	0.206	2.021	Do not reject
Duration			
Winter	2.476	2.021	Reject
Spring	1.307	2.021	Do not reject
Summer	1.346	2.021	Do not reject
Fall	4.522	2.021	Reject

The results of the rank sum tests show that in all cases the regulation and prediction datasets are identically distributed, for all seasons taken together and each season examined individually. The results of the paired t-tests show that the differences between the regulation and prediction values are normally distributed for all three characteristics (trigger flow rate, pulse volume, and pulse duration) when all seasons are taken together; however, when each season is examined individually, each characteristic has non-normally distributed differences between the value pairs in one or two seasons. In future work, further investigation of these “Reject” results may be useful for adding insight into the seasonal variations within the pulse characteristics. Taken as a whole, though, these results indicate that the Pulse Scaling Method generates predictions that, overall, successfully replicate the characteristics given in regulations documents.

PULSE SCALING METHOD SUMMARY

Using three key relationships found in the written environmental pulse flow regulations for fifteen points in the Trinity, San Jacinto, Sabine, and Neches basins, a Pulse Scaling Method was developed for calculating pulse flow characteristics appropriate at point B using known pulse flow characteristics at point A. Based on statistical analysis and comparison of calculated characteristics with known characteristics at the same point, this Pulse Scaling Method is successful in reproducing environmental pulse flow trigger flow rates, volumes, and durations at points of interest not included in regulation documents that are similar to trigger flow rates, volumes, and durations included in regulation documents when the known and unknown points are within the same basin.

Pulse flow events are complicated and the effects they have on ecosystems are extremely difficult to accurately and comprehensively quantify. Thus the development of environmental pulse flow requirements is a complicated process with no clear-cut answers; there is no straightforward methodology that can easily be applied at many locations, rather a long and complex study and consideration of many factors are needed to generate environmental pulse flow regulations. For this reason, generating the characteristics of pulse flow that should be included in legal documents at points other than original study points is complex; the method presented herein is a mathematically based procedure for generating these characteristics at unknown points such that certain relationships among those characteristics are preserved. The procedure also meets the requirements of a state water management agency, such as that it cannot take a large amount of time to repeat the procedure for each new point of interest.

This study was completed using fifteen points in four basins – all of the points included in already published environmental flow regulations documents for the state of

Texas[7]. The results should be verified for additional basins as regulations are published for other locations in Texas, and the "Reject" results in the seasonal paired t-tests should be further explored. In addition, the above analysis and testing should be repeated using naturalized flows from the Water Availability Model to check whether that dataset is preferable or comparable to the NHDPlus mean annual flow dataset. It would also be interesting to compare both regulations written in existing legal documents and regulations calculated using the Pulse Scaling Method to historical flow records. Using historical flow records was found not to be a useful way of approaching this problem because of their extremely complex nature (pulse events vary wildly, frequently overlap, etc.) and because the pulses preserved by environmental flow regulations are not equivalent to naturally occurring flow pulses; however, further verification of the method might result from modeling scenarios in which published and calculated regulations are applied to historical flow records and the flow patterns preserved by those regulations analyzed.

[7] The exception is Sabine River near Gladewater, 08020000, which was excluded as noted previously.

Chapter 4: Information Access for Watermaster Operations

The Texas Commission on Environmental Quality (TCEQ) is responsible not only for issuing legal permits for users to withdraw water from state waterbodies but also, in some regions, for overseeing those withdrawals on a daily basis to ensure compliance. In times of drought, this oversight mechanism also allows for careful distribution of a scarce resource to those who have priority under the law. This active regulation is carried out by the watermaster program, which is housed in the Water Availability division of TCEQ's Office of Water (Office of Water 2012). Watermasters, who are currently established in only certain basins in the state, "ensure compliance with water rights by monitoring stream flows, reservoir levels, and water use…Before diverting, a water-right holder must notify the watermaster of the intent to divert at a specific time and the specific amount of water to be diverted. If the water is available and the water-right holder will not exceed its annual authorized appropriation of water, the watermaster then authorizes the diversion and records this against the right" (Watermasters 2013). During droughts, watermasters also consider the availability of water and the priority order (according to the "first in time, first in right" doctrine) of users so that water is distributed appropriately, and junior right-holders are not allowed to divert water at the expense of senior right-holders (What Your Water Right Means 2012).

The South Texas Watermaster handles these duties for the Guadalupe, Lavaca, Nueces, and San Antonio river basins; with over 800 right-holders in the Guadalupe basin alone, managing all of the requests to divert water can be challenging, especially when potentially difficult decisions are required in times of scarcity. Compounding the challenge is a fundamental problem of data access: the information relating to legal permit documents is stored in the Water Availability Model (WAM) database in TCEQ's

Austin office, while the South Texas Watermaster's diversion data is stored in a Texas Watermaster Accounting System (TXWAS) database in TCEQ's San Antonio office. The two databases do not use common identifiers for records, and there can be complicated many-to-many relationship between records in the two systems.

Not only do watermaster staff need to access data from two separate databases, they need additional information on hydrologic conditions and, ideally, insight into the consequences of any particular combination of diversions, especially in drought conditions when one large diversion could have a major impact on downstream users. Such data might come from United States Geological Survey (USGS) observations, output from river flow models, rainfall amounts and predictions, and many other sources. Yet there is no existing system that allows staff to simultaneously access data from all of these sources, much less a system that aids in the synthesis of data to provide information for decision-making. The objective of this work was to provide a pilot system that would allow watermaster staff to quickly and easily access the information they need for decision-making, and to make the system accessible from any location, including in the field.

THE COMMON OPERATING PICTURE: PILOT SYSTEM DESIGN AND IMPLEMENTATION

Given the widely varied information needs of watermaster staff, it was determined that a web-based system would be the most appropriate technology for allowing simultaneous access to all necessary data. As discussed in the literature review, it is becoming common for online map interfaces to be used as access points to multiple data sources, using services-oriented architectures to drive the functionalities. Essentially this means that each data-providing agency can offer its own web services, built according to certain accepted standards, and then a web-map can act as an aggregator of those services and thus allow one user to simultaneously access the data from all of the included agencies (see Figure 15). When data is desired from an agency that does not offer adequate services, the data can be otherwise acquired through automated computer routines and then offered as a service by the institution generating the map interface, in this case the Center for Research in Water Resources (CRWR) at the University of Texas at Austin.

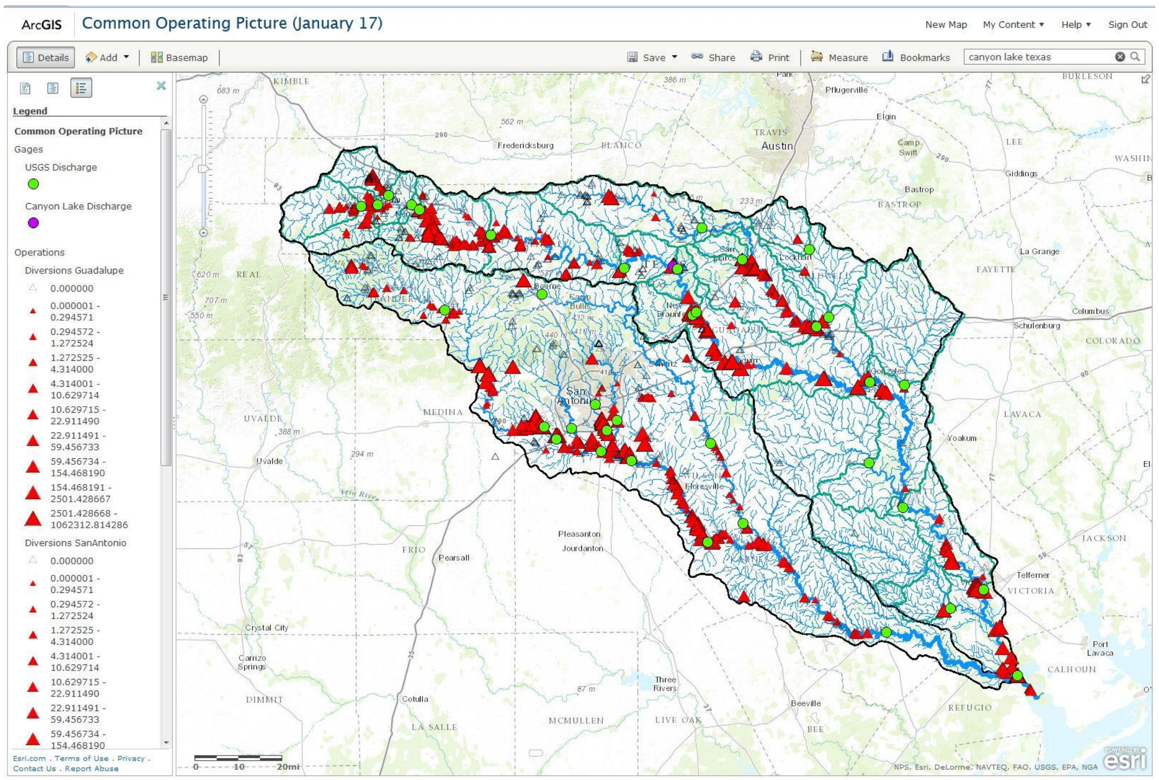

Figure 15. A Single Web Map Offering Simultaneous Access to Data from Many Sources

The scope of the pilot study is the combined Guadalupe and San Antonio basins. These basins are considered relatively simple in operational terms: they have few of what TCEQ managers consider complicated water rights, and in the two basins there is only a single major reservoir, Canyon Lake. The combined drainage area of the two basins is

10,250 mi^2 or 26,547 km^2 (Guadalupe River Basin n.d.), and there are approximately 1400 water rights that have been issued for this region. These basins have also been used in the past by CRWR researchers for pilot studies that are relevant to this project, namely a river routing model that is discussed below. Of course the primary criterion is that these basins are indeed under the management of a watermaster.

The data sources that have thus far been identified for inclusion in this system include, of course, data from both the WAM and TXWAS databases on water rights permit points and past and current diversions occurring at those points, as well as locations of streams and rivers from the National Hydrography Dataset's NHDPlus (a product that also includes information from the National Elevation Dataset and the Watershed Boundary Dataset); USGS stream gages, for streamflow measurements and other hydrologic data at specific points; soil wetness data from the National Land Data Assimilation Service and additional soil wetness information generated through another CRWR research effort; reservoir discharge, in this case coming from the Army Corps of Engineers for Canyon Lake dam releases; discharge, runoff, and precipitation historical data along with both short- and medium-term forecasts from the National Weather Service; and modeled stream flow values from a model called the Routing Application for Parallel computatIon of Discharge, or the RAPID model, created by previous CRWR researcher Cedric David (n.d.). These sources include both measured and modeled data, because observations alone leave gaps in space and time, but models are best used in conjunction with measurements for comparison. For example, relying on USGS gages alone for streamflow information would not allow for finding values at most points along the streams, whereas including RAPID information allows for finding streamflow at any point on the stream network.

As previously mentioned, the goal of the pilot implementation was to create a system that aggregates data from all of the above sources (and likely others in the future) by way of web services. According to the World Wide Web Consortium, “a Web service is a software system designed to support interoperable machine-to-machine interaction over a network” (Web Services Glossary 2004). The important thing to understand about a web service is that it can be “used by anyone, anywhere, and with any kind of devices” (Le Hégaret 2003); web services make information available in various formats so that they can be ingested by any program or system. For many web services the standard format is called eXtensible Markup Language, or XML; water-related web services use a format based on XML that is called WaterML. The Open Geospatial Consortium has recognized WaterML2.0 as the standard format for hydrological observations data (OGC WaterML 2013), so agencies are encouraged to use the format and remain in compliance with international standards. Much of the data included in this project come from agencies with their own hydrological data web services, which can be directly incorporated into an aggregator system. However, not all of the needed data is currently available via web services, and some of the desired data is offered via web services that do not meet the current WaterML 2.0 standard, and it was decided that WaterML 2.0 should be used in this system whenever possible. Therefore, some of the data included in the pilot system are offered via web services published by CRWR.

In order to publish these services, various data brokers are used to collect data from remote sources and store them on servers at CRWR, where they can be manipulated if needed and published as web services in WaterML 2.0. For example, to handle data from the National Weather Service, a server at CRWR automatically collects the needed data on a regular basis using Unidata Local Data Manager software, which “acquires data and shares them with other networked computers (Unidata LDM Factsheet 2012); the data are then stored on another server in a Kisters WISKI database system (discussed below). To publish web services for data from the USGS, a piece of software called KiDAT (part of the Kisters software suite) calls on USGS web services to collect data in the offered format (which is not WaterML) and stores the data directly in the WISKI database. Data stored in the WISKI database are made available as WaterML 2.0 web services via another piece of software called KiWIS (also in the Kisters suite).

The types of information being used in this project are primarily time series measured or modeled at specific locations: time series are data collected over time, with chronological order having importance. For example, listing the streamflow values for the last six months in order from largest to smallest is not particularly useful for the primary goals of this project; on the contrary, seeing the streamflow values for the last six months in the sequence in which they occurred is what is needed. Managing these types of data and, moreover, integrating time series with geospatial information, is nontrivial. The solution chosen for this project was to implement a WISKI system, built by the company Kisters and designed for effective and efficient time series management. The WISKI system includes a database that stores the collected time series data, and it offers many features for turning that data into information, such as graph generation and statistical analysis tools (WISKI Overview 2011). The choice to use WISKI allowed for the focus of this project to be on curating and displaying relevant data as useful information rather than on constructing a database model to store and manage data.

Similarly, rather than construct from scratch a web portal through which the information can be accessed, CRWR chose to use an existing online mapping solution offered by the company ESRI: ArcGIS Online, which is a website that allows for uploading and creating of both static and interactive maps using web services and uploaded files. ArcGIS Online offers online map viewers within which data from various sources – including online sources such as web services, and files of various types uploaded directly from a local desktop – can be compiled to generate new maps. These maps can be saved and made accessible only to the creator, they can be shared publicly, or a group can be created that requires permission to join and access to maps can be restricted to members of certain groups. These maps are stored in the ESRI cloud (i.e. on ESRI's servers), and any that are accessible are also searchable and can be added to other maps for endless "mashups" combining data in an infinite variety of ways. ArcGIS Online maps also feature legends, tables of contents that allow for certain map layers to be made visible or invisible (so that only certain portions of the information is shown at one time), and easily configurable popups that display additional information when map features (points, lines, or polygons) are clicked (see Figure 16). This collection of features addresses the primary functionalities desired in the pilot system being created for this project, and CRWR plans to work with ESRI to incorporate new features as they are needed or become available.

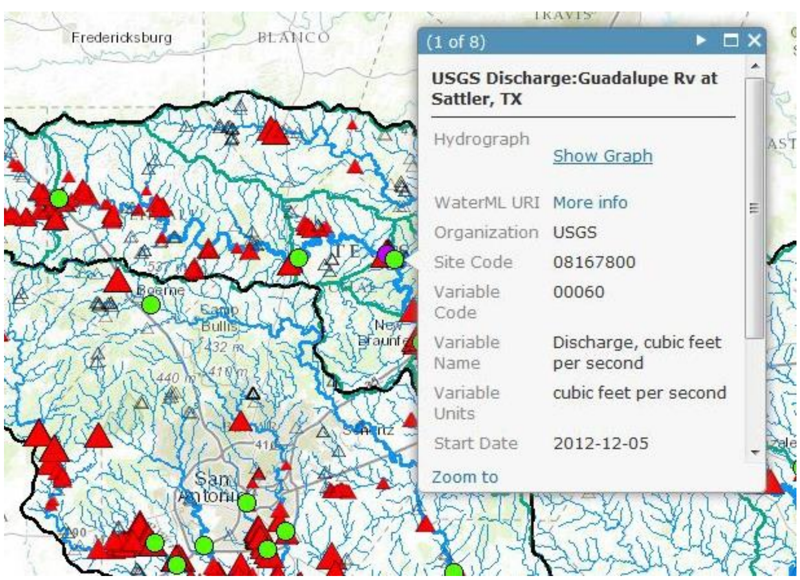

Figure 16. Pop-Up Window Showing Data Associated with the Chosen Point Feature

With data assembled from the chosen sources using the chosen technologies, a pilot system was relatively straightforward to implement. Some of the chosen time series data are available via existing web services; to manage the other data, routines were established on CRWR servers to automatically acquire the data from the generating agencies and transfer that data into the WISKI system. A map was generated using ArcGIS desktop mapping software, with links to the relevant web services embedded in the attributes of the features. For example, each point on the map that represents a USGS stream gage is attributed with a hyperlink that calls the associated web service; the web service is what provides the time series data related to that location. The map was then published as a map service – a specific type of web service – which allows it to be updated automatically if changes are made to its underlying geodatabase (spatially enabled database), just as time series web services allow automatically up-to-date access to measured or modeled time series data. Some of the desired datasets were collected into a single primary map service, while others were published as individual map services; again, each map service contains the geospatial information about the features to be displayed – which might be points, lines, or polygons – and attached to those features are hyperlinks to the time series web services that provide the measured or modeled data associated with each location. The pilot implementation is currently accessible by visiting http://www.arcgis.com/home/ and typing "COP Guadalupe" into the search box: because it brings together a wide variety of data in order to support TCEQ operations, it is called the Common Operating Picture.

COMMON OPERATING PICTURE SUMMARY

The Common Operating Picture is a layered map allowing simultaneous access to one or more spatially-related datasets (see Figure 17). By its very nature as a dynamic map with associated time series, the Common Operating Picture presents data as information in a way that can support water resource management and decision-making. Hydrologic data can be accessed as time-value pairs in chronologically sequenced lists with associated metadata (see Figure 18), but they can also be viewed as graphs (see Figure 19) showing the measured or modeled variable over time. This type of visualization allows for easy understanding of patterns and progression, such as the relationship between current flow at a point in a stream and flow at that same point over the previous 30 days. These graphs are linked from map features – points, lines, or areas on the map – so that they can also be easily understood within the context of the spatial relationship of the features. This connection between space and time is perhaps the most important aspect of the Common Operating Picture: "real world" decisions occur in both space and time, so it is crucial to incorporate both pieces in any effective decision-making support system.

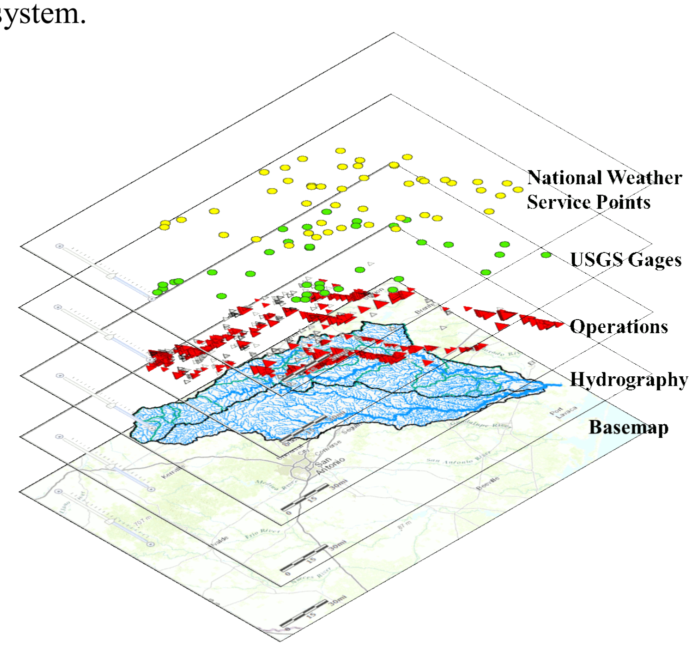

Figure 17. Illustration of the Map Layers of the Common Operating Picture, Including Base Map, Hydrography (Rivers and Basins), Diversion Locations, USGS Gage Locations, and National Weather Service Points

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    <value censorCode="nc" dateTime="2012-02-09T09:00:00" timeOffset="-06:00" dateTimeUTC="2012-02-09T15:00:00" methodCode="4" sourceCode="5" qualityControlLevelCode="0">63</value>
    <value censorCode="nc" dateTime="2012-02-09T10:00:00" timeOffset="-06:00" dateTimeUTC="2012-02-09T16:00:00" methodCode="4" sourceCode="5" qualityControlLevelCode="0">58</value>
    <value censorCode="nc" dateTime="2012-02-09T11:00:00" timeOffset="-06:00" dateTimeUTC="2012-02-09T17:00:00" methodCode="4" sourceCode="5" qualityControlLevelCode="0">55</value>
    <value censorCode="nc" dateTime="2012-02-09T12:00:00" timeOffset="-06:00" dateTimeUTC="2012-02-09T18:00:00" methodCode="4" sourceCode="5" qualityControlLevelCode="0">55</value>
    <value censorCode="nc" dateTime="2012-02-09T13:00:00" timeOffset="-06:00" dateTimeUTC="2012-02-09T19:00:00" methodCode="4" sourceCode="5" qualityControlLevelCode="0">55</value>
```


Figure 18. Example of WaterML-Formatted Time Series of Data

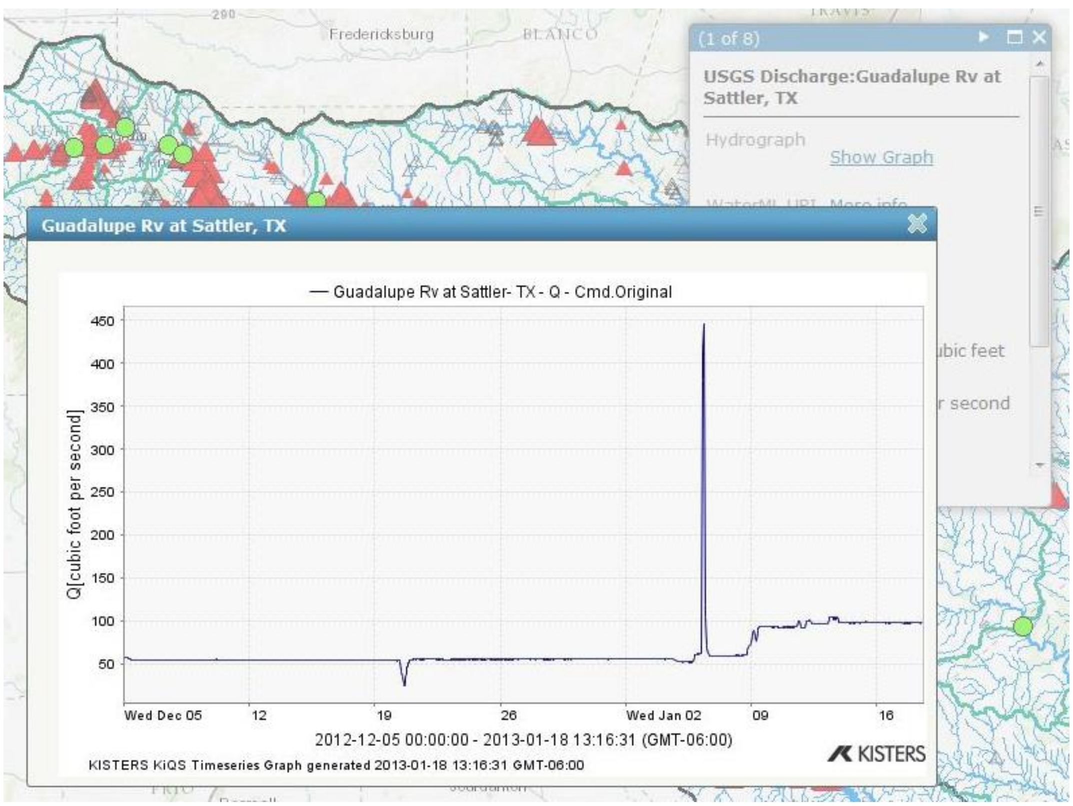

Figure 19. Pop-Up Window Showing Graph of Time Series of Data

Additional work planned (some of which is already being tackled by other researchers at CRWR and the University of Illinois at Urbana-Champaign) includes:

- Automation of real-time operations data updates,
- Automation of real-time forcing data (precipitation and runoff) and ensemble forecast updates,
- Error-correction of the RAPID model,
- Further progress on RAPID model-as-service,
- Real-time and forecast updates of the RAPID model output using real-time and forecast data and RAPID model-as-service,
- Automation of geospatial data updates when permit and/or diversion points are added by TCEQ.

Together, these and other additional work goals will create a map that offers streamflow values in real-time, short-term prediction, and medium-term forecast. In addition, the model-as-service capabilities will allow a user, with no knowledge of the inner workings of the RAPID model, to choose a scenario such as "allow these certain diversions to proceed," send the appropriate input data to the model, which will run as a web-service and return results based on that scenario input. This setup will go far beyond the current cached-results schemes that run a model in advance according to predefined scenarios, store the results, and offer these stored results to a user who chooses one of the predefined scenarios; the user will instead be able to define a unique scenario, based on real requests to divert water by users in need, and receive results of the model run for that unique scenario, without requiring the user to access a supercomputer or otherwise understand how to run the model. These results will then be contextualized within the map interface, allowing watermaster staff to easily view the potential consequences of a scenario in both time and space. This type of information access will drastically improve ease and consistency of operations compared to the current situation, which requires pen-and-paper calculations and expert judgment based on uninterpreted, unsynthesized data that must be collected from myriad sources.

Chapter 5: Conclusions

Active water management is a challenging field, and one that will continue to grow and change to meet new demands from population growth, climate change, and other evolving scenarios, and to incorporate new strategies and technologies as they become available. This progress will "[require] close cooperation between scientists and water managers…There is clearly a need for a range of scientists including those exploring understanding of fundamental issues and those who produce tools for water management" (Acreman 2005). The work described herein has enhanced understanding of fundamental issues in order to produce tools for management by addressing the management problems of applying environmental pulse flows at points of interest not named in regulations documents and of providing effective and efficient display of information needed, from many sources, for decision-making.

The Pulse Scaling Method for transposing environmental pulse flow regulations from points named in regulations to additional points of interest is based on an understanding of environmental flows and statistical analysis of the existing regulations. The method uses the ratio of mean annual flows at a location at which environmental flow pulse regulations are known and a location at which they are not known as the basis for a series of straightforward calculations that transposes the characteristics of a regulated pulse from the known location to the unknown location. The method also meets the needs of a busy state management agency: it is a straightforward process that can be applied quickly by a manager without need for specialized software or datasets beyond what TCEQ currently uses in the ordinary course of operations. Testing of the method shows that it yields environmental pulse flow regulation requirements that are statistically similar to existing pulse flow requirements, and thus it is expected to successfully extend

Texas's environmental flow implementation throughout basins, beyond individual regulation points. However, in accordance with active management principles, the implementation of the Pulse Scaling Method should be monitored and evaluated over time to ensure that the goals of ecosystem preservation in conjunction with adequate service of human needs are satisfactorily met.

The Common Operating Picture is an aggregation of hydrometeorological, water operations, and related data with a geovisualized interface to provide easy access to information needed by TCEQ watermasters for daily decision-making. The project is currently in the pilot stage, with a number of data sources included and an interface available, but with additional work planned and further testing needed before larger-scale implementation.

In generating the Pulse Scaling Method and the Common Operating Picture, we began to answer, to greater or lesser degree, the research questions posed at the outset of this thesis:

1. What does it mean to define and quantify a flow pulse?
2. What does it mean to "preserve" a flow pulse as it moves through a river network system?
3. How can rigorous science and emerging or recently available technologies be used to support the decision-making needs of a governmental agency?

It was found that defining and quantifying a flow pulse is not straightforward, as pulses in real flow records are extremely complex and varied. Naturally occurring flow pulses are defined by their magnitude, frequency, duration, timing, and rate of change, all of which vary based on locational characteristics, and vary at any given location depending on precipitation input and antecedent conditions. Pulse events can overlap, making it difficult to separate individual pulses from a historical record. Several early lines of research focused on historical pulse events and attempted to quantify and preserve these naturally occurring pulses. These approaches gave insight into the difficulty of the problem and helped to clarify the task at hand: the objective was not truly to categorize and preserve flow pulses, but to understand certain *representative characteristics* of pulses and transpose those characteristics from one location to another to achieve certain environmental goals.

It is indeed possible to capture many of the locational characteristics that shape pulses: descriptors of pulse condition as opposed to baseflow condition (trigger flow rate) and pulse size (volume and duration) can be considered as representative of the population of pulses at that location. Because these characteristics are heavily influenced by location-dependent details, such as drainage area, they remain similar from pulse to pulse at that location; because these characteristics are also influenced by time varying conditions (precipitation, antecedent moisture, etc.), they are not truly constant from pulse to pulse at the given location. In addition, it was found that some characteristics of pulses have a degree of regional consistency. Specifically, while pulse trigger flow rates and volumes tend to vary from location to location, durations tend to remain relatively constant within geographic regions. These findings show that static sets of pulse characteristics are useful for describing flow pulses based on location, but they are by no means comprehensive.

In spite of the difficulty in characterizing pulses, describing how they move through river network systems is relatively straightforward. However, understanding how pulses travel does not necessarily imply understanding what it means to "preserve" pulses as they move. There are many well-established methods for routing pulses, or flood waves, downstream along flow paths, including the Muskingum-Cunge method. These routing algorithms can be used to describe the movement of the pulse and its attenuation (flattening and spreading of the peak of the wave); however, the theoretical task of describing the reverse motion of a pulse moving upstream is not so straightforward. Some literature exists on the subject, but none was found that applied to directly routing a single pulse upstream for a known distance along a branching river. Part of the difficulty of this task lies in that a pulse at a downstream location is composed of pulse flows from various upstream branches of the river network along with flow entering the stream at or just upstream of the given location. These inputs combine in different ways during each pulse event, depending on the location of the precipitation causing the pulse. In other words, a rainstorm over the east branch of a river will cause a pulse in the east branch but little or no pulse in the west branch, while a rainstorm over the west branch will cause a pulse in the west branch and little or no pulse in the east branch, yet these two rainstorms might result in identical flow pulses at some point downstream of the confluence of the two branches. Preserving downstream pulses is thus much more complicated than simply preserving upstream pulses at all possible locations equally: it is possible that on one occasion, one upstream location will have no pulse at all preceding a downstream pulse, while on another occasion that same upstream location will have a large pulse that contributes significantly to the downstream pulse. This complexity in the interaction of pulses throughout river network systems makes it very difficult to set simple rules that will have the effect of "preserving" all historically observed pulses. Understanding this problem led to better understanding of the focus of this work, which was not ultimately on preserving individual flow pulses but on describing certain representative characteristics of pulses that will help to achieve environmental goals, and on maintaining certain relationships between those characteristics.

From the complexities discussed above, one can easily see some of the challenges associated with applying rigorous science and advanced technologies to governmental decision support. As Acreman (2005) wrote, “scientists seek the best theory to explain the data that are available, with recognition that it is not definitive. They are driven by innovation and understanding, rather than consistency,” whereas decision-makers “[seek] consistency, so that similar decisions are made in similar circumstances.” However, this disparity does not necessarily mean that scientists and decision-makers cannot successfully work together. Researchers can use the results of rigorous research to generate tools that can be used without specialized training, that give results that meet the needs of decision-makers to a large degree, and that can be applied within the timeframe appropriate to decision-making procedures. Decision-makers can allow for a small amount of ambiguity in results that requires application of professional judgment from time to time rather than always requiring absolute answers. Most importantly, scientists and agency personnel need to work together so that researchers understand decision-makers’ needs and can provide tools accordingly, and so that decision-makers understand the parameters and limitations of research and can adjust their expectations if needed.

No single tool or technology can meet all the needs of all decision-makers; however, some general, flexible technologies may be adaptable to a very wide range of decision-making needs. Standardized formats, such as those endorsed by the Open Geospatial Consortium and similar organizations, can help make it easier for technologies to accommodate a wide range of applications. In some cases, instances of these broad technologies can be customized to address the specific needs of an agency; in other cases, a custom solution will need to be developed from more fundamental scientific inquiry. In most cases, researchers and decision-makers all benefit from collaborations that both drive innovation and solve management problems. Such partnerships between researchers and decision-makers will help the field of active water management to grow, to more accurately and more comprehensively address water management needs, and to adapt to the ever-changing inputs of climate, hydrology, and human water use.

List of Acronyms

BBASC – Basin and Bay Area Stakeholder Committee

BBEST – Basin and Bay Expert Science Team

CFS – cubic feet per second

CRWR – Center for Research in Water Resources

GIS – Geographic Information System

HEFR – Hydrology-Based Environmental Flow Regime

IHA – Indicators of Hydrologic Alteration

MAF – Mean Annual Flow

NHD – National Hydrography Dataset

RAPID – Routing Application for Parallel computatIon of Discharge

SAC – Science Advisory Committee

SB1 – Senate Bill 1

SB3 – Senate Bill 3

TCEQ – Texas Commission on Environmental Quality

TXWAS – Texas Watermaster Accounting System

USGS – United States Geological Survey

WAM – Water Availability Model

WBD – Watershed Boundary Dataset

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