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Environmental flow requirements in a water availability modeling system

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A B S T R A C T

The Texas Water Availability Modeling (WAM) System consists of the generalized Water Rights Analysis Package (WRAP), which is applicable for river systems located anywhere, and WRAP input datasets for the river basins of Texas. The WRAP/WAM system has been applied for over a decade in planning studies and administration of a water rights allocation system. Environmental flow standards for selected river systems in Texas have recently been established through a legislatively mandated process based on flow regimes with subsistence, base, pulse, and overbank flow components that describe the magnitude, frequency, duration, and timing of flows required to maintain sound ecosystems. WRAP and WAM capabilities for integrating environmental flow requirements in water allocation and associated water availability modeling have been greatly expanded as necessary to implement the new environmental flow standards. The modeling system and lessons learned in its implementation in Texas are relevant elsewhere.

1. Introduction

The Water Rights Analysis Package (WRAP) simulates management of water resources of river/reservoir systems subject to priority-based water allocation (Wurbs, 2015b). The modeling system is used to assess hydrologic and institutional water availability and reliability for supplying for municipal, industrial, agricultural, and other off-stream uses, hydroelectric energy generation, and instream flow needs. Reservoir operations for flood control are also simulated. WRAP also includes optional salinity simulation capabilities. Basin-wide impacts of water resources development projects, water use, and management practices are evaluated in terms of supply reliability and stream flow and reservoir storage frequency metrics. Wurbs (2011) reviews the literature of modeling river/reservoir management and compares WRAP with other similar generalized modeling systems including MODSIM (Labadie and Larson, 2007), Riverware (Zagona et al., 2001), HEC-ResSim (Hydrologic Engineering Center, 2007), and CalSim (Draper et al., 2004).

WRAP has been applied by researchers and practitioners in several countries and has been applied extensively in Texas within a Water Availability Modeling (WAM) system maintained by the Texas Commission on Environmental Quality (TCEQ). The public domain software is generalized for application anywhere, with model users creating input datasets for river systems of concern. In Texas, WRAP is typically applied by modifying input datasets from the WAM system to reflect proposed changes in water use or management strategies.

The WRAP datasets in the TCEQ WAM system for the 15 major river basins and eight coastal basins of Texas (Fig. 1) simulate a water rights permit system with over 6000 permits, five interstate compacts, two international treaties, and various

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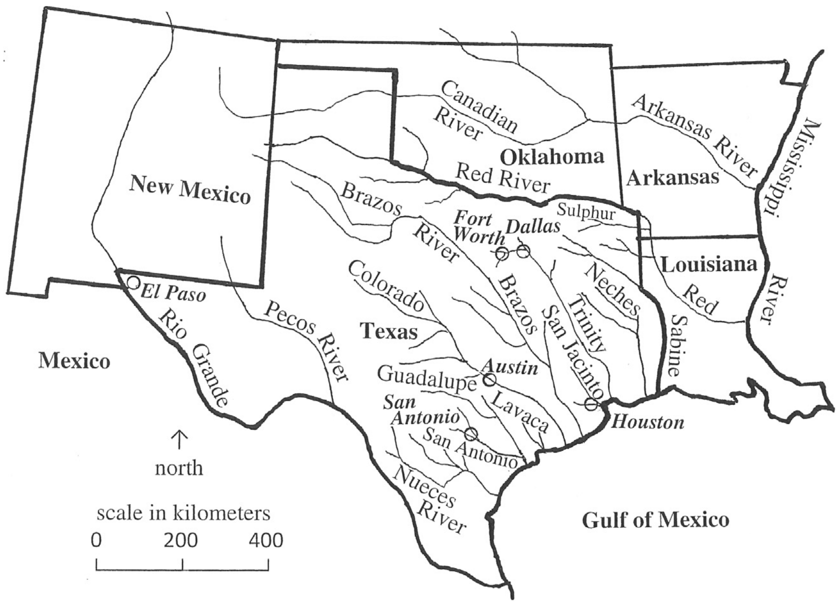

Fig. 1. Map showing largest cities and major rivers of Texas.

other agreements between water management entities, along with constructed facilities that include 3400 reservoirs and a variety of conveyance structures, hydroelectric power plants, and other infrastructure (Wurbs, 2005, 2015a). The WAM system supports planning, water right administration, and other water management activities. Modeling capabilities are being expanded to better support integration of environmental flow needs into comprehensive water allocation and management.

Protecting environmental flows in the river systems of Texas has been of concern for many years. Efforts in establishing expanded environmental flow standards have greatly intensified pursuant to recent legislation. WRAP/WAM capabilities have been expanded to incorporate flow standards in planning and water rights permitting. Interactions between environmental flow requirements and municipal, industrial, agricultural, and other water users are modeled. This paper briefly outlines the recently created institutional process for establishing environmental flow standards and then focuses on the expanded water allocation modeling capabilities developed to integrate the flow standards in comprehensive water management.

2. Institutional framework for water planning and allocation in Texas

The Texas Legislature in 1997 enacted major water management legislation that created a regional and statewide planning process and authorized development of the WAM system to support both the planning process and administration of the water rights permit system. Planning is based on dividing the state into 16 regions with water plans for each region being prepared and merged into a statewide plan in a five-year planning cycle. The Texas Water Development Board (TWDB) is the lead agency, and committees representing local interests have been established to guide plans for each of the 16 regions. The regional and statewide plans were initially completed in 2002 and updated in 2007 and 2012. Work is underway on the 2017 plans. The WAM system is applied by the TWDB and regional planning groups in these studies (Wurbs, 2015a).

The TCEQ, as lead agency, TWDB, Texas Parks and Wildlife Department (TPWD), university researchers, and consulting firms implemented the WAM system during 1997–2003 (Wurbs, 2005). The generalized WRAP modeling system developed at Texas A&M University (TAMU) was adopted and greatly expanded. Input datasets were developed for each of the river basins. WRAP has continued to be expanded at TAMU. The TCEQ continues to update the datasets as new and revised water right permits are approved and new modeling features are added. The TCEQ requires that water right permit applicants or their consultants apply the WAM system to determine the reliabilities at which the water needs addressed in permit applications can be supplied and to assess the impacts on all other water rights in the river system. TCEQ staff applies the modeling system to evaluate the permit applications.

Water rights in Texas are granted by a state license, or permit, which authorizes the holder to divert a specified amount of water annually at a specific location, for a specific purpose, and to store water in reservoirs of specified capacity. Any person or organization may apply for a new water right permit or a modification of an existing permit at any time. TCEQ approval of a permit application requires a beneficial use of the water, unappropriated water available with adequate reliability, demonstration that existing water rights will not be impaired, and a water conservation plan. The proposed actions must be consistent with regional water plans. Priorities are based on dates specified in the permits that were established based on historical water use and dates that permit applications are administratively approved.

Few of the several thousand permits issued before 1985 address environmental flows. The Texas Legislature established environmental flow protection provisions in 1985 that affected only applications for new permits or amendments to existing permits. For water right permits issued or revised since 1985, the TCEQ has used special permit conditions to require consideration of instream uses, freshwater inflows, water quality, and fish and wildlife habitat. Requirements are defined in terms of minimum flow limits imposed upon the particular permit. However, much more sophisticated environmental flow standards are now being established pursuant to legislation enacted by the Texas Legislature in 2007.

3. Institutional framework for establishing environmental flow standards

Ecosystems contribute greatly to human welfare, and ecosystem preservation involves complex challenges (Volk, 2015; Seifert-Dähnn et al., 2015). Water resources development has altered the flow of rivers around the world (Tharme, 2003). Water managers are concerned with the challenges of providing reliable and affordable water supplies for growing populations while preserving environmental resources (O'Keefe, 2012). Environmental flow needs are defined in terms of the magnitude, frequency, timing, duration, spatial distribution, and water quality of the flows required to sustain freshwater and estuarine ecosystems (Arthington, 2012). The scientific literature related to environmental flows is extensive. However, implementation of policies and practices to protect environmental flows has lagged far behind the recognition of the importance of protective actions (Poff and Zimmerman, 2009; Richter, 2009). Intensified demands on limited water resources have forced action in Texas.

The Texas Instream Flow Program (TIFP) authorized by the Texas Legislature in 2001 is jointly administered by the TWDB, TPWD, and TCEQ. The goal is to establish appropriate flow regimes for an ecologically sound environment, conserving fish and wildlife resources while also providing sustained benefits for human uses of water resources. The Legislature directed the agencies to establish data collection and evaluation programs and to conduct studies and analyses to develop appropriate methodologies for determining environmental flow needs. TIFP studies consider a wide range of environmental variables such as habitat, hydrology, biology, geomorphology, water quality, and stream system connectivity, dictating a multiple-disciplinary collaboration. The TCEQ, TPWD, and TWDB (2008) provide an overview of methods proposed for performing environmental instream flow studies. The process of developing these methods included a review by the National Research Council (2005). The TWDB maintains a TIFP website at which relevant reports and information are compiled for convenient public access.

Many years will be required to perform detailed studies for all streams in the state under the TIFP. Recognizing the need to expeditiously determine appropriate amounts of water to set aside for the environment, the Texas Legislature enacted Senate Bill 3 (SB-3) in 2007, creating an accelerated process for establishing instream flow standards for selected priority river systems using existing information and the best available science. Results of continuing TIFP studies are expected to facilitate future refinements of the environmental flow standards.

The 2007 SB-3 introduced a new regulatory strategy for protecting environmental flows that generates recommendations regarding flow regimes that lead to the adoption by the TCEQ of standards and set-asides to satisfy the standards. "*Set-asides*" refer to unappropriated water set aside by the TCEQ in the WAM system and applied in the administration of the water rights permit process to meet specified environmental flow standards. Only new water rights or amendments to existing water right permits are subject to the new standards.

The process will require many years to fully implement statewide, but flow standards were established by the TCEQ based on recommendations of science teams and stakeholder committees for the following priority river systems during 2009–2014: Sabine and Neches Rivers and Sabine Lake Bay; Trinity and San Jacinto Rivers and Galveston Bay; Colorado and Lavaca Rivers and Matagorda and Lavaca Bays; Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, San Antonio Bays; Nueces River and Corpus Christi and Baffin Bays; Brazos River and estuary system; and lower Rio Grande and Laguna Madre.

The SB-3 process is based on regional public participation, statewide agency oversight, and technical support by the science community. Local stakeholders and technical experts develop recommendations regarding the appropriate environmental regime for particular river systems. The TCEQ, TPWD, and TWDB provide administrative oversight and technical support. Reports and other information created or used are available at TCEQ websites.

A Basin and Bay Area Stakeholder Committee (BBASC) is appointed for each priority river system. Each BBASC establishes a Basin and Bay Expert Science Team (BBEST) which develops proposed flow regimes based solely on environmental needs. The BBASC reviews the BBEST report and develops environmental flow regimes based on consideration of all water needs. Each BBASC submits a recommendations report to the TCEQ proposing environmental flow standards and a plan for continuing to review, monitor, validate, and refine the environmental flow standards and strategies for achieving the standards.

Upon approval, the flow standards are incorporated into the WAM system. Priorities are assigned based on the date the TCEQ receives environmental flow regime recommendations from the applicable BBEST. The TCEQ will not issue a permit for a new appropriation or amendment to an existing water right permit that increases the amount of water authorized to be stored, taken, or diverted if any environmental flow standard would be violated.

Environmental flow standards adopted by the TCEQ consist of a set of flow metrics and rules that vary seasonally or by hydrologic condition and by location that govern decisions to curtail diversion and/or storage of stream flows by junior water rights. The standards are defined in terms of flow regimes that describe the magnitude, frequency, duration, timing, and rate of change of flows required to preserve environmental resources. In the past, environmental flow requirements have been specified as a minimum instream flow target that may vary seasonally. The SB-3 process has adopted a framework recommended by studies performed pursuant to the TIFP that defines a flow regime that includes four components: subsistence flows, base flows, within-bank high flow pulses, and overbank high flow pulses.

Tharme (2003) and Arthington (2012) review numerous methods for quantifying environmental flow needs reported in the literature involving field and office studies, computations, and models. Wurbs and Hoffpauir (2013) summarize methods proposed and adopted in Texas. More sophisticated methods employ scientific expertise from a variety of disciplines and difficult and expensive data collection and modeling studies. The SB3 environmental flow standards in Texas were developed based on the commonly applied, much simpler approach of determining metrics for the flow standards based on statistical analyses of daily stream flows. Concepts associated with the indicators of hydrologic alteration developed by the Nature Conservancy (Mathews and Richter, 2007), which have been widely applied in many countries, were adopted by the agencies and science teams in Texas to perform statistical analyses for the individual flow regime components.

4. Water Rights Analysis Package (WRAP) modeling system

The generalized WRAP modeling system and WRAP input datasets from the TCEQ WAM system for individual river basins, called water availability models (WAMs), play the following roles in establishing and applying environmental flow standards in Texas.

- In administering the water rights permit system, environmental flow standards are incorporated in the WAMs to properly assess stream flow availability for permit applications for water supply diversions and/or storage. Likewise in planning studies, the effects of the instream flow standards are included in WAM assessments of water supply capabilities.
- Sequences of monthly or daily naturalized flows or regulated flows for a specified water development and use scenario from the WAM system may be used as input for other methods used to establish environmental flow standards.
- Design of environmental flow standards may include evaluations of the effectiveness of alternative proposed standards in protecting environmental flows based on WAM simulation results. Likewise, design of environmental flow standards also includes WAM evaluations of the impacts on agricultural, municipal, industrial, and other water uses.

The original WRAP and WAM system employ a monthly step time. Recent developmental versions of WRAP also include daily simulation capabilities designed for modeling environmental flow standards. The monthly WRAP routinely employed in the WAM system is documented by Wurbs et al. (2013) and Wurbs (2015b,c), and the new daily WRAP modeling system is documented by Wurbs and Hoffpauir (2015). Both monthly and daily simulations may be applied with the results of each used to support particular decision processes. Alternatively, daily instream flow targets computed in a daily simulation can be aggregated to monthly target series for input to a monthly simulation using WRAP features that facilitate this modeling strategy (Wurbs and Hoffpauir, 2013).

WRAP consists of a set of computer programs and manuals available at a WRAP website maintained at Texas A&M University, which links to the TCEQ WAM website providing datasets and various information, and the Texas Water Resources Institute website where a number of relevant technical reports can be found. WRAP pre-simulation programs facilitate developing and updating simulation input data. Post-simulation programs are used to perform reliability and frequency analyses and otherwise organize simulation results. An interface connects programs to each other and to data files. The HEC-DSS data storage system developed by the Hydrologic Engineering Center (2009) is incorporated in WRAP for various data management, analysis, and display functions. The WRAP simulation model is based on computational algorithms developed specifically for the model rather than linear programming or other generic mathematical programming methods.

4.1. Simulation model

A WRAP simulation study involves assessing capabilities for meeting specified water demands during a repetition of historical hydrology. A conventional monthly simulation includes the following tasks.

1. Hydrology and water rights datasets are compiled. Hydrology input data sequences covering a specified hydrologic period-of-analysis include monthly naturalized flows at primary (gauged) control points and reservoir net evaporation rates. Water rights input data describe water demands, constructed facilities, system operation rules, and water allocation rules.
2. Naturalized flows are distributed from primary (gauged) to secondary (ungauged) control points within the simulation based on watershed parameters read from an input file.
3. The reservoir/river/use system is simulated, with water allocated to each right in priority order. Each model water right consists of a set of water management and use specifications.
4. Simulation results are organized and water supply reliability indices, flow and storage frequency relationships, and other summary statistics are computed.

Task 1 has been completed for all of the river basins in Texas, but the datasets continue to be updated and otherwise modified. Tasks 2 and 3 occur each time the simulation model is executed. Post-simulation programs are used for task 4.

WRAP simulates capabilities for meeting specified water management and use requirements for given sequences of naturalized stream flows and reservoir net evaporation less precipitation rates. Historical hydrology is used to capture the hydrologic characteristics of a river basin. The water management and use scenario might be actual current water use, projected future conditions, the premise that all permit holders use their full authorized amounts, or some other scenario of interest. Simulation results are organized in optional formats including tabulations and plots of entire time sequences, summary tables, water budgets, frequency relationships, and various types of reliability indices.

The WRAP simulation model is an accounting system for tracking stream flow sequences, subject to reservoir storage and operating rules; water supply diversion and return flow, hydroelectric power, and instream flow requirements; and priority-based water allocation rules. The basic monthly simulation computations are performed in a water rights priority sequence embedded within a monthly sequence as illustrated by Fig. 2 (Wurbs 2005, 2015b). Monthly-to-daily disaggregation and forecasting and routing are added in a daily simulation.

The WRAP modeling process consists of a series of adjustments to stream flow sequences covering the hydrologic period-of-analysis. The WAM datasets have periods-of-analysis dating back to about 1940 covering a full range of fluctuating dry and wet periods including the 1950–1957 most hydrologically severe drought on record. The relevant forms of monthly or daily stream flow volumes include actual flows observed at gauging stations and WRAP computed naturalized, regulated, and unappropriated flows which are defined as follows.

A simulation begins with naturalized stream flows, which are flows that would have occurred historically in the absence of the water management activities reflected in the water rights input data. Naturalized flows at primary control points are developed by adjusting sequences of observed monthly flows from a gauging station to remove the historical effects of water development. The simulation model includes methods for transferring naturalized flows from gauged primary to ungauged secondary control points.

Regulated and unappropriated flows computed during the simulation reflect changes to naturalized flows resulting from a specified scenario of water resources development and use. Regulated flows are physical flows considering all water resources development, management, and use reflected in the water rights input dataset. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. By definition, the regulated flow is never less than the unappropriated flow at a site. Regulated flows at a site may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream locations.

The adjustments that convert naturalized flows to regulated flows and unappropriated flows include both depletions and additions. Stream flow depletions include the quantities of water appropriated to meet water supply diversion requirements and refill reservoir storage. Water supply return flows and reservoir releases are added back to stream flows. Channel losses are considered as flow adjustments are cascaded downstream.

4.2. Daily WRAP modeling system

WRAP capabilities for modeling and analysis of environmental flow requirements have recently been greatly expanded, primarily through development of a daily modeling system. The new capabilities are being implemented in the WAM system. The new daily modeling system includes: disaggregation of monthly naturalized flows to daily; flow routing and forecasting; disaggregation of diversion, hydropower, and instream flow targets; simulation of pulse flow environmental flow requirements; and simulation of reservoir flood control operations. Fundamental differences between daily and monthly simulations are as follows.

- Water rights data are read from an input file.
- Parameters for distributing naturalized flows are read from an input file.
- Water rights are ranked in priority order.
- Various other data manipulations are performed.

- Loop repeated for each month of hydrologic period-of-analysis
  - Naturalized flows and net reservoir evaporation rates are read.
  - Naturalized flows are distributed from gauged to ungauged sites.
  - Loop repeated for each water right in priority order
    1. Diversion, instream flow, or hydropower target is set.
    2. Water availability is determined.
    3. Operating decisions are made.
    4. Water balance computations are performed
    5. Available stream flow is adjusted.
    6. Simulation results for this water right are recorded.
  - Simulation results for control points are recorded.

Fig. 2. Outline of conventional monthly simulation.

- Flow rates that vary continuously over time in the real world are modeled as volumes occurring during discrete time intervals. The smaller computational time interval improves accuracy and is particularly relevant in simulating environmental flows and flood control operations. Effects of a smaller computational time step are diminished by reservoir storage and tend to be least pronounced for water supply with large reservoir storage capacity.
- In a monthly model, effects of reservoir releases and water management/use actions on stream flows at downstream locations are assumed to propagate through the river system within the same month, precluding flow forecasting and routing computations. However, flow forecasting and routing are important with a daily time step.
- Features for modeling environmental pulse flows can be meaningfully incorporated in a daily model. Likewise, reservoir flood control operations can be incorporated in a daily model. Flood control operations can affect environmental pulse flows.

The daily modeling system includes disaggregating monthly naturalized flows from the WAM datasets based on patterns defined by daily flows while maintaining the original monthly volumes. WRAP provides flexible options for making the best use of available sequences of daily flows, allowing flows at selected locations to serve as patterns for disaggregating flows at multiple other sites. Daily naturalized flows have been developed in some river systems by adjusting gaged flows to remove the effects of regulation and water use. For relatively unregulated tributary streams, observed flows have been adopted for use as pattern hydrographs without adjustments. The Soil and Water Assessment Tool watershed precipitation-runoff model (Neitsch et al., 2011) has been applied to develop pattern hydrographs for several river basins.

A lag and attenuation routing method was developed for the WRAP daily simulation (Wurbs and Hoffpauir, 2015). Water supply diversions, return flows, reservoir releases and storage refilling result in changes in stream flows at downstream locations. Routing refers to the downstream propagation of changes. Two input parameters called lag and attenuation factors are determined with a calibration procedure for each specified routing reach. A reverse routing algorithm replicates the effects of routing in the procedure for forecasting flow availability.

Flow forecasting significantly complicates the simulation computations. River flows diverted or stored by a particular water user today may diminish flows available to other water users further downstream in future days. Flood control reservoir operations are based on making no releases that contribute to flows exceeding non-damaging flow limits at downstream gages that may be located several days of flow travel time below the dam. Flow forecasting is based on a forecast simulation used solely to derive future flow availability information. For each day of the simulation, the final simulation for that day is preceded by a simulation covering a future forecast period that generates stream flow availability information for that current day.

4.3. Environmental instream flow targets

Instream flow targets are set in essentially the same manner as water supply diversion or hydroelectric energy generation targets, using a flexible set of target building options that range from simple to complex. An instream flow water right or requirement in the model consists of specified rules and information that control computation of target minimum regulated flow limits at a location. Constraints placed on the stream flow available to diversion and storage rights junior to an instream flow requirement may result in these rights being curtailed to minimize shortages to the instream flow target. In some cases, reservoir releases for downstream instream flow needs are limited to inflows to the reservoirs. In other cases, releases from storage may be specified to meet instream flow targets.

Any number of instream flow targets may be specified for a particular location, with the next more junior flow target replacing the latest more senior target or optionally the largest or smallest controlling at different priorities. Thus, the stringency of flow limits may be modified in the priority sequence. Junior diversion and storage rights are curtailed as necessary to prevent or minimize violation of senior instream flow rights.

Each instream flow target is built in each time step of the simulation by combining various options. Flow targets can be specified as combinations of functions of: month of the year; current or beginning-of-season reservoir storage contents; naturalized flow, regulated flow, unappropriated flow, diversions, other instream flow targets or shortages; various limits; cumulative volume of specified variables over a specified preceding time span; switches that completely or partially turn targets on-or-off depending on the cumulative volume of a selected switch variable; or a hydrologic index such as the Palmer hydrologic drought index. These options are applicable in either a monthly or daily simulation. Pulse flow targets are applicable only in a daily simulation.

4.4. Environmental pulse flow targets

High flow pulses are associated with rainfall-runoff events with rapid changes in flow rates. Peaks may be either within banks or overflow the banks to inundate the floodplain. Daily pulse flow targets are minimum regulated flow limits that dictate curtailing junior diversion and storage refilling rights in the same way as for instream flow targets determined using any other target-setting options. Parameters defining pulse flow requirements in the model are generalized allowing flexibility in combining various options.

Pulse tracking can be either seasonal or continuous. A pulse event is engaged when it has been initiated and is being tracked. An engaged pulse may set daily pulse targets. A pulse event is engaged based on regulated flow exceeding the trigger criterion and satisfaction of optional initiation criteria. The decision to declare that a pulse event is no longer engaged is based on satisfaction of either the total event volume or maximum duration parameter or satisfaction of other optional termination criteria.

Targets are developed for each day during a pulse flow event. The pulse targets are set at quantities that are less than or equal to the regulated flow as of the priority of the instream flow requirement. The computed target may be either the complete final target or a component of the target-building process for the instream flow right. Daily pulse targets are not used to set a final target if the frequency criterion has already been met. A frequency parameter limits the number of pulse events meeting the specified criteria during the tracking period that are adopted as target setting events. When the number of pulse events exceeds the frequency parameter, events may be tracked for information purposes but are not used to set targets.

4.5. Post-simulation analyses

Simulation results consist of hydrologic period-of-analysis sequences of monthly or daily quantities for 40 variables. These variables and others derived from them are included in the various analyses and displays performed with WRAP post-simulation programs. Analyses of simulation results include time series plots, flow and storage frequency metrics, water supply reliability indices, and other summaries and displays.

Post-simulation analyses may serve the two different purposes of (1) evaluating capabilities for the river system to provide the flow regimes needed for the environment and (2) evaluating the impact of environmental flow standards on municipal, industrial, agricultural, and other water uses. Water supply reliability and storage frequency metrics are important for assessing the impacts of environmental flow requirements on other water users. Flow frequency metrics are useful in assessing effectiveness in meeting instream flow requirements.

5. Brazos River Basin case study

The 118,000 km^2 Brazos River Basin extends from New Mexico southeasterly across Texas to the Gulf of Mexico. Climate, vegetation, topography, land use, and water use vary greatly across the basin. Mean annual precipitation varies from 48 cm in the upper basin which lies in the High Plains to 115 cm in the lower basin in the Gulf Coast Region.

Over a thousand water districts, cities, companies, and individuals hold permits to use the waters of the Brazos River and its tributaries. Water rights associated with the 14 reservoirs shown in Fig. 3 account for 77% of the 5.8 billion m^3 conservation storage capacity of the 678 permitted reservoirs and 34% of the 3.0 billion m^3/year permitted annual water supply diversions in the basin. The Brazos River Authority owns and operates Possum Kingdom, Granbury, and Limestone Reservoirs and has contracted with the U.S. Army Corps of Engineers for the conservation storage capacity of nine multiple-purpose reservoirs shown in Fig. 3, which the Corps operates for flood control. Whitney is the largest reservoir with conservation and flood control capacities of 0.785 and 1.68 billion m^3. The West Central Texas Municipal Water District operates Hubbard Creek Reservoir to supply water for several member cities.

The TCEQ finalized environmental flow standards for the Brazos River Basin in 2013 based on BBEST and BBASC recommendation reports (Brazos River Basin and Bay Expert Science Team, 2012; Brazos River and Associated Bay and Estuary System Basin and Bay Area Stakeholders Committee, 2012). Brazos River Basin WAM studies reported by Wurbs et al.

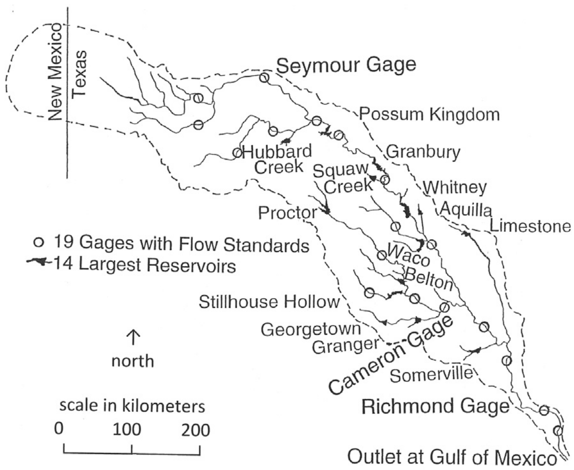

Fig. 3. Brazos River Basin map showing the 14 largest reservoirs and 19 gauge locations with SB-3 environmental flow standards.

(2012) and Wurbs and Hoffpauir (2013) represent an inaugural application of the daily modeling system with the expanded capabilities for modeling environmental flow requirements. The daily Brazos WAM has since been further refined, and daily WAM input datasets with instream flow standards generated through the SB-3 process have been developed at Texas A&M University for the TCEQ for five other river basins. The latest developmental versions of the six daily WAM datasets and reports documenting them are available at the WRAP website.

5.1. Brazos River Basin water availability model (Brazos WAM)

The Brazos WAM dataset includes monthly naturalized flows at 77 control points, most of which are gauging stations. These monthly flows are distributed to over 2000 ungauged sites during each execution of the simulation model based on watershed parameters provided in the input dataset. Monthly flows are disaggregated to daily within the simulation at each control point in the model based on daily hydrographs input for 43 sites while maintaining the monthly volumes.

About 1200 water right permits authorizing water supply diversions and/or storage in 678 reservoirs are modeled in the Brazos WAM. About 120 of these permits contain special conditions, that predate the SB-3 process, requiring minimum instream flow rates be maintained at the diversion site or a downstream gage. The specified flow rates vary seasonally in many cases. About half of the flow limits are primarily designed to protect senior water supply rights downstream, and about half are specifically designed to preserve environmental flows.

The WAM was converted from monthly to daily by incorporating monthly-to-daily disaggregation of naturalized flows and other variables and adding flow routing and forecasting. Flood control reservoir operations and SB-3 environmental flow standards were added to the daily model. Other refinements included updating the original 1940–1997 hydrologic period-of-analysis to 1940–2012.

5.2. SB-3 environmental instream flow standards

Environmental flow standards have been established through the SB-3 process at the sites of the 19 gauging stations shown in Fig. 3, with flow requirements determined based on frequency metrics of daily flows. Base and pulse flow quantities for the Brazos River at the gauging station near Richmond are reproduced in Table 1 to illustrate the general format of the environmental flow standards. The subsistence flow at this site is 16.6 cm. Three seasons are employed, defined as winter (November-February), spring (March-June), and summer (July-October). Dry, normal, and wet hydrologic conditions are defined by whether the Palmer hydrologic drought index (PHDI) falls within the lowest 25% quartile, between the 25th and 75th percentiles, or highest 25% quartile. For other river systems, hydrologic conditions have been defined based on stream flows or reservoir storage rather than the PHDI.

The default subsidence flow limit of the 5th percentile flow of observed daily flow was adjusted in some cases. Under dry hydrologic conditions, with actual flows between the subsistence and base limits, 50% of the difference between the actual flow and subsistence limit is protected. The base flow components of the flow requirements are minimum flow limits for each of the 19 sites that vary between seasons and between hydrologic conditions. The base flows under dry, average, and wet hydrologic conditions were set at the 25th, 50th, and 75th percentile flows computed from observed daily flows in each season.

The BBASC high flow pulse requirements at the 19 sites also vary between seasons and hydrologic conditions. For a given season and hydrologic condition, a pulse flow event is defined in terms of the daily trigger flow rate that activates the pulse event, cumulative volume and duration criteria that terminate the pulse, and frequency as illustrated by the metrics for the Richmond gauge shown in Table 1. Specified frequencies range from 1 to 4 seasonal events per year. For the spring season, pulse events are specified for all three hydrologic conditions at each of the 19 sites. For winter and summer, pulse events are

Table 1
Environmental flow standards for Brazos River at Richmond.

Season	Hydrologic condition	Base flow (cm)	High flow pulses			
			Trigger (cm)	Frequency (pulses/year)	Volume (10^6 m^3)	Duration (days)
Winter	Dry	28.0	182	1	74.8	11
	Average	46.7	182	3	74.8	11
	Wet	93.7	351	2	185	16
Spring	Dry	33.7	253	1	116	13
	Average	60.6	253	3	116	13
	Wet	113	462	2	265	19
Summer	Dry	26.3	69.7	1	20.2	6
	Average	37.7	69.7	3	20.2	6
	Wet	62.0	154	2	57.1	10

included for all, none, or some of the three hydrologic conditions depending on the site, with fewer pulses specified in the upper basin.

5.3. WRAP simulation results

Wurbs and Hoffpauir (2013) describe incorporation of the environmental flow requirements into the daily version of the Brazos WAM and presents simulation results. The discussion here focuses on flows at gauging stations on the Brazos River near Seymour and Richmond, which have watershed areas of 15,500 and 93,300 km^2, and on the Little River near Cameron which has a watershed area of 18,400 km^2. The relative magnitude and variability of the daily flows and environmental flow targets during the 26,663 days of the 1940–2012 hydrologic period-of-analysis are illustrated by Table 2 and Figs. 4 and 5.

Naturalized, regulated, and unappropriated flows and SB-3 environmental flow targets and shortages at the sites of the three gauges are compared in Table 2. The quantities in Table 2 include 1940–2012 means and daily mean flows that are equaled or exceeded during specified percentages of the 26,663 days of the simulation.

The SB-3 environmental flow targets and associated shortages are also shown in Table 2. Shortages are the target less regulated flow during days of the simulation with targets exceeding regulated flows. The SB-3 instream flow standards are placed in the model at a priority junior to all existing water rights, and thus affect only future water right permit applicants. The unappropriated flows in Table 2 are daily flow volumes at the three locations available for appropriation after the addition of the SB-3 environmental flow requirements.

Naturalized daily flows and SB-3 daily environmental flow targets for the Brazos River at Richmond are plotted in Figs. 4 and 5. Daily naturalized, regulated, and unappropriated stream flows and SB-3 environmental flow targets and shortages are aggregated to annual volumes for comparison in Fig. 6. The most hydrologically severe drought on record for most of the Brazos River Basin and most of Texas began gradually in 1950 and ended with a major flood in April 1957. The single driest year on record statewide is 2011. The great variability characteristic of stream flow throughout Texas, including extreme droughts, are evident in the flow plots.

Annual summations of the daily environmental flow targets for the Brazos River at the Richmond gage plotted in Fig. 5 are compared with the associated shortages in meeting the targets and with annual naturalized, regulated and unappropriated flow volumes in Fig. 6. The difference between naturalized and regulated flows represents the effects of water resources development and use. At this site, the primary difference between regulated flows and unappropriated flows is the environmental flow requirements. Unappropriated flows are greatly reduced by the SB-3 environmental flow standards.

5.4. Effects of flow standards on water availability

SB-3 environmental flow standards are junior to and thus do not affect WRAP/WAM computed water supply reliabilities for existing senior water rights but significantly reduce unappropriated flows available to future junior water right permit applicants. The priority date of the SB-3 environmental flow standards is set at March 1, 2012 in the Brazos WAM, representing the date that the Science Team submitted its recommended flow standards to the TCEQ. The SB-3 requirements to set-aside flows in the WAM system for environmental flows conceptually do not affect holders of senior water right permits with

Table 2
Frequency metrics for flows, flow targets, and shortages.

	Mean flow	Percent of days equaled or exceeded							
		98%	95%	90%	75%	50%	25%	10%	5%
Stream flow and environment flow target and shortage (m^3/s)									
Richmond gage									
Naturalized flow	228	5.15	9.34	14.8	33.3	85.4	244	570	910
Regulated flow	177	5.98	10.2	15.7	26.6	57.9	190	472	771
Unappropriated	114	0.00	0.00	0.00	0.00	0.00	90.7	364	648
Flow target	59.6	15.6	15.6	19.2	37.7	46.7	62.0	113	113
Shortage	8.98	0.00	0.00	0.00	0.00	0.00	11.1	30.9	45.5
Cameron gage									
Naturalized flow	52.8	0.11	0.49	1.06	4.11	13.3	45.0	122	221
Regulated flow	40.5	0.23	0.40	0.57	2.15	8.09	30.8	130	228
Unappropriated	23.2	0.00	0.00	0.00	0.00	0.00	0.48	79.4	172
Flow target	8.6	0.91	0.91	1.05	4.53	5.38	9.35	21.5	21.5
Shortage	1.6	0.00	0.00	0.00	0.00	0.00	2.06	4.87	7.82
Seymour gage									
Naturalized flow	9.34	0.00	0.00	0.00	0.29	1.13	4.24	16.4	36.5
Regulated flow	8.97	0.00	0.00	0.00	0.28	1.11	4.09	15.7	34.7
Unappropriated	2.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.66
Flow target	0.75	0.03	0.03	0.11	0.37	0.54	0.71	0.99	1.30
Shortage	0.12	0.00	0.00	0.00	0.00	0.00	0.09	0.45	0.68

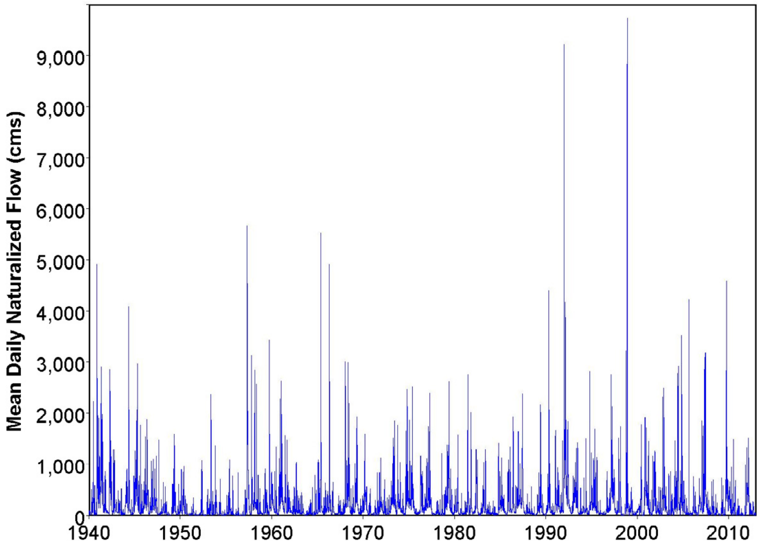

Fig. 4. Daily naturalized flows of the Brazos River at the Richmond gauge.

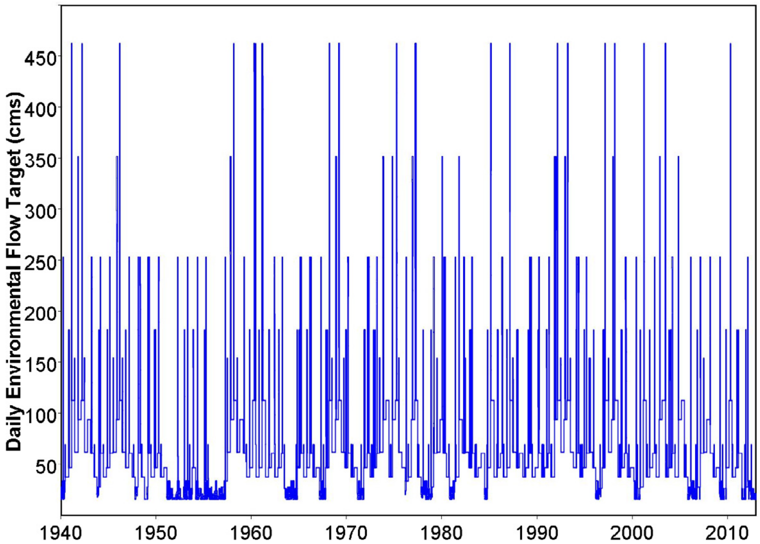

Fig. 5. Daily environmental flow targets for the Brazos River at the Richmond gauge.

priority dates prior to March 1, 2012, but do constrain applications for new water right permits or modifications to existing permits.

A "system" water right permit application submitted to the TCEQ by the Brazos River Authority (BRA) in 2004 provides an example of the complexities of water allocation in Texas. The BRA operates a system of 12 large reservoirs that were constructed and permitted as individual projects over a period of many years. However, simulation studies with the Brazos WAM have demonstrated significant increases in water supply capabilities achieved by multiple-reservoir system operations, which motivated submission of the system water right permit application. As of 2016, after over 12 years of permit application related activities involving development of a system water management plan, WRAP/WAM simulation studies, stakeholder participation, and agency public hearings, the BRA permit application is not yet approved by the TCEQ but expected to be approved perhaps by 2017. The system permit will significantly increase the amount of water available to the BRA to sell to its customers. The recently established SB-3 environmental flow standards are an important consideration in the formulation and assessment of the BRA permit application and associated water management plan.

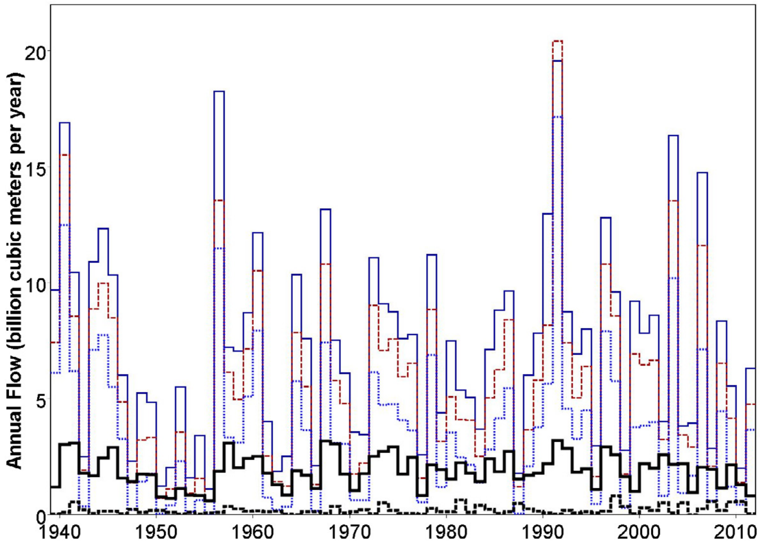

Fig. 6. Annual naturalized flow (solid line), regulated flow (dashed line), unappropriated flow (dotted line), environmental flow target (thick solid line) and environmental flow shortage (thick dashed line) for Brazos River at the Richmond gauge.

6. Complexities and limitations

Water allocation and modeling thereof are complex endeavors. Conventional monthly WRAP water availability modeling with the massive Texas WAM datasets reflecting numerous water users and diverse water management facilities and practices is complicated. Converting to daily and adding more sophisticated environmental flow requirements adds much more complexity. WRAP provides considerable flexibility for simulating diverse and complex reservoir/river system management practices. Water management in Texas and elsewhere is governed by extreme hydrologic variability that includes severe multiple-year droughts and infrequent major floods as well as seasonal and continual fluctuations. The modeling system is designed for dealing with hydrologic variability as measured by a variety of reliability and frequency metrics.

The WRAP modeling system deals only with monthly or daily flow and storage volumes. Stream flow stage and velocity and other parameters relevant to environmental flow needs are not directly addressed in the simulation.

WRAP includes capabilities for tracking salinity loads and concentrations through a river/reservoir system (Wurbs, 2009). However, actual practical application of WRAP salinity simulation features have been limited to date. Salinity or other water quality constituents have not been considered in the WAM simulations incorporating SB3 environmental flow standards.

The daily modeling system is being implemented in Texas to supplement rather than replace the monthly models. The monthly WRAP/WAM system has been proven to work well for planning and water rights administration applications prior to incorporation of SB-3 environmental flow standards. The daily modeling system is more accurate for analyzing environmental flow requirements in general and essential for simulating high pulse flows. Daily models are much more complex. Both monthly and daily simulations are applied with the results of each used to support particular decision processes. Daily instream flow targets computed in a daily simulation also can be summed to monthly target volumes for input to a monthly simulation.

Use of historical gaged flows versus synthesized WAM naturalized or regulated flows in establishing flow needs is an issue. Environmental flow needs in Texas and elsewhere are often evaluated based on historical observed flows, which are typically nonhomogeneous due to construction of dams and other water control facilities and increased water use over time. The WRAP/WAM system is built on the concept of homogeneous sequences of computed naturalized, regulated, and unappropriated flows. The modeling system provides capabilities for dealing with nonhomogeneities inherent in actual flows. Observed gaged flows were used by the science team and stakeholder committee in determining environmental flow requirements for the Brazos River system. WAM naturalized flows were used in developing environmental flow standards for other river systems.

Buying and selling of water rights are encouraged, subject to TCEQ approval and WAM analysis, to address increasing demands where adequate unappropriated flows are not available. The SB-3 process does not protect environmental flows from holders of senior water rights already in existence when standards are adopted. Transferring existing rights from other uses to environmental flows is an important water management issue that will continue to be addressed in the future. Such transfers can be readily modeled in the WRAP/WAM system.

Modeling capabilities designed to support planning and administration of the water right permitting process are described in this paper. Additional different analysis capabilities are needed for real-time monitoring of flows and actual curtailment of water use in accordance with the water rights permit system. Administration of curtailment actions based on a prior appropriation water rights system has complexities that are different than those encountered in issuing the permits.

7. Summary and conclusions

The WRAP/WAM system significantly contributes to effective water management in Texas and continues to be expanded as needed to support water allocation and planning processes. The daily modeling system provides flexible capabilities for simulating subsistence, base, and high pulse environmental flow requirements and their impacts on water availability for other water users.

Legislatively mandated environmental set-asides are implemented in the SB-3 process by incorporating flow standards in the WAM system. The environmental flow standards do not affect existing senior water rights but reduce unappropriated flows available for future water right applicants. The SB-3 process recognizes needs for continued revisions to environmental flow standards in the future with the development of improved analysis methods and databases along with exploration of alternative strategies for achieving the flow standards and expanded monitoring capabilities. The WRAP modeling system provides flexible capabilities for investigating alternative water management scenarios and environmental flow issues that may be considered in the future along with the environmental flow standards recently established through the SB-3 process.

The Texas experience in dealing with environmental flow needs illustrates the following basic water resources management concepts. Complex issues are typically addressed over long time spans by a diverse water management community within an institutional framework of policies and practices. Environmental flows are an integral aspect of the overall river/reservoir system management enterprise. Water resources are allocated among multiple types of use and numerous water users in a setting of intensifying demands on limited resources. Water availability assessments are essential for effective water resources planning, allocation, and management. The WRAP modeling system and lessons learned in its application in Texas are relevant elsewhere as well.

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