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Integrating Environmental Flows into Multi-Objective Reservoir Management for a Transboundary, Water-Scarce River Basin: Rio Grande/Bravo

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Abstract Integrated water management seeks to balance the interests of multiple stakeholders who desire many end-uses for water within the context of institutions and regulations. This problem is particularly complex in transboundary and water-scarce basins. In the Big Bend region of the Rio Grande/Bravo, an arid, monsoonal climate combines with multiple human and environmental water demands and established treaty requirements to stress available water resources. We analyzed reservoir operation strategies in the basin to integrate environmental flow (EF) considerations into existing management objectives using a linear programming model to assess reservoir operation policies. Five potential EF regimes are evaluated for improving aquatic and riparian habitat in the Big Bend region. The model uses the historical hydrologic record of river inflows, data for flood control and bi-national water allocation requirements, and parameters for human demands and infrastructure; to compare current and optimized operations of Luis L. Leon reservoir for multiple objectives. Results indicate that alternative operational policies for monthly reservoir storage (compared to historic values) can increase EF allocations without affecting water deliveries or treaty allocations. Some tradeoffs may exist, however, in managing reservoirs for both EFs and flood control. Our approach informs management strategies for the water-stressed basin that seek to incorporate environmental goals into existing infrastructure and operations.

Keywords Environmental flows · Integrated water resources management · Rio Grande · Rio Bravo · Simulation · Optimization

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1 Introduction

Multi-objective approaches for managing reservoirs are well established. Analysts can use operations research to identify improved policies across a variety of objectives. Linear, non-linear, dynamic programming, or simulation can all combine hydrologic modeling with optimization to develop decision-support systems and analyze reservoir operations (Wurbs 1993). Optimizing multi-reservoir systems for flood control or hydropower operations is more complex, but statistics and visualizations can reveal potential operational policies (Lund and Ferreira 1996). As priorities change for reservoir and river management, reservoir operation models can assess policies to provide downstream flows across a set of climatic and policy conditions (Harman and Stewardson 2005; Pang et al. 2013).

In particular, instream *environmental flow* (EF) targets are one of these emerging considerations. While environmental goals for managing water resources traditionally emphasized water quality standards and minimum flow requirements, in recent decades, the increasingly seek to meet human demands while emulating natural flow regimes with temporal variability (Postel 2003). A growing body of research is considering EF requirements along with human demands for water supply, flood control, and hydropower (Richter and Thomas 2007; Yin et al. 2011; Sandoval-Solis and McKinney 2014; Cohen Liechti et al. 2015).

Though dams have large environmental effects, operational adjustments that incorporate EFs can simulate important environmental processes (Konrad et al. 2011; Meijer et al. 2012). For instance, re-operating reservoirs to release EFs is a recognized river management approach. *EF regimes identify streamflow patterns of appropriate quantity, quality, and timing to sustain river functions and services while meeting human water demands* (Poff and Zimmerman 2010). EF regimes are expressed as: average annual flow regime prescriptions; hydrographs with seasonal variability; pulse flows; or specified flow levels based on the natural or reference flow regime (Tharme 2003). Re-operating dams to improve ecosystems is challenging due to complex ecological and geomorphic patterns in rivers, as well as uncertainty of restoration outcomes. Highly-altered current flow regimes in many rivers present difficulties for multi-objective management (Ai et al. 2013).

EFs are typically determined using one of four approaches: (1) statistical methods, such as the Indicators of Hydrologic Alteration (IHA) method, which identify natural flow conditions and prescribe flow recommendations (Richter et al. 1996); (2) hydro-geomorphic methods, which relate river hydrodynamics and morphology to achieve sufficient habitat design (Pasternack 2011); (3) instream habitat methods, such as the Instream Flow Incremental method, which use the predetermined preferences of identified fish species to relate flow and habitat change (Bovee 1978); and (4) holistic methods, which define EFs based on multidisciplinary expert opinions and extensive research to achieve identified environmental objectives (Tharme and King 1998).

This paper presents a novel integration of methods and tools for the BB region based on a linear programming formulation that integrates EF requirements into an optimization of multi-objective reservoir operations. We present a model to assess operational policies to improve EFs while meeting human needs for flood protection, water demands, and international treaty requirements. The formulation minimizes the difference between the current flow regime in the Big Bend (BB) region and the natural flow regime prior to river regulation. It incorporates a 41-year record (Jan/1969-Dec/2009) of streamflow data, water demands, infrastructure and international treaty agreements based on a prior water allocation model for the region (Sandoval-Solis et al. 2011).

2 Water Management in the Rio Grande/Bravo (RGB) Basin

The RGB Basin is a transboundary river basin shared by the U.S. and Mexico, its mainstem designates the border between the United States (U.S.) and Mexico for over 2000 kilometers. The BB reach of the RGB basin includes protected natural areas with clear indicators of ecological degradation (Upper Rio Grande Basin and Bay Expert Science Team 2012). Water resources in the RGB basin are highly stressed due to natural water scarcity, the desert climate, population growth, and water demands across agricultural, municipal and industrial sectors (World Wildlife Fund 2007). Extended droughts and projected climate change effects, combined with over-allocated water rights, inefficient irrigation, and international agreements, make water management in the basin technically complex and politically challenging (SECURE Water Act Section 9503(c) 2011; Ingol-Blanco and McKinney 2011; Hoekstra et al. 2012).

The RGB begins in the San Juan Mountains of Colorado, flows through the San Louis Valley into New Mexico, continues south to divide the State of Texas (U.S.) and Mexico, and finally spills into the Gulf of Mexico. In total, the river travels approximately 3060 km through a 557,722 km^2 watershed. The southern area of the upper basin flows through the Chihuahuan desert, where annual precipitation averages 200 mm, most of which comes as widely scattered summer monsoon thunderstorms (Schmandt, 2002). Water resources in the basin are stressed from the combination of natural water scarcity and heavy anthropogenic use (Mix et al. 2012; World Wildlife Fund 2007). Historically, cyclic periods of drought and wet conditions occurred in the basin, including: dry conditions from the late 1940s (1947–1957) to the mid-1960s (1961–1965); wet conditions from the mid-1960s to the early 1990s; and dry conditions again from the mid-1990s to the mid-2000s (1994–2007) (Kim et al. 2002; Vigerstøl 2003; Sandoval-Solis and McKinney 2014).

The RGB and its tributaries are important sources of water for populations in both countries. The cities of Albuquerque, Las Cruces, El Paso, Brownville, and McAllen in the U.S., and Monterey, Ciudad Juarez, Matamoros, and Reynosa in Mexico, all depend on the RGB system for water supplies. Extensive agriculture also uses approximately 80 % of the water in the RGB Basin to produce forage, cotton, pecans and vegetables (Booker et al. 2005). Remaining river flows are important supplies for groundwater recharge, riparian systems, and areas of habitat conservation.

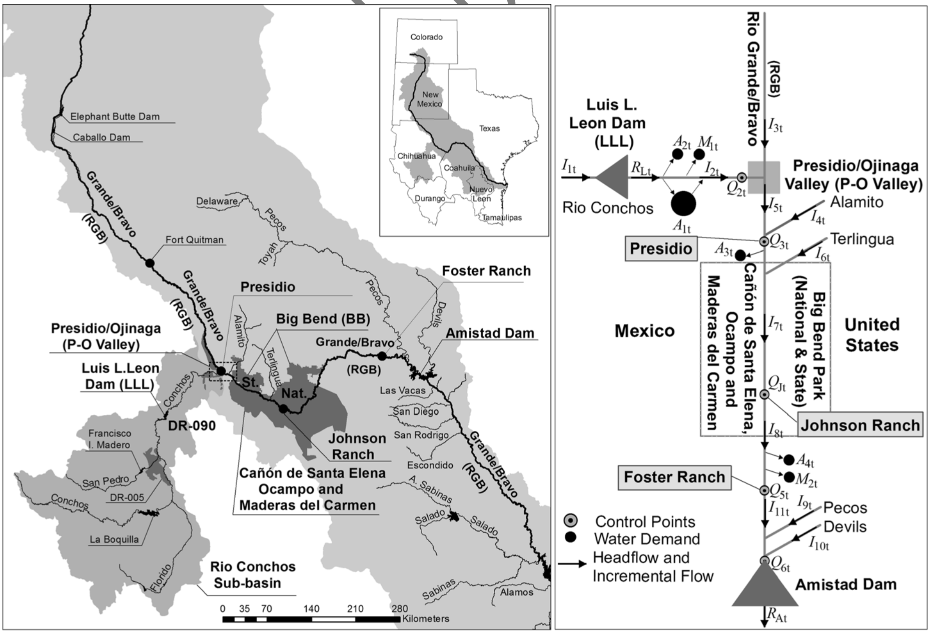
Historically, water resources in the basin were exclusively allocated to human needs (Enriquez-Coyro 1976). The Conventions of 1906 and 1944 signed between both countries (IBWC, 1906; IBWC 1944) and the Rio Grande Compact ratified in 1939 between the States of Colorado, New Mexico and Texas (TCEQ 1938), form the foundation of long-term river management, focused on human benefits. Water allocations specified in these agreements consider only human concerns for water supply and flood control, leaving out environmental requirements for habitat and species (Lane et al. 2014; Sandoval-Solis and McKinney 2014; Nava and Sandoval-Solis 2014). Recently, however, overuse has affected even human-driven requirements. In two consecutive 5-year treaty cycles (1992–1997 and 1997–2002), Mexico could not deliver to the U.S. the amount of water as mandated by the 1944 Treaty (SEMARNAT 2004).

Along the border, much of the RGB flow today comes from Mexican tributaries, mainly from the Rio Conchos. The Rio Conchos originates in Sierra Madre Occidental and flows North until it merges the RGB mainstem, which is typically dry, near Presidio, Texas. The Rio Conchos supplies an average of 80 % of the total downstream flow in the BB region. Approximately 70 km downstream of the Rio Conchos' confluence, the RGB passes through important conservation areas in the U.S. (BB National and State Park, and the Black Gap wildlife management area) and Mexico (Maderas del Carmen, Ocampo and Cañon de Santa

Elena Natural Protected Areas). The streamflow regime of this area depends on the water coming from the Rio Conchos, which is regulated upstream. The BB reach is nestled between two dams: LLL (storage capacity 832 million m^3 (mcm)) and Amistad international reservoir (storage capacity 6025 mcm), as shown in Fig. 1. Both dams and the associated reservoirs provide important flood control and water supply functions.

The Treaty of 1944 between the U.S. and Mexico specifies water allocations from six tributaries that originate in Mexico: Rio Conchos, Arroyo Las Vacas, San Diego, San Rodrigo, Escondido and Salado. The treaty stipulated that the U.S. receives one-third of the waters from the six tributaries reaching the main stem of the RGB and half of the gains along the RGB mainstem. Mexico receives two-thirds of the waters from the six tributaries reaching the mainstem of the RGB and half of the gains along the RGB main stem. Each country has its own account to store its respective water allocation in two international reservoirs: Amistad and Falcon. The water delivered to the U.S. must be at least 431.721 mcm per year, averaged over cycles of five consecutive years, called treaty cycles (IBWC 1944). Treaty cycles can expire earlier than 5 years if the U.S. storage is filled in both international reservoirs. The International Boundary and Water Commission (IBWC) is a joint entity established to oversee the fulfillment of the Treaty of 1944.

In Mexico, water management rules are specified in the National Water Law (CONAGUA 2004a). Water allocation is prioritized by use. Municipal and domestic use have the highest priority, followed by agriculture, which constitutes 99.2 % of the total Mexican water demand in the BB (CONAGUA 2004b). Each October, CONAGUA (the national water authority in Mexico) determines the available storage in LLL reservoir for agriculture water users after deducting twice the municipal demand, evaporation, and operation losses (Collado 2002). Subsequently, CONAGUA allocates to irrigation districts (DR-090 Bajo Rio Conchos and Coyame) the smaller of two amounts: their water right or the available storage. The Texas Rio Grande Watermaster Program (TCEQ 1938)



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

Fig. 1 The trans-boundary Rio Grande/Bravo (RGB) basin. (Adapted from Lane et al. 2014) administered by the TCEQ (Texas Commission on Environmental Quality) regulates U.S. water diversions along the RGB mainstem, water is allocated according to prior appropriation based on beneficial use and date of water right.

3 Environmental Flow Objectives for the Big Bend (BB)

The Chihuahuan desert habitat is ecologically threatened because of the lack of water for environmental purposes (Wesson et al. 2014). Recognition of the heavy degradation has led to numerous estimations of EF objectives in three main regions: (1) the Rio Conchos basin (World Wildlife Fund 2006), using the Building Block Method (Tharme and King 1998), which estimated EFs at nine locations (Sandoval-Solis and McKinney 2009); (2) for the RGB mainsteam from Presidio to the Gulf of Mexico, including the BB reach at three locations, using statistical streamflow data analysis and expert-based hydroecological relationships to determine maximum EF volumes (Upper Rio Grande Basin and Bay Expert Science Team 2012); and (3) the BB reach at Johnson Ranch through a statistical analysis of the natural flow regime prior to reservoir alteration (Sandoval-Solis et al. 2010).

This study utilized the EF objectives estimated for the BB reach by Sandoval-Solis et al. (2010) based on a probabilistic analysis of historical streamflow data from the Johnson Ranch gage station using the IHA method (Richter et al. 1996). Pre-1946 conditions are assumed to represent more natural and desired conditions that sustained channel capacity and provided adequate habitat for riparian species. This is due in part to more frequent small floods, compared to current conditions (post-1946) where channel narrowing results from less frequent small floods that carry sediment out of the system. This assumption is based on documented changes to channel dimensions and riparian species assemblages since 1946 (Dean and Schmidt 2011). Hydrographs for pre-alteration (Jan. 1901 to Dec. 1913 and Jan. 1930 to Dec. 1946) and post-alteration (Jan. 1980 to Dec. 2009) were developed based on a statistical analysis of historical mean daily discharge data from IBWC (2015). Three categories of EF objectives were considered: 1) base flows based on the median value of the mean daily flows for each month, 2) high flows between the 75th (56 m^3/s) and 95th (224 m^3/s) percentile of the mean daily flows, and 3) floods with a peak above the 95th percentile (224 m^3/s) of the pre-1946 period, including small floods (224 m^3/s to 1190 m^3/s) lower than levee capacity at Presidio (IBWC 1971) and large floods (>1190 m^3/s). For further details see Sandoval-Solis et al. 2010.

Based on an analysis of pre- and post-alteration conditions, an EF hydrograph was proposed (Fig. 2) to support environmental water needs in the BB. The hydrograph incorporates: (a) base flows with a distribution similar to the pre-1946 period; (b) two small floods, including one small flood fixed in September and another small flood in July, August, or October, with a peak flood flow of at least 400 m^3/s; and (c) high flow pulses in July, August, October and December. The proposed EF hydrograph has an annual volume of 1000 mcm, with monthly streamflow volumes as shown in Table 1.

In an effort to consider environmental water needs under a range of water availability scenarios, we simulated five different EF target scenarios of 600, 800, 1000, 1100, and 1200 mcm by altering annual streamflow volume and corresponding monthly volumes of the proposed target EF hydrograph. The corresponding monthly volumes of each hydrograph were calculated based on a linear scaling of the monthly volumes associated with the 1000 mcm target (Table 1).

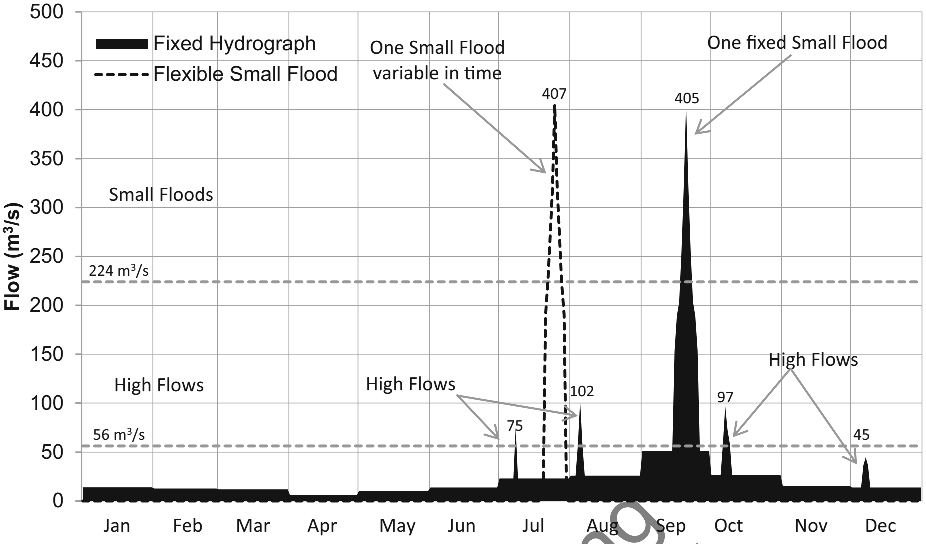


Fig. 2 Proposed hydrograph of flows in the BB Region for the case of an annual volume of 1000×10^6 m^3 (from Sandoval-Solis et al. 2010)

4 Model Development

EF targets set mandatory or desired goals for river flows. When flows meet or exceed those targets, policy objectives are met. During dry months, however, flows may fall below those targets. We used a monthly-time-step water planning model and a linear programming formulation (based on historical hydrologic conditions, physical and operational reservoir constraints) to optimize reservoir releases, demand requirements, flood control needs, and treaty deliveries.

4.1 Formulation

Release decisions for LLL (R_{L_t}) and Amistad (R_{A_t}) reservoirs, which are based on operational policies and rainfall forecasts, determine the success in meeting multiple management outcomes. For critical habitat in the BB region, river flows in the RGB $\left(Q_{J_t}(R_{L_t}, R_{A_t})\right)$ depend on these reservoir operation decisions and may fall above or below the EF targets $\left(Q^E_{J_t}\right)$

Table 1 Proposed target EF hydrograph with annual streamflow volume of 1000×10^6 m^3 (from Sandoval-Solis et al. 2010)

	Streamflow volume (1×10^6 m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Base flows	37	31	32	15	28	36	62	69	132	71	40	37	589
High flows	–	–	–	–	–	–	5	12	–	16	–	7	39
Small floods	–	–	–	–	–	–	191	–	181	–	–	–	372
Total	37	31	32	15	28	36	257	81	313	86	40	43	1000

determined through the water planning model. When river flows exceed environmental targets, a surplus exists $\left(Q^S_{J_t}\right)$. Alternatively, in dry periods, there is a deficit $\left(Q^D_{J_t}\right)$. Together, EF targets are calculated as:

$$Q^E_{J_t} = Q_{J_t}(R_{L_t}, R_{A_t}) - Q^S_{J_t}(R_{L_t}, R_{A_t}) + Q^D_{J_t}(R_{L_t}, R_{A_t}) \tag{1}$$

For any given month *t*, there exists only a surplus or a deficit. Minimizing the sum of deficits (*Z*) for all months, *n*, while still meeting other constraints of human needs and treaty requirements, can optimize reservoir operations to meet EF requirements:

$$Min\ Z = \sum_{t=1}^{n} Q^D_{J_t}(R_{L_t}, R_{A_t}) where\ n \in \{months\ in\ the\ hydrologic\ record\} \tag{2}$$

Continuity equations include primary decision variables for reservoir releases, river flows in downstream reaches that depend on these releases, and known inflow and demand parameters. Known parameters included Rio Conchos inflows into LLL reservoir, (I_{1_t}), inflows from small tributaries throughout the region $(I_{3_t}, I_{4_t}, I_{6_t}, I_{9_t}, I_{10_t})$, incremental flows (IF) $(I_{2_t}, I_{5_t}, I_{7_t}, I_{8_t}, I_{11_t})$, municipal demands (M_{1_t}, M_{2_t}), agricultural demands $(A_{1_t}, A_{2_t}, A_{3_t}, A_{4_t})$, and historical levels evaporation (E_{1_t}, E_{2_t}). We used historical values for evaporation to ease computational requirements; they slightly differed from calculated values. Table 2 lists all parameters and decision variables.

In the headwater of Rio Conchos, LLL reservoir storage $(S_{L_t}(R_{L_t}, R_{A_t}))$ is calculated as the balance of storage in the previous time step, upstream inflows, evaporation, and release decisions:

$$S_{L_t}(R_{L_t}, R_{A_t}) = S_{L_{t-1}}(R_{L_t}, R_{A_t}) + I_{1_{ty}} - R_{L_t} - E_{1_{ty}} \tag{3}$$

Releases from LLL determine instream flows throughout the system. Streamflows were calculated using the continuity equation at: Rio Conchos at Ojinaga $\left(Q_{2_t}\right)$ (Eq. 3), RGB below Ojinaga $\left(Q_{3_t}\right)$ (Eq. 4); RGB at Johnson Ranch $\left(Q_{J_t}\right)$ (Eq. 5); RGB at Foster Ranch $\left(Q_{5_t}\right)$ (Eq. 6); and inflows to Amistad Reservoir $\left(Q_{6_t}\right)$ (Eq. 7). For the Rio Conchos, agricultural returns from DR-090 were estimated as 25 % of its water demands:

$$Q_{2_t}(R_{L_t}, R_{A_t}) = R_{L_t} - A_{1_t} - A_{2_t} - M_{1_t} + (0.25{*}A_{1_t}) + I_{2_t} \tag{3}$$

$$Q_{3_t}(R_{L_t}, R_{A_t}) = Q_{2_t}(R_{L_t}, R_{A_t}) + I_{3_t} + I_{4_t} + I_{5_t} \tag{4}$$

$$Q_{J_t}(R_{L_t}, R_{A_t}) = Q_{3_t}(R_{L_t}, R_{A_t}) + +I_{6_t} + I_{7_t} - A_{3_t} \tag{5}$$

$$Q_{5_t}(R_{L_t}, R_{A_t}) = Q_{J_t}(R_{L_t}, R_{A_t}) + I_{8_t} - A_{4_t} - M_{2_t} \tag{6}$$

$$Q_{6_t}(R_{L_t}, R_{A_t}) = Q_{5_t} + I_{9_t} + I_{10_t} + I_{11_t} \tag{7}$$

RGB flows above the reservoir $\left(Q_{6_t}(R_{L_t}, R_{A_t})\right)$, evaporation losses, prior storage, and release decisions (R_{A_t}), determine storage in the current time period in Amistad $(S_{A_t}(R_{L_t}, R_{A_t}))$:

$$S_{A_t}(R_{L_t}, R_{A_t}) = S_{A_{t-1}}(R_{L_t}, R_{A_t}) + Q_{6_t}(R_{L_t}, R_{A_t}) - R_{A_t} - E_{2_t} \tag{8}$$

Reservoir storage bounds were specified by physical constraints (upper bound) and minimum storage needs to fulfill demands (lower bounds):

Table 2 List of parameters and variables included in the model

Known Inflows, diversions, and demands		Primary decision variables: releases	
Headflows and Incremental Flows (IF)		Water demands	
I_1	Headflow into Luis Leon Reservoir	A_1	Irrigation Diversions (MX) DR-090
I_2	IF from Las Burras to Ojinaga	A_2	Irrigation Diversions (MX) Coyame
I_3	Headflow, RGB above Conchos	A_3	Irrigation Diversions (MX) from RGB
I_4	Headflow, Alamito River	A_4	Irrigation Diversions (USA) from RGB
I_5	IF, from Ojinaga to RGB Gains below Ojinaga	M_1	Urban demands (MX) from Conchos
I_6	Headflow, Terlingua River	M_2	Urban demands (USA) from RGB
I_7	IF, from RGB below Ojinaga to Johnson Ranch	Downstream Flows and Storage	
I_8	IF, from Johnson Ranch to Foster Ranch	$S_L(R_L, R_A)$	Reservoir Level in LLL Reservoir
I_9	Headflow, Pecos River	$S_A(R_L, R_A)$	Reservoir Level in Amistad Reservoir
I_{10}	Headflow, Devils River	$Q_2(R_L, R_A)$	Rio Conchos flow at Ojinaga
I_{11}	Headflow, Pecos River	$Q_3(R_L, R_A)$	RGB flow below Ojinaga
Storage		$Q_4(R_L, R_A)$	RGB flow at Johnson Ranch
R_L	Outflows from LL L Reservoir	$Q_5(R_L, R_A)$	RGB flow at Foster Ranch
R_A	RGB flow below Amistad Reservoir	$Q_6(R_L, R_A)$	RGB flow into Amistad Reservoir
E_1	Historical evaporation from LLL	$T_1(R_L, R_A)$	Annual Treaty flow allotments, calculated
E_2	Historical evaporation from Amistad		

$$55.2mcm \le S_{L_t}(R_{L_t}, R_{A_t}) \le 800mcm \tag{9}$$

$$450mcm \le S_{A_t}(R_{L_t}, R_{A_t}) \le 6000mcm \tag{10}$$

For calibration purposes, to accurately represent management operations in the BB region, releases from each reservoir were limited by operational constraints to a maximum change in the storage between time periods:

$$-300mcm \le S_{L_t}(R_{L_t}, R_{A_t}) - S_{L_{t-1}}(R_{L_t}, R_{A_t}) \le 300mcm \tag{11}$$

$$450mcm \le S_{A_t}(R_{L_t}, R_{A_t}) \le 6000mcm \tag{12}$$

In addition, storage in the last time step of the water year (September) had to be greater than or equal to minimum carryover requirements to prevent both reservoirs from draining:

$$S_{L_{Sept}} \ge 196mcm \tag{13}$$

$$S_{A_{Sept}} \ge 600mcm \tag{14}$$

Fin8ally, flow requirements for the Rio Conchos at Ojinaga $\left(Q_{3_t}\left(R_{L_t}, R_{A_t}\right)\right)$ are subject to treaty stipulations, such that:

$$646mcm \leq \sum_{t=1}^{n} Q_{3_t}\left(R_{L_t}, R_{A_t}\right) \leq 775mcm \text{ and } S_{A_{Sept}} \geq 600mcm \tag{15}$$

We programmed the model in the General Algebraic Modeling System (GAMS) software. Inputs were stored in Excel and read into GAMS utilizing the GAMS GDX Utilities. GAMS performed the optimization and outputted results to Excel using the GDX utilities for post-processing and analysis.

5 Results

Model outputs were analyzed across a series of EF target regimes to determine if optimized reservoir releases meet monthly EF requirements, flood control requirements and human demands. We evaluated reservoir operations in the optimized record by comparing the modeled and historic values for streamflow and storage.

5.1 Meeting Monthly Flow Targets

Model results show fewer months where EF targets were not met in comparison to the historic record, except for 600 mcm annual flow target (Fig. 3). Optimized results for the 800 mcm annual target optimized stands out as the EF volume with fewest months unmet. The largest difference between the historic record and optimized flows occurred in years with larger annual flow targets (1000 & 1200 mcm), while for the 600 mcm annual flow target case, model results showed a slight increase in the number of months where the target was not met. This occurred because the model balances EF requirements with other parameters to maintain

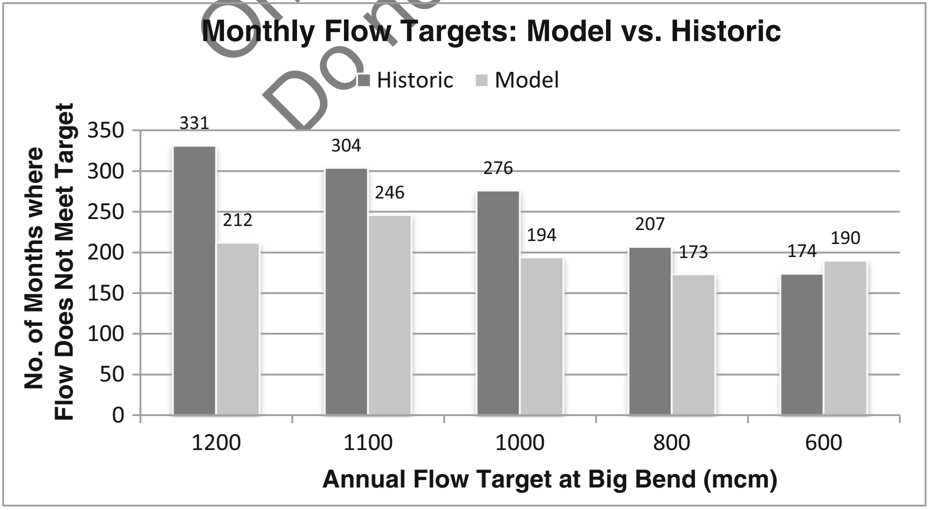


Fig. 3 Number of months where monthly environmental flow (EF) targets were not met

flow throughout the system. EF targets must be large (i.e., prioritized) to increase the likelihood of achieving them.

5.2 Flood Control

EF requirements may be controversial if they increase flood risks. Trade-offs are possible between EF and flood control goals. In traditional flood control management, reducing reservoir storage in rainy seasons limits the opportunity to capture runoff from large storms and prevent downstream flooding. EF requirements may increase reservoir storage in wetter months to keep water for release in drier months with reduced flows. Depending upon management practices, however, EF and flood control priorities may actually be more complementary. In periods of high rainfall, planned floodplain inundation can increase water in critical habitat while only inundating designated areas. The viability such strategies in a particular river basin depends on its topography, hydrology, and institutional practices.

While floodplain inundation does occur during periods of high rainfall in the RGB, for this analysis, we focused on managing reservoir releases to prevent downstream floods given current land-use policies. Analysis compared flooding in historic and modeled cases across the environmental flow regimes. For the largest annual EF regime of 1200 mcm, model results indicated flooding in three additional years as compared to the historic scenario, while for the 1000 mcm EF regime, floods occurred in one additional year (Fig. 4). Alternatively, in both cases, one less instance of flooding occurred. For years with large flooding (1991 and 2008), model results indicated the potential for greater flood damages. More water is held in the reservoir to augment environmental flows during dry periods, but this presents challenges for release operations when from LLL reservoir during large floods with short forecasts. Managed releases in combination with planned downstream inundation could mitigate some of these risks, but within a traditional approach, basin managers must consider such trade-offs.

5.3 Reservoir Storage Analysis

Historic and modeled distributions of monthly reservoir storage levels differ. With the 1000 mcm annual EF regime, model results for LLL reservoir indicate a more linear distribution of storage across years. Historically, reservoir operators hold more than

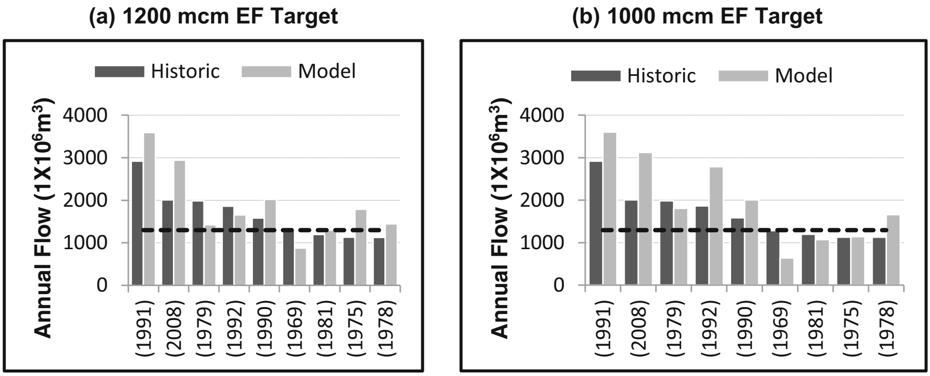


Fig. 4 Flood occurrence in model results and historic volumes across two EF regimes of (**a**) 1200 and (**b**) 1000 mcm. The years listed in the *X*-axis were at or near flood stage in historic hydrology. The threshold of flooding is shown by the *dashed line*

350 mcm about 60 % of the time, as indicated by the sharp increase in storage distributions near that storage threshold (Fig. 5a). An optimized flow regime maintains more water in LLL during a majority of years. Alternatively, storage in Amistad reservoir is lower than historical records across the entire distribution (Fig. 5b). This indicates that increasing EFs in the BB reduces storage in Amistad reservoir, providing greater flood control potential. The model results use LLL reservoir to more actively regulate environmental flows downstream.

6 Discussion

The analysis suggests alternate operational approaches for both reservoirs to integrate EFs. For the LLL reservoir, optimizing flows to meet EF targets results in more months of lower storage volumes (<350 mcm) and less months of higher storage volumes (>350 mcm). While current operations hedge to keep more water in the reservoir in case of drought, the model actively uses the upper reservoir to augment instream flows through a linear operational policy between storage and releases. For Amistad reservoir, model results indicate a significant decrease in storage if managing for EFs. This results because the model releases water below Amistad, given that there is no constraint. This underscores the need for system-wide modeling. For both reservoirs, many current and competing end-users would likely be skeptical of reservoir operations policies that incorporate EF targets.

Multi-objective management seeks to balance inherent trade-offs. Integrated Water Resources Management (IWRM) is a commonly used framework for such analyses that considers the costs and likely benefits of potential actions to promote welfare and mitigate water scarcity across human and environmental end uses (GWP 2000), typically focusing on systems analysis (Mitchell 2005). Stakeholder participation is critical. Management policies to promote conservation, efficiency, reuse, environmental restoration, reservoir reoperation, water quality, and conjunctive use of surface and groundwater resources can all contribute to planning that maximizes economic and social goals in an environmental benign manner (Wilchfort and Lund 1997; Rahaman and Varis 2005; Biswas 2008; Calizaya et al. 2010).

In the RGB system, flood control, water supply, and environmental needs all draw water from stressed basin resources. Moreover, managing water for multiple objectives requires

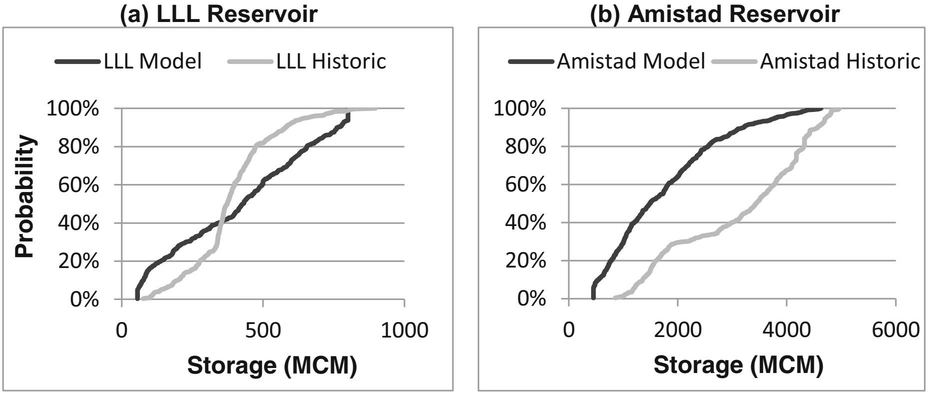


Fig. 5 The distributions of monthly reservoir storage values for model results and historic values for (**a**) Luis L. Leon and (**b**) Amistad reservoir

coordination, which is complicated in the RGB Basin due to international water agreements and sharing of resources. Model results suggest trade-offs between EF requirements and reservoir storage due to the limited available water. Timed releases augmenting flows for key species may reduce available irrigation water. Alternatively, increasing storage during wet periods to augment flows later can reduce reservoir capacity for capturing runoff from a large storm that would otherwise cause downstream flooding. A broader view of basin management, which emphasizes both storage and targeted inundation to reduce floods in important areas, can help to mitigate trade-offs. Additional water management policies to deal with water demand may be required in the basin, such as water conservation, irrigation efficiency, municipal water re-use, conjunctive use of surface and groundwater. Linking EF requirements with hydrologic inputs for a given year can promote IWRM. For instance, environmental flow requirements would reduce during drought. Yet, periodic droughts and chronic water scarcity often exacerbate conflicts. Maintaining environmental mandates such as the U.S. Endangered Species Act during droughts is often controversial (Doremus and Tarlock 2008). The complexities of trans-boundary management complicate the process even further.

Environmental conservation requires a promoter. In the BB region, while endangered species such as the Rio Grande Silvery Minnow do exist, the constituencies are not as strong as in other fisheries, such as for species of Pacific Salmon. Moreover, the nature of international management complicates regulatory actions to promote environmental conservation. Cross-boundary constituencies must promote these interests. In many North American water resource systems today, habitat considerations take root when aligned with other priorities, such as hydropower re-licensing or the promotion of local fisheries. If coordinated interests emerge, even in a water-stressed basin, water managers can build processes that capitalize on these opportunities.

7 Conclusions

Environmental flows in water-stressed regions compete with other uses. This paper presented an analysis of reservoir release policies in the trans-boundary RGB basin to increase EFs in critical habitat areas while meeting water supply and flood control requirements. Model results indicate that sufficient water exists in the basin to increase EFs in the BB region in many years by reconsidering historical reservoir operations. The analysis suggests that meeting EF requirements would not affect water supply allocations to agricultural and municipal users. Achieving EFs would also not inhibit the delivery of water as specified by the international treaty agreement. Results do suggest potential trade-offs in the timing of releases, especially during times of stress. Aligning EF regimes with hydrologic years can help to mitigate such tradeoffs. Additionally, promoting planned inundation in downstream areas during floods can mitigate the potential conflict between keeping water in reservoirs to supplement later seasonal EFs with the need for wet-season releases to increase upstream flood control. This case study reveals the complexities facing managers in arid watersheds. For international watersheds, the mix of coordination and conflict is even more complex. The importance of collaborative approaches and integrated management will likely grow in the water-stressed basin with climate variability, population and water demands growth (Vanham et al. 2009).

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