

**Environmental Flows in a Human-Dominated System:
Integrated Water Management Strategies for the Rio Grande/Bravo Basin**

By

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To Simon and my family, for everything.

Table of Contents

List of Tables	v
List of Figures	vi
Abstract	viii
Acknowledgements	x
1. Introduction.....	1
1.1. Research objectives	2
2. Background	3
2.1. Water resources management	3
2.2. Water management models	5
2.3. Reservoir operations and impacts	6
2.4. Environmental flows	8
2.4.1. Identification	9
2.4.2. Quantification.....	11
2.4.3. Implementation	13
2.4.4. Adaptive management.....	14
2.5. Reservoir re-operation for environmental flows	14
3. Case Study: The BB Reach of the RGB Basin	16
3.1. The RGB Basin.....	17
3.1.1. The Rio Conchos Basin.....	18
3.1.2. Historical water management.....	19
3.2. The BB Reach	20
3.2.1. Hydrologic characterization.....	22
3.2.2. Environmental impacts of hydrogeomorphic alteration.....	27
3.3. IWRM and the BB Reach.....	29
4. Policy development: preliminary methods and analysis.....	30
4.1. Big Bend water planning model.....	32

4.1.1.	Model inputs	33
4.1.2.	Model water balance	35
4.1.3.	Water allocation algorithm.....	36
4.1.4.	Model testing	38
4.2.	BB Reach environmental flow objectives.....	41
4.2.1.	Hydrologic analysis.....	41
4.2.2.	Incorporating ecogeomorphic streamflow thresholds.....	42
4.2.3.	Discussion	47
4.3.	Evaluating water system performance.....	48
4.3.1.	Water management objectives	48
4.3.2.	Performance criteria.....	50
4.4.	Baseline and E-Flow policy development.....	52
4.4.1.	Baseline policy	53
4.4.2.	E-Flow policy.....	56
5.	Results: Model performance under alternative policies	61
5.1.	Human water supply	61
5.2.	International treaty obligations.....	64
5.3.	Flood control	65
5.4.	Environmental flow objectives.....	67
6.	Discussion	71
7.	Conclusions.....	74
7.1.	Limitations	76
References	79	

List of Tables

Table 1. Alternative definitions and metrics of natural rivers	11
Table 2. Log Pearson III extreme flood analysis before and after 1946 (adapted from Sandoval-Solis <i>et al.</i> , 2010).	26
Table 3. Current water demands by country and type of use, based on 2009 values	34
Table 4. BB model streamflow inputs	35
Table 5. BB model goodness-of-fit.....	40
Table 6. Summary table of environmental significance of BB Reach streamflow components ..	43
Table 7. EF objectives under normal conditions after adjusting for empirical environmental thresholds	46
Table 8. Proposed E-Flow policy, including normal EF objectives and monthly reservoir storage thresholds	59
Table 9. Performance of human water supply under Baseline and E-Flow water management policies	64
Table 10. Performance of EF objectives under alternative water management policies	68

List of Figures

Figure 1. Map of (a) the RGB Basin and (b) the BB Reach, including locations of model headflows, incremental flows, demand sites, and environmental flow evaluation sites.....	21
Figure 2. Average monthly discharge (MCM) at Johnson Ranch, 1970-2009.....	23
Figure 3. Pre-1915 median mean daily discharge on the RGB, above and below the Rio Conchos confluence (adapted from Dean and Schmidt, 2011).....	24
Figure 4. Comparison of (a) median monthly flows and (b) maximum annual flows pre- and post- 1946.....	26
Figure 5. Johnson Ranch discharge plotted against channel width, 1946-2009 (adapted from Dean and Schmidt, 2010).....	28
Figure 6. Study methods framework, including key inputs and outputs of linked major components (boxed) and computations performed (indicated by italics).....	31
Figure 7. WEAP interface for the BB Model	33
Figure 8. Historical vs. model annual streamflow at Presidio indicating model goodness-of-fit.	40
Figure 9. Final EF objectives for Presidio, Johnson Ranch and Foster Ranch, including normal (base and high) and drought flows.....	47
Figure 10. WEAP reservoir storage zones under historical LLL operations	54
Figure 11. Historical LLL reservoir operations and storage volumes	55
Figure 12. Proposed LLL reservoir rule curve and storage zones	61
Figure 13. Distribution of (a) annual average and (b) five-year average treaty contributions as provided historically (1955-2009) and under E-Flow policy	65
Figure 14. Largest flooding events under Baseline and E-Flow policies	66
Figure 15. Median daily discharge at Presidio for each month under alternative water management policies.....	67

Figure 16. Performance of normal EF objectives for Foster Ranch as a function of percentage of high Jul/Aug flows required..... 70

Figure 17. Firm yield EF hydrographs under E-Flow policy. Foster Ranch objective and minimum environmental high flows are shown..... 71

Abstract

The transboundary Rio Grande/Bravo (RGB) Basin, shared by the United States and Mexico, has been heavily regulated to provide for human water supply and flood control, and water management is complicated by extreme hydrologic variability, over-allocation of water rights, and international treaty obligations. Dam-induced hydrogeomorphic alteration has degraded the bi-nationally protected Chihuahuan desert riverine ecosystem along the Big Bend Reach of the RGB. This thesis addresses the need for integrated water resources management in the Big Bend by exploring the performance of alternative water management policies and developing an operational reservoir rule curve to improve human and environmental water management trade-offs. A reach-scale water planning model was used to represent current water allocation and reservoir operations, operating on a monthly time-step under repetition of the historical hydrology (1955-2009). Key water management objectives (agricultural and municipal water demands, flood control, and international treaty obligations) were quantified, and a water allocation algorithm was developed to represent transboundary water management and regulations in the basin. The environment was considered by developing (1) spatially-distributed average monthly environmental flow recommendations and (2) an alternative reservoir rule curve to release water for both environmental flows and human objectives based on hydrologic conditions. The model was used to simulate business-as-usual water management (baseline) in the Big Bend and compare water system performance under baseline and environmental flow policies. An iterative simulation and evaluation process was used to adjust monthly reservoir storage zone thresholds and evaluate policy performance with respect to each water management objective based on a suite of water system performance criteria. Finally, a single reservoir operation policy was identified capable of minimizing alterations from spatially-distributed

environmental flows while maintaining human water management objectives. Results from the proposed policy show that, by changing the timing but not the average annual volume of releases, re-operating Luis L. Leon reservoir has the potential to sustain key ecological and geomorphic functions in the Big Bend without significantly impacting current water management objectives. The policy proposed here increased water supply reliability and resilience from baseline water management while reducing system vulnerability in both countries. It also reduced average annual flood risk from the historic 18.2% to 14.5% and maintained the historic average annual outflow distribution from the Rio Conchos to meet Mexico's treaty obligations to the U.S. On a larger scale, this study introduces a novel, interdisciplinary methodology for integrating environmental flows into human-dominated water systems.

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1. Introduction

Managing river basins for human and environmental water needs is challenging, and conflicts often arise between increasing and varied human objectives and the water required to sustain critical river functions and services (Poff *et al.*, 1997). Population growth, economic development, and climate change further exacerbate conflicts over limited water resources. As water demands increase, water supplies become more variable, and riverine ecosystems continue to degrade, the sustainable management of river basins is becoming increasingly important. However, a central challenge remains the development of policies for equitable and efficient allocation of water to multiple end-uses, including both human and environmental objectives (Sandoval-Solis and McKinney, 2012).

For centuries, rivers have supported the economic and social growth of civilizations. Most of the world's rivers have been altered in structure and function to provide for human objectives including agricultural and municipal water supply, flood control, energy, navigation and recreation (Revengea *et al.*, 2000). However, heavy human use and a changing climate have left many river basins ecologically and geomorphically degraded—invaded by exotic species, disconnected from their floodplains, and severely altered in streamflow and sediment regimes (Richter *et al.*, 1997).

The construction and operation of dams, in particular, presents a major threat to river ecosystems (Ward and Stanford, 1995) and the services they provide (Finlayson *et al.*, 2005; Palmer and Filoso, 2009). Dam-induced alterations from natural streamflow and sediment regimes have been pervasive and damaging in terms of geomorphic (Williams and Wolman, 1984) and ecological (Postel and Richter, 2003) impacts. In renegotiating our relationship with rivers, maintenance of natural processes and the quantity, quality, and timing of water required to

support them is now being considered among competing objectives for freshwater (Baron *et al.*, 2003). Recent efforts to better manage regulated rivers have included adjusting reservoir operations to provide environmental flows along with human objectives (Sandoval-Solis and McKinney, 2012; Yin *et al.*, 2011; Richter and Thomas, 2007). However, the potential value of environmental flows is often constrained by biophysical river conditions, basin politics and regulations, and existing infrastructure and water management objectives. Operationalizing environmental flows will require a transparent and scientifically-driven analytical framework capable of integrating these diverse and often conflicting components of water management.

1.1. Research objectives

This study introduces a novel, interdisciplinary methodology for incorporating EF releases into human-dominated water systems. A case study is used to apply this methodology, based on diverse tools and knowledge from water resources engineering, hydrology, ecology, and geomorphology, to an ecologically-degraded, transboundary river system. Key drivers and obstacles of EFs are examined to develop an alternative reservoir operation policy for the BB Reach of the RGB Basin capable of integrating human and environmental water management objectives. The specific objectives of the study were to: (1) characterize the regional hydrology (pre- and post- regulation), water demands, reservoir operations, and water allocation system using a reach-scale water planning model, (2) develop spatially-distributed environmental flow objectives, and (3) design a multi-objective reservoir rule curve to maximize provision of environmental flows while maintaining or improving objectives for water supply, flood control, and international treaty obligations.

2. Background

2.1. Water resources management

Water resources management redistributes water to optimize a region's natural water availability to satisfy competing demands and avoid floods and droughts (Loucks 1997). Water is often not naturally distributed in the quantity and quality in space and time to satisfy desired socioeconomic activities. Major differences in water availability occur from region to region due to climate, topography, and other factors. Supply can also vary temporally, through seasonal and inter-annual variation, and is often difficult to predict. This resource unreliability runs counter to the dominant goals of water management, which have generally sought to dampen the natural variability of rivers to attain steady and dependable water supplies and to moderate extreme water conditions (Loucks 1997).

A river basin, defined as the area bounded by the watersheds of a river network that flows towards the same outlet (GWP 2009), forms a natural unit of water management. Rivers are intimately linked to the land systems that surround them and act as hydrological conduits, receiving excess water from precipitation, infiltration, and groundwater and transferring water across the landscape to watershed outlets, such as rivers, lakes, and oceans (Cai *et al.*, 2006). The atmosphere is the upper bound on a basin, and mass and energy exchange through this boundary influences basin hydrologic characteristics. However, the state of a basin (e.g. water quality, flood risk) and the physical processes within a basin (e.g. streamflow, sediment transport) often also depend on human activities, including water impoundment, diversion, and irrigation. For water management purposes, a river basin consists of the water supply system (surface water and groundwater), the delivery system (canal networks and reservoirs), the water user system

(agricultural, municipal, industrial and environmental), and the drainage collection system (surface and subsurface) (Cai *et al.*, 2006). Because hydrology and climate do not adhere to administrative boundaries or regulations, basins also serves to integrate many of the economic, political, and social factors that surround water management. The river basin is thus characterized by both natural and human components, making it an inherently appropriate unit for the integrated management of water for humans and the environment.

According to Loucks *et al.*, (1997) the sustainability of a water system lies in its ability to meet human water demands while maintaining the range of hydrological variation necessary to preserve ecological integrity. Integrated Water Resources Management (IWRM) provides a framework for the sustainable management of water systems based on the coordinated management of basin resources using tools and knowledge from diverse disciplines (GWP 2009). Effective IWRM models must address the two distinct systems that shape the water management landscape: (1) the natural biophysical and ecological system and (2) the human water management system. A proper representation of hydrological processes and water allocation is also fundamental to predicting the outcome of alternative policies or climate scenarios.

Designing and implementing sustainable water policies in transboundary basins is particularly challenging due to the existence of international agreements and multiple operational systems and regulatory bodies. Transboundary basins, defined as river basins shared by more than one governing body (e.g. state, country), have well-documented additional complexities brought on by strains in riparian relations and institutional limitations (Wolf 1999). The basin-scale is rarely used in transboundary water management due to the difficulty of integrating across sub-basin scale regulations and management bodies. However, with over 250 transboundary

basins worldwide, encompassing 40% of the global population and 47% of the world's land area (Wolf 2002), the development of such policies is critical for social, political and economic stability, sustainable development, and the maintenance of ecosystems.

2.2. Water management models

Using science to guide water management requires that research address difficult questions in complex settings in which experimental controls and replication are often impossible (Poff *et al.*, 1997). Technological advances in hydrologic data collection, streamflow forecasting, and computer technology provide opportunities for exploring and refining water management using mathematical models. Two key categories of models are generally used: (1) simulation and (2) optimization models. A simulation model is a mathematical representation of a system used to predict its behavior under a given set of conditions and can be used to compare performance under alternative management scenarios (Wurbs *et al.*, 1985). Simulation models enable the detailed evaluation of water systems and can be used to address problems related to water allocation, water quality, sediment transport, presence and quality of physical habitat, ecosystem dynamics, and economic valuation of water management alternatives, among others. Optimization models, in contrast, search through large numbers of possible solutions based different combinations of decision variables to find the decision variable combination that maximizes or minimizes a defined objective function within specified boundary constraints (Wurbs *et al.*, 1985). While their application to multi-objective reservoir management has received much attention in the past 30 years for its practicality and efficiency, optimization models have played a smaller role in the design of water management systems compared to

simulation models due to the often greater flexibility and detail possible with simulation models (Wurbs *et al.*, 1985).

Water planning models are a specific type of simulation model that can represent basin hydrology, water allocation and operational systems, and the interactions between water users and types of use. These models can integrate factors related to the biophysical system (availability and movement of water) and water management (storage and allocation) to improve understanding of interactions and interdependencies between them. Water planning model platforms, such as the Water Evaluation and Planning (WEAP) platform (Yates, *et al.* 2005) used in this study, have been used to support the development of IWRM strategies in basins around the world [Jordan (Comair *et al.*, 2012), Morocco (Le Page *et al.*, 2012), Chile (Poblete *et al.*, 2012), California (Ligare *et al.*, 2012), Mexico (Sandoval-Solis *et al.*, 2013)].

2.3. Reservoir operations and impacts

Dams and reservoirs are a cornerstone in water management (Stanford and Ward, 1996), with a vast range of objectives and impacts. For nearly 5,000 years, they have improved water supply and flood control reliability by storing water in times of surplus and releasing it in times of scarcity. In 2005, the world had more than 45,000 large dams, storing about 15% of global annual runoff in their reservoirs (Nilsson *et al.*, 2005). The type and extent of hydrologic and geomorphic alteration imposed depends on the dam's intended purpose. Storage dams, for instance, capture water to modify the magnitude and timing of flow downstream to meet demands. They typically have a large hydraulic head and storage volume, high trap efficiency, long residence time, and total control over the rate at which water is released from the impoundment (Wurbs *et al.*, 1985). Storage dams are often also operated for flood control, which

dramatically alters seasonal flow patterns, or hydropower, which affects streamflow on a scale of hours to days in response to fluctuating electricity demand. Multi-objective dams often fulfill a variety of objectives including flood control, irrigation, navigation, power generation, and recreation- each with different impacts on the downstream hydrology and geomorphology (Poff and Hart, 2002).

In spite of their vast contributions to water management, dams have altered river systems on a global scale. Fluvial geomorphic (Montgomery and Buffington, 1998) and ecological processes (Poff *et al.*, 1997) are largely driven by the magnitude, intensity, duration, and frequency of streamflow. Downstream reaches respond to altered flow regimes and reduced sediment supply in varied ways that are often difficult to predict, although common responses include erosion and lowering of the channel bed (incision) and development of a coarse-grained surface layer (armor) in the channel bed downstream of a dam (Williams and Wolman, 1984). Excessive alteration from the natural flow regime can also lead to changes in water, sediment, and organism dynamics (Richter *et al.*, 1996); these changes may alter driving mechanisms to send river systems into new, and often degraded, states.

The ecological impacts of streamflow alteration are complex and often indirect, but four primary drivers have been identified (Bunn and Arthington, 2002): (1) flow alteration can severely modify channel and floodplain habitats; (2) aquatic species have evolved life history strategies in direct response to natural flow regimes; (3) many species depend on lateral and longitudinal hydraulic connectivity, which can be broken through flow alteration; and (4) the invasion of exotic and introduced species can be facilitated by flow alteration. Driven largely by these four components, streamflow alteration by dams has had varied, and often difficult to predict, impacts on riverine ecosystems, including: disconnecting channel and floodplain habitats

(Postel and Richter, 2003), altering hydraulic geometry and resulting habitat availability and quality (Williams and Wolman, 1984), modifying water quality (Ahearn *et al.*, 2005) and temperature (Thompson *et al.*, 2011), and influencing floodplain vegetation communities (Ligon *et al.*, 1995), among many other impacts. These generalized consequences of flow alteration are explored in more depth with respect to the specific ecogeomorphic conditions of the BB Reach in subsequent sections.

2.4. Environmental flows

Over the past four decades, mounting evidence and awareness of the environmental consequences of traditional river management has led to a call for balanced environmental and human water management policies. Early goals for river restoration emphasized manipulation of channel morphology (Rosgen 1996) and minimum instream flow requirements to sustain valued processes and services or conserve charismatic/ economically-significant species (Jager and Smith, 2008). The popular minimum flow requirement approach has the advantage of using a single streamflow threshold, which simplifies combining environmental with non-environmental objectives. However, it has since been acknowledged that a single minimum instream flow alone cannot sustain natural ecosystem functions (Poff *et al.*, 1997).

A growing body of literature claims that key ecological functions can be recovered by providing carefully targeted ‘environmental flows’ based on components of the natural flow regime (Postel and Richter, 2003). The natural flow regime, which refers to the spatiotemporal distribution of unregulated streamflow, has been called a key driver of ecological processes capable of limiting the distribution and abundance of riverine species (Power *et al.*, 1995). It is also strongly correlated with other ecological drivers including water temperature, channel

geomorphology, and habitat diversity (Poff *et al.*, 1997). Environmental flows (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.*, 2010). 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). Although rivers are dynamic and complex systems, the natural flow regime (based on historic streamflow data or model estimates) follows statistical patterns and is often predictable in probabilistic terms (Suding *et al.*, 2004). River restoration (or reconciliation, in more highly altered systems unlikely to have the option of returning to historical conditions) through the provision of EFs is limited by four main components: the (1) identification, (2) quantification, (3) implementation, and (4) adaptive management of EFs.

2.4.1. Identification

In efforts to restore or sustain important functions through the provision of EFs, value decisions are necessarily made as to which processes/structures/species to prioritize. What defines a natural river in terms of its support of ecosystems and maintenance of system function (Newsom and Large, 2006)? Who should select this set of objectives? What is the *right* or *best* set of environmental objectives that should be aimed for in a given system? How should restoration goals be measured? These questions have led to a variety of responses from the river science community. The complexity of river systems and our limited understanding thereof has driven the development of the natural flow paradigm, which essentially argues that, in the absence of sufficient understanding of river ecosystem drivers and requirements, mimicking the natural hydrology to which species are adapted will intrinsically provide the greatest ecological

benefit even if the driving mechanisms at work are not explicitly understood (King *et al.*, 2003; Richter *et al.*, 1996). An alternative approach to the problem of prioritizing environmental objectives has been to focus on maximizing system biodiversity (Townsend *et al.*, 1997). However, biodiversity for its own sake does not allow for the protection of ecosystems which may require vast, homogenous habitat to exist, nor does it promote a mechanistic understanding of rivers. Social value (popularity) and economic value may also weigh heavily in the determination process. Popular processes [e.g. large streamwood availability, camp beach maintenance (Hazel *et al.*, 2010)] and species (e.g. beavers, salmon) are sometimes prioritized above others, even in situations where such restoration goals may not fit the setting or local conditions (Newsom and Large, 2006). Similarly, restoration of desirable structural features (e.g. sinuosity) has been used as a proxy for process-based restoration even when such structures (or hydrologic indices) may be necessary but not sufficient to recover desired functions (Euliss *et al.*, 2008).

If the overarching goal is to restore a system to its *natural state*, then the problem of defining reference conditions emerges, particularly in settings with limited historical data or where significant long-term anthropogenic impacts have taken place. Practical river restoration applications are often caught in the debate between popular visions of natural rivers and those driven by the poorly linked disciplines of hydrology, geomorphology and ecology (Newsom and Large, 2006). Alternative definitions of natural rivers and their associated performance metrics are shown below (Table 1).

Table 1. Alternative definitions and metrics of natural rivers (adapted from Newsom and Large, 2006)

Discipline	Definition of natural rivers	Performance metrics
Hydrology	Naturalized flow regime; Intact magnitude/frequency/duration of extreme flows; Spatial patterns of flow hydraulics reflecting 'natural' catchment land use	Target (index) flow values at gauges sites; Environmental flow regulation; Abstraction and sustainable flood risk management
Geomorphology	Natural interplay of flows, hydraulics and sediment flux supplied from catchment, banks, bed; Systematic distribution and functionality of channel/floodplain form; Unconstrained transient behavior-site contexts	Conservation of 'wild' rivers; Management of critical morphological habitats; Points-scoring systems for landscape and features
Ecology	Connectivity; Maximum efficiency of resource use; Detail and diversity of structure; Unmanaged functionality via internal regulation	Holistic principles of 'health' or 'integrity' and surrogate indices; Biometrics of food chains, life stages, productivity; Rare species abundance

2.4.2. Quantification

Over 200 methods have been used to quantify 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 statistically-derived flow recommendations, usually expressed as a fixed proportion of some flow component intended to sustain a desired function (e.g. 10% of average annual discharge). These statistical methods include the Tennant Method (Tennant 1975), flow duration curve methods (Tharme 2003), and the Indicators of Hydrologic Alteration (IHA) (Richter *et al.*, 1996). As a result of their rapid, inexpensive but low resolution estimates, hydrology-based methods are often the most appropriate at the planning level, or in low controversy situations (Tharme 1997). Given a lack of empirical streamflow–ecological response data, hydrology-based flow regime characterizations statistically assess the degree of hydrologic change to define *acceptable* levels

of flow regime alteration as management targets. Techniques include using the sum of alterations to a range of hydrologic indicators (Richter *et al.*, 1996), with developments focusing on ecologically-relevant scales of variability (Suen and Eheart, 2006) and comparisons between the natural and regulated flow duration curves (Petts 1996).

Hydraulic-rating methods use basic hydraulic parameters (e.g. depth, velocity, wetted perimeter) as a surrogate for habitat factors believed limit target biota (Tharme 2003). EFs are calculated by plotting the parameter of concern against discharge thresholds below which habitat quality becomes significantly degraded, and minimum EFs are generally set as the discharge producing a fixed percentage reduction in useable habitat. The underlying assumption of such methods is that ensuring specific thresholds of the selected hydraulic parameter in altered flows will restore/sustain the biota or ecosystem under study.

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. Flow-related changes in physical habitat (based on field measurements of one or more hydraulic variable) are modeled using various hydraulic programs [e.g. PHABSIM based on the Instream Flow Incremental Method (IFIM) (Bovee 1978)]. Simulation outputs are linked to habitat suitability curves that constrain “acceptable” conditions for target species or lifestages. The relationship between species habitat availability and streamflow is then used to develop EF recommendations. This approach assumes that the model accurately reflects the key mechanistic effects of flow on target species (Jager and Smith, 2007).

Finally, *holistic methods* recognize rivers as complex, dynamic ecosystems that require naturally variable flow regimes. Such methods identify ‘ecologically-significant’ components of the natural flow regime through either bottom-up or top-down processes that require

considerable resources and multidisciplinary expertise (Tharme 2003; King *et al.*, 2003). The bottom-up approach is used to construct EFs from scratch 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’ degrees of departure from the natural (or reference) flow regime, rendering them less susceptible to omissions of critical flow characteristics or processes than their bottom-up counterparts [i.e. Benchmarking Method (Brizga *et al.* 2001)]. Holistic methods draw from other methods within a broader framework. The EFs developed in this study are based on a combination of the hydrology-based IHA method and the holistic bottom-up approach to quantify EF objectives (described further in section 4.2.).

2.4.3. Implementation

Even with the many methods available to characterize environmental water requirements, designing a practical reservoir operation policy to supply EFs in multi-objective water systems is a major scientific and management challenge. To increase the likelihood of their incorporation into reservoir operations, EF recommendations and proposed rule curves should be explicit and scientifically-defensible. Policies capable of meeting or improving human water objectives are also far more likely to be implemented than those that provide for the environment at the cost of human needs. These goals drive the development of an alternative water management policy in this study.

2.4.4. Adaptive management

The complexities of the physical, biogeochemical and ecological processes acting on rivers and the dearth of quantitative flow alteration – ecological response data limit the accuracy of any EF prescription. Without the implementation of experimental EF releases and iterative adjustment based on monitoring results, prescribed EFs will most likely be unable to meet the needs of river ecosystems. The adaptive management process for refining EF should be based on interdisciplinary collaboration, extensive monitoring and modeling, and incorporation of diverse stakeholder knowledge. Such a process, while beyond the scope of this study, is exemplified in current work on the Bill Williams River in Arizona (see Shafroth *et al.*, 2010).

2.5. Reservoir re-operation for environmental flows

Given the number of methods for quantifying environmental flows and the abundant literature focused on optimization of multi-objective reservoir releases for human uses (see Labadie 2004), very few studies related to multi-objective reservoir operation incorporate environmental objectives beyond minimum flow constraints. Of the hundreds of optimization-oriented reservoir operation studies reviewed by Yeh (1985), Wurbs (1993) and Labadie (2004), Homa *et al* (2005) identified only three studies which focused on the optimal tradeoff among ecological and human flow needs (Sale *et al.*, 1982; Palmer and Snyder, 1985; and Cardwell and Jager, 1996). Other than these studies, instream flow is generally considered as a time-independent constant minimum, despite the fact that recent ecological literature has emphasized the need for complex instream flows (Poff *et al.* 1997).

Of the studies that have incorporated ecological objectives into reservoir operations beyond minimum flow constraints, the methods used have been highly varied and frequently based on

the strengths of the researchers rather than on the creation of a replicable, scientifically-driven framework for the development of improved reservoir operations in coupled human-natural systems. Past research includes a study that developed EF prescriptions by defining statistically-derived ecohydrologic indicators and using a non-dominated sorting genetic algorithm to find the Pareto optimal set of operating rules that could define the optimal trade-off between human and ecosystem objectives (Suen and Eheart, 2006). Similarly, Homa *et al.* (2005) introduced the concept of an “ecodeficit” to evaluate tradeoffs between EF and water supply objectives and define the Pareto frontier of a water management system. Ripo *et al.* (2003) proposed an annual flow duration curve framework to determine how much water could be removed for human needs while still maintaining a similar flow duration curve and avoiding violating minimum flow requirements for riverine ecosystems. Their study proposed a streamflow regime for riparian vegetation and determined the volume and timing of water available for human use while sustaining “ecosystem integrity.” Hughes and Ziervogel (1998) proposed an instream flow requirement model for addressing conflicts between human and environmental water demands at the planning stage. However, this model requires other techniques to design an operational policy. Koel and Sparks (2002) related the natural flow regime to fish abundance, using these relationships as criteria for reservoir operation based on the historical range of variation method (Richter *et al.*, 1998), in which the range of hydrological criteria that the reservoir operations should achieve to sustain natural river processes is determined. Shiau and Wu (2004) used the same method, focusing on the trade-offs between hydrological indicator changes and human water needs. However, these approaches were descriptive, in contrast to the prescriptive EFs and reservoir rule curve presented here.

Overall, few studies have attempted to incorporate EF releases into multi-objective reservoir operations, and fewer still have considered environmental objectives beyond statistical indices derived from the natural flow regime. Such a gap in the literature illustrates the difficulty of integrating concepts from diverse disciplines (e.g. water resources engineering, hydrology, ecology, geomorphology) to solve complex, multi-objective water management problems. This study attempts to develop such a methodology, and the following section introduces the case study used to present it.

3. Case Study: The BB Reach of the RGB Basin

The RGB is a highly water-stressed, transboundary river basin shared by the U.S. and Mexico. Extended regional drought and projected climate change impacts have combined with over-allocation of water rights and international agreements to make water management in the basin technically complex and politically challenging (Porse *et al.*, submitted 2014). Historical water management activities for flood control and irrigation have altered the hydrology and geomorphology through the BB Reach, with significant environmental consequences. Despite clear indicators of ecological degradation, no environmental water management policy is currently implemented for the reach. However, in spite of current constraints on RGB Basin water resources, existing hydraulic infrastructure and long-term hydrologic datasets provide a unique opportunity to design an alternative water management policy for the BB Reach to improve both human and the environmental objectives.

3.1. The RGB Basin

The San Juan Mountains of Colorado comprise the headwaters of the RGB mainstem. From there, the river flows south through New Mexico to El Paso, Texas, where it becomes the border between Mexico and the U.S., and then southeast to the Gulf of Mexico (Figure 1.a), draining a total area of 557,722 km², with 52% in the U.S. and 48% in Mexico (Patiño-Gomez 2005). The climate varies significantly along the length of the RGB, moving along a gradient from hot, arid desert in the north to monsoon-driven semi-tropical to the southeast (USBR 2011). The basin includes parts of the States of Colorado, New Mexico and Texas in the U.S., and Chihuahua, Coahuila, Nuevo León, and Tamaulipas in Mexico.

The RGB supports the basin's 10.5 million inhabitants. The river is the primary drinking water source for populations on both sides of the border, including Albuquerque, Las Cruces, El Paso, Brownville, and McAllen in the U.S., and Monterey, Ciudad Juarez, Matamoros, and Reynosa in Mexico (Porse *et al.*, submitted 2014). Extensive agriculture in the upper sub-basins depends heavily on the RGB for irrigation. Over 80% of the water in the RGB and its tributaries is diverted for irrigation, mainly for forage, cotton, pecans and vegetables (Booker *et al.*, 2005). The remaining instream and return flows are important for groundwater recharge, downstream demands and riverine ecosystems. However, water in the RGB is so heavily allocated that the river is often dry by the time it reaches El Paso, Texas; the stretch of the RGB between El Paso and the Rio Conchos confluence is often referred to as *the forgotten river* (Benke and Cushing, 2005).

Natural water scarcity has combined with heavy anthropogenic use to place the RGB among basins with “the highest potential for conflict and crisis in the world, especially under drought conditions” (DOI 2003). The RGB Basin is considered one of the most water-stressed

regions in the world, with less than 500 m³ of water available per person per year (Giordano and Wolf, 2002), and the basin's population is projected to double within three decades (Sandoval-Solis and McKinney, 2012). In addition, over the next 50 years, municipal water use is expected to increase by 100% and industrial water use by 40% (TWDB 2012).

An increasing population and concomitant water demands are being compounded by decreasing water availability due to long-term regional drought and projected climate change impacts. Over the centuries, the RGB climate has experienced alternating periods of drought and wet conditions (Vigerstøl 2003). In addition, climate projections suggest that the average basin temperature will increase by more than five degrees by the end of the century and mean annual runoff will decrease by seven to 14% by 2050 (USBR 2011). Less and earlier runoff translates to water supply reductions with major implications for human and environmental water management. Lower flows and warmer conditions are increasing stress on native fish, increasing instream flow needs to moderate temperature changes, and exacerbating invasive species infestations (Heard 2012). In addition, decreases in spring and early summer runoff are reducing water for irrigation demands, harming crop production, and increasing winter flood control challenges. Finally, the upper RGB Basin relies heavily on groundwater for municipal and rural uses, and warmer conditions could increase evaporation and decrease runoff, which may reduce natural groundwater recharge and water table levels (USBR 2011).

3.1.1. The Rio Conchos Basin

The Rio Conchos is the main tributary to the RGB, located in the Mexican state of Chihuahua. It is the RGB's largest tributary and one of the most important rivers in northern Mexico. Like the RGB, the Rio Conchos has several reservoirs to supply water for agriculture

and hydropower. The Rio Conchos basin drains an area of 67,808 km² (~14% of the RGB Basin), providing most (~55%) of the water deliveries to the U.S. required under the bi-national water allocation treaty of 1944 (Patiño-Gomez *et al.*, 2007). Total water availability in the Rio Conchos basin is approximately 4,077 million cubic meters [MCM] per year, of which 67% is surface water and 33% groundwater (Ingol and McKinney, 2011). Of that water, around 77% is allocated within the basin, while the remaining average 800 MCM flow to the confluence with the RGB each year (Ingol and McKinney, 2011).

The Rio Conchos sub-basin is characterized by recurrent water stress and long droughts, such as those in the 1950s, 1960s, and most recently from 1992 to 2003 (Ingol and McKinney, 2011). In addition to high water stress for human users, the ecological integrity of the basin is severely threatened. A recent assessment by the World Wildlife Fund (WWF 2006) rates the Rio Conchos' biological distinctiveness as globally outstanding while its conservation status is ranked as critically endangered, making it a very high priority for international conservation (Obama and Calderon, 2010).

3.1.2. Historical water management

The RGB Basin is characteristic of many heavily managed rivers, with flow and sediment regimes dramatically altered by dam construction and operations. In 1916, the construction of two large reservoirs in the upper basin, La Boquilla on the Rio Conchos (2,903 MCM; Mexico) and Elephant Butte on the upper RGB (2.6 MCM; New Mexico), permanently altered the hydrology of the basin to provide for irrigation, hydropower, and flood control (CONAGUA 2008). The construction of Caballo Reservoir on the RGB (0.424 MCM; New Mexico, 1938), Francisco Madero Reservoir on the San Pedro River (565 MCM; Mexico, 1947) and Luis L.

Leon Reservoir on the Rio Conchos (832 MCM; Mexico, 1967) further modified flow conditions, storing the remaining flood waters from the upper RGB and Rio Conchos sub-basins (Ingol and McKinney, 2011; Sandoval-Solis 2011).

3.1.3. Water Management Concerns

Water resources in the RGB Basin, including the Rio Conchos, have historically been exclusively leveraged to supply human water needs in Mexico and the U.S. (Porse *et al.*, submitted 2014). The Conventions of 1906 and 1944 between Mexico and the U.S. (IBWC 1906; IBWC 1944) provided the foundations for long-term water management focused on human benefits (IBWC 1906, 1944; TCEQ 2006). The water allocations specified in these agreements consider only the human concerns for water supply and flood control, entirely omitting environmental water needs (Sandoval-Solis and McKinney 2009). Recently, however, these human obligations have become stressed from long-term over-use of the basin's water resources. In the five-year treaty cycle from 1992 to 1997, Mexico was unable to deliver the amount of water to the United States that is mandated by the 1944 Treaty, which strained politics between the two countries (SEMARNAT 2004).

3.2. The BB Reach

The BB Reach has been declared a region of environmental and economic significance by the presidents of both countries (Obama and Calderon, 2010). Regional water resources are subject to many competing human uses, including agricultural, municipal, and industrial water supply, international water treaties, flood control, and downstream demands. The endemism of

its river ecosystems (Heard 2012) as well as its value for agriculture, flood control and recreation, make the reach a suitable case study in which to explore the potential for IWRM strategies. The BB Reach extends from the Mexican Rio Conchos below Luis L. Leon (LLL) reservoir to its confluence with the RGB mainstem near Ojinaga (Mexico) and Presidio (U.S.) and down the mainstem, which defines the international border through binational protected regions, to Amistad reservoir (Figure 1.b).

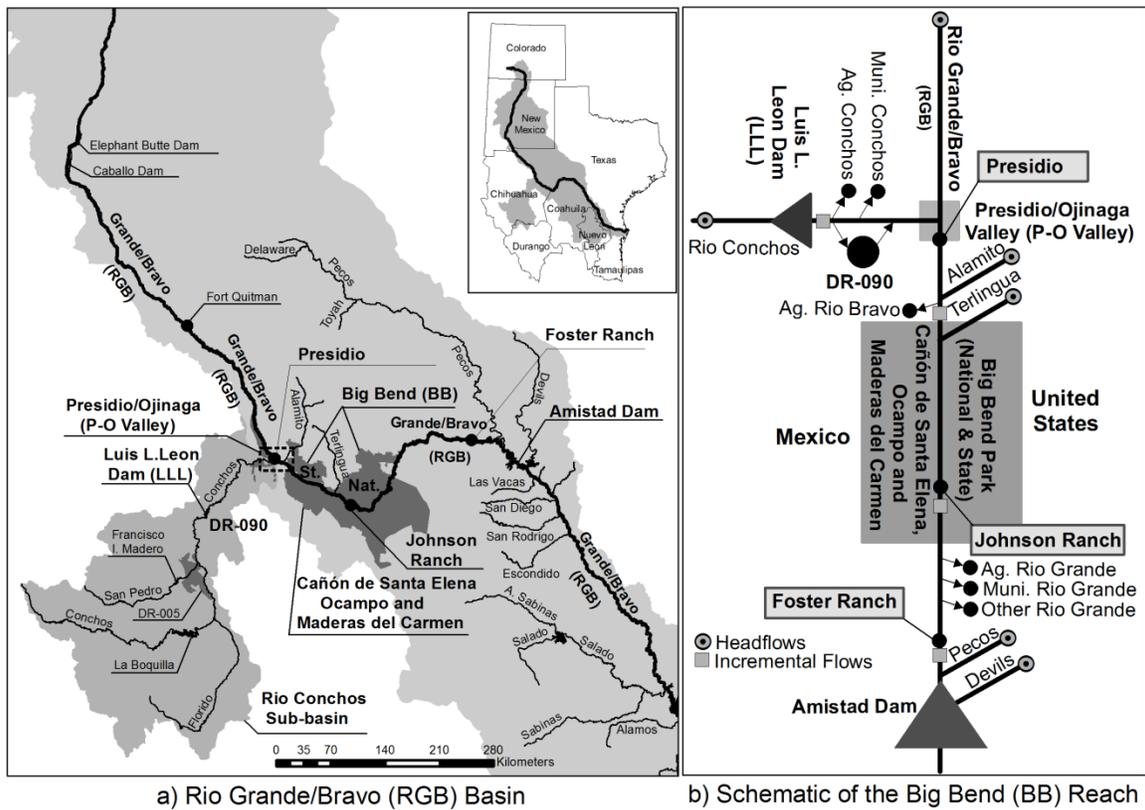


Figure 1. Map of (a) the RGB Basin and (b) the BB Reach, including locations of model headflows, incremental flows, demand sites, and environmental flow evaluation sites.

The BB Reach consists of wide alluvial valleys in structural basins and narrow canyons cut through intervening ranges, with an average channel slope of 0.0013 in the alluvial valleys and 0.002 in the canyons (Dean and Schmidt, 2011). The RGB channel bed is predominantly

sand and mud, with gravel bars forming at the mouths and downstream from ephemeral tributaries (Dean and Schmidt, 2011).

The BB Reach contains riparian and aquatic ecosystems unique to the arid southwest, including over 12,000 km² of protected natural areas on both sides of the border (BBEST 2012). The RGB Basin is a globally important region for freshwater biodiversity; it supports 121 fish species, 69 of which are endemic, as well as numerous endemic bird species and a very high level of mollusk diversity (Revega *et al.*, 2000). Presidents Obama (U.S.) and Calderon (Mexico) recently recognized the BB Reach in particular as “one of the largest and most significant ecological complexes in North America” for conservation (Obama and Calderon, 2010). In spite of its ecological significance, decades of heavy water use in the RGB Basin, together with regional population growth and extended drought, have left the reach severely altered in both streamflow and sediment regimes, as described in the following section. Despite clear indicators of geomorphic and ecological degradation, the environment has not been considered as an integral part of water management in the BB Reach.

3.2.1. Hydrologic characterization

The hydrology of the BB Reach is determined by inflows from: (a) the RGB at Fort Quitman, Texas, (b) the Rio Conchos in Chihuahua, Mexico, and (c) other large ephemeral tributaries in both countries. Extreme hydrologic variation in these inputs, both seasonally and annually, has combined with water management activities to create a highly varied streamflow regime through the reach (Ingol and McKinney, 2011). Figure 2 illustrates the variability in RGB discharge across months and years (1970-2009) under the current assemblage of hydraulic infrastructure.

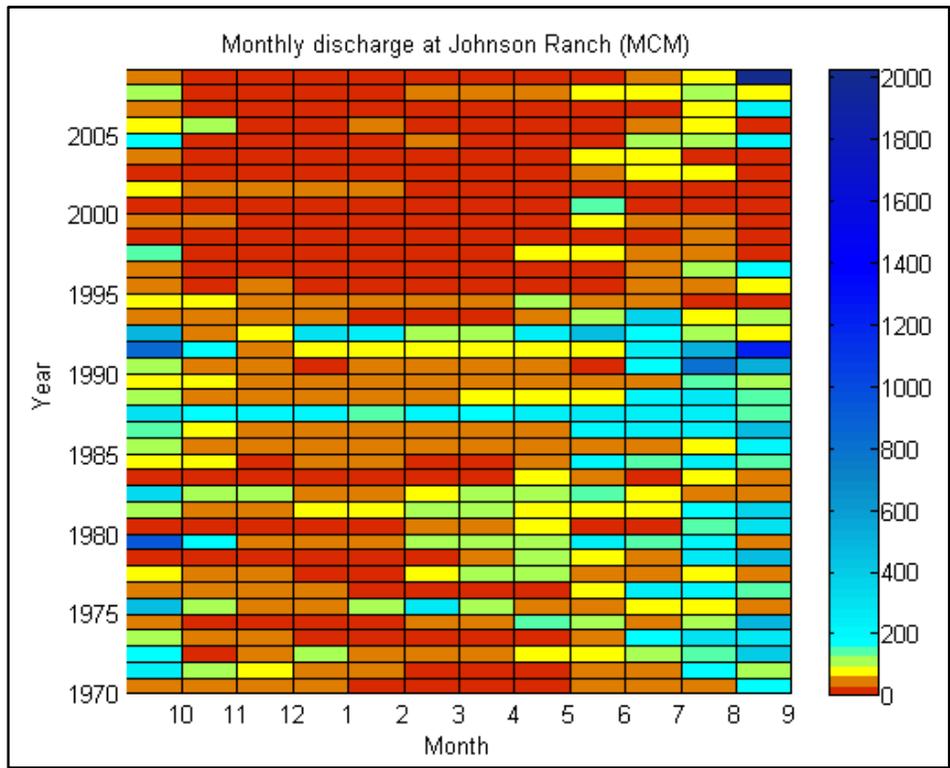


Figure 2. Average monthly discharge (MCM) at Johnson Ranch, 1970-2009

In the basin's current regulated state, the Rio Conchos contributes over 80% of the flow through the reach (Schmandt 2002). The prevailing climate of the Rio Conchos basin is warm and semi-humid, with temperatures ranging from an average maximum of 32°C in the lower basin to a minimum of 9°C in the Chihuahan Mountain headwaters (Ingol and McKinney, 2011) and annual precipitation averaging around eight inches (Schmandt 2002). The hydrology of the Rio Conchos basin is characterized by two different regimes: the first is a monsoon-driven wet period in late summer to early fall in the Sierra Madre Occidental, with annual maximum streamflows in August and September. The second is a dry period from November to June in which base flow is predominant in the river. Taken together, these regimes indicate a high seasonal variation; approximately 66% of the basin's runoff is generated by 30% of the basin's area, mostly in the upper basin (Schmidt *et al.*, 2003).

In contrast to the rain-driven Rio Conchos, before reservoir regulation most flow along the RGB mainstem was delivered by spring snowmelt runoff from the Rocky Mountains in southern Colorado and northern New Mexico. As Figure 3 illustrates, before regulation, more than 66% of the total streamflow through the BB Reach came from the Rio Conchos between the months of August and February (Schmidt *et al.*, 2003). Streamflow through the reach was only dominated by upper RGB inflows during the Rocky Mountain snowmelt pulse between April and June (Dean and Schmidt, 2011).

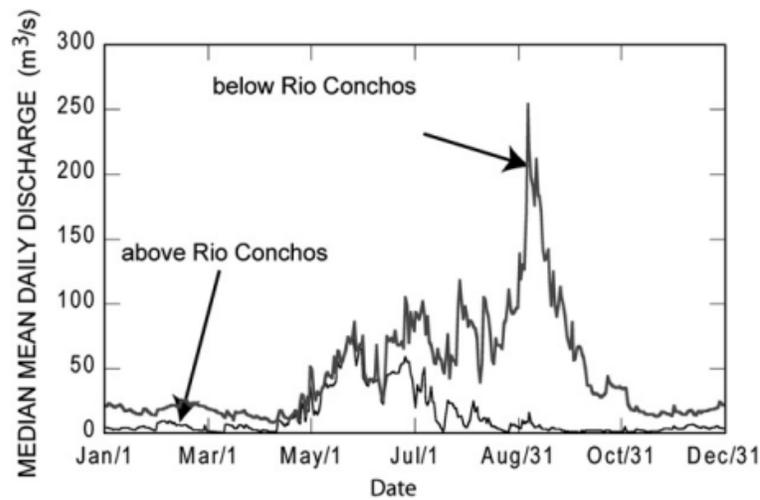


Figure 3. Pre-1915 median mean daily discharge on the RGB, above and below the Rio Conchos confluence (adapted from Dean and Schmidt, 2011)

More recently, upper-basin compacts have not required any water to pass downstream of Elephant Butte Reservoir, leaving the river frequently dry downstream of El Paso, with remaining flows mainly due to direct precipitation inputs and agricultural return flows (Benke and Cushing, 2005). While the upper RGB basin now provides a very small portion of surface flow to the reach, direct groundwater contributions from the Cretaceous limestone Edwards-Trinity Plateau Aquifer underlying the reach account for as much as two-thirds of the streamflow

in the lower section, sustaining vital aquatic habitats and water quality during dry years (Bennett 2007).

A comparison of daily streamflow before and after 1946 at Johnson Ranch provides a clear illustration of the extent of hydrologic alteration (Figure 4) (Sandoval-Solis and McKinney, 2012). The median peak flow, which naturally occurred in July with a magnitude of 197 MCM, now occurs in October with a magnitude of 21.8 MCM. This implies that the peak spring runoff period has been delayed by three months and reduced by almost 90% since 1946. A Log Pearson III extreme flood analysis before and after 1946 (Table 2) shows that flows of 1,000 MCM, which historically occurred around once every five years, now occur fewer than once every 20 years. Median monthly flows have also been severely dampened by upstream infrastructure and extractions, particularly in the summer months when upstream agricultural demands are greatest.

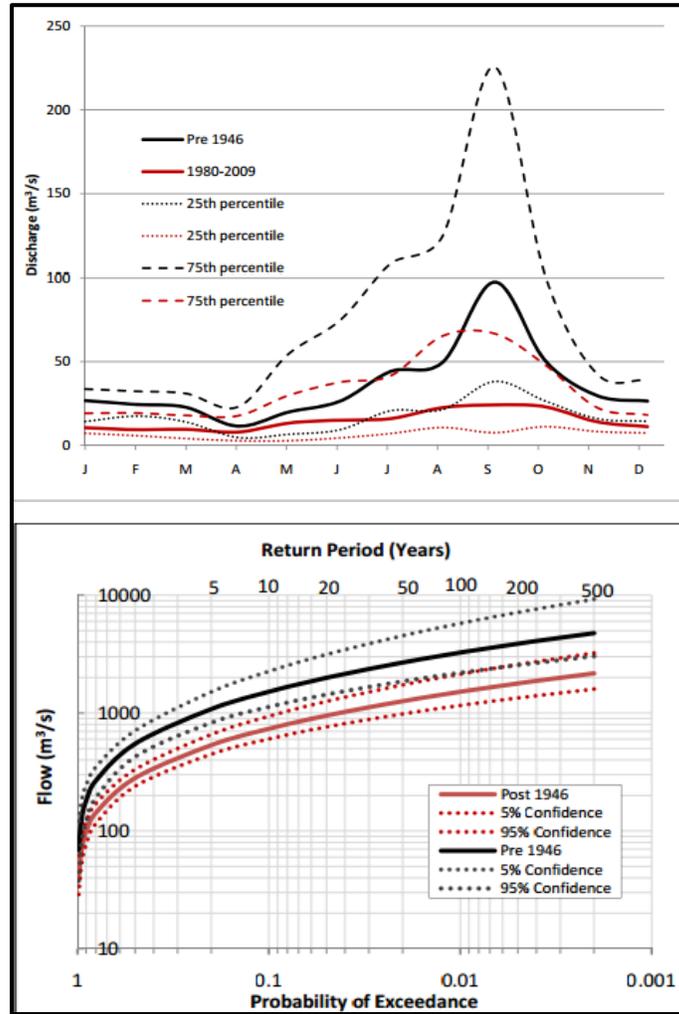


Figure 4. Comparison of (a) median monthly flows and (b) maximum annual flows pre- and post- 1946 at Johnson Ranch (adapted from Sandoval-Solis 2012)

Table 2. Log Pearson III extreme flood analysis before and after 1946 (adapted from Sandoval-Solis *et al.*, 2010).

Return Period (years)	Expected Annual Max Flow (m ³ /s)		
	1900-1946	1947-2009	Reduction
1	38	46	---
2	531	264	50%
5	1121	523	53%
10	1617	764	53%
20	2347	1056	55%
50	2957	1539	48%
100	3617	1993	45%
200	4326	2538	41%
500	5339	3424	36%
			48%

3.2.2. Environmental impacts of hydrogeomorphic alteration

Geomorphic impacts

Historically, large sediment loads to the BB Reach came from the upper RGB and Rio Conchos sub-basins as well as the numerous ephemeral tributaries draining the sparsely vegetated Chihuahuan Desert (Dean and Schmidt, 2011). The long-duration high flows and large sediment supply produced a dynamic river that changed course from year to year, with a diverse physical template including numerous migrating in-channel bars, side-channels, and backwaters (Everitt 1998; Dean and Schmidt, 2011). Under current water management (post-1946), the RGB through the BB Reach has become predominantly a narrow, single-threaded channel. Declines in median and peak flows, coupled with a relatively unchanged sediment supply, have progressively narrowed the channel over the last 60 years. Narrowing has occasionally been interrupted by large, long duration floods in excess of 990 m³/s (shown in Figure 5) that reset the channel by eroding accumulating sediment, scouring vegetation, and returning the channel morphology towards its historic form. In the early 1900s, floods of this magnitude occurred approximately once every five years. In the past 60 years, however, such floods have occurred just five times. Following each of these floods, channel narrowing has resumed, and each subsequent channel resetting flood has failed to reset the channel to widths following the previous reset. Between 1946 and 2008, the RGB channel narrowed by over 50% in some places (Figure 5). Non-native vegetation has exacerbated channel narrowing by stabilizing banks, increasing channel margin roughness, and inducing additional sediment deposition (Dean and Schmidt, 2011).

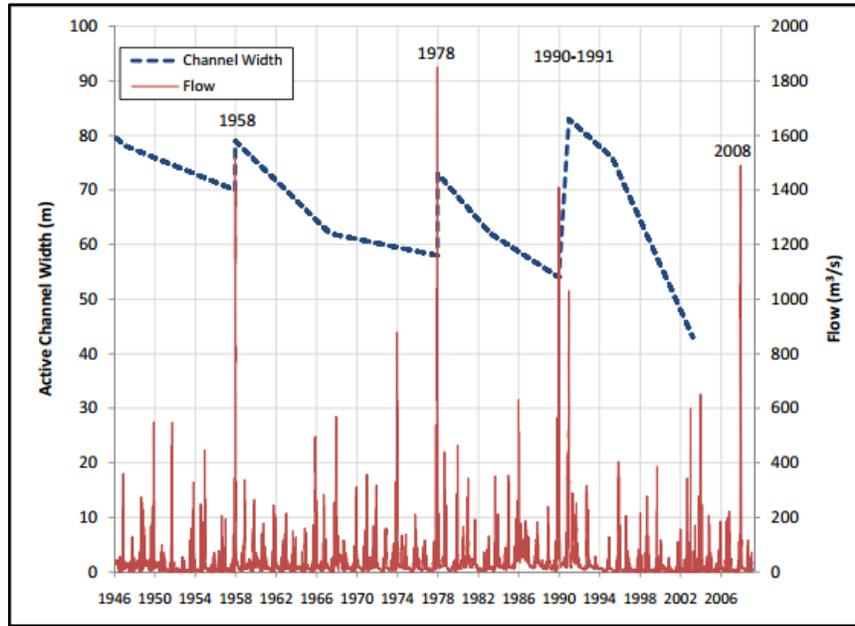


Figure 5. Johnson Ranch discharge plotted against channel width, 1946-2009 (adapted from Dean and Schmidt, 2010)

Ecological impacts

Shifts in the hydrology and geomorphology have undermined dependent plant and animal communities. Indicators of the ecological degradation of the BB Reach since heavy regulation of the RGB include the out-competition of native riparian species by exotics, e.g. salt cedar (*Tamarix spp*) and giant cane (*Arundo donax*) (Everitt 1998) and the near complete extinction of endemic riverine biota, e.g. Rio Grande silvery minnow (*Hybognathus amarus*) (Bestgen and Platania, 1991). While no quantitative analysis of historic riparian conditions along the reach exists, a qualitative assessment by BB National Park staff (BBEST 2012) suggests the past existence of narrow, discontinuous riparian vegetation distributed along a wide, shallow and dynamic channel. In its current state, the banks of the RGB are dominated largely by dense infestations of exotic and invasive vegetation, and plant diversity has decreased substantially (BBEST 2012). The freshwater fauna has also fared poorly; eight of 53 native BB fish species have been identified as threatened, five have been extirpated, two are extinct, and 13 are

introduced (Hubbs *et al.*, 2008). While BB National Park staff recently reported intact fish populations in the reach relative to other sections of the RGB, they also reported continuing extirpations of native fish, competition with invasive species, and persistent water quality and quantity issues (Heard 2012). Freshwater mussels are widely recognized as one of the most rapidly declining animal groups in North America. They are important elements of aquatic ecosystems and appear to be severely affected by environmental degradation in part due to their sensitivity to changes in water and habitat quality. Historically, 16 species of mussels inhabited the RGB Basin. Between 1990 and 2000, only six native species were found alive, and since 2002 only exotic bivalves have been seen in biological assessments by the BB National Park (BBEST 2012).

3.3. IWRM and the BB Reach

In 2002, a consortium of universities, non-governmental and governmental research agencies from both countries was formed to develop strategies to improve the environmental water management in the RGB Basin (NHI 2006). More recently, a BB specific bi-national task force did the same (Sandoval-Solis and McKinney, 2012). Results highlight the potential for re-operating LLL reservoir to provide EFs for three main reasons: (a) there is sufficient water volume upstream of LLL reservoir (over 80% of streamflow through the reach comes from the Rio Conchos) but current operations do not consider environmental needs; (b) the reservoir infrastructure already exists to deliver water upstream of an ecologically-valued and degraded reach, and (c) water for EFs is not necessarily consumptive (except for evaporative and conveyance losses) because releases can be re-captured downstream of the BB Reach at Amistad reservoir (BBEST 2012).

Under the auspices of the working group described above, Sandoval-Solis *et al.* (2010) developed the first EFs recommendations for the BB Reach (at Johnson Ranch), using the hydrology-based method to create annual and sub-annual average monthly water volume requirements based on a statistical analysis of historic streamflow patterns. While this study was an important step towards regional environmental management, it was intended only to estimate the maximum volume of water available in the system for the environment. Furthermore, the proposed EFs were based solely on statistical indices in the absence of regional data availability (Sandoval-Solis *et al.*, 2010). This study expands on the previous work to develop an IWRM policy to improve human and environmental water objectives at three locations and quantify EF objectives based on a combination of the hydrology-based method and the holistic bottom-up approach (see section 2.4.2.).

4. Policy development: preliminary methods and analysis

With the overarching goal of developing a methodology for incorporating EF releases into human-dominated water management systems, this section describes the methods and preliminary analysis related to the development of an IWRM policy (hereafter called ‘E-Flow policy’) to improve environmental management in the BB Reach. First, the reach-scale water planning model used to simulate the BB hydrology and water system is introduced, including key equations, data sources, and testing. Next, spatially-distributed EF objectives are developed for multiple hydrologic conditions. Then, key water management objectives are quantified and performance criteria developed for evaluating model results with respect to specified objectives under alternative policies. Next, the development of a baseline water management policy and an E-Flow policy is described, where a ‘policy’ consists of a unique set of monthly reservoir storage

zone thresholds, called rule curves. Figure 6 provides a study methods framework, including key inputs and outputs of linked major components (boxed) and computations performed (indicated by italics). Several sets of monthly rule curves were evaluated using an iterative process according to steps 1-4 and bold arrows as shown in the figure. Finally, a single E-Flow policy is identified, consisting of the operational rule curve that minimized alterations from EF objectives while maintaining specified human water management objectives. Simulation results under alternative water management policies are compared and discussed.

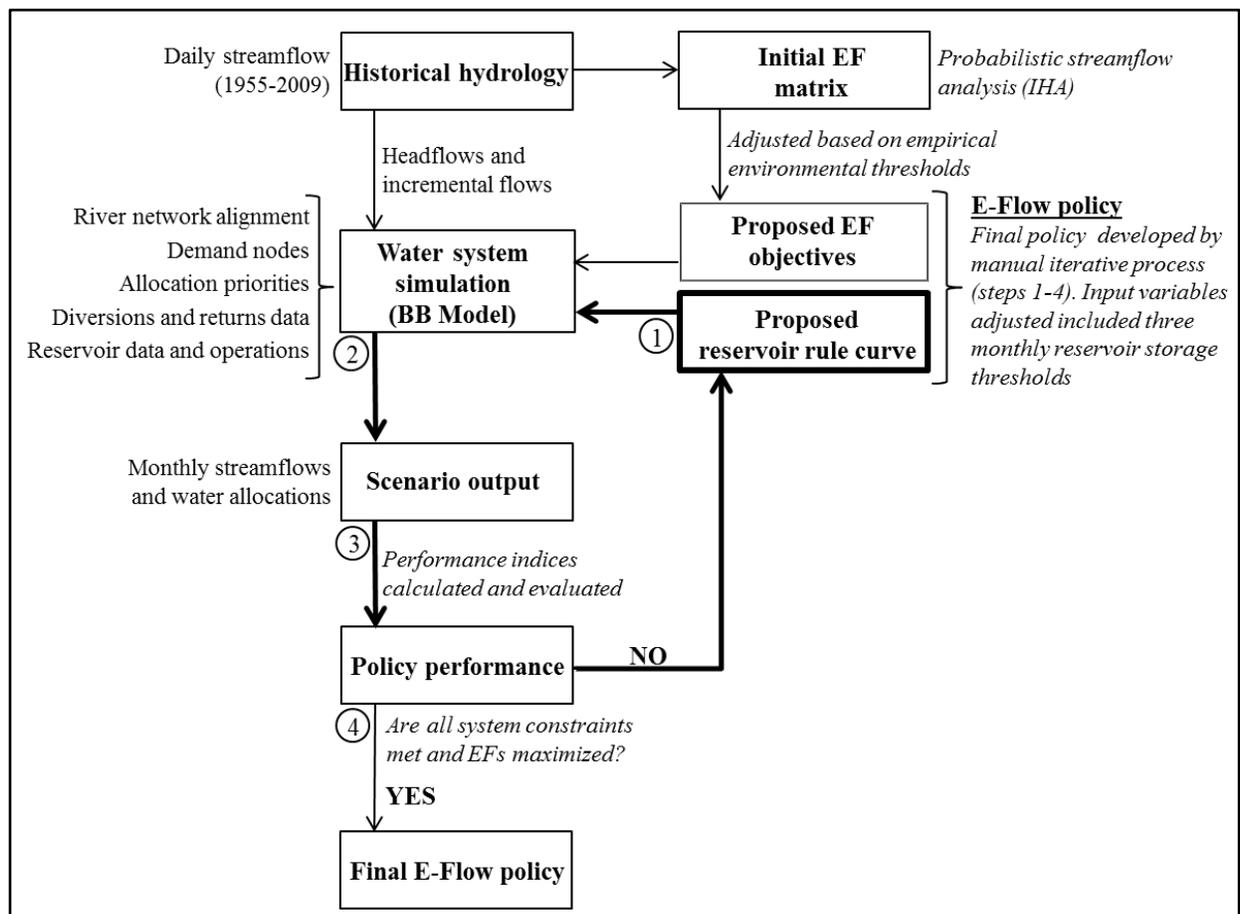


Figure 6. Study methods framework, including key inputs and outputs of linked major components (boxed) and computations performed (indicated by italics)

4.1. Big Bend Water Planning Model

Due to its internationally recognized ecological, economic and social importance, the RGB Basin has been the subject of numerous mathematical representations. Models of the RGB have included planning models to address: drought strategies (Vigerstol 2002), conflict resolution (Tate 2002), water availability (Brandes 2004), and water management scenarios (Sandoval-Solis 2011). To date, only the Big Bend Water Planning (BB) Model - developed by Sandoval-Solis and McKinney (2012) and refined in this study- has specifically addressed the regional water management of the BB Reach.

The BB Model was used here to characterize regional hydrology and water management and simulate baseline and alternative water policies. The model uses a one-dimensional water routing algorithm and a priority-based water allocation system to integrate regional hydrology, infrastructure and water management. The WEAP platform (Yates *et al.*, 2005a and 2005b) (Figure 7) 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 to September 2009). Reservoir simulation accounted for operating rules, storage thresholds, evaporation, and priorities of downstream users. WEAP is a scenario-driven decision support system for evaluating the relationships between reservoir operations, hydrology, human water demands, and instream flow requirements. It allows for the integration of demand- and supply-based information together with hydrological simulation capabilities to facilitate integrative analysis of policy alternatives. Excel Visual Basic scripts were used to move between the WEAP interface and Excel for more efficient scenario management.

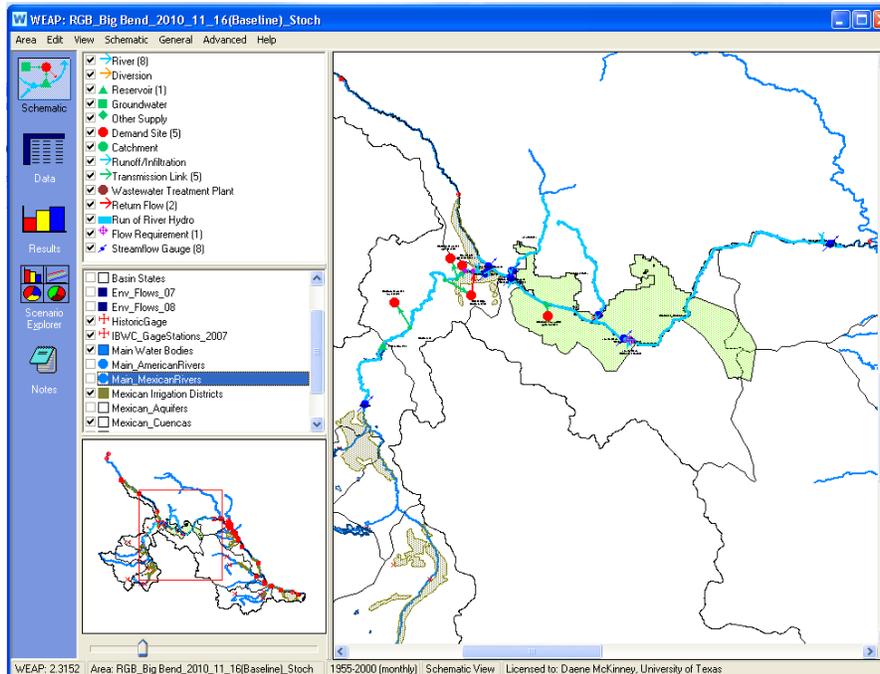


Figure 7. WEAP interface for the BB Model

4.1.1. Model inputs

Input data for the model included operational reservoir data (storage zone capacities), physical reservoir data (e.g. storage-elevation curves and evaporation losses), historical reservoir data (e.g. storage volumes), historical diversion and return flows for municipal, industrial, and irrigation uses (1955-2009), and water allocation priorities. This data was provided by the Mexican National Water Commission (CONAGUA, by its Spanish acronym), the Texas Commission on Environmental Quality, and the International Boundary and Water Commission (IBWC) (Patiño-Gomez *et al.*, 2007; CONAGUA 2008; IBWC 2013). Streamflow data was provided by CONAGUA (2008) and IBWC (2013) based on gage stations run by the U.S. Geological Survey, and daily average historical streamflow values were summed to create a time series of monthly streamflow volume. The monthly timescale of the model was constrained by monthly reservoir storage and operations data, and historic water demand and return flow data.

A mass water balance was executed along six rivers included in the model: the bi-national RGB mainstem from Fort Quitman to Amistad reservoir, the Rio Conchos in Mexico, and Alamito, Terlingua, Pecos, and Devils Rivers in the U.S. (Figure 1.b). A total of seven water demands were considered, three in the US and four in Mexico, with agriculture making up the vast majority (~99%) of water use. Each water demand has an associated monthly distribution. Along the Rio Conchos section of the BB Reach, from LLL reservoir to the confluence with the RGB mainstem, there are three Mexican surface water users: *DR-090 Bajo Rio Conchos*, *Municipal Rio Conchos* and *Agriculture Rio Conchos*. The section of the RGB from the Rio Conchos confluence to Amistad Reservoir contains four additional users: *Ag. Rio Bravo* in Mexico, and *Mun. Rio Grande*, *Ag. Rio Grande* and *Other Rio Grande* in the U.S. (see Figure 1.b for demand site locations). Table 3 provides a summary of water demands by country and type of use.

Table 3. Current water demands by country and type of use, based on 2009 values

Water User	Annual Demand (MCM)	% of demand
United States		
Ag. Rio Grande	43.2	24.4%
Mun. Rio Grande	0.8	0.5%
Other Rio Grande	0.1	0.1%
<i>Sub-total</i>	<i>44.1</i>	<i>25%</i>
Mexico		
Ag. DR 090	85	48%
Ag. Rio Conchos	30	17%
Ag. Rio Bravo	17.7	9.8%
Mun. Rio Conchos	0.3	0.2%
<i>Sub-total</i>	<i>111.6</i>	<i>75%</i>
Total	177.1	

The main sources of water for these demands are reservoir releases, tributary headflows, and incremental flows. Headflows refer to the input of rivers and creeks into the model, and monthly headflow values are based on historical streamflow data from six gage stations: RGB

above Ojinaga, Rio Conchos at Las Burras (LLL inflows), Alamito, Terlingua, Pecos, and Devils (Table 4). Incremental flows refer to gains or losses along a stretch of river between gage stations downstream of headflow inputs.

Table 4. BB Model streamflow inputs

Name	Flow Type
RGB above Ojinaga	Headflow
Rio Conchos, LLL inflows	Headflow
Rio Conchos above Ojinaga	Incremental
RGB at Presidio	Incremental
RGB at Johnson Ranch	Incremental
RGB at Foster Ranch	Incremental
RGB below Amistad	Incremental
Alamito Creek	Headflow
Terlingua Creek	Headflow
Devils River	Headflow
Pecos River	Headflow

4.1.2. Model water balance

The BB Model WEAP platform (Yates *et al.*, 2005a) is governed by the conservation of mass equation for a sub-reach i in month t (Eq. 1):

$$\Delta Storage_t^i = Inflows_t^i - Outflows_t^i + IF_t^i \quad [1]$$

where $\Delta Storage_t^i$ is the change of storage, $Inflows_t^i$ are the inflows, $Outflows_t^i$ are the outflows, and IF_t^i are the incremental flows in sub-reach i during month t . Equation 2 estimates the outflows in sub-reach i for the outlet streamflow located at downstream gage station d ($Streamflow_t^d$) based on m number of water exports ($Exports_t^m$), w diversions by water users ($Diversion_t^w$), and e water losses due to evaporation from a reservoir located in sub-reach i ($Evaporation_t^e$). Evaporation is estimated by the model using the storage-elevation curves provided by CONAGUA (2013).

$$Outflows_t^i = Streamflow_t^{d \in i} + \sum_{m=1 \in i}^{m=M \in i} Exports_t^m + \sum_{w=1 \in i}^{w=W \in i} Diversion_t^w + Evaporation_t^{e \in i} \quad [2]$$

Equation 3 estimates the inflows in sub-reach i considering u gage stations immediately upstream ($Streamflow_t^u$) of gage station d , n number of water imports ($Imports_t^n$), r water returns ($Returns_t^r$).

$$Inflows_t^i = \sum_{u=1 \in i}^{u=U \in i} Streamflow_t^u + \sum_{n=1 \in i}^{n=N \in i} Imports_t^n + \sum_{r=1 \in i}^{r=R \in i} Return_t^r \quad [3]$$

Equation 4 estimates the change of storage of a reservoir located in sub-reach i .

$$\Delta Storage_t^i = Storage_t^i - Storage_{t-1}^i \quad [4]$$

Equation 5 estimates the incremental flows (IF_t^i) for a sub-reach i in month t , defined as water gains ($Gains_t^g$) (e.g. groundwater additions to the river) minus water losses ($Losses_t^l$) (e.g. seepage).

$$IF_t^i = \sum_{g=1 \in i}^{g=G \in i} Gains_t^g - \sum_{l=1 \in i}^{l=L \in i} Losses_t^l \quad [5]$$

Combining Equations 1 to 5, incremental flows (IF_t^i) were calculated for every sub-reach i and month t using Equation 6 (Wurbs 2006; CONAGUA 2000).

$$IF_t^i = \Delta Storage_t^i + Outflows_t^i - Inflows_t^i \quad [6]$$

Incremental flow values were considered positive ($IF_t^i > 0$) when water gains outweighed water losses, and negative ($IF_t^i < 0$) when losses outweighed gains. These gains or losses were added or subtracted, respectively, from the streamflow at each sub-reach i .

4.1.3. Water allocation algorithm

The water allocation algorithm in the model distributes water in a stepwise procedure according to user-defined priorities (Yates *et al.*, 2005a). The BB Model first allocates water between the two countries according to the international Treaty of 1944 (IBWC 1944) and then supplies water according to the regulations of each country. The Treaty of 1944 addresses water

in the international segment of the RGB from Fort Quitman, Texas, to the Gulf of Mexico, allocating water based on percentage of flows from each country's tributaries to the RGB. In the BB reach, the U.S. receives an allocation of: (1) all water reaching the RGB from Pecos River, Devils River, Alamito Creek, and Terlingua Creek, (2) one-third of the flow from Rio Conchos, (3) one-half of the water at Fort Quitman, and (4) one-half of the gains along the RGB mainstem. In the BB reach Mexico receives: (1) two-thirds of the flow reaching the RGB from Rio Conchos, (2) one-half of the water at Fort Quitman, and (3) one-half of the gains along the RGB mainstem. The treaty stipulates that one-third of the combined flow of the Rio Conchos and five other Mexican tributaries is allotted to the U.S. for a total of 431.721 MCM per year, as averaged over five year cycles (Sandoval-Solis 2012, IBWC 1944).

Once water is distributed among both countries according to the international water treaty, water is allocated according to the respective laws and regulations of the U.S. (TCEQ 2006) and Mexico (CONAGUA 2012). The U.S. portion of the BB Reach resides in the Upper RGB Basin, which is administered by the TCEQ Rio Grande Watermaster Program. Under U.S. regulations, water is distributed among users according to prior appropriation based on beneficial use and date of water rights (i.e. "first in time, first in 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 (i.e. "municipal users have higher priority than agriculture") (CONAGUA 2012). Remaining instream flows and water user return flows eventually become inflows to international Amistad reservoir.

LLL reservoir on the Rio Conchos is the main infrastructure supplying water to the BB Reach. Reservoir releases occur mainly to meet Mexican water demands along the Rio Conchos or to increase flood storage capacity in preparation for the monsoon season, as determined by

CONAGUA operators (IBWC 2013). Each October, CONAGUA determines the water allocation for each user based on LLL reservoir storage volume and type of use. Domestic and municipal users have the highest priority and twice their annual water demand is stored in LLL. The available storage for agricultural users is then determined by deducting municipal allocations, evaporation and operational losses from LLL's storage volume. If the available water storage exceeds the total volume of agricultural water rights, CONAGUA allocates the water right volume; otherwise, they allocate the remaining available storage. 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.

4.1.4. Model testing

Model testing was performed to evaluate confidence in the model to represent the regional hydrology and the water allocation system. Unimpaired flows (headflows and IFs) were estimated considering historic water demands, streamflow, and reservoir storage data. The period of analysis is 55 years (Oct 1954 to Dec 2009). The BB Model was adjusted to fit historic streamflow and reservoir storage data by: (1) calculating headflows and incremental flows (reach gains and losses) using the equations explained in the section 4.1.2 Model Water Balance, and (2) adjusting the water allocation system and reservoir operation storage via numerous model inputs. The accuracy of the model in predicting historical streamflows and reservoir storage was evaluated over a 40-year period (Oct 1969 - Sep 2009) because both reservoirs were in operation during this period and the historical data for this period is more reliable than for early periods (Patiño-Gomez *et al.* 2007, CONAGUA 2008b, Lane *et al.*, submitted 2014). This period also contained a range of hydrologic events, including a wet period (1984-1993) and a severe and

extended drought (1994-2007). Results from the model were methodically compared against historical reservoir storage and streamflow data using goodness-of-fit indices.

The performance of the model in predicting monthly and annual streamflow and water allocations was determined based on the following goodness-of-fit indices: the Coefficient of Determination (R^2 , -1 to 1), the Index of Agreement (IA, 0 to 1) and the Coefficient of Efficiency (CE, $-\infty$ to 1) (Legates and McCabe, 1999). R^2 is the square of the Pearson's product-moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model (Legates and McCabe, 1999). However, the R^2 index is limited in that it standardizes for differences between the observed and predicted means and variances by only evaluating linear relationships between variables. It is also oversensitive to outliers which can bias towards extreme events (Nash and Sutcliffe, 1970). IA is the ratio of the mean square error to the squared absolute differences of the simulated and observed values and their averages. CE, which has been widely used to evaluate the performance of hydrologic models, is the ratio of the mean square error to the variance in the observed data, subtracted from unity (Nash and Sutcliffe, 1970).

These goodness-of-fit indices were used compare annual storage for two reservoirs, LLL and Amistad. Reservoir storage is an appropriate measure of model functionality because it depends on accurate representations of inflows and outflows (Legates and McCabe, 1999). Performance of annual and monthly streamflow volumes was evaluated at two gage stations: *Rio Conchos at Ojinaga* and *RGB at Johnson Ranch*. *Ojinaga* was used because the Rio Conchos provides 80% of the water to the BB Reach and is therefore highly significant in the basin water balance. *Johnson Ranch* was used because it is an ecologically degraded site where environmental water management strategies are being evaluated.

Table 5. BB Model goodness-of-fit summary

Model output	R ²	IA	CE
<i>Reservoir Storage</i>			
Amistad	0.99	1.00	0.99
Luis L. Leon	0.97	0.99	0.97
<i>Annual Streamflow Volume</i>			
Rio Conchos at Ojinaga	0.99	1.00	0.99
Rio Grande at Johnson Ranch	0.98	1.00	0.98
<i>Monthly Streamflow Volume</i>			
Rio Conchos at Ojinaga	0.99	1.00	0.99
Rio Grande at Johnson Ranch	0.98	0.99	0.98

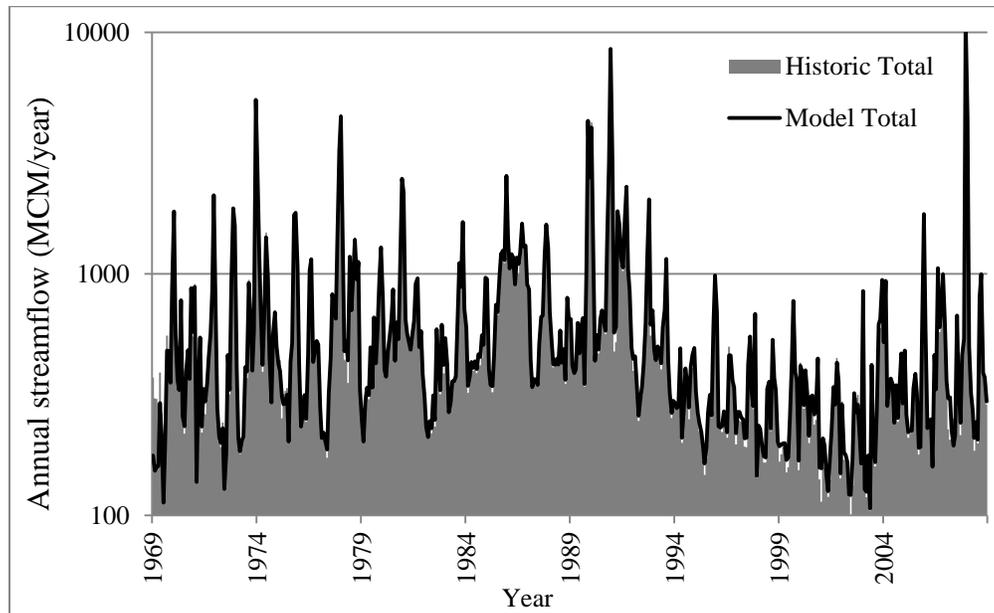


Figure 8. Historical vs. modeled annual streamflow at Presidio indicating model goodness-of-fit

All goodness-of-fit indices for both reservoir storage and streamflow model outputs exceeded 0.97 (Table 5). Such values indicate that the model captures the streamflow regime and reservoir operating rules very well, according to Moriasi *et al.* (2007), and can thus be used as a tool for evaluating alternative water management policies. Figure 8 further illustrates the strong relationship between historic and modeled data for annual streamflow volumes at *RGB at Ojinaga*. Remaining error in the model is likely due to inaccurate streamflow data (particularly

after flood events when gage stations often require maintenance) (IBWC 2011), time-step constraints, and inability to capture real-time operational decisions by reservoir managers.

4.2. BB Reach environmental flow objectives

Spatially-distributed EF objectives were developed for the BB Reach to characterize environmental water needs according to the hydrologic and ecogeomorphic context without regard for water management goals. As Figure 6 above shows, an initial EF matrix was first created based on a probabilistic historical streamflow analysis, and these recommendations were then adjusted based on empirical environmental streamflow thresholds to form annual EF hydrographs for three locations along the BB Reach (Presidio, Johnson Ranch, and Foster Ranch).

4.2.1. Hydrologic analysis

The Texas legislature recently established the development of EF standards for major river basins across the state (BBEST 2012). The Upper Rio Grande Basin and Bay Expert Science Team (BBEST), a group of U.S. governmental and non-governmental organizations and universities, was charged with creating a regional EF analysis based on available science and without regard for the water needs of other users (2012). BBEST derived a preliminary EF matrix for the BB Reach based on a probabilistic streamflow analysis using the IHA method (Richter *et al.*, 1996). This method uses statistical indices related to the frequency, timing, duration, and magnitude of the unregulated flow regime to characterize key components of the natural flow regime. Historical mean daily streamflow data for numerous locations in the reach

was obtained from IBWC (BBEST 2012; IBWC 2011). The period of analysis (1936-1967) consisted of all data prior to the construction of LLL reservoir (pre-1968) because that period is believed to have “supported an ecologically diverse system and sustained key geomorphic features for a functional aquatic ecosystem,” and is thus considered representative of current environmental management goals for the reach (BBEST 2012). The period also included documented natural cycles of dry (1945-1985) and wet (1936-1944) conditions (Dean and Schmidt, 2011). See the “Environmental Flows Recommendation Report” by the BBEST for more information regarding their EF development process (2012).

4.2.2. Incorporating ecogeomorphic streamflow thresholds

EFs were refined in this study based on expert-defined empirical streamflow thresholds for the maintenance of specific ecological and geomorphic functions. The objective of these adjustments was to refine 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 *holistic bottom-up method* of EF quantification (see section 2.4.2.).

Streamflow thresholds were determined based on an extensive literature review of river science and related studies in the RGB Basin and the BB Reach, as well as personal communication with BB National Park (U.S.) and Área de Protección Cañón de Santa Elena (Mexico) staff. Geomorphic studies were heavily weighted in the review process because the rapidly changing geomorphic template of the BB Reach is considered one of the largest drivers of regional ecological degradation (Dean and Schmidt, 2012; Heard 2012). High flows (or lack

thereof) are believed to dictate the rate, magnitude, and trajectory of geomorphic change in the reach, with major implications for habitat quality and availability (Dean and Schmidt, 2012).

Table 6 summarizes the environmental significance of various streamflow components in the BB Reach (BBEST 2012). The specific thresholds and resulting adjustments to EF hydrographs are described in the following paragraphs.

Table 6. Summary table of environmental significance of BB Reach streamflow components

Flow Component	Hydrology	Geomorphology	Ecology	Water Quality
No Flow	flow ceases between perennial pools	deposition of fine sediment causes vegetation encroachment into channel	generally stressful for fish communities	raise water temps, decrease oxygen levels and concentrate contaminants
Base Flows	average condition	maintain soil moisture and water table levels; diversity of habitats; transport sediment	provide suitable aquatic habitat; provide longitudinal connectivity	provide suitable instream water quality
High Flows	short duration pulses below bankfull	transport/deposit sediment; development of inset floodplains; prevent riparian vegetation encroachment to river channel	serve as recruitment events for biota; provide connectivity to near-channel water bodies	restore instream water quality after prolonged low flows; episodic in nature
Flood Flows	infrequent high flows that exceed channel capacity	long-term maintenance of existing channel morphology	maintain foundation for physical instream habitat features; provide lateral floodplain connectivity	restore water quality in channel and floodplain

EF hydrographs consist of *base flow* ($Base_t^{Normal}$ or $Base_t^{Drought}$) and *high flow* (HF_t) components. For each location, EFs were developed for two conditions: *normal* ($Eflows_t^{Normal}$) (Eq. 7) and *drought* ($Eflows_t^{Drought}$) (Eq. 8). Drought base flows ($Base_t^{Drought}$) consist of 10% of normal condition base flows and no high flows. This percentage was used to maintain the shape of the EF hydrographs released during drought while significantly reducing the volume. The percentage value could be adjusted based on stakeholder or scientific inputs as desired.

$$Eflows_t^{Normal} = Base_t^{Normal} + HF_t \quad [7]$$

$$Eflows_t^{Drought} = Base_t^{Drought} = 0.1 * Base_t^{Normal} \quad [8]$$

Normal *Base flows* ($Base_i^{Normal}$) are the median value of average daily streamflows for each month at a given location. These long duration low flows are intended to provide adequate habitat through longitudinal connectivity and maintaining suitable water temperatures for aquatic species (BBEST 2012). Currently, they are driven by a combination of groundwater inputs, reservoir releases to supply irrigation and municipal demands, and return flows. The proposed base flow value for drought conditions during winter (Table 7; Figure 9) is 1.13 m³/s because a study quantifying habitat availability for endangered Rio Grande Silvery Minnow (BBEST 2012) suggests this value can provide adequate habitat for this species at Johnson Ranch under low flow conditions.

High flows refer to longer duration (5+ days) flows with a peak between the 75th and 95th percentile of pre-1968 average daily streamflow. Current high flows through BB are driven by water transfers from LLL to Amistad reservoir and releases to provide flood storage capacity. In the Big Bend's ephemeral tributaries, high intensity monsoonal rainfall creates short-duration flows (<5 days) that transport high loads of sediments, causing channel aggradation and narrowing in the RGB mainstem. High flow pulses are needed to limit channel narrowing by providing sufficient flow frequency and magnitude to mobilize bed deposits of a sufficient duration to evacuate accumulated fine sediment from the channel (Dean and Schmidt, 2010). BBEST (2012) recommend an annual monsoonal high flow pulse at Johnson Ranch of 297 m³/s for a minimum duration of 5 days to evacuate sediment from the channel. The July high flow pulse proposed in these hydrographs is intended to meet this objective (Table 7; Figure 9).

Floods, defined as any flows exceeding the 95th percentile (1,100 m³/s), were not incorporated into these EF objectives because they will occur naturally regardless of policy whenever streamflow inputs and storage volumes are high enough to overwhelm the reservoir's

capacity. Furthermore, releasing flood flows has the potential to cause flood damages in the Presidio- Ojinaga (P-O) Valley (Sandoval-Solis and McKinney, 2012). The flood risk analysis presented later in this study provide an initial, coarse evaluation of the impacts of policy change on flood risks, but further flood risk modeling is recommended to improve understanding of the potential costs and benefits before any such flows are released.

Regardless of these concerns, an effective environmental water management policy for the BB Reach must distinguish between short duration flash floods, in which monsoonal flood flows from ephemeral tributaries cause sediment deposition and channel narrowing, and long duration (7+ days) channel resetting floods, which erode accumulated sediment and re-widen the river channel to sustain ecologically significant geomorphic processes. BBEST (2012) suggested that an annual monsoonal high flow pulse of $297 \text{ m}^3/\text{s}$ with a minimum duration of five days is capable of fulfilling the geomorphic goals of channel resetting floods in the upper reach (i.e. Presidio and Johnson Ranch). According to Dean and Schmidt (2011), however, the high flow pulses proposed here for July and August, which fall under their “small to moderate floods” ($<5,000 \text{ m}^3/\text{s days}$) category, would still constitute depositional events and contribute to channel narrowing and vertical floodplain accretion. Based on their study of historical hydrology and geomorphic response, only floods greater than $1,000 \text{ m}^3/\text{s}$ ($>10,000 \text{ m}^3/\text{s days}$) (such as those of 1978, 1990, and 1991) have been able to cause channel bank erosion and channel widening.

Monthly time-step constraints and the intended goal of developing *average annual* EF recommendations make it impossible to capture rare, channel resetting hydrologic events within EF objectives beyond the discussion above. However, releases from LLL reservoir are only one component of flow pulses through the BB Reach. Inflows from ephemeral tributaries downstream from Presidio have been shown to significantly contribute to the magnitude of

floods at Johnson Ranch in some cases. For example, the 1990 flood at Johnson Ranch was 80% larger than at Presidio because of inflow from ephemeral tributaries, and more than 60% larger at Johnson Ranch in 1986 and 2004 (Dean and Schmidt, 2011). Proposed releases from LLL reservoir, although coarsely defined and constrained by flood-risk concerns, may infrequently provide sufficient discharge to drive channel resetting events when combined with periodic inflows from ephemeral tributaries. A similar approach is recently being used in the Grand Canyon of the Colorado River, where experimental high flows are being released from Lake Mead only when geomorphic conditions in unregulated tributaries to the Grand Canyon maximize potential for downstream flood flow objectives (Hazel *et al.*, 2010).

Table 7. EF objectives under normal conditions after adjusting for empirical environmental thresholds

Location	Flow component	Units	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann, volume (MCM)
Presidio	Base Flow	m ³ /s	15	17	17	17	17	10	10	10	10	15	15	15	
	High Flow (Duration)	m ³ /s (days)	---	---	---	---	---	---	---	---	---	297 (5)	41 (14)	---	
	Monthly Volume	MCM	41	43	45	45	40	26	26	26	26	169	41	39	617
Johnson Ranch	Base Flow	m ³ /s	11	14	14	14	14	7	7	7	7	11	11	11	
	High Flow (Duration)	m ³ /s (days)	---	---	---	---	---	---	---	---	---	297 (5)	41 (14)	---	
	Monthly Volume	MCM	31	37	39	39	35	20	19	20	19	159	31	30	527
Foster Ranch	Base Flow	m ³ /s	22	19	20	19	19	17	17	17	17	22	22	21	
	High Flow	MCM	---	---	---	322	529	---	---	210	---	256	201	---	
	Monthly Volume	MCM	56	50	52	52	47	45	44	45	44	284	156	54	2,317

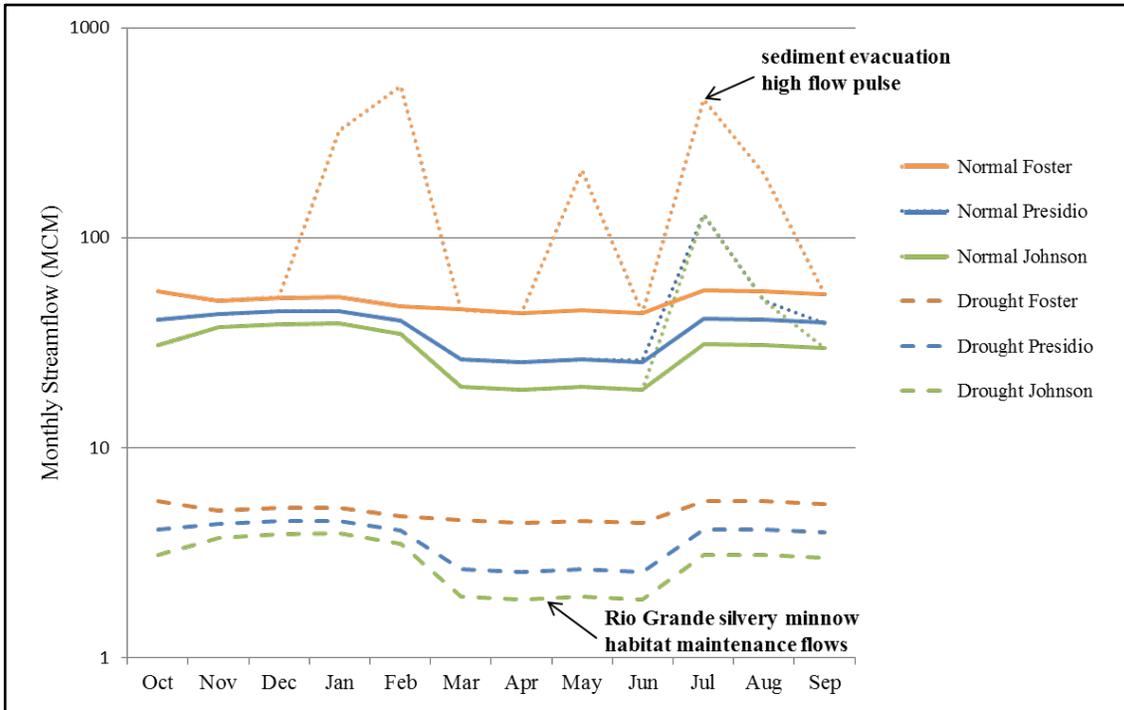


Figure 9. Final EF objectives for Presidio, Johnson Ranch and Foster Ranch, including normal (base and high) and drought flows

4.2.3. Discussion

The methods above were used to develop annual EF hydrographs of average monthly environmental water volume requirements under normal and drought conditions for three ecologically-significant locations along the BB Reach (Table 7; Figure 9). EFs were intended to characterize the magnitude, timing, and duration of streamflow necessary to support key environmental functions that were provided under the natural flow regime and meet specified environmental streamflow thresholds as determined by regional experts. To put these values in perspective, the annual EF volume recommended for Johnson Ranch is approximately 55% of the historical average annual volume (1,004 MCM/year) at this location, thus providing the shape but not the volume of the natural flow regime.

The EFs developed in this study are intended only as a coarse template of environmental water objectives. EFs were developed on a monthly scale for easy incorporation with the monthly time-step of BB water planning model. Monthly EFs cannot capture the many ecological and geomorphic processes acting over shorter time-scales. This study attempts to incorporate daily processes by indicating the specific streamflow (m^3/s) and duration (days) required to meet defined geomorphic thresholds even though the sub-monthly allocation of water cannot be accounted for in the model. However, even if a sub-monthly model time-step were possible, environmental data limitations remain very constraining. A very limited understanding (both theoretically and empirically) of complex river processes, ecohydrologic – streamflow relationships and insufficient long-term monitoring data (both in the study site and in general) make development of finer scale EFs very challenging. EFs for the BB Reach should be refined as more studies are performed and adjusted based on results of experimental EF releases according to an adaptive management framework, as described in section 2.4 above.

4.3. Evaluating water system performance

4.3.1. Water management objectives

Many factors, from lack of scientific data to lack of political will, have inhibited the inclusion of the environmental in BB water management, even as clear ecogeomorphic degradation highlights the need for an IWRM policy. The main obstacles to environmental water management in the BB Reach are: (a) a lack of understanding that re-operating the water system to provide for environmental objectives could also improve human water objectives, (b) the high flood risk in the P-O Valley, and (c) equity issues between Mexico and the U.S. related to the bi-

national water allocation treaty of 1944. Equity issues arise from the concept that the re-operation of a reservoir owned by *one* country will provide environmental benefits for *both* countries. Historic water disputes between the U.S. and Mexico and increasing constraints on basin water resources have left both countries concerned about the political implications of any change to management. For instance, some Mexican water authorities fear that an adjusted reservoir operation policy will be transformed into a fixed water delivery from the Rio Conchos to the U.S. The RGB Basin's fragmented water management mosaic further complicates equity concerns by inhibiting dialogue amongst stakeholders and water managers (Sandoval-Solis *et al.*, 2013).

Based on the obstacles to environmental water management described above, the following objectives were used to evaluate the impacts of alternative policies on the BB Reach water system: (1) human water supply, (2) international treaty obligations, and (3) flood control. Reliable provision of human water demands, consisting of monthly water volumes required by municipal, agricultural, and industrial users, was required for a policy alternative to be considered feasible in the evaluation process. International water treaty obligations (as defined in section 4.1.3.) were considered by minimizing alteration from the historic distribution of Rio Conchos outflows, as calculated over five-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 similar allocations to those provided historically. The average annual Rio Conchos outflow (782 MCM/year) over the study period (1955-2009) was used as a benchmark of acceptable treaty performance.

Due to the monthly time-step of the model, flood control objectives for the BB Reach were more difficult to quantify. While monthly model outputs prohibited a detailed flood risk

analysis, daily historical streamflow data provided some insight. The P-O Valley levee has a 25-year flood design capacity of 1,190 m³/s (IBWC 1971). Historical daily flows that have surpassed the levee capacity and caused flooding correspond to a monthly flood volume threshold in the model of 550 MCM at the Presidio gage station; this value was used to identify months likely to experience flood events in the model. Under historical management, Presidio experienced flood conditions (>550 MCM/month) in 10 months over the period of record, which represents an 18.2% flood risk, or a flood return period of 5.5 years. This flood risk probability, in combination with the historical annual average levee overflow volume (929 MCM) and the monthly streamflow volume at Presidio during the 10 largest events occurring over the period of study (Figure 14), were used to compare the flood control performance of the water system under alternative policies.

4.3.2. Performance criteria

Five performance criteria were used to evaluate model results under alternative policies with respect to specified water management objectives: (1) time-based reliability, (2) volumetric reliability, (3) resilience, (4) vulnerability, and (5) the sustainability index. These criteria were selected to represent key characteristics desired by water system stakeholders: a reliable water supply, in time and volume, that recovers quickly from deficits (high resilience) and when deficits do occur they are small (low vulnerability). Performance criteria relate water demanded ($Demand^j_t$) and water supplied ($Supply^j_t$) for a determined j^{th} water user; where a water user is defined as an agricultural or municipal demand, or an EF requirement. A water supply deficit (D_j^t) is defined as the difference between water demand ($Demand^j_t$) and water supply ($Supply^j_t$) (Eq. 9).

$$D_t^j = \begin{cases} Demand_t^j - Supply_t^j & \text{if } Demand_t^j > Supply_t^j \\ 0 & \text{if } Demand_t^j = Supply_t^j \end{cases} \quad [9]$$

Time-based reliability (Rel_{time}^j) is the frequency with which the water demand of a water user j is fully supplied ($Demand_t^j = Supply_t^j$) during the simulation period (Hashimoto *et al.*, 1982) (Eq. 10).

$$Rel_{time}^j = \frac{N_S}{N} \times 100\%; \quad 0 \leq Rel_{time}^j \leq 100\% \quad [10]$$

Where N_S is the number of time-steps 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 j^{th} water user during the simulation period (N) (Eq. 11).

$$Rel_{vol}^j = \frac{\sum_{t=1}^{t=N} Supply_t^j}{\sum_{t=1}^{t=N} Demand_t^j} \times 100\%; \quad 0 \leq Rel_{vol}^j \leq 100\% \quad [11]$$

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 ($D_t^j=0$) follows a water deficit event ($D_t^j>0$) for a j^{th} water user (Eq. 12).

$$Res^j = \frac{Frequency(D_t^j=0 \text{ follows } D_t^j>0)}{Frequency(D_t^j>0)} \times 100\%; \quad 0 \leq Res^j \leq 100\% \quad [12]$$

Vulnerability (Vul^j) represents the average severity of a deficit. This study made the vulnerability dimensionless by dividing the volumetric reliability by the annual water demand (Sandoval-Solis *et al.*, 2011) (Eq. 13).

$$Vul^j = \frac{\left(\frac{\sum_{t=1}^{t=N} D_t^j}{Frequency(D_t^j>0)} \right)}{\sum_{t=1}^{t=12} Demand_t^j}; \quad 0 \leq Vul^j \leq 100\% \quad [13]$$

The Sustainability Index (SF^j), the geometric mean of the above performance criteria (Eq. 14) (Sandoval-Solis *et al.*, 2011), was created to summarize model performance results. Such an index facilitates comparison between policies with complex trade-offs and reduces the time requirement of a manual iterative evaluation process. The SI weights each of the four indices

described above equally, which assumes that they are all of equal importance to creating a sustainable water supply. However, weights could be distributed differently based on stakeholder input related to the relative value of different aspects of the water system.

$$SI^j = \{Rel_{time}^j * Rel_{Vol}^j * Res^j * (1 - Vul^j)\}^{1/4} * 100\%; \quad 0 \leq SI^j \leq 100\% \quad [14]$$

4.4. Baseline and E-Flow policy development

This section describes the development of a business-as-usual water management (Baseline) policy and a multi-objective E-Flow policy for the BB Reach. The BB Model was used to simulate and compare water management alternatives under chronological repetition of the historical hydrology (1955-2009). Monthly municipal and agricultural water demands were fixed at their 2009 levels (Table 3) for all simulations to represent current water demands in the basin. Human demands were constrained under the assumption that agricultural water demands have been capped by the legal constraints of water authorities in both countries since 2009 to prevent further over-allocation of water rights (CONAGUA 2008; *personal communication* Carlos Rubenstein 2011) and municipal water is a very small portion of total human water demand (<1%) and therefore considered negligible. Performance was evaluated with respect to each specified water management objective [human water supply (Table 8), international treaty obligations (Figure 13), flood control (Figures 14 and 15) and EF objectives (Table 9)] based on performance criteria derived from model outputs (water supplied) and quantified objectives (water demanded).

4.4.1. Baseline policy

The business-as-usual Baseline policy was simulated as a reference condition to provide insightful comparisons of water system performance under current and alternative management policies. Model results from the Baseline policy depict monthly streamflow and water allocations in the BB Reach under current water demands, infrastructure, and reservoir operations.

Historical LLL reservoir operations

Figure 10 illustrates the three LLL reservoir storage zones (Inactive, Conservation, and Flood Control) and their thresholds (Top of Inactive = 50 MCM, Top of Conservation = variable for each month and defined in this study, and Total Storage = 832 MCM). Nominal and operational reservoir operations are distinguished; *nominal* data represents the official reservoir information provided by CONAGUA (2008). *Operational* data, in contrast, is based on historical storage records and was used instead for model simulation to more realistically represent current operations. Operation of LLL reservoir is physically constrained by its Total Storage Capacity ($S_{Capacity}$) and Top of Inactive ($S_{Inactive}$) storage thresholds. The Inactive storage zone consists of water that cannot be used to supply downstream demands because it lies below the outflow channel. While structural changes to the reservoir may be possible, they are beyond the scope of the current study.

The official objective of LLL reservoir management is to keep storage within the Conservation zone to balance trade-offs between flood control and water supply conservation. The Conservation zone is constrained by the Top of Inactive threshold and the Top of Conservation threshold (S_{Flood}), which delineates the maximum storage level to allow allotted

floodwater space in the reservoir. The Flood Control zone, which is intended to store floodwaters in the event of a flood, is between the Top of Conservation and Total Storage thresholds. The nominal Top of Conservation threshold, which refers to the nominal maximum storage volume allowance to maintain sufficient flood control capacity, is reached when the reservoir contains 292 MCM. However, the actual operation of LLL reservoir does not follow the nominal storage thresholds. The operational Top of Conservation threshold ($S_{Flood}(baseline)$) that has historically been used by managers ranges between 700 MCM in dry months (Nov– Jun) and 580 MCM in the monsoon season (Jul - Oct) based on an analysis of historical reservoir storage (see Figure 11) (CONAGUA 2008; *personal communications* CONAGUA 2010).

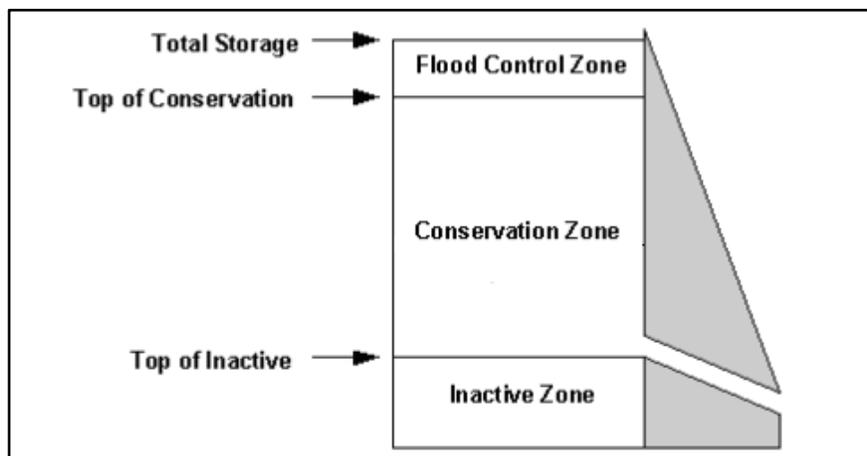


Figure 10. WEAP reservoir storage zones under historical LLL operations

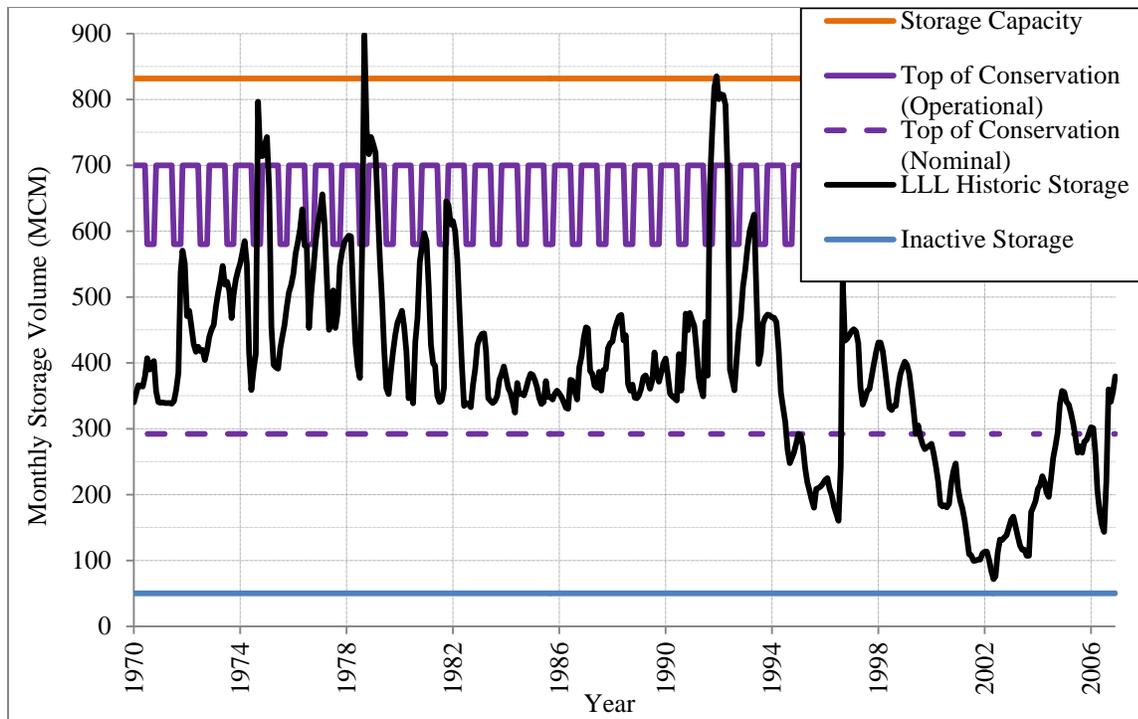


Figure 11. Historical LLL reservoir operations and storage volumes

Figure 11 illustrates historical reservoir operations and resulting storage volumes over time (1970-2007), including both nominal and operational Top of Conservation storage thresholds. The figure shows that reservoir storage has historically remained almost entirely above the nominal Top of Conservation threshold, storage that is supposed to be conserved for flood control. This indicates that reservoir operators are allowing more water to be stored in the Flood Control zone than is officially required. Such operations are likely intended to account for the extreme seasonal variation of the RGB Basin hydrology; more water is kept in the reservoir during the dry season when the chances of large streamflow inputs are low, and water is released at the start of the wet season to provide storage space for floodwater capture. However, even in the wet season, an average of 288 MCM more water is stored in the reservoir than is officially allowed. This indicates that historical LLL operations have emphasized hedging to keep more water in the reservoir in case of drought rather than preemptively releasing for flood control.

Figure 11 also illustrates that historical operations, as depicted by the LLL historic storage curve, have been highly variable; they are based on real-time, un-transparent operational decisions by CONAGUA reservoir managers.

4.4.2. E-Flow policy

With the goal of developing an IWRM policy capable of maintaining or improving specified human water management objectives while providing EFs, an iterative process was used to simulate and evaluate the performance of alternative policies and identify the single policy that maximized EF performance within the constraint of specified objectives for water supply, treaty obligations, and flood control. Two components were used as initial model inputs for the E-Flow policy development (as shown in Figure 6): (1) the EF objectives described above, and (2) a proposed alternative reservoir rule curve to balance multi-objective water management tradeoffs.

Modifying reservoir operations

The EF recommendations developed in this study were aimed solely at the recovery or maintenance of environmental functions, without consideration for human water management objectives. Similarly, human water demands and system constraints were quantified independently of one another and of environmental pressures. However, quantifying water management objectives is only the first step towards an IWRM policy. A reservoir rule curve was therefore developed to better balance management trade-offs in the model. LLL reservoir operations are based on the conflicting objectives of maximizing available water in storage for

supply purposes (e.g. irrigation, municipal, etc.) and maximizing floodwater storage capacity to reduce downstream flood damages, all while abiding by international treaty obligations.

Alternative reservoir operations were explored to evaluate the impacts of re-allocating reservoir storage between flood control and water supply conservation while incorporating EF releases and accounting for seasonal inflows and storage volume based on a monthly rule curve.

The proposed rule curve (Equation 15) for LLL reservoir considers five storage zones and five associated thresholds in any given month t : (1) the Flood Control zone above the Top of Conservation threshold, which is held empty whenever possible to store potential floodwaters (Figure 12 shows the current operational Top of Conservation threshold ($S_{Flood} (Baseline)$) and the proposed threshold ($S_{Flood} (Proposed)$); (2) the Environmental Flows zone, with storage dedicated to both environmental ($Eflows_t^{Normal}$) and human water needs ($Human_t$); (3) the Transition zone, the buffer zone between the normal (S_{Normal}) and drought ($S_{Drought}$) storage thresholds in which storage is dedicated solely to human water supply ($Human_t$) while there is sufficient water to sustain ecosystems. This transitional zone is meant for times when it is uncertain whether or not the reservoir storage level will fall into the drought zone and the environment is not at immediate risk; (4) the Drought zone, with storage dedicated to both human water supply ($Human_t$) and drought EFs ($Eflows_t^{Drought}$) when ecosystems are potentially at-risk from extended low water levels; and (5) the Inactive zone below the Top of Inactive threshold ($S_{Inactive}$) in which water is inaccessible because it sits below the dam outlet.

Drought EFs ($Eflows_t^{Drought}$) were released in place of normal EFs for the entire wet (Jun-Oct) or dry season (Nov-May) when reservoir inflows from the previous wet ($I_{Season-1}^{Wet}$) or dry ($I_{Season-1}^{Dry}$) seasons were 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 can be adjusted based on stakeholder needs (Sandoval-Solis and McKinney, 2012). Releases from LLL reservoir ($Releases_t^{LLL}$) based on storage in month t (S_t^{LLL}) are specified in Eq. 15.

$$Release_t^{LLL} = \begin{cases} Human_t + Eflows_t^{Normal} & \text{If } S_{Flood} > S_t^{LLL} > S_{Normal} & \text{For } t = 1, \dots, 12 \\ Human_t & \text{If } S_{Normal} > S_t^{LLL} > S_{Drought} & \text{For } t = 1, \dots, 12 \\ Human_t + Eflows_t^{Drought} & \text{If } S_{Drought} > S_t^{LLL} > S_{Dead} & \text{For } t = 1, \dots, 12 \\ Human_t + Eflows_t^{Drought} & \text{If } I_{Season-1}^{Wet} < 250 & \text{For } t = 7, \dots, 10 \\ Human_t + Eflows_t^{Drought} & \text{If } I_{Season-1}^{Dry} < 200 & \text{For } t = 11, 12, 1, \dots, 6 \\ 0 & \text{If } S_t^{LLL} < S_{Dead} & \text{For } t = 1, \dots, 12 \end{cases} \quad [15]$$

Developing an E-Flow policy

The BB water system was explored and the final E-Flow policy developed based on the following iterative simulation process (steps 1-4 of Figure 6): (1) EF objectives and the alternative reservoir rule curve were proposed as inputs to the BB Model, (2) the water system was simulated under the proposed inputs, (3) VBA scripts were used to extract model results and calculate specified performance indices to determine performance of the water system with respect to specified objectives, and (4) input variables were manually adjusted. Input variables adjusted in the iterative simulation process consisted of monthly volume thresholds for three storage zones [Top of Conservation ($S_{Flood}(proposed)$), normal storage (S_{Normal}) and drought storage ($S_{Drought}$)]. 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 input variables 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 supply demands, did not significantly increase flood risk from historic levels, and abided by international water treaty obligations (see

section 4.3.1.). 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 while maintaining specified objectives.

The resulting reservoir rule curve is shown in Table 8 and Figure 12. Table 8 contains the proposed policy in term of monthly EF objectives and a reservoir rule curve to provide them among other objectives. Under the proposed policy, monthly Top of Conservation storage thresholds were adjusted to maintain more flood storage capacity in the reservoir than under current management, with the goal of reducing flood risk while releasing instream flows in a more natural manner. As shown in Figure 12, the maximum floodwater capacity under proposed reservoir operations is available in June at the start of the wet season (historically in July), and the Top of Conservation threshold is ramped up earlier in the year to increase available supply for human and environmental demands throughout the dry season. Normal and Drought storage thresholds were set at constant values of 275 and 215 MCM, respectively (Table 8).

Normal and Drought thresholds do not vary monthly because they are intended to maintain water supply reliability and drought resilience under hydrologic uncertainty, and these objectives do not vary substantially with time. While it is possible that allowing normal and drought storage thresholds to vary seasonally as well could further refine a reservoir re-operation policy, it was not considered here to limit the time requirement for manual iteration. Automating the iterative simulation process (e.g. through the use of a genetic algorithm model within Excel) could reduce the time constraint and allow for further variation among policy alternatives, but this was beyond the scope of the current study.

Table 8. Proposed E-Flow policy, including normal EF objectives and monthly reservoir storage

Location	Flow Component	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Proposed EF objectives														
Presidio	Base Flow	41	43	45	45	40	26	26	26	26	41	41	39	
	High Flow	---	---	---	---	---	---	---	---	---	128	50	---	
	Total Volume	41	43	45	45	40	26	26	26	26	169	91	39	617
Johnson Ranch	Base Flow	31	37	39	39	35	20	19	20	19	31	31	30	
	High Flow	---	---	---	---	---	---	---	---	---	128	50	---	
	Total Volume	31	37	39	39	35	20	19	20	19	159	81	30	527
Foster Ranch	Base Flow	56	50	52	52	47	45	44	45	44	56	56	54	
	High Flow	---	---	---	322	529	---	---	210	---	256	201	---	
	Total Volume	56	50	52	374	576	45	44	255	44	312	257	54	2,119
Reservoir storage zone thresholds														
Flood Control	S _{Capacity}	832	832	832	832	832	832	832	832	832	832	832	832	
	S _{Flood Control}	650	650	650	650	650	650	650	650	500	550	550	600	
Drought Control	S _{Normal}	275	275	275	275	275	275	275	275	275	275	275	275	
	S _{Drought}	215	215	215	215	215	215	215	215	215	215	215	215	
	S _{Dead}	50	50	50	50	50	50	50	50	50	50	50	50	

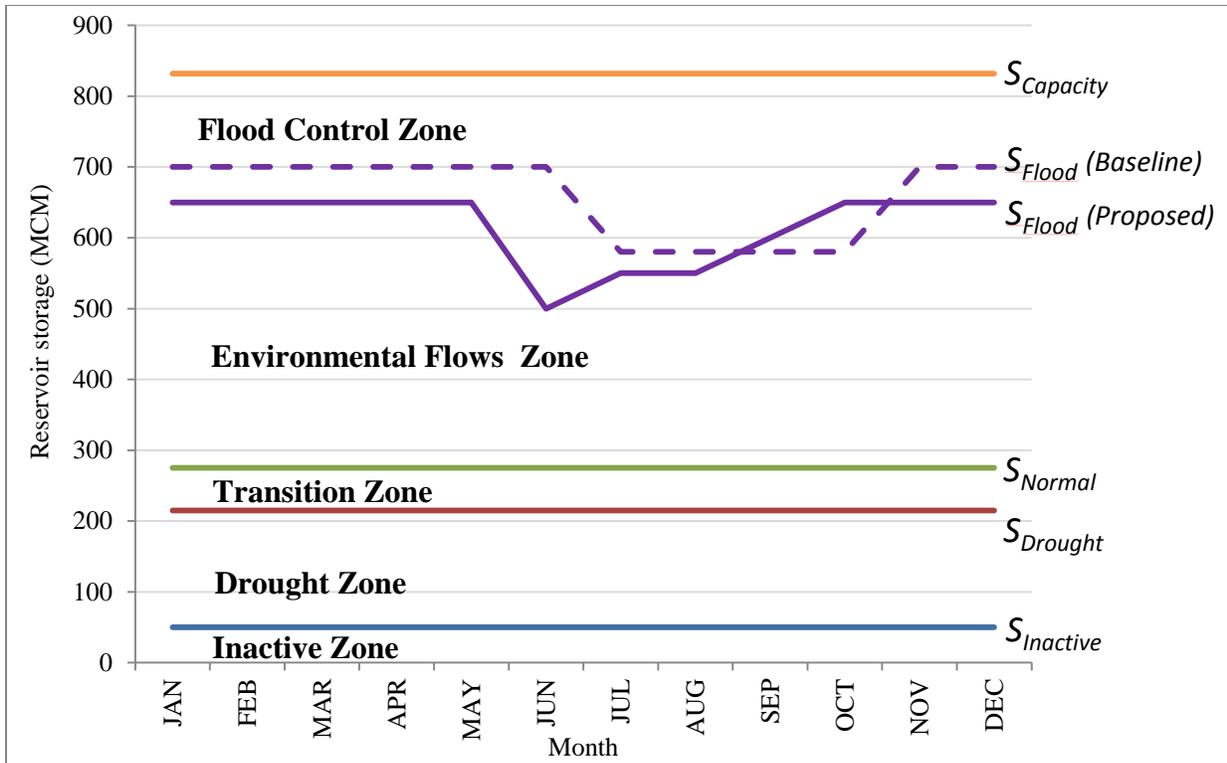


Figure 12. Proposed LLL reservoir rule curve and storage zones

5. Results: Model performance under alternative policies

Water system performance results under the Baseline and final E-Flow policies are discussed below with respect to (1) human water supply, (2) international treaty obligations, (3) flood control, and (4) EF objectives.

5.1. Human water supply

Table 9 shows the performance of the system for all water users in both countries under the Baseline and E-Flow policies based on reliability (time-based and volumetric), resilience, vulnerability, and SI. The performance of human water supply under baseline reservoir operations was generally poor, with SI values ranging from 0 to 60%. Mexican water users

showed higher performance overall, likely as a result of their upstream locations and resulting higher allocation priority in the model. The E-Flow policy significantly improved the performance of agricultural, municipal, and industrial compared with baseline operations. Water supply reliability increased in time and volume, while vulnerability was reduced from as high as 90% (*U.S. Other Rio Grande*) down to 0% to provide 100% SI for all water users. Such performance improvements indicate that the water system is not currently being operated to optimize human water supply objectives and that sufficient water volume exists in the system to meet these objectives with minor, operational changes to LLL reservoir.

Table 9. Performance of human water supply under Baseline and E-Flow water management policies

Water User	Annual Demand (MCM/year)	Baseline				E-Flow					
		Rel Time (%)	Rel Volume (%)	Res (%)	Vul (%)	SI (%)	Rel Time (%)	Rel Volume (%)	Res (%)	Vul (%)	SI (%)
United States											
<i>Mun. Rio Grande</i>	0.8	13	42	4	67	20	100	100	100	0	100
<i>Ag. Rio Grande</i>	43.2	11	41	4	66	20	100	100	100	0	100
<i>Other Rio Grande</i>	0.1	0	11	0	90	0	100	100	100	0	100
Mexico											
<i>Mun. Rio Bravo</i>	0.3	11	39	4	68	20	100	100	100	0	100
<i>Ag. DR 090</i>	63.6	69	89	35	36	60	100	100	100	0	100
<i>Ag. Rio Bravo</i>	30	11	39	4	68	20	100	100	100	0	100
<i>Ag. Rio Bravo</i>	17.7	11	39	4	68	20	100	100	100	0	100

5.2. International treaty obligations

The 1944 Treaty specifies water allocations for both countries (as described in section 4.1.3), including the allocation of one-third of all water arriving to the RGB from the Rio Conchos and six other Mexican tributaries to the U.S. Historical median annual outflow from the Rio Conchos (661 MCM/year, 1955-2009) has made up ~51% of treaty obligations, as accounted over five-year treaty cycles (IBWC 1944). Under the E-Flow policy, the median annual outflow was 694 MCM/year, one-third of which is 231 MCM or 54% of treaty obligations. This implies that, under the E-flow policy, Rio Conchos outflow will almost exactly meet its historical contribution to the treaty; i.e., the same amount of water will be provided, only in an environmentally friendly pattern. Figure 13 shows the distributions of annual volume of outflow from the Rio Conchos as averaged over (a) one-year and (b) five-year periods, both historically and under the E-Flow policy. Both averaging schemes illustrate similar distributions between historical and proposed water management policies.

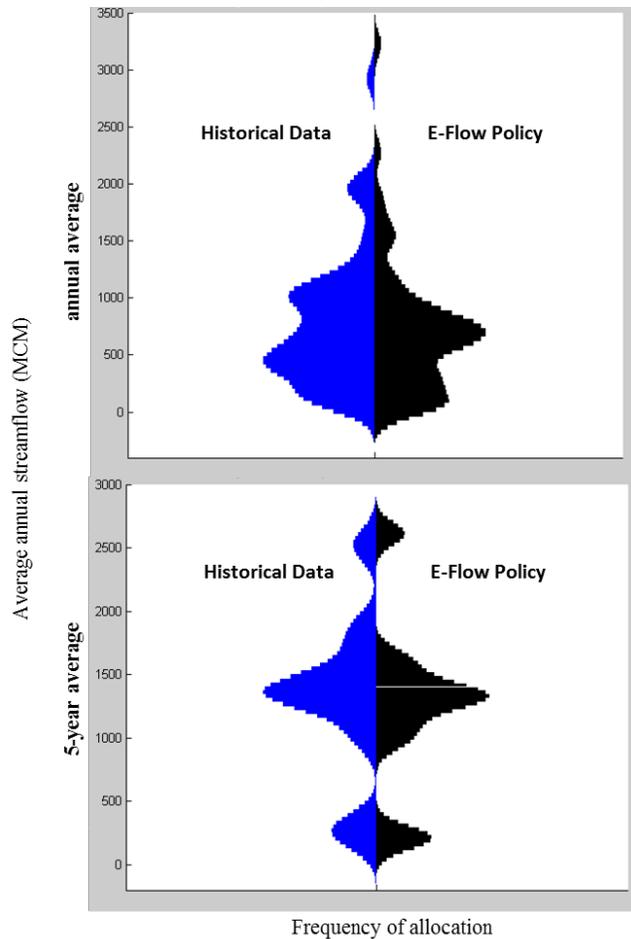


Figure 13. Distribution of (a) annual average and (b) five-year average treaty contributions as provided historically (1955-2009) and under E-Flow policy.

5.3. Flood control

Any IWRM policy for the BB Reach must account for flood control in the P-O Valley due to the high flood risk and the projected regional increase in extreme precipitation events with climate change (USBR 2011). Under the Baseline policy, 10 months experienced flood conditions (>550 MCM at Presidio), which represents an 18.2% flood risk, or a flood return period of 5.5 years. Alternatively, only 8 floods occurred under the E-Flow policy, and average flood risk was reduced to 14.5% or a 6.9-year return period. The average annual overflow volume was very similar under both policies (Baseline 929 MCM; E-Flow 1,023 MCM),

indicating that, on average, the E-Flow policy would not substantially increase the severity of flood events. However, in the two largest flood events (Sep-08 and Sep-91), the overflow volume was larger under the E-Flow than the Baseline policy (Figure 14). Further research in flood management is needed at a finer time scale to define a reservoir policy that is able to reduce the potential damage of flood events.

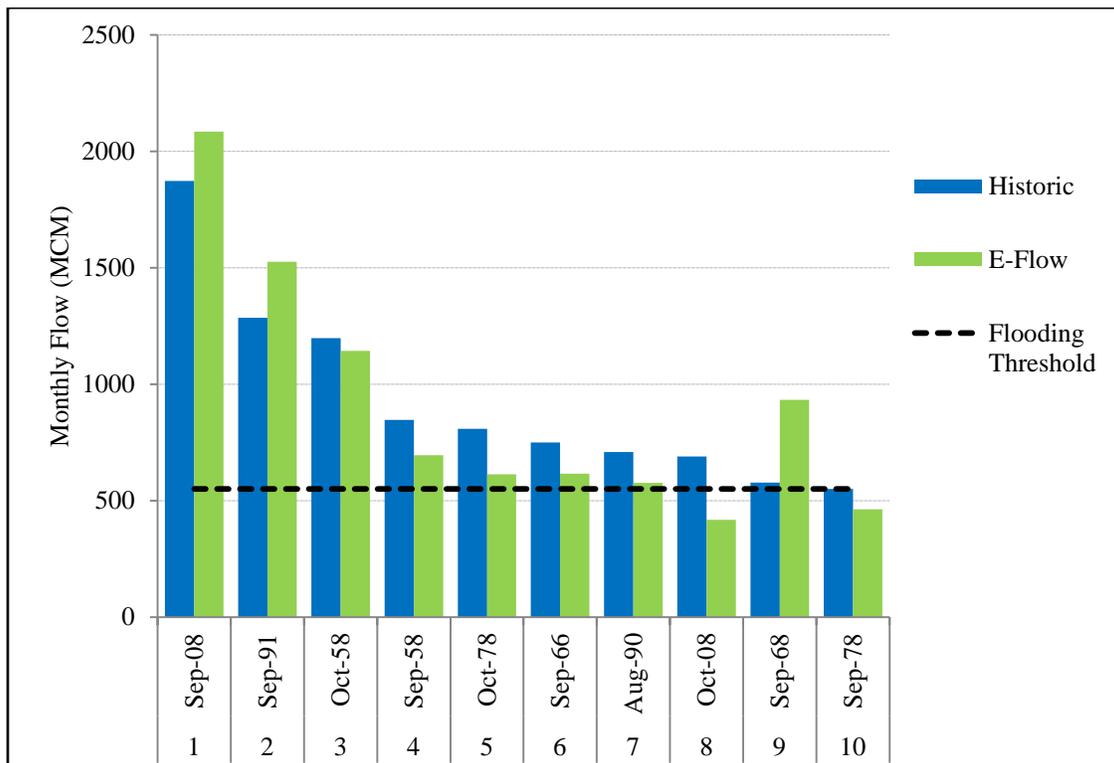


Figure 14. Largest flooding events under Baseline and E-Flow policies

September is one of the most at-risk months for flooding under both policies; 6 out of 10 of the largest flooding events occurred in September in Figure 14. The flood of September 1968 in particular stands out as an event that was significantly worsened under the proposed policy. This may be due to an increased fall flood risk under the E-Flow policy. Figure 15 illustrates the shift in the median daily discharge at Presidio for each month from a gradual peak in September under Baseline operations to a steeper, larger peak in July under the E-Flow policy. This shift

represents an increase in flood risk in August - October (shaded region in Figure 15) as the Top of Conservation reservoir storage threshold is ramped up earlier in the year to provide more storage space for the subsequent dry season (see rule curve in Figure 12). This may account for the increased flood severity in Sep-68 under the E-Flow policy.

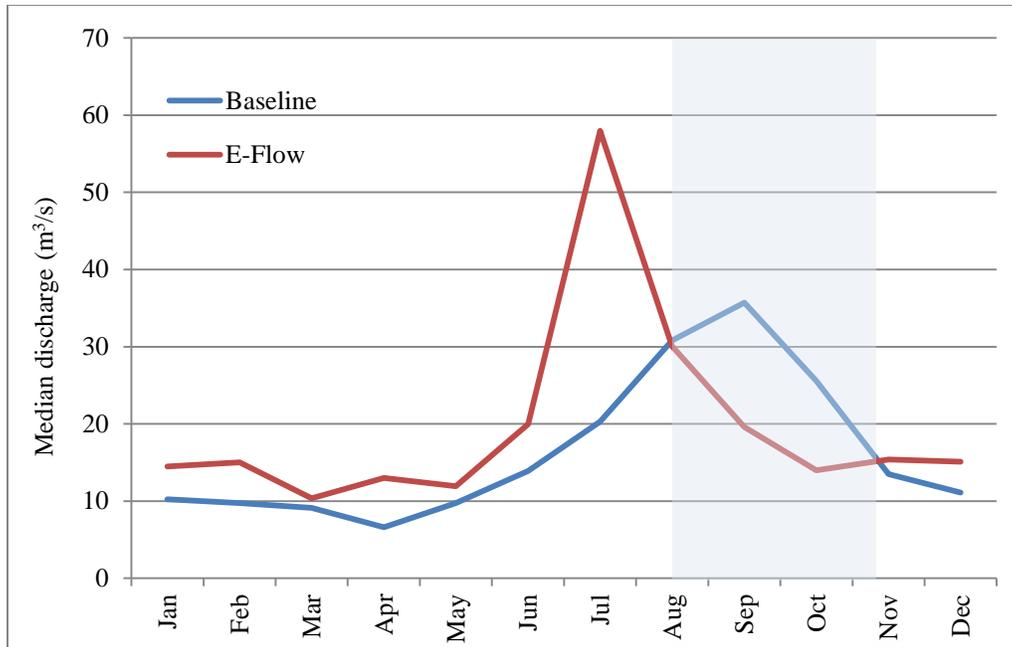


Figure 15. Median daily discharge at Presidio for each month under alternative water management policies

5.4. Environmental flow objectives

Table 10 depicts water system performance under alternative policies with respect to EF objectives. Baseline performance values indicate that reliability of environmental water supply in *time* is very low (Presidio 22%; Johnson Ranch 29%; Foster Ranch 31%) but reliability in *volume* (Presidio 81%; Johnson Ranch 80%; Foster Ranch 42%) is much higher, particular in the upper reach. This implies that the annual volume of water being released is nearly sufficient to supply environmental objectives, but is not being released in the proper timing. The E-Flow

policy, which is intended to re-allocate water among the months to increase the effectiveness of water towards maintaining environmental functions, provides an SI increase from Baseline of 54%, 54% and 22% at Presidio, Johnson Ranch, and Foster Ranch, respectively. This performance increase represents a significant improvement in environmental water management compared with Baseline, assuming EF objectives are capable of capturing key regional environmental functions.

Under the E-Flow policy, reliability (time-based and volumetric) and resilience of EF objectives were 100% and vulnerability was reduced to 0% at Presidio and Johnson Ranch (Table 10). This indicates that the proposed rule curve would fully supply monthly EF objectives at both locations throughout the period of analysis within specified constraints. At Foster Ranch, however, no policy was able to meet EF objectives at all times without negatively affecting other system constraints. Results from Foster Ranch show that the reliability (time-based and volumetric), resilience, and vulnerability of EF objectives under the E-Flow policy are 29%, 100%, 5%, and 58%, respectively, for an overall SI score of 33%. Four of the five criteria performed worse under the E-Flow policy than under Baseline, indicating poor performance of the BB water system with respect to Foster Ranch EF objectives.

Table 10. Performance of EF objectives under alternative water management policies

Performance criteria	EF evaluation site					
	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
Sustainability Index (SI) (%)	46	100	46	100	11	33

Further analysis of environmental performance at Foster Ranch

To further analyze the environmental performance of the proposed policy at Foster Ranch, simulation results were re-arranged to estimate the firm yield of EFs, or the streamflow that would be provided *at all times and all locations* under the E-Flow policy. EFs defined in this manner, while not directly incorporated into the water management explorations of this study, may be more easily understood by managers and stakeholders, since they represent the time- and climate- independent lower-bound on regional environmental water provided under the proposed policy. These minimum monthly volumes are often surpassed under the policy, and are intended only to illustrate the firm yield available for EFs.

A sensitivity analysis was performed to evaluate the response of the water system's performance with respect to Foster Ranch EF objectives. Performance was considered as a function of the percentage of July and August high flow volume (Figure 16). High flow objectives for January, February and May (Figure 9; Table 7) were not included in the analysis because they occur during the dry period when average water demands frequently outweigh supplies and the model could only meet them in select wet years, and often at the expense of other system constraints. As Figure 16 illustrates, performance decreased as the proportion of high flows required increased, as expected. A clear performance threshold occurred when 50% of Jul/Aug high flows were required by the model. Beyond this threshold, performance decreased rapidly (particularly temporal reliability and resilience), although volumetric reliability remained at 100% regardless of the percentage of high flows required at Foster Ranch.

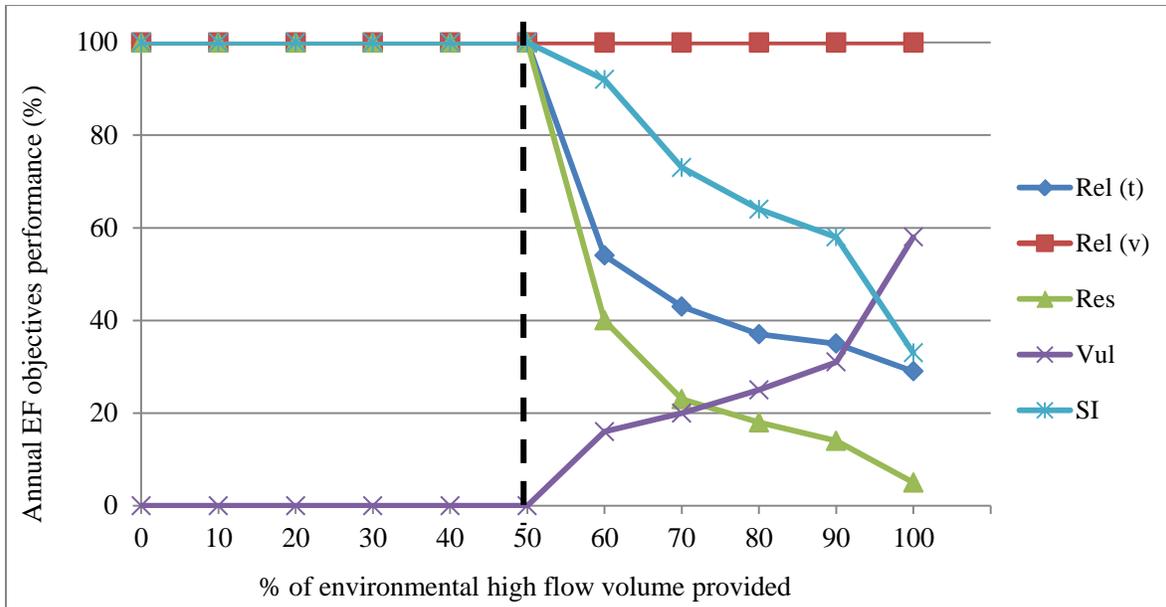


Figure 16. Performance of normal EF objectives for Foster Ranch as a function of percentage of high Jul/Aug flows required

At Foster Ranch, an adjusted normal EF hydrograph consisting of 100% of base flows and 50% of Jul/Aug high flows, for a total volume of 929 MCM/year, could be supplied with an SI of 100% under the proposed E-Flow policy (Figure 17). This volume represents 40% of the recommended annual water allocation of 2,317 MCM. This adjusted EF hydrograph represents the firm yield of instream flows that could be provided every month at Foster Ranch. The annual volumes supplied at Presidio and Johnson Ranch with 100% SI are 617 and 527 MCM/year, respectively; or 167% and 100% of the original EF objectives. The minimum EFs provided to the BB Reach in all years under the E-Flow policy are shown in Figure 17.

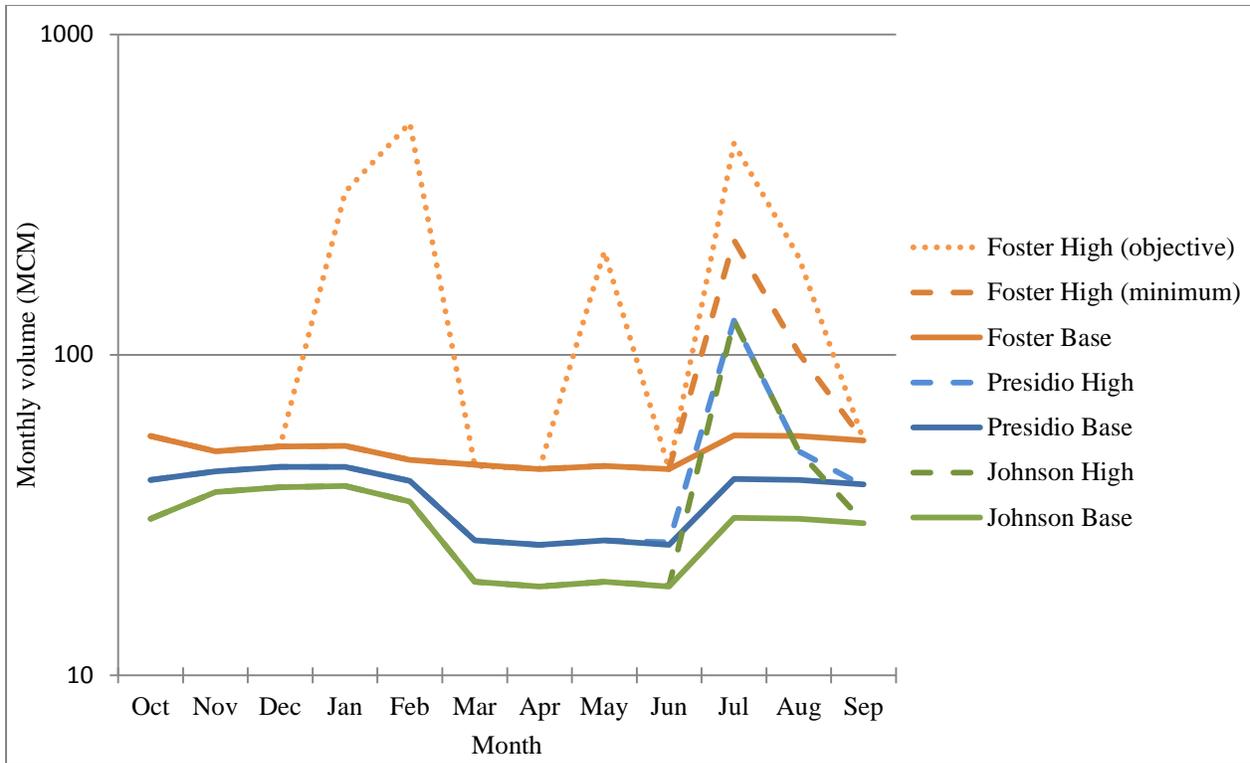


Figure 17. Firm yield EF hydrographs under E-Flow policy. Foster Ranch objective and minimum environmental high flows are shown

6. Discussion

Multi-objective management includes inherent trade-offs. In the BB water system, flood control, water supply, and environmental needs all draw resources from a single, highly water-stressed, transboundary basin. Moreover, managing water for multiple objectives requires coordination and analysis, which is complicated in the RGB Basin due to international regulations and politics, and un-transparent, real-time operational decisions. Results from this study demonstrated water management trade-offs between environmental and human objectives due to conflicting goals and timing of objectives and hydrologic uncertainty. However, total water availability and suboptimal current operations suggest significant room to improve regional water management for human and environmental objectives.

The hydrology of the BB Reach establishes a potential synergy between flood control management, which would seek to keep reservoir storage low in the monsoon season in preparation for storms, and EF management, which would seek to release water during this period for high flows and as a result to keep the reservoir storage lower than the historical average. Baseline policy simulation results show that historical LLL operations have emphasized hedging to keep more water in the reservoir in case of drought. Under alternative E-Flow policies, average flood risk in P-O valley decreased with increasing EF allocations as less water was stored in the reservoir to provide for EF objectives, 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 significantly reduce flood risk under historical streamflow inputs without impacting human water supply.

Linking EF releases with hydrologic inputs for a given year offers an opportunity to reduce water management tradeoffs. The policy proposed here addresses these trade-offs by requiring significantly diminished EFs during drought years (10% of normal base flows) to prioritize human demands. It also uses Normal and Drought storage zone thresholds to refine reservoir operations to account for uncertain hydrologic inputs. During periods of sufficient water availability, as defined by reservoir storage and inflows, environmental and human objectives are both supplied. Under the proposed policy, normal EFs are released while storage is in the Environmental Flows zone. When storage drops into the Transition zone, only human demands are supplied to conserve water while operators wait to determine if hydrologic inputs will be sufficient to return to normal operations or if drought EFs must be released to sustain at-risk ecosystems. The transitional storage zone improves system resilience; it acts as a buffer to

dampen the potential impacts of hydrologic uncertainty by making the system capable of responding to either sustained drought or a return to normal operations once the conditions are established with more certainty. When storage levels fall into the drought zone, drought EFs are released to help sustain ecosystems put at risk by the low water levels while continuing to meet human demands.

Drought EFs provided only a small percentage of the streamflow required for specified EF objectives, and extended drought periods could lead to degradation of the ecological functions considered here if drought-flow releases were continued for too long. However, just as major disturbances (i.e. floods and droughts) occurred under the natural flow regime, allowing for deviation from the coarse-scale average annual EFs proposed here during periods of insufficient water supply (i.e. allowing for natural-like extended drought conditions) may in fact be beneficial to some ecological functions not accounted for in these EF recommendations.

Policy performance with respect to environmental objectives is integral to its value for environmental water management. Under the E-Flow policy, EF objectives were met with 100% SI at Presidio and Johnson Ranch. However, Foster Ranch EFs were only supplied with 33% SI, which constitutes only a 22% increase in performance from baseline management. Further analysis estimated the EF firm yield that could be supplied in all years, consisting of a hydrograph at Foster Ranch with full base flows and 50% of Jul/Aug high flows. This hydrograph represents the minimum streamflow provision under the E-Flow policy. While the poor performance of Foster Ranch EFs indicates 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 according to the most recent BBEST report (2012).

Therefore, the proposed policy is still expected to significantly improve environmental management in the BB Reach.

The proposed policy has the potential to improve water management for human as well as environmental objectives. Results showed that, by changing the timing but not the average annual volume of reservoir releases, water allocations could provide specified environmental objectives without impacting human water supply or international treaty obligations. The E-Flow policy increased SI for major water users in both the U.S. and Mexico from as low as 0% (U.S. industrial) to 100%. The policy was also able to maintain historical average annual outflow distributions from the Rio Conchos to meet Mexico's treaty obligations to the U.S. Furthermore, regardless of operational policy, water released from LLL can be re-captured in Amistad Reservoir where it can be stored and redistributed without affecting downstream water users. These results imply that there is sufficient water volume in the system, even under drought conditions, to provide for water supply requirements with improved reliability and resilience and reduced vulnerability. Suboptimal reservoir operations under the current water management paradigm provide 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.

7. Conclusions

The methods developed in this thesis provide a framework for the integrated management of water resources for humans and the environment in a complex, human-dominated system. The study explored environmental streamflow requirements and regional water management objectives to develop an IWRM policy capable of meeting EF objectives while improving human

water supply provisions, abiding by international treaty requirements, and maintaining similar flood risk. The simulation model used in this study was calibrated to accurately represent historical river inflows, regional water demands, water storage and infrastructure, and reservoir operations. The model was then used to explore alternative IWRM policies. The water system performance under each policy was evaluated in terms of reliability, resilience, and vulnerability with which specified water management objectives could be met. Using an iterative approach, EF objectives and a proposed reservoir rule curve were simulated and manually modified. A single policy was identified capable of meeting all specified objectives while minimized alteration from spatially-distributed monthly EF objectives. The proposed policy was defined in terms of (1) annual EF hydrographs of monthly volume objectives that could be met with 100% SI and (2) a rule curve for LLL reservoir to balance water management trade-offs between flood control, water conservation storage, and EF objectives. EFs were developed for normal and drought conditions based on a probabilistic analysis of historic daily streamflow and empirical ecogeomorphic streamflow thresholds.

Sustainable water management in human-dominated systems will require a delicate, scientifically-driven balancing act between ecosystem water needs and the human demands placed on rivers. Management often has the potential to influence many of the societal functions that rivers provide, yet most projects fail to consider these in a comprehensive manner. Many major reservoirs that are currently operated for a limited set of human objectives could be re-operated to achieve environmental restoration goals while simultaneously improving services for humans (Golet *et al.*, 2006). Also, while many effects of dams are inextricable from their structure, streamflow alteration can be addressed to some extent through operational changes to

reservoirs that often do not require structural changes or large capital expenditures (Konrad et al., 2011).

By explicitly and scientifically coupling the human and environmental needs of the BB Reach, it was possible to design a water management policy with the potential to simultaneously benefit humans and improve ecogeomorphic functions. Given multiple and often competing water management objectives, both the volume and timing of water releases from a dam will likely differ from the natural flow regime. To increase the likelihood of their incorporation into reservoir operations, proposed EFs and rule curves must be explicit and scientifically-defensible. Furthermore, policies capable of meeting or improving human water management objectives are far more likely to be implemented than those that provide for the environment at the cost of human needs. For instance, environmental water policies are unlikely to be accepted or persist if they increase regional flood risk. Finally, the complexities of river basins and their water management systems promote the integration of more theoretical and empirical ecological studies with more quantitative, practical engineering solutions. These goals drove the development of an alternative BB water management policy in this study.

7.1. Limitations

This study had several limitations. First, results from all model scenarios were obtained assuming a repetition of the historical streamflow, without considering potential alternative streamflow patterns or non-stationarity of the hydrology due to climate change. A Monte Carlo synthetic streamflow simulation based on the distribution of historic inflows could yield improved, probabilistic inputs to the BB Model. However, the historical hydrologic record used in the model included extreme floods and droughts and was considered sufficient given the

monthly scale of the model. The hydrographs presented in this paper are a simplification of daily and sub-daily processes on a monthly time-step, and further refinement in timescale would be required to encompass the many ecological and geomorphic processes that act over shorter scales. Data inputs related to reservoir operations and human water demands limited the time-step of the model, so alternative data sources or probabilistic inputs would be necessary to improve temporal resolution. Third, as stated in the introduction, pilot EF releases and environmental monitoring are necessary to evaluate the true impacts of the proposed policy on humans and the environment, and adaptations to management should be made accordingly. The policy proposed here is intended to be simple enough to be by water managers and sufficiently transparent and straight-forward to be understood by all BB stakeholders. However, emphasizing simplicity may sacrifice important complexities, both managerial and scientific; the author believes that the adaptive management process is where these complexities should be addressed. Fourth, further study related to the fluvial geomorphic processes acting on the BB Reach, both historically and under current management, could provide a better understanding of the hydrologic drivers of geomorphic change and their potential environmental implications. The complexities of these processes and their interactions, as well as the scarcity of studies relating streamflow variables (magnitude, duration, timing, rate of change) to empirical ecogeomorphic thresholds or functions, are the major limitations to the development of functional EFs for the BB. The potential effects of increased sediment accumulation in Amistad Reservoir on available conservation storage also need to be addressed in further research. Fifth, flood risk results are a coarse approximation of the true performance of the system, and detailed flood analysis and modeling are needed to properly address the potential impacts (both hydrologic and economic) of reservoir re-operation on flood risk in P-O Valley. Finally, groundwater is only accounted for

in this study as streamflow gain and loss estimations between gage stations. However, particularly in the lower end of the reach and during dry periods, groundwater plays a major role in providing habitat and maintaining adequate water quality levels for native species. A better understanding of the full hydrologic system, including the interactions between surface and groundwater, would allow for a more accurate representation of regional water management. Coupling a regional groundwater model with the BB Model could provide further insight into water management opportunities and limitations.

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