LAG AND ATTENUATION PARAMETERS FOR ROUTING DAILY FLOW CHANGES THROUGH LARGE RIVER SYSTEMS

A Thesis

by

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ABSTRACT

The 2007 Senate Bill 3 (SB3) initiated the establishment of environmental flow standards and the incorporation of them in the Water Availability Modeling System (WAM) of Texas. This led to the creation of Water Rights Analysis Package (WRAP) daily modeling capabilities. The effects of water use and management actions propagate downstream to other locations of interest in water availability modeling over periods ranging from several hours to several days. Hence unlike the WRAP Monthly Simulation Model (SIM), the Daily Simulation Model (SIMD) includes routing of the effects of flow change events to downstream control points.

The previously developed six case study daily WAMs use routing parameters estimated through calibration using hydrographs at upstream and downstream ends of a river reach with computations performed with a genetic search algorithm. In this research, two new methods have been developed to estimate routing parameters.

1. Wave Travel Velocity Equation: Motivated by Manning's equation and National Resources Conservation Service (NRCS) lag time equation. This equation calculates lag time based on flow, slope, and length of the reach.
2. DFLOW program: This program calculates the lag time between upstream and downstream control points for different flow change events in a time series record, and provide statistical measures of the results.

The wave travel velocity equation was applied to different reaches of the Brazos River and its tributaries and the DFLOW program was applied to the Neches, Brazos, and Trinity River Basins. Comparative analysis of different sets of routing parameters shows that lag times from the optimization-based parameters are unrealistically low for the Brazos and Neches River Basins. Lag times from DFLOW and the wave travel velocity equation are higher than optimization-based lag times and are more realistic when compared to typical average stream velocities.

Simulation results using different simulation options and routing parameters were compared to gauge the sensitivity of simulation results to different routing and forecasting options. Simulation results are sensitive to different routing parameters and routing and forecasting options but do not vary dramatically for any of these options.

DEDICATION

This thesis is dedicated to my parents, Abdul Wahab and Asiya.

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NOMENCLATURE

BRA	Brazos River Authority
DFLOW	Daily Flow
e-flow	Environmental Flow
GIS	Geographic Information System
GSA	Guadalupe and San Antonio
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
K	Conveyance Factor
L	Length of the Reach
LRCA	Lower Colorado River Authority
NRCS	National Resources Conservation Service
Q	Flow
RAS	River Analysis System
S	Slope of the Reach
SB3	Senate Bill 3
SIM	Simulation Model
SIMD	Daily Simulation Model
T	Time
TCEQ	Texas Commission on Environmental Quality
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
V_{AVE}	Average Velocity in River
V_T	Travel Velocity
V_W	Wave Celerity
WAM	Water Availability Modeling
WRAP	Water Rights Analysis Package

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CHAPTER I

INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) maintains a Water Availability Modeling (WAM) System for all the river basins of Texas. The WAM consists of the generalized modeling system Water Rights Analysis Package (WRAP) and its input datasets for all the river basins of Texas, and related information (Wurbs 2005). The generalized WRAP combined with an input dataset from the TCEQ WAM System is called a water availability model (WAM). The monthly WAMs have been routinely applied in Texas for over a decade. The TCEQ has sponsored research at Texas A&M University over the past several years that has included the development of daily time step WRAP modeling and corresponding daily versions of six of the 20 Texas WAMs.

The daily modeling system expands the capabilities of WRAP for simulating Senate Bill 3 environmental flow standards and the corresponding effects on water supply reliabilities (Wurbs and Hoffpauir 2013). The daily modeling system includes disaggregation of monthly naturalized flows and water demands to daily units, flow forecasting and routing, simulation of flood control reservoir operations, and recording high-flow pulses of certain frequencies for environmental flow standards along with subsistence and base flows.

The WRAP daily modeling system is documented by the Daily Manual (Wurbs and Hoffpauir 2015). The WRAP program for daily simulation is called SIMD. The six daily WAMs of Texas for the Brazos, Colorado, Trinity, Neches, Sabine, and Guadalupe and San Antonio (GSA) are in the developmental stage.

Flow routing and forecasting capabilities were added to the Daily Simulation Model as the effects of reservoir operations and other water management and use actions usually propagate through a river/reservoir system in less time than a month. These effects do not transfer to the next month typically in a monthly model. Daily WAM simulations can be performed without routing and forecasting too. Simulation results for the six daily WAMs are changed significantly but not dramatically by completely removing routing and forecasting. Routing and forecast parameters are necessarily approximate. Changes in values of routing and forecast parameters can significantly affect simulation results.

The current techniques of determining routing parameters for daily WAMs have some issues as described later. The purpose of this research is to develop routing parameters determination technique(s) and to incorporate these technique(s) in the WRAP/WAM system. This research on simulating the downstream propagation of flow changes provides an enhanced understanding of river hydraulics as well as improved WRAP/WAM modeling capabilities.

Water Rights Analysis Package (WRAP)

The Water Rights Analysis Package (WRAP) is a system of multiple computer programs purposefully developed for simulating and analyzing water resources management, allocation, development and use in a single river basin or multiple–basin region. WRAP is built for the priority (time) based water allocation system called prior appropriation water rights. It is used to assess the reliability of supplying water to particular water rights. These water rights can be industrial/municipal water supply needs, hydroelectric power generation needs, instream/environmental flow needs, and reservoir storage allocation. Flood control and reservoir operations can also be simulated through WRAP. Additional capabilities include tracking of salinity load and concentrations. The modeling system is general i.e. it can be applied in any part of the world, with input files developed for the basin/region of interest (Wurbs 2015b).

The Water Rights Analysis Package has been developed at Texas A&M University under the supervision of Dr. Ralph Wurbs. It is implemented routinely in the state of Texas in the United States. TCEQ maintains input files for the Texas river basins. The modeling system supports administration of water allocation systems, regional and statewide planning, and other water management activities.

Within the WRAP package, there are two separate simulation models based on the size of the time step. The monthly model (SIM) was developed initially and is well established. The monthly model is available for the public use. Sub-monthly (or daily) model (SIMD) was developed recently and is seeing continuous improvements. The main force behind the development of the daily model is Senate Bill 3 (SB3) environmental flow standards. WRAP is documented by a Reference Manual (Wurbs 2015b), Users Manual (Wurbs 2015c), Daily Manual (Wurbs and Hoffpauir 2015), and several other manuals.

The modeling strategy implemented in WRAP is as follows (Wurbs 2005)

1. Time-series records of naturalized flows covering the period of interests are given by the user to the program at selected control points. The user also provides other information such as evaporations at reservoirs, water rights priority order, water rights diversion amount, return flows, etc. etc.
2. Naturalized flows are distributed from those control points to all control points based on user define criteria.
3. The water management system is simulated, under the priority based allocation to each water right.
4. Simulation results are summarized in the form of water supply reliability indices, flow, and storage frequency relationships, and regulated and unappropriated flow records.

Texas Water Availability Models (WAMs)

The Texas commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) system consists of WRAP and WRAP input files for the all the 23 river basins of Texas. Three of the basins are combined with adjacent river basins. The 20 WAM datasets are available at the TCEQ WAM website. The WAM assess availability and reliability of water resources in a river basin based on historical hydrology and authorized (permitted) or current conditions of human development and water use. The WAM system supports government agencies in a wide spectrum of statewide planning and management activities. Major applications include water rights permit evaluations and statewide planning studies. The WAM system is currently being updated to incorporate modeling of Senate Bill 3 environmental flow standards.

Daily Simulation Model (SIMD)

The Daily Simulation Model (SIMD) is an expansion of the Monthly Simulation Model (SIM) to enable daily time step modeling. The motivation for the development of SIMD arises from the need of assessing water supply reliabilities after satisfying SB 3 environmental flow standards. Beside the capabilities of monthly time step model, SIMD possesses the following major additional capabilities (Wurbs and Hoffpauir 2015):

1. Disaggregation of monthly naturalized flow to daily time step.
2. Disaggregation of monthly targets of streamflow diversion, hydropower and environmental flow to daily targets.
3. Routing and attenuation of current day flow changes to downstream control points at later days.
4. Forecasting of available stream flows at downstream control points for future days based on the flow changes at an upstream control point in the current day.
5. Simulation of available channel capacity for flood control reservoir operations.
6. Recording of daily and aggregated monthly simulation results.

The routing and forecasting were not required in the monthly model because the effects of flow changes usually get transferred to all downstream control points within the same time step. In the daily model, it is necessary to incorporate routing and forecasting to better assess regulated flows at downstream control points and to protect senior water rights from the diminishing effect of water use by junior water right at upstream in previous days.

Literature Review

Flow Routing

Flow routing is a technique to track the characteristics of a wave, which is superimposed on the flow itself, in a river at different spatial locations. These characteristics may be magnitude, time, and spread. In a typical use of flow routing, characteristics of flood waves from different storm events are analyzed for downstream locations (Akan 2006). In WRAP, routing is used to analyze the effects of water withdrawal or addition by upstream users at downstream points as the wave created by flow change propagates downstream.

Wave Celerity

The speed of the propagation of disturbance is called celerity (or celerity of gravity waves in shallow water), and it is estimated as $c \text{ or } V_W = \sqrt{gD}$, where D is the flow depth. Celerity is not equal to average velocity at a river cross section.

Wave Celerity (V_W) is related to average velocity as follows (USACE 1994):

Table 1.1: Relationship between Wave Velocity and Average Velocity for Different River Cross Sections

Channel Shape	V_W/V_{AVE}
Triangular	1.33
Parabolic (Wide)	1.44
Rectangular (Wide)	1.67

For natural channels, use of a conversion factor of 1.5 is acceptable because the shape of a natural stream can be estimated as rectangular or parabolic (USACE 1994).

Muskingum Model

The Muskingum routing method, developed by McCarthy in 1938, is a hydrologic model which applies the continuity equation and a storage versus flow relationship to route flood flows (Fallah-Mehdipour et al. 2016). The two fundamental equations of Muskingum routing are:

$$\frac{dS_t}{dt} = I_t - O_t$$

$$S_t = K[xI_t + (1 - x)O_t]$$

Here, S_t, I_t, and O_t are storage, inflow, and outflow at time interval (t). Muskingum is the most widely used method of hydrologic routing. The Muskingum method requires parameters which must first be calibrated and then applied in the prediction phase. Muskingum parameters K, X, and m (for nonlinear Muskingum modeling) represents the characteristics of the river. Hence, they must first be determined using historical data (Das 2007). There are two ways in which Muskingum parameters can be estimated 1: Mathematical Techniques and 2. Phenomena-mimicking algorithms.

The x parameter of Muskingum model is not measurable, it is a weighing factor that tells the relative importance of flows at upstream and downstream in the calculation of storage in channel reach.

K is a storage constant that relates storage with discharge, it can also be considered as the difference of time between similar points on inflow and outflow hydrographs which can be peaks or centroids.

Hoffpauir incorporated Muskingum routing in the original WRAP daily simulation model SIMD (Hoffpauir 2010).

Muskingum Parameter Estimation

The initial approach to parameter estimation was based on a graphical trial and error method. A value of x is chosen from x= 0 to 0.5 and the storage is plotted against $xI_t + (1 - x)O_t$. The graph generated are then compared and the value of x which forms the narrowest loop is considered to be the most correct estimate. A line is marked to fit the loop and the slope of this line gives the value of K. This method requires historical flow data for a storm event. This approach is time consuming and susceptive to human error. Gill (1978) recommended a least square method to find the parameters in Muskingum model. Karahan (2009) developed spreadsheet and other methods to find Muskingum parameter. These methods are flexible and easy to use. Yoon and Padmanabhan (1993) have described the different methods used for parameter estimation. Recent methods have applied techniques such as genetic algorithm (Mohan 1997) and harmony search (Kim et al. 2001) to calibrate the routing parameters. Genetic algorithm approach is efficient in parameter estimation for nonlinear models.

Lag Model

The simple lag model is used in Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) as well as in urban drainage applications (HEC 2000). This model is similar to the lag and attenuation model used in WRAP except that the model does not take into account attenuation. It is important to mention here that the attenuation parameter in most reaches for modeling in WRAP is set to be 1 which means that there is no attenuation. In the Lag Model the downstream hydrographs just get lagged without being attenuated. The lag can be estimated the same way as K of Muskingum can be estimated. Another variation of lag model, called ‘lag and route’, uses a similar procedure except that the flow at the outlet is routed through a computational reservoir to provide attenuation.

Hydraulic Routing

Hydraulic routing is based on the momentum and continuity equations. In hydraulic routing, hydrographs are calculated simultaneously at several locations along the river. Unlike methods of hydrologic routing described above, hydraulic routing takes into consideration the stages at different time and at different flows. Hydraulic modeling is much more complex than hydrologic modeling and requires much more data for computation. The basic theory of hydraulic routing methods comes from complete differential equations of one-dimensional unsteady flow i.e. Saint-Venant equations:

$$S_f = S_O - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t}$$

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

NRCS Empirical Lag Equation for Watersheds

The NRCS National Engineering Handbook contains an empirical equation that is based on watershed parameters and it estimates lag time in the watershed. It is known as National Resources Conservation Service (NRCS) lag time equation. It was developed in 1961 by Mockus. The equation is developed by using the data from 24 small watersheds.

$$L = \frac{l^{0.8}(S+1)^{0.7}}{1{,}900Y^{0.5}}$$

Here l = flow length in feet

Y = average land slope in %

S = maximum potential retention in inches

L = lag time in hours

The equation is developed through regression approach (USDA 2010). It is important to note here that this lag is different from the lag in rivers/channels on which this study is based on. The equation to be developed in this study for lag time in rivers has used a similar empirical approach.

Assumptions & Limitations in Parameter Estimation

Strelkoff (1980) found that the accuracy of models based on flood wave speed are limited by assuming uniform velocity distribution. Attenuation increases with the increasing steepness of flood wave, i.e. steep rise of inflow hydrograph, similarly the attenuation increases for rare large overbank flood events. He also found that propagation speed of flow peaks is nearly same as the wave speed.

Backwater effects of tributary inflows and man-made structures can cause attenuation and lag of flood waves. No hydrologic models can simulate the effect of downstream boundary conditions on channel routing. Hydraulic modeling will be required to achieve this feat.

The assumption made in the lag model and the Muskingum model that the lag time or K remains constant is not valid in the real world. As flow increases the travel time decreases because of less resistance to flow from boundaries, but when flow increases so much that it goes into over bank floodplains, the wave speed decreases because the flow encounters resistance from over banks that usually contain shrubs and vegetation.

The Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) reference manual (HEC 2000) outlines the following conditions for data that should be used in model calibration:

1. The mass of water should be conserved. Lateral inflows should be minimum so that the mass entering the reach and leaving it should be approximately equal.
2. The hydrographs at upstream and downstream should be for the same time period.
3. The size of the events on which calibration is based should be similar to the time for which these parameters are used.

The duration of downstream should be large enough to capture the volume of the upstream hydrograph.

Research Scope and Objectives

The broad objective of this research is to improve routing parameters for TCEQ daily WAMs so as to improve overall daily modeling analyses capabilities of WRAP/WAM. The more detailed objectives of this work are:

- To develop a generalized empirical equation that will calculate the travel time of travel waves.
- To develop two equations through regression for relationships between conveyance factor and normal and high flows.
- To select routing reaches for the selected daily WAMs.
- To estimate lag parameter from the developed equation.
- To specify a methodology to apply DAY program daily flow analysis capabilities on different river basins and to estimate lag and attenuation parameters using that methodology.
- To compare the results from different methods and suggest the best method for use in daily WAMs.

The travel time equation is motivated by the Manning's equation and the corresponding two relationship equations (one for normal flows and the other for high flows) are developed through regression of multiple data points.

The scope of the study focuses on routing parameters for the lag and attenuation method of routing implemented in the WRAP daily simulation model SIMD.

CHAPTER II

ROUTING AND FORECASTING IN WRAP SIMULATION MODEL

As discussed earlier, in the real world, the effects of reservoir operations and other water management and use actions usually propagate through a river/reservoir system to downstream locations of interest in water availability modeling over periods ranging from several hours to several days. Thus, this could diminish the flows for downstream users in future days. Thus, in the daily model, everything cannot be assumed to be happening within the same computational time step as in a monthly model. Prior upstream events affect water supply capabilities for downstream users. Likewise, SIMD flood control operations also affect channel flood flow capacities in future days. Flood control operations are performed keeping in mind that the flow released from a reservoir should not cause flows at downstream locations, located some days of travel time below the dam, to reach damaging levels.

To include these real-world effects in modeling, routing and forecasting is introduced in the daily WRAP. The monthly model does not have these features as it is not possible and somewhat insignificant to transfer impacts of one month to the next month because the model does not know the distribution of flows within a month.

In both daily and monthly models, a water rights priority based computation loop is nested within a period based computational loop. The computations progress through time. In each time step, calculations are made for each water right (set of water control and use requirements) based on the priority date assigned to it. The following operations are carried out for each water right requirements within SIM and in SIMD (along with routing and forecasting). Flow forecasting in SIMD is performed in combination with the first task given below while routing is performed in combination with the 1st and 4th task. These tasks are taken from the WRAP Daily Modeling Manual (Wurbs and Hoffpauir 2015):

“1. The amount of water available to that water right is determined as the minimum of available stream flows at the control point of the water right and at control points located downstream. In the SIMD simulation of flood control operations, the amount of channel flood flow capacity below maximum allowable (non-damaging) limits is determined at all pertinent control points.

2. The water supply diversion target, hydroelectric power generation target, minimum instream flow limit, or non-damaging flood flow limit is set.

3. Decisions regarding reservoir storage and releases, water supply diversions, and other water management/use actions are made; net evaporation volumes are determined, and water balance accounting computations are performed.

4. The stream flow array used to determine water availability and remaining flood control channel capacity at all downstream control points is adjusted for the effects of the water management actions."

It is not only that the water use decisions today affect future water use but the decisions are themselves affected by future flow conditions in rivers. Forecasting addresses this issue, it considers future flow conditions while making today's decisions. Task 1, the very first task determines the available water for that water right by considering downstream water availability. The available water is that quantity of water which after withdrawal does not adversely affect the water rights that are senior to this water right. In SIM this task requires consideration of water availability at control points located downstream alone but with flow forecasting capabilities of SIMD, the computational algorithms also look a certain number of days, the forecast period, into the future in determining water availability and/or remaining flood flow capacities. The flow forecasting feature allows two simulations in each time step so as to consider the future stream flows before making today's diversion and flood control decisions.

Routing is performed in task 4 mentioned above where the flows at downstream control points are adjusted for withdrawal, return flows, and reservoir management decisions occurring upstream. Routing allows the computations to consider the delay in effects happening at downstream due to travel time. This time can vary from less than a day for shorter reaches to many days for longer reaches. Reverse routing occurs in combination with task 1.

Routing Methods in SIMD

Most watershed and river system models route total flow hydrographs. Conversely, the WRAP SIMD simulation model routes changes in flows caused by return flows, reservoir releases, and streamflow depletions for filling reservoir storage and supplying diversion targets. Hydraulic (dynamic) routing as implemented in the Hydrologic Engineering Center River Analysis System (HEC-RAS) and other hydraulic models with a computational time step of typically less than an hour is not practical for a daily water accounting model like WRAP. Any of the hydrologic routing methods, such as Muskingum, reported in the literature are necessarily approximate for various reasons including having lag parameters that are constant for all flows even though high flows typically have much faster travel times than low flows.

SIMD has two alternative routing methods: (1) the Muskingum method and (2) the lag and attenuation method. The initial versions of SIMD included only the Muskingum method which was developed by the United States Army Corps of Engineers (USACE) for flood control studies decades ago and is included in many hydrology books. Computational instabilities and other issues with applying Muskingum routing in daily SIMD simulations led to the creation of the SIMD lag and attenuation method specifically for SIMD. The lag and attenuation method is the recommended standard default and is applied in all six of the daily WAMs. Improved methods for calibration of the lag and attenuation parameters is a significant issue in this research.

Other generalized models of river/reservoir system management adopt the following routing procedures (Wurbs 2012; Zagona et al. 2001)

Table 2.1: Routing Methods Used in Different River/Reservoir System Management Models

Model Name	Descriptive Name	Methods of Routing Used
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation	Muskingum, Muskingum-Cunge, Modified Puls
RiverWare	River and Reservoir Operations	Time Lag, Muskingum, Muskingum-Cunge, MacCormack, Kinematic Wave, Storage Routing
MODSIM	River Basin Management Decision Support System	Lag flow

Routing Parameters

SIMD has input options to enter two different sets of routing parameters, one for normal flow operations and one for flood control operations. Stream flow depletions or returns due to the WR records (the normal flow operations) are performed under conditions of moderate to low flows, hence the changes are routed using the normal flow routing parameters. Stream flow depletions or returns due to the FR records (the flood control operations) are performed during high flows, hence the associated changes are routed using the high flow routing parameters. The lag time for higher flows is generally lower than that for moderate or low flows.

The lag and attenuation method of routing requires two parameters for each reach. Reach is the segment of river between an upstream control point and a downstream control point. The lag parameter is the time it takes for effects of flow changes to arrive at the downstream point. It can be roughly related to Muskingum K. The attenuation parameter between two points is related to dispersion of flow change over time. The attenuation parameter cannot be less than 1.0 day and for most of the routing reaches it is set at 1.0 day in the current WAMs. Judgment is applied to select river reaches for which routing is applied.

One of the following set of routing parameters is inputted to SIMD via DCF files and on RT records for each reach of interest based on the method of routing that is being used:

- LAG and ATT for normal operations and LAGF and ATTF for flood operations for use in the SIMD lag and attenuation routing method.
- MK and MX for normal operations and MKF and MXF for flood operations for use in the SIMD adaptation of the Muskingum routing method.

Original Method of Calibrating Routing Parameters

The current set of routing parameters used in all six daily WAMs come from calibration studies based on hydrographs of either gaged or naturalized streamflows at upstream and downstream control points. The original WRAP program DAY has the capability to calibrate routing parameters based on replicating the entire hydrographs that optimize a specified objective function using a genetic algorithm.

In program DAY, the user provides calibration strategies based on objective functions, and the program comes up with a set of routing parameters after performing calibration of routing parameters. The output file also contains a table having related input and computational results. The DAY program is documented in the Daily Manual of WRAP.

The calibration routine of the DAY program uses optimization technique of genetic search algorithm. It tries to find the values of best routing parameters by doing iterative simulations. The user can control the selection of best routing parameters by specifying objective functions that minimize deviations between computed and known downstream hydrographs.

The five objective functions are:

1. Objective function 1 is to minimize the root mean square error.
2. Objective function 2 is to minimize the absolute mean error.
3. Objective function 3 is to minimize the mean absolute error in daily lateral inflow volume.
4. Objective function 4 is based on minimizing the weighted average of objective function 1 and 3.
5. Objective function 5 is based on minimizing the weighted average of objective function 2 and 3.

The results of the calibration are presented in an output file as the optimized routing parameters and the values of the corresponding objective functions.

Issues with Routing Parameters through Replication of Hydrographs

Some of the issues with the current set of routing parameters used in all six daily WAMs that motivated this research are listed here:

1. Routing is closely connected to disaggregation of monthly flows to daily. Calibration of routing parameters is based on the daily naturalized flows. Therefore, a consistency in pattern and timing (lag) of the daily flows at the upstream and downstream ends of a routing reach must be achieved in order to have meaningful values for the routing parameters. This can be a problem

particularly if daily flow hydrographs at different control points are derived from different sources.

2. Parameter calibration is complicated by flow gains and losses between the upstream and the downstream ends of the routing reach. Channel losses include seepage, evapotranspiration, and unaccounted diversions. Precipitation runoff from local incremental watersheds as well as subsurface flows may enter the river along the routing reach. The same control point may be the downstream limit of two or more tributary streams. Multiple tributaries may enter the river reach at various locations between its upstream and downstream ends. Calibration is more accurate for river reaches with minimal change in volume between the upstream and downstream ends.
3. There are two routing parameters which calibration routine calculates through one objective function. It is possible that the DAY program gives acceptable values of objective function but the routing parameters are far from true. This can happen if errors in both parameters cancel out each other’s effect in objective function calculation.

CHAPTER III

WAVE TRAVEL VELOCITY EQUATION

The National Resources Conservation Service (NRCS) has developed an empirical equation to estimate lag time in a watershed. The equation is discussed in the literature review in Chapter I. The NRCS equation provides the concept for developing an empirical equation, called wave travel velocity equation, to calculate lag times in river reaches. The objectives of the work documented in this chapter are:

- To develop a generalized empirical equation that will calculate the travel time of flood waves based on reach parameters.
- To develop two equations through regression for relationships between a conveyance factor (used in the above equation) and the normal and high flows.

The theoretical basis of travel time equation will be the Manning's equation. The corresponding two relationship equations (one for normal flows and the other for high flows) required to relate travel velocity with reach parameters will be developed through regression of multiple data points.

Theoretical Basis of Travel Time Equation

Manning's Equation is one of the most frequently used and well-established equation of hydraulics. It relates average velocity with roughness coefficient, hydraulic radius, and slope.

$$V = \frac{1}{n} R^{\frac{2}{3}} \sqrt{S}$$

Based on the same principle, travel velocity of a wave (V_T) for a river reach is estimated with the following equation as a function of conveyance factor (K) and slope (S) of water surface profile.

$$V_T = K\sqrt{S} \qquad \text{……… 3.1}$$

The conveyance factor (K) is analogous to conveyance in Manning's equation and roughly accounts for roughness, hydraulic radius, and other flow conditions. Eq 3.1 can be rewritten as

$$V_T = \frac{L}{T} = K\sqrt{S}$$

$$T = \frac{L}{K\sqrt{S}} \qquad \ldots\ldots\ldots \; 3.2$$

Where T is the time required for flow wave to travel the whole reach and L is the length of the reach.

Data Collection

Calculation of travel time from Eq. 3.2 requires length of the reach (L), slope (S), and conveyance factor (K). Conveyance factor (K) approximately accounts for the conditions of flow in the river. Though conditions of flow in the river are dependent on several things, the amount of water flowing per unit time (Q) is the most important factor. It is assumed that conveyance factor (K) is loosely related to flow (Q) and if an approximate relationship is found between these two, for normal and high flow conditions, K can be found out for all reaches based on the historical normal and high flows in the reach.

To develop relationships between conveyance factor and flow, for normal and high flow conditions, reliable observed or modeled datasets of travel time in different reaches were required.

Normal Flow Dataset

Normal flow datasets were obtained from the Brazos River Authority (BRA) Water Management Plan. The travel time values are based on historical observations and were last updated in 2011. These are the best estimates that BRA has with regards to travel times for normal flow conditions, such as would be expected when BRA would be making reservoir water supply releases for its downstream water supply customers. Table 3.1 contains the Brazos River Authority dataset for normal flows.

Table 3.1: Brazos River Authority Dataset for Travel Times under Normal Flow Conditions

From	To	L (miles)	T (days)	Velocity (miles/day)
Possum Kingdom	Palo Pinto Gage	20.20	0.51	39.61
Palo Pinto Gage	Dennis Gage	77.50	1.96	39.54
Dennis Gage	Lake Granbury	47.30	1.53	30.92
Lake Granbury	Glen Rose Gage	31.20	1.70	18.35
Glen Rose Gage	Lake Whitney	68.90	4.30	16.02
Lake Whitney	Aquilla Creek/Brazos Confluence	25.30	0.56	45.18
Lake Aquilla	Aquilla Creek gage	5.00	0.12	41.67
Aquilla Creek gage	Aquilla creek / Brazos Confluence	18.20	0.44	41.36
Aquilla creek / Brazos Confluence	Waco gage	16.90	0.44	38.41
Waco gage	Highbank gage	53.60	1.39	38.56
Lake Proctor	Leon River at Gates Ville gage	129.10	4.27	30.23
Leon River at Gates Ville gage	Lake Belton	82.30	2.73	30.15
Lake Belton	Leon River at Belton Gage	3.50	0.19	18.42
Leon River near Belton Gage	Little River Gage	19.10	0.91	20.99
Lake Stillhouse Hollow Dam	Lampasas River near Belton gage	3.00	0.14	21.43
Lampasas River near Belton gage	Little River gage	18.90	0.95	19.89
Little River gage	Little /San Gabriel Confluence	51.50	1.72	29.94
Lake Georgetown	N San Gabriel Gage	1.00	0.03	33.33
N San Gabriel Gage	Lake Granger	35.50	0.97	36.60
Lake Granger	Laneport Gage	5.00	0.13	38.46
Laneport Gage	Little /San Gabriel Confluence	26.20	0.68	38.53
Little /San Gabriel Confluence	Little River at Cameron Gage	10.70	0.36	29.72

Table 3.1: Continued

From	To	L (miles)	T (days)	Velocity (miles/day)
Little River at Cameron Gage	Brazos /Little Confluence	33.60	1.12	30.00
Highbank gage	Brazos /Little Confluence	34.60	0.90	38.44
Brazos /Little Confluence	Bryan gage	30.90	0.80	38.63
Bryan gage	Brazos/Yegua Confluence	38.10	0.99	38.48
Lake Somerville	Yegua gage	1.30	0.07	18.57
Yegua gage	Brazos/Yegua Confluence	18.80	1.01	18.61
Brazos/Yegua Confluence	Brazos/Navasota Confluence	16.60	0.43	38.60
Lake Limestone	Easterly gage	25.80	1.21	21.32
Easterly gage	Brazos/Navasota Confluence	105.70	5.31	19.91
Brazos/Navasota Confluence	Hempstead gage	33.40	0.87	38.39
Hempstead gage	Richmond Gage	101.00	2.62	38.55
Richmond Gage	Rosharon Gage	35.30	0.92	38.37
Rosharon Gage	The Gulf of Mexico	-	-	-

Some normal flow travel times for the lower Colorado River were also taken from the Lower Colorado River Authority (LCRA) website. However, no other similar observed travel time data were found in the published literature.

High Flow Datasets

High flow datasets of travel time in different river basins of Texas were obtained from the West Gulf River Forecast Center. These travel time estimates use the maximum lag value from a National Weather Service (NWS) watershed modeling system for each reach of interest. These are modeled estimates, not the observed lag times.

Length of the Reaches

Length is one of the input parameters of the Eq. 3.2. The normal flow dataset from BRA had the lengths of the reaches. For all the other data sets length of each reach of interest was calculated from flowlines in the GIS files of TCEQ WAM website. The lengths of the river reach can vary with time and with the amount of flow. The flowlines are based on river paths for a particular snapshot in time. All lengths for the rivers in this study will be measured in miles.

Water Surface Elevations for Slope Calculation

Another input for equation development is the slope. The slope is calculated as the difference in elevation of water surfaces (median value for normal flows and 10% exceedance probability value for high flows) divided by the length of the reach. In the case of the lake as the upstream or downstream end, water surface elevations were taken from USGS historical data records for lakes. In the case of a gage as the upstream or downstream end of the reach, USGS gage height data were combined with the datum of the gage to get the water surface elevations. Where there is no gage at the upstream or downstream end or the end is a confluence, the nearest gaging station is used for that end and the slope is adjusted accordingly.

Flow

The discharge was collected for each gaging station of interest from USGS historical data records. The median discharge was used for normal flows and 10% exceedance probability discharge was used for high flows. Discharge of a reach is the average discharge of upstream and downstream ends. If one end comprised of a lake or confluence, discharge of that end is ignored. The unit of discharge is cfs throughout the calculations.

K vs Q Relationship Equation through Regression

Conveyance factor (K) is loosely related to flow (Q) through a non-linear relationship built on the basis of regression. If we know the flow we can find K through this relationship.

Normal Flow Equation

Normal flow K vs Q relationship is derived using normal flow data sets. K is found for each reach using Eq. 3.2. Length, slope and travel time of each reach is entered into Eq. 3.2 to find conveyance factor of that reach. All conveyance factors were plotted against the corresponding average median flow in the reach. Least square regression method is applied to find the best fit curve. A spreadsheet of detailed calculations is attached in Appendix A. Figure 3.1 shows the plotted points and the best fit curve and its equation. The equation comes out to be

$$K = 353.24 \cdot Q^{0.278}$$

Where Q is in cfs and the unit of K is mile/day. The R^2 value for the fit is 0.475. This generic equation can now be used to approximate conveyance factor for any reach for which we have average median flow.

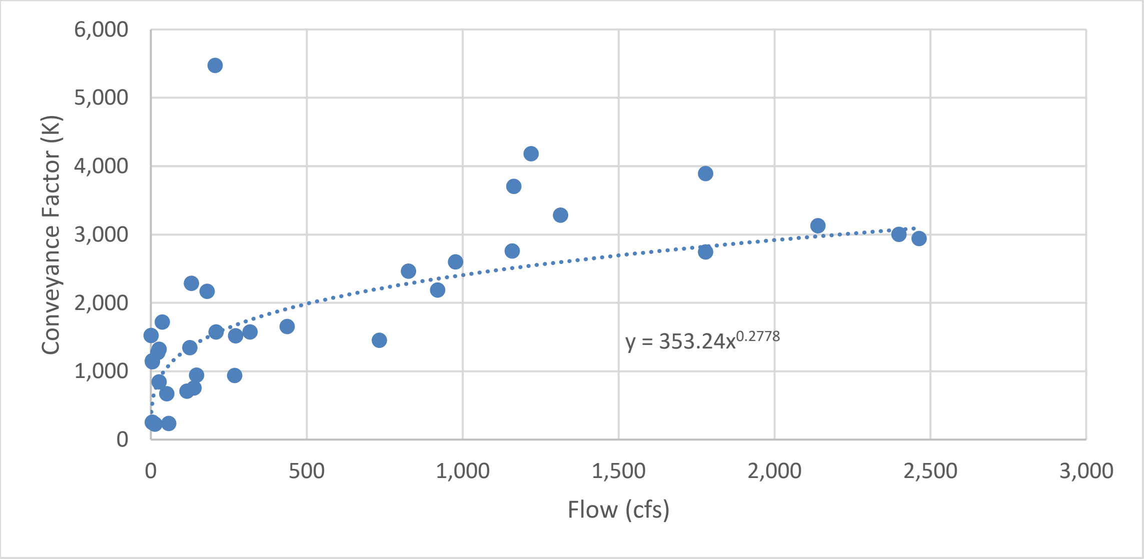

Figure 3.1: Plot of K vs Q for Normal Flow Conditions in Brazos and Lower Colorado Basin

High Flow Equation

The high flow equation is derived from the NWS West Gulf River Forecasting Center travel time estimates. Only three river basins, Brazos, Colorado, and Trinity, were used to prepare this equation but other river basins can also be used in the future to further improve the equation. The higher number of data points yields a better relationship between flow and conveyance factor (K). K is found with the same procedure as followed in the normal flow equation. Length, slope and travel time of each reach is entered into Eq. 3.2 to find the conveyance factor of that reach. All conveyance factors were plotted against corresponding average 10% exceedance probability flow in the reach. Regression method is applied to find the best fit curve. A spreadsheet of detailed calculation for Brazos River basin is attached in Appendix B, similar spreadsheets were prepared for other basins. Figure 3.2 shows the plotted points and the best fit curve and its equation. The equation comes out to be

$$K = 656.84 \cdot Q^{0.148}$$

Where Q is in cfs and the unit of K is mile/day. The R^2 value for the fit is 0.288. This generic equation now can be used to approximate a high flow conveyance factor for any reach for which we have average 10% exceedance probability flow.

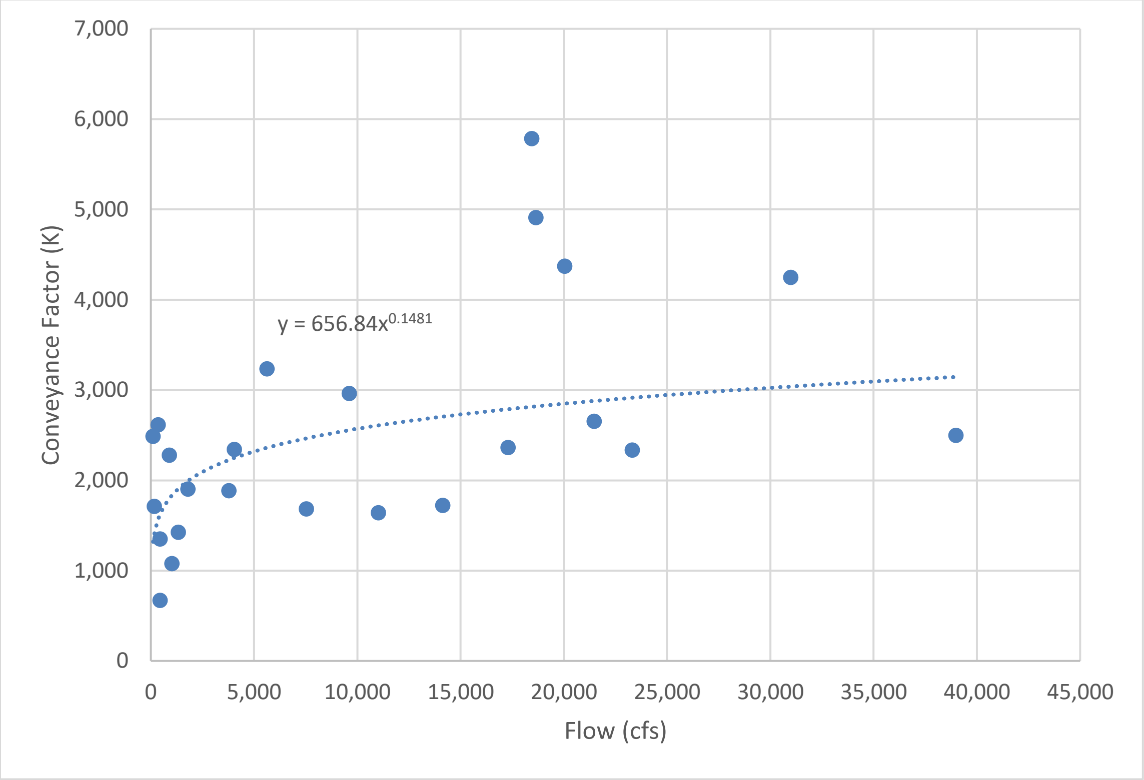

Figure 3.2: Plot of K vs Q for High Flow Conditions in Brazos, Colorado, and Trinity River Basins

Application of Wave Travel Velocity Equation

Brazos River Basin

As a pilot study, the lag parameters for the Brazos River Basin was found using the new method for the same reaches as in the existing WRAP simulation DCF file. For these reaches using median flow value, the relative conveyance factor was found. The conveyance factor, length, and slope were then entered into Eq. 3.2 to find the respective lag times. The results are compared with the old parameters found using the calibration technique. The travel time from the Wave Travel Velocity Equation is generally significantly higher than the calibrated lag parameter. Chapter V of this report will compare the results of this method with other methods described in this report. Appendices C & D document the detailed calculations for the application of normal flow and high flow wave travel velocity equations.

Table 3.2: Application of Wave Travel Velocity Equation on the Brazos River Basin

U/S Control Point WAM ID	D/S Control Point WAM ID	Length	Slope	Avg Flow	K (Normal Flows)	Normal Flows Lag from Equation	High Flows Lag from Equation
		miles		cfs	mile/day	days	days
DMAS0E	BRSE1E	115	0.0006	24	854	5.38	2.69
SFAS0E	BRSE1E	108	0.0006	23	841	5.17	2.63
CFNU1E	CFFG1E	96	0.0007	16	768	4.71	2.53
CFFG1E	BRSB2E	77	0.0004	65	1097	3.44	1.83
BRSE1E	BRSB2E	97	0.0005	74	1134	4.01	2.13
BRSB23	51553R	66	0.0000	108	1249	9.32	5.16
51553R	BRDE29	101	0.0003	158	1375	4.12	2.40
BRDE29	515631	46	0.0001	208	1475	5.45	2.82
51563R	BRGR30	32	0.0004	148	1352	1.14	0.65
BRGR3E	515731	65	0.0001	273	1581	3.79	2.29
51573R	CON070	28	0.0002	535	1875	1.08	0.64
51583R	AQAQ34	-	-	3	504	not applicable	not applicable
AQAQ34	CON070	19	0.0010	2	435	1.37	0.49
227901	NBCL36	22	0.0012	23	843	0.75	0.38
NBCL3E	509431	40	0.0007	23	843	1.80	0.91
50943R	BRWA41	10	0.0004	371	1709	0.31	0.18
CON070	BRWA41	16	0.0005	735	2033	0.37	0.24
BRWA4E	BRHB42	60	0.0002	829	2096	1.94	1.18
51593R	LEGT47	120	0.0006	23	843	5.72	2.60
LEGT4E	516031	77	0.0003	37	951	4.47	2.09
51613R	CON095	15	0.0008	14	743	0.71	0.25
CON095	LRLR53	7	0.0055	221	1498	0.06	0.04
51603R	LRLR53	23	0.0008	140	1333	0.60	0.30
51623R	GAGE56	5	0.0030	19	802	0.11	0.06
SGGE55	GAGE56	3	0.0028	21	823	0.07	0.04
GAGE56	516331	28	0.0010	32	916	0.99	0.57
51633R	CON102	26	0.0008	52	1037	0.87	0.44
CON102	LRCA58	16	0.0006	439	1783	0.37	0.22
LRLR5E	LRCA58	62	0.0004	330	1659	1.96	1.03
LRCA5E	BRBR59	67	0.0002	1110	2258	1.88	1.09
BRHB42	BRBR59	68	0.0002	1352	2374	1.85	1.14
51653R	NAEA66	17	0.0029	27	878	0.36	0.15
NAEA6E	CON137	14	0.0002	27	878	1.04	0.36

Table 3.2: Continued

U/S Control Point WAM ID	D/S Control Point WAM ID	Length	Slope	Avg Flow	K (Normal Flows)	Normal Flows Lag from Equation	High Flows Lag from Equation
		miles		cfs	mile/day	days	days
CON137	NABR67	20	0.0003	54	1047	1.14	0.49
NABR67	CON145	39	0.0002	54	1047	2.50	1.00
CON145	CON231	21	-	-	-	not applicable	not applicable
51643R	CON129	14	0.0004	6	594	1.25	0.34
BRBR5E	CON147	56	0.0002	1780	2546	1.72	1.04
CON129	CON147	23	-	-	-	not applicable	not applicable
CON231	CON147	6	-	-	-	not applicable	not applicable
CON147	BRHE68	32	0.0002	2410	2750	0.80	0.48
BRHE6E	BRRI70	105	0.0001	2158	2673	3.25	1.88
BRRI7E	BRRO72	38	0.0002	2488	2772	1.09	0.70
BRRO7E	OUT	0	-	3070	2924	not applicable	not applicable

Neches River Basin

Using the same methodology as discussed above, the wave travel velocity equation was applied on selected reaches of Neches River Basin. It is important to note here that most of the data used to drive the equations were from the Brazos River basin, hence the most accurate results are that of Brazos River Basin only. More accurate results for other river basins can be obtained by incorporating data points from other basins in the derivation of the equation or by having a different set of equations for each river basin.

Table 3.3: Application of Wave Travel Velocity Equation on Neches River Basin

U/S Control Point WAM ID	D/S Control Point WAM ID	Length	Slope	Avg. Flow	K	Normal Flows Lag from Equation
		miles		cfs	mile/day	days
NENE	NEAL	61	0.0244	370	1707	2.29
NEAL	NEDI	75	0.0166	563	1900	3.07
NEDI	NERO	47	0.0132	750	2044	2.00
NETB	NEEV	53	0.0176	3105	2933	1.36
ANAL	ANLU	41	0.0212	367	1703	1.65
VIKO	NEBA	37	0.0134	1817	2559	1.25
PISL	NEBA	31	0.0060	1690	2512	1.59

CHAPTER IV

DEVELOPMENT OF NEW ROUTING PARAMETERS

DFLOW Method

A new WRAP program called DFLOW (daily flow) was developed at Texas A&M University with capabilities for analyzing flow time series, computing lag and attenuation and performing statistical analysis. DFLOW reads input files of observed, naturalized, or simulated daily stream flows, performs statistical, lag/attenuation, and other analyses using these datasets, and creates output files containing datasets of daily stream flows and the results of the various computations. Lag and attenuation analysis to support estimation of SIMD routing parameters is a primary motivation for supplementing the original program DAY with the new DFLOW. To perform lag and attenuation analysis, the program is provided an input file with upstream and downstream hydrographs of observed flows. The program calculates flow changes both upstream and downstream and then relates flow change events in terms of lag and attenuation. The program has multiple options to limit the calculations to specific flow change events. This is to get tailored results for routing parameter for different purposes. Using these options, the final analysis can be filtered to ignore the lag values that are because of the natural rain events or that are based on extreme flow events. This chapter discusses the utilization of these resources to estimate routing parameters for different reaches of different river reaches.

General Methodology for Application of DFLOW

The DFLOW program can be used to estimate lag and attenuation for selected stream reaches in any river basin using the following general approach. There must be daily gauged data available for application of DFLOW. Ideally the DFLOW approach can only be applied on a reach if there is no reservoir and confluence between the upstream and downstream ends of the reach, different techniques can be used to avoid these problems. A reservoir in the reach would suppress the traveling wave, hence there would be no effect on downstream flows because of upstream flow changes. High lateral flows or confluences can distort the correlation between upstream and downstream flows.

The general methodology adopted in this research is as follows:

1. Routing reaches were selected for which DFLOW analysis is to be performed in a particular basin.
2. Daily gauged streamflow data was downloaded from the U.S. Geological Survey (USGS) National Water Information System (NWIS) website either directly or using HEC-DSSVue for upstream and downstream points of these reaches.
3. A check was performed for missing data in USGS records, only periods of time where there is no large missing data were adopted for analysis. Few odd missing values were estimated using different techniques including the built-in option of DSSVue.
4. Simple DFLOW calculations were performed to analyze the correlation between upstream and downstream flows, 90th percentile values of flows and median flows.
5. For reaches that have reservoir or confluences, the following techniques were used to determine values for the routing parameters:
    i. Lags from upstream and downstream reaches were used for the parts of reaches upstream and downstream of the confluence or reservoir.
    ii. For the reach having a reservoir, the data before the construction of the dam was used.
    iii. For reaches having confluences, DFLOW was used if there is a high correlation between upstream and downstream flows.
    iv. Lag/mile value was used from similar reaches if the physical and flow characteristics of the reaches are similar.
6. A lag parameter (LP record) option in DFLOW was used to separate flood flows from normal flow calculations and to remove rain events that contribute lateral flows and low flow changes that might be destabilizing for the calculations.

Application of DFLOW Program on Three Daily WAMs

Neches River Basin

The Neches River Basin, as shown in Figure 4.1, is in East Texas and drains into Sabine Lake which drains into the Gulf of Mexico. The northern and eastern sides of the basin are bounded by the Sabine River Basin, and the western and southern sides are bounded by the Trinity River Basin and Neches-Trinity coastal basin respectively. The Neches River Basin has a drainage area of about 10,000 square miles of which about one-third is drained by the Angelina River and two-thirds by the Neches River, Pine Island Bayou, and Village Creek. The basin has a length of about 200 miles. The 2010 population of the Neches River Basin of about 802,000 is projected by the Texas Water Development Board to increase by 34% by the year 2030. The mean annual precipitation is about 49 inches/year (Wurbs et al. 2014).

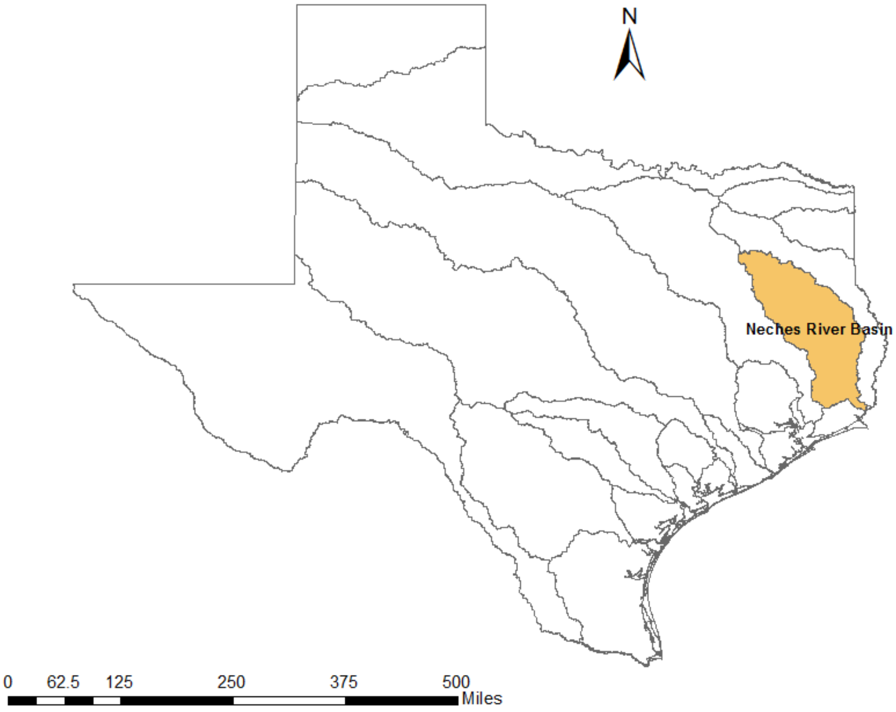

Figure 4.1: Neches River Basin Located in Texas

There are 20 primary control points in the Neches water availability model (WAM) of the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System. Together these 20 control points make 19 river reaches. Figure 4.2 shows these reaches and the average slope between the upstream and the downstream point. There are 11 reservoirs within the basins with a capacity of more than 5,000 acre-feet. Sam Rayburn Reservoir is the largest accounting for 75.2 percent of the total conservation storage capacity (Wurbs et al. 2014).

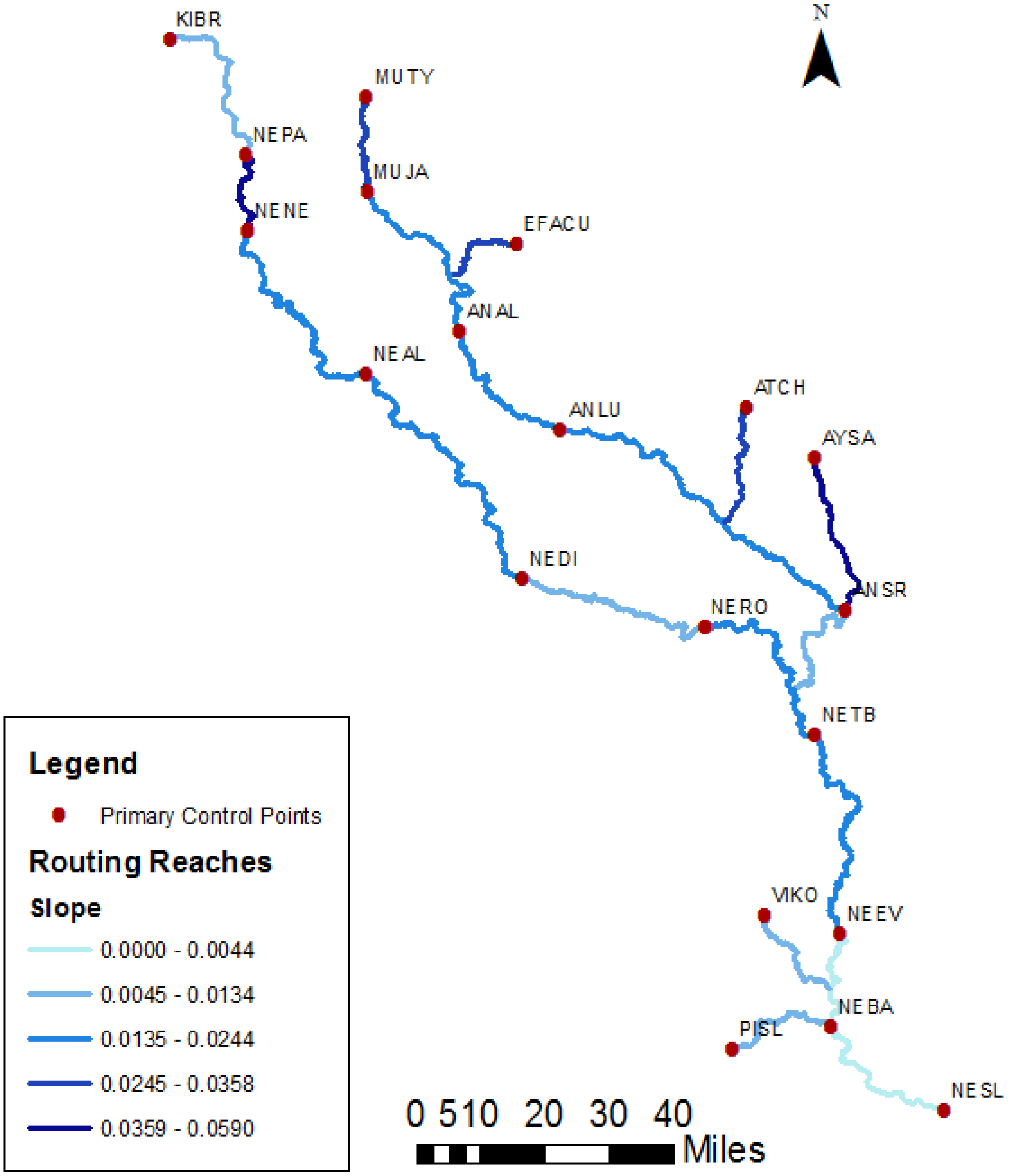

Figure 4.2: Neches Primary Control Points and the Reaches Formed by Them

DFLOW Methodology for Neches Basin

River segments between all primary control points are selected to apply DFLOW (Figure 4.2). Each reach's lag and attenuation were calculated either using DFLOW or using lag/mile from another similar reach or reaches. The following criteria were developed to perform analysis for the Neches River Basin.

1. For the reaches with a confluence, DFLOW was used between upstream and downstream control points only if there is a correlation of 0.5 or more between the flows at two points.
2. LP record options activated in the DFLOW input file were used to refine results. The following criteria were used to exclude or modify lags:
    - i. Flows below the 90th percentile were used. Lags for days having flow above the 90th percentile was not used in the final calculation.
    - ii. Flows less than 100 cfs were not used. Lags for days having flow less than 100 cfs were ignored in the final calculation.
    - iii. Flow events with less than 30 cfs change were also ignored.
    - iv. If there is a change of 50% or more (compared to the change at upstream) at a downstream control point on the same day as upstream peak day, then those days were also ignored in the final calculation. This criterion eliminates flow change event due to precipitation.
3. Minimum lag for each reach was assigned based on 0.01 day/mile criterion. In the computations, if between upstream and downstream flow change events, lag is less than (0.01 x length of reach), the calculation will shift to the next downstream flow change event.
4. All calculations for normal flow routing parameters were performed based on flow decreases. This is because for low and normal flows in WAMs we are more concerned with the effect of withdrawals on flow propagations.
5. All calculations for high flow routing parameters were performed based on flow increases. This is because for high flows/flood control operations in WAMs we are more concerned with the effect of increase in the volume on flow propagations.

Discussion on Selected Stream Reaches

Consider upstream points VIKO, PISL, and NEEV, each of these control points have NEBA as a downstream control point. DFLOW was used between NEEV and NEBA because there is a high correlation between flows at these two control points. The other two upstream control points are not major contributors of flow to the downstream control point and hence do not have a high correlation with the downstream control point. Therefore, DFLOW is not used directly for these two reaches (Figure 4.3).

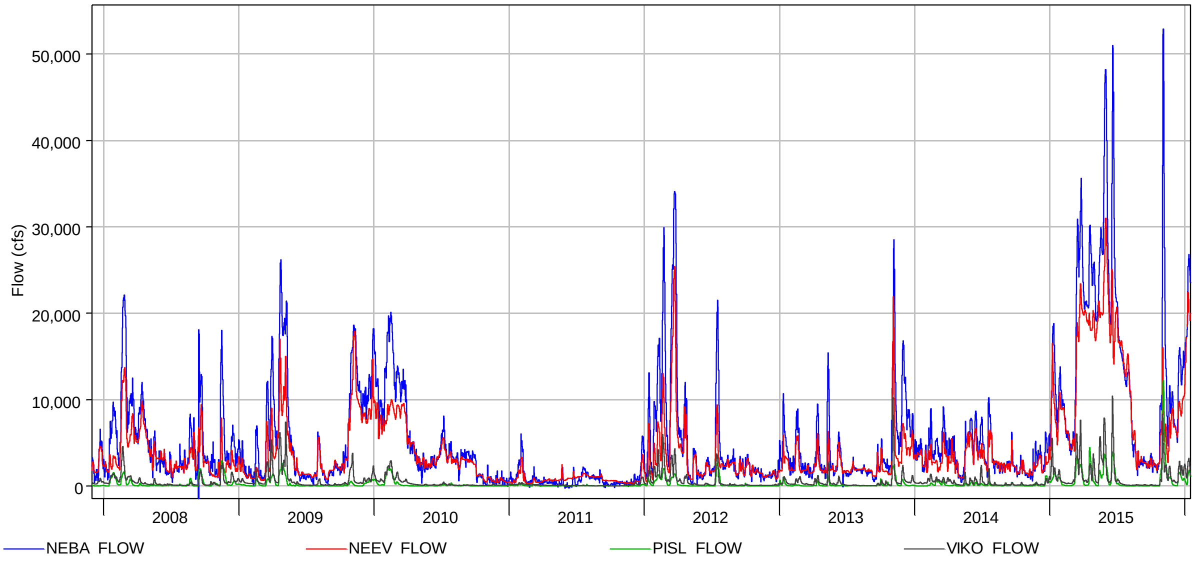

Figure 4.3: USGS Gauged Flows at Upstream Control Points VIKO, PISL, & NEEV and Downstream Control Point NEBA

In Figure 4.2, the NERO to NETB stream reach has a major confluence that is affecting the correlation between upstream and downstream flows. To deal with this issue in this and other streams, for the part of the reach before the confluence, the lag/mile value from the previous stream reach (NEDI to NERO) was used and for the part of reach that is after the confluence the lag/mile value from the next stream reach (NETB to NEEV) is used.

For the reach from PISL to NEBA, DFLOW analysis could not be performed because the upstream control point does not have USGS daily streamflow records, so a control point in between these two points is used to perform DFLOW analysis on this pseudo reach. The lag from this analysis is then projected to the remaining part of the upstream. A similar method was used for reach between ANLU and ANSR.

High flow computation for the pseudo reach of PISL to NEBA reach had only three flow change events for lag computation and the resulting lag was unusually high (10.97 days for a 22-mile-long reach), therefore normal flow lag is adopted for high flows as well.

Appendix E contains information about analysis on all the 19 reaches of Neches River Basin, resulting and adopted routing parameters, and the method adopted for each river reach.

Results

Results of the DFLOW approach applied to the Neches river system are shown in Table 4.1. Results for some of the reaches were modified for different reasons. The results show that DFLOW lag is generally decreasing with increasing flow which is justifiable because low flows encounter more resistance to flow because of the small hydraulic radius. High flow lag time was higher for some reaches and lower for other, the higher lag time for high flows may have been because of high flow extending into overbanks and having to overcome more resistance from the flat overbanks and vegetation.

Table 4.1: Lag and Attenuation from DFLOW for Neches River Basin

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
KIBR	NEPA	31	2.06	1.00	0.067	2.14	1.00	0.069
NEPA	NENE	20	1.33	1.00	0.067	1.38	1.00	0.069
NENE	NEAL	61	4.07	1.00	0.067	4.22	1.00	0.069
NEAL	NEDI	75	4.04	1.00	0.054	5.07	1.00	0.068
NEDI	NERO	47	3.00	1.00	0.064	4.23	1.00	0.090
NERO	NETB	45	2.52	1.00	0.056	3.61	1.00	0.080
NETB	NEEV	53	1.96	1.00	0.037	3.00	1.00	0.057
NEEV	NEBA	25	1.14	1.00	0.046	2.13	1.00	0.085
NEBA	NESL	28	1.03	1.00	0.037	1.58	1.00	0.057
MUTY	MUJA	26	2.72	1.00	0.105	1.56	1.00	0.060
MUJA	ANAL	47	4.93	1.00	0.105	2.82	1.00	0.060
ANAL	ANLU	41	2.55	1.00	0.062	3.65	1.00	0.089
ANLU	ANSR	83	5.50	1.00	0.066	4.35	1.00	0.052
ANSR	NETB	38	2.14	1.00	0.056	2.04	1.00	0.054
EFACU	ANAL	44	4.61	1.00	0.105	2.64	1.00	0.060
ATCH	ANSR	64	6.71	1.00	0.105	3.84	1.00	0.060
AYSA	ANSR	35	3.67	1.00	0.105	2.1	1.00	0.060
VIKO	NEBA	37	2.61	1.00	0.071	3.01	1.00	0.081
PISL	NEBA	31	2.48	1.00	0.080	2.48	1.00	0.080

Lag/mile value converts the extensive lag value to intensive lag/mile value. These values for each stream is plotted in Figure 4.4 to show how lag/mile is generally decreasing gradually from upstream reaches to downstream reaches.

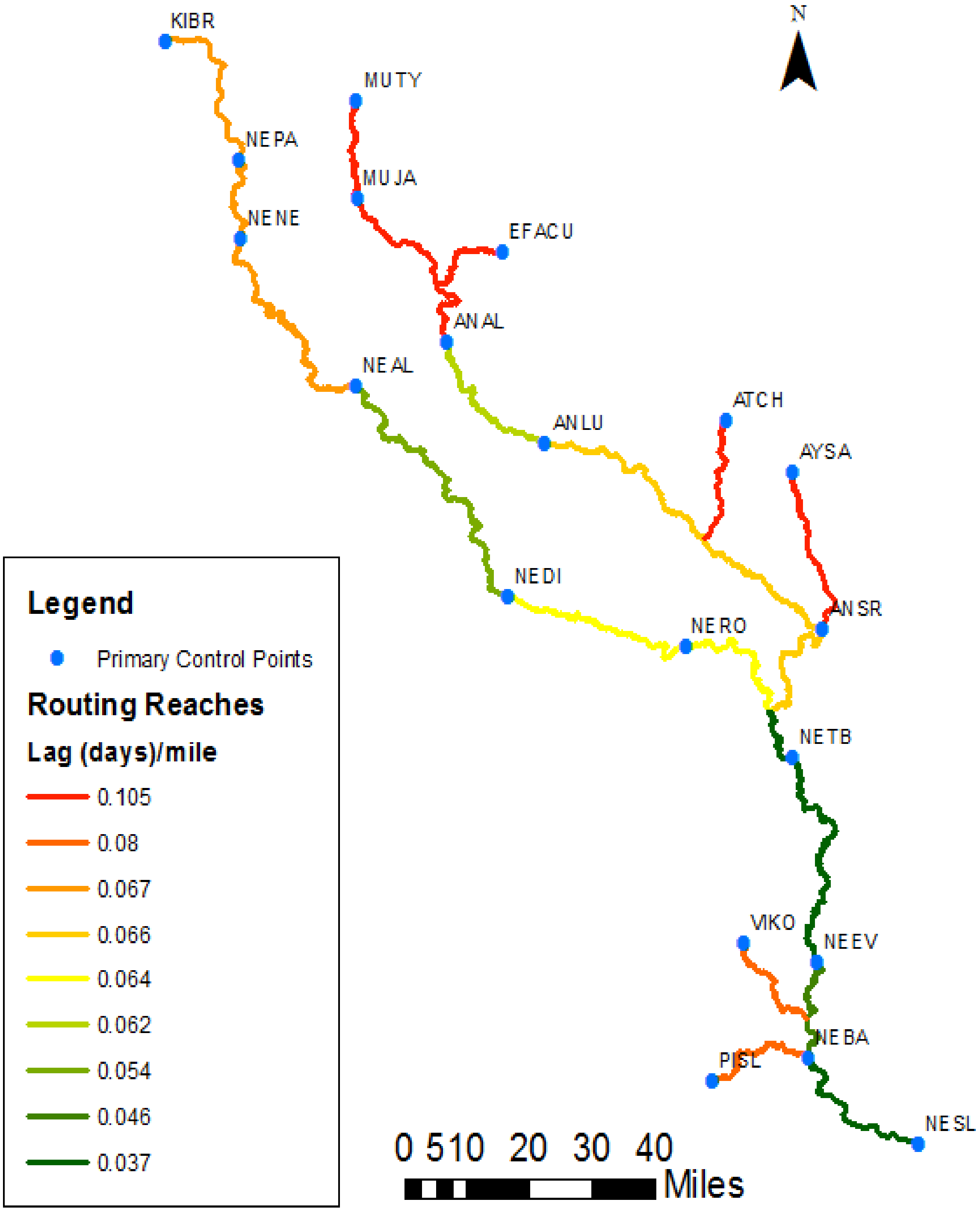

Figure 4.4: Lag (Days/Mile) for All Reaches of Neches River Basin for Normal Flows

Brazos River Basin

The Brazos River Basin, as shown in Figure 4.5, is one of the largest river basins of Texas, and drains into the Gulf of Mexico. The upper portion of the basin is a flat arid area with minimal contribution to stream flow. The Brazos River Basin has a drainage area of about 45,600 square miles, a small part of which is in New Mexico. The river has a length of about 900 miles. The 2010 population of the Brazos River Basin was about 2,440,000 people. The mean annual precipitation varies greatly across the basin, increasing from 19 inches/year in the western basin to 45 inches/year in the eastern basin (Wurbs et al. 2012).

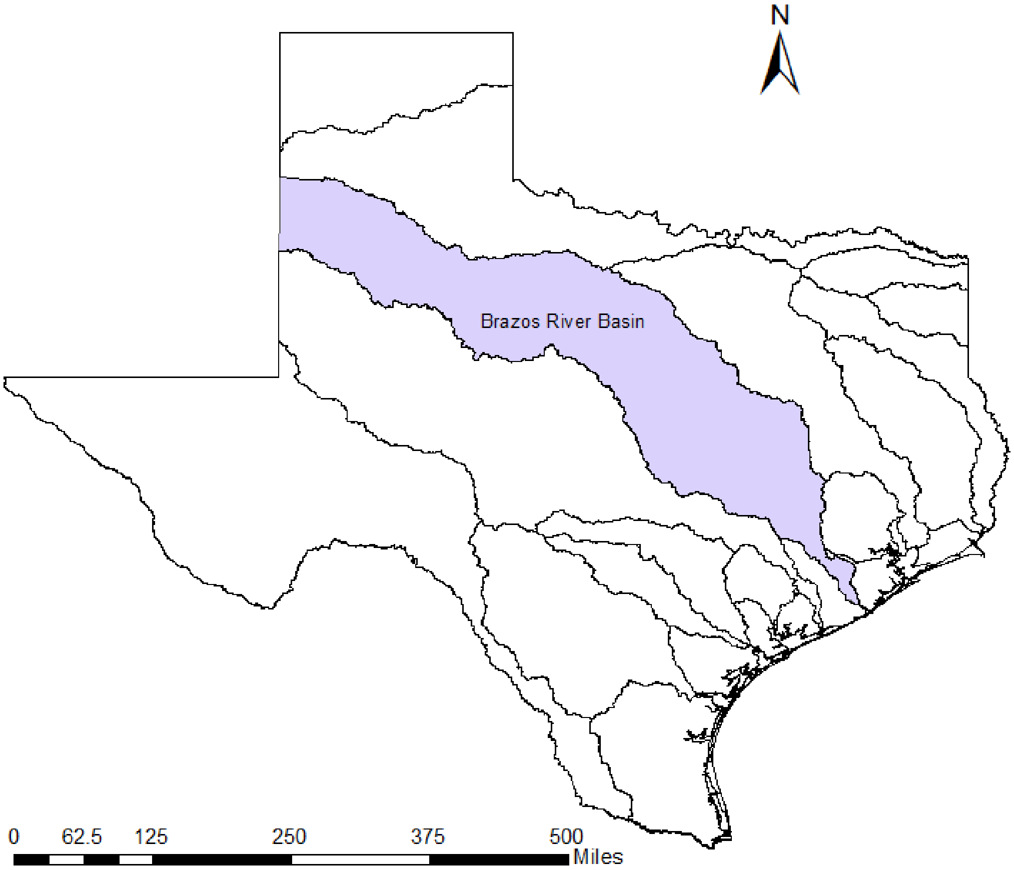

Figure 4.5: Brazos River Basin Located in Texas

There are 77 primary control points in the Brazos WAM. These 77 control points define 72 river reaches, after ignoring the reaches in the coastal basins. Figure 4.6 shows these reaches and the average slope between upstream and downstream ends. There are 37 reservoirs within the basin with a capacity of more than 10,000 acre-feet. This include the proposed Allen's Creek Reservoir which is not yet constructed.

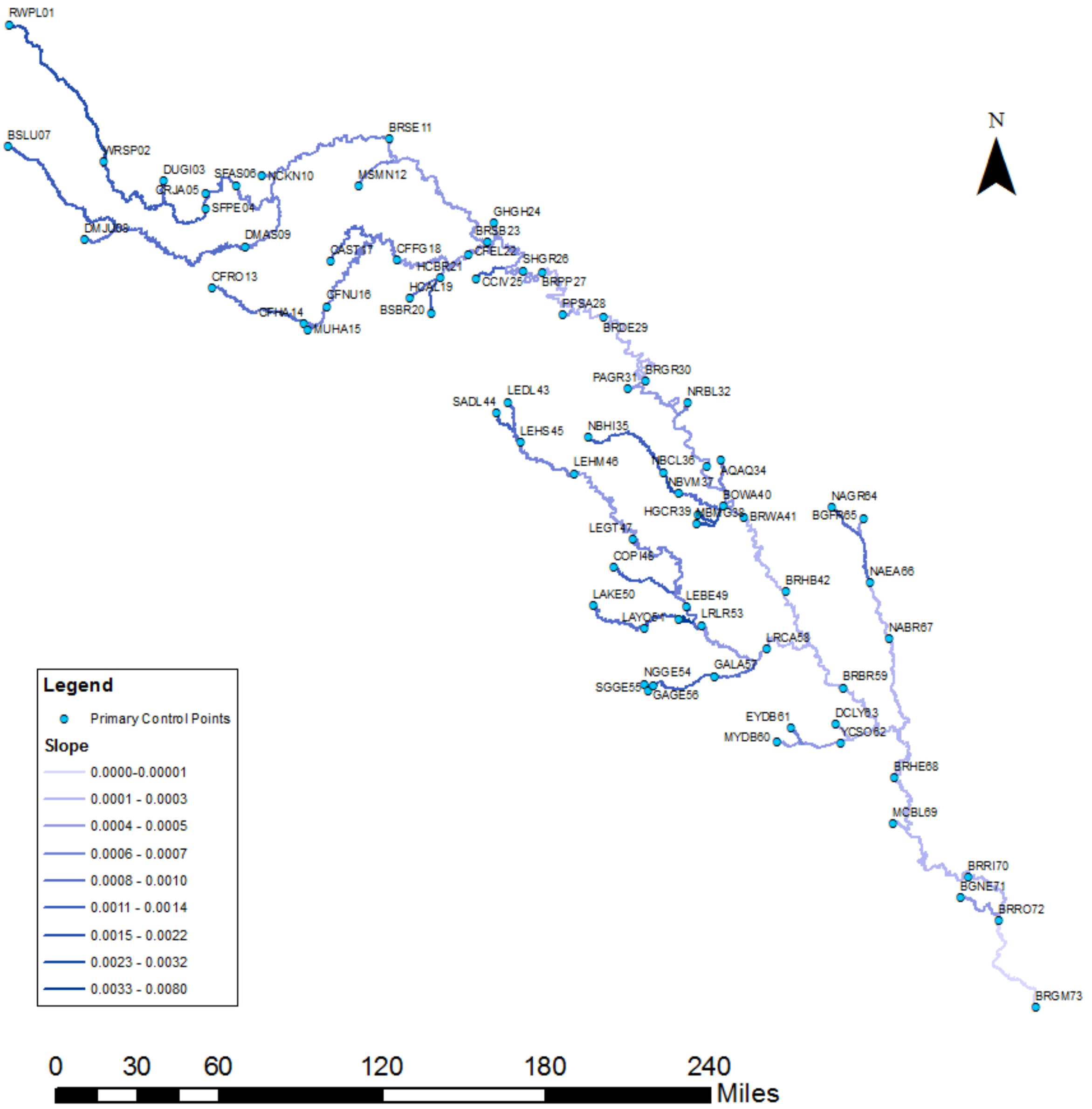

Figure 4.6: Brazos Primary Control Points and the Reaches Formed by Them

DFLOW Methodology for Brazos Basin

River segments between primary control points are selected to apply DFLOW (Figure 4.6). Each reach’s lag and attenuation was calculated either using DFLOW or using lag/mile from another similar reach or reaches. The following criteria were developed to perform the analysis for the reaches of the Brazos River and its tributaries.

1. For the reaches with a confluence, DFLOW was applied between the upstream and downstream control points only if there is a correlation of 0.5 or more between the flows at two points.
2. The following criteria was used to exclude or modify lags:
    i. Flows below the 90th percentile were used. Lags for days having flow above the 90th percentile were not used in the final calculation. For reaches that had such low flow, that excluding the top 10th percentile flows would result in very few flow change events feasible for lag calculations, this criterion was not used.
    ii. Flows less than 100 cfs were not used. Lags for days having flow less than 100 cfs were ignored in the final calculation. Just like previous criteria for reaches that had such low flow, that excluding below 100 cfs flows would result in very few flow change events feasible for lag calculations, this criterion was not used.
    iii. Flow events with less than 30 cfs change were also ignored in the case of sufficient average flows in the stream. If the average flow in the stream is low, the 30 cfs number was either changed to 15 cfs or 0.
    iv. If there is a change of 50% or more (compared to the change upstream) at a downstream control point on the same day as upstream peak day, then those days were also ignored in the final calculation. This criterion eliminates flow change event due to precipitations.
3. Minimum lag to each reach was assigned based on 0.01 days/mile criteria. In computations, if between upstream and downstream flow change events, lag is less than (0.01 x length of reach), the calculation will shift to the next downstream flow change event.

4. All calculations for normal flow routing parameters were performed based on flow decreases. This is because for low and normal flows in WAMs we are more concerned with the effect of withdrawals on flow propagations.
5. All calculations for high flow routing parameters were performed based on flow increases. This is because for high flows/flood control operations in WAMs we are more concerned with the effect of increase in the volume on flow propagations.

Discussion on Selected Stream Reaches

Consider the stream between BRGR30 and BRAQ33, Lake Whitney was created in this stream by damming the river during 1947-1951. Once the lake is created, the flows at two control points are not directly related anymore. Therefore, DFLOW is used only for a period of records of 1939-1946. Figure 4.7 compares the gauged flows of the Brazos River at Aquilla (BRAQ33, red line) and the Brazos River at Glen Rose (BRGR30, blue line). The flows at the two sites are very similar before 1951 when the initial impoundment of Lake Whitney started. After that, the lake is capturing the peak flows from the upstream control point i.e. BRGR30 and the downstream control point has less number of peaks and less quantity of flow.

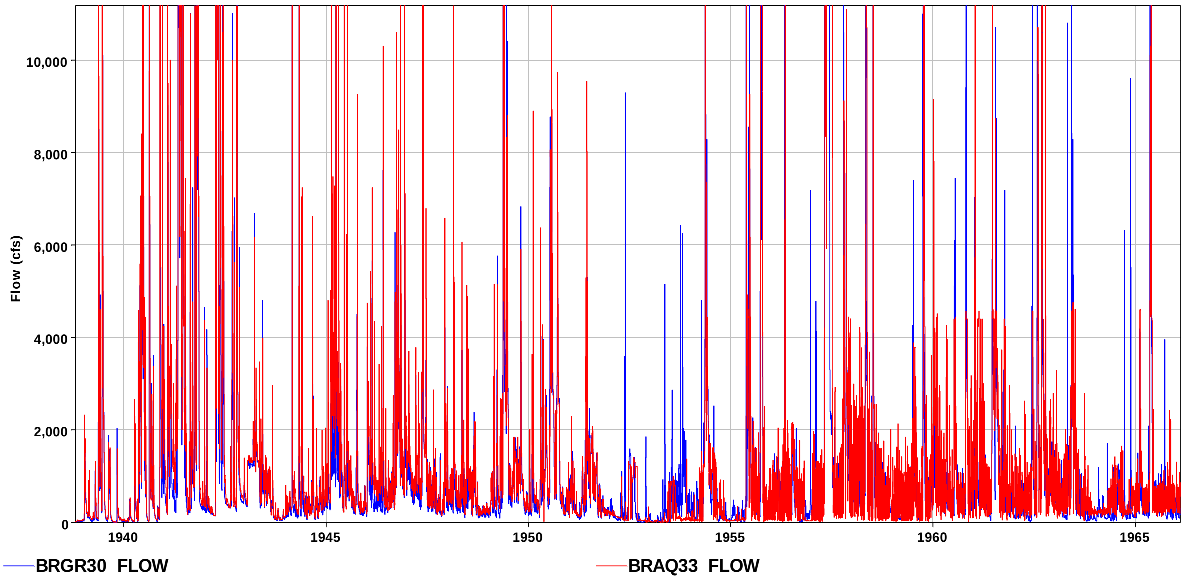

Figure 4.7: USGS Gauged Flows at U/S point BRGR30 and D/S point BRAQ33

For the reach BOWA40 to BRWA41, DFLOW analysis could not be performed because the upstream control point, having comparatively low flow, is merging into the main Brazos River having high flow. The distance between the confluence and upstream control point is insignificant, hence the lag from the main Brazos river reach in which this stream is draining is applied to the whole reach.

High flow computation for some of the reaches ran into erroneous results because of lack of data points. The normal flow routing parameters were adopted for those reaches instead of original DFLOW routing parameters for high flows. The judgment to select these reaches was based on the number of data points for calculation, magnitude of high flow lag versus low flow, and attenuation of high flow versus low flow. For example, the PPSA28 to BRDE29 reach had 163 flow change events in the normal flow calculations, a lag of 1.96 and attenuation of 1. The high flow analysis for the same reach give only 7 flow change events and the lag and attenuation of 2.6 and 1.5, which is significantly higher than normal flows. Most of reaches of the Brazos River have high flow lag less than normal flow, therefore normal flow lag is adopted for high flows reaches with erroneously large high flow lag and lesser number of flow change events. Beside PPSA28 to BRDE29 reach, other reaches for which normal flow routing parameters were adopted are CFEL22 to BRSB23, HCBR21 to CFEL22, LABE52 to LRLR53, and GAGE56 to GALA57.

Appendix F contains information about analysis on all the 72 reaches of Brazos River Basin, resulting and adopted routing parameters, and the method adopted for each river reach.

Results

Results of the DFLOW approach applied to the Brazos River and its tributaries are shown in Table 4.2. Results for some of the reaches were modified for different reasons. The results show that DFLOW lag is generally consistent in the main channel, and the upper reaches of the river system have faster lag times. This could be because of high slopes in areas where streams are initiating. High flow lag time was generally consistently lower than normal flow lag. It is justifiable because water flowing over water will have less resistance to overcome. This would happen as long as the channel is well defined and the high flows do not extend into overbanks.

Table 4.2: Lag and Attenuation from DFLOW for Brazos River Basin

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
RWPL01	WRSP02	93	no routing	-	-	no routing	-	-
WRSP02	SFPE04	90	6.75	1.00	0.075	1.72	1.00	0.019
SFPE04	SFAS06	30	2.06	1.00	0.069	1.02	1.00	0.034
SFAS06	BRSE11	106	4.16	1.00	0.039	3.04	1.00	0.029
BRSE11	BRSB23	93	2.18	1.00	0.023	1.80	1.00	0.019
BRSB23	SHGR26	65	3.25	1.00	0.050	3.22	1.00	0.050
SHGR26	BRPP27	20	1.00	1.00	0.050	0.99	1.00	0.050
BRPP27	BRDE29	79	2.01	1.00	0.025	1.84	1.00	0.023
BRDE29	BRGR30	76	1.93	1.00	0.025	1.77	1.00	0.023
BRGR30	BRAQ33	73	1.10	1.00	0.015	0.99	1.00	0.014
BRAQ33	BRWA41	35	1.00	1.00	0.029	1.01	1.00	0.029
BRWA41	BRHB42	57	1.07	1.00	0.019	1.00	1.00	0.018
BRHB42	BRBR59	67	1.81	1.00	0.027	1.00	1.00	0.015
BRBR59	BRHE68	86	1.98	1.00	0.023	1.00	1.00	0.012
BRHE68	BRRI70	104	2.62	1.00	0.025	2.62	1.00	0.025
BRRI70	BRRO72	36	0.92	1.00	0.026	0.92	1.00	0.026
BRRO72	BRGM73	58	1.57	1.00	0.027	0.87	1.00	0.015
DUGI03	SFPE04	53	3.00	1.00	0.057	1.01	1.00	0.019
CRJA05	SFAS06	23	1.58	1.00	0.069	0.78	1.00	0.034
DMJU08	DMAS09	127	4.23	1.00	0.033	3.22	1.00	0.025
DMAS09	BRSE11	113	3.12	1.00	0.028	3.00	1.00	0.027
BSLU07	DMAS09	185	7.46	1.00	0.040	4.30	1.00	0.023
NCKN10	BRSE11	75	2.07	1.00	0.028	1.99	1.00	0.027
MSMN12	BRSB23	102	no routing	-	-	no routing	-	-
CFRO13	CFHA14	68	2.12	1.00	0.031	1.96	1.00	0.029
CFHA14	CFNU16	20	1.98	1.00	0.099	1.10	1.00	0.055
CFNU16	CFFG18	95	2.92	1.00	0.031	1.89	1.00	0.020
CFFG18	CFEL22	62	2.01	1.00	0.032	1.00	1.00	0.016

Table 4.2: Continued

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
CFEL22	BRSB23	15	1.05	1.00	0.070	1.05	1.00	0.070
MUHA15	CFNU16	18	no routing	-	-	no routing	-	-
CAST17	CFFG18	67	2.08	1.00	0.031	1.69	1.00	0.025
HCAL19	HCBR21	16	1.15	1.00	0.072	0.78	1.00	0.049
HCBR21	CFEL22	28	2.01	1.00	0.072	1.36	1.00	0.049
BSBR20	HCBR21	17	1.22	1.00	0.072	0.83	1.00	0.049
GHGH24	SHGR26	59	1.84	1.00	0.031	1.55	1.00	0.027
CCIV25	SHGR26	35	1.82	1.00	0.052	1.32	1.00	0.038
PPSA28	BRDE29	33	1.96	1.00	0.059	1.96	1.00	0.059
PAGR31	BRAQ33	74	1.12	1.00	0.015	1.00	1.00	0.014
NRBL32	BRAQ33	42	1.09	1.00	0.026	0.85	1.00	0.020
AQAQ34	BRWA41	35	1.71	1.00	0.049	1.72	1.00	0.049
NBHI35	NBCL36	51	4.28	1.00	0.084	3.92	1.00	0.077
NBCL36	NBVM37	13	1.09	1.00	0.084	1.00	1.00	0.077
NBVM37	BOWA40	28	2.35	1.00	0.084	2.15	1.00	0.077
BOWA40	BRWA41	9	0.26	1.00	0.029	0.26	1.00	0.029
MBMG38	BOWA40	16	1.34	1.00	0.084	1.23	1.00	0.077
HGCR39	BOWA40	16	1.34	1.00	0.084	1.23	1.00	0.077
LEDL43	LEHS45	23	0.96	1.00	0.042	0.58	1.00	0.025
LEHS45	LEHM46	46	1.92	1.00	0.042	1.15	1.00	0.025
LEHM46	LEGT47	76	1.95	1.00	0.026	1.78	1.00	0.023
LEGT47	LEBE49	82	2.10	1.00	0.026	1.92	1.00	0.023
LEBE49	LRLR53	19	0.91	1.00	0.048	1.12	1.00	0.059
LRLR53	LRCA58	62	1.09	1.00	0.018	1.04	1.00	0.017
LRCA58	BRBR59	66	1.21	1.00	0.018	1.25	1.00	0.019
SADL44	LEHS45	16	0.67	1.00	0.042	0.40	1.00	0.025
COPI48	LEBE49	40	2.22	1.00	0.056	1.11	1.00	0.028
LAKE50	LAYO51	36	2.00	1.00	0.056	1.00	1.00	0.028
LAYO51	LABE52	23	1.28	1.00	0.056	0.64	1.00	0.028

Table 4.2: Continued

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
LABE52	LRLR53	20	1.25	1.00	0.063	1.25	1.00	0.063
NGGE54	GAGE56	5	no routing	-	-	no routing	-	-
GAGE56	GALA57	32	1.19	1.00	0.037	1.00	1.00	0.031
GALA57	LRCA58	38	1.96	1.00	0.052	1.16	1.00	0.031
SGGE55	GAGE56	4	no routing	-	-	no routing	-	-
MYDB60	YCSO62	33	3.76	1.00	0.114	3.76	1.00	0.114
YCSO62	BRHE68	67	2.58	1.00	0.038	2.06	1.00	0.031
EYDB61	YCSO62	28	3.19	1.00	0.114	3.19	1.00	0.114
DCLY63	BRHE68	74	3.12	1.00	0.042	2.62	1.00	0.035
NAGR64	NAEA66	32	2.48	1.00	0.078	2.53	1.00	0.079
NAEA66	NABR67	36	2.79	1.00	0.078	2.85	1.00	0.079
NABR67	BRHE68	100	3.14	1.00	0.031	3.14	1.00	0.031
BGFR65	NAEA66	50	3.88	1.00	0.078	3.96	1.00	0.079
MCBL69	BRRI70	70	2.23	1.00	0.032	2.25	1.00	0.032
BGNE71	BRRO72	32	2.48	1.00	0.078	2.53	1.00	0.079

Lag/mile values for Brazos River reaches are plotted in Figure 4.8 which shows that lag/mile value is generally low in main-river and high in contributing small upstream tributaries. It can be seen just from graphical visualization of Figure 4.6 and Figure 4.8 that even though slope of upstream reaches is steeper than main-river but the small amount of flow in them is preventing a faster lag time.

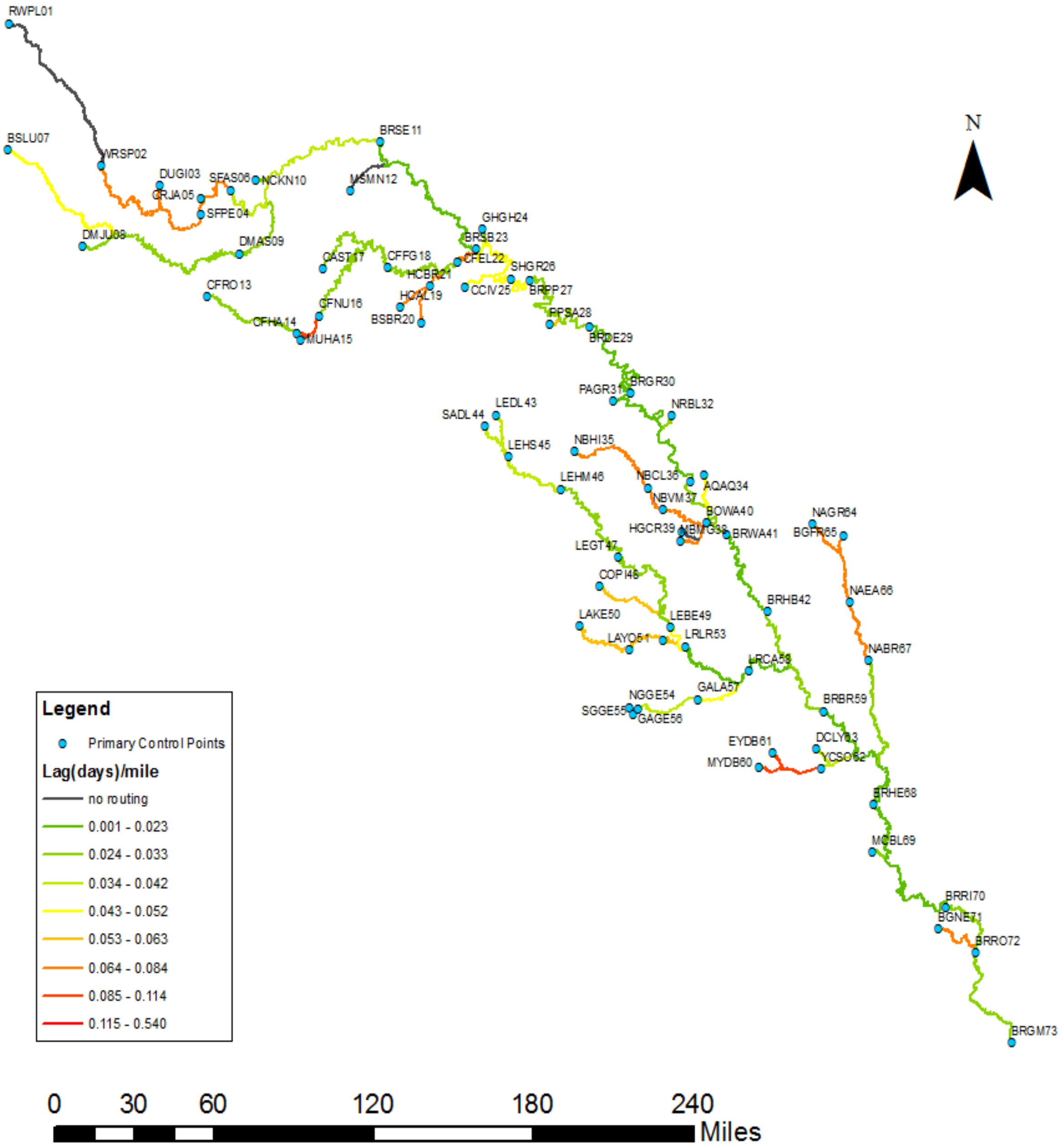

Figure 4.8: Lag (Days/Mile) for all Reaches of the Brazos River Basin

Trinity River Basin

The Trinity River Basin, as shown in Figure 4.9, spans across North Central Texas to East Texas, and drains into Galveston Bay. The northern and eastern sides of the basin are bounded by the Neches River Basin, and the western and southern sides are bounded by the Brazos River Basin. The Trinity River Basin has a drainage area of about 18,000 square miles. The basin has a length of about 400 miles. The major concentration of population in the basin is located in the Dallas-Fort Worth area, where water users rely primarily on surface water sources. The mean annual precipitation varies across the basin, increasing from 29 inches/year in the northwestern part near the Oklahoma Border to 53 inches/year in the most southeastern point of the basin near Galveston Bay (Hoffpauir et al. 2014).

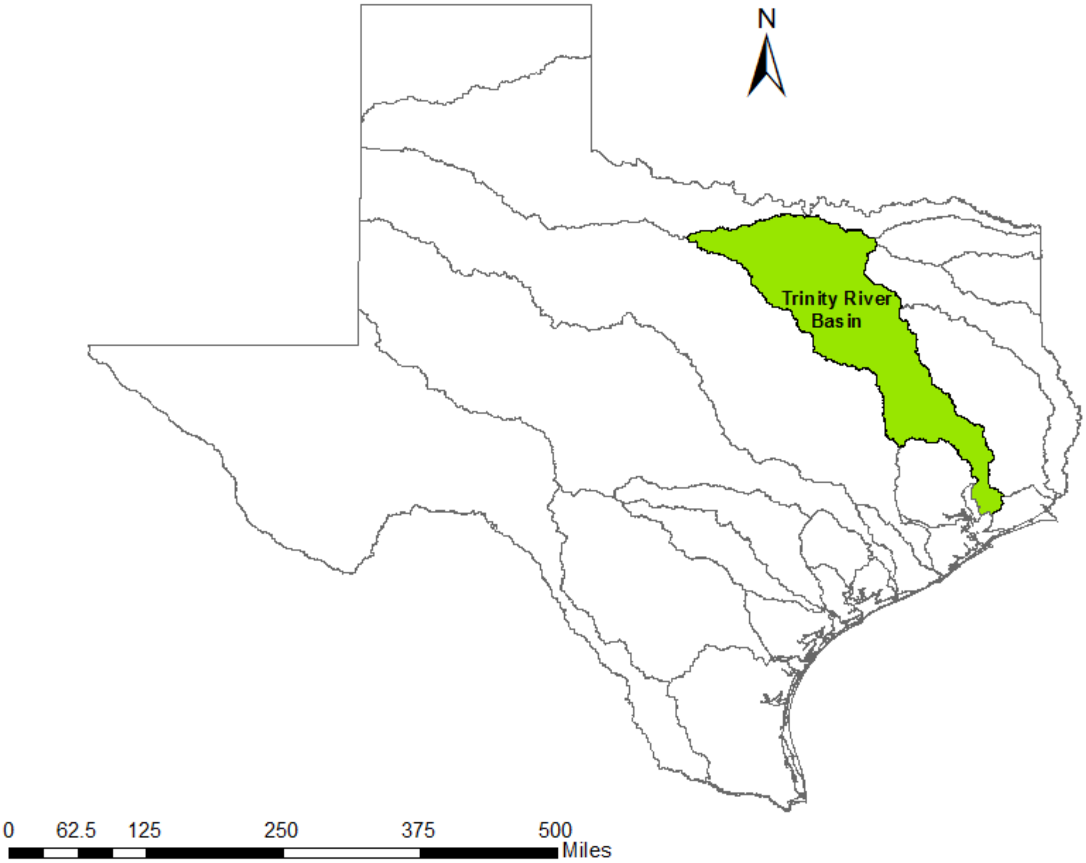

Figure 4.9: Trinity River Basin Located in Texas

There are 40 primary control points in Trinity Water Availability Model of the Texas Commission on Environmental Quality (TCEQ). Together these 40 control points make 39 river reaches. Figure 4.10 shows these reaches and the average slope between upstream and downstream point. There are 32 reservoirs within the basins with a capacity of more than 5,000 acre-feet, together these 32 reservoirs accounts for 98% of total storage in the Basin. There are 4 control points associated with SB3 environmental standards.

DFLOW Methodology for Trinity Basin

River segments between all primary control points are selected to apply DFLOW (Figure 4.10). Each reach's lag and attenuation were calculated either using DFLOW or using lag/mile from another similar reach or reaches. The following criteria adopted for the Trinity River and its tributaries are similar to the criteria employed with the other two river systems.

1. For the reaches with a confluence, DFLOW is used between upstream and downstream control point only if there is a correlation of 0.5 or more between the flows at two points.
2. LP records in the DFLOW input file were used to refine results. The following criteria was used to exclude or modify lags:
    i. Flows below the 90th percentile were used. Lags for days having flow above 90th percentile was not used in final calculation. For reaches that had such low flow, that excluding the top 10th percentile flows would results in very few flow change events feasible for lag calculations, this criteria was not used.
    ii. Flows less than 100 cfs were not used. Lags for days having flow less than 100 cfs were ignored in final calculation. Just like previous criteria for reaches that had such low flow, that excluding below 100 cfs flows would results in very few flow change events feasible for lag calculations, this criteria was not used.
    iii. Flow events with less than 30 cfs change were also ignored in case of sufficient average flows in the stream. If the average flow in the stream is low the 30 cfs number was either changed to 15 cfs or 0.
    iv. If there is a change of 50% or more (compared to the change at upstream) at a downstream control point on the same day as upstream peak day, then those

days were also ignored in the final calculation. This criterion eliminates flow change event due to precipitations.

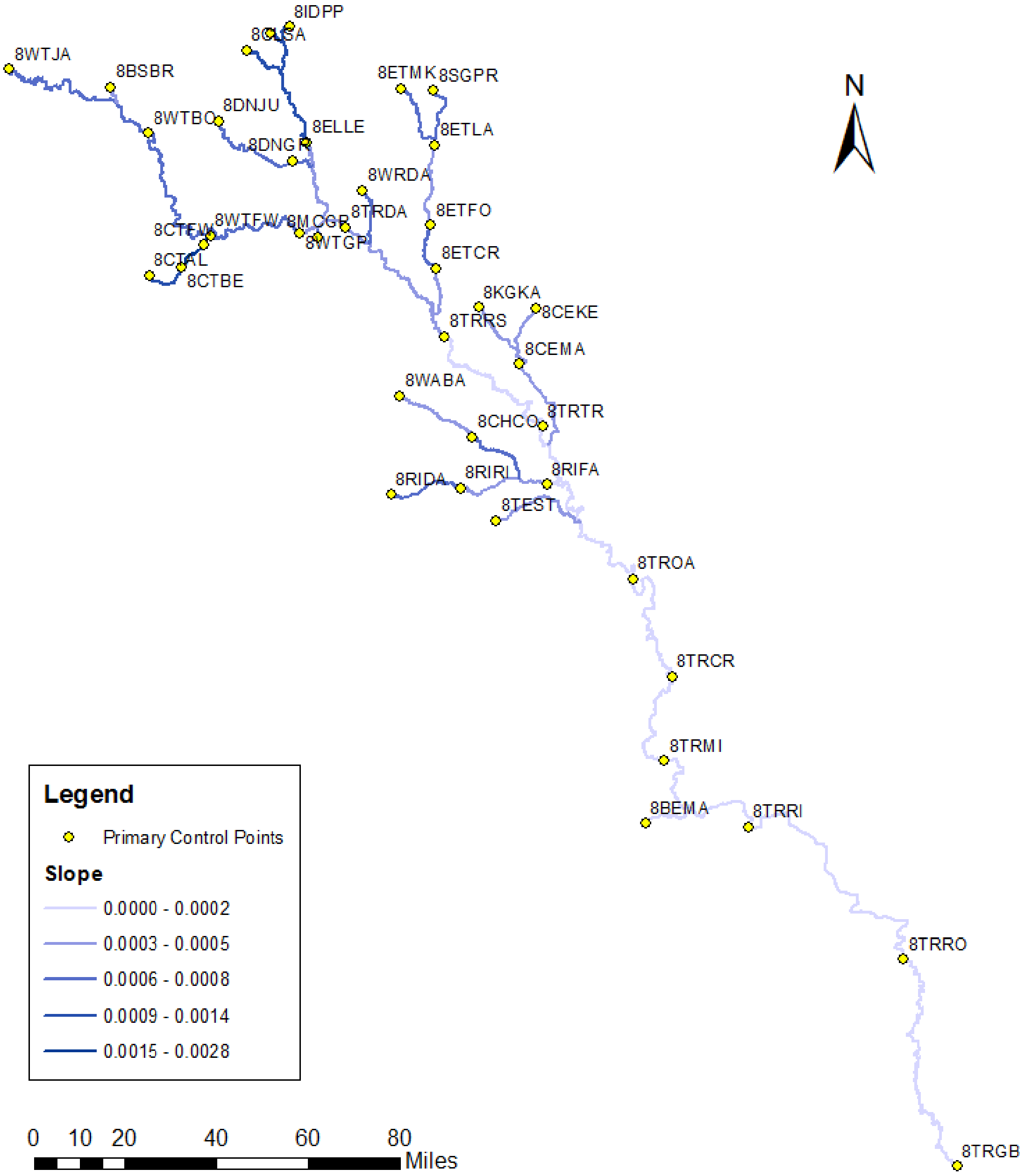

Figure 4.10: Trinity Primary Control Points and the Reaches Formed by Them

3. Minimum lag for each reach was assigned based on 0.01 days/mile criteria. In computations, if between upstream and downstream flow change events, lag is less than (0.01 x length of reach), calculation will shift to the next downstream flow change event.
4. All calculations for normal flow routing parameters were performed based on flow decreases. This is because for low and normal flows in WAMs we are more concerned with the effect of withdrawals on flow propagations
5. All calculations for high flow routing parameters were performed based on flow increases. This is because for high flows/flood control operations in WAMs we are more concerned with the effect of increase in volume on flow propagations.

Discussion on Selected Stream Reaches

Consider the reach between control points 8WTGP and 8TRDA which is 14 mile long. As expected its normal flow lag is less than a day (0.35 days). When for the same reach high flow analysis is performed, the lag was 2.99 days and the attenuation was 0.5 days. For such a short reach these results are not acceptable hence the high flow lag was calculated based on high flow lag/mile from the upstream reach which had the same normal flow lag/mile as this reach. The possible reason for these erroneous results is that there are two river confluences within this short reach which is destabilizing the calculations.

Appendix G contains information about analysis on all the 39 reaches of Trinity River Basin, resulting and adopted routing parameters, and the method adopted for each river reach.

Results

Results of DFLWO approach applied to Trinity River basin is shown in Table 4.3. Results for some of the reaches were modified for different reasons. The results show that DFLOW lag is generally decreasing with increasing flow which is justifiable because low flows encounter more resistance to flow because of the low hydraulic radius. High flow lag time was higher for some reaches and lower for other, the higher lag time for high flows may have been because of overflow into floodplains and having to overcome more resistance from the flat overbanks and vegetation.

Table 4.3: Lag and Attenuation from DFLOW for Trinity River Basin

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
8WTJA	8WTBO	63	6.36	1.00	0.101	5.74	1.00	0.091
8WTBO	8WTFW	46	2.07	1.00	0.045	2.28	1.00	0.050
8WTFW	8WTGP	39	0.99	1.00	0.025	1.03	1.00	0.026
8WTGP	8TRDA	14	0.35	1.00	0.025	0.37	1.00	0.026
8TRDA	8TRRS	47	2.00	1.00	0.043	3.04	1.00	0.065
8TRRS	8TRTR	58	1.04	1.00	0.018	3.15	1.00	0.054
8TRTR	8TROA	76	1.96	1.00	0.026	4.05	1.00	0.053
8TROA	8TRCR	47	1.00	1.00	0.021	3.86	1.00	0.082
8TRCR	8TRMI	32	1.00	1.00	0.031	3.83	1.00	0.120
8TRMI	8TRRI	66	1.08	1.00	0.016	4.79	1.00	0.073
8TRRI	8TRRO	69	2.00	1.00	0.029	3.05	1.00	0.044
8TRRO	8TRGB	87	2.52	1.00	0.029	3.85	1.00	0.044
8BSBR	8WTBO	18	1.82	1.00	0.101	1.64	1.00	0.091
8CTAL	8CTBE	11	1.11	1.00	0.101	1.00	1.00	0.091
8CTBE	8CTFW	9	0.91	1.00	0.101	0.82	1.00	0.091
8CTFW	8WTFW	2.3	0.10	1.00	0.043	0.11	1.00	0.050
8MCGP	8TRDA	10	0.25	1.00	0.025	0.26	1.00	0.026
8ELSA	8ELLE	35	2.10	1.00	0.060	2.40	1.00	0.069
8ELLE	8TRDA	33	2.14	1.00	0.065	1.99	1.00	0.060
8IDPP	8ELLE	36	2.84	1.00	0.079	2.82	1.00	0.078
8CLSA	8ELLE	35	2.11	1.00	0.060	2.40	1.00	0.069
8DNJU	8DNGR	32	3.23	1.00	0.101	2.92	1.00	0.091
8DNGR	8TRDA	31	2.02	1.00	0.065	1.87	1.00	0.060
8WRDA	8TRRS	58	3.63	1.00	0.063	3.75	1.00	0.065
8ETMK	8ETLA	19	1.25	1.00	0.066	1.28	1.00	0.067
8ETLA	8ETFO	22	1.45	1.00	0.066	1.48	1.00	0.067

Table 4.3: Continued

U/S CP	D/S CP	River Miles	Normal Flows			High Flows		
			Lag (days)	Attenuation (days)	lag(days)/ mile	Lag (days)	Attenuation (days)	lag(days)/ mile
8ETFO	8ETCR	15	0.99	1.00	0.066	1.01	1.00	0.067
8ETCR	8TRRS	20	1.05	1.00	0.053	1.96	1.00	0.098
8SGPR	8ETLA	13	0.85	1.00	0.065	0.88	1.00	0.067
8CEKE	8CEMA	20	1.32	1.00	0.066	1.35	1.00	0.067
8CEMA	8TROA	94	3.40	1.00	0.036	5.35	1.00	0.057
8KGKA	8CEMA	21	1.38	1.00	0.066	1.41	1.00	0.067
8RIDA	8RIRI	22	0.98	1.00	0.045	1.09	1.00	0.050
8RIRI	8RIFA	29	1.30	1.00	0.045	1.44	1.00	0.050
8RIFA	8TROA	63	1.63	1.00	0.026	3.36	1.00	0.053
8WABA	8CHCO	18	2.00	1.00	0.111	1.16	1.00	0.064
8CHCO	8RIFA	31	2.82	1.00	0.091	1.86	1.00	0.060
8TEST	8TROA	63	3.88	1.00	0.062	4.49	1.00	0.071
8BEMA	8TRRI	40	1.49	1.00	0.037	2.49	1.00	0.062

Lag/mile values for Trinity River reaches are plotted in Figure 4.11 to show how lag/mile is generally decreasing gradually from upstream reaches to downstream reaches. This justify the argument that flow is one of the major parameter that influence lag time. The other parameter is slope, but it can be seen just from graphical visualization of Figure 4.10 and Figure 4.11 that even though slope of upstream reaches are steeper than main-river but the small amount of flow in them is preventing a faster lag time.

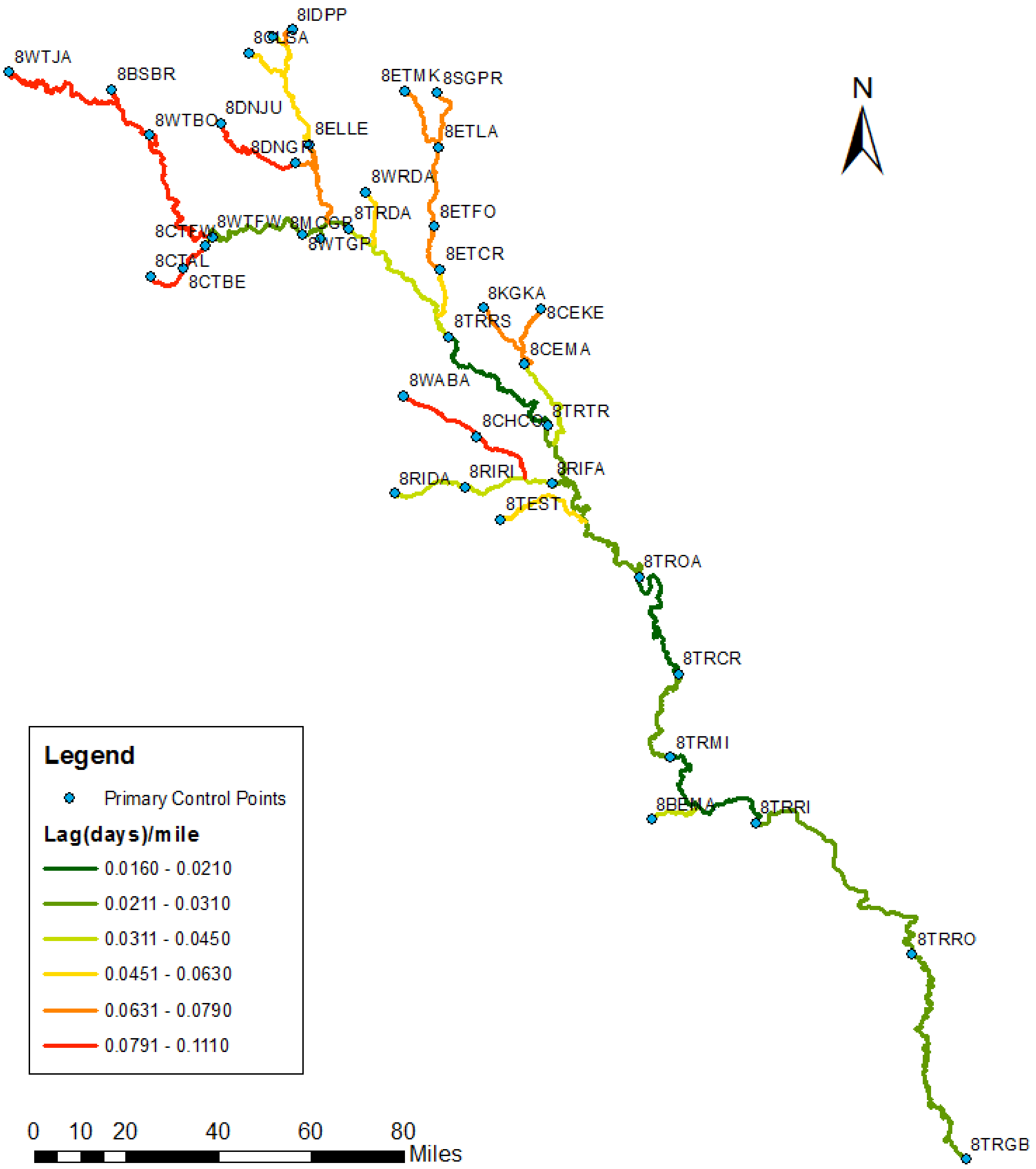

Figure 4.11: Lag (Days/Mile) for all Reaches of the Trinity River Basin for Normal Flows

Attenuation

Attenuation is 1 day for most reaches. For reaches that have no attenuation or attenuation other than 1, it is reasonable to assume attenuation of 1 day for all practical purposes as length of the reaches are small in all the analysis.

CHAPTER V

COMPARATIVE ANALYSIS

The purpose of this research is not only to develop a new method of estimating routing parameters for daily WAMs but also to compare these new parameter values with those currently in use with the daily WAMs and to suggest which routing parameter set is best and should be used. The sets of new routing parameter values presented in Chapters III and IV and the original values previously developed as discussed in Chapter II are compared and differences are analyzed. The comparative analyses are designed to facilitate adoption of the most appropriate methods and parameter values for the daily WAMs. The first part of this chapter compares the results of different methods for each of the three river basins while the later part compares the SIMD simulation results from different sets of routing parameters.

Comparison of Different Sets of Routing Parameters for Neches River Basin

Comparison between Lag Values

The DFLOW method for calibration of the lag and attenuation parameters is based on statistical analyses of lags and attenuations observed in defined flow change events identified in observed daily flows. The previously employed methodology for calibration of the lag and attenuation parameters is based on applying a genetic optimization algorithm with a specified objective function to search for parameter values that best replicate entire sequences of observed or naturalized daily flows. The term optimization method is adopted here to refer to this previously used technique.

Lags estimated with the DFLOW method are significantly higher than those previously incorporated in the daily WAMs that were estimated using the optimization method. The comparison for both is shown in Table 5.1. The old lag values are inconsistent, for example, the PISL to NEBA reach is 31 miles long and has significantly lower flow in comparison to the NEBA to NESL reach which is 28 miles long. The former reach has a lag of 0.66 days while the later reach has 0 lag.

Table 5.1: Comparison of Lags Estimated with the DFLOW versus Optimization Methods for Reaches in the Neches River Basin

Reach	U/S CP	D/S CP	River Miles	DFLOW Lag (days)	Optimization Lag (days)
R1	KIBR	NEPA	31	2.07	0.1
R2	NEPA	NENE	20	1.33	0.21
R3	NENE	NEAL	61	4.07	0.13
R4	NEAL	NEDI	75	4.04	0.13
R5	NEDI	NERO	47	3.00	0.2
R6	NERO	NETB	45	2.52	0.5
R7	NETB	NEEV	53	1.96	-
R8	NEEV	NEBA	25	1.14	0.3
R9	NEBA	NESL	28	1.04	0
R10	MUTY	MUJA	26	2.73	0
R11	MUJA	ANAL	47	4.93	0.41
R12	ANAL	ANLU	41	2.55	0.14
R13	ANLU	ANSR	83	5.51	0.5
R14	ANSR	NETB	38	2.14	0.25
R15	EFACU	ANAL	44	4.62	0
R16	ATCH	ANSR	64	6.71	0.4
R17	AYSA	ANSR	35	3.67	0
R18	VIKO	NEBA	37	2.62	0.38
R19	PISL	NEBA	31	2.48	0.66

Comparison between River Velocities

As discussed in the previous section, the lags from two different methods are vastly different. To gauge which one is more reasonable, the comparison is performed with expected average river velocities. The average river velocities are usually in the range of 1 ft/sec for low flows and 6 ft/sec for high flows. Table 1.1 reports ratio of wave celerity (V_W) to average river velocity (V_{AVE}). For natural channels, use of a conversion factor of 1.5 is acceptable because the shape of a stream can be estimated as rectangular or parabolic. The lag time is the travel time of wave thus the corresponding average velocities for DFLOW lags is found out to see whether they are in the reasonable range of velocities or not.

The corresponding average velocities in rivers is lower than 1 ft/sec for most of the reaches. In a smaller basin like the Neches lower velocities were expected to be lower but some of the values for upper reaches are very small. On the other hand, the corresponding average velocities from previous lag values are very fast and cannot be justified. For the gauge on the Neches River at the Saltwater Barrier at Beaumont (control point NEBA), the USGS has a record for maximum and mean velocities for some days (Figure 5.2). It is the only available gauge with velocity data among all 20 control points. The average of these values is 1.2 ft/sec. The value of average velocity from corresponding lag is 1.102 ft/sec which is close to the USGS measured value. Table 5.2 list the corresponding average stream velocities for each control point.

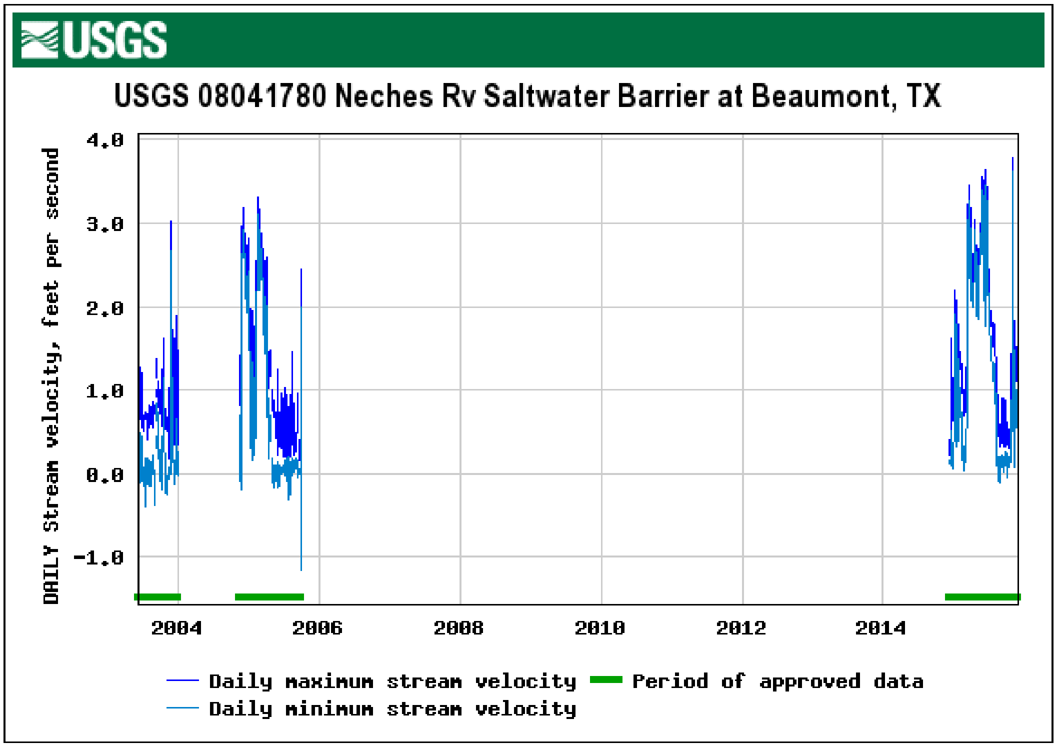

Figure 5.1: Stream Velocity Record for NEBA from USGS (USGS Website)

Table 5.2: Corresponding Average Stream Velocities Based on Lag Values for Reaches in the Neches River Basin

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Average Velocity of Stream - DFLOW (ft/sec)	Average Velocity of Stream - Optimization (ft/sec)
R1	KIBR	NEPA	31	0.0080	0.611	12.630
R2	NEPA	NENE	20	0.0590	0.611	3.880
R3	NENE	NEAL	61	0.0244	0.611	19.117
R4	NEAL	NEDI	75	0.0166	0.756	23.504
R5	NEDI	NERO	47	0.0132	0.638	9.574
R6	NERO	NETB	45	0.0180	0.727	3.667
R7	NETB	NEEV	53	0.0176	1.102	no lag
R8	NEEV	NEBA	25	0.0099	0.893	3.395

Table 5.2: Continued

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Average Velocity of Stream - DFLOW (ft/sec)	Average Velocity of Stream - Optimization (ft/sec)
R9	NEBA	NESL	28	0.0044	1.102	no lag
R10	MUTY	MUJA	26	0.0358	0.388	no lag
R11	MUJA	ANAL	47	0.0225	0.388	4.670
R12	ANAL	ANLU	41	0.0212	0.655	11.931
R13	ANLU	ANSR	83	0.0195	0.614	6.763
R14	ANSR	NETB	38	0.0114	0.723	6.193
R15	EFACU	ANAL	44	0.0268	0.388	no lag
R16	ATCH	ANSR	64	0.0272	0.388	6.519
R17	AYSA	ANSR	35	0.0586	0.388	no lag
R18	VIKO	NEBA	37	0.0134	0.576	3.967
R19	PISL	NEBA	31	0.0060	0.509	1.914

Discussion

The estimates of lag and attenuation from the application of DFLOW are more logical as compared to those from the optimization method. Results are more consistent with regard to reach parameters like slope, flow, and length. The average velocities of streams based on the lags that were previously used in Neches daily WAM are too high and unrealistic.

Comparison of Different Sets of Routing Parameters for Brazos River Basin

Comparison between Lag Values

Just like in the Neches River Basin, lags from DFLOW are significantly higher than what have previously been used in the daily Brazos WAM. The comparison for both is shown in Table 5.3. Lags using the Wave Travel Velocity Equation, developed in chapter III, are also compared with the lags from the other two methods. The lags from the equation are even higher than the DFLOW lags. While the lags from DFLOW and wave velocity equation are generally consistent with each other, lags from the optimization method are very low in comparison. In Table 5.3 only those reaches are presented which had lags from all three different methods.

Table 5.3: Comparison of Lags from DFLOW, Wave Travel Velocity Equation, and Optimization Methods for Reaches in the Brazos River Basin

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Lag - DFLOW (days)	Lag - Equation (days)	Lag - Optimization (days)
R4	SFAS06	BRSE11	106	0.0582	4.16	5.17	0.71
R5	BRSE11	BRSB23	93	0.0515	2.18	4.01	0.79
R10	BRGR30	BRAQ33	73	0.0355	1.10	3.79	0.5
R12	BRWA41	BRHB42	57	0.0243	1.07	1.94	0.72
R15	BRHE68	BRRI70	104	0.0157	1.68	3.25	1.21
R16	BRRI70	BRRO72	36	0.0184	1.94	1.09	0.53
R21	DMAS09	BRSE11	113	0.0608	3.12	5.37	1.3
R52	LRLR53	LRCA58	62	0.0373	1.09	1.96	1.24
R53	LRCA58	BRBR59	66	0.0255	1.21	1.88	0.79

Comparison between River Velocities

As discussed in the previous section, the lags from DFLOW and Equation 3.2 are vastly different from lags from calibration of hydrographs. To gauge which of these sets of lags is more reasonable, the comparison is performed with the expected average river velocities. As discussed earlier the average river velocities are usually in the range of from 1 ft/sec for low flows to 6 ft/sec for high flows.

The lag time is the travel time of the flow change wave. Thus, the corresponding average river velocities for DFLOW lags are calculated to see whether they are in the reasonable range of velocities or not. Table 5.4 lists the corresponding average stream velocities for each control point.

The corresponding average velocities in rivers is in the acceptable range for all the methods. Based on Table 5.4 it can be seen that the DFLOW river velocities are in the medium range while average-river velocities from the equation are on the lower side, close to 1 feet per second, the average river velocities from the calibration method are on the higher side. No gauged data of river velocities was available for Brazos River Basin. Hence the results cannot be compared with real data.

Table 5.4: Corresponding Average Stream Velocities Based on Lag Values for Reaches in the Brazos River Basin

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Average Velocity of Stream - DFLOW (ft/sec)	Average Velocity of Stream - Equation (ft/sec)	Average Velocity of Stream - Optimization (ft/sec)
R4	SFAS06	BRSE11	106	0.0582	1.04	0.83	6.08
R5	BRSE11	BRSB23	93	0.0515	1.74	0.94	4.80
R10	BRGR30	BRAQ33	73	0.0355	2.70	0.78	5.95
R12	BRWA41	BRHB42	57	0.0243	2.17	1.20	3.23
R15	BRHE68	BRRI70	104	0.0157	2.52	1.30	3.50
R16	BRRI70	BRRO72	36	0.0184	0.76	1.35	2.77
R21	DMAS09	BRSE11	113	0.0608	1.48	0.86	3.54
R52	LRLR53	LRCA58	62	0.0373	2.32	1.29	2.04
R53	LRCA58	BRBR59	66	0.0255	2.22	1.43	3.40

Discussion

The estimates of lag and attenuation from the application of DFLOW and the wave velocity equation are more reasonable as compared to the optimization method of calibrating parameters based on replicating entire hydrographs. Results are more consistent with regard to reach parameters like slope, flow, and length.

Comparison of Different Set of Routing Parameters for Trinity River Basin

Comparison between Lag Values

In Trinity River Basin, lags from DFLOW and calibration both are close to each other and unlike previous two basins, the calibration lags are not significantly lower than the DFLOW lags. While DFLOW lags are generally consistent in comparison to DFLOW lags from previous two basins, the calibration lags for Trinity River Basin are significantly high in comparison to calibration lags from previous two basins. The comparison for both is shown in Table 5.5, only those reaches are presented which had lags from both methods.

Table 5.5: Comparison of lags from DFLOW and calibration method for Reaches in the Trinity River Basin

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Lag - DFLOW (days)	Lag - Optimization (days)
R1	8WTJA	8WTBO	63	0.0592	6.36	1.9
R5	8TRDA	8TRRS	47	0.0363	2.00	1.3
R6	8TRRS	8TRTR	58	0.0153	1.04	1.6
R10	8TRMI	8TRRI	66	0.0003	1.08	1.36
R13	8BSBR	8WTBO	18	0.0495	1.82	0.5
R16	8CTFW	8WTFW	2.3	0.2141	0.10	0.02
R24	8WRDA	8TRRS	58	0.0571	3.63	1.04
R28	8ETCR	8TRRS	20	0.0388	1.05	2.53
R30	8CEKE	8CEMA	20	0.0294	1.32	1.89

Comparison between River Velocities

To assess which of the two sets of routing parameters is more reasonable, estimated average river velocities are compared. As discussed earlier, the average river velocities typically range from 1 ft/sec to 6 ft/sec.

The lag time is the travel time of the flow change. Thus, the corresponding average river velocities for DFLOW lags are calculated to see whether they are in the reasonable range of velocities or not. Table 5.6 lists the corresponding average stream velocities for each control point.

The corresponding average velocities in rivers are lower than expected for DFLOW lags for most of the reaches, while the average river velocities based on the optimization method are moderate. River velocities from both methods are compared in Table 5.6. No gauged data of river velocities was available for Trinity River Basin. Hence the results cannot be compared with real data.

Table 5.6: Corresponding Average Stream Velocities Based on Lag Values for Reaches in the Trinity River Basin

Reach No.	U/S CP	D/S CP	River Miles	Slope (%)	Average Velocity of Stream - DFLOW (ft/sec)	Average Velocity of Stream – Calibration (ft/sec)
R1	8WTJA	8WTBO	63	0.0592	0.40	1.35
R5	8TRDA	8TRRS	47	0.0363	0.96	1.47
R6	8TRRS	8TRTR	58	0.0153	2.27	1.48
R10	8TRMI	8TRRI	66	0.0003	2.49	1.98
R13	8BSBR	8WTBO	18	0.0495	0.40	1.47
R16	8CTFW	8WTFW	2.3	0.2141	0.91	4.69
R24	8WRDA	8TRRS	58	0.0571	0.65	2.27
R28	8ETCR	8TRRS	20	0.0388	0.78	0.32
R30	8CEKE	8CEMA	20	0.0294	0.62	0.43

Discussion

The estimates of lag and attenuation from the application of DFLOW and calibration methods are similar for Trinity River Basin. With the limited data that is available, it is not possible to conclude with certainty which set of routing parameters is better than the other.

Comparison of Simulation Results

Simulations were performed with the WRAP daily simulation model SIMD for the three river basins using the latest daily WAM input files. The purpose of the simulation study was to analyze the sensitivity of the simulation results to routing and forecasting itself and as well as to the routing parameters. To compare results, the simulation was performed with four different options:

1. Without routing and forecasting activated
2. With routing and without forecasting
3. With routing and forecasting using optimization-based routing parameters
4. With routing and forecasting using new DFLOW routing parameters

Total storage contents in the large reservoirs which account for most of the total storage capacity of all reservoirs in the WAMs was compared for each option. Instream flow targets and instream flow shortages were also compared for each of the SB3 environmental flow control points in each river basin.

Neches River Basin

The Neches River Basin has 11 reservoirs with a capacity of more than 5,000 acre-feet each. These major reservoirs account for the majority of the storage capacity in the basin. Figure 5.2 compares the summation of simulated end-of-day total storage contents of the 11 reservoirs for each of the four simulation options described earlier. The total volume of water stored in the 11 largest reservoirs in the basin at the end of each day of the 1940-2015 hydrologic period-of-analysis during authorized use scenario WAM simulations are plotted in Figure 5.2. The simulations are based on the premise that all water right permit holders divert and store the full amounts authorized by their permits during a repetition of 1940-2015 natural river basin hydrology.

With routing and forecasting deactivated, the simulated storage plotted in Figure 5.2 is lower than with routing and forecasting employed with either alternative set of routing parameter values. Routing and forecasting result in more stream flow being available to refill storage. The simulation employing the original values for routing parameters determined with the optimization method generally result in higher storage levels. The differences in storage between the four alternative simulations are more pronounced during extreme low and high flow conditions.

There are five gauging stations in the Neches River Basin with Senate Bill 3 (SB3) environmental flow standards. These instream flow requirements are incorporated in the Neches WAM at control points ANALE, NEEVE, NENEE, NEROE, and VIKOE. As discussed in Chapter I, the purpose of improving daily modeling capabilities is to be better equipped to model environment flow needs. The effects of different simulation options and routing parameters on SB3 environmental flow (e-flow) targets and shortages at these five control points are explored in Table 5.7. The mean, median, and range of regulated flows at these sites are compared in Table 5.8.

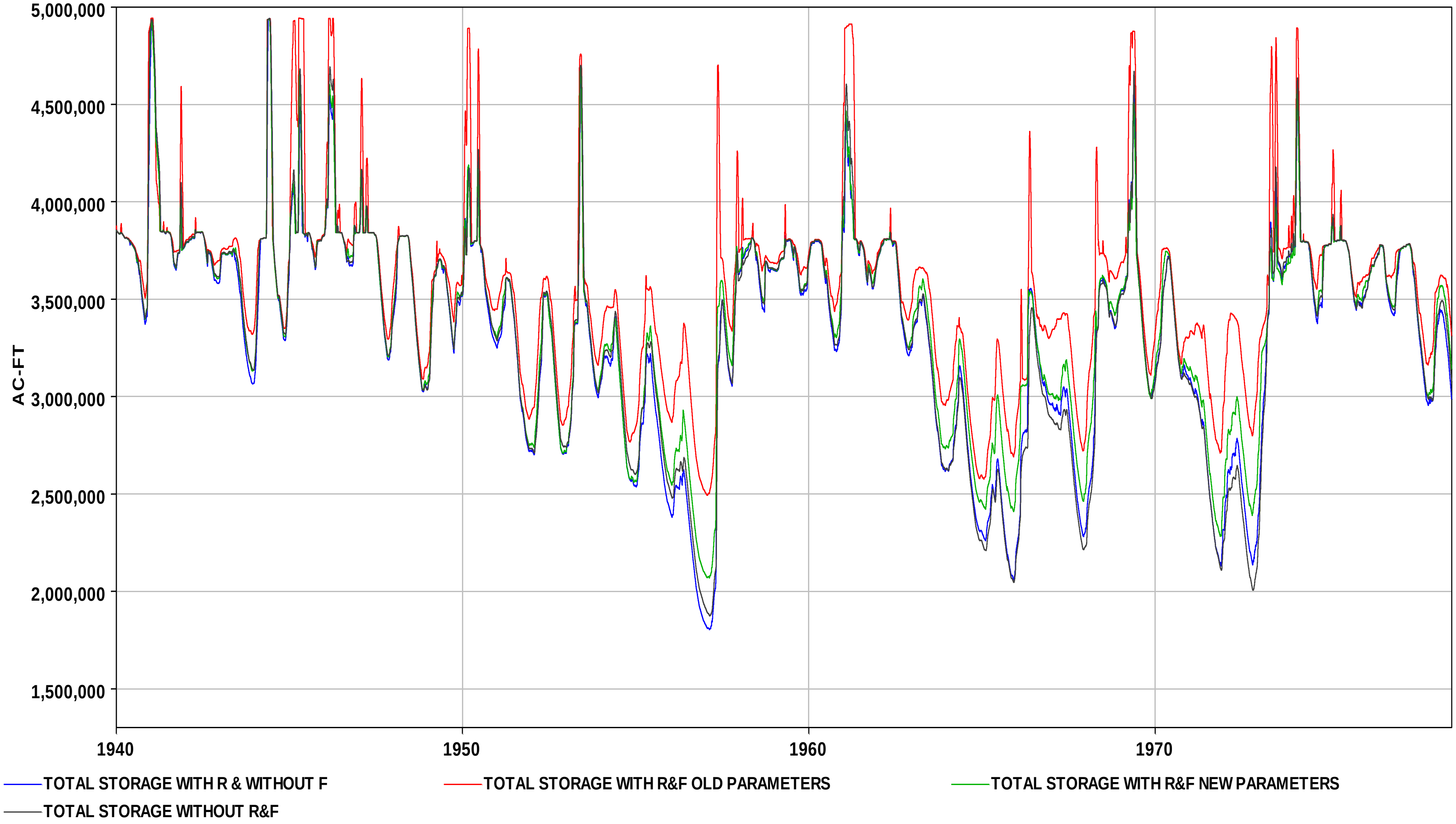

Figure 5.2: Storage in Large Reservoirs of Neches River Basin for Different Simulation Options

Table 5.7: Instream Targets and Shortages for E-Flow Control Points of Neches

	Instream Targets (Ac-Ft)				Instream Shortages (Ac-Ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	ANALE	ANALE	ANALE	ANALE	ANALE	ANALE	ANALE	ANALE
Mean	286.53	279.65	330.59	282.68	2.54	4.38	0.62	3.88
Minimum	21.8	21.8	21.8	21.8	0	0	0	0
Median	103.1	103.1	109.1	103.1	0	0	0	0
Maximum	3213.2	3213.2	3213.2	3213.2	109.1	109.1	47.36	109.1
CP	NEEVE	NEEVE	NEEVE	NEEVE	NEEVE	NEEVE	NEEVE	NEEVE
Mean	1751.36	1743.54	2201.67	1699.74	52.14	72.44	5.54	94.99
Minimum	452.2	452.2	452.2	452.2	0	0	0	0
Median	1015.5	1015.5	1150.4	1015.5	0	0	0	0
Maximum	7596.7	7596.7	7596.7	7596.7	527.6	3818.2	422.99	7596.7
CP	NENEE	NENEE	NENEE	NENEE	NENEE	NENEE	NENEE	NENEE
Mean	198.42	175.21	262.7	173.82	1.05	8.75	0.91	8.59
Minimum	23.8	23.8	23.8	23.8	0	0	0	0
Median	101.2	91.2	158.7	91.2	0	0	0	0
Maximum	1652.2	1652.2	1652.2	1652.2	101.2	101.2	25.8	101.2
CP	NEROE	NEROE	NEROE	NEROE	NEROE	NEROE	NEROE	NEROE
Mean	636.16	642.62	703.92	639.7	3.92	2.79	0.21	3.3
Minimum	41.7	41.7	41.7	41.7	0	0	0	0
Median	178.5	178.5	178.5	178.5	0	0	0	0
Maximum	6109.1	6109.1	6109.1	6109.1	132.9	132.9	38.58	132.9
CP	VIKOE	VIKOE	VIKOE	VIKOE	VIKOE	VIKOE	VIKOE	VIKOE
Mean	369.61	369.54	369.86	369.72	0.59	0.59	0.58	0.59
Minimum	81.3	81.3	81.3	81.3	0	0	0	0
Median	194.4	194.4	194.4	194.4	0	0	0	0
Maximum	3986.8	3986.8	3986.8	3986.8	61.86	61.86	61.86	61.86

Table 5.8: Regulated Flows for E-Flow Control Points of Neches

	Regulated Flows (Ac-Ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	ANALE	ANALE	ANALE	ANALE
Mean	1379.75	1381.46	1835.46	1385.67
Minimum	0	0	0	0
Median	385.94	353.6	676.33	358.88
Maximum	99927.56	103504.28	104520.61	103504.3
CP	NEEVE	NEEVE	NEEVE	NEEVE
Mean	9302.53	9315.33	13156.82	9316.85
Minimum	0	0	29.21	0
Median	2302.09	2345.33	6106.87	1957.89
Maximum	145061.92	136479.08	189000.86	171597.53
CP	NENEE	NENEE	NENEE	NENEE
Mean	783.46	788.92	1477.03	784.66
Minimum	0	0	0	0
Median	196.18	101.39	582.68	99.84
Maximum	86403.29	87392.83	87478.89	87392.01
CP	NEROE	NEROE	NEROE	NEROE
Mean	4011.52	4017.23	4806.45	4012.46
Minimum	0	0	3.12	0
Median	1119.39	1114.55	1811.76	1091.15
Maximum	97086.88	97283.33	97892.07	97284.62
CP	VIKOE	VIKOE	VIKOE	VIKOE
Mean	1725.33	1725.33	1726.33	1725.34
Minimum	19.44	19.44	19.44	19.44
Median	648.74	648.84	649.83	648.85
Maximum	123236.86	123233.2	123228.61	123232.81

The general observation from the above comparisons is that regulated flows for the simulation with the optimization-based routing parameter values are generally higher than the regulated flows from the three other simulations. The instream flow targets are also higher with the original parameters and the shortages are lower.

Brazos River Basin

There are 15 large reservoirs in the Brazos River Basin excluding the proposed Allen's Creek Reservoir. These reservoirs are responsible for about 80% of the storage capacity in the basin. Figure 5.3 compares the storage in these reservoirs for each of the four alternative simulation scenarios described earlier. As was the case with Neches WAM, storage levels are lower without routing and forecasting activated. The differences are greater during extreme low and high flow conditions in the basin. Storage is higher with the original routing parameter values determined with the optimization method than with the new values estimated with DFLOW.

There are nineteen gauging stations in the Brazos River Basin with SB3 environmental flow standards. These instream flow requirements are incorporated in the Brazos WAM at control points BRBR5E, BRGR3E, BRHE6E, BRPP2E, BRRI7E, LRLR5E, NAEA6E, LRCA5E, BRRO7E, BRSB2E, BRSE1E, BRWA4E, CFFG1E, NBCL3E, SFAS0E, LEGT4E, CFNU1E, DMAS0E, and LAKE5E. The effects of different simulation options and routing parameters on SB3 environmental flow (e-flow) targets and shortages at these nineteen control points are explored in Table 5.9. The mean, median and range of regulated flows at these sites are compared in Table 5.10.

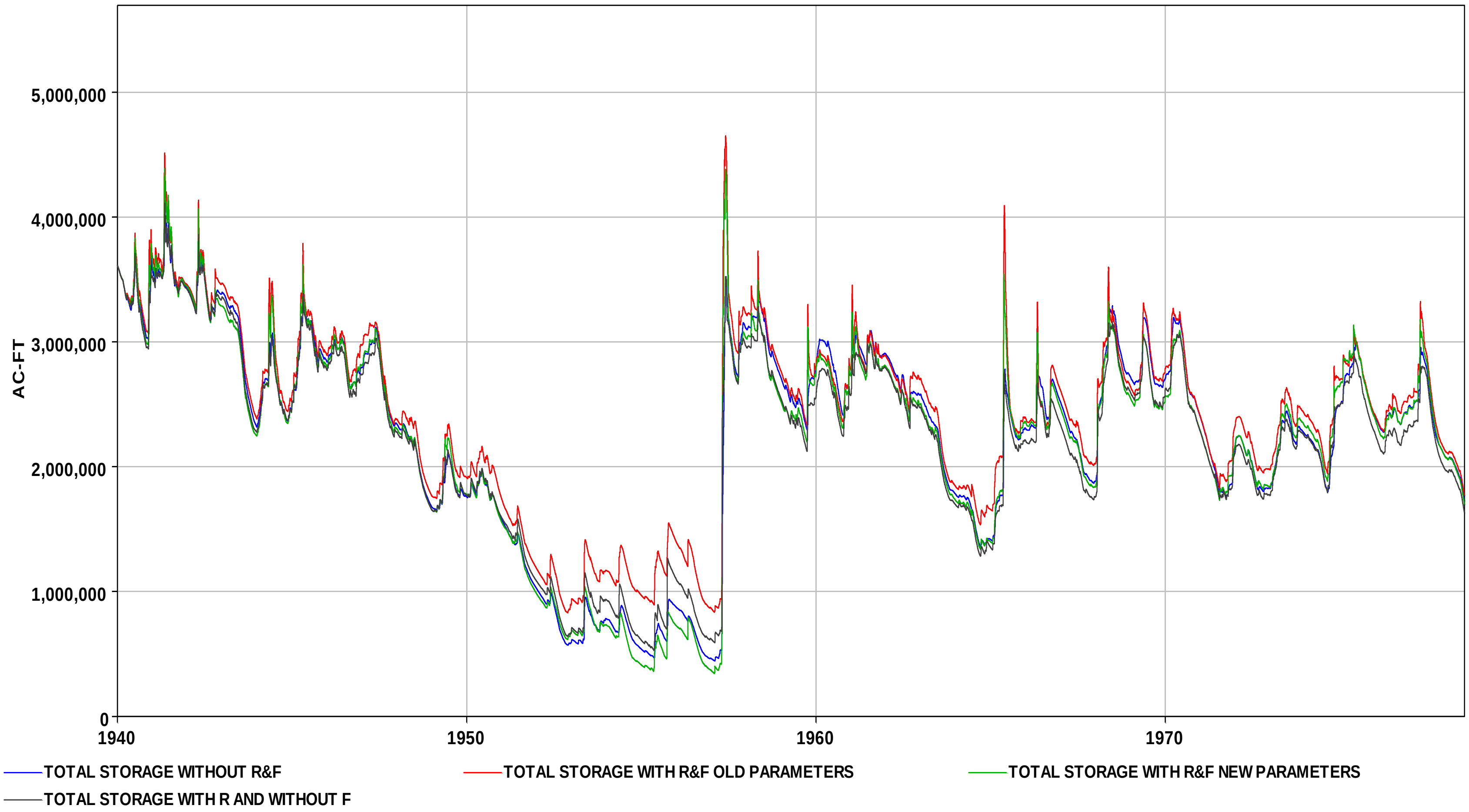

Figure 5.3: Storage in Large Reservoirs of Brazos River Basin for Different Simulation Options

Table 5.9: Instream Targets and Shortages for E-Flow Control Points of Brazos

	Instream Targets (Ac-ft)				Instream Shortages (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	BRBR5E	BRBR5E	BRBR5E	BRBR5E	BRBR5E	BRBR5E	BRBR5E	BRBR5E
Mean	2426.79	2408.86	2431.57	2410.7	355.79	484.45	332.47	439.27
Minimum	595	595	595	595	0	0	0	0
Median	1824.8	1824.8	1824.8	1824.8	0	0	0	0
Maximum	20628	20628	20628	20628	4608.13	4879.3	11999.08	11241.66
CP	BRGR3E	BRGR3E	BRGR3E	BRGR3E	BRGR3E	BRGR3E	BRGR3E	BRGR3E
Mean	382.28	374.94	377.28	377.92	38.08	50.74	37.32	51.78
Minimum	31.7	31.7	31.7	31.7	0	0	0	0
Median	152.7	152.7	152.7	152.7	0	0	0	0
Maximum	12853	12853	12853	12853	337.2	337.2	337.2	337.2
CP	BRHE6E	BRHE6E	BRHE6E	BRHE6E	BRHE6E	BRHE6E	BRHE6E	BRHE6E
Mean	3872.48	3862.67	3883.1	3856.41	509.03	675.89	481.98	612.27
Minimum	1011.6	1011.6	1011.6	1011.6	0	0	0	0
Median	2856.2	2856.2	2856.2	2856.2	0	0	0	0
Maximum	33322	33322	33322	33322	6455.13	11345	22211.74	26792.03
CP	BRPP2E	BRPP2E	BRPP2E	BRPP2E	BRPP2E	BRPP2E	BRPP2E	BRPP2E
Mean	246.57	246.67	241.82	245.46	36.49	43.56	38.51	45.29
Minimum	33.7	33.7	33.7	33.7	0	0	0	0
Median	142.8	142.8	142.8	142.8	0	0	0	0
Maximum	6684	6684	6684	6684	235.23	238	238	238
CP	BRRI7E	BRRI7E	BRRI7E	BRRI7E	BRRI7E	BRRI7E	BRRI7E	BRRI7E
Mean	4186.22	4181.64	4197.57	4186.5	707.66	812.22	651.07	750.97
Minimum	1090.9	1090.9	1090.9	1090.9	0	0	0	0
Median	3272.7	3272.7	3272.7	3272.7	0	0	0	0
Maximum	32331	32331	32331	32331	7888.06	12714	24595	28288.07

Table 5.9: Continued

	Instream Targets (Ac-ft)				Instream Shortages (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	BRRO7E	BRRO7E	BRRO7E	BRRO7E	BRRO7E	BRRO7E	BRRO7E	BRRO7E
Mean	4815.09	4802.28	4816.55	4813.13	1291.17	1377.56	1255.45	1333.62
Minimum	852.9	852.9	852.9	852.9	0	0	0	0
Median	4145.5	4145.5	4145.5	4145.5	0.04	204.81	0.02	90.27
Maximum	28165	28165	28165	28165	9391.8	20242.21	18325.31	28165
CP	BRSB2E	BRSB2E	BRSB2E	BRSB2E	BRSB2E	BRSB2E	BRSB2E	BRSB2E
Mean	143.04	142.24	143.16	142.29	21.74	25.94	21.48	25.26
Minimum	2	2	2	2	0	0	0	0
Median	119	119	119	119	0	0	0	0
Maximum	4919	4919	4919	4919	238	238	238	238
CP	BRSE1E	BRSE1E	BRSE1E	BRSE1E	BRSE1E	BRSE1E	BRSE1E	BRSE1E
Mean	51.88	51.84	51.88	51.76	6.73	6.85	6.81	7.15
Minimum	2	2	2	2	0	0	0	0
Median	37.7	37.7	37.7	37.7	0	0	0	0
Maximum	2063	2063	2063	2063	82.95	91.2	87.18	91.2
CP	BRWA4E	BRWA4E	BRWA4E	BRWA4E	BRWA4E	BRWA4E	BRWA4E	BRWA4E
Mean	800.78	784.17	808.23	795.08	56.12	110.24	68.77	107.83
Minimum	111.1	111.1	111.1	111.1	0	0	0	0
Median	495.9	495.9	495.9	495.9	0	0	0	0
Maximum	26975	26975	26975	26975	1365.19	8291	26975	26975
CP	CFFG1E	CFFG1E	CFFG1E	CFFG1E	CFFG1E	CFFG1E	CFFG1E	CFFG1E
Mean	33.97	33.57	33.9	33.42	7.96	9.35	7.91	9.52
Minimum	2	2	2	2	0	0	0	0
Median	25.8	25.8	25.8	25.8	0	1.76	0	2
Maximum	2440	2440	2440	2440	67.4	67.4	67.4	67.4

Table 5.9: Continued

	Instream Targets (Ac-ft)				Instream Shortages (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	CFNU1E	CFNU1E	CFNU1E	CFNU1E	CFNU1E	CFNU1E	CFNU1E	CFNU1E
Mean	16.97	16.27	16.49	16.25	2.15	5	2.15	4.83
Minimum	2	2	2	2	0	0	0	0
Median	11.9	11.9	11.9	11.9	0	0	0	0.12
Maximum	1170	1170	1170	1170	25.8	25.8	25.8	25.8
CP	DMAS0E	DMAS0E	DMAS0E	DMAS0E	DMAS0E	DMAS0E	DMAS0E	DMAS0E
Mean	14.26	14.17	14.26	14.13	2.33	2.64	2.39	2.94
Minimum	2	2	2	2	0	0	0	0
Median	6	6	6	6	0	0	0	0
Maximum	1131	1131	1131	1131	29.8	29.8	29.8	29.8
CP	LAKE5E	LAKE5E	LAKE5E	LAKE5E	LAKE5E	LAKE5E	LAKE5E	LAKE5E
Mean	64.23	64.09	64.27	64.03	12.02	12.18	11.96	12.23
Minimum	19.8	19.8	19.8	19.8	0	0	0	0
Median	53.6	53.6	53.6	53.6	0	0	0	0
Maximum	2598	2598	2598	2598	85.28	85.3	85.17	85.3
CP	LEGT4E	LEGT4E	LEGT4E	LEGT4E	LEGT4E	LEGT4E	LEGT4E	LEGT4E
Mean	50.77	50.79	51.6	50.82	8.47	10.64	8.9	11.22
Minimum	2	2	2	2	0	0	0	0
Median	39.7	39.7	39.7	39.7	0	0	0	0
Maximum	1250	1250	1250	1250	107.1	1250	1250	1250
CP	LRCA5E	LRCA5E	LRCA5E	LRCA5E	LRCA5E	LRCA5E	LRCA5E	LRCA5E
Mean	611.1	610.44	621.24	612.98	111.9	113.76	113.02	120.18
Minimum	63.5	63.5	63.5	63.5	0	0	0	0
Median	376.9	376.9	376.9	376.9	0	0	0	0
Maximum	9501	9501	9501	9501	1450.93	5334.93	9493.22	9093.35

Table 5.9: Continued

	Instream Targets (Ac-ft)				Instream Shortages (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	LRLR5E	LRLR5E	LRLR5E	LRLR5E	LRLR5E	LRLR5E	LRLR5E	LRLR5E
Mean	340.41	342.12	354.5	342.84	75.17	79.33	81.51	87.59
Minimum	109.1	109.1	109.1	109.1	0	0	0	0
Median	238	238	238	238	0	0	0	0
Maximum	6526	6526	6526	6526	674.4	3612.38	6526	6526
CP	NAEA6E	NAEA6E	NAEA6E	NAEA6E	NAEA6E	NAEA6E	NAEA6E	NAEA6E
Mean	48.66	48.41	48.18	49.12	3.6	5.92	3.31	5.54
Minimum	2	2	2	2	0	0	0	0
Median	27.8	27.8	27.8	27.8	0	0	0	0
Maximum	2658	2658	2658	2658	57.5	98.46	57.5	57.5
CP	NBCL3E	NBCL3E	NBCL3E	NBCL3E	NBCL3E	NBCL3E	NBCL3E	NBCL3E
Mean	37.51	37.5	37.58	37.63	4.17	4.75	4.13	4.46
Minimum	2	2	2	2	0	0	0	0
Median	23.8	23.8	23.8	23.8	0	0	0	0
Maximum	1408	1408	1408	1408	58.48	65.5	65.21	65.5
CP	SFAS0E	SFAS0E	SFAS0E	SFAS0E	SFAS0E	SFAS0E	SFAS0E	SFAS0E
Mean	8.77	8.71	8.78	8.69	1.27	1.48	1.3	1.62
Minimum	2	2	2	2	0	0	0	0
Median	4	4	4	4	0	0	0	0
Maximum	595	595	595	595	17.9	17.9	17.9	17.9

Table 5.10: Regulated Flows for E-Flow Control Points of Brazos

	Regulated Flows (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	BRBR5E	BRBR5E	BRBR5E	BRBR5E
Mean	8714.27	8735.82	8662.99	8688.92
Minimum	0.09	0	0	0
Median	2503.5	2283.52	2573.52	2331.11
Maximum	634275.12	700301.25	298670.12	662459.12
CP	BRGR3E	BRGR3E	BRGR3E	BRGR3E
Mean	2164.76	2161.37	2165.61	2155.8
Minimum	0	0	0	0
Median	459.53	394.49	451.2	382.47
Maximum	256915.03	250203.52	233547.45	268464.19
CP	BRHE6E	BRHE6E	BRHE6E	BRHE6E
Mean	12085.06	12110.75	12043.36	12087.14
Minimum	0.13	0	0	0
Median	3942.99	3634.2	4058.07	3757.31
Maximum	654715.75	753263	304073.44	748760.31
CP	BRPP2E	BRPP2E	BRPP2E	BRPP2E
Mean	1623.33	1638.9	1610.41	1612.95
Minimum	2.66	0	0	0
Median	353.34	287.2	339.3	283.39
Maximum	174810.06	202917.58	185702.09	192411.59
CP	BRRI7E	BRRI7E	BRRI7E	BRRI7E
Mean	12973.35	13007.58	12933.6	12978.91
Minimum	0	0	0	0
Median	3892.17	3842.97	4118.79	3932.83
Maximum	520225.72	635461	294468.66	611991.06

Table 5.10: Continued

	Regulated Flows (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	BRRO7E	BRRO7E	BRRO7E	BRRO7E
Mean	12645.15	12738.83	12608.08	12690.14
Minimum	8.44	0	0	0
Median	3324.75	3197.74	3395.68	3226.86
Maximum	372546.84	382886.47	334672.06	382364.25
CP	BRSB2E	BRSB2E	BRSB2E	BRSB2E
Mean	1436.52	1441.22	1423.79	1415.27
Minimum	0	0	0	0
Median	215.58	191.16	216.79	190.92
Maximum	184254.09	184577.36	179752.94	184572.8
CP	BRSE1E	BRSE1E	BRSE1E	BRSE1E
Mean	597.12	595.98	588.08	583.32
Minimum	0	0	0	0
Median	87.94	87.11	87.17	83.41
Maximum	92764.84	92766.9	83584.77	92727.05
CP	BRWA4E	BRWA4E	BRWA4E	BRWA4E
Mean	3801.72	3791.16	3795.55	3801.96
Minimum	0	0	0	0
Median	1192.65	1028.91	1189.99	1049.84
Maximum	403305.56	409562.03	114922.61	376713.31
CP	CFFG1E	CFFG1E	CFFG1E	CFFG1E
Mean	350.19	348.91	334.87	335.66
Minimum	0	0	0	0
Median	29.06	19.64	29.49	17.1
Maximum	160242.41	160721.27	159959.7	160721.25

Table 5.10: Continued

	Regulated Flows (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	CFNU1E	CFNU1E	CFNU1E	CFNU1E
Mean	177.63	179.25	162.33	169.95
Minimum	0	0	0	0
Median	30.85	10.63	31.24	10.11
Maximum	36662.69	38215.62	29378.11	37769.96
CP	DMAS0E	DMAS0E	DMAS0E	DMAS0E
Mean	250.97	249.55	237.71	231.57
Minimum	0	0	0	0
Median	19.1	16.15	18.39	10.79
Maximum	110208.44	110268.51	96482.35	110240.66
CP	LAKE5E	LAKE5E	LAKE5E	LAKE5E
Mean	316.69	316.92	316.74	316.49
Minimum	0	0	0	0
Median	52.54	52.29	52.61	51.66
Maximum	93076.46	93077	92939.51	93075.49
CP	LEGT4E	LEGT4E	LEGT4E	LEGT4E
Mean	654.61	656.74	638.74	641.2
Minimum	0	0	0	0
Median	85.94	71.54	89.54	64.54
Maximum	94353.9	94458.88	75989.27	93359.14
CP	LRCA5E	LRCA5E	LRCA5E	LRCA5E
Mean	3000.58	3024.41	2951.61	2965.03
Minimum	0	0	0	0
Median	568.38	586.09	621.79	572.94
Maximum	269230.91	294935.66	264398.22	287497.38

Table 5.10: Continued

	Regulated Flows (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	LRLR5E	LRLR5E	LRLR5E	LRLR5E
Mean	1722.58	1739.78	1690.13	1697.59
Minimum	0	0	0	0
Median	284.7	301.96	323.4	278.88
Maximum	190340.41	196806.45	125557.66	182225.5
CP	NAEA6E	NAEA6E	NAEA6E	NAEA6E
Mean	656.78	658.85	660.13	672.68
Minimum	0	0	0	0
Median	36.86	28.89	39.25	28.97
Maximum	136185.78	136156.28	135624.89	136117.23
CP	NBCL3E	NBCL3E	NBCL3E	NBCL3E
Mean	449.86	447.93	450.18	449.98
Minimum	0	0	0	0
Median	40.8	37.6	40.8	39.27
Maximum	183097.48	182987.23	182822.36	183003.22
CP	SFAS0E	SFAS0E	SFAS0E	SFAS0E
Mean	173.76	172.91	169.92	168.69
Minimum	0	0	0	0
Median	12.48	10.82	12.25	9.34
Maximum	46213.51	46213.68	42798.14	46213.51

The general observation from the above comparisons is that the regulated flows for the simulation with optimization-based routing parameters values are generally higher than the regulated flows from the three other simulations. This pattern in the Brazos is not as consistent as it was for the Neches River Basin. The instream flow targets and shortages are similar for all the simulations. For some of the control points, the high regulated flows with the optimization-based parameters values cause mean shortages to be lower than the other simulations.

Trinity River Basin

The total simulated end-of-day storage from the thirteen large reservoirs of the Trinity River Basin for different simulation options is summarized in Figure 5.4. These thirteen reservoirs account for most of the storage capacity in the basin. With routing and forecasting activated, the simulated storage is higher than simulated storage with routing and forecasting deactivated. The simulation employing optimization-based routing parameters values result in higher storage levels than the simulation with DFLOW-based routing parameters.

There are four gauging stations in the Trinity River Basin with SB3 environmental flow standards. These instream flow requirements are incorporated in the Trinity WAM at control points 8TRDAE, 8TROAE, 8TRROE, and 8WTGPE. As discussed in Chapter I, the purpose of improving daily modeling capabilities is to be better equipped to model environmental flow needs. The effects of different simulation options and routing parameters on SB3 e-flow targets and shortages at these five control points are explored in Table 5.11. The mean, median, and range of regulated flows at these sites are compared in Table 5.12.

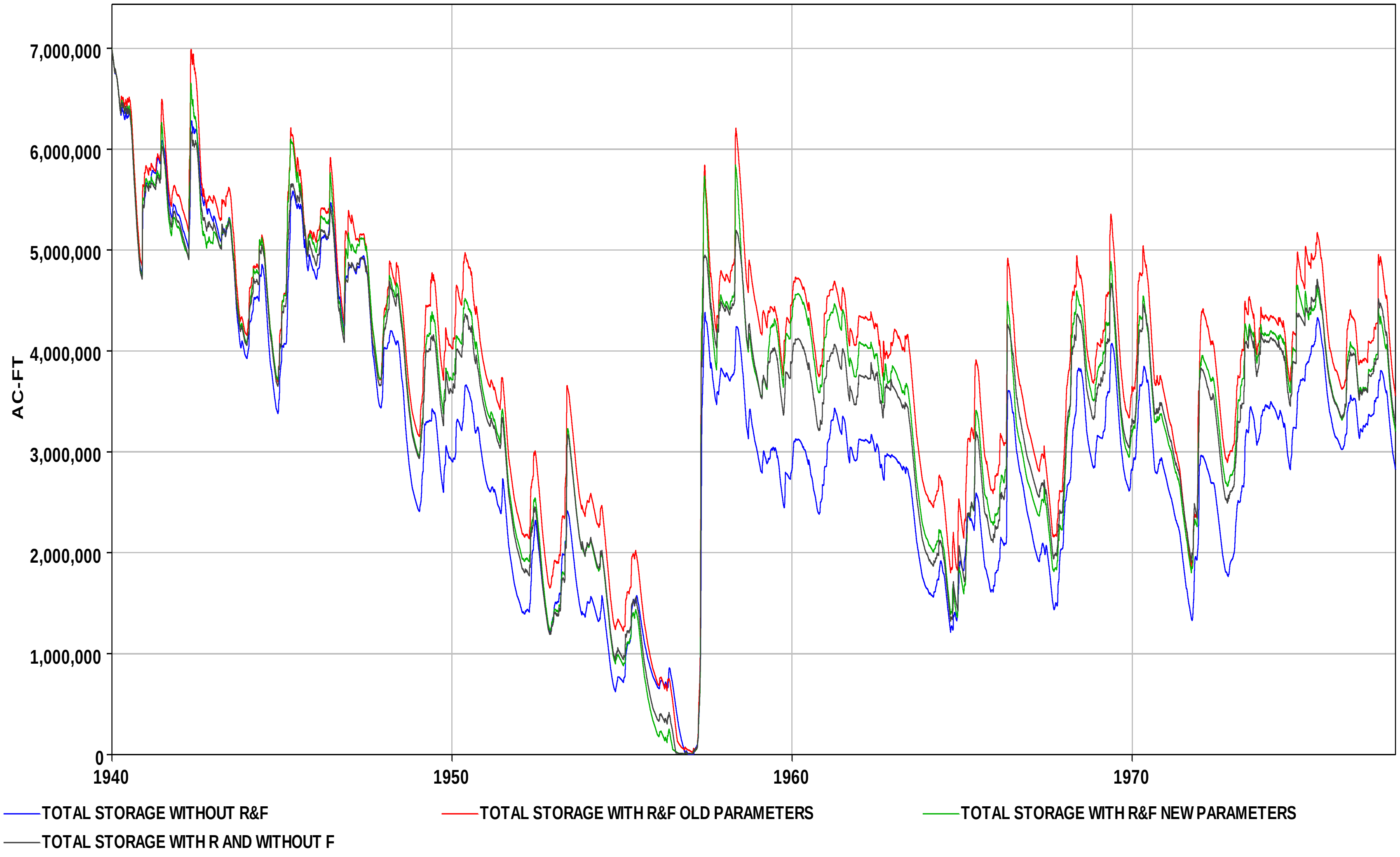

Figure 5.4: Storage in Large Reservoirs of Trinity River Basin for Different Simulation Options

Table 5.11: Instream Targets and Shortages for E-Flow Control Points of Trinity

	Instream Targets (Ac-ft)				Instream Shortages (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	8TRDAE	8TRDAE	8TRDAE	8TRDAE	8TRDAE	8TRDAE	8TRDAE	8TRDAE
Mean	211.8	192.78	231.51	185.54	6	17.72	23.43	24.53
Minimum	29.8	29.8	29.8	29.8	0	0	0	0
Median	99.2	79.3	99.2	73.4	0	0	0	0
Maximum	7933.9	7933.9	7933.9	7933.9	101.78	548.38	7933.9	7933.9
CP	8TROAE	8TROAE	8TROAE	8TROAE	8TROAE	8TROAE	8TROAE	8TROAE
Mean	927.96	972.2	989.43	968.05	29.76	20.99	40.57	32.81
Minimum	148.8	148.8	148.8	148.8	0	0	0	0
Median	515.7	515.7	515.7	515.7	0	0	0	0
Maximum	13884.3	13884.3	13884.3	13884.3	674.76	2772.79	13884.3	13302.06
CP	8TRROE	8TRROE	8TRROE	8TRROE	8TRROE	8TRROE	8TRROE	8TRROE
Mean	2157.59	2098.28	2128.82	2117.59	9.15	49.2	45.67	55.24
Minimum	396.7	396.7	396.7	396.7	0	0	0	0
Median	1239.7	1239.7	1239.7	1239.7	0	0	0	0
Maximum	19834.7	19834.7	19834.7	19834.7	1109.16	10503.52	19834.7	16840
CP	8WTGPE	8WTGPE	8WTGPE	8WTGPE	8WTGPE	8WTGPE	8WTGPE	8WTGPE
Mean	99.95	100.31	101.5	97.89	6.06	6.84	6.5	8.42
Minimum	37.7	37.7	37.7	37.7	0	0	0	0
Median	69.4	69.4	69.4	69.4	0	0	0	0
Maximum	2380.2	2380.2	2380.2	2380.2	89.64	410.3	2380.2	2380.2

Table 5.12: Regulated Flows for E-Flow Control Points of Trinity

	Regulated Flows (Ac-ft)			
	Without R&F	With R and Without F	With R&F Old Parameters	With R&F New Parameters
CP	8TRDAE	8TRDAE	8TRDAE	8TRDAE
Mean	2673.24	2779.03	2046.89	2425.06
Minimum	-2.58	0	0	0
Median	424.32	145.86	436.74	63.57
Maximum	309597.97	312169.41	166151.16	304047.28
CP	8TROAE	8TROAE	8TROAE	8TROAE
Mean	8453.81	8329.8	7518.67	7967.68
Minimum	-2.29	0	0	0
Median	1910.24	2317.15	2193.3	2296.12
Maximum	357262.31	396348.91	417345.12	400782.41
CP	8TRROE	8TRROE	8TRROE	8TRROE
Mean	12840.59	12725.37	11920.67	12379.98
Minimum	0	0	0	0
Median	4348.76	4598.51	4433.53	4558.83
Maximum	416692.88	523828.53	500920.09	360382.5
CP	8WTGPE	8WTGPE	8WTGPE	8WTGPE
Mean	1057.8	1013.91	985.01	973.34
Minimum	-2.58	0	0	0
Median	175.65	189.36	191.72	166.24
Maximum	131242.61	106069.29	115549.52	101622.34

The general observation from the above comparisons is entirely different from that of the results of the Brazos and Neches River Basins. With routing and forecasting activated, the mean of regulated flow is lower than the mean with routing and forecasting deactivated. The median of regulated flows is similar for all the simulation options. Unlike the other river basins, optimization-based routing parameters values were not very small and were close to the

DFLOW-based routing parameters values for Trinity River Basin. Instream flow targets from all the simulations were similar. Instream flow shortages were higher for simulation with routing and forecasting activated, this is because of low simulated regulated flows.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Routing and forecasting capabilities are components of the daily version of the WRAP simulation model recently developed to integrate environmental flow standards into the TCEQ WAM System. Routing adjusts the available flows at the downstream control points for withdrawal, return flows, and reservoir management decisions occurring upstream. Routing allows the computations to consider the delay in effects happening at downstream due to travel time in rivers. Forecasting considers future flow conditions while making today's decisions. This protects downstream senior water rights in future days from negative effects of junior upstream water rights. The forecasting computational algorithms allow model to look a certain number of days, the forecast period, into the future in determining water availability and/or remaining flood flow capacities.

The lag and attenuation method for routing flows is used in all six of the daily WAMs. The lag and attenuation method of routing requires two parameters for each reach. The lag parameter is the time taken by the effects of flow changes at upstream point to arrive at the downstream point. The attenuation parameter between two points is related to dispersion of flow change over time. The attenuation parameter cannot be less than 1.0 day and for most of the routing reaches it is set at 1.0 day in the current WAMs.

The three strategies discussed in this research to estimate routing parameters are:

1. Optimization of routing parameters based on comparison of hydrographs at upstream and downstream points. This function is available in the DAY program.
2. Wave travel velocity equation, which is developed using historical observed travel times in Brazos River and its tributaries.
3. Statistical analysis of lags and attenuations based on the flow change events in the time series record of upstream and downstream control points. This function is available in the DFLOW supplementary program of DAY program.

The results of the comparisons between different routing parameters sets show that the routing parameters currently used in the Brazos and Neches WAMs are unrealistic and cannot be justified if compared with the physical characteristics of the reach like length, flow, slope, and average river velocity. DFLOW-based routing parameters for these reaches have been developed and should be adopted in the daily WAMs of Brazos and Neches. The Trinity WAM's current routing parameters have values in the same range as of the new routing parameters from DFLOW.

The comparison of the graphs of simulated end-of-day reservoir storage in the basin for different simulation options show a consistent trend of the storage being high for simulations with the optimization-based routing parameters values. Generally, the simulations employing DFLOW-based routing parameters have slightly lower storages and are closer to the storages of simulations without routing and forecasting activated.

Similarly, the regulated flows from the simulations employing optimization-based routing parameters values are generally high in comparison to regulated flows from the other simulations. This is leading to fewer shortages of environmental flows at the e-flow control points for simulation employing optimization-based routing parameters.

With very limited observed data available for lag times in the rivers, it is hard to comment on the validity of any method and results. Future research involving comparisons with observed data can be useful in gauging the accuracy of DFLOW method.

Wave travel velocity equation developed in this research is another alternative method for estimating the lag times in reaches. The equation can be significantly improved by incorporating more data points or developing separate equations for each river basin. Other factors such as cross-sectional shape of the stream, lateral inflows, vegetation can also be included in the equation to improve the correlation between the equation and data points.

Attenuation parameter is adopted as 1 day for all kinds of reaches in this research as well as in previously adopted routing parameters. The research fails to find any conclusive reason for not adopting attenuation parameter as 1 day. Less attention has been paid to the measure of attenuation in this research as well as generally in the literature. More research is required to justify the adoption of 1 day routing parameter for all the reaches and to suggest in what kind of reaches the attenuation will not be 1 day.

It must be noted here that the estimation of routing parameter is approximate for any kind of method as nothing is directly based on the laws of physics. All the research done in this study is empirical and prone to human understanding of the subject.

In the continuation of this research, the DFLOW method should be applied to the remaining three Texas Daily WAMs. The results should be analyzed to see if they are following the same pattern as in this research. DFLOW should also be applied on reaches of the river from other parts of the world that have observed lag times and the results should be compared with the observed data.

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APPENDIX A

Calculations for Data Points of Normal Flow Equation for Conveyance Factor

From	Water Surface Elevation	Flow	To	Water Surface Elevation	Flow	Length	Lag	Slope	V_T	lag (days)/ mile	$K = \frac{L}{-T\sqrt{S}}$	Avg Flow
-	feet	cfs	-	feet	cfs	miles	days	-	miles/days	-	-	cfs
Possum Kingdom	866	107	Palo Pinto Gage	836	155	20	0.51	0.0003	39.61	0.025	2285	131
Palo Pinto Gage	836	155	Dennis Gage	700	207	78	1.96	0.0003	39.54	0.025	2169	181
Dennis Gage	700	207	Lake Granbury	692	-	47	1.53	0.0000	30.92	0.032	5474	207
Lake Granbury	634	22	Glen Rose Gage	567	272	31	1.70	0.0004	18.35	0.054	944	147
Glen Rose Gage	567	272	Lake Whitney	527	-	69	4.30	0.0001	16.02	0.062	1518	272
Lake Whitney	527	-	Aquilla Creek/Brazos confluence	-	-	25	0.56	-	45.18	0.022	-	-
Lake Aquilla	537	-	Aquilla Creek gage	485	2	5	0.12	0.0020	41.67	0.024	937	269
Aquilla Creek gage	485	2	Aquilla creek / Brazos confluence	414	-	18	0.44	0.0007	41.36	0.024	1525	2
Aquilla creek / Brazos confluence	414	-	Waco gage	352	733	17	0.44	0.0007	38.41	0.026	1454	733
Waco gage	352	733	Highbank gage	282	920	54	1.39	0.0002	38.56	0.026	2467	827
Lake Proctor	1118	9	Leon River at Gates ville gage	727	37	129	4.27	0.0006	30.23	0.033	1274	23
Leon River at Gates ville gage	727	37	Lake Belton	593	-	82	2.73	0.0003	30.15	0.033	1719	37
Lake Belton	593	-	Leon River at near Belton Gage	480	58	4	0.19	0.0061	18.42	0.054	236	58
Leon River near Belton Gage	480	58	Little River Gage	403	219	19	0.91	0.0008	20.99	0.048	757	139
Lake Stillhouse Hollow Dam	622	-	Lampasas River near Belton gage	482	14	3	0.14	0.0088	21.43	0.047	228	14
Lampasas River near Belton gage	482	14	Little River gage	403	219	19	0.95	0.0008	19.89	0.050	708	117
Little River gage	403	219	Little /San Gabriel confluence	305	200	52	1.72	0.0004	29.94	0.033	1575	210
Lake Georgetown	785	-	N San Gabriel Gage	693	6	1	0.03	0.0173	33.33	0.030	253	6
N San Gabriel Gage	693	6	Lake Granger	504	-	36	0.97	0.0010	36.60	0.027	1152	6
Lake Granger	504	-	Laneport Gage	418	52	5	0.13	0.0033	38.46	0.026	673	52
Laneport Gage	418	52	Little /San Gabriel confluence	305	200	26	0.68	0.0008	38.53	0.026	1347	126
Little /San Gabriel confluence	305	200	Little River at Cameron Gage	284	438	11	0.36	0.0004	29.72	0.034	1573	319
Little River at Cameron Gage	284	438	Brazos /Little confluence	226	-	34	1.12	0.0003	30.00	0.033	1653	438
Highbank gage	282	920	Brazos /Little confluence	226	-	35	0.90	0.0003	38.44	0.026	2186	920
Brazos /Little confluence	226	-	Bryan gage	194	1780	31	0.80	0.0002	38.63	0.026	2744	1780
Bryan gage	194	1780	Brazos/Yegua confluence	174	-	38	0.99	0.0001	38.48	0.026	3892	1780
Lake SomeRiverille	238	-	Yegua gage	201	6	1	0.07	0.0054	18.57	0.054	252	6
Yegua gage	201	6	Brazos/Yegua confluence	174	-	19	1.01	0.0003	18.61	0.054	1138	6
Brazos/Yegua confluence	174	-	Brazos/Navasota Confluence	149	-	17	0.43	0.0003	38.60	0.026	2286	-
Lake Limestone	362	-	Easterly gage	276	27	26	1.21	0.0006	21.32	0.047	846	27

Calculations for Data Points of Normal Flow Equation for Conveyance Factor

From	Water Surface Elevation	Flow	To	Water Surface Elevation	Flow	Length	Lag	Slope	V_T	lag (days)/ mile	$K = \frac{L}{-T\sqrt{S}}$	Avg Flow
-	feet	cfs	-	feet	cfs	miles	days	-	miles/days	-	-	cfs
Easterly gage	276	27	Brazos/Navasota Confluence	149	-	106	5.31	0.0002	19.91	0.050	1322	27
Brazos/Navasota Confluence	149	-	Hempstead gage	120	2400	33	0.87	0.0002	38.39	0.026	3005	2400
Hempstead gage	120	2400	Richmond Gage	39	1880	101	2.62	0.0002	38.55	0.026	3129	2140
Richmond Gage	39	1880	Rosharon Gage	8	3050	35	0.92	0.0002	38.37	0.026	2944	2465
Rosharon Gage	8	-	Gulf of Mexico	-	-	-	-	-	-	-	-	-
Mansfield Dam	490	1100	Bastrop	311	1340	84	1.00	0.0004	84.00	0.012	4181	1220
Mansfield Dam	490	1100	La Grange	214	1230	142	2.00	0.0004	71.00	0.014	3704	1165
Mansfield Dam	490	1100	Columbus	157	1530	183	3.00	0.0003	61.00	0.016	3286	1315
Mansfield Dam	490	1100	Wharton	62	1220	249	5.00	0.0003	49.80	0.020	2759	1160
Mansfield Dam	490	1100	Bay City	4	856	282	6.00	0.0003	47.00	0.021	2601	978

APPENDIX B

Calculations for Data Points of High Flow Equation for Conveyance Factor

From	Water Surface Elevation	Flow	To	Water Surface Elevation	Flow	Length	Time	Slope	VT	lag (days)/ mile	$K = \frac{L}{T\sqrt{S}}$	Avg Flow
-	feet	cfs	-	feet	cfs	miles	days	-	miles/days	-	-	cfs
West Fork Trinity River near Jacksboro	875	111	Bridgeport Reservoir above Bridgeport	836	-	36	1.00	0.0002	35.90	0.028	2486	111
Bridgeport Reservoir above Bridgeport	836	-	West Fork Trinity River near Boyd	671	451	28	1.25	0.0011	22.40	0.045	670	451
West Fork Trinity River near Boyd	671	451	Eagle Mountain Reservoir above Fort Worth	649	-	26	1.50	0.0002	17.00	0.059	1349	451
Lake Worth above Fort Worth	594	-	West Fork Trinity River at Fort Worth	521	1030	10	0.25	0.0014	40.00	0.025	1077	1030
West Fork Trinity River at Fort Worth	521	1030	West Fork Trinity River at Grand Prairie	415	1660	40	1.25	0.0005	31.92	0.031	1424	1345
West Fork Trinity River at Grand Prairie	415	1660	Trinity River at Dallas	395	5910	13	0.38	0.0003	32.89	0.030	1886	3785
Trinity River at Dallas	395	5910	Trinity River near Rosser	317	9164	50	1.75	0.0003	28.80	0.035	1684	7537
Trinity River near Rosser	317	9164	Trinity River at Trinidad	262	12900	60	2.75	0.0002	21.75	0.046	1641	11032
Trinity River at Trinidad	262	12900	Trinity River near Long Lake (Oakwood)	208	15400	75	3.75	0.0001	20.00	0.050	1721	14150
Trinity River near Long Lake (Oakwood)	208	15400	Trinity River near Crockett	168	19200	46	1.50	0.0002	30.67	0.033	2364	17300
Trinity River near Crockett	168	19200	Trinity River near Riverside	133	18100	130	3.75	0.0000	34.69	0.029	4910	18650
Trinity River near Goodrich	63	23650	Trinity River at Romayor	51	23000	14	0.50	0.0002	28.60	0.035	2334	23325
Trinity River at Romayor	51	23000	Trinity River at Liberty	21	39000	47	1.00	0.0001	46.80	0.021	4246	31000
Trinity River at Liberty	21	39000	Trinity River at Moss Bluff	14	-	27	1.50	0.0001	18.00	0.056	2497	39000
Lake Alan Henry near Justiceburg	2220	-	Mountain Fork Brazos River near Aspermont	1625	182	127	2.50	0.0009	50.92	0.020	1711	182
Double Mountain Fork Brazos River near Aspermont	1625	182	Brazos River at Seymour	1242	546	115	1.75	0.0006	65.71	0.015	2616	364
Brazos River at Seymour	1242	546	Brazos River near South Bend	1009	1250	97	2.00	0.0005	48.50	0.021	2278	898
Brazos River near South Bend	1009	1250	Possum Kingdom Lake near Graford	999	-	66	1.00	0.0000	66.00	0.015	12012	1250

Calculations for Data Points of High Flow Equation for Conveyance Factor

From	Water Surface Elevation	Flow	To	Water Surface Elevation	Flow	Length	Time	Slope	VT	lag (days)/ mile	$K = \frac{L}{T\sqrt{S}}$	Avg Flow
-	feet	cfs	-	feet	cfs	miles	days	-	miles/days	-	-	cfs
Possum Kingdom Lake near Graford	999	-	Brazos River near Dennis	703	1800	101	2.25	0.0006	44.89	0.022	1904	1800
Brazos River near Dennis	703	1800	Lake Granbury near Granbury	693	-	46	0.50	0.0000	92.00	0.011	14414	1800
Lake Granbury near Granbury	693	-	Brazos River near Glen Rose	569	2500	32	0.04	0.0007	800.00	0.001	29594	2500
Brazos River near Glen Rose	569	2500	Lake Whitney near Whitney	533	-	65	0.75	0.0001	86.67	0.012	8482	2500
Brazos River below Whitney Dam near Aquilla	415	3070	Brazos River at Waco	356	5020	33	0.75	0.0003	43.33	0.023	2342	4045
Brazos River at Waco	356	5020	Brazos River near Highbank	286	6240	60	1.25	0.0002	48.00	0.021	3233	5630
Brazos River near Highbank	286	6240	Brazos River at SH 21 near Bryan	202	13000	68	1.50	0.0002	45.33	0.022	2961	9620
Brazos River at Washington	158	24660	Brazos River near Hempstead	133	18300	32	1.00	0.0001	32.00	0.031	2654	21480
Brazos River near Hempstead	133	18300	Brazos River at Richmond	52	18600	105	1.50	0.0001	70.00	0.014	5784	18450
Brazos River at Richmond	52	18600	Brazos River near Rosharon	25	21500	38	0.75	0.0001	50.67	0.020	4373	20050

APPENDIX C

Application of Wave Travel Velocity Equation on Brazos River Basin for Normal Flow Conditions

U/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	D/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	Length	Slope	Avg Flow	K	Lag from Equation	Lag from Calibration	Lag/mile from Equation	Lag/mile from Calibration
		ft	cfs			ft	cfs	miles		cfs	mile/day	days	days	days/mile	days/mile
DMAS0E	08080500	1621	8	BRSE1E	08082500	1240	40	115	0.0006	24	854	5.38	1.30	0.05	0.01
SFAS0E	08082000	1592	6	BRSE1E	08082500	1240	40	108	0.0006	23	841	5.17	0.71	0.05	0.01
CFNU1E	08084000	1534	10	CFFG1E	08085500	1177	22	96	0.0007	16	768	4.71	1.38	0.05	0.01
CFFG1E	08085500	1177	22	BRSB2E	08088000	1008	108	77	0.0004	65	1097	3.44	1.38	0.04	0.02
BRSE1E	08082500	1240	40	BRSB2E	08088000	1008	108	97	0.0005	74	1134	4.01	0.79	0.04	0.01
BRSB23	08088000	1008	108	51553R	08088435	996		66	0.0000	108	1249	9.32	0.52	0.14	0.01
51553R	08088610	867	108	BRDE29	08090800	700	208	101	0.0003	158	1375	4.12	1.44	0.04	0.01
BRDE29	08090800	700	208	515631	08090900	692		46	0.0000	208	1475	5.45	0.26	0.12	0.01
51563R	08090905	634	22	BRGR30	08091000	567	273	32	0.0004	148	1352	1.14	0.50	0.04	0.02
BRGR3E	08091000	567	273	515731	08092500	527		65	0.0001	273	1581	3.79	0.50	0.06	0.01
51573R	08093100	412	535	CON070	-	391	-	28	0.0002	535	1875	1.08	0.29	0.04	0.01
51583R	08093360	485	2	AQAQ34	08093500	-	4	-	-	3	504	not applicable	0.29	not applicable	not applicable
AQAQ34	08093360	485	2	CON070	-	390	-	19	0.0010	2	435	1.37	0.00	0.07	0.00
227901	-	747	-	NBCL36	08095000	607	23	22	0.0012	23	843	0.75	0.18	0.03	0.01
NBCL3E	08095000	607	23	509431	08095550	460		40	0.0007	23	843	1.80	0.50	0.04	0.01
50943R	08095600	368	7	BRWA41	08096500	352	735	10	0.0004	371	1709	0.31	0.05	0.03	0.01
CON070	-	390	-	BRWA41	08096500	352	735	16	0.0005	735	2033	0.37	0.40	0.02	0.03
BRWA4E	08096500	352	735	BRHB42	08098290	282	923	60	0.0002	829	2096	1.94	0.72	0.03	0.01
51593R	08099500	1118	9	LEGT47	08100500	727	37	120	0.0006	23	843	5.72	2.50	0.05	0.02
LEGT4E	08100500	727	37	516031	08102000	593		77	0.0003	37	951	4.47	1.47	0.06	0.02
51613R	08104100	482	14	CON095	-	432	-	15	0.0008	14	743	0.71	0.29	0.05	0.02
CON095	0	432	-	LRLR53	08104500	403	221	7	0.0055	221	1498	0.06	0.29	0.01	0.04
51603R	08102500	480	58	LRLR53	08104500	403	221	23	0.0008	140	1333	0.60	0.38	0.03	0.02
51623R	08104700	693	6	GAGE56	08105000	646	32	5	0.0030	19	802	0.11	0.17	0.02	0.03
SGGE55	08104900	690	10	GAGE56	08105000	646	32	3	0.0028	21	823	0.07	0.17	0.02	0.06
GAGE56	08105000	646	32	516331	08105600	504		28	0.0010	32	916	0.99	0.50	0.04	0.02
51633R	08105700	418	52	CON102	-	334	-	26	0.0008	52	1037	0.87	0.44	0.03	0.02
CON102	-	334	-	LRCA58	08106500	284	439	16	0.0006	439	1783	0.37	0.00	0.02	0.00
LRLR5E	08104500	403	221	LRCA58	08106500	284	439	62	0.0004	330	1659	1.96	1.24	0.03	0.02
LRCA5E	08106500	284	439	BRBR59	08109000	197	1780	67	0.0002	1110	2258	1.88	0.79	0.03	0.01
BRHB42	08098290	282	923	BRBR59	08109000	197	1780	68	0.0002	1352	2374	1.85	1.16	0.03	0.02
51653R	0	336	-	NAEA66	08110500	276	27	17	0.0029	27	878	0.36	0.50	0.02	0.03
NAEA6E	08110500	276	27	CON137	-	258	-	14	0.0002	27	878	1.04	1.00	0.07	0.07
CON137	-	258	-	NABR67	08111000	228	54	20	0.0003	54	1047	1.14	1.00	0.06	0.05
NABR67	08111000	228	54	CON145	-	183	-	39	0.0002	54	1047	2.50	1.50	0.06	0.04

Application of Wave Travel Velocity Equation on Brazos River Basin for Normal Flow Conditions

U/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	D/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	Length	Slope	Avg Flow	K	Lag from Equation	Lag from Calibration	Lag/mile from Equation	Lag/mile from Calibration
		ft	cfs			ft	cfs	miles		cfs	mile/day	days	days	days/mile	days/mile
CON145	-	-	-	CON231	-	-	-	21	-	-	-	not applicable	0.25	not applicable	0.01
51643R	08110000	201	6	CON129	-	176	-	14	0.0004	6	594	1.25	0.17	0.09	0.01
BRBR5E	08109000	197	1780	CON147	-	148	-	56	0.0002	1780	2546	1.72	0.64	0.03	0.01
CON129	-	-	-	CON147	-	-	-	23	-	-	-	not applicable	0.16	not applicable	0.01
CON231	-	-	-	CON147	-	-	-	6	-	-	-	not applicable	0.00	not applicable	0.00
CON147	-	156	-	BRHE68	08111500	120	2410	32	0.0002	2410	2750	0.80	0.58	0.02	0.02
BRHE6E	08111500	120	2410	BRRI70	08114000	39	1905	105	0.0001	2158	2673	3.25	1.21	0.03	0.01
BRRI7E	08114000	39	1905	BRRO72	08116650	8	3070	38	0.0002	2488	2772	1.09	0.53	0.03	0.01
BRRO7E	08116650	8	3070	OUT	-	0		0	-	3070	2924	not applicable	0.00	not applicable	-

* WSE = Water Surface Elevation

APPENDIX D

Application of Wave Travel Velocity Equation on Brazos River Basin for High Flow Conditions

U/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	D/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	Length	Slope	Avg Flow	K	Lag from Equation	Lag from Calibration	Lag/mile from Equation	Lag/mile from Calibration
		ft	cfs			ft	cfs	miles		cfs		days	days	days/mile	days/mile
DMAS0E	08080500	1625	182	BRSE1E	08082500	1242	546	115	0.0006	364	1573	2.91	0.00	0.03	0.00
SFAS0E	08082000	1592	110	BRSE1E	08082500	1242	546	108	0.0006	328	1549	2.81	0.00	0.03	0.00
CFNU1E	08084000	1534	101	CFFG1E	08085500	1181	272	96	0.0007	187	1425	2.55	0.00	0.03	0.00
CFFG1E	08085500	1181	272	BRSB2E	08088000	1009	1250	77	0.0004	761	1755	2.14	0.00	0.03	0.00
BRSE1E	08082500	1242	546	BRSB2E	08088000	1009	1250	97	0.0005	898	1798	2.53	0.00	0.03	0.00
BRSB23	08088000	1009	1250	51553R	08088435	999	-	66	0.0000	1250	1888	6.36	0.00	0.10	0.00
51553R	08088610	868	897	BRDE29	08090800	703	1800	101	0.0003	1349	1910	2.98	0.63	0.03	0.01
BRDE29	08090800	703	1800	515631	08090900	693	-	46	0.0000	1800	1993	3.62	0.21	0.08	0.00
51563R	08090905	636	122	BRGR30	08091000	569	2500	32	0.0004	1311	1902	0.81	0.47	0.03	0.01
BRGR3E	08091000	569	2500	515731	08092500	533	-	65	0.0001	2500	2093	3.04	0.50	0.05	0.01
51573R	08093100	415	3070	CON070	-	391	-	28	0.0002	3070	2157	0.87	0.22	0.03	0.01
51583R	08093360	487	94	AQAQ34	08093500	-	179	-	-	137	1360	not applicable	0.25	-	-
AQAQ34	08093360	487	94	CON070	-	390	-	19	0.0010	94	1287	0.46	0.00	0.02	0.00
227901	-	748	-	NBCL36	08095000	609	344	22	0.0012	344	1560	0.41	0.18	0.02	0.01
NBCL3E	08095000	609	344	509431	08095550	463	-	40	0.0007	344	1560	0.97	0.22	0.02	0.01
50943R	08095600	372	966	BRWA41	08096500	356	5020	10	0.0004	2993	2149	0.25	0.05	0.02	0.01
CON070	-	390	-	BRWA41	08096500	356	5020	16	0.0004	5020	2320	0.34	0.33	0.02	0.02
BRWA4E	08096500	356	5020	BRHB42	08098290	286	6240	60	0.0002	5630	2360	1.71	0.64	0.03	0.01
51593R	08099500	1120	310	LEGT47	08100500	730	730	120	0.0006	520	1658	2.92	1.58	0.02	0.01
LEGT4E	08100500	730	730	516031	08102000	596	-	77	0.0003	730	1744	2.44	1.19	0.03	0.02
51613R	08104100	485	779	CON095	-	432	-	15	0.0009	779	1761	0.29	0.26	0.02	0.02
CON095	0	432	-	LRLR53	08104500	414	3160	7	0.0035	3160	2167	0.05	0.12	0.01	0.02
51603R	08102500	483	1920	LRLR53	08104500	414	3160	23	0.0008	2540	2098	0.40	0.38	0.02	0.02
51623R	08104700	695	164	GAGE56	08105000	647	284	5	0.0030	224	1464	0.06	0.17	0.01	0.03
SGGE55	08104900	691	99	GAGE56	08105000	647	284	3	0.0028	192	1430	0.04	0.17	0.01	0.06
GAGE56	08105000	647	284	516331	08105600	506	-	28	0.0010	284	1516	0.60	0.33	0.02	0.01
51633R	08105700	421	722	CON102	-	334	-	26	0.0009	722	1741	0.51	0.38	0.02	0.01
CON102	-	334	-	LRCA58	08106500	293	4870	16	0.0005	4870	2310	0.31	0.00	0.02	0.00
LRLR5E	08104500	414	3160	LRCA58	08106500	293	4870	62	0.0004	4015	2245	1.44	1.07	0.02	0.02
LRCA5E	08106500	293	4870	BRBR59	08109000	202	13000	67	0.0003	8935	2527	1.66	0.75	0.02	0.01
BRHB42	08098290	286	6240	BRBR59	08109000	202	13000	68	0.0002	9620	2555	1.74	0.82	0.03	0.01
51653R	0	344	-	NAEA66	08110500	283	824	17	0.0029	824	1775	0.18	0.50	0.01	0.03
NAEA6E	08110500	283	824	CON137	-	258	-	14	0.0003	824	1775	0.43	1.00	0.03	0.07
CON137	-	266	-	NABR67	08111000	236	1480	20	0.0003	1480	1936	0.61	1.00	0.03	0.05
NABR67	08111000	236	1480	CON145	-	183	-	39	0.0003	1480	1936	1.26	1.50	0.03	0.04

Application of Wave Travel Velocity Equation on Brazos River Basin for High Flow Conditions

U/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	D/S Control Point WAM ID	USGS Gage Number	Median WSE*	Median Flow	Length	Slope	Avg Flow	K	Lag from Equation	Lag from Calibration	Lag/mile from Equation	Lag/mile from Calibration
		ft	cfs			ft	cfs	miles		cfs		days	days	days/mile	days/mile
CON145	-	-	-	CON231	-	-	-	21	-	-	-	not applicable	0.25	-	0.01
51643R	08110000	206	928	CON129	-	182	-	14	0.0004	928	1807	0.41	0.13	0.03	0.01
BRBR5E	08109000	202	13000	CON147	-	154	-	56	0.0002	13000	2671	1.64	0.52	0.03	0.01
CON129	-	-	-	CON147	-	-	-	23	-	-	-	not applicable	0.12	-	0.01
CON231	-	-	-	CON147	-	-	-	6	-	-	-	not applicable	0.00	-	0.00
CON147	-	169	-	BRHE68	08111500	133	18300	32	0.0002	18300	2810	0.78	0.56	0.02	0.02
BRHE6E	08111500	133	18300	BRRI70	08114000	52	18600	105	0.0001	18450	2814	3.08	0.97	0.03	0.01
BRRI7E	08114000	52	18600	BRRO72	08116650	25	21500	38	0.0001	20050	2848	1.15	0.53	0.03	0.01
BRRO7E	08116650	25	21500	OUT	-	0		0	-	21500	2878	not applicable	0.00	-	-

* WSE = Water Surface Elevation

APPENDIX E

Application of DFLOW on Reaches of Neches River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R1	KIBR	NEPA	31	lag/mile from R3	2.06	-	1.00	-	-	2.14	-	1.00
R2	NEPA	NENE	20	lag/mile from R3	1.33	-	1.00	-	-	1.38	-	1.00
R3	NENE	NEAL	61	DFLOW	4.07	1.00	1.00	81	4.22	4.22	1.00	1.00
R4	NEAL	NEDI	75	DFLOW	4.04	1.00	1.00	60	5.07	5.07	1.00	1.00
R5	NEDI	NERO	47	DFLOW	3.00	1.00	1.00	94	4.23	4.23	0.75	1.00
R6	NERO	NETB	45	lag/mile from R5 before confluence and and R7 after confluence	2.52	-	1.00	-	-	3.61	-	1.00
R7	NETB	NEEV	53	DFLOW	1.96	0.80	1.00	196	3.00	3.00	0.83	1.00
R8	NEEV	NEBA	25	DFLOW, because there is high correlation between flows in U/S and D/S gage despite being a confluence in between	1.14	1.50	1.00	10	2.13	2.13	1.33	1.00
R9	NEBA	NESL	28	lag/mile from R7	1.03	-	1.00	-	-	1.58	-	1.00
R10	MUTY	MUJA	26	lag/mile from R11	2.72	-	1.00	-	-	1.56	-	1.00
R11	MUJA	ANAL	47	DFLOW, because there is high correlation between flows in U/S and D/S gage despite being a confluence in between	4.93	1.00	1.00	38	2.82	2.82	0.50	1.00
R12	ANAL	ANLU	41	DFLOW	2.55	1.00	1.00	50	3.65	3.65	2.00	1.00
R13	ANLU	ANSR	83	DFLOW with an intermediate control point and then projecting the lag/mile to get the total lag	5.50	-	1.00	4	4.35	4.35	1.00	1.00
R14	ANSR	NETB	38	lag/mile from R13 before confluence and and R7 after confluence	2.14	-	1.00	-	-	2.04	-	1.00
R15	EFACU	ANAL	44	lag/mile from R11 as it is the most similar reach	4.61	-	1.00	-	-	2.64	-	1.00
R16	ATCH	ANSR	64	lag/mile from R11 as it is the most similar reach	6.71	-	1.00	-	-	3.84	-	1.00
R17	AYSA	ANSR	35	lag/mile from R11 as it is the most similar reach	3.67	-	1.00	-	-	2.10	-	1.00
R18	VIKO	NEBA	37	lag/mile from R19 as it is the most similar reach before confluence and lag/mile from R7 after confluence	2.61	-	1.00	-	-	3.01	-	1.00
R19	PISL	NEBA	31	DFLOW with an intermediate control point and then projecting the lag/mile to get the total lag	2.48	-	1.00	3	15.46	2.48	2.50	1.00

APPENDIX F

Application of DFLOW on Reaches of Brazos River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R1	RWPL01	WRSP02	93	Downstream has no gauge and there are very low flows, hence ignoring this reach	no routing	-	1.00	-	no routing	no routing	-	-
R2	WRSP02	SFPE04	90	Upstream has no gauge, using lag from R18 because of similar flows	6.75	-	1.00	-	0.00	1.72	-	1.00
R3	SFPE04	SFAS06	30	DFLOW	2.06	-	1.00	55	1.02	1.02	1.00	1.00
R4	SFAS06	BRSE11	106	Low correlation bewteen u/s and d/s, hence using lag/mile form uppper reach before confluence and from R21 after confluence	4.16	-	1.00	-	106.00	3.04	-	1.00
R5	BRSE11	BRSB23	93	DFLOW	2.18	1.00	1.00	273	1.80	1.80	1.00	1.00
R6	BRSB23	SHGR26	65	Using lag/mile from R7	3.25	-	1.00	-	0.00	3.22	-	1.00
R7	SHGR26	BRPP27	20	DFLOW	1.00	1.00	1.00	97	0.99	0.99	1.00	1.00
R8	BRPP27	BRDE29	79	DFLOW	2.01	1.00	1.00	385	1.84	1.84	1.00	1.00
R9	BRDE29	BRGR30	76	Using lag/mile form R10 before confluence and from R21 after confluence	1.93	-	1.00	-	0.00	1.77	-	1.00
R10	BRGR30	BRAQ33	73	DFLOW before dam was built	1.10	1.00	1.00	24	0.99	0.99	1.00	1.00
R11	BRAQ33	BRWA41	35	DFLOW	1.00	1.00	1.00	122	1.01	1.01	1.00	1.00
R12	BRWA41	BRHB42	57	DFLOW	1.07	1.00	1.00	206	1.00	1.00	1.00	1.00
R13	BRHB42	BRBR59	67	DFLOW	1.81	1.00	1.00	82	1.00	1.00	1.00	1.00
R14	BRBR59	BRHE68	86	DFLOW	1.98	1.00	1.00	189	1.00	1.00	1.00	1.00
R15	BRHE68	BRRI70	104	DFLOW	2.62	1.00	1.00	63	5.85	2.62	0.50	1.00
R16	BRRI70	BRRO72	36	DFLOW	0.92	1.00	1.00	113	1.78	0.92	1.00	1.00
R17	BRRO72	BRGM73	58	There is no down stream gauge, hence using R13 lag/mile because of simliarities	1.57	-	1.00	-	0.00	0.87	-	1.00
R18	DUGI03	SFPE04	53	DFLOW	3.00	-	1.00	22	1.01	1.01	1.00	1.00
R19	CRJA05	SFAS06	23	No Correlation, hence using R3 because that is the stream which forming the major portion of this reach	1.58	-	1.00	-	0.00	0.78	-	1.00
R20	DMJU08	DMAS09	127	Flows are too low and correlation is also low, using R18 before conflence and downstream reach after confluence	4.23	-	1.00	-	128.00	3.22	-	1.00
R21	DMAS09	BRSE11	113	DFLOW	3.12	1.00	1.00	295	3.00	3.00	1.00	1.00
R22	BSLU07	DMAS09	185	u/s is lake use, hence using similar reach	7.46	-	1.00	-	185.00	4.30	-	1.00
R23	NCKN10	BRSE11	75	No Correlation b/w u/s and d/s, hence using lag/mile from R21 which is forming the major operation of this reach	2.07	-	1.00	-	0.00	1.99	-	1.00
R24	MSMN12	BRSB23	102	No Correlation b/w u/s and d/s also the upstream flow is really low, hence ignoring this reach	no routing	-	1.00	-	no routing	no routing	-	1.00
R25	CFRO13	CFHA14	68	DFLOW	2.12	1.00	1.00	42	1.96	1.96	0.67	1.00
R26	CFHA14	CFNU16	20	DFLOW	1.98	1.00	1.00	41	1.10	1.10	1.00	1.00
R27	CFNU16	CFFG18	95	DFLOW	2.92	1.00	1.00	425	1.89	1.89	1.00	1.00

Application of DFLOW on Reaches of Brazos River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R28	CFFG18	CFEL22	62	DFLOW	2.01	1.00	1.00	85	1.00	1.00	1.00	1.00
R29	CFEL22	BRSB23	15	DFLOW	1.05	1.00	1.00	18	2.95	1.05	0.20	1.00
R30	MUHA15	CFNU16	18	No Correlation b/w d/s and u/s also the upstream CP is really close to the dominant stream R26. Using R26 lag/mile	no routing	-	1.00	-	no routing	no routing	-	1.00
R31	CAST17	CFFG18	67	No Correlation b/w d/s and u/s, using R25 lag/mile before confluence, and R27 lag/mile after confluence	2.08	-	1.00	-	67.00	1.69	-	1.00
R32	HCAL19	HCBR21	16	Dam in between u/s CP and d/s CP, hence using downstream reach lag/mile	1.15	-	1.00	-	0.00	0.78	-	1.00
R33	HCBR21	CFEL22	28	DFLOW	2.01	-	1.00	8	1.36	1.36	1.00	1.00
R34	BSBR20	HCBR21	17	Dam in between u/s CP and d/s CP, hence using downstream reach lag/mile	1.22	-	1.00	-	0.00	0.83	-	1.00
R35	GHGH24	SHGR26	58.5	Very low flow upstream and no correlation b/w u/s and d/s. Using R33 lag/mile before confluence and R7 lag/mile after confluence	1.84	-	1.00	-	19695.00	1.55	-	1.00
R36	CCIV25	SHGR26	35	Very low flow upstream and no correlation b/w u/s and d/s. Using R33 lag/mile before confluence and R7 lag/mile after confluence	1.82	-	1.00	-	5935.00	1.32	-	1.00
R37	PPSA28	BRDE29	33	DFLOW, though flow is vastly different correlation is 0.5	1.96	-	1.00	7	2.60	1.96	1.50	1.00
R38	PAGR31	BRAQ33	74	Vast flow difference, too close to dominant stream, dam in between, hence using R10 lag/mile	1.12	-	1.00	-	0.00	1.00	-	1.00
R39	NRBL32	BRAQ33	42	Vast flow difference, dam in between, hence using similar reach's lag/mile	1.09	-	1.00	-	880.00	0.85	-	1.00
R40	AQAQ34	BRWA41	35	Using lag/mile form R68 before confluence and from R10 after confluence	1.71	-	1.00	-	3861.00	1.72	-	1.00
R41	NBHI35	NBCL36	51	Upstream has no discharge data, using downstream reach's lag/mile	4.28	-	1.00	-	0.00	3.92	-	1.00
R42	NBCL36	NBVM37	13	DFLOW	1.09	-	1.00	24	1.00	1.00	1.00	1.00
R43	NBVM37	BOWA40	28	Dam in between, using similar reach's lag/mile	2.35	-	1.00	-	0.00	2.15	-	1.00
R44	BOWA40	BRWA41	9	U/s CP is very close to dominant stream R21 hence using it's lag/mile	0.26	-	1.00	-	0.00	0.26	-	1.00
R45	MBMG38	BOWA40	16	Dam in between, Use R42	1.34	-	1.00	-	0.00	1.23	-	1.00
R46	HGCR39	BOWA40	16	Dam in between, Use R42	1.34	-	1.00	-	0.00	1.23	-	1.00
R47	LEDL43	LEHS45	23	Dam in between, using downstream reach's lag/mile	0.96	-	1.00	-	0.00	0.58	-	1.00
R48	LEHS45	LEHM46	46	DFLOW	1.92	0.50	1.00	65	1.15	1.15	1.00	1.00
R49	LEHM46	LEGT47	76	DFLOW	1.95	1.00	1.00	134	1.78	1.78	1.00	1.00
R50	LEGT47	LEBE49	82	Dam in between and no flow data before that, hence using upper reach's lag/mile	2.10	-	1.00	-	0.00	1.92	-	1.00
R51	LEBE49	LRLR53	19	DFLOW	0.91	1.00	1.00	43	1.12	1.12	1.17	1.00
R52	LRLR53	LRCA58	62	DFLOW	1.09	1.00	1.00	193	1.04	1.04	1.00	1.00
R53	LRCA58	BRBR59	66	DFLOW	1.21	1.00	1.00	72	1.25	1.25	1.00	1.00

Application of DFLOW on Reaches of Brazos River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R54	SADL44	LEHS45	16	Dam in between and no flow data before that, hence using lower reach's lag/mile	0.67	-	1.00	-	0.00	0.40	-	1.00
R55	COPI48	LEBE49	40	Dam in between and no flow data before that, hence using R56 lag/mile because of similar flows	2.22	-	1.00	-	0.00	1.11	-	1.00
R56	LAKE50	LAYO51	36	DFLOW	2.00	0.80	1.00	35	1.00	1.00	0.67	1.00
R57	LAYO51	LABE52	23	Dam in between and no flow data before that, hence using upper reach's lag/mile	1.28	-	1.00	-	0.00	0.64	-	1.00
R58	LABE52	LRLR53	20	DFLOW	1.25	1.00	1.00	12	2.05	1.25	2.00	1.00
R59	NGGE54	GAGE56	4.5	Very short reach for routing. Ignoring routing.	no routing	-	1.00	-	-	-	-	1.00
R60	GAGE56	GALA57	32	DFLOW	1.19	1.00	1.00	14	1.00	1.00	0.50	1.00
R61	GALA57	LRCA58	38	DFLOW	1.96	0.75	1.00	100	1.16	1.16	1.00	1.00
R62	SGGE55	GAGE56	3.5	Very short reach for routing. Ignoring routing.	no routing	-	1.00	-	-	no routing	-	1.00
R63	MYDB60	YCSO62	33	Dam in between and no flow data before that, hence using R65 lag/mile because of similar flows	3.76	-	1.00	-	0.00	3.76	-	1.00
R64	YCSO62	BRHE68	67	Low flow corrlealtion (0.47) b/w u/s and d/s CPs, using R68 lag/mile before confluence and R14 lag/mile after confluence	2.58	-	1.00	-	12549.00	2.06	-	1.00
R65	EYDB61	YCSO62	28	DFLOW	3.19	1.00	1.00	5	7.05	3.19	0.60	1.00
R66	DCLY63	BRHE68	74	Low flow corrlealtion b/w u/s and d/s CPs, using R68 lag/mile before confluence and R14 lag/mile after confluence	3.12	-	1.00	-	13830.00	2.62	-	1.00
R67	NAGR64	NAEA66	32	Dam in between and no flow data before that, hence using lower reach's lag/mile	2.48	-	1.00	-	0.00	2.53	-	1.00
R68	NAEA66	NABR67	36	DFLOW	2.79	1.00	1.00	183	2.85	2.85	0.83	1.00
R69	NABR67	BRHE68	100	DFLOW	3.14	1.25	1.00	76	4.12	3.14	1.50	1.00
R70	BGFR65	NAEA66	50	Dam in between and no flow data before that, hence using lower reach's lag/mile	3.88	-	1.00	-	0.00	3.96	-	1.00
R71	MCBL69	BRRI70	70	Low flow corrlealtion b/w u/s and d/s CPs, using R68 lag/mile before confluence and R15 lag/mile after confluence	2.23	-	1.00	-	5490.00	2.25	-	1.00
R72	BGNE71	BRRO72	32	Low flow corrlealtion b/w u/s and d/s CPs, using R68 lag/mile	2.48	-	1.00	-	0.00	2.53	-	1.00

APPENDIX G

Application of DFLOW on Reaches of Trinity River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R1	8WTJA	8WTBO	63	Lake in between u/s and d/s CPs, so using R13 lag/mile because of similar flows	6.36	-	1.00	-	-	5.74	-	1.00
R2	8WTBO	8WTFW	46	Lake in between u/s and d/s CPs, so using R33 lag/mile because of similar flows	2.07	-	1.00	-	-	2.28	-	1.00
R3	8WTFW	8WTGP	39	DFLOW	0.99	1.00	1.00	198	1.03	1.03	1.00	1.00
R4	8WTGP	8TRDA	14	Correlation of 0.81 is there, but two streams flow into this reach, hence not using the original 0.214 lag/mile but the lag/mile of upper Reach	0.35	1.00	1.00	-	2.99	0.37	0.50	1.00
R5	8TRDA	8TRRS	47	DFLOW	2.00	1.00	1.00	277	3.04	3.04	0.81	1.00
R6	8TRRS	8TRTR	58	DFLOW	1.04	1.00	1.00	135	3.15	3.15	0.65	1.00
R7	8TRTR	8TROA	76	DFLOW	1.96	1.00	1.00	74	4.05	4.05	0.83	1.00
R8	8TROA	8TRCR	47	DFLOW	1.00	1.00	1.00	60	3.86	3.86	1.07	1.00
R9	8TRCR	8TRMI	32	DFLOW	1.00	1.00	1.00	8	3.83	3.83	1.05	1.00
R10	8TRMI	8TRRI	66	DFLOW	1.08	1.00	1.00	17	4.79	4.79	1.25	1.00
R11	8TRRI	8TRRO	69	DFLOW	2.00	1.00	1.00	54	3.05	3.05	0.88	1.00
R12	8TRRO	8TRGB	87	Using upstream lag/mile	2.52	-	1.00	-	-	3.85	-	1.00
R13	8BSBR	8WTBO	18	DFLOW	1.82	1.00	1.00	94	1.64	1.64	1.09	1.00
R14	8CTAL	8CTBE	11	Using R13 lag/mile	1.11	-	1.00	-	-	1.00	-	1.00
R15	8CTBE	8CTFW	9	Using R13 lag/mile	0.91	-	1.00	-	-	0.82	-	1.00
R16	8CTFW	8WTFW	2.3	Using R13 lag/mile	0.10	-	1.00	-	-	0.11	-	1.00
R17	8MCGP	8TRDA	10	Using R3 lag/mile because R4 forms the major portion of this reach and that uses R3 lag/mile	0.25	-	1.00	-	-	0.26	-	1.00
R18	8ELSA	8ELLE	35	Using R21 lag/mile because it is a similar stream	2.10	-	1.00	-	-	2.40	-	1.00
R19	8ELLE	8TRDA	33	DFLOW	2.14	0.75	1.00	38	1.99	1.99	0.62	1.00
R20	8IDPP	8ELLE	36	DFLOW	2.84	1.33	1.00	7	2.82	2.82	1.83	1.00
R21	8CLSA	8ELLE	35	DFLOW	2.11	1.33	1.00	15	2.40	2.40	1.24	1.00
R22	8DNJU	8DNGR	32	Using R13 lag/mile	3.23	-	1.00	-	-	2.92	-	1.00
R23	8DNGR	8TRDA	31	Using R19 lag/mile because R19 forms the major portion of this reach	2.02	-	1.00	-	-	1.87	-	1.00
R24	8WRDA	8TRRS	58	Using R36 lag/mile before confluence and R5 after confluence	3.63	-	1.00	-	-	3.75	-	1.00
R25	8ETMK	8ETLA	19	Using R27 lag/mile because this reach is the upstream of R27 reach	1.25	-	1.00	-	-	1.28	-	1.00
R26	8ETLA	8ETFO	22	Using R27 lag/mile because this reach is the upstream of R27 reach	1.45	-	1.00	-	-	1.48	-	1.00
R27	8ETFO	8ETCR	15	DFLOW	0.99	1.00	1.00	120	1.01	1.01	1.00	1.00
R28	8ETCR	8TRRS	20	DFLOW	1.05	1.00	1.00	94	1.96	1.96	0.71	1.00
R29	8SGPR	8ETLA	13	Using R27 lag/mile because this reach is the upstream of R27 reach	0.85	-	1.00	-	-	0.88	-	1.00

Application of DFLOW on Reaches of Trinity River Basin

Reach	U/S CP	D/S CP	River Miles	Method Used	Normal Flows			High Flows				
					Lag (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)	No. of Days in DFLOW Analysis	Lag - DFLOW (days)	Lag - Adopted (days)	Attenuation - DFLOW (days)	Attenuation - Adopted (days)
R30	8CEKE	8CEMA	20	Using R27 lag/mile because of similarities	1.32	-	1.00	-	-	1.35	-	1.00
R31	8CEMA	8TROA	94	Using R27 lag/mile before confluence and R7 lag/mile after confluence	3.40	-	1.00	-	-	5.35	-	1.00
R32	8KGKA	8CEMA	21	Using R27 because of same kind of stream system	1.38	-	1.00	-	-	1.41	-	1.00
R33	8RIDA	8RIRI	22	DFLOW	0.98	1.00	1.00	32	1.09	1.09	1.00	1.00
R34	8RIRI	8RIFA	29	Using upstream lag/mile	1.30	-	1.00	-	-	1.44	-	1.00
R35	8RIFA	8TROA	63	Using R7 lag/mile because R7 forms the major portion of this reach	1.63	-	1.00	-	-	3.36	-	1.00
R36	8WABA	8CHCO	18	DFLOW	2.00	0.59	1.00	12	1.16	1.16	0.67	1.00
R37	8CHCO	8RIFA	31	Using R27 lag/mile before confluence and R33 lag/mile after confluence	2.82	-	1.00	-	-	1.86	-	1.00
R38	8TEST	8TROA	63	Using R13 lag/mile before confluence and R7 lag/mile after confluence	3.88	-	1.00	-	-	4.49	-	1.00
R39	8BEMA	8TRRI	40	Using R33 lag/mile before confluence and R10 lag/mile after confluence	1.49	-	1.00	-	-	2.49	-	1.00