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ENVIRONMENTAL FLOWS IN A HUMAN-DOMINATED SYSTEM: INTEGRATED WATER MANAGEMENT STRATEGIES FOR THE RIO GRANDE/BRAVO BASIN

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ABSTRACT

Water management in the transboundary Rio Grande/Bravo (RGB) Basin, shared by the US and Mexico, is complicated by extreme hydrologic variability, overallocation, and international treaty obligations. Heavy regulation of the RGB has degraded binationally protected ecosystems along the Big Bend Reach of the RGB. This study addresses the need for integrated water management in Big Bend by developing an alternative reservoir operation policy to provide environmental flows while reducing water management trade-offs. A reach-scale water planning model was used to represent historical hydrology (1955–2009), water allocation, and reservoir operations, and key human water management objectives (water supply, flood control, and binational treaty obligations) were quantified. Spatially distributed environmental flow objectives and an alternative reservoir rule curve were developed. We simulated current and alternative water management policies and used an iterative simulation–evaluation process to evaluate alternative policies based on water system performance criteria with respect to specified objectives. A single optimal policy was identified that maximized environmental flows while maintaining specified human objectives. By changing the timing but not the volume of releases, the proposed reservoir re-operation policy has the potential to sustain key ecological and geomorphic functions in Big Bend without significantly impacting current water management objectives. The proposed policy also improved water supply provisions, reduced average annual flood risk, and maintained historical treaty provisions.

KEY WORDS: integrated water management; environmental flows; reservoir re-operation; transboundary basin

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INTRODUCTION

Re-operating reservoirs to release environmental flows (EFs) while maintaining traditional water management goals is an emerging tool for sustaining critical environmental functions in human-dominated river systems (Richter and Thomas, 2007; Sandoval-Solis and McKinney, 2012; Yin *et al*., 2011). EFs refer to the flow regime of appropriate quantity, quality, and timing of water to sustain natural functions and services while meeting human water demands (Poff *et al*., 1997). EFs can be expressed as average annual flow regime prescriptions, seasonally varying hydrographs, pulse flows, or acceptable levels of alteration from natural or reference conditions (Tharme, 2003).While reservoirs already provide many functions, including flood control and water supply reliability, they can often also provide EFs through operational changes to reservoirs without large structural expenditures (Konrad *et al*., 2011). However, water policies and regulations, existing infrastructure, and the ability to integrate EF releases into current basin management objectives are increasingly challenging, particularly in transboundary basins. This constrains opportunities to restore environmental functions through reservoir re-operations.

This study introduces a methodology for incorporating EF releases into human-dominated water systems based on diverse tools and knowledge from water resource engineering, hydrology, ecology, and geomorphology. The methodology is applied to the ecologically degraded, transboundary Rio Grande/Bravo (RGB) Basin. Key drivers of and obstacles to EFs are examined to develop an alternative reservoir operation policy for the Big Bend (BB) Reach of the RGB. The specific objectives of the study were to as follows: (i) characterize the regional hydrology (pre-regulation and post-regulation), water demands, reservoir operations, and water allocation system using a reach-scale water planning model; (ii) develop spatially distributed EF objectives; and (iii) design a multi-objective reservoir operation policy to provide EFs while maintaining or improving human objectives for water supply, flood control, and international treaty obligations.

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CASE STUDY: BIG BEND REACH OF THE RIO GRANDE/BRAVO BASIN

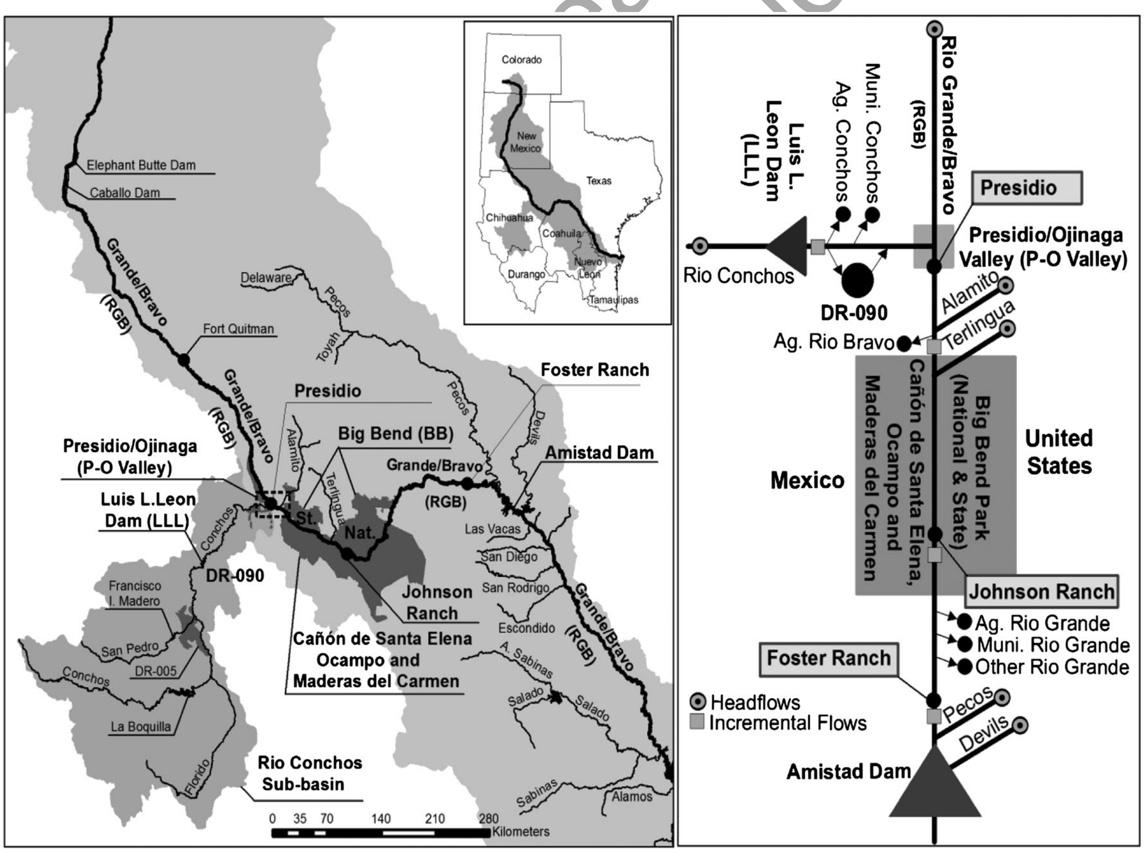
RGB Basin

The RGB is a transboundary river basin shared by the USA and Mexico (Figure 1a). The RGB flows south from its headwaters in Colorado to form the US–Mexico border near El Paso, Texas, and then south-east towards the Gulf of Mexico. The basin is one of the most water stressed in the world (Giordano and Wolf, 2002) and was recently identified among basins with 'the highest potential for conflict and crisis in the world, especially under drought conditions' (DOI, 2003). Increasing population, long-term drought, and climatic uncertainty are magnifying water management concerns. The basin's population of 10.5 million is projected to double over the next three decades (Patino-Gomez *et al.*, 2007), while climate projections suggest that mean annual run-off will decrease by 7 to 14% by 2050 (USBR, 2011), which translates to significant water supply reductions.

BB Reach

The BB Reach consists of the Rio Conchos in Mexico from Luis L. Leon (LLL) reservoir [capacity 832 million cubic metres (MCM)] to its confluence with the binational RGB mainstem and down the RGB to Amistad reservoir (capacity 6000 MCM; Figure 1b). Presidents Obama (USA) and Calderon (Mexico) (Obama and Calderon-Hinojosa 2010) declared BB a region of environmental and socio-economic significance because of its unique and degraded ecosystems as well as its importance for agriculture and tourism. The reach contains riparian and aquatic ecosystems unique to the Chihuahuan Desert, including over 12 000 km^2 of protected natural areas in both countries and numerous endangered and endemic species (Sandoval-Solis and McKinney, 2012).

Decades of heavy human use have altered the hydrology (Sandoval-Solis *et al.*, 2010) and geomorphology (Dean and Schmidt, 2011) of the basin, with severe ecological consequences, including increases in invasive riparian species such as salt cedar (*Tamarix* spp.) and giant cane (*Arundo donax*; (Everitt, 1998) and the near-complete



a) Rio Grande/Bravo (RGB) Basin   b) Schematic of the Big Bend (BB) Reach

Figure 1. Map of (a) the RGB Basin and (b) the BB Reach, including locations of model headflows, incremental flows, demand sites, and EF evaluation sites

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extinction of endemic fish species, for example, Rio Grande silvery minnow (Bestgen and Platania, 1991). Streamflow and sediment alterations have been disconnecting the river from its floodplain and reducing the availability and quality of habitat (Dean and Schmidt, 2011). Despite scientific recognition of streamflow regulation as a key driver of river ecosystem degradation (Poff *et al*., 1997), no environmental water management policy exists for the BB Reach.

Sandoval-Solis and McKinney (2012) identified an upper bound on the water available in BB for environmental water management using the Indicators of Hydrologic Alteration (IHA) method (Richter *et al*., 1996). The study was based on statistical streamflow analysis at a single location (Johnson Ranch). This study improves on past research to develop a multi-objective water management policy for BB by as follows: (i) using empirical ecogeomorphic streamflow thresholds as well as statistical analysis to develop EFs for multiple locations and (ii) developing an operational reservoir rule curve to release these EFs in the context of current human objectives.

POLICY DEVELOPMENT: PRELIMINARY METHODS AND ANALYSIS

An alternative reservoir operation policy (hereafter called ‘e-flow policy’) was developed for LLL using a multi-step methodology (Figure 2), which included the following: (i) developing a reach-scale water planning model; (ii) identifying spatially distributed EF objectives that were developed for multiple hydrologic conditions; (iii) quantifying human water management objectives to determine performance criteria for evaluating model results with respect to specified objectives; (iv) proposing an initial e-flow policy, where a ‘policy’ consisted of a unique set of monthly reservoir storage zone thresholds; and finally (iv) identifying a single e-flow policy that maximized EF performance while maintaining specified human objectives using an iterative process (steps 1–4 and bold arrows in Figure 2).

BB water planning model

The BB model was used to simulate alternative water management policies in the BB Reach (Sandoval-Solis and McKinney, 2012). The model integrates a one-dimensional water routing model with a priority-based water allocation system to represent regional hydrology, infrastructure, and water management on a monthly time step. The Water Evaluation and Planning System (WEAP) platform (Yates *et al*., 2005) was used to calculate a monthly water balance of inflows, changes in reservoir storage, and outflows based on a 55-year hydrologic record (October 1955–September 2009). Visual Basic scripts converted data between WEAP and Excel.

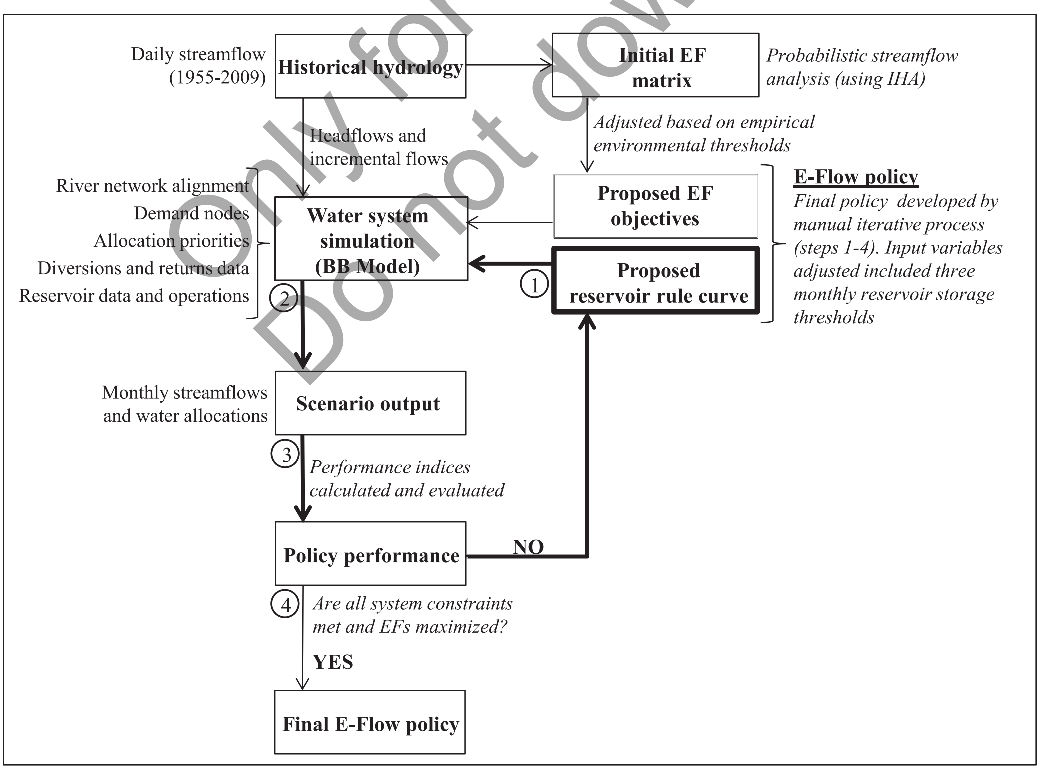

Figure 2. Study method framework, including key inputs and outputs of linked major components (boxed) and computations performed (indicated by italics)

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Model inputs included historical reservoir data (operational and physical), diversion and return flows, and monthly streamflows (Patino-Gomez *et al*., 2007; Comisión Nacional del Agua (CONAGUA), 2008; International Boundary and Water Commission (IBWC), 2013). Historical streamflow data were based on US Geological Survey gauge station data (CONAGUA, 2008; IBWC, 2013); median daily flows were summed to create a monthly streamflow volume time series. The monthly time step was constrained by input data. Seven water demands were considered in the model, with agriculture making up the vast majority (~99%) of use (refer to section on Results: Water Supply). Water for demand sites came from reservoir releases, tributary headflows, and incremental flows (IFs; Figure 1b).

The BB model is governed by the continuity equation for an *i*th subreach in month *t* (Equation 1):

$$\Delta\text{Storage}_t^i = Inflows_t^i - Outflows_t^i + IF_t^i \tag{1}$$

where $\Delta\text{Storage}_t^i$ is the change of reservoir storage, $Inflows_t^i$ include streamflow inputs, water imports, and returns, $Outflows_t^i$ include streamflow, water exports, and diversions out of the reach, and IF_t^i, or IFs, refer to water gains (e.g. groundwater inputs) minus losses (e.g. evaporation and seepage) between gauge stations. Historical streamflow, diversions and returns, reservoir storage, and evaporation data were used to estimate IFs (Patino-Gomez *et al*., 2007; CONAGUA, 2008; IBWC, 2013), and gains and losses were adjusted in the model calibration process (Lane, 2014).

Model testing. The BB model was adjusted to fit historical streamflow and reservoir storage data by as follows: (i) calculating headflows and IFs (based on reach gains and losses) and (ii) adjusting water allocations and reservoir operations via numerous model inputs. Model accuracy was evaluated over a 40-year period (October 1969–September 2009) during which both reservoirs were in operation and historical data were reliable (Patino-Gomez *et al*., 2007, CONAGUA 2008). Goodness-of-fit indices [coefficient of determination (R^2, 0 to 1), index of agreement (IA, 0 to 1) and coefficient of efficiency (CE, $-\infty$ to 1; Legates and McCabe, 1999)] were used to evaluate performance of two reservoirs [LLL ($R^2 = 0.97$, IA = 1.00, CE = 0.99) and Amistad ($R^2 = 0.99$, IA = 0.99, CE = 0.97)] and two gauge stations [Rio Conchos at Ojinaga ($R^2 = 0.99$, IA = 1.00, CE = 0.99) and RGB at Johnson ($R^2 = 0.98$, IA = 0.99, CE = 0.98)]. The high values indicate that the model performs very well (Moriasi *et al*., 2007).

Water Allocation Algorithm. The model water allocation algorithm distributes water in a stepwise procedure, first between the two countries according to the Treaty of 1944 and then according to the countries' respective regulations. The 1944 Treaty allocates one third of the flow reaching the RGB from the Rio Conchos to the USA and two thirds to Mexico (IBWC, 1944). Under US regulations, RGB water is distributed among users according to prior appropriation based on date of water right (TCEQ, 2006). In Mexico, water is allocated based on national water law, which distributes water according to prior appropriation based on type of use (CONAGUA, 2012).

Luis L. Leon reservoir on the Rio Conchos supplies ~80% of water to BB. Its releases primarily supply water demands along the Rio Conchos or increases floodwater storage capacity (IBWC, 2013). Neither RGB users nor EFs are considered in the release policy. Each October, CONAGUA determines allocations based on reservoir storage volume and type of use. Water-rights holders with the same type of use have equal priority; during droughts, they share water shortages in equal proportion (CONAGUA, 2012). The current operational policy for LLL does not consider water supply for RGB mainstem users or EFs.

DEVELOPING ENVIRONMENTAL FLOW OBJECTIVES

Over 200 methods exist for quantifying EFs, which can be divided into four distinct categories: hydrology-based, hydraulic-rating, habitat simulation, and holistic methods (Tharme, 2003). *Hydrology-based methods* use historical streamflow records to develop rapid, statistically derived EFs, usually based on some natural flow component intended to sustain a desired function [e.g. Tennant method (Tennant, 1975)]. *Hydraulic-rating methods* use hydraulic habitat requirements of target biota to set EFs as the discharge producing a fixed reduction in useable habitat. *Habitat simulation methods* quantify suitable instream habitat availability for target species under different flow regimes on the basis of integrated hydrological, hydraulic, and biological response data [e.g. Instream Flow Incremental Method (Bovee, 1978)]. *Holistic methods* draw from other methods to identify ecologically significant components of the natural flow regime through either bottom-up or top-down approaches requiring considerable resources and multidisciplinary expertise. The bottom-up approach constructs EFs on an element-by-element basis, where each element represents a flow component intended to achieve a particular objective [e.g. building blocks method (Tharme and King, 1998)]. In contrast, top-down approaches define EFs in terms of 'acceptable' alteration from a natural (or reference) flow regime. This study developed EFs by coupling the hydrology-based and bottom-up holistic methods.

Monthly average EF objectives were developed for three locations along the BB Reach (Presidio, Johnson Ranch, and

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Foster Ranch) to characterize reach-scale environmental water needs according to the hydrologic and ecogeomorphic context without regard for human water management goals. These EFs are simplifications of processes acting over shorter timescales and intended only as a coarse template; timescale refinement was limited by environmental and model input data constraints.

An initial EF matrix was created for the reach by the interdisciplinary Upper Rio Grande Basin and Bay Expert Science Team (BBEST, 2012). BBEST used the hydrology-based IHA method (Richter *et al.*, 1996) to statistically characterize key components of the natural flow regime based on historical daily streamflow data (IBWC, 2013). The period of analysis (1936–1967) consisted of all data prior to the construction of LLL reservoir and included cycles of wet (1936–1944) and dry (1945–1985) conditions (Dean and Schmidt, 2011).

These EFs were refined by the authors based on expert-defined empirical streamflow thresholds for the maintenance of specific ecological and geomorphic functions, with the goal of refining environmental water objectives by ecologically calibrating the otherwise entirely statistical EFs to the specific ecogeomorphic context of the site. While not mechanistic in nature, these thresholds are regionally specific and based on important environmental functions as determined by expert opinion, according to the bottom-up holistic method for EF development (Tharme, 2003). The three locations were chosen for data availability and to represent ecologically and hydrologically unique sites.

The resulting EF hydrographs (Figure 3 and Table 1) consist of *base flow* ($Base_t^{Normal}$ or $Base_t^{Drought}$) and *high flow* (HF_t) components. For each location, monthly volume objectives were developed for two hydrologic conditions: *normal* ($Eflows_t^{Normal}$) and *drought* ($Eflows_t^{Drought}$). Drought flows ($Base_t^{Drought}$) constitute 10% of normal base flows and no high flows. This percentage was chosen to significantly reduce the volume of EFs provided under drought while maintaining the timing and could be adjusted based on stakeholder input.

$$Eflows_t^{Normal} = Base_t^{Normal} + HF_t \tag{2}$$

$$Eflows_t^{Drought} = Base_t^{Drought} = 0.1 * Base_t^{Normal} \tag{3}$$

Normal *base flows* ($Base_t^{Normal}$), the median value of average daily streamflows for each month, aim to provide adequate habitat through longitudinal connectivity and water temperature maintenance (BBEST, 2012). RGB base flows are currently driven by groundwater inputs, reservoir releases to supply demand sites, and return flows. The proposed drought base flow in the winter was adjusted to 1.13 $m^3 s^{-1}$ at Johnson Ranch (indicated in Figure 3) following a study suggesting that this threshold may sustain adequate habitat for the endangered Rio Grande silvery minnow (BBEST, 2012).

High flows (HF_t) have a peak between the 75th and 95th percentile of pre-1968 daily streamflow (BBEST, 2012). High flows are currently driven by water transfers from LLL to Amistad reservoir and releases to increase flood storage capacity. Episodic tributary floods create short-duration flows (<5 days) that transport high loads of sediments,

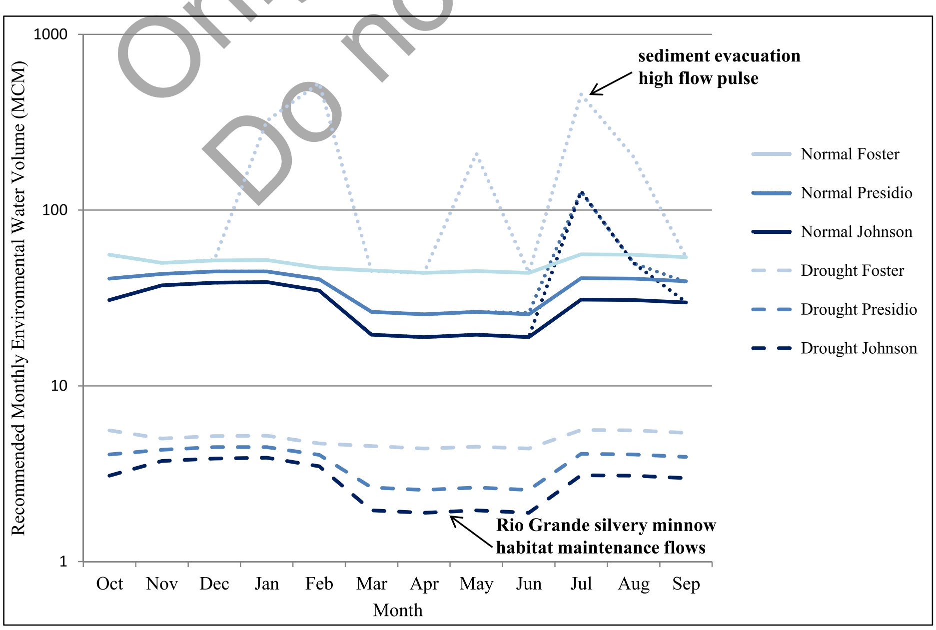

Figure 3. Final EF objectives for Presidio, Johnson Ranch, and Foster Ranch, including normal (base and high) and drought flows

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Table I. Proposed e-flow policy, including normal EF objectives and monthly reservoir storage thresholds

Location	Flow component	Units	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	Annual Total
Proposed EF objectives															
Presidio	Base Flow	MCM	41	43	45	45	40	26	26	26	26	41	41	39	
	High Flow	$m^3 s^{-1}$ (days)	—	—	—	—	—	—	—	—	—	297 (5)	41 (14)	—	
	Monthly Total	MCM	41	43	45	45	40	26	26	26	26	169	91	39	**617**
Johnson Ranch	Base Flow	$m^3 s^{-1}$	11	14	14	14	14	7	7	7	7	11	11	11	
	High Flow	$m^3 s^{-1}$ (days)	—	—	—	—	—	—	—	—	—	297 (5)	41 (14)	—	
	Monthly Total	MCM	31	37	39	39	35	20	19	20	19	159	81	30	**529**
Foster Ranch	Base Flow	$m^3 s^{-1}$	22	19	20	19	19	17	17	17	17	22	22	21	
	High Flow	MCM	—	—	—	322	529	—	—	210	—	256	201	—	
	Monthly Total	MCM	56	50	52	374	576	45	44	255	44	312	257	54	**2,119**
Reservoir storage zone thresholds (MCM)															
Flood control	$S_{Capacity}$	MCM	832	832	832	832	832	832	832	832	832	832	832	832	
	$S_{Flood\ Control}$	MCM	650	650	650	650	650	650	650	650	500	550	550	600	
EFs	S_{Normal}	MCM	275	275	275	275	275	275	275	275	275	275	275	275	
Drought control	$S_{Drought}$	MCM	215	215	215	215	215	215	215	215	215	215	215	215	
	S_{Dead}	MCM	50	50	50	50	50	50	50	50	50	50	50	50	

Note.MCM, million m^3

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causing the RGB to aggrade and narrow, and high flow pulses are needed to limit channel narrowing by providing sufficient magnitude and duration to mobilize and transport accumulated sediment from the channel (Dean and Schmidt, 2011). BBEST recommended an annual high flow pulse of 297 $m^3 s^{-1}$ (5+ days) at Johnson Ranch to reset the channel (2012); the July high flow proposed here is intended to meet this objective (Figure 3), although the monthly time step of the model precluded the incorporation of daily objectives beyond noting the duration and peak discharge recommended (Table 1).

Floods, or daily flows above the 95th percentile, were not incorporated into EFs because they occur naturally regardless of management scheme whenever inflows and storage volume are high enough to overwhelm reservoir capacity. Releasing flood flows could also cause damages to the Presidio–Ojinaga (P–O) Valley (Sandoval-Solis and McKinney, 2012), and further flood analysis at a finer timescale is needed.

EVALUATING WATER SYSTEM PERFORMANCE

Water management objectives

Based on an assessment of key obstacles to environmental water management in BB (Lane, 2014), the following human objectives were considered in the model: (i) water supply; (ii) international treaty obligations; and (iii) flood control. Reliable provision of water demands, consisting of monthly requirements by BB users, was required for a policy alternative to be considered feasible in the evaluation process. International water treaty obligations were considered by minimizing alteration from the historic distribution of Rio Conchos outflows, as calculated over 5-year averages according to the IBWC treaty accounting method. The goal was not to improve the treaty allocations for the benefit of one country or another but rather to maintain historical provisions. The average annual Rio Conchos outflow (782 MCM $year^{-1}$) over the study period (1955–2009) was used as a benchmark of acceptable treaty performance.

Because of the monthly time step of the model, flood control objectives for the BB Reach were more difficult to quantify. The P–O Valley levee has a 25-year flood design capacity of 1190 $m^3 s^{-1}$ (IBWC, 1971), and historical daily flows that have surpassed levee capacity and caused flooding correspond to a monthly flood volume threshold in the model of 550 MCM at the Presidio gauge station according to a probabilistic analysis. This value was used to identify months likely to experience flood events in the model. Under current LLL operations, Presidio experienced flood conditions (>550 MCM $month^{-1}$) in the model in 10 months over the period of record, representing an 18.2% flood risk or a flood return period of 5.5 years. This flood risk, in combination with the historical average annual levee overflow (929 MCM) and monthly Presidio streamflow during the 10 largest events over the period of study (refer to section Results: Flood Control), was used as a performance benchmark for alternative policies.

Performance criteria

Five performance criteria were used to evaluate model results under alternative policies with respect to specified water management objectives: (i) time-based reliability; (ii) volumetric reliability; (iii) resilience; (iv) vulnerability; and (v) the sustainability index. Performance criteria relate water demand ($Demand_t^j$) and supply ($Supply_t^j$) for a determined jth water user, defined as an agricultural or municipal demand or an EF objective. A water supply deficit (D_j^t) is the difference between $Demand_t^j$ and $Supply_t^j$ (Equation 4).

$$D_t^j = \begin{cases} Demand_t^j - Supply_t^j & \text{if } Demand_t^j > Supply_t^j \\ 0 & \text{if } Demand_t^j = Supply_t^j \end{cases} \quad (4)$$

Time-based reliability (Rel_{time}^j) is the frequency with which the water demand of a water user j is fully supplied $\left(Demand_t^j = Supply_t^j\right)$ during the simulation period (Hashimoto *et al*., 1982; (Equation 5).

$$Rel_{time}^j = \frac{N_S}{N}\, x100\%; \quad 0 \le Rel_{time}^j \le 100\% \quad (5)$$

where N_S is the number of time steps that the water demand was fully supplied and N is the total number of steps (McMahon *et al*., 2006). Volumetric reliability (Rel_{vol}^j) is the total volume of water supplied divided by the total water demand for a jth water user during the simulation period (N; Hashimoto *et al*., 1982; (Equation 6).

$$Rel_{Vol}^j = \frac{\sum_{t=1}^{t=N} Supply_t^j}{\sum_{t=1}^{t=N} Demand_t^j}\, x100\%; \quad 0 \le Rel_{Vol}^j \le 100\% \quad (6)$$

Resilience (Res^j) is a measure of a system's capacity to adapt to adverse conditions, defined as the probability that a no-deficit event ($D_j^t = 0$) follows a water deficit event (D_j^t 0) for a jth water user (Equation 7).

$$Res^j = \frac{Frequency\left(D_t^j = 0\, follows\; D_t^j > 0\right)}{Frequency\left(D_t^j > 0\right)} \quad (7)$$

$$x100\%; \quad 0 \le Res^j \le 100\%$$

Vulnerability (Vul^j) represents the average severity of a deficit during the total number of years simulated (Y). This study made the vulnerability dimensionless by dividing the volumetric reliability by the annual water demand (Sandoval-Solis *et al*., 2012; Equation 8).

$$Vul^j = \frac{\left(\frac{\sum_{y=1}^{y=Y}\left(\sum_{t=1}^{t=12} D_t^j \in y\right)}{No.\ of\ Years\ D_t^j>0\ occurred}\right)}{\sum_{t=1}^{t=12} Demand_t^j} \times 100\%;\ 0 \le Vul^j \le 100\% \quad (8)$$

The Sustainability Index (SI^j), the geometric mean of the previously mentioned performance criteria (Loucks, 1997; Sandoval-Solis *et al*., 2012; Equation 9), summarizes model performance results to facilitate comparison among complex trade-offs.

$$SI^j = \left\{Rel_{time}^j * Rel_{Vol}^j * Res^j * \left(1 - Vul^j\right)\right\}^{1/4} \quad (9)$$
$$x100\%; \quad 0 \le SI^j \le 100\%$$

DEVELOPMENT OF PROPOSED POLICY

This section describes the development of an optimal e-flow policy for the BB Reach. The BB model was used to simulate alternative policies under chronological repetition of the historical hydrology (1955–2009). All policy results assume repetition of the historical streamflow, and the authors acknowledge potential hydrologic non-stationarity, although the historical record included extreme floods and droughts (Patino-Gomez *et al*., 2007). Water demands were fixed at their 2009 levels because agricultural demands have since been capped to prevent further overallocation of water rights (CONAGUA, 2008), and municipal demands represent <1% of total water demands, and any increase is therefore considered negligible.

Baseline policy

A business-as-usual (baseline) policy was simulated as a reference condition to compare the performance of proposed policies against current water management. Model results depict monthly BB streamflow and water allocations under current water demands, infrastructure, and reservoir operations.

Historical LLL reservoir operations. Historical LLL operations are based on three reservoir storage zones and associated thresholds. Operations are physically constrained by inactive (S_{Dead} = 50 MCM) and storage capacity ($S_{Capacity}$ = 832 MCM) thresholds; the inactive storage zone lies below the outflow channel. The top of conservation threshold, the maximum storage volume maintained to allow for flood risk, is nominally reached at 292 MCM, although the average operational value (S_{Flood} (*baseline*)) ranges between 700 MCM in the dry season (November–May) and 580 MCM in the wet season (June–October). Historical operations have been highly variable and based on real-time operational decisions by reservoir managers (CONAGUA, 2008).

E-flow policy

Two components were used as initial model inputs for the e-flow policy (Figure 2): (i) proposed EF objectives and

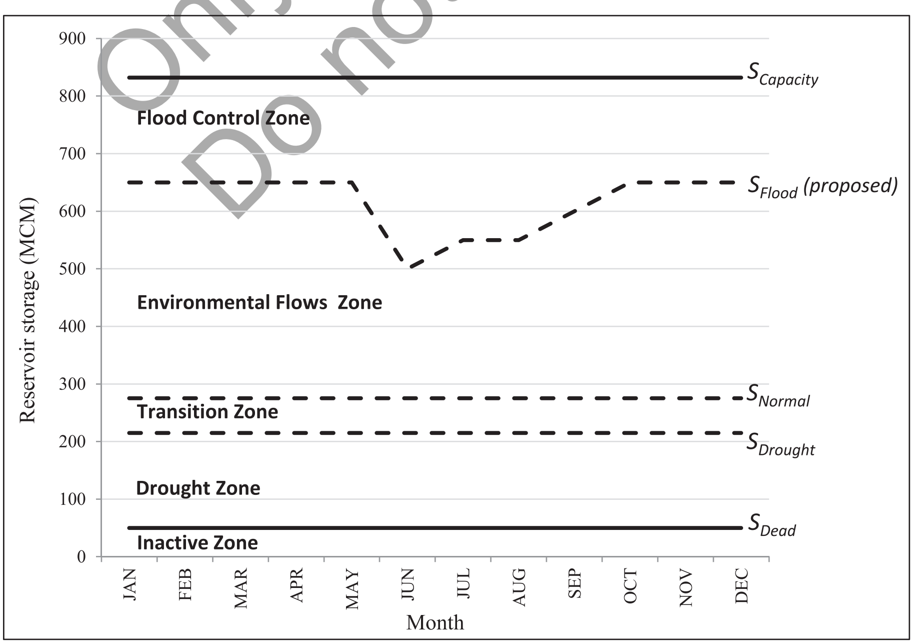

Figure 4. Proposed rule curve for LLL reservoir including five storage zones and thresholds

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(ii) an alternative reservoir rule curve to balance water management trade-offs based on hydrologic conditions.

Proposed reservoir rule curve. The proposed rule curve for LLL reservoir (Figure 4) considered five storage zones in any given month t: (i) flood control, held empty to store floodwaters; (ii) EFs, with water storage dedicated to both environmental ($Eflows_t$) and human ($Human_t$) objectives; (iii) transition, the buffer zone between normal and drought conditions, with human-dedicated storage; (iv) drought, which supplies human objectives and drought EFs when ecosystems are at risk from extended low water levels; and (v) inactive, for unusable storage. Drought EFs were released in place of normal EFs for the entire wet (June–October) or dry (November–May) season when reservoir inflows from the previous wet $\left(I^{Wet}_{Season-1}\right)$ or dry $\left(I^{Dry}_{Season-1}\right)$ seasons are less than 250 or 200 MCM respectively. These drought release thresholds were defined based on a probabilistic analysis of historical reservoir inflows to allow for a 30% risk of flow non-exceedance, which could be adjusted based on stakeholder needs (Sandoval-Solis and McKinney, 2012). Releases from LLL reservoir ($Release^{LLL}_t$) based on storage in month t (S^{LLL}_t) are specified in Equation 10. Alternative policies in terms of three monthly storage thresholds (indicated by dashed lines in Figure 4) were simulated to evaluate the impacts of re-allocating reservoir storage capacity between flood control, supply conservation, and EF while accounting for seasonal inflows and storage volume.

$$
\mathrm{Re}lease^{LLL}_t = \begin{cases}
Human_t + Eflows^{Normal}_t & If\ S_{Flood} > S^{LLL}_t > S_{Normal} \quad For\ t=1,\ldots,12 \\
Human_t & If\ S_{Normal} > S^{LLL}_t > S_{Drought} \quad For\ t=1,\ldots,12 \\
Human_t + Eflows^{Drought}_t & If\ S_{Drought} > S^{LLL}_t > S_{Dead} \quad For\ t=1,\ldots,12 \\
Human_t + Eflows^{Drought}_t & If\ I^{Wet}_{Season-1} < 250 \quad For\ t=7,\ldots,10 \\
Human_t + Eflows^{Drought}_t & If\ I^{Dry}_{Season-1} < 200 \quad For\ t=11,12,1,\ldots,6 \\
0 & If\ \mathrm{S}^{LLL}_t < S_{Dead} \quad For\ t=1,\ldots,12
\end{cases} \qquad (10)
$$

The final e-flow policy was developed based on the following iterative simulation process (steps 1–4 in Figure 2): (i) EFs and an alternative rule curve were proposed as inputs to the BB model; (ii) the water system was simulated under proposed inputs; (iii) Visual Basic for Applications scripts were used to extract model outputs and calculate performance indices with respect to specified objectives; and (iv) monthly reservoir storage zones thresholds [top of conservation (S_{Flood} (*proposed*)), normal storage (S_{Normal}) and drought storage ($S_{Drought}$)] were manually adjusted by the authors. Physically constrained dead storage (S_{Dead}) and storage capacity ($S_{Capacity}$) thresholds were held constant. If model performance under a policy did not meet all specified objectives, the combination of monthly thresholds making up that policy was disregarded, and variables were iteratively adjusted to create a set of feasible policies. Policies were considered feasible when the model was able to meet all human water requirements, did not significantly increase average flood risk from historic levels, and abided by water treaty obligations. The iterative process was then repeated using only those policies whose results fell within the feasible solution space until a single policy was identified that maximized performance of EF objectives (Table 1 and Figure 4).

RESULTS

Water system performance results under the baseline and final e-flow policies are discussed in the succeeding texts with respect to water supply, treaty obligations, flood control, and EF objectives.

Water supply

Table 2 shows the performance of both policies for all water users based on reliability (time based and volumetric), resilience, vulnerability, and SI of water supply. The e-flow policy significantly improved human water supply allocations from baseline management, increasing reliability and resilience while reducing vulnerability from as high as 90% down to 0% to provide 100% SI for all water users. Such capacity for improvement indicates that the water system is not currently being operated to optimize water supply objectives and that sufficient water volume exists in the system to meet these objectives with operational changes to LLL reservoir.

Treaty obligations

The 1944 Treaty specifies water allocations for both countries, including one third of all water arriving to the RGB from the Rio Conchos, and six other Mexican tributaries to

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Table II. Performance of municipal and agricultural water supply under baseline and e-flow water management policies

Water user	Annual demand	Baseline policy					E-flow policy				
	(MCM year^{-1})	Reliability of time (%)	Reliability of volume (%)	Resilience (%)	Vulnerability (%)	SI (%)	Reliability of time (%)	Reliability of volume (%)	Resilience (%)	Vulnerability (%)	SI (%)
USA											
Mun. Rio Grande	0.8	13	42	4	67	20	100	100	100	0	100
Ag. Rio Grande	43.2	11	41	4	66	20	100	100	100	0	100
Other Rio Grande	0.1	0	11	0	90	0	100	100	100	0	100
Mexico											
Mun. Rio Bravo	0.3	11	39	4	68	20	100	100	100	0	100
Ag. DR 090	63.6	69	89	35	36	60	100	100	100	0	100
Ag. Rio Bravo	30	11	39	4	68	20	100	100	100	0	100
Ag. Rio Bravo	17.7	11	39	4	68	20	100	100	100	0	100

the US historical median annual outflows from the Rio Conchos (661 MCM, 1955–2009) have made up 51% of treaty obligations, as accounted over 5-year treaty cycles (IBWC, 1944). Under the e-flow policy, the median annual outflow was 694 MCM year^{-1}, one third of which is 231 MCM or 54% of treaty obligations. This implies that, under the E-flow policy, the Rio Conchos outflow will almost exactly meet its historical contribution to the treaty; that is, the same amount of water will be provided but through a pattern with greater benefits for environmental end uses. Figure 5 shows the distributions of as follows: (i) annual average and (ii) 5-year average treaty contributions as provided historically (1955–2009) and under the e-flow policy, illustrating the similarity in treaty provisions under both policies.

Flood control

Under the baseline policy, 10 months experienced floods, representing an 18.2% flood risk or a 5.5-year return period. Alternatively, only eight floods occurred under the e-flow

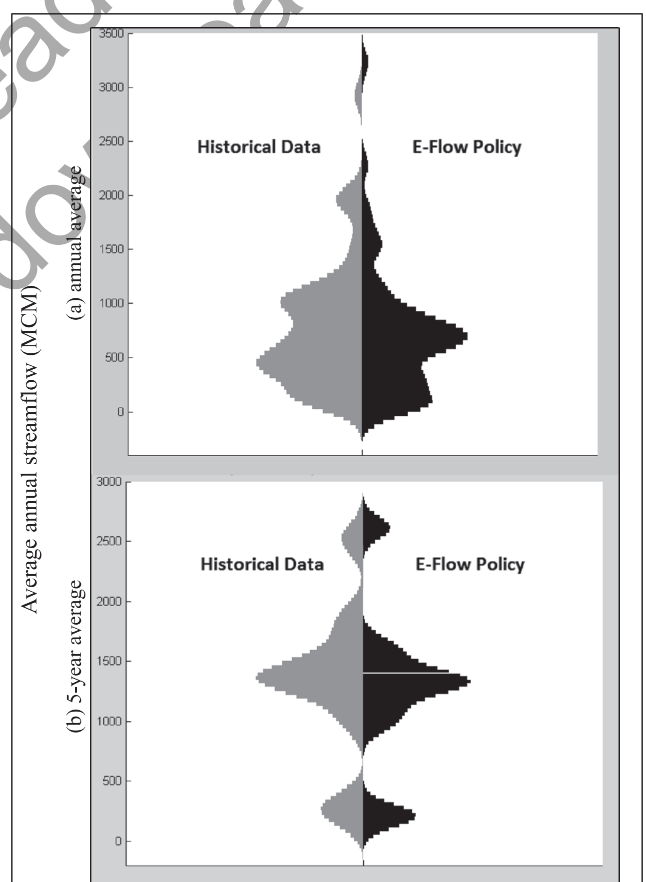

Figure 5. Distribution of (a) annual average and (b) 5-year average treaty contributions as provided historically (1955–2009) and under e-flow policy

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policy, reducing average annual flood risk to 14.5% or a 6.9-year return period. The average overflow volume was very similar under both policies (929-MCM baseline; 1023-MCM e-flow), indicating that, on average, the e-flow policy would not substantially increase the severity of flood events or the cost of flood damages. However, in the largest two floods (September 2008 and September 1991), the total flood volume was greater under the E-flow policy (Figure 6). The flood of September 1968 also stands out as an event that was significantly worsened under the e-flow policy. This may be because of an increased flood risk from August to October under the e-flow policy as the top of conservation reservoir storage threshold is ramped up earlier in the year to increase water storage for the subsequent dry season. Further flood risk modelling is needed at a shorter time step to determine the influence of alternative policies on potential flood damages.

EF objectives

Table 3 depicts policy performance with respect to EF objectives. Baseline performance indicates that the reliability of EFs in *time* is very low, but reliability in *volume* is much higher, particularly in the upper reach. This implies that the annual volume released from LLL is nearly sufficient to supply environmental and human objectives but not with the appropriate timing. The e-flow policy provided an SI increase from baseline of 54, 54, and 22% at Presidio, Johnson Ranch, and Foster Ranch respectively, representing a significant improvement in environmental water management. SI at Presidio and Johnson Ranch was also increased to 100% (Table 3), indicating that the proposed rule curve could fully supply EFs at both locations throughout the period of analysis. At Foster Ranch, however, no policy was able to meet EF objectives in all months without negatively affecting other objectives.

The SI of Foster Ranch EFs was 33%, and the performance of three of the five criteria decreased from baseline under the e-flow policy. Poor performance is likely because of the significantly higher and more variable EF objectives proposed for Foster Ranch than that for the upper reach (Table 1, Figure 3). Foster Ranch's natural flow regime included significant groundwater and episodic tributary inputs (BBEST, 2012), and average monthly EFs and reservoir releases cannot fully capture the historical variability of the site. Furthermore, dry season high flow objectives could not be met without impacting water supply or flood control objectives. Nonetheless, while performance results indicate that the e-flow policy may fail to sustain important environmental functions at Foster Ranch, only Presidio and Johnson Ranch locations are currently deemed 'ecologically unsound' (BBEST, 2012). Thus, the proposed policy is still expected to improve BB environmental water management.

DISCUSSION

Multi-objective management includes inherent trade-offs. In BB, flood control, water supply, and EF needs all draw resources from a single water-stressed, transboundary basin. Moreover, managing water for multiple objectives requires coordination, which is complicated in the RGB by international regulations and untransparent, real-time operational decisions. Study results demonstrated trade-offs between environmental and human water management objectives because of conflicting goals and timing, and hydrologic uncertainty. However, total water availability and suboptimal current operations suggest opportunities to improve regional water management.

The BB hydrology establishes a potential synergy between flood control management, which seeks to reduce

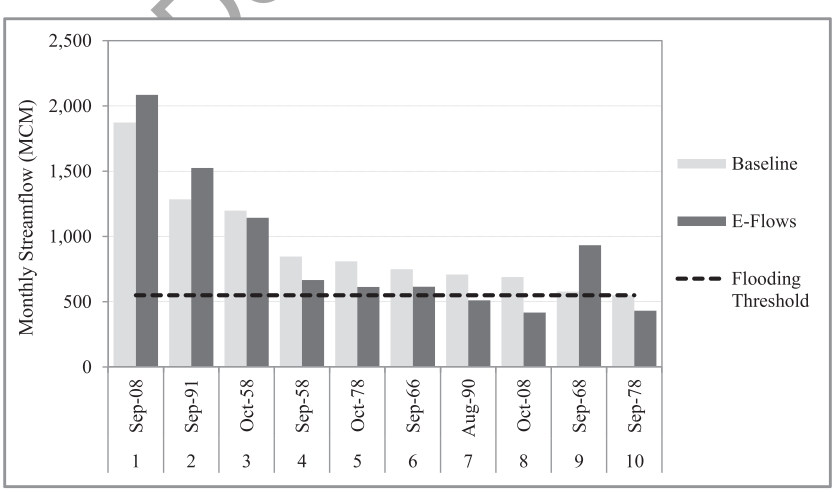

Figure 6. Largest flooding events under baseline and e-flow policies.

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Table III. Performance of EF objectives under alterative water management policies

Performance criteria	EF control point					
	Presidio		Johnson Ranch		Foster Ranch	
	Baseline	E-flow	Baseline	E-flow	Baseline	E-flow
Reliability (time; %)	22	100	29	100	31	29
Reliability (volume; %)	81	100	80	100	42	100
Resilience (%)	16	100	15	100	16	5
Vulnerability (%)	24	0	19	0	25	58
SI (%)	46	100	46	100	11	33

reservoir storage in the monsoon season, and EF management, which seeks to release high flows for the environment during this period and as a result keeps reservoir storage low. Baseline policy simulation results showed that historical LLL operations have emphasized hedging to keep more water in the reservoir in case of drought (Lane, 2014). Under alternative e-flow policies, average annual flood risk in P–O Valley decreased with increasing EF allocations as less water was stored in the reservoir, but both activities limited water supply conservation. Furthermore, flood risk was highly sensitive to monthly top of conservation storage threshold values, particularly around the monsoon season when streamflow inputs were more variable. No policy was able to reduce all flood events under the historical hydrology without impacting water supply objectives. Linking reservoir releases with hydrologic inputs offers an opportunity to reduce trade-offs.

The e-flow policy addressed management trade-offs by requiring significantly diminished EFs during drought years to prioritize human demands and incorporating *normal* and *drought* storage zone thresholds to refine reservoir operations by accounting for uncertain hydrologic inputs. During periods of sufficient reservoir storage and inflows, environmental and human objectives were both supplied. When storage dropped into the transition zone, only human demands were supplied to conserve water until operators could determine if hydrologic inputs would be sufficient to return to normal operations (EF zone) or if drought EFs must be released to sustain at-risk ecosystems (drought zone). The addition of a transitional storage zone improved system resilience by dampening potential impacts of hydrologic uncertainty by allowing the system to respond to either sustained drought or a return to normal operations once the conditions are established with more certainty.

Results indicate that changing the timing (but not quantity) of reservoir releases can improve specified environmental objectives while maintaining or improving human objectives. The e-flow policy increased SI for major water users in both the USA and Mexico from as low as 0% (US industrial) to 100%. It also maintained historical average annual outflows from the Rio Conchos to meet Mexico's treaty obligations to the USA. These results imply that there is sufficient water volume in the system, even under drought conditions, to significantly improve water supply performance. Suboptimal performance under the current water management policy provides an opportunity to significantly improve human water objectives. Such a situation also increases the potential for environmental water needs to be incorporated into an alternative policy.

River basin management involves objectives across many end uses, yet most projects consider only a subset of these objectives (Poff *et al*., 1997). Many reservoirs currently operated for selected water supply and hydropower objectives could be re-operated to achieve simultaneous environmental restoration goals. By explicitly and scientifically coupling the human and environmental needs of the BB Reach, a water management policy was identified with the potential to benefit humans while sustaining key environmental functions. The study improved on previous research by as follows: (i) developing spatially distributed EFs that coupled the IHA and holistic methods and (ii) proposing an environmental water policy within the feasible context of human constraints on the basin. On a broader scale, the methods developed here represent a valuable and novel tool for environmental water management in complex, human-dominated systems.

REFERENCES

BBEST - Upper Rio Grande Basin and Bay Expert Science Team. 2012. Environmental flows recommendations report. TCEQ, Texas.

Bestgen KR, Platania, SP. 1991. Status and conservation of the Rio Grande silvery minnow, Hybognathus amarus. *The Southwestern Naturalist*.

Bovee KD. 1978. The incremental method of assessing habitat potential for coolwater species, with management implications. *American Fisheries Society Special Publication* **11**: 340–346.

CONAGUA. -Comision Nacional del Agua. 2008. Acuerdo por el que se da a conocer el resultado de los estudios de disponibilidad media anual de las aguas superficiales en la cuenca del Rio Bravo. Diario Oficial de la Federación: México D.F. (in Spanish).

DOI: 10.1002/rra

CONAGUA. 2012. Ley de aguas nacionales y su reglamento. *México, D.F.* (in Spanish).
Dean DJ, Schmidt JC. 2011. The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. *Geomorphology* **126**: 333–349.
Everitt BL. 1998. Chronology of the spread of tamarisk in the central Rio Grande. *Wetlands* **18**(4): 658–668.
Giordano MA, Wolf AT. 2002. The world's freshwater agreements: historical developments and future opportunities. *United National Environment Programme*.
Hashimoto T, Stedinger JR, Loucks DP. 1982. Reliability, resiliency and vulnerability criteria for water resources system performance evaluation. *Water Resources Research* **10**(1): 14–20.
IBWC - International Boundary and Water Commission. 1944. Treaty between the United States and Mexico: Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande. Washington, DC.
IBWC. 1971. Report on international coordinated flood control plan for the Presidio-Ojinaga Valley. El Paso, TX.
IBWC. 2013. Rio Grande historical mean daily discharge data. El Paso, TX.
Konrad CP, Olden JD, Lytle DA, Melis TS, Schmidt JC, Bray EN, Williams JG. 2011. Large-scale flow experiments for managing river systems. *BioScience* **61**(12): 948–959.
Lane BA. 2014. Environmental flows in a human-dominated system: integrated water management strategies for the Rio Grande/Bravo Basin. M.S. Thesis, University of California, Davis, CA.
Legates DR, McCabe GJ. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* **35**(1): 233–241.
Loucks DP. 1997. Quantifying trends in system sustainability. *Hydrological Science* **42**(4): 513–530.
McMahon TA, Adebayo J, Sen-Lin Z. 2006. Understanding performance measures of reservoirs. *Journal of Hydrology*, **324**: 359–382.
Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* **50**(3): 885−900.
Obama B, Calderón-Hinojosa F. 2010. Joint statement from President Barack Obama and President Felipe Calderón. The White House: Washington D.C.
Patino-Gomez C, McKinney DC, Maidment DR. 2007. Sharing water resources data in the bi-national Rio Grande/Bravo Basin. *Water Resources Planning and Management.* **133**(5): 416–426.
Poff N, LeRoy J, Allan D, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *BioScience* **47**(11): 769–784.
Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrological alteration within ecosystems. *Conservation Biology* **10**(4): 1163–1174.
Richter BD, Thomas GA. 2007. Restoring environmental flows by modifying dams operations. *Ecology and Society* **12**(1): 12. http://www.ecologyandsociety.org/vol12/iss1/art12/
Sandoval-Solis S, Reith B, McKinney DC. 2010. Hydrologic analysis before and after reservoir alteration at the Big Bend reach, Rio Grande/Rio Bravo. CRWR Online Report 10-06. University of Texas at Austin
Sandoval-Solis S, McKinney DC, Loucks DP. 2012. Sustainability index for water resources planning and management. *Water Resources Planning and Management* **137**(5): 381–390.
Sandoval-Solis S, McKinney DC. 2012. Integrated Water Management for Environmental Flows in the Rio Grande. *Water Resources Planning and Management* **140**(3): 355–364.
TCEQ - Texas Commission on Environmental Quality. 2006. Allocation and distribution of waters: upper Rio Grande and all Rio Grande tributaries. Texas Administrative Code Title 30: Part 1, Chapter 303, Subchapter C. Austin, TX.
Tennant DL. 1975. Instream flow regimes for fish, wildlife, recreation and related environmental resources. *Journal of Fisheries* **1**(4): 6–10.
Tharme RE, King JM. 1998. Development of the Building Block Methodology for instream flow assessments. *Water Research Commission Report*.
Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**(**5-6**): 397–441.
USBR - United States Bureau of Reclamation. 2011. SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011, Section 6 - Basin Report: Rio Grande 2011.
DOI - United States Department of Interior. 2003. Water 2025: Preventing crises and conflict. Bureau of Reclamation: Washington, DC.
Yates D, Seiber J, Purkey D, Huber-Lee A. 2005. WEAP21 – A demand-, priority-, and preference driven water planning model part 1: model characteristics. *Water International* **30**(4): 487–500.
Yin XA, Yang ZF, Petts GE. 2011. Reservoir operating rules to sustain environmental flows in regulated rivers. *Water Resources Research* **47**(8).