Environmental Flow Attainment Metrics for Water Allocation Modeling

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Abstract: Environmental flow standards established according to a consensus-based, legislatively mandated process are being incorporated in the water rights permitting system for selected priority river systems in Texas. The flow standards for several of the rivers have been simulated as a part of a university research study using the new daily version of the Water Rights Analysis Package (WRAP) modeling system with modified input data sets from the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) system. Metrics have been evaluated using time series of simulated streamflows and flow targets to characterize the engagement and attainment of the environmental flow standards. The metrics help determine the extent to which the standards are achieved within a river system water allocation simulation and enable the comparison of results between the different environmental flow regime components, different locations, and alternative river system development scenarios. **DOI: 10.1061/(ASCE)WR.1943-5452.0000652.** *© 2016 American Society of Civil Engineers.*

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Introduction

The Texas Commission on Environmental Quality (TCEQ) maintains a Water Availability Modeling (WAM) system that consists of the generalized Water Rights Analysis Package (WRAP) developed at Texas A&M University (TAMU) and input data sets for the river basins of Texas (Wurbs 2005). The WAM system has been applied for over a decade in planning studies and administration of a water rights permit system. Environmental flow standards established through a process instigated by legislation enacted in 2007 are currently being incorporated into the WAM system (Wurbs 2014). WRAP/WAM system capabilities for modeling environmental flow requirements and their impacts on water management and use have been greatly expanded as necessary to implement the new environmental flow standards (Wurbs and Hoffpauir 2013e).

The Texas Instream Flow Program (TIFP) created in 2001 is jointly administered by the Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), and TCEQ with the goal of establishing appropriate flow regimes for an ecologically sound environment, conserving fish and wildlife resources while providing for human uses of water resources. Recognizing that many years will be required to perform detailed studies for all streams in the state under the TIFP, the Texas Legislature in its 2007 Senate Bill 3 (SB3) created an accelerated process for establishing environmental flow standards for selected priority river systems using existing information and the best available science. Under the SB3 process, TCEQ adopts standards based on the recommendations of stakeholder committees and science teams that are incorporated in the WAM system. Only new permits or amendments to existing permits are affected by the new standards. The process will require many years to fully implement statewide, but flow standards were established for several selected priority river systems during 2010–2014. SB3 environmental flow standards and strategies for achieving the standards are subject to future improvements as advances in scientific knowledge and water management capabilities are achieved through the TIFP (Wurbs 2014).

Environmental flow needs are defined in terms of the magnitude, frequency, timing, duration, and spatial distribution of streamflows required to sustain freshwater and estuarine ecosystems. Poff and Zimmerman (2009) review numerous methodologies reported in the literature for quantifying environmental flow needs. The National Research Council (2005) and Wurbs and Hoffpauir (2013e) summarize methods that have been considered or adopted in Texas. Instream flow requirements were initially prescribed in Texas primarily as minimum flow limits. However, in Texas like elsewhere, the importance of considering all elements of a flow regime is now well recognized. The SB3 methodology defines environmental flow standards with subsistence, base, within-bank pulse, and overbank flow components.

Metrics for characterizing the engagement and attainment of environmental flow requirements are important for balancing human and environmental needs for water (O'Keefe 2012). For SB3 standards, attainment metrics are relevant to the process by which the standards are evaluated and revised by scientists and decision makers. More detailed methods for analyzing capabilities for achieving environmental flow requirements are necessary as more complex flow regimes are specified.

This paper presents the results of university research designed to improve capabilities for assessing water availability for satisfying environmental flow requirements (Pauls 2014). The paper explores metrics that can be adopted in the WRAP/WAM system or other similar modeling systems to quantify the reliability and extent to which environmental flow standards and each component thereof can be satisfied. Environmental flow standards and associated attainment metrics are illustrated in this paper by a simulation of the Colorado River Basin of Texas. Though motivated by the WRAP/WAM system, the attainment metrics are generally applicable in other modeling systems as well.

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Environmental Flows in Water Allocation Models

Environmental flows have been incorporated in numerous river/reservoir system water allocation models. A variety of metrics are implemented to characterize the engagement and attainment of environmental flows. Palmer and Snyder (1985) incorporated monthly minimum environmental flows into a computer model of the Seattle water supply system to evaluate the trade-offs between the performance of the water supply system and specified levels of environmental flows. Gippel and Stewardson (1995) used the Melbourne Water Corporation water supply simulation model to evaluate the impact of minimum monthly environmental flow requirements on water supply availability. Hughes and Ziervogel (1998) developed a model to simulate daily reservoir conditions for evaluating the effects of operating rules on demands for withdrawals at the reservoir and downstream environmental flow needs. Environmental flow needs were specified as minimum monthly low and high values for maintenance and drought conditions. Pearsall et al. (2005) developed a daily time-step linear programming model to evaluate the effects of reservoir operations on tree species establishment downstream, related to the frequency and duration of flow events causing inundation of riparian areas during the growing season. Matthews and Richter (2007) discussed the Indicators of Hydrologic Alteration (IHA) software program, including its ability to calculate flow statistics for key components of the flow regime, its utility when coupled with ecological models or flow-ecology relationships, and its value in supporting water management decisions. The IHA have been applied both nationally and globally. Butler (2011) incorporated daily operating requirements for two reservoirs in a monthly time-step planning model for the Colorado River Basin in the western United States. The daily operating rules reflected environmental flow requirements for base flows and flood flow pulses, which varied based on annual hydrologic conditions. Various flow deviation metrics were evaluated to characterize the expected reliability for meeting the environmental flow requirements.

Several papers describe the incorporation of environmental instream flows in generalized river/reservoir system water management models. Vogel et al. (2007) implemented a variety of operating rules for multiple reservoirs in a water evaluation and planning (WEAP) model to characterize the relationship between reservoir storage, instream flow, and water supply yield. The seasonal ecodeficit/ecosurplus concept, based on analysis of the flow duration curve, was introduced as a simple metric for evaluating the impact of reservoir operations on the environmental flow regime. Palmer (2008) described the manner in which a computer model developed using the operational analysis and simulation of integrated systems (OASIS) assisted decision makers in evaluating alternative river system development scenarios proposed by the Tennessee Valley Authority for the Duck River, including considerations for future demands and ecosystem health requirements. Gippel et al. (2009) incorporated preferred environmental flow recommendations into a daily time-step integrated quality and quantity model (IQQM). Using various approaches for assessing the degree of compliance of a flow series with a specified flow regime, a risk assessment approach was used to derive suboptimal environmental flow regimes. Compliance metrics implemented in the analysis included the frequency of occurrence of high-flow pulse events compared to the required frequency, the percentage of years in which all environmental flow components were satisfied, the percentage of time periods of a specified length in which the frequency requirement of a flow component was met, and the percentage of time periods of a specified length for which flows exceeded a specified value a specified percentage of time. Sandoval-Solis and McKinney (2009) incorporated environmental flow requirements in a monthly time-step WEAP model for the Rio Grande/Bravo river basin. The environmental flows consisted of annual *maintenance* and *drought* volumes at five locations. Performance criteria were used to evaluate the achievement of the flows, including metrics for reliability, resilience, and vulnerability. In another paper, Sandoval-Solis and McKinney (2014) incorporated base flows and small flood flows specified according to reservoir storage levels into a monthly time-step WEAP model. Podger et al. (2010) proposed methods for modeling complex environmental flow requirements for basin-scale planning using IQQM, including the incorporation of multiple levels of high-flow pulse specifications based on magnitude, frequency, and duration requirements. Black and Podger (2012) developed guidelines for modeling water sharing rules, including common performance metrics to consider for environmental flows such as the frequency and duration of inundation events for wetland areas as well as the duration of intervals between events.

Texas Water Availability Modeling (WAM) System

The WAM system consists of WRAP and input data sets for each of the 23 river basins of Texas (Wurbs 2005). The generalized WRAP modeling system continues to be expanded at TAMU sponsored by the TCEQ and other agencies. TCEQ continues to update the WAM data sets as new and revised water right permits are approved and new WRAP modeling features are added. WRAP is generalized for application to river basins located anywhere. For applications in Texas, WRAP input data sets from the WAM system are modified to reflect changes in water demands, proposed new facilities, and alternative water management strategies. The modeling system is used to determine water supply reliability and streamflow and reservoir storage frequency metrics for specified water demands and management strategies. Impacts of proposed actions on all water users in a river basin are assessed.

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 a permit application can be supplied and to assess the impacts on the reliabilities of all other water rights in the river system. TCEQ staff applies the modeling system to evaluate the permit applications. TWBD, regional planning groups, other agencies, and their consultants apply the WAM system in planning studies. In administering the water rights permit system, instream flow standards are incorporated in the models to properly assess streamflow availability for permit applications for water supply diversions and/or storage. Likewise, in planning studies, impacts of instream flow needs on existing and future new water users and water management strategies are simulated.

WRAP is documented by a set of manuals (Wurbs 2013a, b, c, d, 2014; Wurbs and Hoffpauir 2013f). Wurbs (2011) compares WRAP with other river system management models. WRAP combines a repetition of historical hydrology represented by input sequences of naturalized streamflows and net reservoir evaporation less precipitation rates with a specified scenario of river system development infrastructure, water use demands, and water management strategies. Hydrologic periods-of-analysis spanning at least 50 years, typically longer, are adopted in the WAM datasets. The water development/use scenario might reflect actual current water use, projected future conditions, or the premise that all water right holders use the full amounts authorized by their permits.

A simulation begins with naturalized streamflows, which are flows that would have occurred historically in the absence of the water management activities reflected in the water rights input

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data set. Naturalized flows are compiled by adjusting actual gauged flows to remove the impacts of water development and use. Regulated and unappropriated flows computed during the simulation reflect the specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input data set. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flows may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream locations.

Simulation results are organized in various formats including time series tabulations and plots, summary tables, water budgets, and frequency and reliability relationships. Supply reliability and storage frequency metrics are important for assessing impacts of environmental flow requirements on water users. Flow frequency metrics are useful in assessing capabilities for satisfying instream flow requirements.

The original WRAP/WAM system employs a monthly step time. Recent versions include capabilities for daily simulations designed for modeling environmental flow standards. 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 strategy.

Environmental instream flow requirements have been included as minimum flow targets in the monthly WRAP and the WAM system since their inception. However, capabilities for modeling environmental flow requirements have recently been greatly expanded (Wurbs and Hoffpauir 2013f, e). New WRAP features include a daily modeling system with monthly-to-daily disaggregation and flow routing and forecasting, simulation of reservoir operations for flood control, environmental pulse flow requirements, various other options for defining instream flow targets, and additional postsimulation analysis options. The WRAP program has multiple options for monthly-to-daily disaggregation, including a uniform distribution, a linear spline interpolation routine, and user-defined daily flow patterns.

The terms instream flow *rights*, *requirements*, or *standards* are used interchangeably and include priorities, computed target flow rates, limits, and on/off switches. Instream flow targets are set in the model in essentially the same manner as water supply diversion and hydroelectric energy generation targets, using a flexible set of options allowing targets to be built as a function of month of the year, current flows, cumulative flow volume, reservoir storage, drought indices, and other variables. An instream flow target is a minimum regulated flow limit at a location. Constraints placed on the 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. Multiple instream flow requirements with different priorities may be input for a particular location, allowing the stringency of flow limits to 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.

High-flow pulses represent 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 any other instream flow targets. A pulse event is considered to be 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 other 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 each day during a pulse flow event. A frequency parameter limits the number of pulse events meeting the specified criteria during the tracking period that are adopted as target setting events.

A report prepared to support the SB3 process (Science Advisory Committee 2010) describes several methods for incorporating environmental flow requirements in monthly water availability models, highlights the advantages of a daily time step in modeling environmental flows, and discusses the need for compliance information related to the attainment of environmental flows to assist in balancing human and environmental needs for water. The daily WRAP modeling system with expanded capabilities for simulating SB3 environmental flow standards has been applied with several river basin data sets from the WAM system as a part of research and development efforts at Texas A&M University. The inaugural application was a Brazos River Basin case study documented in detail by Wurbs et al. (2012) and further refined by Wurbs and Hoffpauir (2013e). Wurbs and Zhang (2015) assess long-term trends in streamflows and water availability in Texas using WRAP/WAM simulation results.

Environmental Flow Attainment Metrics

Ten attainment metrics, as summarized in Table 1, have been determined for use with daily time series of simulated streamflows and flow targets (Pauls 2014). The metrics are evaluated for a subset of days in the hydrologic period-of-analysis based on the values of three data selection parameters: the minimum instream flow target, maximum instream flow target, and range of allowable months. The attainment metrics are evaluated for the subset of days which occur within the range of allowable months for which the instream flow target is greater than or equal to the minimum instream flow target and less than or equal to the maximum instream flow target.

The data selection parameters enable flexibility in assessing specific environmental flow regime components, a subset of environmental flow regime components, or all of the environmental flow regime components at a location. For example, in order to assess the attainment metrics for a seasonal base flow requirement, the allowable months would be set to the months included in the relevant season and the minimum and maximum instream flow targets would be set equal to the base flow level. In order to assess all environmental instream flow components at a location, the

Table 1. Attainment Metric Abbreviations and Descriptions

Abbreviation	Description
E	Percentage of time instream flow target is engaged
EVR	Engaged volume reliability
EPR	Engaged period reliability
CE	Consecutive days instream flow target is engaged
CEM	Consecutive days instream flow target is engaged and met
CES	Consecutive days instream flow target is engaged with a shortage
CBE	Consecutive days between engagement of an instream flow target
S	Instream flow shortage
PS	Instream flow shortage as a percentage of the instream flow target
ASPAT	Average instream flow shortage as a percentage of the average instream flow target

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allowable months would be set to all months, the minimum instream flow target would be set to zero, and the maximum instream flow target would be set to a value greater than or equal to the maximum instream flow target, such as the maximum high-flow pulse event target magnitude.

An instream flow target is *engaged* if it is within the range of allowable instream flow targets specified by the data selection parameters. The target engagement (E) is the percentage of the total number of days in the simulation for which an instream flow target is engaged. Four of the metrics listed in Table 1 are derived using the target engagement, including the consecutive number of days in which an instream flow target is engaged (CE), the consecutive number of days in which an instream flow target is engaged and met (CEM), the consecutive number of days in which an instream flow target is engaged with a shortage (CES), and the consecutive number of days between engagement of an instream flow target (CBE). In order to determine metric CBE, a tracking parameter was incremented each day that an instream flow target was *not* engaged and set to zero each day that an instream flow target *was* engaged.

An instream flow shortage (S) is recorded when the observed instream flow is less than the target instream flow for days in which an instream flow target is engaged. The instream flow shortage is also computed as a percentage of the instream flow target (PS).

A variety of statistics may be applied to metrics CE, CEM, CES, CBE, S, and PS. The average value of the metrics is useful for making general comparisons between environmental flow regime components, different locations, or alternate river system development scenarios. Exceedance frequency plots of the metrics are useful for making comparisons and for investigating more complex characteristics of the environmental flow regime. Engaged exceedance frequency plots summarize exceedance frequency statistics for days in which the instream flow target is engaged.

The engaged volume reliability (EVR) is the cumulative volume of observed instream flows divided by the cumulative volume of instream flow targets for days in which the instream flow target is engaged. The engaged period reliability (EPR) is the percentage of days in which the instream flow target is engaged for which the observed instream flow meets or exceeds the instream flow target.

The average instream flow shortage is evaluated relative to the average engaged instream flow target, including both days in which shortages are observed and days in which the flow target is met, using metric ASPAT. The average value of metric PS differs from metric ASPAT in that the average value of metric PS only considers days in which shortages are observed.

Colorado River Basin Case Study

The Colorado River Basin extends approximately 1,000 km across Texas as shown in Fig. 1 and has a total drainage area of 110,000 km^2, of which approximately 30,600 km^2 are noncontributing. Its climate varies from arid in the northwest with average annual precipitation of 36 cm to humid subtropical in the southeast with average annual precipitation of 112 cm. The river discharges to Matagorda Bay south of Bay City. Major tributaries include Beals Creek, Elm Creek, Pecan Bayou, Concho River, San Saba River, Llano River, Pedernales River, and Onion Creek.

Water right permits to divert waters from the Colorado River and its tributaries and streams in the adjoining Brazos–Colorado Coastal Basin have been issued to over 2,000 entities. The largest is the Lower Colorado River Authority, which operates Lakes Buchanan, Inks, LBJ, Marble Falls, Travis, and Austin on the Colorado River and Lakes Bastrop and Fayette County on tributaries. The Colorado River Municipal Water District is the largest water supplier in the upper Colorado River Basin and operates Lakes J.B. Thomas, E.V. Spence, and O.H. Ivie for water supply and nine other reservoirs to prevent high salinity water from flowing downstream. The U.S. Army Corps of Engineers owns and operates Hords Creek and O.C. Fischer Reservoirs and operates the flood control pools of Lakes Travis and Twin Buttes.

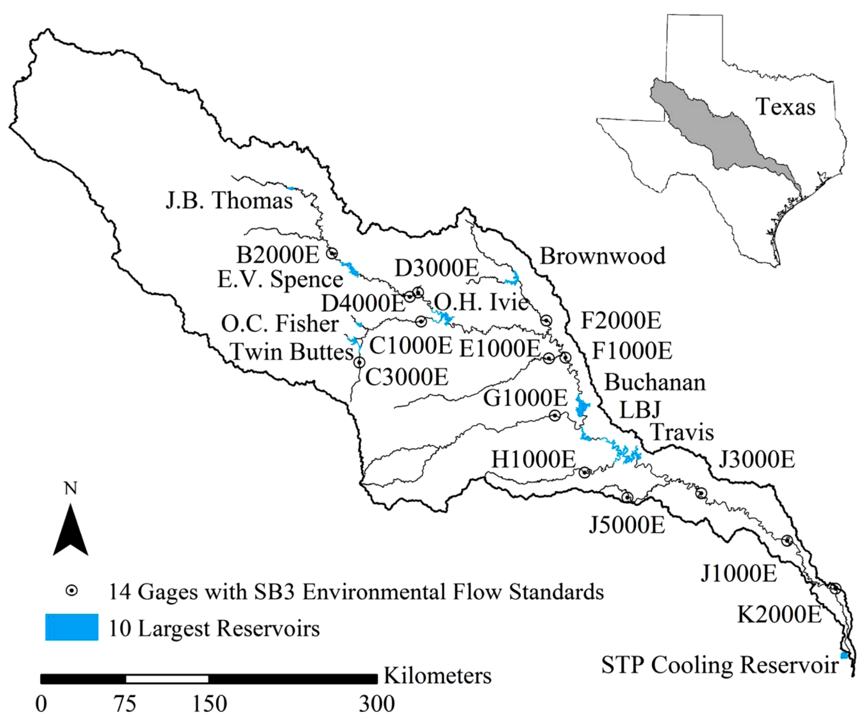

Fig. 1. Map of largest reservoirs and SB3 environmental flow sites in the Colorado River Basin

Table 2. Locations of SB3 Environmental Flow Standards in the Colorado River Basin

WAM control point	USGS gauge number	Gauge name	Contributing drainage area (km^2)
B2000E	08123850	Colorado River above Silver	11,810
C3000E	08128000	South Concho River at Christoval	668
C1000E	08136500	Concho River at Paint Rock	13,429
D4000E	08126380	Colorado River near Ballinger	15,773
D3000E	08127000	Elm Creek at Ballinger	1,202
E1000E	08146000	San Saba River at San Saba	7,894
F2000E	08143600	Pecan Bayou near Mullin	5,372
F1000E	08147000	Colorado River near San Saba	51,359
G1000E	08151500	Llano River at Llano	10,881
H1000E	08153500	Pedernales River near Johnson City	2,334
J5000E	08158700	Onion Creek near Driftwood	321
J3000E	08159200	Colorado River at Bastrop	74,022
J1000E	08161000	Colorado River at Columbus	78,332
K2000E	08162000	Colorado River at Wharton	79,256

Colorado Water Availability Model

The WRAP input data set for the Colorado River Basin and adjoining Brazos–Colorado Coastal Basin in the TCEQ WAM system is called the Colorado WAM. The authorized use scenario version of the Colorado WAM adopted in this study is based on the premise that all water right holders use the full amounts authorized in their permits. About 2,100 water rights permits and 518 reservoirs are simulated in the Colorado WAM. The input data set includes naturalized flows at 45 control points corresponding to the locations of gauging stations. The monthly naturalized flows are distributed to about 2,400 ungauged sites using watershed parameters provided as input. Monthly flows are disaggregated to daily average flows within the simulation at each control point based on daily flow patterns provided at 48 locations.

A daily version of the Colorado WAM was developed at TAMU by modifying the monthly WAM. Environmental flow standards established pursuant to the SB3 process at the 14 sites shown in Fig. 1 and listed in Table 2 were added. Flood control operations were added for the four reservoirs with flood control pools. The official Colorado WAM data set has a hydrologic period-of-analysis of 1940–1998, which was extended in the TAMU study to cover 1940–2012.

Senate Bill 3 Environmental Instream Flow Standards

SB3 environmental flow standards for the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays were established for 21 locations, which include 14 sites in the Colorado River Basin, as described in Texas Administrative Code Title 30, Part 1, Chapter 298, Subchapter D. The scientific basis upon which the environmental flow standards were developed is described in a 2011 report by the Colorado Basin and Bay Expert Science Team (2011). The 14 sites in the Colorado River Basin are the locations of the USGS gauging stations and Colorado WAM control points listed in Table 2. The SB3 environmental flow standards do not affect existing senior diversion and storage rights but reduce unappropriated flows available for future water rights applicants. Quantities defining the SB3 environmental flow requirements at control point B2000E on the upper Colorado River are provided in Table 3 as an example. The SB3 environmental flow requirements for the other 13 sites in the Colorado River Basin may be found in the Texas Administrative Code, as referenced earlier.

The environmental flow standards at the 14 sites consist of seasonal subsistence and base flow requirements and three levels of high-flow pulse event requirements. The environmental flow

Table 3. SB3 Environmental Instream Flow Standards at Control Point B2000E

Season	Hydrologic condition	Subsistence flow (cm)	Base flow (cm)	Pulse flow frequency	Pulse flow trigger (cm)	Pulse flow volume (m^3)	Pulse flow duration (days)
Winter	Severe	0.03	0.06	—	—	—	—
	Dry	N/A	0.06	—	—	—	—
	Average	N/A	0.11	—	—	—	—
	Wet	N/A	0.20	—	—	—	—
	N/A	—	—	2 per season	0.51	148,018	13
	N/A	—	—	1 per season	1.19	370,045	15
Spring	Severe	0.03	0.06	—	—	—	—
	Dry	N/A	0.06	—	—	—	—
	Average	N/A	0.14	—	—	—	—
	Wet	N/A	0.34	—	—	—	—
	N/A	—	—	2 per season	16.99	3,083,705	9
	N/A	—	—	1 per season	50.97	9,744,507	11
Summer	Severe	0.03	0.03	—	—	—	—
	Dry	N/A	0.03	—	—	—	—
	Average	N/A	0.08	—	—	—	—
	Wet	N/A	0.23	—	—	—	—
	N/A	—	—	2 per season	2.83	431,719	6
	N/A	—	—	1 per season	9.34	1,726,875	9
Fall	Severe	0.03	0.03	—	—	—	—
	Dry	N/A	0.03	—	—	—	—
	Average	N/A	0.11	—	—	—	—
	Wet	N/A	0.28	—	—	—	—
	N/A	—	—	2 per season	2.83	493,393	6
	N/A	—	—	1 per season	12.18	2,220,267	9
—	—	—	—	Annual	84.95	16,775,353	17

Table 4. Attainment Metric Comparison for Environmental Flow Regime Components at Control Point B2000E

	IF target (cm)	E (%)	EVR (%)	EPR (%)	Average CE (days)	Average CEM (days)	Average CES (days)	Average CBE (days)	Average S (cm)	Average PS
Subsistence and base flows	0.03	5	1,661	39	2	0	1	1,670	0.03	93%
	0.06	6	2,762	47	4	1	1	2,168	0.06	89%
	0.08	7	2,688	52	2	0	0	646	0.08	86%
	0.11	19	1,612	56	8	2	2	378	0.08	78%
	0.14	13	1,724	54	6	1	1	523	0.11	77%
	0.20	15	359	41	8	1	3	494	0.14	69%
	0.23	8	1,371	51	2	0	1	602	0.17	79%
	0.28	7	1,041	49	2	0	0	607	0.20	70%
	0.34	16	966	46	6	1	1	411	0.25	74%
Pulse flows	0.51	0.48	580	100	0	0	0	279	0.00	0%
	1.19	0.26	370	100	0	0	0	380	0.00	0%
	2.83	0.63	348	100	0	0	0	179	0.00	0%
	9.34	0.18	205	100	0	0	0	392	0.00	0%
	12.18	0.20	232	100	0	0	0	359	0.00	0%
	16.99	0.28	198	100	0	0	0	322	0.00	0%
	50.97	0.10	124	100	0	0	0	1,194	0.00	0%
	84.95	0.15	198	100	0	0	0	603	0.00	0%
	Variable	1.93	—	—	—	—	—	—	—	—

standards vary depending on whether the control point is located on the lower Colorado River below Lake Travis, upper Colorado River above Lake Travis, or on tributaries. Control points J3000E, J1000E, and K2000E are on the lower Colorado River. The other 11 sites are on the upper Colorado River or tributaries of the Colorado River.

Seasons, hydrologic conditions, and environmental instream flow targets are specified according to two schemes depending on location. For control points on the upper Colorado River or tributaries, the winter season consists of the four months from November to February, the spring season is the four months from March to June, the summer season is July and August, and the fall season is September and October. Four hydrologic conditions (severe, dry, average, and wet) are defined based on 12-month cumulative streamflows. For all 14 sites, hydrologic conditions are evaluated on the last day of the preceding season and applied for the entire season.

The subsistence flow standard varies seasonally and is applicable during severe hydrologic conditions when flow is less than the dry base flow standard. The base flow standard varies seasonally and according to hydrologic conditions and is applicable when flow is less than any applicable high-flow pulse event trigger magnitudes and greater than the dry base flow level. Three levels of high-flow pulse events are specified, including a two-per-season pulse, a one-per-season pulse, and an annual pulse. If a high-flow pulse event trigger magnitude is met, junior water rights holders may not make any diversions until either the specified volume or duration time has passed, except when flow levels exceed the high-flow pulse event trigger magnitude.

For control points on the lower Colorado River, the month of November is included in the fall season instead of the winter season. Three hydrologic conditions (severe, dry, and average) are evaluated based on the combined storage in Lakes Travis and Buchanan. The subsistence flow standard varies by month and is applicable during severe hydrologic conditions when flow is less than the dry base flow standard. The base flow standard varies by month and according to hydrologic conditions and is applicable when flow is less than any applicable high-flow pulse event trigger magnitudes and greater than the dry base flow level.

Three levels of high-flow pulse events are specified, including a two-per-season pulse, a one-per-18-month pulse, and a one-per-2-year pulse. If a high-flow pulse event trigger magnitude is met, junior water rights holders may not make any diversions until the specified duration time has passed, except when streamflow levels exceed the high-flow pulse event trigger magnitude. Engagement of a high-flow pulse event is independent of hydrologic conditions.

WRAP Simulation Results

The SB3 environmental flow standards at 14 sites were incorporated in a daily time-step version of the Colorado WAM. The attainment metrics defined in Table 1 are used to characterize the engagement and attainment of the environmental flow standards within the priority-order simulation of water allocation. Comparisons are made in Table 4 between environmental flow regime components at control point B2000E. Attainment metrics for all 14 control points are tabulated in Tables 5 and 6. Selected metrics for B2000E and K2000E, the most upstream and downstream sites on the Colorado River, are compared in Fig. 2.

Table 5. Attainment Metric Comparison for All Instream Flow Targets

Control point	EVR (%)	EPR (%)	Average CEM (days)	Average CES (days)	Average S (cm)	Average PS (%)	ASPAT (%)
B2000E	494	51	14	16	0.14	77	24
C3000E	164	47	31	38	0.17	41	38
C1000E	286	66	23	4	0.42	60	43
D4000E	375	55	16	10	0.25	71	28
D3000E	561	62	37	13	0.03	80	14
E1000E	208	60	38	9	0.74	36	27
F2000E	483	69	18	4	0.17	80	21
F1000E	241	66	18	5	2.21	42	28
G1000E	221	61	43	13	1.33	36	28
H1000E	291	57	38	13	0.59	53	31
J5000E	350	78	92	9	0.20	64	51
J3000E	288	80	54	2	3.17	29	21
J1000E	214	67	25	5	7.70	38	31
K2000E	183	52	9	7	9.74	43	40

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Table 6. Attainment Metric Comparison for High Flow Pulse Event Targets

Control point	E (%)	EVR (%)	EPR (%)	Average CBE (days)
B2000E	4	207	100	83
C3000E	0.3	336	100	448
C1000E	4	194	100	62
D4000E	4	192	100	73
D3000E	3	288	100	72
E1000E	3	216	100	82
F2000E	6	189	100	54
F1000E	4	158	100	76
G1000E	3	221	100	112
H1000E	2	238	100	121
J5000E	3	155	100	159
J3000E	5	197	100	84
J1000E	5	204	100	76
K2000E	5	216	100	93

Metrics are tabulated in Table 4 for individual environmental flow regime components at control point B2000E based on results of the WRAP/WAM simulation with the SB3 standards being junior to all other water rights. Metric E shows the percentage of time that each instream flow target was engaged. Subsistence and base flow targets were engaged 95.8% of the time and high-flow pulse event targets were engaged the remaining 4.2% of the time. For high-flow pulse events, the instream flow target is set equal to the trigger magnitude on the first day that the high-flow pulse event is engaged. On subsequent days, the instream flow target may be set equal to either the trigger magnitude or a variable target equal to available streamflow or the remaining volume required to meet the high-flow pulse event volume termination criterion. Variable high-flow pulse event targets were set 1.93% of the time, approximately half the time that high-flow pulse events were engaged.

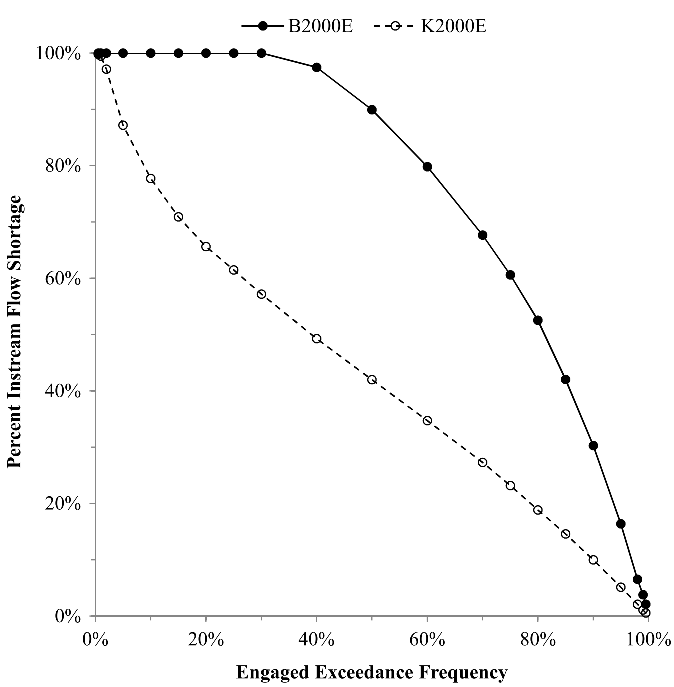

Fig. 2. Engaged exceedance frequency plot of instream flow shortage as a percentage of the instream flow target for all instream flow targets at control points B2000E and K2000E

Metric EVR ranges from 124 to 2,762% in Table 4 and is generally greater for the subsistence and base flow targets compared to the high-flow pulse event targets. Metric EPR ranged from 39 to 56% for the subsistence and base flow targets and was generally greatest for the targets corresponding to average hydrologic conditions. Metric EPR was 100% for all of the high-flow pulse event targets. The eight high-flow pulse event targets listed in Table 4 correspond to trigger magnitudes, which are set on either the first day that a high-flow pulse event is engaged or subsequent days in which the observed streamflow exceeds the high-flow pulse event trigger magnitude and the high-flow pulse event trigger magnitude exceeds the remaining volume for the high-flow pulse event volume termination criterion.

The average value of metric CE at B2000E ranged from 2 to 8 days for the subsistence and base flow targets and was approximately zero for all high-flow pulse event targets. The average values of metrics CEM and CES ranged from 0 to 3 days for the subsistence and base flow targets and were approximately zero for all high-flow pulse event targets. The average values of metrics CEM and CES were low compared to the average values of metric CE for subsistence and base flow targets, indicating that periods of consecutive subsistence and base flow target engagement were generally composed of both days in which the target was met and days in which a shortage was observed. The average value of metric CBE ranged from 179 to 2,168 days. The average value of metric CBE was relatively large for the subsistence and base flow targets corresponding to severe and dry hydrologic conditions and for the spring one-per-season high-flow pulse event.

The average values of metrics S and PS ranged from 0.03 to 0.25 cm and from 69 to 93%, respectively, for the subsistence and base flow targets. The base flow targets corresponding to wet hydrologic conditions had the greatest and least average values for metrics S and PS, respectively. The average values of metrics S and PS were equal to zero for all high-flow pulse events because the targets were completely met 100% of the time.

In Table 5, several metrics are evaluated for all instream flow targets at each of the 14 control points in the Colorado River Basin based on results of the initial simulation. Metric EVR ranged from 164 to 561% and metric EPR ranged from 47 to 80%. The average values of metrics CEM and CES ranged from 9 to 92 days and from 2 to 38 days, respectively. The average value of metric CEM was generally greater than the average value of metric CES, with the exception of control points B2000E and C3000E.

The average values of metrics S and PS in Table 5 range from 0.14 to 9.74 cm and from 29 to 80%, respectively. Metric ASPAT ranged from 14 to 51%. The average value of metric S generally increased with increasing drainage area. The average value of metric PS was greater than metric ASPAT at all 14 control point locations. Because metric PS is computed for days in which a shortage is observed and metric ASPAT is computed for both days in which a shortage is observed and days in which the instream flow target is met, metric ASPAT should be less than the average value of metric PS as long as there are a sufficient number of days in which instream flow targets with magnitudes greater than the average shortage are met. For control points B2000E, D4000E, D3000E, and F2000E, the average value of metric PS was significantly greater than the value of metric ASPAT.

As seen in Fig. 2, instream flow shortages equivalent to 100% of the instream flow target were observed approximately 30% of the time at control point B2000E, corresponding to days with zero streamflow. The significant percentage of time in which zero streamflows were observed inflated the average value of metric

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Table 7. Attainment Metrics for All Instream Flow Targets at Control Point B2000E

Priority scenario	EVR (%)	EPR (%)	Average CEM (days)	Average CES (days)	Average S (cm)	Average PS (%)	ASPAT (%)
Junior	494	51	14	16	0.14	77	24
Senior	462	55	21	15	0.13	75	21

PS relative to metric ASPAT. It is likely that zero streamflows were also observed a significant percentage of time at control points D4000E, D3000E, and F2000E. Control point K2000E, nearest the watershed outlet, is also included in the engaged exceedance frequency plot of Fig. 2. As expected, near-zero streamflows were observed a much smaller percentage of time at this location.

Four metrics are presented in Table 6 for all high-flow pulse event targets at each of the 14 control points. Metric E ranged from 2 to 6% for all control points except C3000E. At control point C3000E, metric E was 0.3%. The comparatively small value of metric E at C3000E is a result of the comparatively small number of high-flow pulse events specified at C3000E in the environmental flow standards. Two high-flow pulse events are specified at C3000E, compared to nine high-flow pulse events at other control points. Metric EVR ranged from 155 to 336%. Metric EPR was 100% at all 14 control points. The average value of metric CBE ranged from 54 to 159 days for all control points excluding C3000E. At control point C3000E, the average value of metric CBE was 448 days.

Water Rights Priorities

Priority dates for each of the permits in the prior appropriation Texas water rights permit system are based on either historical water use or dates that permits were approved. Approval of permit applications now requires demonstration by WAM analyses that acceptable levels of reliability can be provided by unappropriated flows. Buying and selling of existing water rights are encouraged where adequate unappropriated flows are not available. Market transactions are subject to WAM analyses and TCEQ approval.

Priorities for SB3 environmental flow standards are set at the dates that recommended standards are submitted to the TCEQ by appropriate committees. The flow standards for the Colorado River Basin have a priority date of March 1, 2011, which is junior to all the other water rights included in the WAM. This junior priority date is adopted for the WRAP/WAM simulation discussed in the preceding section. However, for purposes of comparison, results are also presented in Table 7 and Fig. 3 for an alternate simulation with the SB3 instream flow standard at control point B2000E assigned a priority senior to all other water rights in the basin.

Table 7 compares the results for the instream flow targets at control point B2000E for the initial and alternate simulations with the environmental flow standard junior versus senior to all other water rights. There was a slight improvement in the achievement of the environmental flow standards for the alternate (senior priority) simulation relative to the initial (junior) simulation, as evidenced by greater values of metrics EPR and CEM and lesser values of metrics CES, S, PS, and ASPAT. Fig. 3 is an engaged exceedance frequency plot of metric PS at control point B2000E for the initial and alternate simulations. Metric PS improved slightly at all of the exceedance frequency values except those corresponding to a 100% instream flow shortage.

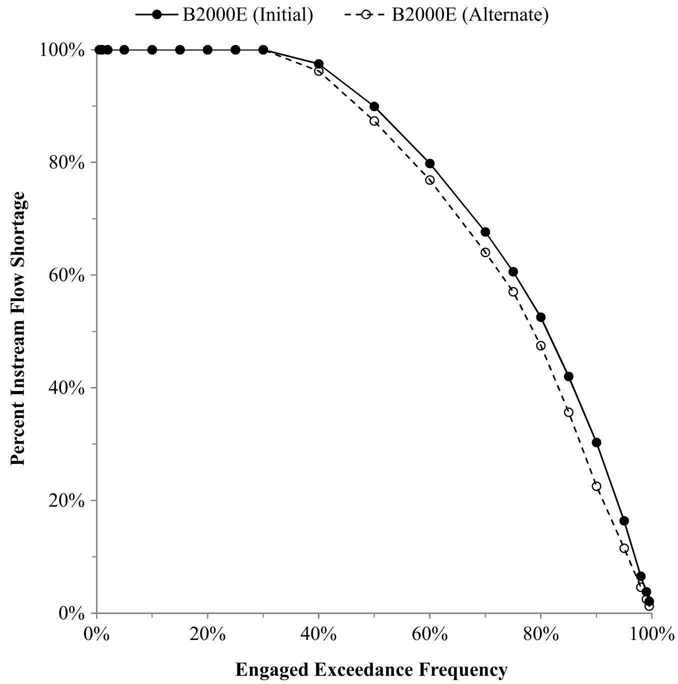

Fig. 3. Engaged exceedance frequency plot of instream flow shortage as a percentage of the instream flow target for all instream flow targets at control point B2000E for junior versus senior priorities

Conclusions

Streamflow throughout Texas, like elsewhere, is extremely variable, subject to severe multiyear droughts and infrequent extreme flood events as well as seasonal and continuous fluctuations. Highly variable streamflow is allocated among numerous water users representing diverse types of use and management practices. Ecosystem needs are an important consideration in integrated river/reservoir system management. Environmental flows must be preserved while providing reliable and affordable water supplies for growing populations. Assessments of hydrologic and institutional water availability and reliability for an array of uses and users are essential for effective water management.

Water supply reliability and reservoir storage and streamflow frequency metrics provided by the WRAP/WAM system are fundamental to water resources planning and administration of the water rights permit system in Texas. The SB3 process results in establishing environmental flow standards that are implemented within the WRAP/WAM system. The SB3 environmental standards with subsistence flow, base flow, within-bank pulse flow, and overbank pulse flow components are much more complex than the minimum instream flow limits of the past, necessitating development of additional new attainment metrics.

The reliability, frequency, and duration metrics for assessing the achievement of environmental flow standards explored in this paper are evaluated from the results of a water allocation simulation model, which in Texas is the WRAP/WAM system. Parameters are used to select the data for which the metrics are developed, providing flexibility for evaluating individual environmental flow regime components, a subset of environmental flow regime components, or all of the environmental flow regime components at a site. The attainment metrics are illustrated in this paper by application to SB3 environmental flow standards at 14 control points in the Colorado River Basin based on simulation results from the daily WRAP modeling system with an expanded version of an input data set from the WAM system. The metrics can be used to support comparative evaluations of alternative environmental flow standards, the different components of the standards, and interactions between environmental flow requirements, human water users, and various aspects of river/reservoir system operations.

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