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Economic effects of a reservoir re-operation policy in the Rio Grande/Bravo for integrated human and environmental water management

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ABSTRACT

Study region: The study region is the Big Bend Reach of the Rio Grande/Bravo, from Luis L. Leon reservoir in the Rio Conchos to Amistad reservoir in the Rio Grande/Bravo mainstem. This reach is part of the Rio Grande trans-boundary river basin between United States and Mexico, an area of recognized environmental and socioeconomic significance by both countries.

Study focus: A central challenge of Integrated Water Resources Management is the design and implementation of policies to allocate water to both humans and the environment in a sustainable manner. This study uses the results from a water-planning model of the Big Bend Reach of the Rio Grande/Bravo to quantify and compare the economic benefits of two water management policies: business as usual (Baseline) policy and a proposed reservoir re-operation policy to provide environmental flows (EFs).

New hydrological insights: This study determines the economic feasibility of the EF policy. Results show that a proposed Environmental Flow policy would increase irrigated agriculture profit, slightly decrease recreational activities profit, and reduce costs from flood damage and environmental restoration compared to the baseline policy. In addition to supporting ecological objectives, the proposed EF policy would increase the economic benefits of water management objectives.

1. Introduction

Balancing trade-offs between environmental and human economic objectives for reservoirs has become a major goal for Integrated Water Resources Management (IWRM) (Palmer et al., 2008; Postel and Richter, 2003; Richter and Thomas, 2007). IWRM is "a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership, 2000). Traditionally, reservoirs have supported four primary objectives: water supply (for agriculture, industries, and households), flood management, energy production, and recreation activities (Loucks

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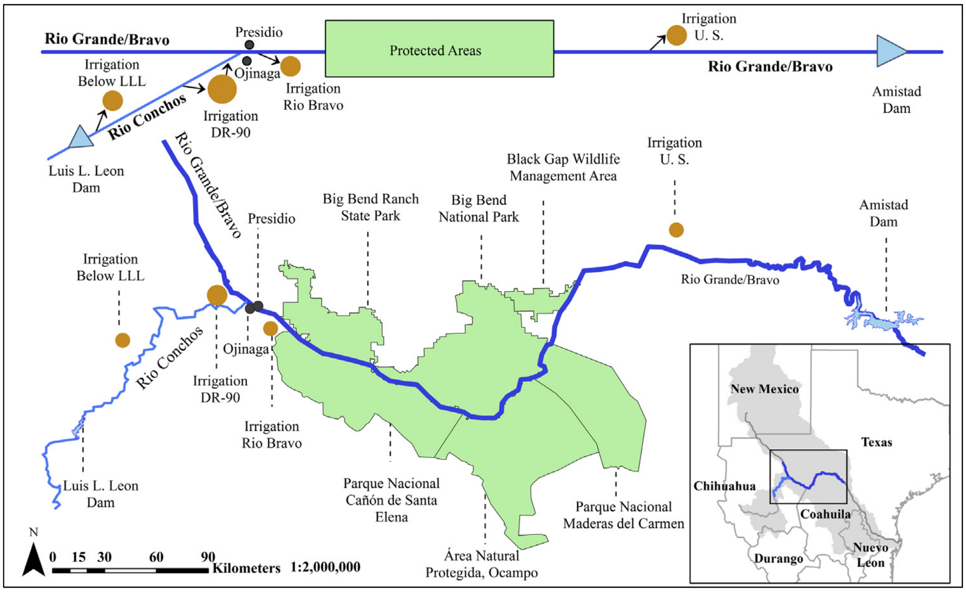

Fig. 1. Schematic of Big Bend Reach.

et al., 2005). The economic values and priorities associated with these objectives provide the basis for many reservoir operation policies. Recently, a fifth objective has emerged from the IWRM literature: water management for restoration or conservation of aquatic and riparian ecosystems. Understanding how this last objective fits within the economic framework is essential for balancing environmental and economic benefits.

There is a strong social and scientific impetus for *reservoir re-operation* (modification of a reservoir's operational method of storing and releasing water in time and volume) to balance the aforementioned objectives (Ai et al., 2013; Labadie, 2004; Lane et al., 2014; Sandoval-Solis and McKinney, 2014). Past studies have approached this problem by searching for trade-offs between reservoir environmental releases and hydropower production (Rheinheimer et al., 2016, 2013). Results from these studies show an overall reduction in hydropower gains as environmental releases increase, however, environmental and economic benefits were not quantified. For the reservoir in this study, hydropower is not an objective and therefore there are no economic losses related to energy production. The main concerns for environmental water releases in this study are instead related to irrigated agriculture and flood management.

This study is based on previous research by Lane et al. (2014). They demonstrated that, in the Big Bend Reach (BBR) of the Rio Grande/Bravo (RGB) (Fig. 1), there is sufficient water availability in time and volume to improve the health of aquatic and riparian ecosystems through reservoir re-operation (of Luis L. León reservoir). Reservoir re-operation is a commonly considered strategy for balancing human and environmental water management objectives, called *environmental flow* (*EF*) *policies*. EFs are important for maintaining the ecosystem functions and services provided by aquatic and riparian ecosystem in terms of provision of food and water supply, healthy floodplain maintenance for flood mitigation, provision of habitat, and better recreational opportunities, among others (Dyson et al., 2008; Postel and Richter, 2003). The current study expands on the previous body of research by performing a cost-benefit analysis of the current water management (baseline) policy and a proposed policy to provide EFs in the BBR.

The objective of this study is to estimate and compare the costs and benefits of key water-related economic drivers under a baseline and EFs policy. The four *key water-related economic drivers* in the BBR consist of irrigated agriculture, recreation, flood damage, and the environment. The main hypothesis is that the EF policy will provide greater economic benefits than the baseline policy in addition to supporting the BBR river ecosystem. If this assumption is true, then the EF policy is not only hydrologically feasible but also economically desirable. Such results would support a balanced water policy for what are often conflicting *water management objectives* in this basin: water supply (mostly for agriculture), flood management for Presidio-Ojinaga (P-O), and EFs for the BBR ecosystem. Specifically, this study aims to: estimate the economic value of water-related economic drivers (Table 1), integrate the economic value with the outputs of the existing BBR water allocation model, and compare the current and proposed water management policies using cost-benefit analysis (Fig. 2). This analysis builds upon the previously established hydrologic feasibility of implementing EFs in the BBR by quantifying the economic impacts of such a change in reservoir operational policy.

1.1. Big Bend Reach (BBR) of the Rio Grande/Bravo (RGB)

The RGB is a transboundary basin shared by the United States (U.S.) and Mexico. The BBR was selected for its bi-nationally recognized environmental and socioeconomic significance (Obama and Calderón-Hinojosa, 2010), its severe ecological

Table 1
Data inputs for economic analysis (Step 1 in study design, Fig. 2).

Water related economic drivers	Inputs	Source
Irrigated agriculture	• Crop values • Crop water requirements • Average water supply volumes	CONAGUA (1997–2013), TDA (2009), Lane et al. (2014)
Recreation	• River user-days • Castolon daily streamflow time-series • Johnson Ranch monthly streamflow time-series • Prices of commercial rafting trip	NPS (2014), USGS (2015), Desert Sports (2015), Far Flung Outdoor Center (2015)
Flood management	• Monthly flow volumes for each flood event • Capital cost of local flood management project • Historic peak daily discharge values • Historic streamflow time-series (1955–2009): ○ *Below Ojinaga* daily • *Below Ojinaga* monthly	Lane et al. (2014) IBWC (1971)
Environment	• Silvery minnow reintroduction costs • Land area of tamarisk coverage • Tamarisk removal costs	USFWS (2010), Zavaleta (2000)

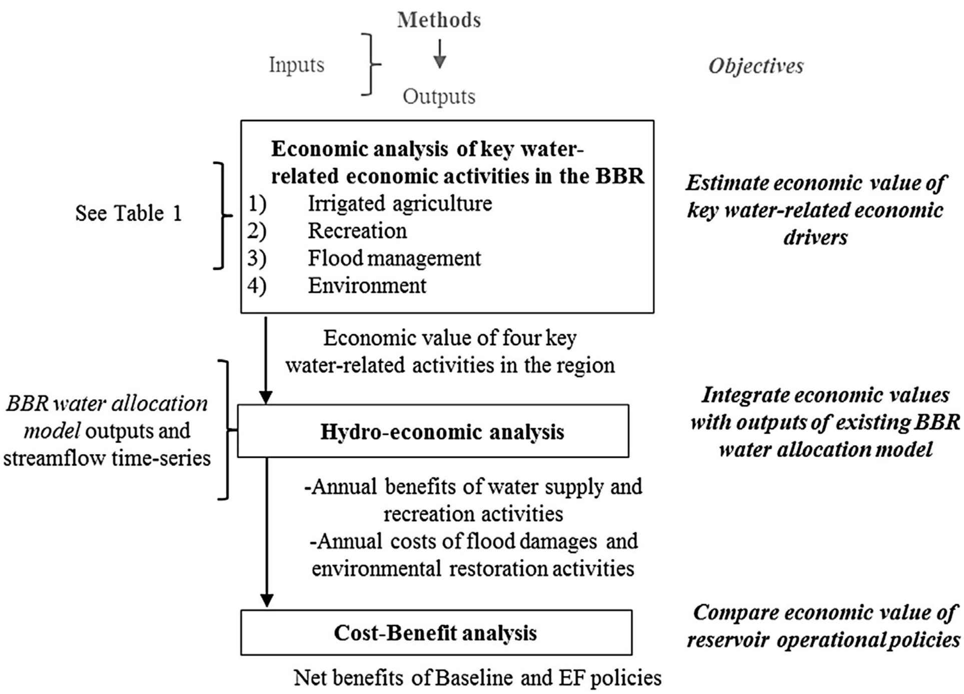

Fig. 2. Research objectives and study design.

degradation due to hydrologic and geomorphic alterations (Bestgen and Platania, 2012; Dean and Schmidt, 2011; Everitt, 1998; Sandoval-Solis et al., 2010; Schmidt et al., 2003), and the established hydrologic feasibility of providing EFs (Lane et al., 2014; Sandoval-Solis and McKinney, 2014). An existing water allocation model (Sandoval-Solis and McKinney, 2014) and proposed EF policy (Lane et al., 2014) make the BBR a suitable setting for performing a cost-benefit analysis of alternative reservoir operational policies.

The BBR refers to the stretch of river from Luis L. León (LLL) dam on the Rio Conchos in Mexico to Amistad Dam along the RGB mainstem (Fig. 1). The BBR encompasses four key water-related economic drivers. First, irrigated agriculture, which includes one agricultural area in the U.S. (a group of individual water rights called Irrigation U.S. in this study) and three in Mexico [Irrigation District 90 (DR-090), Irrigation below LLL, and Irrigation Rio Grande]. Second, recreation, primarily including river-related recreation activities along the RGB mainstem. Third, flood management, considering the protection of Presidio and Ojinaga cities from floods. The last driver is the environment, including conservation activities for the endangered silvery minnow fish (*Hybognathus amarus*) and the control and removal of invasive vegetation species, in particular, salt cedar (tamarisk, *Tamarix* spp.) and giant reed (giant cane, *Arundo donax*).

1.2. Regional water allocation model

The BBR water allocation model was developed using the Water Evaluation and Planning (WEAP) platform (Yates et al., 2005), a one-dimension water routing model governed by the continuity equation. The model calculates a monthly mass balance over a 55-year period of record (Oct. 1955–Sep. 2009) of inflows, outflows, changes in reservoir storage, water demands, and returns flows. A water distribution algorithm defines the water allocation for agricultural and urban purposes in the U.S. (TCEQ, 2006) and Mexico (CONAGUA, 2014). It considers the water division agreement established by the Treaty of 1944 by both countries (IBWC, 1944). The reader can refer to Sandoval-Solis and McKinney (2014) and Lane et al. (2014) for a comprehensive description of this model.

1.3. Baseline policy

The baseline policy considers the current upper RGB water allocation system within the U.S. (TCEQ, 2006) and the current water allocation system in Mexico (CONAGUA, 2014). The baseline also includes the Treaty of 1944 between both countries, the historical hydrology (including flood events), and the existing level of development (urban and agricultural) and infrastructure. Increased water demands beyond 2004 are not considered because the basin has been declared over-allocated (CONAGUA, 2013). LLL reservoir has three storage zones: Inactive, Conservation, and Flood Control. The inactive storage is 50 million cubic meters [mcm], the top of conservation varies each month, and the total storage of the reservoir is 832 mcm.

1.4. Proposed environmental flows (EFs) policy

EFs are flow regimes intended to support river ecosystems while maintaining human water management objectives (Dyson et al., 2008; Poff et al., 1997), which in this study includes water supply, flood management, and international treaty obligations. Despite scientific recognition of streamflow regulation as a major driver of river ecosystem degradation in the BBR (Dean and Schmidt, 2013; Everitt, 1998; Sandoval-Solis et al., 2010), no environmental water management policy has yet been implemented for the reach. Lane et al. (2014) proposed an *EF policy for LLL reservoir* that attempts to balance trade-offs between *EF targets* and human water management objectives (HWMO). These EF targets follow Hydrology-based (statistically derived) and Holistic (identifying ecologically significant components) methods as explained by Tharme (2003). The *EF targets* were estimated for three sites along the BBR (RGB below Ojinaga, Johnson Ranch, Foster Ranch) based on an analysis of historical daily streamflow data following the generally accepted concept that native aquatic and riparian species are adapted to the natural magnitude and variability of the unimpaired flow regime (Poff et al., 1997). These EF targets were then refined based on expert-defined empirical streamflow thresholds for the maintenance of key ecological and geomorphic functions within the region (e.g. limit channel narrowing, silvery minnow habitat maintenance) (CEC, 2014).

The *EF policy* defined five reservoir storages zones for LLL reservoir and water release policies for each zone: (1) an inactive zone (*Dead Storage* = 50 mcm) that no water can be released from, (2) a drought zone (*Drought Storage* = 215 mcm), in which releases are made to meet HWMO and drought EF targets, (3) a transition zone (*Normal Storage* = 275 mcm), in which releases are only made for HWMO until hydroclimatic conditions become more certain, (4) an EF zone (*Top of Conservation* = 650 mcm from October to May, 500 mcm in June, 550 mcm in July and August, and 600 mcm in September) in which releases support HWMO and normal EF targets; and (5) a flood management zone, which is kept empty when possible for flood management (Fig. 3a) (Lane et al., 2014).

For the EF policy, the rules for LLL releases ($Release_t^{LLL}$) for HWMO ($HWMO_t$) and Environmental Flows during normal ($Eflows_t^{Normal}$) and drought conditions ($Eflows_t^{Drought}$) are presented in Eq. (1). These releases depend on two factors, the initial monthly storage at LLL (S_t^{LLL}), and the inflows to LLL in the previous wet season ($I_{Season-1}^{Wet}$) and dry season ($I_{Season-1}^{Dry}$) from July to October and from November to June, respectively.

$$Release_t^{LLL} = \begin{cases} HWMO_t + Eflows_t^{Normal} & if\ S_{Flood} > S_t^{LLL} > S_{Normal} \quad For\ t = 1, \ldots, 12 \\ HWMO_t & if\ S_{Normal} > S_t^{LLL} > S_{Drought} \quad For\ t = 1, \ldots, 12 \\ HWMO_t + Eflows_t^{Drought} & if\ S_{Drought} > S_t^{LLL} > S_{Dead} \quad For\ t = 1, \ldots, 12 \\ HWMO_t + Eflows_t^{Drought} & if\ I_{Season-1}^{Wet} < 250 \quad For\ t = 7, \ldots, 10 \\ HWMO_t + Eflows_t^{Drought} & if\ I_{Season-1}^{Dry} < 200 \quad For\ t = 11, 12, 1, \ldots, 6 \\ 0 & if\ S_t^{LLL} < S_{Dead} \quad For\ t = 1, \ldots, 12 \end{cases} \tag{1}$$

The EFs policy would better manage the timing of release to match with agricultural demands, create a storage cap to reduce flood risk, and increase releases to support aquatic and riparian ecosystems (Fig. 3b). Lane et al. (2014) used the BBR water allocation model to (*i*) define water volume thresholds for the five reservoir storages zones, (*ii*) calculate the average

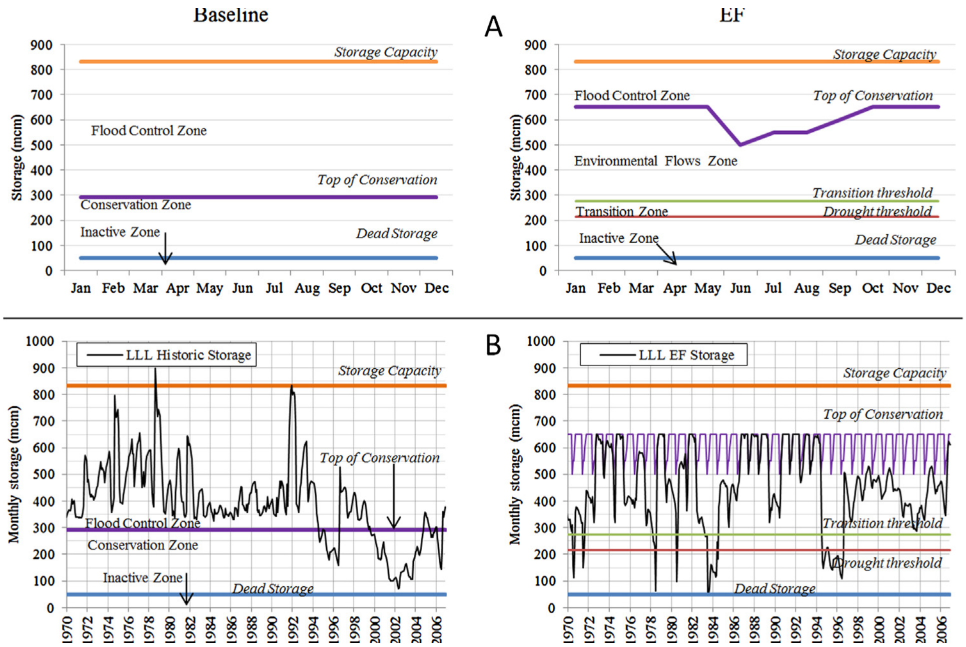

Fig. 3. A) Baseline and EF reservoir operation policies and storages zones; B) LLL Storage for the Baseline and EF policy.

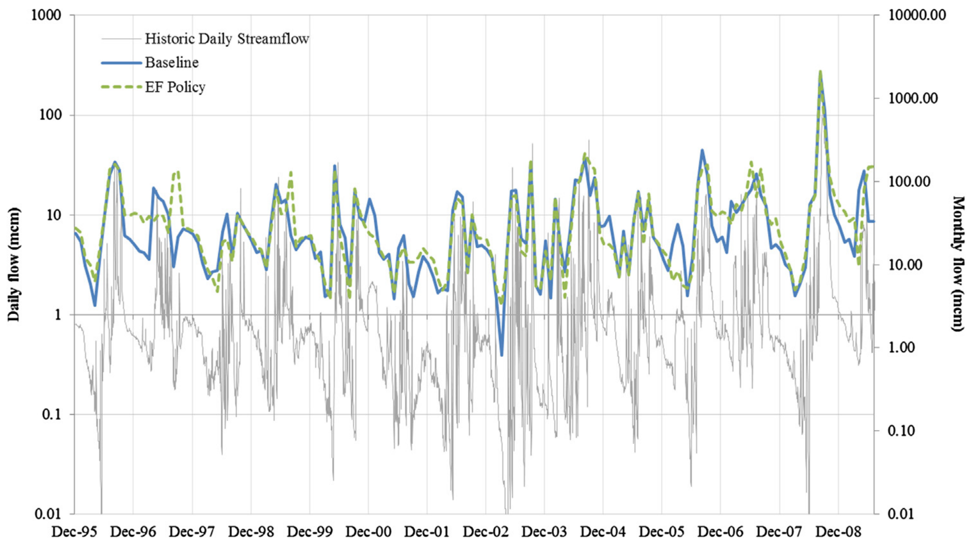

Fig. 4. Historic daily streamflow and monthly volumes outputs from the model.

water supply provided to meet agricultural, urban, and EF targets, and (*iii*) estimate monthly streamflow volumes during major historic flood events under the baseline and EF policies. The volumes calculated in *ii* and *iii* are used here as inputs for the economic analysis of water supply and flood damages, respectively. The present study provides a comprehensive economic evaluation of four key water-related economic drivers in the BBR: irrigated agriculture, recreation, flood damages, and the environment. In the following sections, we outline these key water-related economic drivers linked to the operation of LLL reservoir and estimate their economic value under baseline and EF policies. Fig. 4 shows the monthly streamflow for the Baseline and EF policy, as well as the historical daily streamflow at Johnson Ranch (Jan/1995 to Sep/2009). This figure illustrates the severity and length of droughts, it includes part of the 1992 to 2007 drought; it shows the flash flooding nature of the basin when looking at the September 2008 flood event; as well as the difference in monthly streamflow for the Baseline and EF policy. During the drought, monthly streamflows for the EF scenario are higher than baseline flows.

2. Background

2.1. Key water-related economic drivers

2.1.1. Irrigated agriculture

In the Rio Conchos sub-basin of the RGB, agriculture accounts for 93 percent of total water use, while domestic and other purposes represent only seven percent (CONAGUA, 1997a). The biggest irritated area is located in Mexico; its average sown area is about 3500 ha where the main crops are cotton, alfalfa, grasses, nut trees, and sorghum. The average gross annual income is around $4.5 million (CONAGUA, 1997–2013). The U.S. and Mexican governments have implemented projects to modernize irrigation districts (IBWC, 2002, 2003) and reduce agricultural water demand (Sandoval-Solis et al., 2011). Current water supply challenges are related to over-allocation of agricultural water rights (i.e. more water allocated than available for use), and any change to reservoir operations must consider methods for improving water supply reliability for regional irrigation districts.

2.1.2. Recreation

The economic value of recreation activities in the Big Bend National Park (BBNP) is substantial for the RGB region. Since 1990, more than 300,000 people per year (15 million since its establishment in 1944) have visited BBNP (NPS, 2015); in 2011, visitors spent over 16 million dollars (Cui et al., 2013). The park helps to support 225 jobs with $4.5 million of labor income (Cui et al., 2013). Part of this revenue is related to in-stream touristic and recreation activities. The quality and frequency of recreation activities can decrease with insufficient flows through BBR. These flow-related problems affect the economic value of river-based recreation by decreasing the rate of river use (Poulos et al., 2012; Shults, 2009). According to Kelly (2001), well maintained streams and spring flows are important to attract visitors and improve the revenue of local economies. Shults (2009) suggests that river related activities represent significant jobs and incomes for the people employed in them. The RGB corridor passes through three main canyons: Santa Elena, Boquillas, and Mariscal. These canyons draw substantial tourism for canoeing and rafting. Providing more predictable flows is expected to increase river recreation profits by allowing tourists to plan their trips further in advance (Ligare et al., 2011) (Henington, personal communication, 2013).

2.1.3. Flood damages

The P-O Valley is an extremely flood-prone region comprising 135 km^2 of urban and agricultural land; any water policy for the region must consider flood damages due to this flood risk. The occurrence of high flows and floods are mainly driven by tropical storm remnants that move large volumes of moisture from the Pacific Ocean and/or the Gulf of Mexico to the Rio Conchos watershed. At times, the Rio Conchos can supply nearly all of the total streamflow to the RGB below its confluence (Dean et al., 2011). Major historic floods have resulted from extended periods of steady rainfall associated with tropical storms and hurricanes, although high intensity localized monsoonal thunderstorms occasionally produce short-duration damaging flood peaks (Ingol-Blanco and McKinney, 2010). The Presidio Valley Flood management System provides flood protection through a levee system with a design flood of 102 m^3/s for the RGB reach upstream the confluence with the Rio Conchos and 1190 m^3/s below this confluence (IBWC, 1971). Historical daily flows have surpassed the levee capacity and caused flooding events, for instance, 1460 m^3/s in September 1978. Because the BBR water allocation model has a monthly time step, a proxy was used to identify months when daily flow surpassed the levee capacity, which corresponds to monthly flow volumes of at least 550 mcm that occurred on September 1978 at the Rio Conchos gage station (Sandoval-Solis and McKinney, 2014). This threshold is used as to identify months prone to flood events with the model.

2.1.4. Environment

Costly actions are currently being implemented in attempts to restore the native riparian ecosystem, including the reintroduction of the silvery minnow and the removal of tamarisk and giant reed (USFWS, 2010; Windell et al., 2009; Zavaleta, 2000). An EF policy is expected to reduce the need for these actions. Streamflow alterations by reservoir operations have impacted riverine ecosystem worldwide (Collier et al., 2000; Shields et al., 2000; Williams and Wolman, 1984). Reservoirs alter streamflow patterns and sediment transport by reducing peak flows and increasing low flows (Richter and Thomas, 2007), reducing the ecological benefits provided by natural flood and low flows (Poff et al., 1997). Flow regime alterations can affect aquatic and riparian species by decreasing habitat quality, facilitating invasive species, and modifying natural disturbance regimes. In the BBR, the native silvery minnow has been extirpated; even though the cause of its extirpation has not been determined, substantial geomorphic changes occurred, and key habitats of the silvery minnow were lost (Dean et al., 2011).

The silvery minnow is an endemic RGB fish species listed as endangered since 1994 that has been used as a biological indicator of aquatic ecosystem health (USFWS, 1994). Its decline is related to channel modification and streamflow alteration due to dams and diversions (USFWS, 2010). For the last 15 years, intensive efforts have been made to sustain this species in the middle RGB and reintroduce it in the BBR. In contrast, tamarisk and arundo donax are invasive riparian plants prevalent in the RGB that can reduce water availability and quality, and may out-compete native riparian species under certain hydrologic scenarios (McCormick et al., 2009). The cost of removing these species is estimated to be over $495 per hectare (Seawright et al., 2009; Windell et al., 2009), not including a complete extermination or restoration. However, research suggests that controlled high flow releases may facilitate its control (Dean et al., 2011; Postel and Richter, 2003; Richter and Thomas, 2007). The magnitudes of high flows and floods, needed to maintain the historical river channel morphology and support native species, have been reduced by nearly 50 percent, resulting in a proliferation of invasive species and significant channel narrowing (Dean and Schmidt, 2011; Far West Texas Water Planning Group, 2011).

2.1.5. Rationale: the EF policy will provide greater economic benefits than the current policy

The socioeconomic benefits of the RGB for agriculture, recreation, flood management, and fish and wildlife habitat are dependent on the river's flow regime. The effects of upstream impoundments, channelization, diversions, and irrigation have profoundly altered natural streamflow patterns, degrading ecological conditions, water quality, and potential recreation use (NPS, 1992). Some of these negative effects can potentially be reversed through reservoir re-operation for balancing human and environmental water needs (Dean et al., 2016). Lane et al. (2014); Porse et al. (2015); Sandoval-Solis and McKinney (2014) have shown the hydrologic feasibility of improving water supply reliability and maintaining current flood risk while providing EFs in the BB Richter and Thomas (2007) argued that reservoir re-operation to release more natural peak flows has the potential to reduce economic costs associated with restoration efforts. The main rationale is that given the hydrologic feasibility of an EF policy in the BBR, it is likely that this policy also augments the benefits or reduces the cost of the key water-related economic drivers.

3. Methods and results

A cost-benefit analysis is performed for the four water-related economic drivers in the region. Their individual methods and results are explained in this section.

3.1. Benefits

3.1.1. Irrigated agriculture

In Mexico, three agriculture units divert water from LLL: Irrigation District 090 (DR-090), Coyame (Irrigation below LLL), and Irrigation Unit Rio Grande. Crop value and water supply data (1997–2013) was obtained for DR-090 from irrigation district reports (CONAGUA, 1997–2013). This information was used to estimate the gross annual income per unit of water, which was then converted to a present value of 2015, considering 3.02% as the average interest rate in Mexico from 1998 to 2013 (The World Bank, 2016), resulting in a gross annual income of $113,000 per mcm. The annual gross revenue value per unit of water from DR-090 was assumed to represent the annual income of *Irrigation below LLL* and *Irrigation Rio Grande* because no specific data exists for these units, and crops and agricultural conditions are similar across irrigation units (Caballero, personal communication, 2013). In the U.S., crop values and estimates of applied water were obtained from the Texas Department of Agriculture (TDA, 2009) to estimate a gross annual income of $25,000 per mcm.

Water demands are the 2004 face value of the respective water right for each water user, i.e., this is the maximum legal amount that each user can divert from the corresponding water source declared in the water right. Average water supply is estimated as water demand minus the vulnerability (average water deficit). Vulnerability (Hashimoto et al., 1982) is a performance criterion that expresses the average deficit that a water user experiences during water supply failure throughout the period of analysis (Eq. (2)). Alternatively, average water supply can be estimated as the arithmetic mean of the annual water supply delivered to each water user over *n* years. However, using the term (1 − Vulnerability) highlights the severity of a water deficit when a failure occurs. Multiplying the gross annual income by the average water supply provides the average gross annual revenue for each irrigation unit (Eq. (3)).

$$Avg.Water\ Supply = (1 - Vulnerability) * Water\ demand = \frac{\sum_{t=1}^{t=55} Water\ supply}{n} \tag{2}$$

$$Avg.gross\ annual\ income = Avg.Water\ Supply * Gross\ Annual\ Income \tag{3}$$

Average water supply and estimated average gross annual income for each agricultural unit in the system was calculated (Table 2). The values for municipal water demands are not shown because no changes are expected and municipal demands are not vulnerable under the baseline or EF policy (vulnerability = 0%).

The historic water supply performance of the current reservoir operation policy, implemented in 1968 when LLL was built, was never evaluated to estimate its efficacy to meet the water demands. The proposed EF policy has been designed and tested to improve the water supply performance, specifically in decreasing the vulnerability for all water users within the system while proving EF (Lane et al., 2014; Sandoval-Solis and McKinney, 2014). EF policy allows allocating water when it is demanded, increasing the water supply performance for agriculture and as a result, its gross income. The economic increase is expected to bring social benefits as well. These benefits include job stability, reduction of immigration from the rural population to the cities, increase family union, food production, and an overall adequate stewardship of natural resources.

3.1.2. Recreation

In this study, the economic value of recreation is based on: (a) the price of commercial rafting, canoeing, or other in-river activities, (b) trip costs, such as fuel, food, and lodging, and (c) the annual number of river user-days (one person using the

Table 2
Estimated regional gross income from agriculture.

	Water demand (mcm)	Baseline			EF		
		Vulnerability (%)	Avg. Ag.Water Supply (mcm)	Avg. Gross Annual Income ($M)	Vulnerability (%)	Avg. Ag.Water Supply (mcm)	Avg. Gross Annual Income ($M)
Irr. DR-090	63.64	35.5	41.05	4.63	0.0	63.64	7.18
Irr. below LLL	30.00	68.4	9.47	1.07	0.0	30.00	3.39
Irr. Rio Grande	17.69	68.4	5.58	0.63	0.0	17.69	2.00
Irrigation U.S.	43.20	66.4	14.50	0.37	0.0	43.20	1.09
Total	154.53		70.59	6.70		154.53	13.66

mcm, million cubic meters; $M, million dollars; Irr, irrigation.

Table 3
Economic profit from river recreation activities and related costs under Baseline and EF policies.

	Baseline		EF
Average annual river usage (user-days/year)	2152		2027
Rafting/Canoeing Trip-with meals- ($/day)		168	
Travel ($/day)		50	
Lodging ($/day)		75	
Total ($/day)		293	
Average annual profits ($M/year)	0.631		0.594

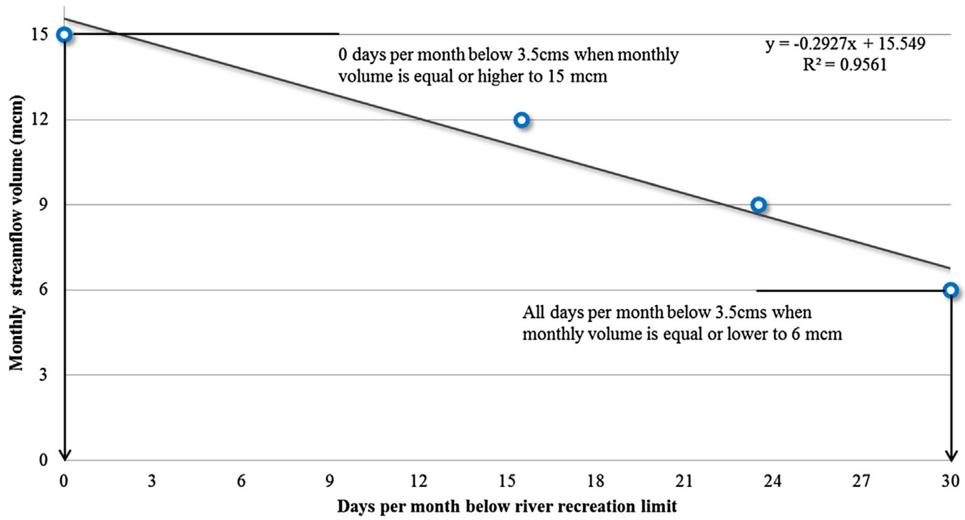

Fig. 5. Expected number of days with streamflow below raftable limit (3.5 cm) for a given monthly streamflow volume (mcm). Fig. 4 Largest flood events under baseline and EF policies (Lane et al., 2014).

river for one day) (Table 3). The economic data regarding river recreation was obtained from the National Park Service (NPS, 1996, 2014), white water rafting company webpages (Desert Sports, 2015; Far Flung Outdoor Center, 2015), and through personal communication with rafting operations (Henington, personal communication, 2013).

In this study, there is no water demand assigned for recreational purpose, instead, the number of days with streamflow above the raftable limit are calculated because this value is an input to determine the average annual number of river user-days. When flows drop below 3.5 m^3/s in Santa Elena Canyon, BBNP limits the number of commercial rafting due to the low velocity and shallow depth of the water, severely limiting or prohibiting river recreation (NPS, 1996); canoeing trips can happen at flows as low as 2.8 m^3/s (100 cfs) (NPS, 2006). An estimate of the average number of days per year when the flow is above 3.5 m^3/s under both policies is needed to estimate and compare the resulting economic benefits of recreation. For the baseline policy, the number of days per month below these thresholds is obtained from the daily mean discharge at Castolon gauge station. For the EF policy, this value was estimated because the BBR model runs on a monthly time step. Monthly streamflow volumes were calculated from mean daily discharge data for Santa Elena Canyon (Aug 2007–Dec 2014) (USGS, 2015) and related to the number of days per month below the estimated raftable limit of 3.5 m^3/s (Fig. 5). This relationship was then used to estimate the number of days per year below the limit based on monthly streamflow volume model outputs. Results show that months with cumulative streamflow volumes below 6 mcm are unlikely to provide any days above the minimum rafting threshold. The numbers of days with sufficient streamflow for rafting per month increases as the monthly

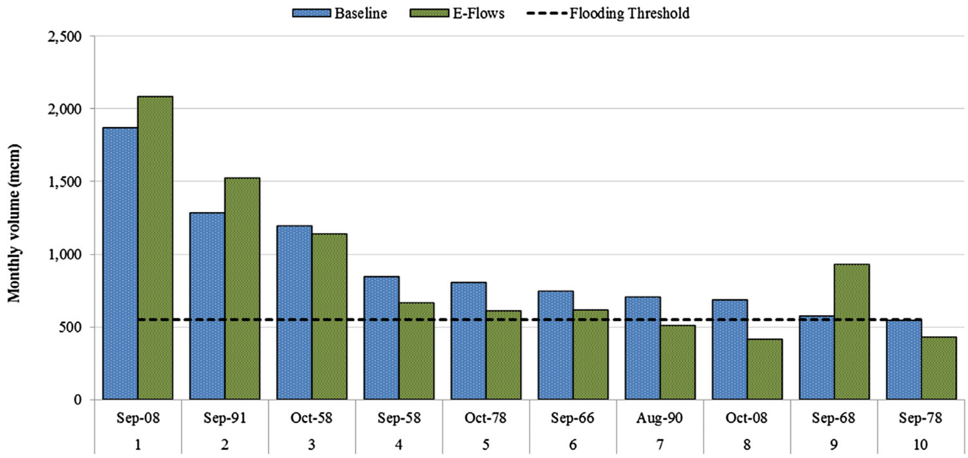

Fig. 6. Largest flood events sorted by magnitude under baseline and EF policies (Lane et al., 2014).

volume increases. In months with streamflow volumes above 15 mcm all the days are considered above the flow limit for rafting (Fig. 5).

Under the baseline and the EF policies, 28 and 47 days per year are expected to fall below the limits for river recreation, respectively. A reduction of 125 river user-days per year is predicted with the EF policy compared to baseline, representing an annual income loss of $36,625. However, the ability to advertise periods of raftable days in advance due to more predictable releases is expected to increase the number of river user-days per year, allowing the rafting industry to adjust and plan to minimize or compensate for this loss. Strategies such as concentrating user-days for certain periods of higher flows and advertising for these periods in advance could be used to minimize the loss of revenue (Henington, personal communication, 2013). If no strategies are found to counteract the economic loss from recreation, some potential social impacts are the loss of primarily related jobs (i.e. water rafting guides). In addition, less people would be exposed to aesthetics of the river, its history, and the environmental education intrinsic to in-stream recreation activities.

3.2. Costs

3.2.1. Flood damages

Although a major objective of LLL reservoir operations is flood management, there have been numerous levee-breaching floods in the P-O Valley since the dam's construction in 1968. Flood damage information was obtained from the Binational Flood Control Project for P-O valley (IBWC, 1971). The project had an initial capital cost of $13.4 million (2015 value, 4.18% interest rate) towards flood management, an estimated average annual cost over a 50-year period of $0.972 million with annual benefits of $1.32 million, for an annual benefit to cost ratio of 1.36. Economic costs related to flood damages for the baseline and EF policies were calculated from a relationship between peak discharge and economic damage. Peak discharges were calculated indirectly, using a regression equation (explained below) that relates monthly flow volumes for each flood event and historical peak flow events. Monthly flow volumes show that under the baseline policy, ten months experienced floods (Fig. 6), which represents an 18.2

percent flood risk (5.5-year return period). Conversely, only eight floods occurred under the EF policy (Fig. 6), and flood risk was reduced to 14.5 percent (6.9-year return period) (Lane et al., 2014). The average overflow volume over the period of record considered (1955–2009) was similar under both policies (929 mcm Baseline; 1023 mcm EF), indicating that, on average, the EF policy would not substantially increase the severity of flood events or the cost of flood damages.

The Binational Flood Control Project for P-O valley created correlations between peak streamflows and their economic impacts due to crop losses, land and facility damages, loss of business and gainful occupation, and profit opportunity losses (IBWC, 1971). A logarithmic relationship (Fig. 7) [$Q_t^{Peak} = 1182\ln(Q^{Month})$-7189, $R^2 = 0.799$] was developed between monthly streamflow volume (Q_t^{Month}) and peak daily discharge (Q_t^{Peak}) for that month (t). Using this relationship and the data provided by (IBWC, 1971), the economic losses due to peak flood damages were estimated for each month over the model period of record based on monthly streamflow volumes. For a 50 years period, the flood costs under the baseline and EF policies are estimated to be $58.65 and $49.10 million respectively (Table 4). These values represent annual costs of $1.17 and $0.98 million in present value (2015), respectively.

Results show a 16 percent decrease in the costs associated with flood damages over the period of record by implementing the EF policy. However, some individual flood events are increased under the EF policy (e.g. Sep-08, Table 4). Further flood risk modeling is needed at a shorter time step to determine the influence of alternative policies on flooding and to quantify with higher certainty the economic damages of flood events.

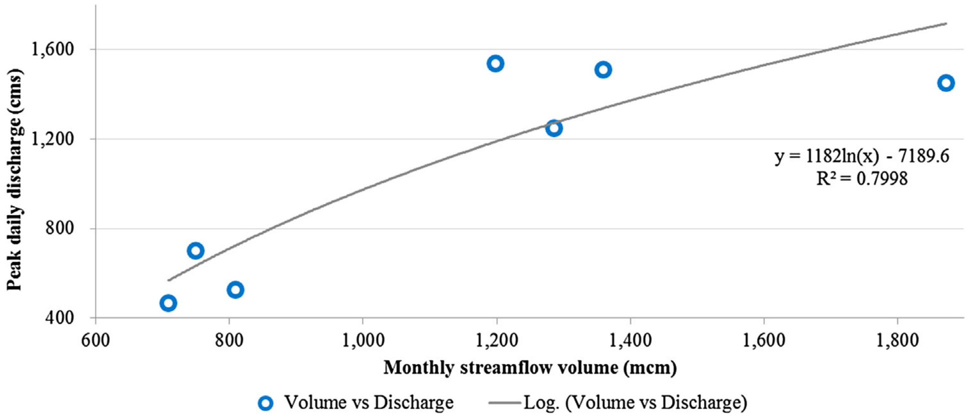

Fig. 7. Monthly volume and peak discharge correlation.

Table 4
Economic losses (1000$) for baseline (BL) and EF (EF) policies for different historic flood events.

	Sep-08		Sep-91		Oct-58		Sep-58		Oct-78	
	BL	EF	BL	EF	BL	EF	BL	EF	BL	EF
Monthly Flow (mcm)	1873	2085	1286	1526	1198	1144	847	696	809	613
Discharge (m^3/s)	1717	1844	1272	1475	1189	1135	779	547	725	397
Crop losses	1.79	1.82	1.63	1.71	1.57	1.54	1.15	0.58	1.03	0.15
Land and facility damage	7.39	7.69	5.57	6.66	5.27	4.97	2.85	1.09	2.54	0.18
Railroad damage	0.31	0.33	0.28	0.30	0.27	0.26	0.19	0.06	0.16	–
Business and gainful losses	1.85	1.91	1.51	1.73	1.42	1.36	0.85	0.36	0.70	0.09
Profit opportunity losses	2.79	2.85	2.36	2.60	2.30	2.24	1.45	0.73	1.21	0.09
Total	14.12	14.59	11.36	12.99	10.83	10.37	6.49	2.82	5.64	0.51

	Sep-66		Aug-90		Oct-08		Sep-68		Sep-78	
	BL	EF	BL	EF	BL	EF	BL	EF	BL	EF
Monthly Flow (mcm)	750	616	708	577	690	418	578	933	550	463
Discharge (m^3/s)	635	402	568	326	536	N/A	328	893	269	N/A
Crop losses	0.82	0.15	0.67	–	0.58	–	–	1.30	–	–
Land and facility damage	1.70	0.18	1.33	–	1.09	–	–	3.63	–	–
Railroad damage	0.11	–	0.08	–	0.06	–	–	0.22	–	–
Business and gainful losses	0.51	0.09	0.42	–	0.36	–	–	0.42	–	–
Profit opportunity losses	0.91	0.09	0.85	–	0.73	–	–	1.73	–	–
Total	4.05	0.51	3.35	–	2.82	–	–	7.31	–	–

Social benefits associated with lowering flood risk and economic damage are the reduction of non-monetary losses (lives and injuries, memorabilia, and cultural heritage), and monetary losses (buildings, cars, crops, infrastructure). This damage reduction increases the stability of human settlements (P-O valley) and conserves economic activities (businesses, agricultural land) and public infrastructure (for transportation, water, and energy).

3.3. *Environment*

3.3.1. *Endangered Rio Grande Silvery Minnow*

This section considers the costs to support the reintroduction of the endangered native silvery minnow and quantifies the cost of the actions that could be avoided (avoided costs) under the EF policy. Economic data was obtained from the Rio Grande Silvery Minnow Recovery Plan (SMRP) (USFWS, 2010), which establishes basin-wide restoration and reintroduction actions. Only the actions related to the BBR are considered in this analysis (Table 5). Under the baseline policy, the SMRP has a proposed budget of $167.7 million for 25 years, representing an annualized value of $11.23 million in 2015. The SMRP was used to identify restoration actions that could be avoided by providing EFs. Average annual avoidable costs of river-related environmental restoration were estimated as $1.4 million, reducing annual costs for the silvery minnow reintroduction to $9.83 million. The difference between the annualized costs of restoration actions under the baseline and EF policies represents the avoided costs under the EF policy.

Table 5
Avoided Cost from silvery minnow reintroduction.

Action Description	Annualized cost (2015) $1000s
Implement habitat restoration projects throughout the middle Rio Grande and the historic range where appropriated	625.8
Design proposed instream and floodplain projects in a manner that enhances their habitat value for the Rio Grande silvery minnow	41.6
Work with Mexico to provide water delivery to the Rio Grande/Rio Bravo del Norte (Big Bend region)	4.0
Encourage flows within the Big Bend Reach that support Rio Grande silvery minnow populations	5.0
Provide for storage of water to augment stream flow in reintroduces areas	332.9
Identify how reservoir operations for water conveyance affect riverine habitat development and habitat availability	33.3
Investigate legal, institutional, and technical feasibility of implementing a program of conjunctive use of surface and groundwater in reintroduces areas.	1.7
Retrofit or change the operation of inflow gates at dams where sediment retention is detrimental to the appropriate geomorphology in reintroduced areas	116.5
Investigate the potential of habitat construction that, during periods of low flow, will provide suitable habitat for the silvery minnow in reintroduces areas	20.0
Develop a plan for reestablishment of Rio Grande silvery minnow for each reintroduction location	63.9
Monitor the reintroduced populations of Rio Grande silvery minnow	151.5
Total	1396.1 ≈ 1.4$M

Adapted from USFWS (2010).

3.3.2. Invasive riparian species

The cost to remove a unit area of tamarisk is estimated to be $11,560 per hectare (2015 value) (Zavaleta, 2000). This cost considers a comprehensive extermination and restoration of the invasive riparian species over a 20-year period of planning, eradication, revegetation, and monitoring. Giant reed removal cost has been estimated at $62,000 per hectare ($25,000 per acre) (Giessow et al., 2011). The spatial distribution of these invasive species in the BBR was estimated by the authors due to data limitations. As a conservative estimate (the BBR is heavily infested by tamarisk and giant reed) (Dean and Schmidt, 2011; Everitt, 1998) we considered the 3-m strip of land straddling the river to contain tamarisk and/or giant reed along the entire 650 kilometers (LLL to Amistad Dam), resulting in 390 ha of invasive vegetation (Sirotnak, personal communication, 2013). This estimation was also confirmed by a field campaign and aerial photo collection. The estimated area of invasive vegetation to be removed represents an average annual cost of $0.303 million.

As it is infeasible to avoid the total cost of invasive species removal under the EF policy, this study considers that the cost avoided by the EF policy is less than or equal to $0.303 million. A more detailed approach to addressing this cost is needed, such as estimating the riparian invasive species removal area after flood events of varying discharge and duration using remote sensing analysis. Also, the value of increased water availability (water not consumed by the vegetation) should be considered for future economic analysis. For New Mexico, Texas, and Great Basin region large streams with high invasive species concentrations, this value has been estimated between $3.2 to $9.1 million per year (Zavaleta, 2000). Such increase in water availability would only occur if flood disturbance were enough to eradicate nonnative vegetation and leave bare soil. Otherwise, another type of vegetation would be expected to recolonize and water savings would likely be nonexistent or negligible.

Enhancements of ecosystem health translate to social benefits by improving drinking water supplies, fish health, species conservation, river aesthetics, river related activities and therefore a reconnection of the society with the river system.

3.4. Summary of results

Net benefits were calculated for all the water-related economic drivers. Our analysis shows that three out of four water-related economic drivers considered have higher benefits under the EF policy than current LLL reservoir operations (Fig. 8): (1) irrigated agriculture, as the major economic driver of the region, doubles its benefits under the EF policy due to increased water supply reliability; (2) recreation benefits are expected to decrease slightly because the EF policy increases the frequency of low flows (normal and drought) to support a variety of ecosystem functions (Postel and Richter, 2003) that are below the threshold for rafting and canoeing; (3) some floods may be more severe, however, the EF policy reduces the average annual flood risk of flood events, reducing the expected annual flood damages by 16%; and (4) environmental costs are minimally reduced, as funds have already been allocated to support the current environmental projects.

4. Discussion

Agricultural water supply availability is the largest water-related economic component in the BBR region. It is responsible for the vast majority of water use, translating to the highest water-related economic value. Results from this economic analysis indicate that the agricultural sector could double its economic benefits under the EF policy for a net profit of $7 million.

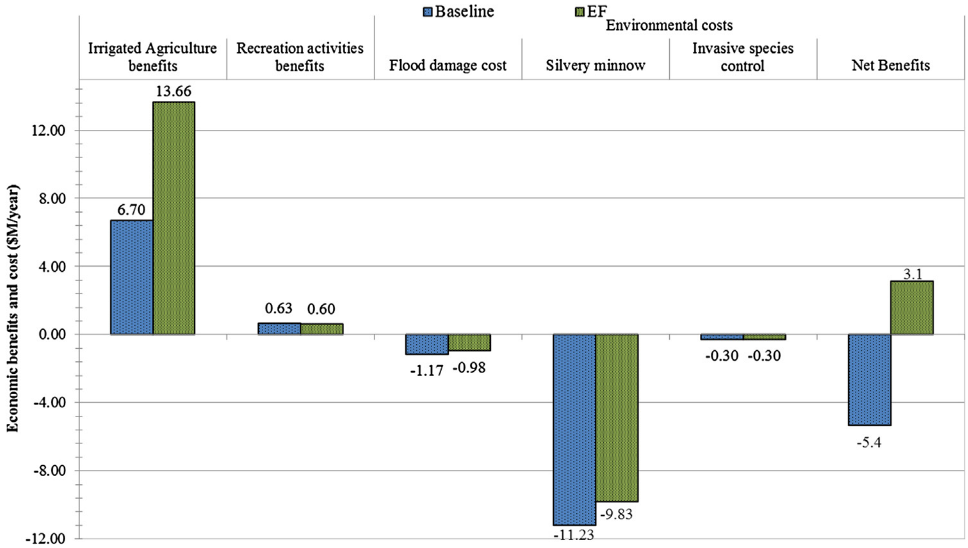

Fig. 8. Total costs and benefits of the baseline and EF policies for LLL reservoir.

The economics of recreation are challenging to quantify because river recreation rates are also heavily influenced by the regional economy. This study considers average monthly river-use rates over a period of 17 years based on the estimated minimum water level required for rafting and canoeing in the BBR. A decrease of 19 raftable days per year is estimated under the proposed EF policy, translating into an annual loss of $0.03 million. This economic loss can be interpreted as a transaction cost for improving the environment and the economic value of other water-related drivers. However, rafting company owners in the BBR indicated that, to counteract this lost income, rafting companies could better advertise their rafting season under the EF policy because it would provide more predictable high (raftable) flow periods (Henington, personal communication, 2013).

Flood risk analysis indicated an annual decrease in flood-related costs of $0.19 million under the EF policy. However, these results are based on coarse approximations of flooding risk using 1971 data. More detailed flood analysis and modeling are needed to fully address the potential economic impacts of reservoir re-operation on flooding in P-O Valley.

The avoided costs of reintroducing the silvery minnow and removing riparian invasive species under the EF policy represent a 10% decrease in environmental expenditures ($1.4 million). The cost of reintroducing the silvery minnow is almost as high as the total economic profits obtained from agriculture in the BBR under the baseline policy, emphasizing the potential economic benefits of an EF policy related directly to environmental and natural resources management. Although the analysis indicates major opportunities for environmental cost avoidance in the BBR under the EF policy, it is too late to avoid most of the current costs associated with recovering the silvery minnow, as the projects are already underway and the money allocated. These findings are consistent with Palmer et al. (2008) who suggested that proactive actions to conserve the river ecosystems would be cheaper than the late restoration efforts as might be the case of the BBR. The present example can instead act as an incentive for further research to prevent these avoidable costs in other regions. In future studies, the value of the increased water availability due to invasive riparian species removal must also be considered, as it is expected to increase the profits provided by local agriculture.

Social and environmental benefits should be able to support the transition to an EFs policy. The EF policy is expected to have positive social effects mainly focused on reducing immigration (increasing family unit), decreasing flood non-monetary losses, and increasing the number of people that reconnect with the river. For the environment, the baseflows provided by this policy would support adequate water depth and improved water quality for the entire period of analysis at Presidio and Johnson Ranch, and 29% of the time at Foster Ranch (Lane et al., 2014). High flow pulses provided by the EF policy are expected to improve sediment transport along the mainstem, decreasing the rate of channel narrowing and thus decelerating habitat degradation due to channel incision. Drought flows are recommended by this policy and are intended to provide subsistence condition for the aquatic ecosystem supported by the RGB under dry climate conditions.

Pilot releases from LLL would be needed to test the functionality of the proposed EF policy. An adaptive management framework should be implemented to provide pilot releases, monitor the effects on habitat and sediment transport, and evaluate the success on aquatic and riparian ecosystem using key indicator species, such as silvery minnow. A methodology to measure social effects should also be incorporated to evaluate the policy. This adaptive management framework should be able to adjust EF releases according to previous pilot releases, monitoring, and results analysis. This would be an iterative learning process. As a result, the economic benefits may be adjusted as the adaptive management framework is implemented.

5. Robustness and limitations

By grounding this study on results from a previous study, we are adopting its uncertainties and limitations. The proposed re-operation policy results are obtained assuming a repetition of the historic hydrology in the region. In addition, the monthly time-step of the model is not appropriate for flood management scenarios. A shorter time-step would better represent flood conditions in P-O valley to improve damages calculations. A shorter time-step would also improve the quantification of days below the raftable threshold.

Aquatic and riparian species may require more complex hydrology than that considered under the EF policy. The environmental flow policy considers only the time and volume of reservoir releases to support environmental water needs, but other factors such as sediment concentration and water quality should be incorporated to better address the effects on river ecosystems. Also, inundation plain and flow relationships, duration of floodplain innunation, water temperature, and flow recession are some of the parameters that should be addressed under an operational scenario, as they are not represented under the monthly time step and are relevant for fish spawning cues. Efforts to better address these parameters are undergoing.

The notion of transboundary basins is not fully elaborated within the paper, and should be considered within an adaptive management framework for the implementation of the policy. Both countries must agree and coordinate for implementing such an EF policy; it may require legal instruments such as minutes, like the one written for environmental flow release in the Colorado River Delta [Minute 319, IBWC (2015)].

6. Conclusions

Reservoir re-operation provides an opportunity to minimize economic and environmental trade-offs to balance water management objectives. Results from this study fail to reject the driving hypothesis that an EF policy would provide greater economic benefits than the baseline water management policy in the BBR in addition to ecological benefits. Such results indicate that reservoir re-operation for EFs is not only hydrologically feasible but also economically desirable. These findings support a balanced policy for three seemingly conflicting water management objectives: water supply, flood management, and environmental management.

Results for the EF policy show higher profits for agriculture while reducing the costs of flood management and environmental restoration. For river recreation, a decrease in profit of less than six percent is estimated under the EF policy. However, it is possible to develop actions to mitigate these losses by capitalizing on more predictable flow releases. The economic evaluations of the benefits associated with altering LLL operations provide justification for the costs of re-operation. The present study shows the hydrologic and economic feasibility of reservoir re-operation for EF in the BBR. Future work is needed to adapt the proposed framework to other RGB reaches of ecologic and economic significance, such as the Rio Conchos Basin and at the mouth of the RGB at the Laguna Madre.

In summary, managing LLL reservoir according to the proposed EF policy can meet demands for environmental objectives while maintaining human water management objectives and increasing economic profits from key water-related regional economic drivers. Therefore, the re-operation of LLL under an EF policy is economically desirable.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2016.08.004.

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