Watershed assessment framework and modeling tools for human and environmental water resources management

Case of study: Rio Grande/Bravo basin

By

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A mi papá, por enseñarme a disfrutar el trabajo, y a mi mamá, por enseñarme que no todo en la vida es trabajar

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Abstract

Thousands of reservoirs have contributed to human and economic development through stable water supply, flood control, hydropower generation and other benefits, but in many cases their social and environmental costs have become unacceptable. A central challenge of water resources management is the design and implementation of policies to sustainably allocate water to both humans and the environment. Because of this, there is a critical need to design and implement a framework to identify problems, evaluate performance, and systematically improve water resources management, and to develop quantitative tools to increase economic revenue and human welfare while protecting the hydrologic and environmental integrity of the basin. To address this need, this research first analyses current strategies and research gaps and then develops innovative tools to evaluate alternatives for optimal regional water allocation.

The framework was applied to the Rio Grande/Bravo and it systematically identified the need to quantify economic impacts of including environmental water allocation, quantify such impacts using a simulation model, and optimized regional water allocation using a novel stochastic optimization methodology. Results show that reservoir re-operation provides an opportunity to minimize economic and environmental trade-offs to balance water management objectives and that in some cases, reservoir re-operation for environmental flows is not only hydrologically feasible but also economically desirable. In addition, this research demonstrates the usefulness of using a two-stage stochastic optimization to build robust operations for multipurpose reservoirs. Robust, stochastic modeling generally performs better than non-informed decisions and could be used to address future climate change impacts (e.g. extreme floods and droughts). Overall, this research shows the feasibility of allocating water for environmental purposes while meeting current and future social and economic water use objectives.

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Introduction

Water management and ecosystem health have been at odds in basins all over the world, including some of the largest rivers: the Amazon, Nile, Yangtze, and Colorado. Human infrastructure is one of the main sources of this contention, including reservoirs which change the natural flow of the rivers (Poff et al. 1997). Thousands of reservoirs have contributed to human and economic development through stable water supply, flood control, hydropower generation and other benefits, but in many cases their social and environmental costs have remained unacceptably large (Scudder 2012; WCD 2000). Because of such impacts, there is a strong societal and scientific impetus to balance human and environmental water resources management goals. Human and environmental water resources management is a process to coordinate the development and management of water, land, and other resources among basin users, while maximizing socioeconomic welfare and protecting or restoring natural ecosystems. The motivation for this research is to answer the question: *how can water resources be allocated to provide water for the preservation and restoration of aquatic and riparian ecosystems without affecting current and future urban, agriculture, and recreational water uses, and without increasing flood risk?* The overall goal is to develop a framework capable of identifying, evaluating, and improving water resources management for current and future generations, and design tools to test such strategies. Given the complexity of the question, the framework is focused on the transboundary Rio Grande/Bravo basin (RGB), one of the largest basins in North America, and among the most water stressed international basins in the world (Giordano and Wolf 2002). The framework provides information to support decisions and improve regulations related to water in the RGB.

To develop this framework, this dissertation is divided into three chapters that systematically address questions within the scope of the main research goal. In the first chapter, I review and describe all available water-related information, available tools, and data gaps, which leads to the identification of unanswered research questions. Such information was compiled into a water management geodatabase for the RGB basin to provide information to stakeholder groups, governmental and non-governmental organizations, and scientific communities. The main outcome from this chapter was the realization that despite the recognition of the need to implement environmental flows (EFs), there were no attempts to quantify the economic impacts from their implementation. Therefore, in the second chapter, I focus on the Big Bend Reach of the RBG and identify and quantify the main water-related economic drivers in the region, which is an area of environmental and socioeconomic importance for both the U.S. and Mexico. Then, I use the results of a water-planning model to compare the economic effects of two water management policies: business as usual (baseline policy) and a proposed reservoir re-operation policy to provide EFs. This study determines that the proposed EF policy is economically feasible. Given such feasibility, in Chapter 3, I present a novel two-stage stochastic optimization framework that maximizes regional economic benefits from reservoir deliveries while integrating EFs. The proposed methodology integrates stochastic inflows to find a robust reservoir operation policy that improves regional water allocation while considering hydroclimatic uncertainty.

Together, my three chapters expand the global research on human and environmental water resources management, including simulation and optimization models for reservoir operations that provide EFs. This research challenges the current paradigm in which human and environmental objectives are mutually exclusive, calls for binational considerations in the management of transboundary river basins, and lays the foundation for future research focused on the integration of environmental health and economic feasibility into water resources management.

Dissertation structure

The dissertation is divided into three chapters that systematically address specific research goals. The chapters are designed to stand alone and therefore each of them contain its own abstract, introduction, methods, results, conclusion, and references. At the end of the dissertation I present an overall discussion, conclusions and outline further research needs.

1. The first chapter includes a comprehensive literature of water resources studies and tools that were developed for the RGB and a geographic characterization of such studies and tools in the basin to determine research opportunities for improving water management in the region. The hypothesis is that geographical references for water management tools and data can be used to identify information gaps and determine the research needs for developing modeling tools to improve water resources management. The main output from this chapter was the identification of the need to quantify the economic impact of implementing EFs.
2. Chapter two includes an evaluation of water-related economic drivers and quantification of net monetary benefits under different human and environmental water allocation strategies. The hypothesis is that the identification of water-related economic drivers can be used to value current and alternative water allocation strategies. This information can be used to develop innovative tools to design policies that are hydrologically feasible, economically desirable, and protective of the environment.

3. Given the hydrologic and economic feasibility of environmental flow implementation, Chapter 3 presents a stochastic optimization methodology to derive a robust water allocation policy under hydroclimatic uncertainty using the already quantified water-related economic drivers in Chapter 2. The hypothesis is that optimized robust operations outperform historical reservoir management, improving regional economic benefits and increasing environment water allocation.

This study builds upon the array of existing information for the RGB and incorporates new and updated information related to available water resources, water-related economics drivers, natural flow regimes, environmental flow objectives, optimization methods, and water resources modeling. While the area of study is a transboundary river basin, the developed framework and tools are applicable to river basins of various sizes and characteristics around the globe.

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Chapter 1 State of the art of water resources management in the Rio Grande/Bravo basin

Abstract

The RGB is a tightly constrained river system where human water demands have exceeded the natural water availability of the basin, water quality has been degraded, and aquatic and riparian ecosystem have been heavily damaged. The main objective of this project was to assess the state of the art in water resources management, policies, and planning tools for the basin. This research describes the history of water management, identified water-related dataset from different sources and merged them into a single geodatabase and develops an inventory of water management information and available models that can be used to evaluate human and environmental water management objectives. The study identifies the applicability of those models to evaluate trade-offs for meeting societal and environmental flow requirements to restore native ecosystems. The study also identifies information gaps that merit additional research and resources and describes promising future steps to integrate and improve existing systems models. Findings from this research show that there is a variety of models that can assist planning activities to implement environmental flows across the RGB but no models consider economic implications of implementing environmental flows in regions of the basin.

Key Outcomes

- Rio Grande/Bravo water management geodatabase publicly available in the ScienceBase repository of the USGS.
- Characterization of planning tools to support the evaluation of human and environmental water management in the basin.
- Results from the characterization show that no models consider economic implications of implementing environmental flows in regions of the basin.

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1.1 Introduction

The RGB is one of 263 transboundary river basins in the world (UN-Water 2008) and, as many of those, it connects cultures, ecosystems, and natural landscapes; and the societies living in these catchments have an effect on each other's water resources management and allocation approaches, aggravated from climate variability. Moreover, communities in the basin often share policies that affect water availability management, which involve regulations on land use, water allocation, water quality, flood management, and the environment. The RGB basin consists of the mainstem and tributaries across three States in the United States (U.S.) and five in Mexico.

The RGB is one of three large drainage basins in North America whose stream flow is divided between U.S. and Mexico. The RGB has two significant headwaters – the San Juan Mountains of Colorado and the Sierra Madre Occidental of Chihuahua (Figure 1-1). The downstream part of the RGB watershed has a sub-humid climate where there is greater annual rainfall that augments seasonal stream flow. As an exotic river, snowmelt from the San Juan Mountains and the precipitation-excess runoff from the Sierra Madre Occidental cross the semi-arid and arid Basin and Range before reaching the Gulf Coastal Plain. The northern branch of the RGB and the Rio Conchos join at La Junta de los Rios near Ojinaga, Chihuahua, and Presidio, Texas, to form the main stem river. 530km further downstream, the Pecos River flows into the RGB. Further downstream, the Rio Salado and the Rio San Juan contribute stream flow from the south. Total watershed area is 557,000 km^2 of which half is in the U.S. and half in Mexico; The RGB share ecosystems, communities, and water problems making it a truly bi-national river.

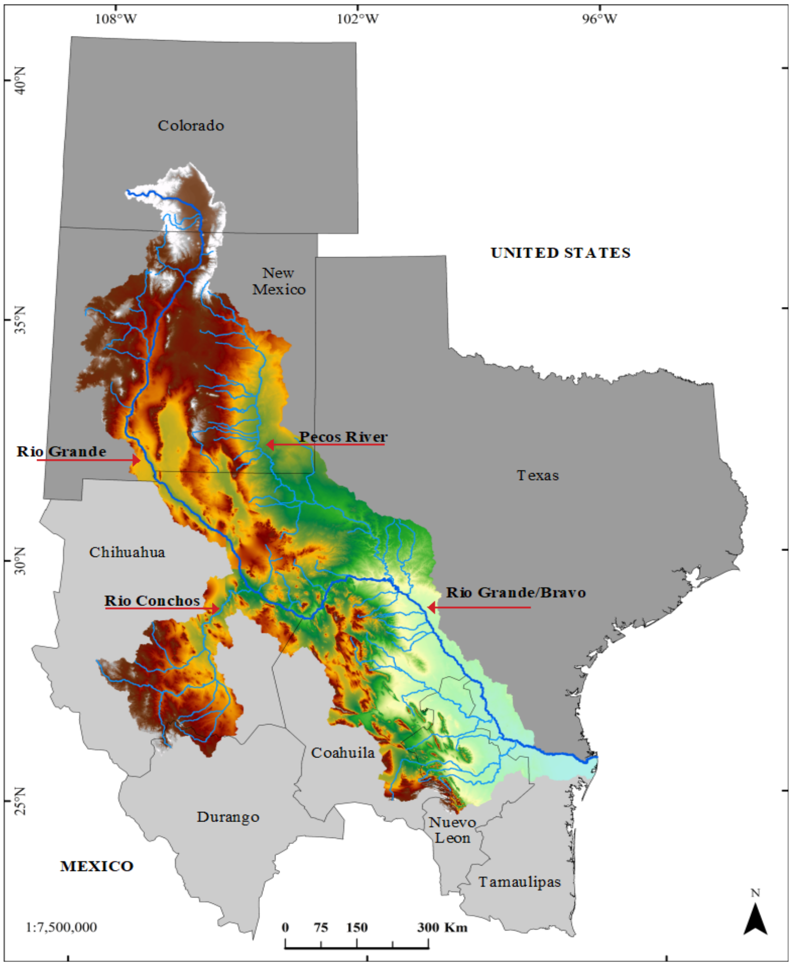


Figure 1-1 Rio Grande/Bravo Basin.

The river forms the border between the two countries for approximately 2,034 km (Patiño-Gomez et al. 2007). Bi-national allocation of the RGB is defined by the Convention for the Equitable Distribution of the Waters of the Rio Grande (IBC 1906) and the Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (IBWC 1944). Various Minutes between the U.S. and Mexican sections of the International Boundary and Water Commission (IBWC) further define water allocation and quality of those shared waters. Within the U.S., the Rio Grande Compact (1938) outlines the distribution of water among Colorado, New Mexico, and Texas along the RGB main stem, and the Pecos River Compact (1948) defines water allocation between New Mexico and Texas.

Today, the RGB is an extensively regulated and diverted river whose ecosystem reflects the long history of human manipulation (Horgan 1984). The high number of stakeholders on the basin has driven multiple efforts to better allocate water resources in the basin, avoid or prevent conflict, or try to recover some of now lost ecosystems. These efforts promoted data collection, but the binational characteristic of the basin has made it hard for some researchers to access it when it was developed in the corresponding foreign side of the basin. The obstacles to access the data are related to language, lack of interest, or it is simply hard to find and access it given the high number of data sources within each state, government organization, or country. Consequently, this data fragmentation has been echoed in some composite datasets or models developed for the basin, meaning that in many cases they only represent either the U.S. or the Mexican side of the basin (Figure 1-2). There is a need to identify and merge correspondent datasets of water-related elements in both sides of the basin into a single geodatabase to facilitate its access and use for different researchers, stakeholders' groups, and governmental and non-governmental organizations. Such an effort would help to identify data discrepancies and gaps in the basin.

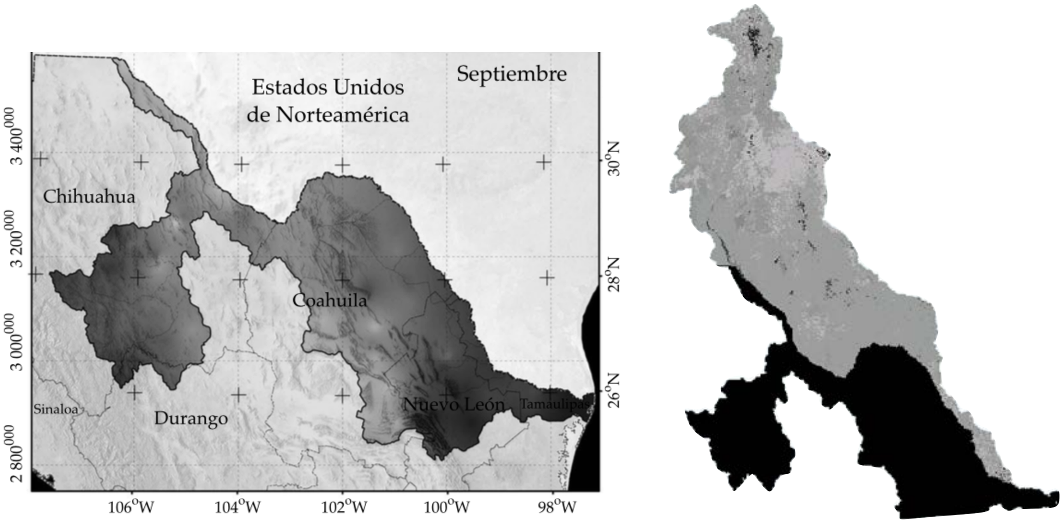


Figure 1-2. Example of composite dataset only available for one side of the border. Left: Precipitation dataset in Mexico, and Right: land use and vegetation for the U.S.

1.1.1 Modeling tools

Other important elements that would help to identify research needs are modeling tools developed to address water challenges in the basin. It is urgent to assess the state of the art in water resources management in the basin, evaluate which of the available models have potential to be used to develop or test environmental flow in different regions and the basin, and identify new areas of research related to environmental flows.

This research summarizes existing and ongoing water management modeling efforts to identify available tools and will describe model boundaries, spatial and temporal resolution, period extent, vector space (e.g., 1-dimensional, 2-dimensional…), driving equations, and model output of such tools. It also highlights models' strengths and limitations, as well as models that include environmental or ecological processes along with agricultural, municipal, and industrial water management objectives. This model inventory helps to identify those reaches that have modeling tools available as well as river segments without modeling support, where models should be developed to improve water management for human and environmental uses. Further, this research improves understanding of models with similar time steps, driving equations, assumptions, or modeled time periods. The primary goals of this chapter are to provide (1) a synthesis of historic and current water resources managements, (2) a geodatabase of water-related elements developed by different agents in the U.S. and Mexico, and (3) an inventory of existing tools that evaluate feedbacks on human and environmental water management strategies for the RGB. This chapter outlines promising next steps to meet long term goals of improved decision support tools and modeling.

1.2 Historic and current water resources management

Water consumption in Mexico along the RGB mainstream (Figure 1-3) and its tributaries (Figure 1-4) has been driven by the high annual precipitation variability of the basin (CONAGUA 2008; Sandoval-Solis 2011). Water use linearly increased due to irrigation district expansion, mostly from 1965 to 1994, and after that, a dramatic decrease in their water supply during the 90's drought (1994-2007). Water consumption before the 90's drought was much higher than the annual average consumption (1950 to 2004) of water users along the RGB and in Mexican tributaries, which are 1,576 and 2,392 million m^3, respectively.

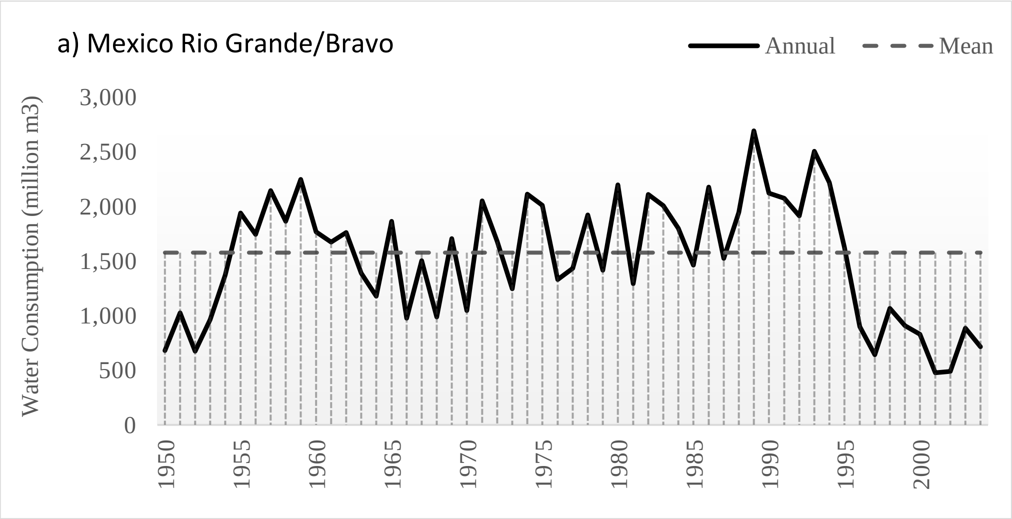


Figure 1-3. Water consumption in Mexico along the Rio Grande/Bravo and in Mexican tributaries from 1950 to 2010.

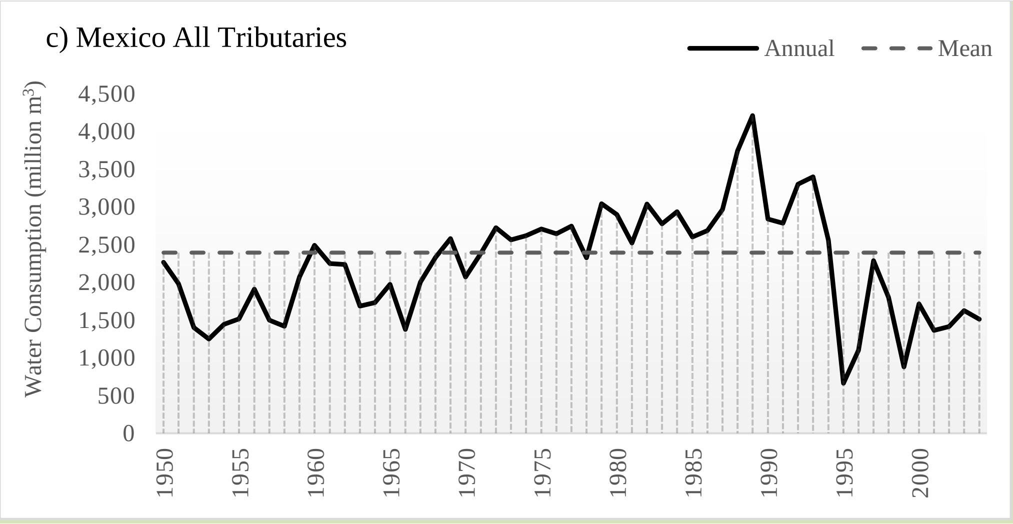


Figure 1-4. Water consumption in in Mexican tributaries to the Rio Grande/Bravo from 1950 to 2010.

In terms of historic water use, water consumption for U.S. has also been driven by the variability of annual precipitation in the basin (Sandoval-Solis 2011). Water consumption for U.S. water users has been close to the mean annual value (1,442 million m^3) except for 1989 when more than 2,000 million m^3 were consumed (Figure 1-5). The mean annual water consumption for Mexican and U.S. water users along the RGB mainstream is similar, 1,576 and 1,442 million m^3 respectively. The main difference is that U.S. water consumption does not vary as much as in Mexico.

By the early 2000s, U.S. and Mexican authorities recognized that it was physically impossible to continue providing the water consumption of the early 1990s (1990-1994); the drought of the 1990s demonstrated that water consumption in the basin prior to 1994 was unsustainable. In 2004, water rights in Mexico and the U.S. were estimated to be 4,532 and 2,129 million m^3/year, respectively (CONAGUA 2004; R. J. Brandes Company 2004). As early as 2003, authorities from both countries began discussing reducing irrigation district water rights (IBWC 2003b; R. J. Brandes Company 2004; SAGARPA 2003). Since then, several policies have been implemented to reduce water rights in the basin, such as water rights buy-backs, infrastructure improvements, and water rights reduction. By 2008, water rights in Mexico and the U.S. had been reduced to 4,401 and 1,953 million m^3/year, respectively. However, these values are still above the historic average annual water consumption for Mexico (3,968 million m^3) and the U.S. (1,442 million m^3)(Sandoval-Solis 2011), emphasizing the continuing challenge of water rights over-allocation in the RGB basin.

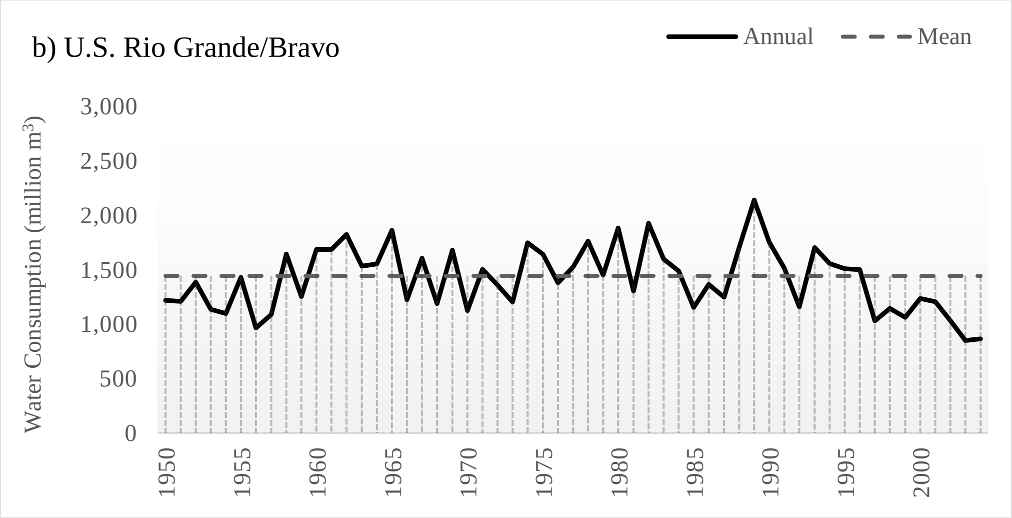


Figure 1-5. Water consumption in the U.S. along the Rio Grande/Bravo from 1950 to 2010.

1.2.1 Reservoirs

Reservoir construction in the basin increased water storage since the early 1900 in both U.S. (Figure 1-6) and Mexico (Figure 1-7). Such stream modification altered the natural flow of the river, degraded the aquatic and riparian ecosystems in the basin. There is evidence that in the Big Bend reach before the mid 1940's, the RGB mainstream preserved a wide, sandy and multi-threaded river. However, after the mid 1940's, a progressive channel narrowing has been the constant in this reach, temporally interrupted by occasional large floods that widen the channel and channel narrowing resumed again (Dean and Schmidt 2011). Narrowing has occurred by the vertical accretion of fine-grained deposit on top of sand and gravel bars. Sand and gravel bars that used to be part of the dynamic channel were progressively invaded by vegetation. The invasion of non-native species, such as salt cedar (*Tamarisk* spp.) since 1910's or giant cane (*Arundo donax)* since 1938 (Everitt 1998), has exacerbated the process of channel narrowing and vertical accretion.

The geomorphic nature of the RGB has changed from a wide, laterally unstable, multi-thread river before mid 1940s; to a stable, single-thread channel with cohesive, vertical blanks, and few active in channel bars after 1940 (Dean and Schmidt 2011). This shift in the geomorphic conditions was caused primarily by dams' construction, mostly since 1915, and it has been exacerbated by the invasion of non-native species after late 1930's.

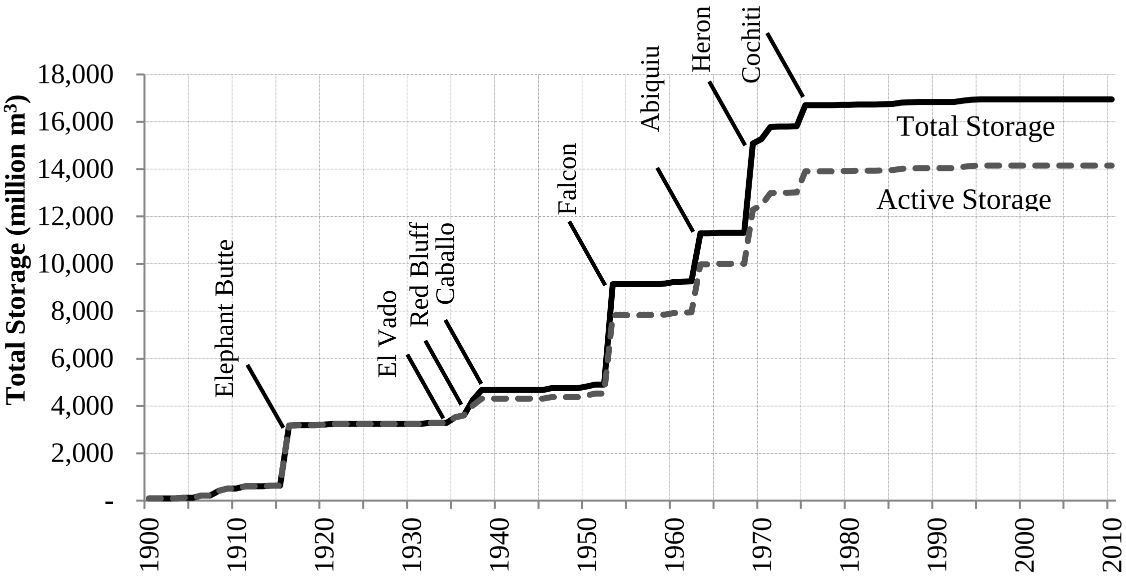


Figure 1-6 Reservoir development in the United States for the Rio Grande/Bravo.

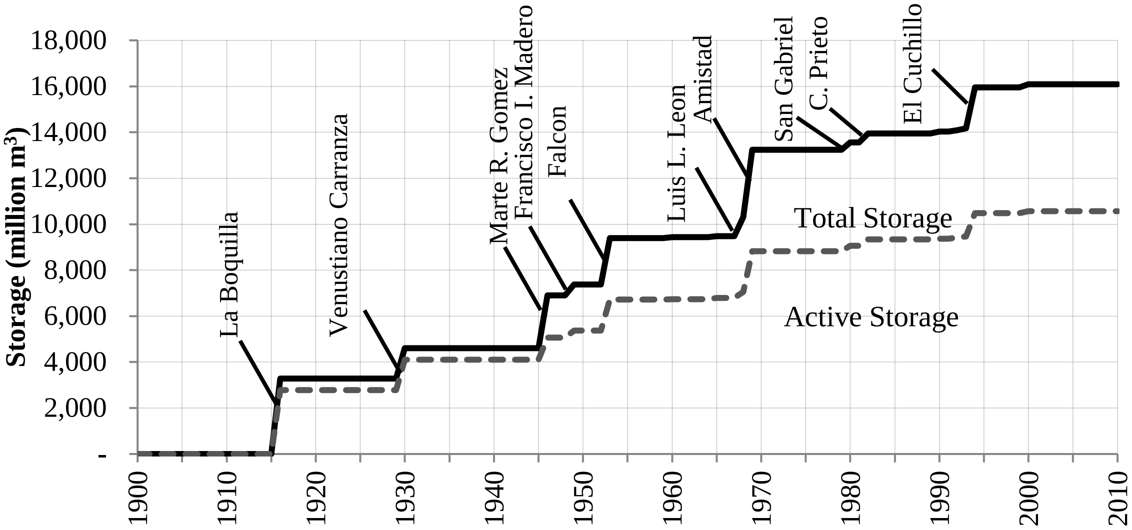


Figure 1-7 Reservoir development in the Mexico for the Rio Grande/Bravo.

Another point of environmental concern is the outlet of the river at the Gulf of Mexico. In February of 2001 the river mouth was blocked by a sand bar caused by low flow conditions due to the 90's drought, upstream diversion and invasive aquatic vegetation (Mathis et al. 2006); it remained closed until September 2001 when the IBWC dredged it open (USACE 2003). Subsequent tidal water changes again closed the mouth until November 2002, when higher tides and increased rainfall runoff partially opened it. The scarcity of flow in this reach is a threat to the estuary's sustainability; side effects include degradation of the environment, lost of species and saline intrusion in aquifers, among others.

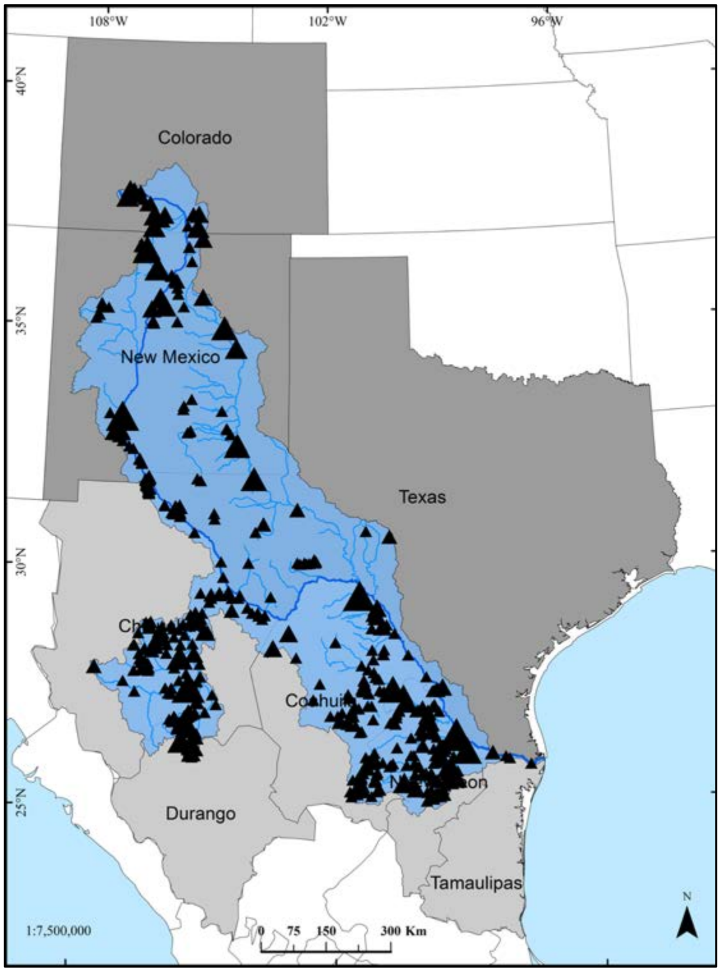


Figure 1-8. Reservoirs in the RGB basin

1.2.2 Water management in the basin

Regarding the water management in the basin, after the publication of the water availability for Mexican water users by CONAGUA (2008), the Rio Bravo basin council started a process of negotiation to define the regulation to allocate water for municipalities and irrigation districts in the basin (Arreguín 2010) these water rights account for 99% of the total Mexican water rights. To build trust among the parties, the basin council is building a water planning model to test the policies. This planning model uses the algorithms and allocation policies of the Rio Grande/Rio Bravo WEAP model built by Sandoval-Solis (2011).

Since 2001, the Texas Water Development Board create a regional water plan that evolves every five years. The purpose of the plans is to provide information to water planner regarding short and long-term water management recommendations. The last plans updates were published in 2016 (TWDB 2016) for the three water planning region groups along the Texas border with Mexico: The Far West Texas Planning Group, The Plateau Water Planning Group, and the Lower Rio Grande Valley Development Council. These documents describe water management policies that will be implemented to deal with the increase of population and energy requirement, such as: water conservation measures in municipalities and irrigation, reuse of water either from municipal or agriculture drains, groundwater development, brackish and seawater desalination, acquisition of additional water rights. Out of the previous policies, four policies account for 75% of the water savings planned: 1) increase in efficiency of on-farm water application, 2) water conservation in conveyance for irrigation, 3) acquisition of water rights through purchase and 4) brackish desalination.

Regarding treaty obligations, cycle 32 is the current treaty cycle, it started on October 25, 2016. Cycle 31 (2010-2015) ended with a debt of 263,250 acre-feet (324.7 mcm), representing 15% of the five-year total. The debt was paid on total on January 25, 2016 (IBWC 2016). Cycle 30 was closed on October 25th 2010, it lasted about one year and a half, and it was closed because of the filling of the U.S. storage capacity at both international reservoirs. Up to March 2017, the storage for the U.S. and Mexico at the international reservoirs, Amistad and Falcon are 65% and 30% of their conservation capacity respectively (IBWC 2017). The biggest reservoirs in Mexico are mostly above 90% of their conservation capacity, with the exceptions of Luis L. León (58%) in the Rio Conchos and Venustiano Carranza (58%) on the Rio Salado (IBWC 2017). In the U.S., Elephant Butte and Caballo reservoirs are at their 15% and 13% conservation capacity, respectively (IBWC 2017).

Regarding the environment, in 2006 the environmental flows for nine control points in the Conchos basin were estimated by the World Wildlife Fund; these flows are used to evaluate the environmental requirements for the basin. More recently, in 2010 Sandoval-Solis et al. (2010) proposed an annual hydrograph for environmental restoration flows at the Big Bend Reach, this hydrograph is based on the hydrologic characteristics prior 1946, when the RGB maintained a wide, sandy, multi-thread channel (Dean and Schmidt 2011). This investigation progressed when new environmental flow targets were set by a group of experts in the basin. Research on environmental flow for the BBR was updated to quantify the feasibility to provide such flows from LLL (on the Rio Conchos) without harming water users, the treaty obligations, or increasing the flooding risk at Presidio/Ojinaga (Sandoval-Solis and McKinney 2014). This research was further developed by to include flow targets at three different locations along the reach (Lane et al. 2015) and optimize the water allocation (Porse et al. 2015). Later, research on the area estimated the economic effects of implementing such a change in LLL reservoir operation policy. Results suggest that net regional benefits would increase with environmental releases and even the agricultural sector would benefit from it (Ortiz-Partida et al. 2016).

In Texas, Senate Bill 3 (2007) provides the legal framework to determine and promote environmental flows for the state. In March 2009, two Science Advisory Committee were formed one for the Upper Rio Grande from Presidio to Amistad dam; and for the Lower Rio Grande from Amistad dam to the Gulf of Mexico. These committees provided an objective perspective, evaluation, and estimation of environmental flows in the RGB stream to the Environmental Flows Advisory Group, which is integrated by members of the senate, House of Representatives and people appointed by the Governor. The groups created a report with environmental flow regime recommendations to sustain the sound ecological environment consistent with Senate Bill 3 (Lower Rio Grande Bay Expert Sciences Team 2012; Upper Rio Grande Bay Expert Science Team 2012).

Regarding water quality, in 2010 there were two main concerns downstream Falcon to the Gulf of Mexico: 1) bacteria, listed as the main concern and 2) mercury, dissolved oxygen and nutrients. The proposed work plan of the Clean River Program for 2010-2011 includes water quality data monitoring in 46 stations, data analysis and reporting, stakeholder participation and outreach. The IBWC Texas Clean River Program has conducted several monitoring campaigns along the RGB mainstream. The analysis of these data has shown problems of bacteria, high salinity, nutrients, and excessive growth of aquatic weeds, especially in the lower part of the basin (IBWC 2013).

1.3 Geodatabase of water-related elements

A collection of geographic datasets of water-related elements on the RGB was made to identify information gaps that merit additional research and resources, describe promising future steps to couple and improve existing systems models, and propose ideas to share and serve science syntheses in a digital and spatially-explicit database (Figure 1-9). Selected elements were categorized in the following topics:

a) Boundaries and populated places
b) Hydrology and climate
c) Environmental
d) Land use and cover
e) Water management

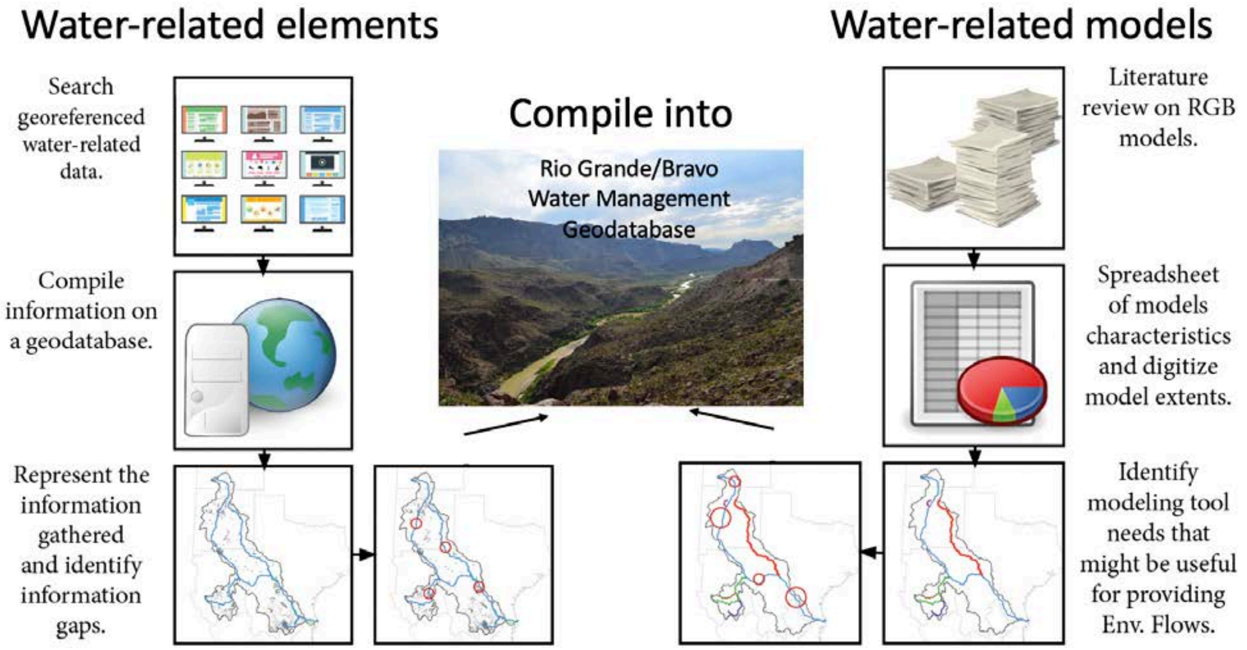


Figure 1-9. RGB geodatabase development process.

The boundary and populated places category includes information about the countries, states, counties, and cities that intersect the basin. Hydrology and climate incorporate data of the watershed, including rivers, water bodies, aquifers, monitoring points, and average precipitation, temperature, and evapotranspiration on the basin. The environmental category covers the natural protected areas, endanger species critical habitat, and national parks, among others. Land use and cover also considers agriculture information and soil types. Lastly, the water management category includes information on water infrastructure (i.e. dams) water districts, water agencies, and an inventory of all water related models that has been develop for different purposes on the RGB.

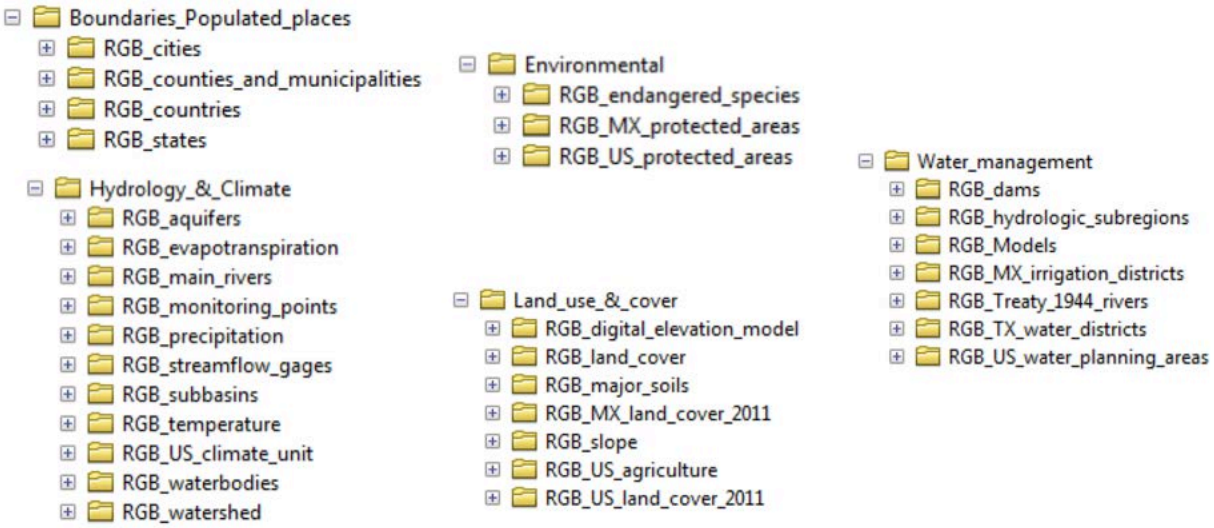
The collection of datasets was built by retrieving information from many different sources that includes state and federal agencies from U.S. and Mexico. Data coming from different agencies is frequently found with different characteristics or formats; an important part of this job was to homogenize such differences, when possible. Three of the most relevant differences are the Geographic Coordinate System (GCS), the Metadata, and the language.

A GCS defines the location of an element on the Earth by using a three-dimensional surface. The selected GCS was the GCS_North_American_1983, as it is the standard used around the world, while the chosen datum was NAD_1983_Contiguous_USA_Albers because of the extent of the RGB watershed across multiple states.

Metadata is used to describe the data; it includes information regarding its purpose, author, description, and usage limitations, among other characteristics. The Federal Geographic Data Committee (FGDC) metadata format was selected to consistently describe the datasets. When the FGDC metadata was already included in the dataset, it was not modified. When metadata was included in the dataset but in a different format, it was changed to FGDC format. There were cases when the metadata had to be created with available information on the specific dataset, in which case it is mentioned in the metadata. After geoprocessing two or more datasets, the metadata from both datasets was mixed into the new dataset to describe how it was made.

1.3.1 Results of geodatabase

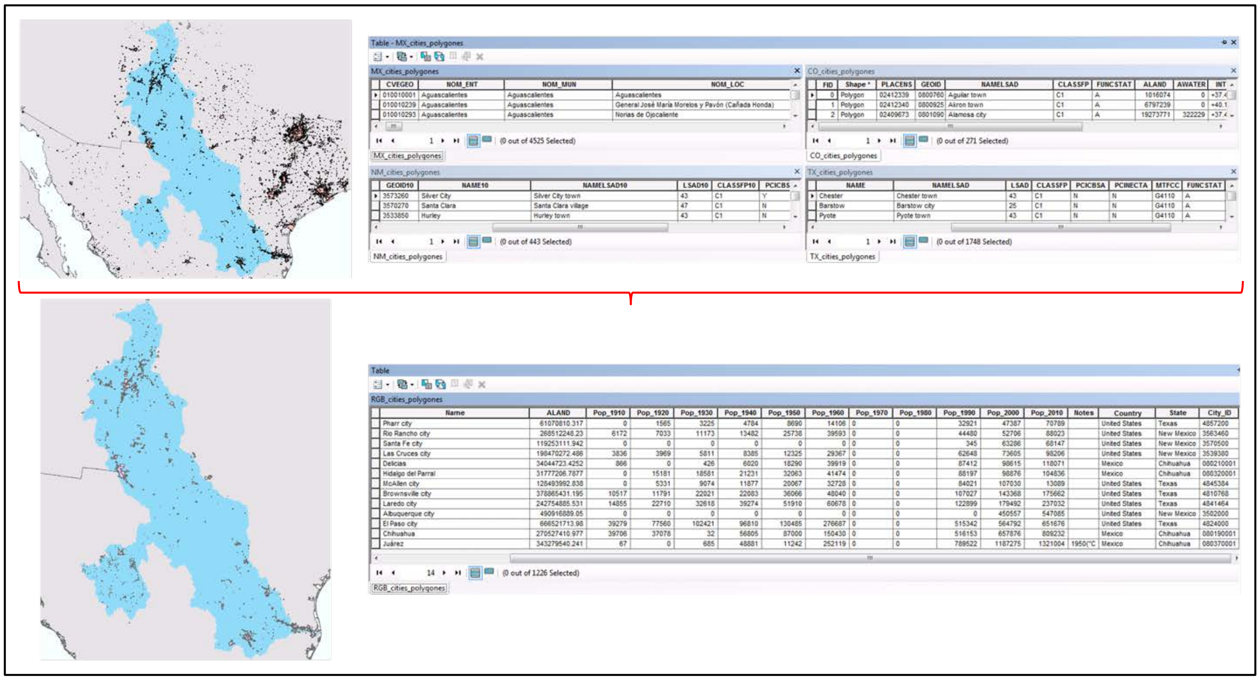
The resultant geodatabase is publicly available to download from the USGS ScienceBase-Catalog (https://www.sciencebase.gov/catalog/item/59271e5ee4b0b7ff9fb5c32c) (Figure 1-10). It contains the original files and the merges of information with specific information for the RGB. For example, the geographic boundaries of the States in the U.S. and Mexico are two different datasets. Such files are included as downloaded from the corresponding source and a new dataset was created with only the relevant States from both countries with consistent GCS and metadata.



- Boundaries_Populated_places
  - RGB_cities
  - RGB_counties_and_municipalities
  - RGB_countries
  - RGB_states
- Hydrology_&_Climate
  - RGB_aquifers
  - RGB_evapotranspiration
  - RGB_main_rivers
  - RGB_monitoring_points
  - RGB_precipitation
  - RGB_streamflow_gages
  - RGB_subbasins
  - RGB_temperature
  - RGB_US_climate_unit
  - RGB_waterbodies
  - RGB_watershed
- Environmental
  - RGB_endangered_species
  - RGB_MX_protected_areas
  - RGB_US_protected_areas
- Land_use_&_cover
  - RGB_digital_elevation_model
  - RGB_land_cover
  - RGB_major_soils
  - RGB_MX_land_cover_2011
  - RGB_slope
  - RGB_US_agriculture
  - RGB_US_land_cover_2011
- Water_management
  - RGB_dams
  - RGB_hydrologic_subregions
  - RGB_Models
  - RGB_MX_irrigation_districts
  - RGB_Treaty_1944_rivers
  - RGB_TX_water_districts
  - RGB_US_water_planning_areas

Figure 1-10. Contents and structure of geodatabase.

When possible, multiple datasets were merged into a single datafile that represent the RGB basin instead of a single state or region (Figure 1-11). The merge of information included the attribute tables and metadata. All the metadata from the Mexican data sources was changed to English. An example is the four different cities shapefiles (CO_cities_polygones, NM_cities_polygones, TX_cities_polygones, and MX_cities_polygones) that displayed the city's boundaries of the entire states or of the entire country in the case of Mexico. Also, the attribute table had different field titles for storing the name of the cities, NAMESAD in Colorado, NAME10 in New Mexico, NAME in Texas, and NOM_LOC in Mexico. Other fields in the attribute table related to the area, an identification numbers, or different classification codes had a similar problem. These differences in the dataset were compiled and fixed when doing so would not represent a substantial modification of the original information of the dataset. Additionally, fields to identify the country and the states within each country were added.



MX_cities_polygones

CVEGEO	NOM_ENT	NOM_MUN	NOM_LOC
010010001	Aguascalientes	Aguascalientes	Aguascalientes
010010239	Aguascalientes	Aguascalientes	General José María Morelos y Pavón (Cañada Honda)
010010293	Aguascalientes	Aguascalientes	Norias de Ojocaliente

(0 out of 4525 Selected)

CO_cities_polygones

FID	Shape *	PLACENS	GEOID	NAMELSAD	CLASSFP	FUNCSTAT	ALAND	AWATER	INT
0	Polygon	02412339	0800760	Aguilar town	C1	A	1016074	0	+37.4
1	Polygon	02412340	0800925	Akron town	C1	A	6797239	0	+40.1
2	Polygon	02409673	0801090	Alamosa city	C1	A	19273771	322229	+37.4

(0 out of 271 Selected)

NM_cities_polygones

GEOID10	NAME10	NAMELSAD10	LSAD10	CLASSFP10	PCICBS
3573260	Silver City	Silver City town	43	C1	Y
3570270	Santa Clara	Santa Clara village	47	C1	N
3533850	Hurley	Hurley town	43	C1	N

(0 out of 443 Selected)

TX_cities_polygones

NAME	NAMELSAD	LSAD	CLASSFP	PCICBSA	PCINECTA	MTFCC	FUNCSTAT
Chester	Chester town	43	C1	N	N	G4110	A
Barstow	Barstow city	25	C1	N	N	G4110	A
Pyote	Pyote town	43	C1	N	N	G4110	A

(0 out of 1748 Selected)

RGB_cities_polygones

Name	ALAND	Pop_1910	Pop_1920	Pop_1930	Pop_1940	Pop_1950	Pop_1960	Pop_1970	Pop_1980	Pop_1990	Pop_2000	Pop_2010	Notes	Country	State	City_ID
Pharr city	61070810.317	0	1565	3225	4784	8690	14106	0	0	32921	47387	70789		United States	Texas	4857200
Rio Rancho city	268512248.23	6172	7033	11173	13482	25738	39593	0	0	44480	52706	88023		United States	New Mexico	3563460
Santa Fe city	119253111.942	0	0	0	0	0	0	0	0	345	63286	68147		United States	New Mexico	3570500
Las Cruces city	198470272.486	3836	3969	5811	8385	12325	29367	0	0	62648	73605	98206		United States	New Mexico	3539380
Delicias	34044723.4252	866	0	426	6020	18290	39919	0	0	87412	98615	118071		Mexico	Chihuahua	080210001
Hidalgo del Parral	31777206.7877	0	15181	18581	21231	32063	41474	0	0	88197	98876	104836		Mexico	Chihuahua	080320001
McAllen city	128493992.838	0	5331	9074	11877	20067	32728	0	0	84021	107030	13089		United States	Texas	4845384
Brownsville city	378865431.195	10517	11791	22021	22083	36066	48040	0	0	107027	143368	175662		United States	Texas	4810768
Laredo city	242754885.531	14855	22710	32618	39274	51910	60678	0	0	122899	179492	237032		United States	Texas	4841464
Albuquerque city	490916889.05	0	0	0	0	0	0	0	0	0	450557	547085		United States	New Mexico	3502000
El Paso city	666521713.98	39279	77560	102421	96810	130485	276687	0	0	515342	564792	651676		United States	Texas	4824000
Chihuahua	270527410.977	39706	37078	32	56805	87000	150430	0	0	516153	657876	809232		Mexico	Chihuahua	080190001
Juárez	343279540.241	67	0	685	48881	11242	252119	0	0	789522	1187275	1321004	1950(°C	Mexico	Chihuahua	080370001

(0 out of 1226 Selected)

Figure 1-11. Example of dataset merge: four different datasets of cities boundaries and corresponding attribute tables were merged into a single dataset.

The process was performed for other datasets, including the states, counties and municipalities, water bodies, rivers, aquifers, land cover, and some climatic variables. When the data was not available for both countries the merge was performed for only one side of the border. Substantial geographic information is now available for the RGB basin and has the potential to be used on multiple projects related to demographics, restoration actions, and modeling tools among others. The datasets, a short description, the source, and the original download link for each of the original datasets are included in Appendix 5.1.

1.4 Existing tools for human and environmental water management

1.4.1 Rio Grande/Bravo model's literature review

An inventory of existing tools that evaluate feedbacks on human and environmental water management strategies for the RGB was created. Numerous models have been developed for a variety of purposes on the basin. Some of them are modifications of previous models or are simply reused for investigating different hypotheses. The models were grouped into six general categories: (1) Groundwater simulation, (2) Water allocation simulation, (3) Hydrologic simulation, (4) Hydraulic simulation, (5) Optimization, and (6) others.

A review of 60 models was performed, however this inventory prioritizes modeling tools with potential to be used for developing or testing environmental flow in different regions and the basin. Specifically, the inventory review includes the following information for every model:

- Model authors
- Year of publication
- Model type (groundwater, water allocation, hydrologic, hydraulic, optimization, others)
- Model source
- Model description
- Location on the basin and related river and streams
- Length/area
- Modeling platform (software)
- Period of analysis
- Time step
- Parameters and inputs
- Calibration and validation
- Publisher institution or journal
- Other Participant Agencies
- Limitations
- Applicability for developing environmental flows

This analysis includes a thorough review of the motivations and decision-making processes for which these tools were developed. Appendix 5.2 contain a summary of each of the models reviewed, identified by its author and in chronological order.

1.4.2 Results of RGB models' inventory

Groundwater models are located mostly in the New Mexico Middle RGB in the area known as the Española Basin (Figure 1-12). Groundwater models tend to be focused on a single basin and have a modeling time-step of one year, as decreasing the temporal scale or increasing the area requires greater computational time. Due to complexity of underground systems, some groundwater models have been updated as new data becomes available. An example is the Kernodle et al. (1995) model that was modified multiple times for almost 10 years until it became Sanford et al. (2004) model.

Water allocation models lead towards a monthly time-step often developed for planning purposes of feasibility studies. In the RGB, the extensions of these models together cover the mainstem and main tributaries except for the upper segment of the Pecos River. Similarly, water allocation models are often updated or used for different purposes. Examples are Danner et al. (2006 Revised 2008) updated by Sandoval-Solis (2011) and applied by Teasley and McKinney (2011) for calculating characteristic functions for a cooperative game analysis. Together, groundwater and water allocation models facilitate water accounting to identify available water for EF at a planning stage. However, EF requires also geomorphic, hydrologic, and hydrochemistry considerations to include floodplain and flow relationships and water quality parameters, which are relevant characteristics for individual aquatic species response. Some of those considerations are accounted in hydraulic, hydrologic, and water quality models.

Hydraulic models in the RGB have been developed for two main functions, design of flood management projects and identification of restoration areas to support aquatic species. The general limitation of these models is their extent because it is difficult to measure channel geometry at different sites along the river, and such geometry may be highly variable from one year to another.

Hydraulic models in the RGB would allow to quantify floodplain and flow relationships, but currently their extent is insufficient even if the geometry of the channel hasn't change since the model where developed. A productive application of these models for EF would include accurate river discharge inputs provided by hydrologic models.

Hydrologic models have been developed for the main tributaries to the RGB, the Pecos River and the Rio Conchos basins. Hydrologic models include climatic measurements of precipitation, temperature, and humidity at small time-steps (seconds, minutes, or hours) that, when combined with soil and land cover characteristics, permit the predictions runoff and ultimately river discharge. The same set of parameters facilitate the application of hydrologic model on climate change future alternatives. A substantial difference with the water allocation models is the extent of the model as a grid matrix instead of streams connected with nodes. In general a matrix representation allow the estimation of river flow in areas without streamflow gages, which would be relevant to test environmental flow targets along the river. However, hydrologic models have numerous data limitations that lead to simplifications of physical process and model assumptions.

Lastly, optimization models, in this context, would be useful to include the different outputs from the diverse models and approximate to optimal allocation of water among agriculture, population centers, recreational activities, and the environment, without increasing the risk of flood events. Yet, combination of different models is challenging because of differences in spatial and temporal resolutions, extent and location in the basin, type, period of analysis, and their limitations.

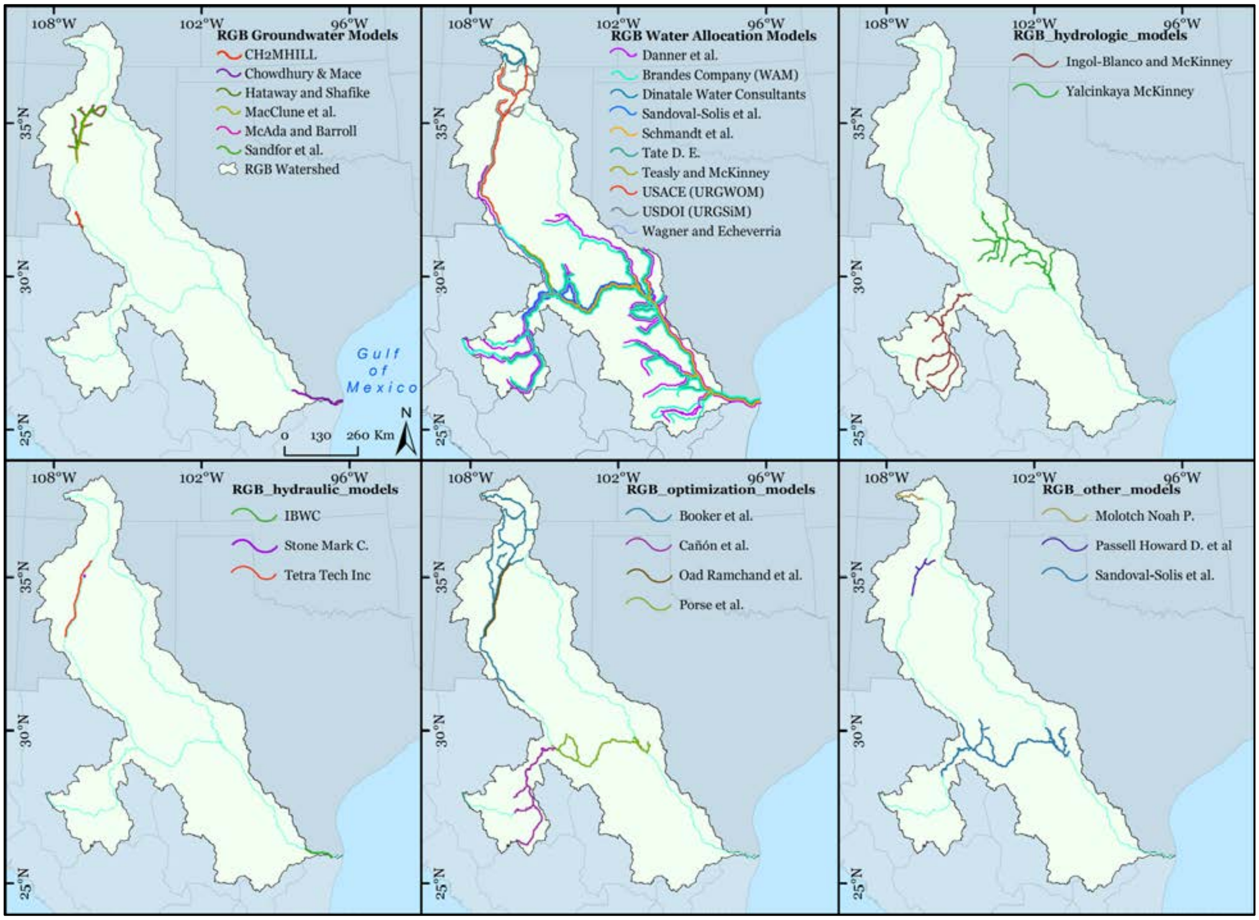


Figure 1-12. Stream segments of RGB mainstem and tributaries that relates with the models.

The following selection was made considering the suitability of model for testing either EF or drought scenarios. Models that could be suitable but were later updated are out of the selection, as well as physical models. Regarding limitations of the models, common errors and uncertainties such as the stability and accuracy of measurements are not included.

Table 1-1. Summary of groundwater simulation models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Natural recharge	Pumping demands	Historic groundwater levels	Seepage from surface water	Discharge from aquifer	Gaged river flows	Vegetation cover	Wastewater return flows	Hydraulic conductivity	Lateral water movement	Limitations
McAda and Barroll (2002)														
Middle RGB, Albuquerque Basin	MODFLOW-2000	Average annual conditions (Prior 1990) Seasonal conditions (1990-2000)	Yearly	X	X	X	X	X	X	X	X			Areas towards the limits of the model have low values of hydraulic conductivities that are highly uncertain. The model should not be used to estimate stream depletion effect of wells on these areas. Steady state conditions assume to exist prior 1900. The further from the Rio Grande, the less the match between measured and simulated groundwater level. Lack of detailed geohydrologic data in some areas. There are uncertainties in the distribution of pumping with depth for each well.
CH2MHILL (2002)														
Middle RGB, Cañutillo Wellfield	MODFLOW-96	1991-1995	Yearly	X	X	X	X	X	X		X			Regional hydraulic conductivity is adequate, but the individual hydraulic conductivity is not well represented in the model. River canal and drain network was simplified in the model, estimates of hydraulic parameter in the Rincon Valley were limited. Agriculture groundwater pumping is implicitly accounted from consumptive water use in agriculture.
Sanford et al. (2004)														
Middle RGB, Albuquerque Basin	MODFLOW & MODPATH	N/A	N/A	X	X	X	X	X	X	X	X			Steady state conditions assumed to exist prior 1900. The further from the Rio Grande, the less the match between measured and simulated groundwater level. Lack of detailed geohydrologic data in some areas. There are uncertainties in the distribution of pumping with depth for each well.
Hathaway and Shafike (2006)														
Middle RGB	MODFLOW-2000	2000-2004	Daily	X	X	X	X		X	X				Some inputs are based on a regional groundwater model that has its own limitations.
MacClune et al. (2006)														
Middle RGB, Albuquerque Basin	MODFLOW & FLO-2D	2003-2004	Weekly	X			X			X				Not was rigorously calibrated.

Zone	Platform	Period of Analysis	Time Step	Natural recharge	Pumping demands	Historic groundwater levels	Seepage from surface water	Discharge from aquifer	Gaged river flows	Vegetation cover	Wastewater return flows	Hydraulic conductivity	Lateral water movement	Limitations
Chowdhury and Mace (2007)														
Lower RGB	MODFLOW-96	1980-2000	Monthly	X	X	X								It is a steady state model. Uncertainty in pumping information projections. Areas with few data points. Rainfall estimates because there were just a little number of rain gages

Table 1-2. Summary of water allocation & reservoir operation simulation models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Historical streamflow	Historic water demands	Infrastructure characteristics	Evapotranspiration	Water rights priorities	Environmental water demand	Historic reservoir storage	Treaty/compacts obligations	Limitations
Schmandt et al. (2000)												
Lower RGB	Spreadsheet	1980-2030 for the model. Other data in the document (Historic up to 1995 with projections from 1900 to 2030)	Monthly	X	X	X	X		X	X	X	Besides the limits of accuracy of the modeling and analytical techniques, there is data limitation in streamflow and water demands. They considered the possibility of additional environmental releases but solely base on a high flood pulse.
Tate (2002)												
Lower RGB	Oasis with OCL	1992-1998	Monthly									Assumes no change to irrigation areas. It does not consider environmental issues such as water quality, endangered and invasive species, instream flow requirements or delta flows

Zone	Platform	Period of Analysis	Time Step	Historical streamflow	Historic water demands	Infrastructure characteristics	Evapotranspiration	Water rights priorities	Environmental water demand	Historic reservoir storage	Treaty/compacts obligations	Limitations
Wagner Gómez and Echeverría Vaquero (2001)												
Lower RGB	Stella Research	1940-1999	Monthly	X	X	X	X			X		It seems to be a very simple model. The document does not explain well all the components and considerations.
R. J. Brandes Company (2004)												
Basin from below New Mexico State line	WRAP (Water Rights Analysis Package)	1940-2000	Monthly	X				X				A lot of data estimations and "zero" values for unavailable data. "It has been assumed that Mexico will continue to impound all upstream inflows to its reservoirs on tributaries of the Rio Grande and that none of this water will be deliberately released for complying with the provision of the 1944 Treaty that requires an average of 350,000 acre-feet per year be delivered to the United States from six named Mexican tributaries."
Teasley and McKinney (2005)												
Lower Rio Grande	HEC-ResSim & Indicators of Hydrologic Alteration (IHA)	1925-1945 & 1984-2004	Monthly	X	X	X				X		Only one site of analysis (Fort Quitman). The model seems to overestimate the historical streamflow in the low flow periods and underestimated during high flow periods.
Danner et al. (2006 Revised 2008) and Teasley and McKinney (2011)												
Middle and lower RGB Basin	WEAP	1976-2000	Monthly	X	X	X		X		X	X	Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand.
Sandoval-Solis (2011)												
Middle and lower RGB Basin	WEAP	1940-2000	Monthly	X	X	X		X	X	X	X	Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand.
USDOI et al. (2013) Upper Rio Grande Simulation Model												
Upper RGB	RiverWare	1975-1999	Monthly	X	X	X	X			X	X	Considers empirical equations and approximations to calculate water demands, evapotranspiration, among others and there are uncertainties associated with them. Uses data from other models that has their own limitations. In general, model performance decreases proportionally to distance downstream. Considerable discrepancies between modeled and observed reservoir residual

Zone	Platform	Period of Analysis	Time Step	Historical streamflow	Historic water demands	Infrastructure characteristics	Evapotranspiration	Water rights priorities	Environmental water demand	Historic reservoir storage	Treaty/compacts obligations	Limitations
												validations. Environmental considerations just as minimum flow requirements
USACE (2014) Upper Rio Grande Water Operations Model												
Upper RGB	RiverWare	1984-2014	Daily	X	X	X		X		X	X	Considers empirical equations and approximations to calculate water demands, evapotranspiration, among others and there are uncertainties associated with them.
Sandoval-Solis and McKinney (2014) and Lane et al. (2014)												
Rio Conchos and RGB	WEAP	1955-2009	Monthly	X	X	X		X	X	X	X	Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand.
RGBRT & Dinatale Water Consultants (2015)												
Upper RGB	RiverWare	1980-2008 Baseline Prediction periods 2009-2037, 2038-2066, 2067-2095	Monthly	X	X	X		X	X	X	X	They used to alter historic hydrology to account for climate change scenarios. It's application is only for the State of Colorado

Table 1-3. Summary of hydrologic simulation models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Catchment area	Precipitation	Temperature	Humidity	Wind speed and direction	Land Use	Deep water capacity	Root zone conductivity	Deep conductivity	Infrastructure characteristics	Limitations
Yalcinkaya and McKinney (2011)														

Pecos River	WEAP	1981-2000	Monthly	X	X	X	X	X	X	X	X	X		Land use and soil data is very limited for the area and the groundwater component is very simplified.
Ingol-Blanco and McKinney (2012)														
Rio Conchos Basin	WEAP	1980-1999	Daily	X	X	X	X	X	X				X	Land use and soil data is very limited for the area and the groundwater component is very simplified.

Table 1-4. Summary of hydraulic simulation models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Channel topography	Discharge	Flood infrastructure capacity	Roughness coefficients	Limitations
IBWC (2003a)								
Lower Rio Grande	HEC-RAS	2003	Seconds	X	X	X	X	Some of the cross sections and roughness coefficients were taken from a study made 1992.
Tetra Tech Inc (2004)								
Middle Rio Grande Valley	FLO-2D	Present	Seconds	X	X		X	Grid element size, floodplain spatially variable roughness and infiltration parameters, model calibration for high flows, modeling details, sediment transport, simulation time.
Stone (2008)								
Middle Rio Grande	HEC-RAS as input and CCHE2D (Center for Computational Hydrosciences and Engineering) to evaluate	2006	N/A	X	X		X	Just 3 km of reach inside Albuquerque. Only focus on Silvery Minnow. There is no validation.

Table 1-5. Summary of optimization models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Parameters /Inputs	Limitations
Booker et al. (2005)					
Upper RGB	GAMS	2004-2009	Yearly	Streamflow gauges. Infrastructure. Water Demands. Consumptive Uses. Return Flows. Net Seepage. Institutional constraints (compacts). Minimum instream flow. Economic benefits	Optimized for total economic benefits; uncertainties exist on estimating the value from ecosystem functions.
Cañón et al. (2009)					

Rio Conchos	Not specified	1000 years Montecarlo analysis	Monthly	Maximum soil holding capacity, maximum infiltration rate, runoff coefficient, and aquifer discharge coefficient	Simplification of the reservoir operation rules. Does not consider environmental components.
Oad et al. (2009)					
Middle RGB	Decision Support System	2003-present	Daily	Priority of deliver, water demand, irrigation efficiency, infrastructure capacity, conveyance loss, irrigated area, crop type, channels layout, service areas, weather, soil type	It has uncertainties in evaporation rates from diversion channels, soils moisture depletion, and return flows.
Porse et al. (2015)					
Rio Conchos and RGB	GAMS	1955-2009	Monthly	Known inflows, diversions, and demands, treaty obligations	Considers only 5 flow regimens (1200, 1100, 1000, 800, 600).

Table 1-6. Summary of other relevant models in the RGB.

Zone	Platform	Period of Analysis	Time Step	Parameters /Inputs	Limitations
Passell et al. (2007)					
Upper RGB	Studio Expert 2001 developed by Powersim. Inc.	1989-2002	Daily	Ammonium (NH4+) concentrations, discharge, temperature, pH	It only considers a small segment along the city of Albuquerque
Molotch (2009)					
Rio Grande Headwaters	Not specified	2001-2002	Daily	Remotely sensed imagery	Simplified vegetation cover data that may affect the results. There is a limited number of high resolution imagery data.
Sandoval-Solis et al. (2010)					
Lower RGB	HEC-SSP & Indicators of Hydrologic Alteration (IHA)	1901-1913 1930-1946 & 1980-2009	Monthly	Stream gages data series	Hydrologic alteration measured at only one site (Johnson Ranch)
Bestgen et al. (2010)					
Physical model	Physically modeled using a swim chamber.	Fish captured in 2001 and 2002	N/A	Water temperature. Water velocity. Fishway characteristics. Fishway substrate.	It includes only the Silvery Minnow. It does not describe how the planning for the silvery minnow may affect other species.

Water resource models have been developed for many different regions and sub-basins of the RGB, including from Elephant Butte to Hudspeth county (USACE 2014), from Elephant Butte to the Gulf of Mexico (Danner et al. 2006), from El Paso to the Gulf of Mexico (TCEQ 2016), for the BBR region (Lane et al. 2014), Rio Conchos (Ingol-Blanco and McKinney 2013), and Pecos River (Yalcinkaya and McKinney 2011). Each tool has a specific objective: explore drought mitigation alternatives (Vigerstol 2002), conflict resolution of international water debts (Tate 2002), climate change evaluation (Ingol-Blanco and McKinney 2011), tradeoffs and economic synergies for both countries (Teasley 2009), water management (Sandoval-Solis et al. 2011a), reservoir re-operations for environmental flows (Lane et al. 2015; Porse et al. 2015), ground-water banking (Sandoval-Solis et al. 2011b), and collaborative modeling (Sandoval-Solis et al. 2013).

The existing body of research addresses some key scientific and management questions for the basin. For instance, in the Big Bend region, there has been documented habitat degradation from channel narrowing (Schmidt et al. 2003), invasive species (saltcedar and giant cane) (Everitt 1998) and near extinction of endemic aquatic species (e.g., silvery minnow) (Bestgen and Platania 2012). Water demands, supply, and allocations have been studied and modeled for the Big Bend region (Sandoval-Solis and McKinney 2014).

There is a variety of models that can assist planning activities to implement environmental flows across the RGB. However, no models consider economic effects of environmental flow implementation. Future research can focus on identifying water-related economic drivers to estimate effects of environmental flows implementation.

1.5 Conclusions

This project described past and present water management objectives, policies, allocation practices and water uses, summarized the state of water resources models that are available to explore Environmental Flows, and outlined a methodology for developing a geodatabase that summarizes water-related elements in the basin and available water modeling tools. The collection of water resources models for the RBG Basin was examined for their management of EF to prioritize future research and monitoring needs for the development of further river system modeling tools. This model inventory identifies reaches that have modeling tools available as well as river segments without modeling support, where models should be developed to improve water management for human and environmental uses. A variety of models that can assist planning activities to implement environmental flows across the RGB. However, no models evaluate economic effects of environmental flows implementation.

1.6 Disclaimer

This chapter is based upon work supported by the U.S. Geological Survey under Grant Agreement No G15AP00174 from the Southwest Climate Science Center. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey. This manuscript is submitted for publication with the understanding that he United States Government is authorized to reproduce and distribute reprints for Governmental purposes.

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Chapter 2 Economic Effects of a Reservoir Re-operation Policy in the Rio Grande/Bravo for Integrated Human and Environmental Water Management

Abstract

A central challenge of integrated water 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 to quantify and compare the economic benefits of two water management policies: (1) a business as usual (Baseline) policy and (2) a proposed reservoir re-operation policy to provide environmental flows (EFs). Results show that the EF policy would increase water supply 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.

Key Outcomes

- Reservoir re-operations provide an opportunity to minimize economic and environmental trade-offs to balance water management objectives.
- Results from an environmental flow policy show higher profits for agriculture while reducing the costs of flood management and environmental restoration.
- Reservoir re-operation for environmental flows is not only hydrologically feasible but also economically desirable.

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2.1 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 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; Rheinheimer et al. 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) (Figure 2-1), 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.

Figure 2-1. Schematic of Big Bend Reach

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, 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 (Figure 2-2). 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.

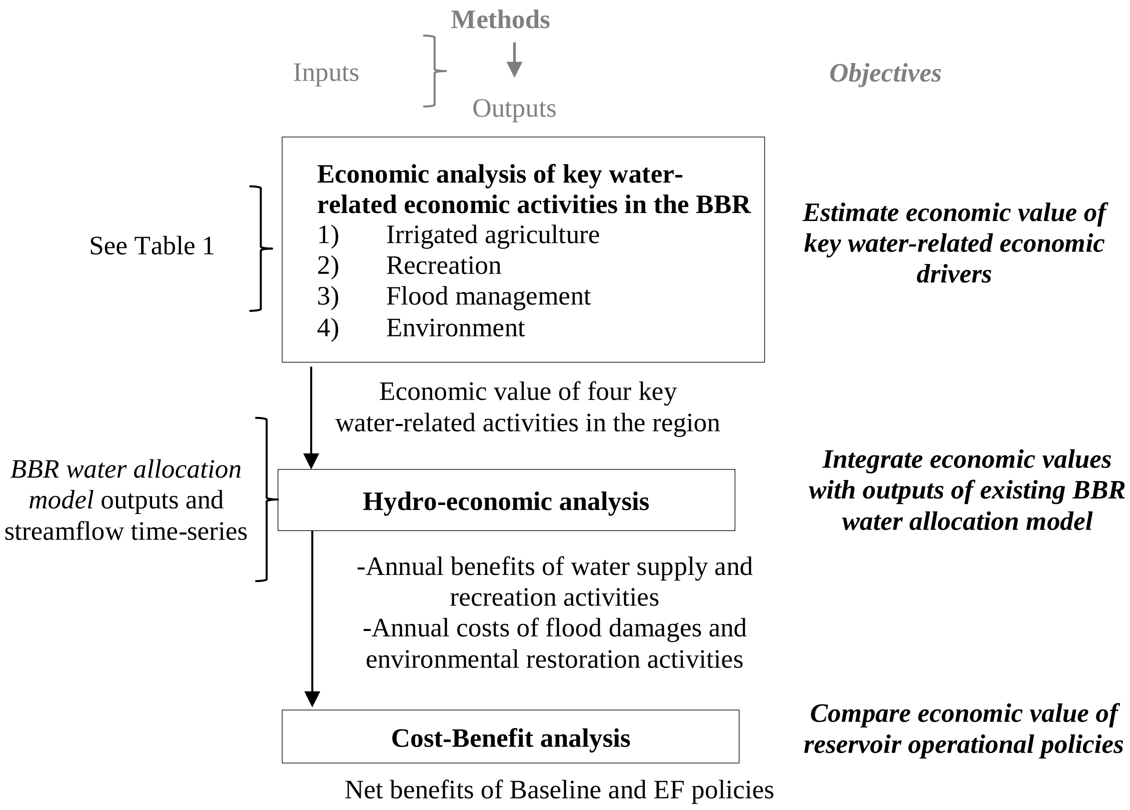

Figure 2-2. Research objectives and study design.

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

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, 2004 USGS, 2015 Desert Sports, 2015 Far Flung Outdoor, 2015
Flood management	• Monthly flow volumes for each flood event • Capital cost of local flood management project	Lane et al, 2014
	• Historic peak daily discharge values • Historic streamflow time-series (1955-2009): o *Below Ojinaga* daily o *Below Ojinaga* monthly	IBWC, 1971
Environment	• Silvery minnow reintroduction costs	USFWS, 2010
	• Land area of tamarisk coverage • Tamarisk removal costs	Zavaleta, 2000

2.1.1 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 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 (Figure 2-1). The BBR encompasses four key water-related economic drivers. First, irrigated agriculture, which includes one agricultural area in the U.S. (saa 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*).

2.1.2 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 to 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.

2.1.3 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.

2.1.4 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 (Figure 2-3a) (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 Equation (2-1). 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.

$$Release_t^{LLL} = \begin{cases} HWMO_t + Eflows_t^{Normal} & If\ \ S_{Flood} > \boldsymbol{S_t^{LLL}} > S_{Normal} \quad For\ t = 1, \dots, 12 \\ HWMO_t & If\ \ S_{Normal} > \boldsymbol{S_t^{LLL}} > S_{Drought} \quad For\ t = 1, \dots, 12 \\ HWMO_t + Eflows_t^{Drought} & If\ \ S_{Drought} > \boldsymbol{S_t^{LLL}} > S_{Dead} \quad For\ t = 1, \dots, 12 \\ HWMO_t + Eflows_t^{Drought} & If\ \ I_{Season-1}^{Wet} < 250 \quad For\ t = 7, \dots, 10 \\ HWMO_t + Eflows_t^{Drought} & If\ \ I_{Season-1}^{Dry} < 200 \quad For\ t = 11,12,1, \dots ,6 \\ 0 & If\ \ \boldsymbol{S_t^{LLL}} < S_{Dead} \quad For\ t = 1, \dots ,12 \end{cases} \qquad \textbf{(2-1)}$$

The EF 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 (Figure 2-3b). 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 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. Figure 2-4 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 streamflow's for the EF scenario are higher than baseline flows.

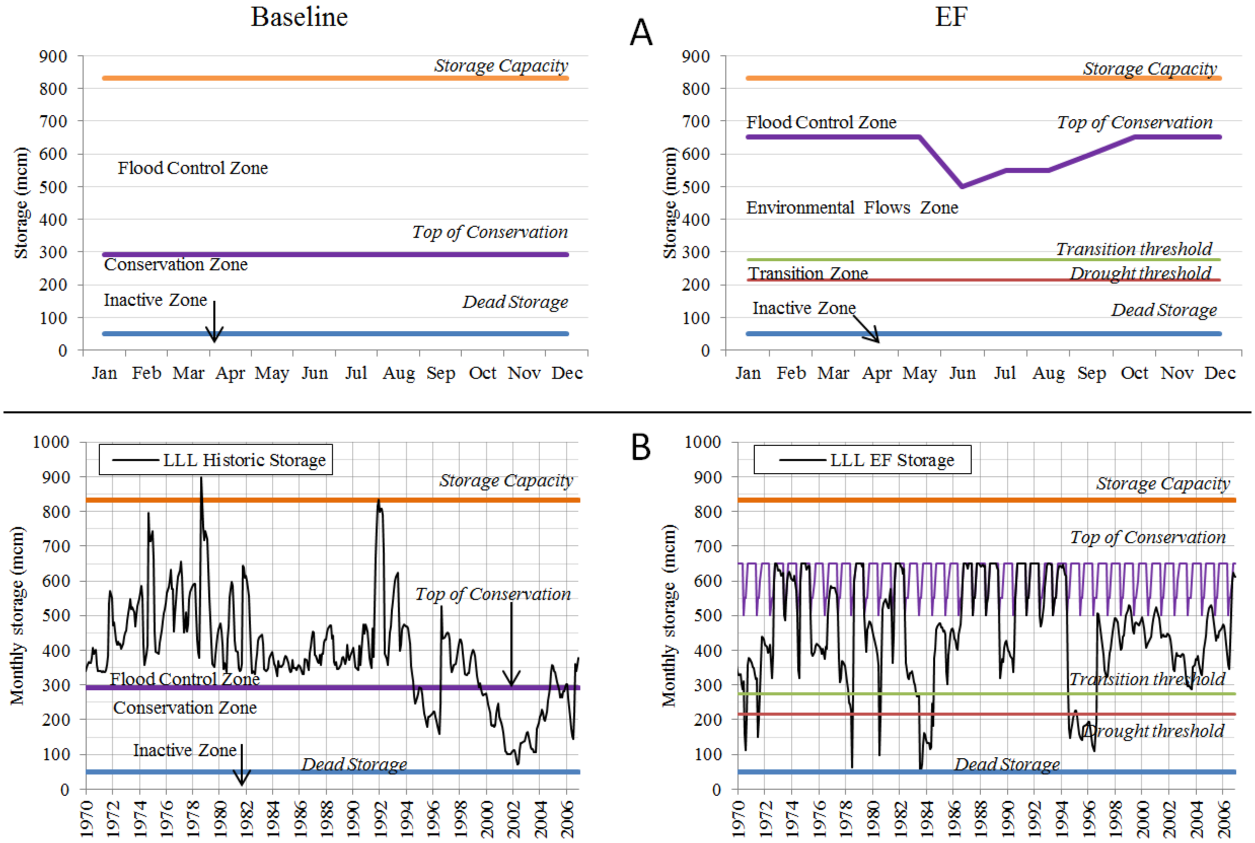

Figure 2-3. a) Baseline and EF reservoir operation policies and storages zones; b) LLL Storage for the Baseline and EF policy.

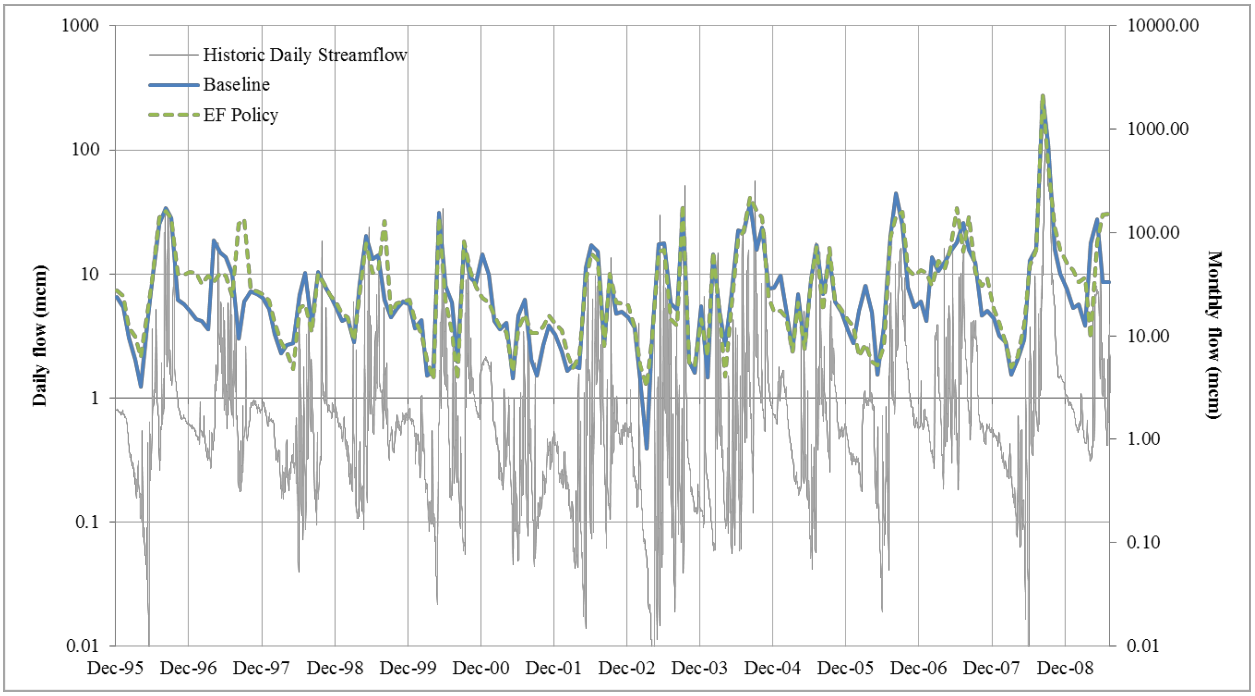

Figure 2-4. Historic daily streamflow and monthly volumes output from the model.

2.2 Background

2.2.1 Key water-related economic drivers

2.2.1.1 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 1997). The biggest irritated area is located in Mexico; its average sown area is about 3,500 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; IBWC 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.

2.2.1.2 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).

2.2.1.3 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 1,190 m^3/s below this confluence (IBWC 1971). Historical daily flows have surpassed the levee capacity and caused flooding events, for instance, 1,460 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.

2.2.1.4 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 Jr 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).

2.2.1.5 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 BBR. 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.

2.3 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.

2.3.1 Benefits

2.3.1.1 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 (Equation (2-2)). 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 (Equation (2-3)).

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

$$Avg. gross\ annual\ income\ = Avg.\ Water\ Supply * Gross\ Annual\ Income \quad \textbf{(2-3)}$$

Average water supply and estimated average gross annual income for each agricultural unit in the system was calculated (Table 2-2). 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%).

Table 2-2 Estimated regional gross income from agriculture

		Baseline			***EF***		
	Water demand (mcm)	**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.

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.

2.3.1.2 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 river for one day) (Table 2-3). The economic data regarding river recreation was obtained from the National Park Service (NPS 1996; NPS 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 (100cfs) (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 (Figure 2-5). 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 volume increases. In months with streamflow volumes above 15 mcm all the days are considered above the flow limit for rafting (Figure 2-5).

Table 2-3. Economic benefits from river recreation activities and related costs under Baseline and EF policies.

	Baseline	EF
Average annual river usage (user-days/year)	2,152	2,027
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**

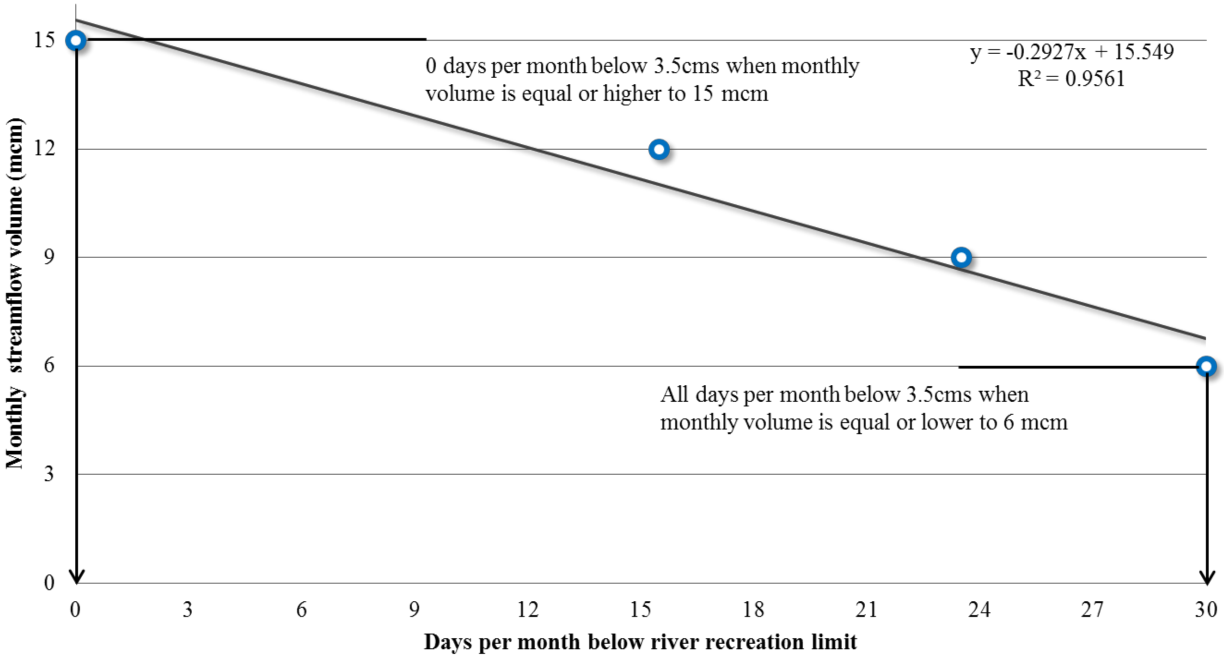

Figure 2-5. Expected number of days with streamflow below raftable limit (3.5cms) for a given monthly streamflow volume (mcm).

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.

2.3.2 Costs

2.3.2.1 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 (Figure 2-6), which represents an 18.2 percent flood risk (5.5-year return period). Conversely, only eight floods occurred under the EF policy (Figure 2-6), 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; 1,023 mcm EF), indicating that, on average, the EF policy would not substantially increase the severity of flood events or the cost of flood damages.

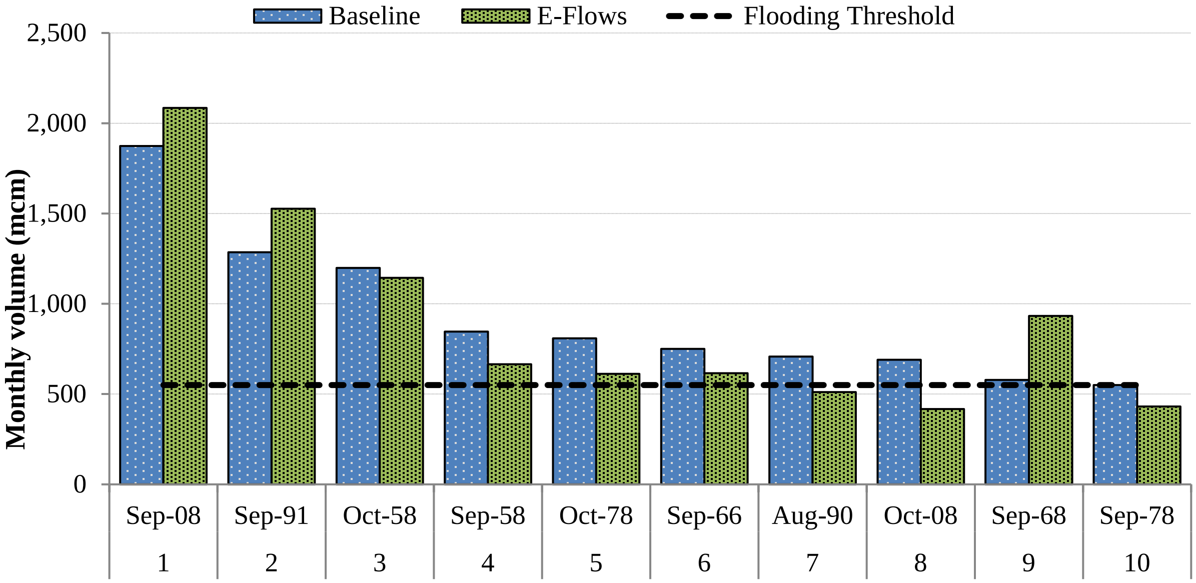

Figure 2-6. Largest flood events sorted by magnitude under baseline and EF policies (Lane et al. 2014).

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 (Figure 2-7) [$Q_t^{Peak}=1182\ln(Q^{Month})-7189$, $R^2=0.799$] 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 2-4). These values represent annual costs of $1.17 and $0.98 million in present value (2015), respectively.

Table 2-4. Present value (2015) of economic losses ($1000) for baseline (BL) and EF policies for historical 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**	**-**	**-**

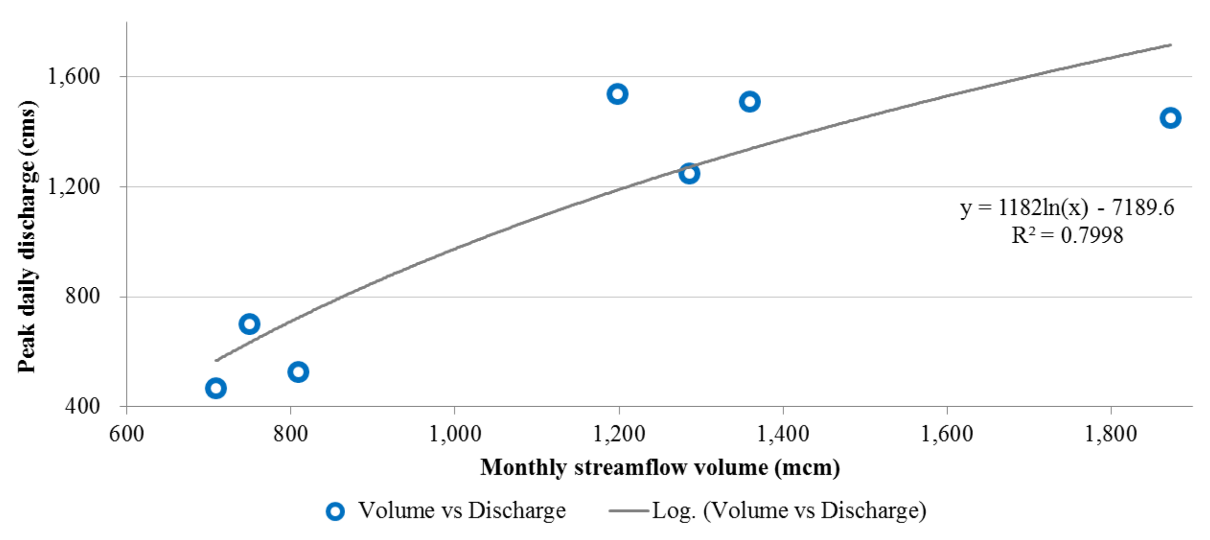

Figure 2-7. Monthly volume and peak discharge correlation.

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 2-4). 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.

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).

2.3.2.2 Environment

2.3.2.2.1Endangered 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 2-5). 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 2-5. Avoided costs from silvery minnow reintroduction (adapted from USFWS, 2010).

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

2.3.2.2.2 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-meter 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 hectares 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.

2.3.3 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 (Figure 2-8): (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.

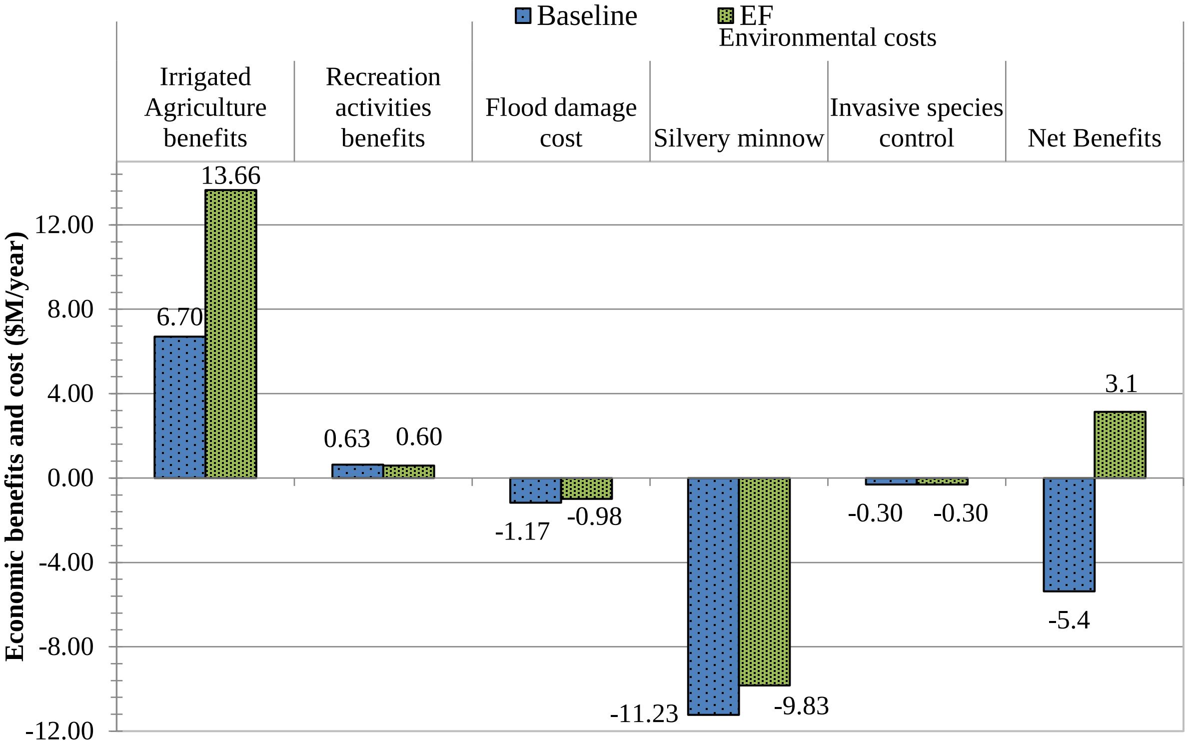

Figure 2-8. Total costs and benefits of the baseline and EF policies for LLL reservoir.

2.4 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.

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.

2.5 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)].

2.6 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 shows 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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Chapter 3 Robust management for multipurpose reservoirs under hydroclimatic uncertainty

Abstract

This study aims to evaluate the performance of operation of multipurpose reservoirs under uncertainty in hydroclimatic conditions. To achieve this objective, we have formulated a two-stage stochastic optimization model that maximizes regional economic benefits from reservoir deliveries and integrates stochastic inflows into a water allocation system with multiple demands and various physical and institutional constraints. The model derives a robust set of monthly reservoir releases that perform well under a wide range of hydroclimatic conditions. This model is applied to the Big Bend Reach of the Rio Grande/Bravo, a transboundary river basin of high importance for the United States and Mexico. The performance of the robust operation policy has been assessed by comparing its outcome to those obtained under observed historical operations and an operation policy derived from a deterministic version of the optimization model that assumes perfect climate knowledge. Results show that the developed set of robust releases outperforms historical reservoir operations and performs similarly to operations under the perfect climate forecasts. Such results suggest that robust reservoir operations are an efficient policy to improve long-term regional economic benefits and increase environmental water allocation in the absence of reliable climate information.

Key Outcomes

- Results indicate that integrating hydrologic variability into optimization models enables a broader planning spectrum and allows managers to prepare for low probability but costly events.
- It is feasible to improve reservoir operations under increasing hydroclimatic uncertainty and more intense and frequent droughts and floods under the imminent climate change
- Modeled robust reservoir operations generally outperform historic reservoir management and performs similarly to the deterministic model with perfect knowledge

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3.1 Introduction

Thousands of reservoirs around the world have contributed to human and economic development through more reliable water supply, flood control, hydropower generation, and other benefits. However, in many cases the social and environmental costs of reservoir development and operations have remained large and sometimes unacceptable (Scudder 2012; WCD 2000). Many existing reservoirs will remain despite causing chronic degradation of river ecosystems (Dugan et al. 2010; Graf 1999; Yang et al. 2011). Moreover, environmental degradation may be exacerbated by increasing hydroclimatic uncertainty and variability, making effective reservoir management critical within basin water allocation systems (Tullos 2017). The need to adopt better reservoir management will become more evident in coming decades with the increasing intensity and occurrence of extreme hydroclimatic events (e.g., floods and droughts) from climate change (Seneviratne et al. 2012; Wouter et al. 2017).

The management of multipurpose reservoirs is challenging because of their high-dimensional, dynamic, nonlinear, and stochastic characteristics (Pan et al. 2015). Multi-purpose reservoirs often face complementary objectives with conflicting water management goals across different water use sectors and the environment (Labadie 2004; Loucks and Sigvaldason 1981). For instance, a water supply objective tries to maintain water elevation near maximum storage to improve water supply reliability while flood management would advocate for a lower water elevation with capacity to manage high, possibly catastrophic, inflows to reduce risks of overtopping. Integrating environmental flow requirements as another objective may create further competition with the question of who gets the water first. Different water users pursue different objectives and potential conflicts arise as to how to minimize trade-offs among competing water management objectives in the presence of various hydroclimatic uncertainties.

These trade-offs are traditionally managed by reservoir operation policies that dictate the range of storage and water elevation at the surface of the reservoir at the end of each month. Operation policies divide the reservoir into different storage zones that serve for water supply, recreation, hydropower, or flood management (Kaczmarek and Kindler 1982; Labadie 2004). Operating policies must comply with laws and regulations while satisfying demands of water users (Labadie 2004; Loucks and Sigvaldason 1981). Developing effective operation policies is challenging because of the considerable uncertainty of system inflows (Oliveira and Loucks 1997).

This study seeks to identify a robust reservoir operation policy that encompasses hydroclimatic uncertainty and improves water management by increasing regional economic benefits. The paper develops and applies a stochastic optimization modeling framework to guide a risk-informed design of cost-effective, sustainable, and robust reservoir operation policies. Moreover, the framework should be able to integrate multiple water management objectives under uncertain climatic conditions. This study addresses reservoir management and how changes in the timing and volume of water releases could maintain socioeconomic growth while reducing or reversing some of its environmental impacts. Within an optimization framework, this research investigates ways to maximize regional economic benefits with uncertain reservoir inflows while meeting human and environmental water demands. The formulation presented can be considered as a form of hedging, in which small deficits may be preferred by some users to reduce the cost of unexpected and more severe droughts or to reduce the risk of flood events. Stochastic optimization explicitly derives a robust policy that in the long term would be better suited, regardless of the inflow scenario (Ermolieva et al. 2016).

This paper is organized as follows. First, a review of optimization techniques to develop reservoir operation policies with a special focus on the area of stochastic optimization of water resources is provided in Section 3.2 . Section 3.3 describes the proposed optimization framework. Section 3.4 describes the study area, and Section 3.5 presents the results of applying the modeling framework and discusses the value of developing robust operations to cope with hydroclimatic uncertainty. Finally, Section 3.6 summarizes the main conclusion.

3.2 Background

3.2.1 Optimizing reservoir operation rules

Since the 1960s, optimizing reservoir management has gained importance as a major research area in water resources management (Yeh 1985). Different reservoir optimization methods have been used in the literature including linear, non-linear, or dynamic programming with different limitations, such as linearizing non-linear variables, finding non-global optima, or having high computational burden, respectively (Husain 2012; Yeh 1985). A common approach to optimize water resource systems is to assume deterministic parameters. Optimization models with stochastic parameters were later introduced to account for the natural variability in parameters such as inflow and evaporation (Klemeš 1977).

Traditional deterministic optimization models are scenario dependent, meaning some variables in real-world systems such as reservoir inflows, water demands, or system losses become fixed parameters in the model. The reason is that, despite recognizing their intrinsic variability, in reality we only have statistical descriptions of hydrologic variables or unreliable forecasts of long-term average conditions. Consequently, deterministic optimization models may fail to include the impacts of low probability but costly events, such as floods or droughts (Farmer and Vogel 2016; Philbrick and Kitanidis 1999). Even when considering multiple deterministic events based on historical records, management decisions may be impacted if such records include long or extreme droughts, because they can misguide non-exceedance probabilities resulting in overly conservative policies (Frevert et al. 1989). Another limitation arises when including analysis for best and worst conditions, which aid in assessing a system's ability to meet desired goals under extreme events but do not necessarily produce good decisions for more stable periods (Huang and Loucks 2000a). Philbrick and Kitanidis (1999) developed a hypothetical reservoir management model and tested reservoir operation policies using deterministic and stochastic approaches with a variety of future inflow scenarios. Operation policies derived from deterministic models were only better when streamflow scenarios were very similar to the real-time forecast. Despite the limitations, some studies developed useful operation rules from deterministic approaches when combining them with simulation models under different scenarios. Such approaches are an example of implicit stochastic optimization because multiple deterministic scenarios are considered and tested to address uncertainty (Lund and Ferreira 1996; Nelson et al. 2016).

Another approach to incorporate variability into the optimization model is to include stochasticity in model inputs to represent their seemingly random behavior (Maier et al. 2016). However, reservoir operators are often skeptical of using optimization models with such complexity (Celeste and Billib 2009; de Santana Moreira and Celeste 2016). In recent years, with the improvements in simulation models as well as computational power, intelligent computational programming has been developed. A prevalent example is Evolutionary Computation, a programming technique with different optimization algorithms such as Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, Honey Bees Mating, Artificial Neural Networks, and others. Ahmad et al. (2014); Choong and El-Shafie (2015) and Hossain and El-shafie (2013) provide a comprehensive review of the use and application of these techniques for reservoir management.

3.2.2 Stochasticity in reservoir operations

The uncertainty underlying several hydrologic processes led to developing stochastic optimization techniques in water resources that integrate random or unknown variables such as precipitation, streamflow, or water demands. These techniques have been widely applied to derive operation rules for single- (Butcher 1971; Karamouz and Vasiliadis 1992; Stedinger et al. 1984) and multi-reservoir systems (Braga et al. 1991; Etkin 2013; Macian-Sorribes et al. 2017) under uncertain hydroclimatic conditions.

Several previous studies included stochasticity in the development of reservoir operation policies. An example is the application of Sampling Stochastic Dynamic Programming (SSDP) to investigate methods for increasing water allocation efficiency of multi-reservoir operations in the Geum River basin of Korea (Eum et al. 2010; Kim et al. 2007). SSDP incorporates annual correlation of streamflow from historical or synthetic data by combining different streamflow scenarios within the optimization model. Results show improved performance by explicitly including inflow uncertainty into the modeling process compared with a deterministic approach using average streamflow (Kim et al. 2007). Another approach is the Stochastic Dual Dynamic Programming (SDDP) (Pereira and Pinto 1991), which was applied for investigating large-scale water resources problems. The SDDP approach has been applied to develop reservoir operation policies for multi-reservoir systems (Tilmant and Kelman 2007) and was later extended and applied to the Jucar basin in Spain to explicitly include stream-aquifer interactions (Macian-Sorribes et al. 2017). Gaivoronski et al. (2012) developed a scenario-based stochastic optimization method to obtain robust policies that minimize the risk of wrong decisions and allow the user to implement an emergency policy in a re-optimization phase. These non-linear problems tend to become computationally intensive and do not guarantee global optimal solutions.

Stochastic linear problems have also been developed in the literature. The Linear Decision Rule (LDR) introduced by Revelle et al. (1969) specified reservoir releases based on the difference in the initial storage and a decision parameter for a particular period. Such parameters include hydropower generation targets, water allocation rights, and minimum navigation flow requirements, among others. To provide a tractable approximation for a multi-period hydropower generation problem, Pan et al. (2015) developed an Iterative Linear Decision Rule (ILDR) considered as a robust optimization (RO) approach. This modification of the LDR allows the integration of non-linear objective functions using piece-wise linearization. They applied the method to the single reservoir system of Three Gorges Dam in China, and to the Shasta-Trinity multi-reservoir system in California. Their results show that the RO performance is similar to the SSDP when implemented on the original historical inflows and it improves performance when tested on generated inflows (Pan et al. 2015). Linear problems, however, tend to have explicit single objectives and consider environmental water demands as constraints within the model.

Stochastic optimization tends to reduce the potential risk of erroneous decisions when compared with deterministic approaches. Celeste and Billib (2009) assessed the performance of different stochastic methods to define optimal reservoir operations by comparing them with the solution of a deterministic model that assumed perfect knowledge of future monthly inflows. This allowed them to measure the performance of the stochastic models relative to first-best operations.

While numerous stochastic models have been developed for reservoir operations optimization, there is a need for a method which can take advantage of linear programming while including stochastic variables. Such method should include a variety of water supply objectives and be able to provide robust operations which cope with a changing climate. Building on the described research and models, the contribution of this study to previous literature includes: (1) the development of a novel two-stage stochastic and dynamic multi-criteria optimization approach for preserving the water mass balance in areas influenced by reservoir management. The approach includes performance indicators for multiple water management objectives including water supply (e.g., agricultural, domestic), flood risk reduction, and environmental flow requirements for healthy ecosystems; (2) strengthening the importance of considering stochastic inflows in the modeling of reservoir operations as an strategy to climate change adaptation; and (3) the derivation of a robust set of adaptable (under extreme flood events) reservoir releases instead of the traditional end-of-month reservoir storage targets.

Similar to the models developed by Eum et al. (2010); Kim et al. (2007) and Macian-Sorribes et al. (2017), the proposed approach explicitly includes inflow uncertainty into the modeling framework and the differences rely on approaching this highly nonlinear, nonconvex, and non-smooth constraints by solving a linear programming problem. This new modeling framework improves on previous linear stochastic approaches by allowing multiple water users to achieve secure water provision within a defined safety level.

3.3 Modeling framework

3.3.1 Problem formulation

This paper develops a stochastic optimization modeling framework to obtain a set of monthly releases from a reservoir that maximize the economic benefits of water use. We begin by briefly describing a traditional deterministic optimization formulation of reservoir management and then describe the proposed stochastic formulation.

A traditional deterministic approach considers a planning horizon of T periods divided into smaller times-steps t. Typical variables for deterministic reservoir operations are terms in the mass balance equation (3-1), which states that the storage at a given time S_t equals to the storage in the previous time-step S_{t-1} plus the inflows I_t minus the releases R_t and evaporation losses E_t, as follows:

$$S_t = S_{t-1} + I_t - R_t - E_t \tag{3-1}$$

The objective function (3-2) of this model maximizes the total benefits from water use $F(R)$, which are the sum of benefits of individual water users i, b_i, as a function of reservoir releases R in each time-step t, subject to water balance equation and other physical reservoir constraints, as follows:

$$Max\ F(R) = \sum_{i} \sum_{t=1}^{T} b_{it}(R_{it}) \tag{3-2}$$

This problem of reservoir management can be reformulated as a two-stage stochastic programming model in which benefits, costs, and water demands are treated as parameters and inflows are unknown and variable. The first stage decisions involve water releases from the reservoir based on a system wide expected deficit. In the second stage, once the deficit is known, it is allocated among users (Figure 3-1).

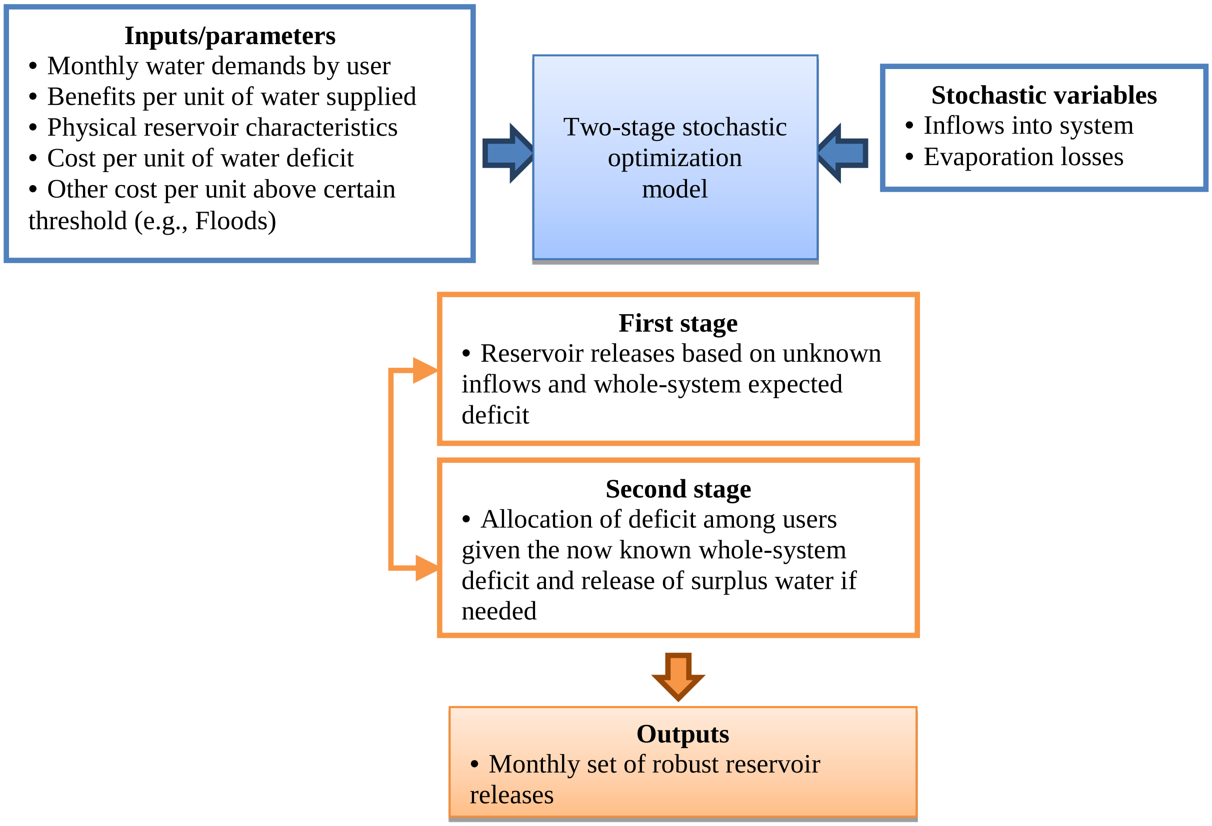

Figure 3-1. Stochastic optimization model workflow.

To allow the flow of excess water, a surplus variable is also included within the second stage. The advantage of this two-stage stochastic formulation is the ability to address problems of input data uncertainty in the creation of policy scenarios (Huang and Loucks 2000b; Huang et al. 2012). Under the first stage, the model decides without knowing exact information about the inflows and expected deficits or surpluses, whereas in the second stage, the model hedges the deficit for optimal water supplies to the system considering the now disclosed variables. Ermolieva et al. (2016) implemented a similar approach for flood mitigation and land use management. The proposed two-stage stochastic optimization objective function is depicted in Equation (3-3) and its linearized model expression is shown in Equations (3-4) to (3-9), as follows:

$$\begin{aligned} Max\ F(R_m) = & \sum_m \sum_i b_{im} \cdot RR_{im} \\ & - \sum_{s=1}^{S} \sum_m \sum_i deiC_{im} \cdot p_m^s \cdot \max\{0, d_{im} - RR_{im}\} \\ & - \sum_{s=1}^{S} \sum_m \sum_i suiC_{im} \cdot p_m^s \cdot \max\{0, RR_{im} - d_{im}\} \end{aligned} \tag{3-3}$$

The objective function of the model (3-4) is to maximize net benefits from water deliveries and minimize occurrences of scenario-specific water deficits $\max\{0, d_{im} - RR_{im}\}$ and surpluses $\max\{0, RR_{im} - d_{im}\}$ to user i where d_{im} defines water demand by user i in month m, RR_{im} is the target water supplied to users i in month m, s denotes a water inflow scenario and S is the number of scenarios. b_{im} denotes net benefits per unit of water supplied to each user I (e.g., irrigated agriculture, urban water supply, environmental flows) in different months $m = 1, \ldots, 12$; $deiC_{im}$ and $suiC_{im}$ are the costs from expected deficits $\sum_{s=1}^{S} p_m^s \cdot \max\{0, d_{im} - RR_{im}\}$ and surpluses $\sum_{s=1}^{S} p_m^s \cdot \max\{0, RR_{im} - d_{im}\}$ for each user i, respectively. $deiC_{im}$ characterizes, in a sense, the price of water (or losses from deficits) for water user i in month m, and $suiC_{im}$ identify losses associated with water oversupply such as flooding or excess water to agriculture. p_m^s is the probability of occurrence of inflow scenario s, which are assumed to be equal to $1/S$, where S is the number of scenarios (years with inflow records). A random scenario generator can produce representative scenarios when a few records are available (Ermoliev and Wets 1988). In this proposed model target reservoir releases R_m and target water supplied to users RR_{mi} are strategic first-stage decisions, which do not depend on an individual inflow scenario. Scenario specific water deficits and surpluses are second-stage decisions. Benefits from water supply are maximized and costs/losses from any deficits and surpluses are minimized. The optimal combination of the first and the second stage decisions brings adaptability to the set of resultant monthly reservoir releases and therefore perform well in scenarios that were not optimized to directly.

These surplus $\max\{0, d_{im} - RR_{im}\}$ and deficit $\max\{0, RR_{im} - d_{im}\}$ variables are non-smooth (due to max operations) and their use in the objective function would lead to a non-smooth stochastic optimization problem (Ermoliev and Wets 1988). To linearize the objective function (3-4), we introduce the terms Deficits $De_{mi}^{s} = \max\{0, RR_{im} - d_{im}\}$ and surpluses $Su_{mi}^{s} = \max\{0, d_{im} - RR_{im}\}$, and add constraints (3-8) and (3-9), making De_{mi}^{s} and Su_{mi}^{s} stochastic positive variables implicitly dependent on inflows (I_m^s) and giving the following linear objective.

$$\begin{aligned} Max\ F(R_m) = \sum_{m}\sum_{i} b_{im} \cdot RR_{im} - \sum_{s=1}^{S}\sum_{m}\sum_{i} deiC_{im} \cdot p_m^s \cdot De_{mi}^{s} \\ - \sum_{s=1}^{S}\sum_{m}\sum_{i} suiC_{im} \cdot p_m^s \cdot Su_{mi}^{s} \end{aligned} \tag{3-4}$$

subject to:

$$R_m = \sum_{i}^{I} RR_{im} \tag{3-5}$$

$$\underline{s}_m^s \leq S_m^s \leq \overline{s}_m^s \tag{3-6}$$

$$S_{m+1}^s = S_m^s + I_m^s - R_m - E_m^s - \sum_{i} Su_{mi}^{s} + \sum_{i} Se_{mi}^{s} \tag{3-7}$$

$$De_{mi}^{s} \geq d_{im} - RR_{im} \tag{3-8}$$

$$Su_{mi}^{s} \geq RR_{im} - d_{im} \tag{3-9}$$

The objective function (3-4) is maximized subject to several constraints (Equations (3-5) to (3-9)). Equation (3-5) states that the sum of reservoir releases for each user must be equal to the total release from the reservoir. Equation (3-6) defines the minimum and maximum reservoir storage for each month and year (i.e., scenario). Equation (3-7) includes the reservoir water balance for the storage S in each time-step including Su_{mi}^{s} and De_{mi}^{s} variables. The Su_{mi}^{s} variable reduces the storage before months where high flows are more probable, and the De_{mi}^{s} variable will hold water before months prone to have deficits. By regulating cost $suiC_{im}$ and $deiC_{im}$, in the maximization of the objective function (3-4) under constraints (3-5) to (3-9), it is possible to avoid surpluses and deficits with predefined probabilities. Equation (3-8) limits deficits to the amount of maximum allocation for each user. Equation (3-9) quantifies the surplus and allows high inflows to be released to avoid or reduce overtopping. The two-stage formulation, as noted in the last two terms of the objective function (3-4), induces the safety constraints on water supply based on the probabilities of deficits and surpluses.

3.3.2 Performance criteria

Four criteria were used to evaluate the performance of observed data and simulations under the different model formulations: time-based reliability, volumetric reliability, resilience, and vulnerability (Hashimoto et al. 1982). Time-base reliability is the probability to fulfill water demands over the period of simulation; volumetric reliability quantifies the total volume of water supplied divided by the total water demand for each user on each time step during the simulation period; resilience is a measure of the ability of the system to recover after a failure; and vulnerability is a measure of severity of a deficit (Sandoval-Solis et al. 2011). In this study, we use the sustainability index as adapted by Sandoval-Solis et al. (2011), referring to the geometric average of performance criteria for each water user.

Water managers and decision makers are familiar with the selected performance criteria, particularly with trying to frequently meet water demands (time-based reliability) and reduce the magnitude of deficits (vulnerability). These criteria have been widely applied within the field of water resources management. A more detailed description of the performance criteria can be found in Appendix 5.3.1 .

3.4 Application of problem formulation to a single reservoir system

3.4.1 Description of the study area

We applied the proposed modeling framework to a single reservoir system in the lower Rio Conchos, the main tributary to the transboundary Rio Grande/Bravo. The Rio Conchos is the main water source to the Big Bend Reach (BBR) of the Rio Grande/Bravo (RGB). The BBR is a region of recognized bi-national importance in which water availability, water quality, flood risk, as well as the preservation of recreational activities, and aquatic and riparian ecosystems of the Chihuahua’s desert are fundamental to the region’s welfare (Obama and Calderón-Hinojosa 2010) (Figure 3-2).

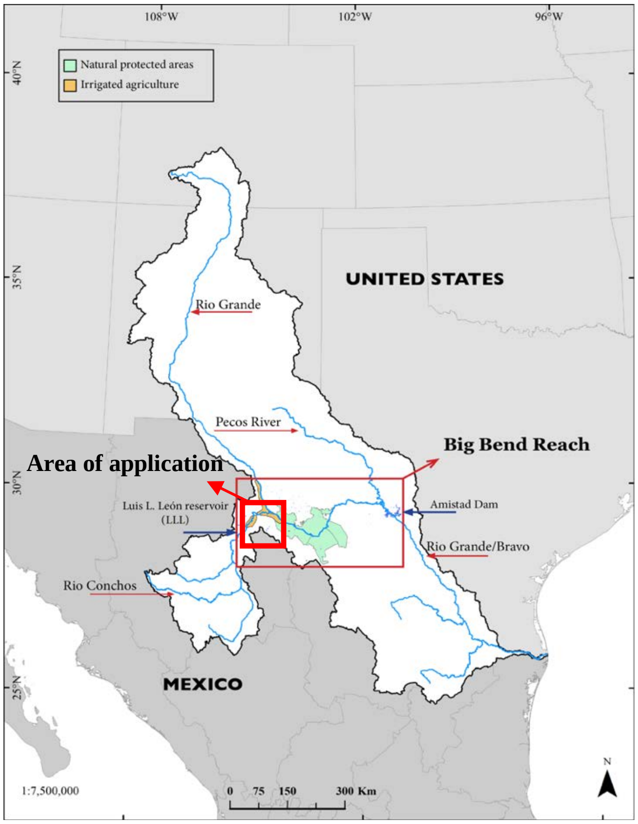

Figure 3-2. Big Bend Reach (BBR) of the Rio Grande/Bravo (RGB) and the area of application.

The study extent consists of the Rio Conchos river channel from Mexican Luis L. León Reservoir (LLL) to the confluence with the RGB mainstream in Presidio and Ojinaga (P-O) Valley (Figure 3-3). LLL has three storage zones: inactive, conservation, and flood control. The inactive storage is 50 million cubic meters [Mm^3], the top of conservation is 292.46 Mm^3 (as it was originally designed for flood control), and the total storage of the reservoir is 832 Mm^3 (Figure 3-4A) (CONAGUA 2011). However, the historical operation of LLL does not follow the nominal top of Conservation and the average historical operation storage is between 580 Mm^3 in the wet season and 700 Mm^3 in the dry season (Lane et al. 2014) (Figure 3-4B). The official objective of LLL reservoir management is to keep storage within the conservation zone to balance trade-offs between flood management and water supply. The conservation zone is constrained by the inactive storage and the top of Conservation, which sets the maximum non-flood storage level. LLL reservoir operations involve conflicting objectives of maximizing available water in storage for water supply purposes (e.g., irrigation, municipal, etc.) and maximizing empty floodwater storage capacity to reduce downstream flood damages, all while meeting international treaty obligations under the Treaty of 1944 (IBWC 1944). The Treaty defines the primary division of the water reaching the RGB mainstream from six tributaries originating in Mexico as one-third to the U.S. and the two-thirds to Mexico. The third shall not be less than 432 Mm^3 per year (350,000 acre-feet/year) as an average over cycles of five consecutive years. Treaty cycles can expire in less than five years if the account of U.S. storage in Amistad and Falcon dams is at full capacity. The International Boundary and Water Commission (IBWC) evaluates the Mexican delivery of water to the U.S. and determines if Mexico meets the Treaty commitments. If there is a deficit in the Treaty delivery, Mexico must provide extra water in the following cycle.

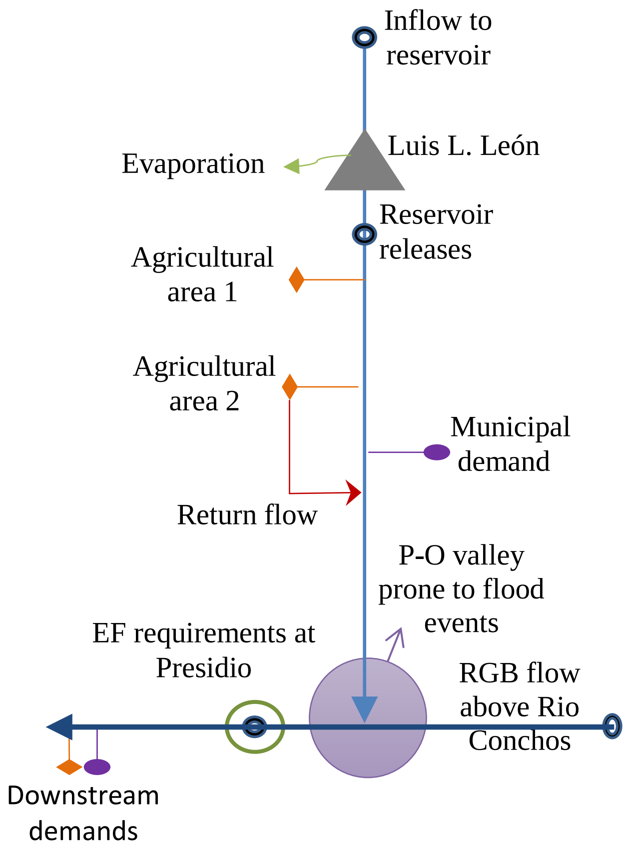

Figure 3-3. Rio Conchos below Luis L. León (LLL) and water demands schematic.

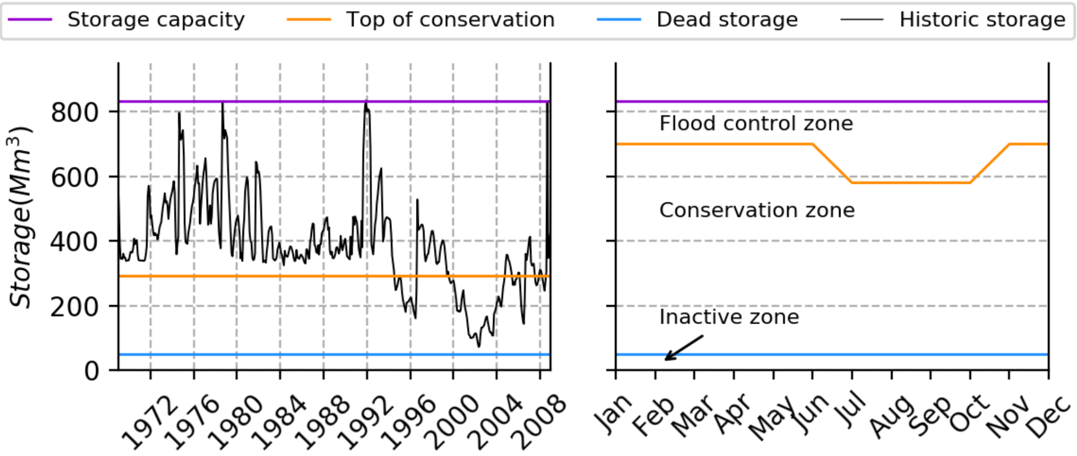

Figure 3-4. Left a): Luis L. León (LLL) reservoir storage zones with the nominal top of conservation. Right b): Average historical top of conservation zone. Source (Lane et al. 2014).

Several optimization models have been developed for areas that include the Rio Conchos from LLL reservoir to the confluence with the RGB (Cañón et al. 2009; Porse et al. 2015). Cañón et al. (2009) created a two-stage non-linear optimization model to minimize water deficits to users and maximize crop production in irrigation districts. Their study included all major reservoirs in the Rio Conchos basin and considered a Drought Frequency Index, a stochastic index using mean return period as an integrated measure of a drought severity and duration. Porse et al. (2015) developed a linear optimization model that minimizes water deficit for different users along the BBR of the RGB. The results show the feasibility of improving environmental flows without harming irrigated agriculture and urban water supply. These optimization models are not stochastic, and their underlying objective functions and spatial scales differ from those considered here. Another study looked at water resource allocation alternatives from a system dynamic perspective (Gastélum et al. 2009).

3.4.2 Model input data and variables

The stochastic formulation presented in section 3 was applied the study area. GAMS software has been used for model development and scenario simulation (Brooke et al. 1988). A detailed description of the model equations, parameters, and data specific to the study area appears in Appendix 5.3.2. Table 3-1 lists empirical model parameters.

Table 3-1. Model parameters (m = month, and s = scenario).

Parameters	Description	Value
Water demands	Maximum water allocation per user, including environmental flow requirements at Presidio and downstream maximum water allocation for users downstream of the confluence with the RG	Appendix 5.3.4
Inflow to reservoir	Inflow to LLL reservoir (42 years of historical records)	Appendix 5.3.5
Evaporation from reservoir	LLL evaporation losses (42 years of historical records)	Appendix 5.3.6
Cost of deficit	Cost of water deficit by user per unit of water	0.05 $\$M/Mm^3$
Cost of flood	Median cost of flood per Mm^3 above threshold	0.02 \$M per Mm^3 above flood threshold
Initial storage	Initial storage of LLL reservoir	196 Mm^3
Maximum storage	Reservoir capacity	832 Mm^3
Minimum storage	Dead storage plus two times annual municipal demand	55.2 Mm^3
End of period storage	Minimum storage at the end of period	196 Mm^3

Model input data included urban and agricultural water demands below LLL in the Rio Conchos and downstream of P-O valley as well as economic benefits of water supplies and cost of deficits to each user (Appendix 5.3.4). Additional inputs included monthly reservoir inflows from Rio Conchos-Las Burras streamflow gauge from 1969 to 2010 (Appendix 5.3.5) as well as estimated monthly evaporation (Appendix 5.3.6).

The environmental flow (EF) requirements developed by the Lower Rio Grande Bay Expert Sciences Team (2012) were adopted here as another water demand in the system. These EF requirements have been previously used in other studies (Lane et al. 2014; Porse et al. 2015). We also incorporated costs related to flood damages caused by monsoons coming from the Gulf of Mexico and the Pacific (IBWC 1971; Sayto-Corona et al. 2017). Other input data included reservoirs and flood infrastructure characteristics, as well as international delivery commitments from Mexico to the United States.

As the models' monthly time-step cannot adequately capture the performance of operation policies for flood events, a proxy of flood probability was considered. A probability analysis identified the historic monthly flow volume (550 Mm^3 at Presidio gauge station) corresponding to daily flow values exceeding the design capacity of the levee (1190 m^3/s) (Lane et al. 2014). We used this value to identify the number of months prone to flood events. During the historical period of records (42 years) there were 4 flood events representing a 10.5% flood probability. Flood probability in this study is defined as the number of years when monthly flow volumes at Presidio exceed 550 Mm^3, divided by the period of records.

Benefits are expected from each unit of water delivered to each user. The monthly economic value per unit of water delivered was estimated considering the agricultural revenue and applied water from 1997-2013 according to irrigation districts statistics from Mexico (CONAGUA 1997-2013). When users do not receive promised water, they have to either obtain water through more expensive alternatives (e.g., groundwater, treated wastewater or water transfer) or modify their water use (e.g., changing crop pattern or reducing irrigated area). Shortage penalties include the acquisition costs of water from alternative sources and the cost of changing use plans (Huang et al. 2012; Li et al. 2008). To quantify economic benefits for agriculture we used economic values derived by Ortiz-Partida et al. (2016).

3.5 Results and Discussion

3.5.1 Reservoir operation under alternative model formulations

Based on comparisons between observed and simulated reservoir storage and flow at Presidio gauge, the deterministic model (with perfect knowledge of future inflows) avoided some of the floods (Figure 3-5b) compared to historical observations (Figure 3-5a). However, given the limited storage capacity and the episodic intensity of reservoir inflows, some floods were unavoidable. Storage in the stochastic model involved releases that decreased water levels every summer during the monsoon season (August and September) to reduce costly future floods despite longer term water supply deficits (Figure 3-5c). This model resulted in highly variable storage from year to year because it calculated storage in each year independently instead of carrying over the storage from the previous year, as in the deterministic model.

The stochastic model reduced the intensity and frequency of floods compared to historical observations. Historically, there were four floods in the P-O valley, in 1978, 1990, 1991, and 2008 (Figure 3-5d). Two floods were avoided under both the deterministic and stochastic models and, when floods were unavoidable, their magnitude was reduced (Figure 3-5e & Figure 3-5f).

Consequently, the deterministic and stochastic models reduced historical economic damages of flood events averaging 1.17million USD/year by 0.5 and 0.4 million USD per year, respectively.

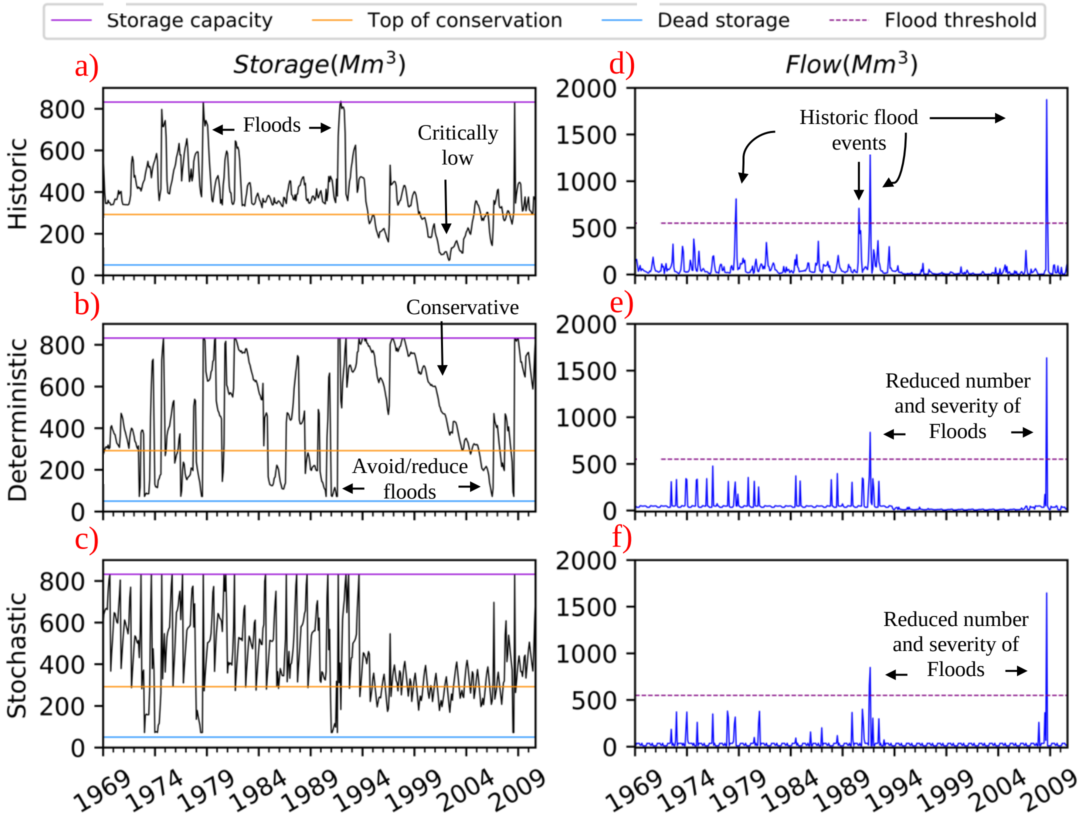

Figure 3-5. Historical observation, deterministic, and stochastic reservoir storage and flow at Presidio.

Figure 6 shows observed and simulated reservoir releases and system deficits. Historical water deliveries from LLL have been mostly inefficient because water is released when it is not needed, probably due to conservative flood operation. Therefore, while releases were larger under the historical observation, larger deficits occurred due to frequent but smaller releases (Figure 3-6). For example, from 1979 to 1987 (Figure 3-6a-inset), considerable releases exceeded the water demand. Under the stochastic model, expected deficits were often overcome when water was released to avoid overtopping. Such releases minimized losses from deficits and surpluses within the system. An example is the drought period from 1993 to 2006 when deficits were even higher under the deterministic model (Figure 3-6e & Figure 3-6f). This is possible because the deterministic model considers only perfect knowledge of inflow condition for one month in advance, while the stochastic model considers a vast range of possible hydroclimatic events.

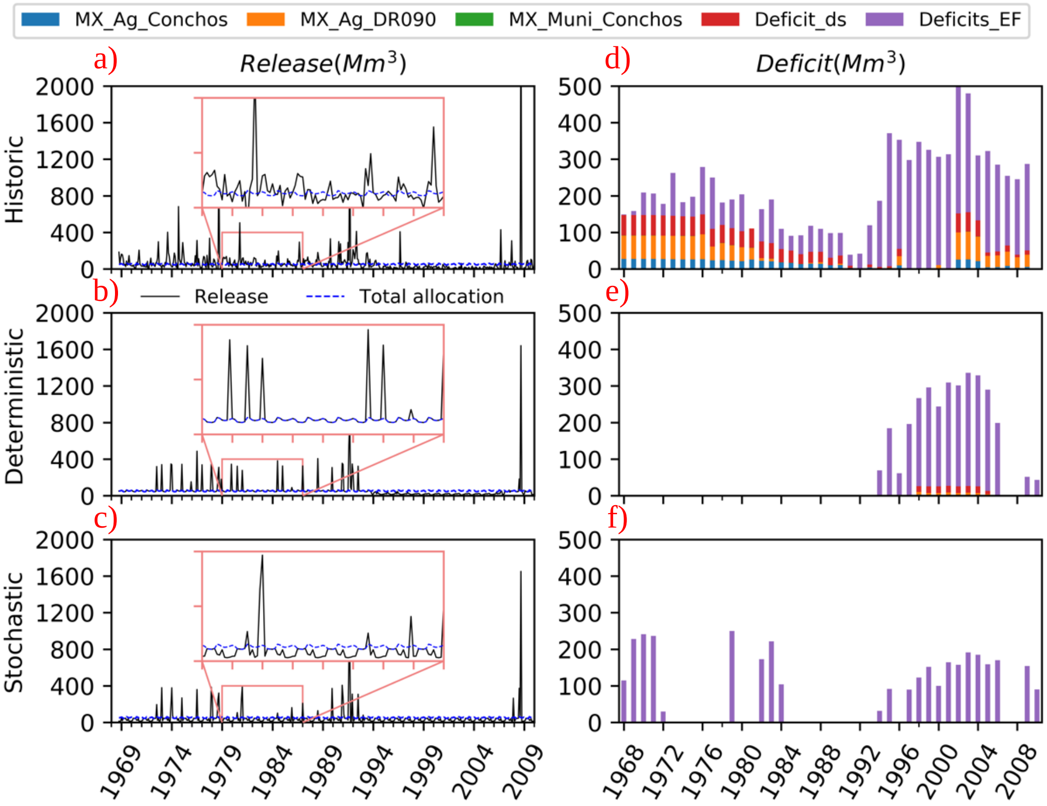

Figure 3-6. Historical observation, deterministic, and stochastic reservoir releases and system deficits. Inset is from 1979 to 1987.

Results from Figure 6 show that for the deterministic and stochastic models, all the deficits are allocated to the environment because environmental flows have lower priority. To reduce water deficits for the environment, deficit could be shared across users. Previous research shows that economic benefits from improved environmental outcomes such as reduced spending on silvery minnow reintroduction, a regional endangered species of fish, may outweigh the costs of increased deficits to other users (Ortiz-Partida et al. 2016).

Figure 7 presents economic outcomes for different uses under the historic observation and stochastic and deterministic models. Total net benefit from water use in the study area amounted to 5.5 million USD/year. This benefit can increase up to 400% under the deterministic model and 350% under the stochastic. The greatest improvement from these models is from avoided deficits in irrigated agriculture. Both models showed that timing of reservoir releases is important to reduce deficits and are more conservative during prolonged droughts, reducing deficits in irrigation demands. Irrigated agriculture resulted in higher benefits, 18.0 and 18.4 million USD/year, in the deterministic and stochastic models, respectively, compared to historical observations ($6.7 million USD/year).

In relation to environmental demands, the deterministic model, in particular, showed major benefits because there is usually sufficient water for human water demands even with increasing environmental water releases. In the stochastic model, it is important to highlight its performance during prolonged periods of drought (1993 to 2006) where it reduces the magnitude of deficits even when compared to the deterministic model.

In addition, the overall performance of the stochastic model falls short from the performance of the deterministic model, making it feasible to maximize regional economic benefits compared to perfect knowledge operations.

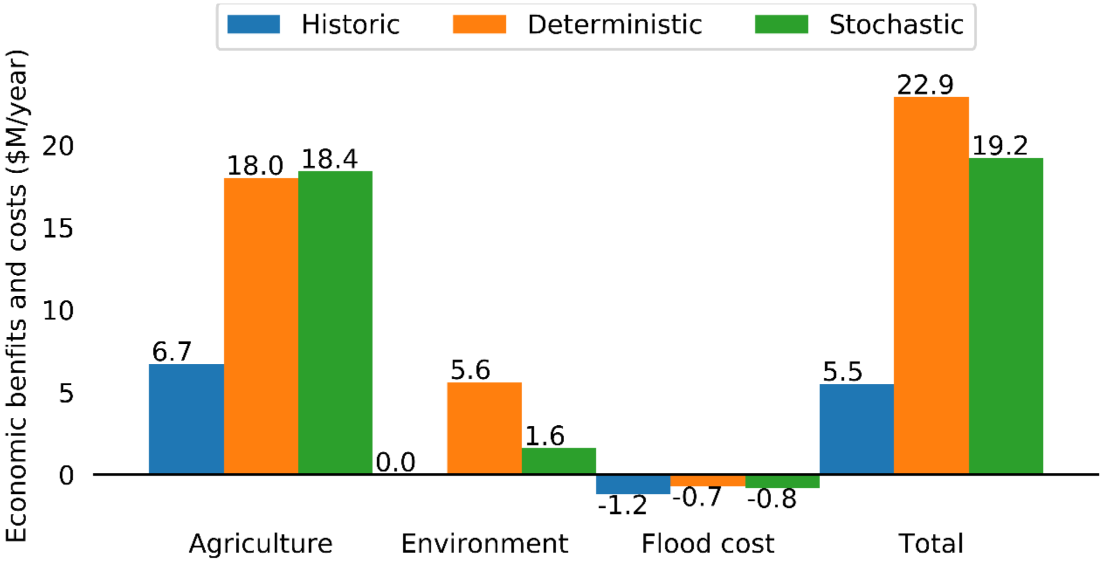

Figure 3-7. Comparison between economic benefits and costs under the historical observation, and the deterministic and stochastic models.

3.5.2 Reservoir operation policy performance

Across the calculated performance criteria, the stochastic model improved system performance considerably with respect to historical operations (Table 3-2). Such results indicate it is possible to increase economic benefits of reservoir management even with uncertain inflows and accounting for environmental water requirements. Historical LLL operations were conservative, making the system unreliable and vulnerable. The deterministic model shows that water availability in the system is sufficient to meet all demands within the Rio Conchos and improve supply to downstream users and environmental flow allocations.

Table 3-2. Comparison of performance of reservoir operation of historical observation and deterministic and stochastic models using the different performance criteria.

		Agricultural area 1 (%)	Agricultural area 2 (%)	Municipal (%)	Downstream demands (%)	EF targets (%)
Historic	Rel_t	11.0	69.0	11.0	13.0	22.0
	Rel_V	39.0	89.0	39.0	42.0	81.0
	Res	4.0	35.0	4.0	4.0	16.0
	Vul	68.0	36.0	68.0	67.0	24.0
	SI	**20.0**	**60.0**	**20.0**	**20.0**	**46.0**
Deterministic	Rel_t	99.2	97.0	100.0	92.9	72.2
	Rel_V	99.6	98.4	100.0	94.9	100.0
	Res	100.0	100.0	100.0	22.2	15.0
	Vul	0.0	0.1	0.0	0.4	49.5
	SI	**99.7**	**98.8**	**100.0**	**66.4**	**48.4**
Stochastic	Rel_t	100.0	100.0	100.0	100.0	49.6
	Rel_V	100.0	100.0	100.0	100.0	100.0
	Res	100.0	100.0	100.0	100.0	29.1
	Vul	0.0	0.0	0.0	0.0	64.9
	SI	**100.0**	**100.0**	**100.0**	**100.0**	**47.5**

Environmental water allocation was improved in terms of reliability in time and volume, particularly for the deterministic case, but given its high vulnerability and low resilience, the sustainability index for environmental flows is similar to the historical observation. However, the geographic location of the environmental flow requirements is far downstream from the reservoir and we neglected gains and losses of water in between, a limitation of the analysis.

Another limitation in the model is the use of a monthly time-step that simplifies floods and ecohydrological processes (e.g., inundation plain and flow relationships, duration of floodplain inundation). Future work should downscale the model to daily or hourly operations. The model may benefit by including variability in water demands and more reliable estimates of economic benefits and costs. Current estimates are considered linear, but costs may be exponential as deficits increase. Lastly, the model lacks water quality parameters (i.e. DO, temperature, sediment concentration) that should be considered for a more complete environmental implementation.

Despite the limitations, this study highlights the need to consider hydroclimatic variability in water management policies. The RGB is a basin with pronounced hydrologic variability through time. In the Rio Conchos, monthly flow can range from around 2 Mm^3 to more than 1800 Mm^3. Many other basins around the world have similar variability that should be included when designing water operations policies. Moreover, the results of this study also demonstrate the potential to improve water management at a relatively low cost by evaluating and adjusting the operation of infrastructure. Changing system operation does not generally involve costly infrastructure and considering the environment has potential to reduce the cost of channel restoration.

While many studies now consider environmental objectives alongside more traditional water demands (Momblanch 2016), challenges remain to balance these objectives. River ecosystems need variability to support various ecosystem functions (Poff et al. 1997). Therefore, in addition to the goal of human water supply, this study considered environmental demand rather than a minimum flow constraint. This decision acknowledges that the environment requires variable hydrology and better allows for synergies between environmental and other user by providing variable flows in the channel when there is sufficient water. Thousands of reservoirs worldwide remain sub-optimally managed, and there is a need to continue to improve operation policies to reduce the often high social and environmental costs of reservoir management and identify synergies between human and environmental water management objectives.

3.6 Conclusions

Unreliable water supply, unmet environmental flow requirements and flood events are often a consequence of uncertainty and limited knowledge about reservoir inflows. Different approaches have been considered in the literature to identify reservoir releases in time and volume that maximize benefits or minimize costs for various users, commonly including agriculture, industry, urban water supply, hydropower, flood control, and recreation. The stochastic optimization framework proposed here is a risk-informed decision support system for water resource management to address water scarcity challenges and inherent risks. A novel two-stage stochastic optimization formulation is shown to develop improved operations for a multipurpose reservoir. The stochastic model generally outperforms historic reservoir management and performs similarly to the deterministic model with perfect hydrologic knowledge. Results indicate that integrating hydrologic variability into optimization models enables a broader planning spectrum and allows managers to prepare for low probability but costly events. This formulation could be particularly useful for improving operations under increasing hydroclimatic uncertainty and more intense and frequent droughts and floods under the imminent climate change. This study also expands the global research on optimizing reservoir operations by determining maximum economic benefit under hydrologic uncertainty while balancing human and environmental water demands.

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Chapter 4 Overall dissertation conclusions and discussion

Discussion and limitations of the framework

The motivation for this research was to answer the question: *how can water resources can allocated to provide water for the preservation and restoration of aquatic and riparian ecosystems without affecting current and future urban, agriculture, and recreational water uses, and without increasing flood risk?* Answering this question involved the identification of water sources, water demands, water-related economic drivers, environmental flow targets, allocation priorities, and other variables for the development of modeling tools capable of representing a regional water system.

The research question was only addressed at a planning level and from a hydrologic perspective. The complexity of the question requires considering sociopolitical aspects to account for stakeholders and government interests in the actual change of reservoir re-operation policies. This framework and future modeling efforts will improve by refining the spatial and temporal scales to better represent hydraulic components and improve the representation of floods and river floodplain-ecosystems dynamics.

There is a vast amount of information available and studies performed in the RGB and yet, there is room for research and scientific advancement. The geodatabase made it evident that the fragmentation of the basin is not only political but also scientific. The geodatabase was developed with the hope of elucidating this scientific fragmentation and incentivizing that new studies consider both sides of the border in their research.

The characterization of modeling tools in the basin served to identify some data gaps, but it would be valuable to assess the connectivity of different models towards developing a holistic modeling tool. Such a tool could link water management with ecosystems response and be included during a decision-making process for water management in the basin. However, given the current fragmentation of the basin, it is hard to visualize a tool that encompasses the diverse and often divergent interest of stakeholders across counties, states, and countries.

With respect to modeling tools, traditional and new methods can be used to address the current challenge of protecting the environment and providing water to meet human goals. However, despite having the available technology and methods to balance human and environmental water needs, changing reservoir operation policies in the basin would require a process of binational negotiation because of the political complexity of a basin. The negotiation would require the involvement of a number of stakeholders, including the International Boundary and Water Commission (IBWC). The complete framework should incorporate a shared vision from stakeholders in the U.S. and Mexico. A first stage should consider pilot reservoir releases and adaptive management with monitoring and evaluation of their effects in the society, water users, and aquatic and riparian ecosystems.

While Chapter 3 incorporates future hydroclimatic uncertainty, the RGB basin is characterized by extreme climatic events that includes intense floods and prolonged droughts. Future research should focus on a detailed estimation of climate variability in the basin and the development of adaptation strategies that goes beyond reservoir re-operation.

Conclusions

This research established a process of identifying, evaluating, and developing strategies to improve water resources management for current and future generations, and designed tools to test strategies that balanced human and environmental water needs. The overall goal of this research was accomplished by developing a framework comprised of three elements: (1) A needs assessment through a literature review and the construction of a geodatabase to characterize studies and tools already completed and built, and to identify key research gaps for human and environmental water resources management that can be addressed through my research; (2) An identification and quantification of key water-related economic drivers informed by the needs assessment, and the use of a water planning model to determine the hydrologic and economic feasibility of environmental flows implementation; and (3) The design of a methodology to derive robust reservoir operation policies for human and environmental water needs that consider hydroclimatic uncertainty. Suggested outcomes should be coupled with land use management, policy development, and local communities' welfare and values. The implementation processes also should consider a cooperative and adaptive management framework to account for the unreliability of future water resources in a changing climate.

Together, my three chapters expand the global research on human and environmental water resources management, including simulation and optimization models for reservoir operations that provide EFs. This research challenges the current paradigm in which human and environmental objectives are mutually exclusive, calls for binational considerations in the management of transboundary river basins, and lays the foundation for future research focused on the integration of environmental health and economic feasibility into water resources management.

Chapter 5 Appendix

5.1 Rio Grande/Bravo datasets and description

The datasets, a short description, the source, and the original download link for each of the original datasets are included in the following tables.

Table 5-1. Data sources acronyms

ASTER	Advance Spaceborne Thermal Emission and Reflection
CCMEO	Canada Center for Mapping and Earth Observations
CDSS	Colorado Decision Support System
CDWR	Colorado Division of Water Resources
Chih	Chihuahua
CO	Colorado
Coah	Coahuila
CONABIO	National Commission for Knowledge and Biodiversity of Mexico
CONAGUA	National Water Commission of Mexico
CONANP	National Commission of Natural Protected Areas of Mexico
CWCB	Colorado Water Conservation Board
Dgo	Durango
DWR	Colorado Division of Water Resources
EDAC	Earth Data Analysis Center
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
GAP	Gap Analysis Program
ISCS	Idaho State Climate Services
INEGI	National Institute of Statistics, Geography, and Informatics of Mexico
IUCN	International Union for Conservation of Nature
MX	Mexico
NACSE	Northwest Alliance for Computational Sciences and Engineering
NHD	National Hydrography Dataset of United States
Nl	Nuevo León
NM	New Mexico
NPS	National Park Service of the United States
NRCS	Natural Resources Conservation Service
OSE	New Mexico Office of the State Engineer
OSE	New Mexico Office of the State Engineer
PADUS	Protected Areas Database of the United States
Tamps	Tamaulipas
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
TX	Texas
US	United States
USCB	United States Census Bureau
USDA	United States Department of Agriculture

USDC	United States Department of Commerce
USDOI	United States Department of the Interior
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

5.1.1 Boundaries and populated areas datasets

Table 5-2 Boundaries and populated places original datasets

Dataset	Short description	Source
US_states	US states boundaries	USDC, and USCB Geography Division
MX_states	MX states boundaries	CONABIO and INEGI
CO_counties	Colorado county boundaries	USDC, and USCB Geography Division
NM_counties	New Mexico county boundaries	USDC, and USCB Geography Division
TX_counties	Texas county boundaries	USDC, and USCB Geography Division
Chih_municipalities	Chihuahua municipalities boundaries	INEGI
Coah_municipalities	Coahuila municipalities boundaries	INEGI
Dgo_municipalities	Durango municipalities boundaries	INEGI
Nl_municipalities	Nuevo Leon municipalities boundaries	INEGI
Tamps_municipalities	Tamaulipas municipalities boundaries	INEGI
CO_cities_polygones	Geographic boundaries of census designated places in Colorado	USDC, and USCB Geography Division
NM_cities_polygones	Geographic boundaries of census designated places in New Mexico	USDC, and USCB Geography Division
TX_cities_polygones	Geographic boundaries of census designated places in Texas	USDC, and USCB Geography Division
MX_cities_polygones	Geographic boundaries of cities in Mexico	INEGI
US_cities	Location of 38,186 populated places in United States	National Atlas of the United States form the USGS
NM_cities	Points for 1600 populated places, cities and towns, in New Mexico	EDAC University of New Mexico
MX_cities	Location of 192,245 populated places in Mexico in 2010	CONABIO and INEGI
Chih_services	Location of city services in the state of Chihuahua (i.e. schools, temples, etc)	INEGI
Coah_services	Location of city services in the state of Coahuila (i.e. schools, temples, etc)	INEGI
Dgo_services	Location of city services in the state of Durango (i.e. schools, temples, etc)	INEGI
Nl_services	Location of city services in the state of Nuevo Leon (i.e. schools, temples, etc)	INEGI

Tamps_services	Location of city services in the state of Tamaulipas (i.e. schools, temples, etc)	INEGI
CO_cities_pop_1910_2014	Population data 1910 - 2014 added to the cities polygons shapefiles in Colorado	USDC, and USCB Geography Division
NM_cities_pop_1910_2014	Population data 1910 - 2014 added to the cities polygons shapefiles in Colorado	USDC, and USCB Geography Division
TX_cities_pop_1860_2014	Population data 1860 - 2014 added to the cities polygons shapefiles in Colorado	USDC, and USCB Geography Division
MX_cities_pop_1910-2010	Population data 1910 - 2010 added to the cities polygons shapefiles in Mexico	CONABIO and INEGI

5.1.2 Hydrology and climate datasets

Table 5-3 Hydrology and climate original datasets

Dataset	Short description	Source
CO_NHD_M08	Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in Colorado	USGS and NHD
NM_NHD_M35	Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in New Mexico	USGS and NHD
TX_NHD_M48	Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in Texas	USGS and NHD
TX_precip_1981-2010_NRCS	Average monthly and annual precipitation for the climatological period 1981-2010.	TWDB with data from NRCS
MX_hydrometric_stations	Location 1126 hydrometric stations within Mexico	CONABIO
RGB_monitoring_points	The monitoring points is a compilation of hydro-climatic stations, streamflow gages, and others. The shapefile contains its name, source, purpose and location	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.

IBWC_streamflow_gages	Geographic location of IBWC streamflow gages from in the Rio Grande/Bravo	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.
USGS_streamflow_gages	Geographic location of USGS streamflow gages from in the Rio Grande/Bravo	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.
MX_streamflow_gages	Geographic location of CONAGUA streamflow gages in the Rio Grande/Bravo	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.
RGB_waterbodies	Geographic boundaries of the Rio Grande/Bravo waterbodies (lakes, reservoirs)	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.
RGB_main_rivers	Extent of main rivers in the Rio Grande/Bravo	Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model.
RGB_FAO_prcXX_mmm	12 Global map of monthly precipitation 1960 - 1990	FAO GeoNetwork
RGB_US_mean_yr_prc	Raster files of annual mean precipitation values in the United States side of the Rio Grande/Bravo (1981-2010)	NACSE, PRISM Climate Group
RGB_MX_mean_yr_prc	Isohyets of mean annual precipitation in the Mexican side of the RGB	INEGI
RGB_MX_nunez_prc_mmm	Raster files of monthly mean precipitation values in the Mexican side of the Rio Grande/Bravo created by Daniel Nunez et al with data from 201 hydro-climatic stations.	Nuñez-Lopez, D., Treviño-Garza, E. J., Reyes-Garza, V. M., Muñoz-Robles, C. A., Aguirre-Calderón, O. A., & Jiménez-Pérez, J. (2013). Interpolación Espacial de la Precipitación Media Mensual en la Cuenca del Rio Bravo/Grande. Tecnología y Ciencias del Agua, IV(2), 185-193.

RGB_US_mean_yr_tmp	Raster files of annual mean temperature values in the United States side of the Rio Grande/Bravo (1981-2010)	NACSE, PRISM Climate Group
RGB_US_max_yr_tmp	Raster files of annual maximum temperature values in the United States side of the Rio Grande/Bravo (1981-2010)	NACSE, PRISM Climate Group
RGB_MX_min_yr_tmp	Raster files of annual minimum temperature values in the United States side of the Rio Grande/Bravo (1981-2010)	NACSE, PRISM Climate Group
RGB_FAO_evpXX_mmm	12 global map of monthly evapotranspiration 1960 - 1990	FAO GeoNetwork
RGB_MX_mean_yr_evap	Mean annual evapotranspiration in the Mexican side of the Rio Grande/Bravo	INEGI
RGB_MX_mean_yr_tmp	Isotherms of mean annual temperature 1910-2009 in the Mexican side of the Rio Grande/Bravo	INEGI
MX_climate_unit	Denomination of climate units in the Mexican side of the Rio Grande/Bravo	INEGI
US_climate_unit	Denomination of climate units in the United States side of the Rio Grande/Bravo according to a Koppen climate classification	ISCS (Point of Contact)
US_Aquifers	Shallowest principal aquifers of the conterminous United States	USGS Water Resources NSDI Node
TX_major_aquifers	The 9 Major aquifers of Texas according to TWDB.	TWDB
TX_minor_aquifers	The 21 Minor aquifers of Texas according to TWDB.	TWDB
MX_aquifers	The 653 aquifers in Mexico	CONAGUA
MX_Hydrogeology	Hydrogeology of Mexico	CONABIO
NM_groundwater_basins	This data represents the locations of the declared ground water basins within New Mexico administered by the New Mexico Office of the State Engineer.	OSE / Interstate stream Commission

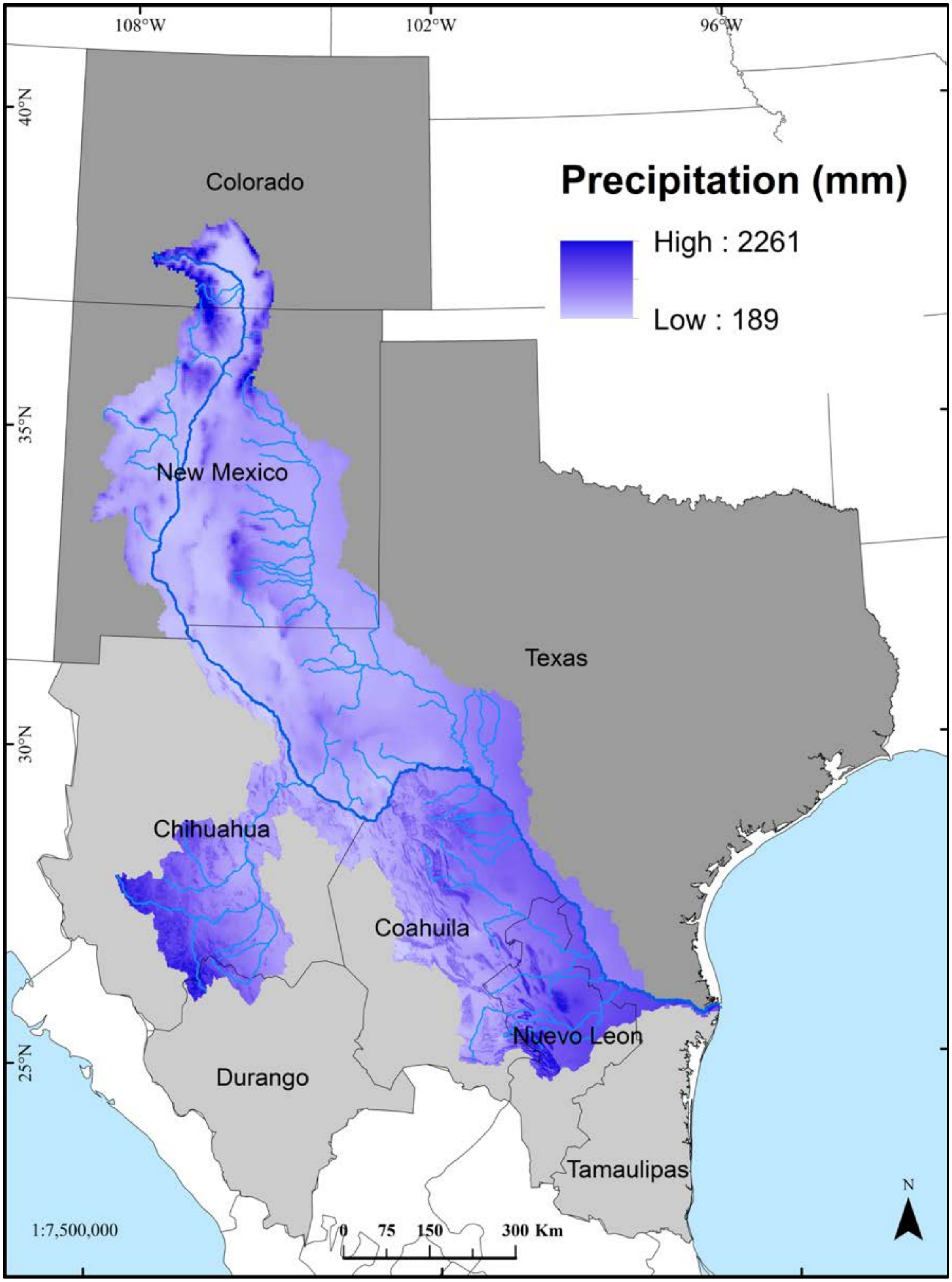

Figure 5-1. Example map: mean precipitation in the RGB basin.

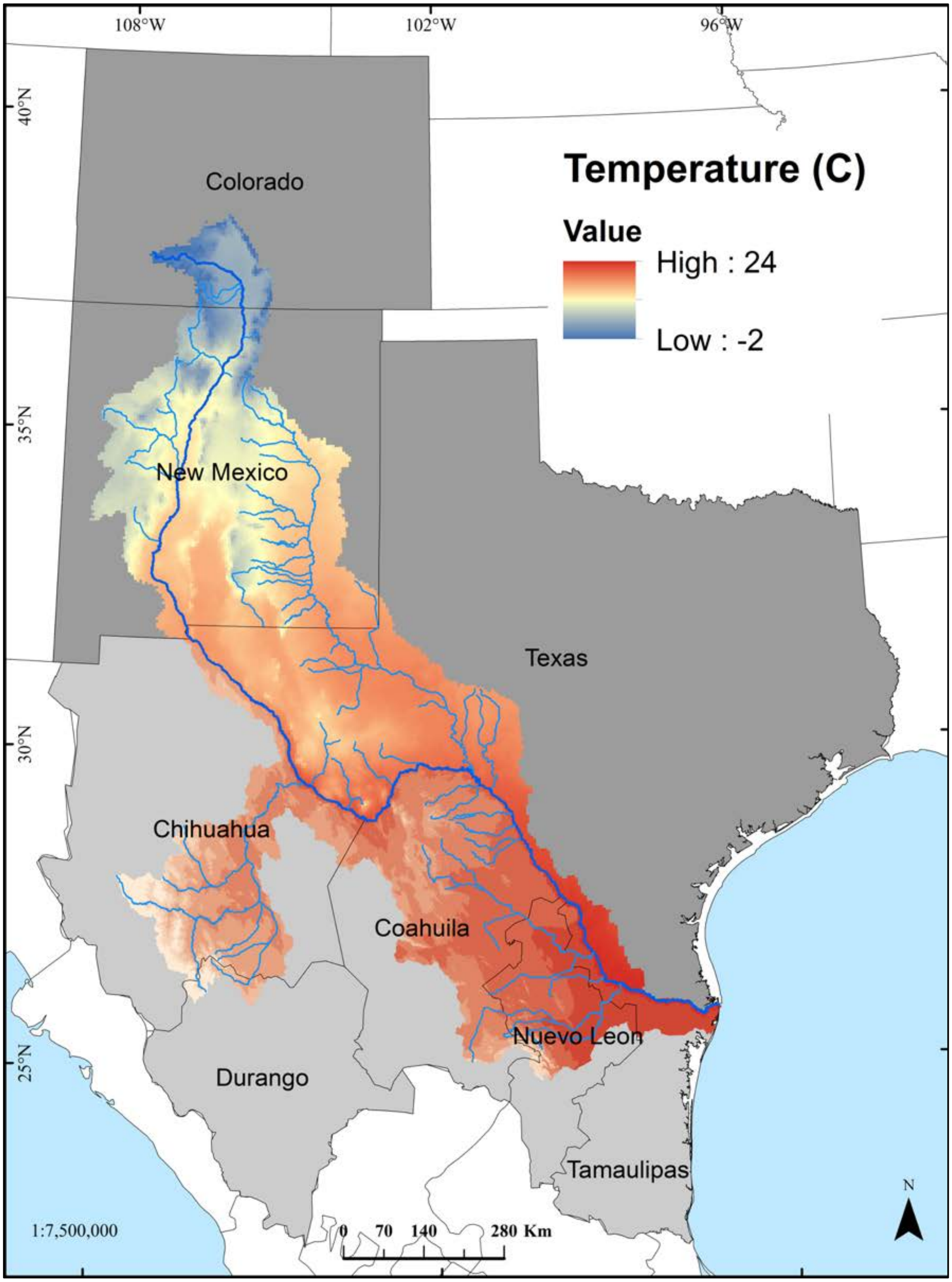

Figure 5-2. Example map: mean temperature in the RGB basin.

5.1.3 Environment datasets

Table 5-4 Environment original datasets

Dataset	Short description	Source
US_Critical_Habitat	Critical habitat are areas considered essential for the conservation of a listed species	USFWS
MX_Natural_Protected_Areas	Geographic boundaries of Federal Natural Protected Areas in Mexico	CONANP
MX_Ramsar_sites	Information and geographic boundaries of 142 Ramsar sites in Mexico	CONANP
CO_protected_areas	Geographic boundaries of protected Areas in Colorado	PADUS, version 1.3, USGS, GAP
NM_protected_areas	Geographic boundaries of protected Areas in New Mexico	PADUS, version 1.3, USGS, GAP
TX_protected_areas	Geographic boundaries of protected Areas in Texas	PADUS, version 1.3, USGS, GAP
Silvery_minnow_range	Hybognathus amarus (Silvery minnow) distribution information on the RGB	The IUCN Red List of Threatened Species(tm))
US_National_parks	National Park boundaries in United States	NPS

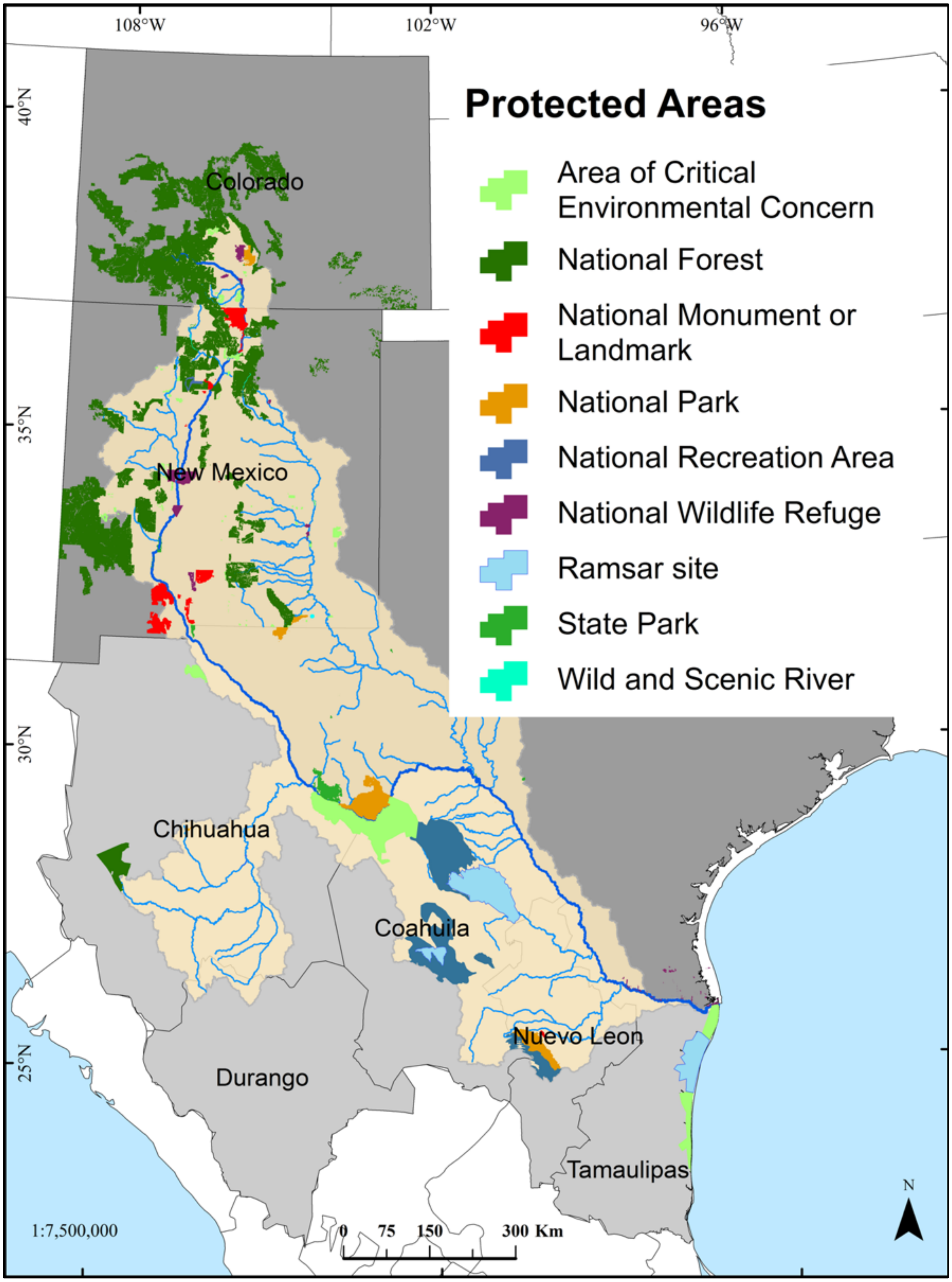

Figure 5-3. Example map: natural protected areas in the RGB basin.

5.1.4 Land use and Cover datasets

Table 5-5 Land use and cover original datasets

Dataset	Short description	Source
CO_div3_districts	Colorado Division of Water Resources (DWR) Water District Boundaries. District boundaries are administrative boundaries set by the State Engineer, which are based primarily on stream drainage systems.	Colorado Decision Support Systems (CDSS) DWR and CWCB
CO_Div3_Irrig_XXXX	A collection on 9 dataset that contain spatial and informational database of irrigated parcels in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in support of the Rio Grande Decision Support Tool (RGDSS).	Colorado Decision Support Systems (CDSS) DWR and CWCB
CO_Div3_Ditches_XXXX	A collection on 9 dataset that contain spatial and informational database of ditch headgates associated with irrigated lands in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in support of the Rio Grande Decision Support Tool (RGDSS).	Colorado Decision Support Systems (CDSS) DWR and CWCB
CO_Div3_Wells_XXXX	A collection on 9 datasets that contain spatial and informational database of wells associated with irrigated lands in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in support of the Rio Grande Decision Support Tool (RGDSS).	Colorado Decision Support Systems (CDSS) DWR and CWCB
RGB_major_soils	Major Soil Groups of the World (FGGD)	FAO GeoNetwork
CO_ssurgo	Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for Colorado. SSURGO (Soil Survey Geographic Database)	USDA and NRCS
NM_ssurgo	Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for New Mexico. (Soil Survey Geographic Database)	USDA and NRCS

TX_ssurgo	Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for Texas. (Soil Survey Geographic Database)	USDA and NRCS
MX_soils	Soil type in the Mexican side of the Rio Grande/Bravo basin.	CONABIO
RGB_ESA_land_cover_2000	Land Cover Map 2000 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA)	Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA)
RGB_ESA_land_cover_2005	Land Cover Map 2005 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA)	Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA)
RGB_ESA_land_cover_2010	Land Cover Map 2010 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA)	Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA)
RGB_MX_land_cover_2011	Land cover in 2011 for the Mexican side of the Rio Grande/Bravo basin	CCMEO, CONABIO, INEGI, USGS
RGB_US_land_cover_2011	National Land Cover Database 2011 for the United States side of the Rio Grande/Bravo basin (NLCD 2011)	USDI and USGS
RGB_US_agriculture_XXXX	Collection of 8 (2008-2016) rasters for the United States side of the Rio Grande/Bravo that represent combine the CropScape and Cropland Data Layers for Colorado, New Mexico, and Texas. The information provide acreage estimates to the Agricultural Statistics Board for the state's major commodities and (2) produce digital, crop-specific, categorized geo-referenced output products.	USDA, National Agricultural Statistics Service
RGB_dem	30m spatial resolution of digital elevation model for the Rio Grande/Bravo basin	ASTER global digital elevation model
RGB_slope	Percentage slope	ASTER global digital elevation model

5.1.5 Water Management datasets

Table 5-6 Water management original datasets

Dataset	Short description	Source
TX_water_districts	Geographic location of water districts within the state of Texas	TCEQ
NM_water_districts	Geographic location of water districts within the state of New Mexico	OSE, Interstate stream Commission
CO_water_districts	Geographic location of water districts within the state of Colorado	DWR and CWCB
MX_Dams	Location of dams in Mexico	CONAGUA
US_Dams	Location of dams in United States	National Atlas of the United States form the USGS

5.2 Rio Grande/Bravo models description summary

Hearne and United States. Bureau of Indian Affairs. (1985)

It is a three dimensional groundwater simulation model of the Tesuque Aquifer System, central New Mexico, build to evaluate the aquifer response of an irrigation development plan. The rivers considered in the model include the Santa Cruz, Pojoaque, Santa Fe, and the RGB. The Pojoaque River resulted in the most affected surface water system by the development. After 50 years of withdrawals a flow reduction of 18.77 cfs ant 10.13 cfs resulted from the simulation with and without the irrigation development respectively. The model was developed using a precursor of MODFLOW and it was superseded by later models that are explained with more detail in this report. Therefore, this model is not suitable for developing or testing environmental flow objectives or assessing drought effects.

Kernodle and Scott (1986) and Kernodle et al. (1987)

It is a three dimensional groundwater simulation model of the Albuquerque-Belen basin in central New Mexico. The purpose of the model was to simulate steady state groundwater flow condition prior to 1960 as there were no significant groundwater level changes prior to that year. The rivers considered in the model include the Rio Puerco, Rio Salado, Jemez River, and the RGB. The model was updated to perform transient simulations of hydraulic head from 1907 to 1979 to better understand the hydrologic system of the basin and evaluate its response to groundwater withdrawals stress. Results showed that about 68% of the groundwater withdrawals came from surface water depletions, 25% directly from the aquifer storage, and 7% was induced horizontal flow from the Santo Domingo basin. Despite not being directly applicable for developing or testing environmental flow objectives or assessing drought effects, results from this model illustrates the degree in which groundwater extractions can reduce surface water flow.

McAda and Wasiolek (1988) and McAda (1990)

It is a three dimensional groundwater simulation model of the Tesuque aquifer, central New Mexico, used to assess the effects of groundwater extractions on the system. The rivers considered in the model include the Pojoaque River, Rio Tesuque, Santa Fe River, and the RGB. The updated version of the model focused on groundwater pumping from a single well and proposed that withdrawals would implicitly capture surface water from nearby rivers, in this case, decreasing the flow of the Rio Grande. Groundwater table was expected to decline as well as discharge to the Rio Grande from tributaries affected by groundwater extractions. The model is not suitable for developing or testing environmental flow objectives or assessing drought effects because of its scale, but it remarks the importance of considering groundwater extractions and their effect on streamflow reductions.

Kernodle et al. (1995)

It is a three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico, to describe groundwater flow under different future scenarios. The rivers considered are the RGB and reaches of the Jemez River, Rio Salado, and Rio Puerco. The model simulated 2,400 square miles to a depth of 2,020 feet below the water table and with 11 layers. The extent of the model made it computationally demanding and therefore insufficiently tested and validated. The efforts, however, improved the understanding of the hydrologic system and serve as foundation for other models. The extent of the model would make it suitable to link with other models and test the system response; however, the model was not rigorously calibrated, validated, or tested.

Frenzel (1995)

It is a three dimensional groundwater simulation model of the Tesuque aquifer, central New Mexico, used to assess the effects of groundwater extractions on the system near Los Alamos. It is a modification of McAda and Wasiolek (1988) model to better simulate vertical groundwater movement. Similarly, the rivers considered in the model include the Pojoaque River, Rio Tesuque, Santa Fe River, and the RGB. The model was used to estimate drawdowns at a well field from projected groundwater extractions in different areas. They suggested that developing a more accurate representation of the Geologic formations would improve the understanding of the systems groundwater flow. Like its previous version, the model is not suitable for developing or testing environmental flow objectives or assessing drought effects because of its scale, but it remarks the importance of considering groundwater extractions and their effect on streamflow reductions.

Tiedeman et al. (1998)

It is a modification of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico created by Kernodle et al. (1995). The modification improved the calibration using non-linear regression analysis, enhanced the representation of the hydrogeology, and revised aquifer parameters. However, they made a discretization of spatial and temporal variables to reduce computational time. The rivers considered are the RGB and reaches of the Jemez River, Rio Salado, and Rio Puerco. Due to its scale, the model could potentially be use for modeling environmental flow alternatives, such as reduction of pumping to keep more water in the river. However, is not included in the selected model because it was later updated.

Bravo-Inclan et al. (1999)

It is a hydrologic model for the RGB and the Pecos River. The model includes topographic, climatologic, and soil data. Despite being the only hydrologic model that includes the whole basin the documentation is incomplete and result lack of utility because they only show simulated and observed data for three points of the entire basin: Otowi Bridge, Cochiti Dam, Elephant Butte, and Red Bluff in the Pecos River). Therefore, there is not enough information to select as suitable for developing or testing environmental flow objectives or assessing drought effects.

Schmandt et al. (2000)

Schmandt et al. developed two different models: A reservoir operation model for Amistad-Falcon reservoir system, and a water allocation model to represent the hydrology from below Falcon reservoir to the Gulf of Mexico using a mass balance approach. The models were coupled to analyze water resources and management issues, and identify options for water management for a sustainable regional development. The rivers included are the mainstem of the RGB from Amistad Reservoir to Brownsville, the Rio Conchos, Pecos and Devils rivers, Rio Salado, and Rio San Juan. The project evaluated water availability under possible future drought and development scenarios. Results show a worst-case scenario in which the quantity of water that can be guaranteed even during a critical period, known as firm yield, decreases by 31% from current conditions of 230 mcm/month for the Amistad-Falcon reservoir system. Results suggest that there is enough water and of acceptable quality to support the increasing population, however there need to be changes in the complex array of local, state, regional, and federal water allocation and management strategies in both countries to maintain aquatic and riparian ecosystems. Due to its extent and characteristics, the model is suitable to test environmental flow objectives and assessing drought effects as it integrates water quality, and ecologic parameters as well as water scarcity future scenarios.

Barroll (2001)

It is a modification of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico created by Tiedeman et al. (1998). It also uses data from hydraulic parameter from Kernodle (1998); Kernodle et al. (1995). The model was used to simulate stream depletions and groundwater drawdowns to support water rights in the Albuquerque Basin. The model considers the RGB from Cochiti Dam to San Acacia, including the Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, and Rio Salado. The model was updated with new hydrogeologic data that was being collected; therefore, this particular model is not suitable for developing or testing environmental flow objectives or assessing drought effect, but the later model is.

Wagner Gómez and Echeverría Vaquero (2001)

It is a water allocation model of the Rio Conchos basin developed to understand water problems and simulate alternative future scenarios considering water conveyance efficiency, irrigation demand restrictions, population growth, allocation policies, and changes in water supply sources. The rivers involved in the model are the Rio Conchos, Rio San Pedro, and Rio Florido. The model successfully represents the system and incorporates parameters to include environmental releases from reservoirs. The model seems focused on reducing the Chihuahua-Sacramento aquifer overdraft by providing water supply to the city from Luis L. Leon reservoir.

There is not enough documentation to evaluate how it would impact agriculture water supply. However, it is a suitable model to evaluate Rio Conchos system responses to EF and drought periods.

McAda and Barroll (2002)

It is an update of Barroll (2001) three dimensional groundwater simulation model of the Santa Fe Group system to better understand the hydrogeology of the basin and provide a tool for water management planners. It considers the mainstem of the RGB from Cochiti Dam to San Acacia and some of the tributaries: Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, and Rio Salado. The model determines the firm yield of the aquifer and apply water management options to revers overdraft conditions that would restore water table levels to allow groundwater to flow into the streams instead of the water percolating into the ground. Similar conditions could be evaluated under drought scenarios. Modified versions of this model are being used by the New Mexico Office of the State (OSE) Engineer and to set boundary conditions for the Upper Rio Grande Water Operation Model (URGWOM).

Weeden (1999)

It is a three dimensional model groundwater simulation model of the Mesilla Bolson aquifer in New Mexico Lower Rio Grande Basin. The purpose of the model was to evaluate the response of the RGB flow to municipal and industrial groundwater pumping and to assess the effects of non-irrigation releases from Caballo reservoir on the water budget to evaluate water supply alternatives to the city of El Paso, Texas. The model considers the mainstem of the RGB below Caballo dam to El Paso del Norte. Similar than models developed upstream, the outputs show decrease in RGB flow as pumping increases. Also, non-irrigation releases from Caballo reservoir do not seem to have significant effects on the water budget. It distinguishes between two seasons; the dry season may be useful to represent drought scenarios. The model was updated by CH2MHILL (2002).

CH2MHILL (2002)

It is a modification from a three dimensional groundwater simulation model of the Mesilla Bolson aquifer, New Mexico Lower Rio Grande Basin, created by Weeden (1999). The model was developed to increase understanding of the groundwater system of the Cañutillo wellfield area and as a water operation tool to analyze different operation scenarios. The model used the newest groundwater data to create boundary conditions for a local scale model. It would be important to consider the surface water interaction to account for instream base flow when setting targets for environmental flow.

Tate (2002)

It is a step by step optimization model for the Lower Rio Grande (Fort Quitman to the Gulf of Mexico). Its purpose was to simulate drought in the basin and allow policy maker to evaluate alternatives. The rivers involved are the RGB, Pecos and Devils rivers, Rio Conchos, San Diego, Rio Escondido, Rio Alamo, and Rio San Rodrigo. Optimization model often needs to incorporate more simplifications than simulation models; this model assumes no change to irrigation areas, and it does not consider environmental issues such as water quality, endangered species, invasive species, in streamflow requirements, or delta outflows. Environmental concerns should be included to be useful for evaluating environmental flow targets.

IBWC (2003)

It is a hydraulic model to re-design a flood control project in the lower RGB, upstream Peñitas (river mile 186) to downstream of Brownville (river mile 28). It was part of the Lower Rio Grande Flood Control Project (LRGFCP). The model was used to determine design flood flows under existing vegetation conditions. It could be used now to determine water stage for evaluating environmental flow targets in relation to aquatic species ecosystem functions; however, the data is old and might have changed dramatically.

Heywood and Yager (2003)

It is a three dimensional groundwater simulation model of the middle RGB to evaluate water management strategies for Hueco Bolson Aquifer. It considers the RGB mainstem across the aquifer in Texas. A monthly temporal discretization allowed improving seepage computation from the river. As the other groundwater models, it could potentially be applied to infer the baseflow and quantify the effects of groundwater pumping in the RGB flow.

Tidwell et al. (2004)

It is a systems dynamics Model for community-based water planning applied to the middle RGB. The purposes were to quantify and compare water management alternatives, provide education on the complexity of regional water systems, and engage the public in the decision process. The model includes the mainstem of the RGB and considers the city of Albuquerque along with several smaller communities, Rio Rancho, Belen, Los Lunas, and Bernalillo are the most representative. The models allow stakeholders to observe groundwater changes, water saved, and cots of certain actions. It was used as an educational and public engagement tool that informed the public about the complex interactions between systems and the water cycle. It does not consider the environment as an independent element in the system. It seems to be included only on the water that is left on the river. It was not expected to be used as a predictive or realistic scenarios management tool, therefore it is only suitable for testing or developing environmental flow targets and drought scenarios on a qualitatively basis.

Sanford et al. (2004)

It is a modified version of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico, developed by McAda and Barroll (2002). The rivers considered are the RGB, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Arroyo Tonque, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado. Compared to previous models, this model incorporated better interpretations of the subsurface and the surfacewater-groundwater interaction in the inner valley. The model was developed to improve estimates of model parameters, including recharge values by using ^{14}C (carbon isotope) activities. This model could be applicable to stablish the predevelopment conditions of the aquifer and recharge rates.

Tetra Tech Inc (2004)

It is a two dimensional hydraulic water routing model to compute overbank flood inundation to support the Upper Rio Grande Water Operations Model (URGWOM), analyses of restoration projects, and the design of flood mitigation projects. The model extends along the RGB from Cochiti reservoir to the headwaters of Elephant Butte reservoir. It could give the depth duration in hours and could be used to identify and conserve areas of protection for the silvery minnow or other aquatic and riparian species; however, the crossection measurements may be unreliable now. Due to its detail and extent, an updated version of this model would be very relevant for developing and testing environmental flow targets.

R. J. Brandes Company (2004) Water Availability Model (WAM)

It is a simulation model governed by the continuity equation for Texas. The model determines water availability in the basin considering different policy and planning scenarios in accordance with the Prior Water Appropriation Doctrine and TCEQ Rio Grande operating rules. The model includes all the main reaches of the basin from below New Mexico state line. The main objectives of the model were to determine the amount of water that would be available during an extended drought for all permit holders; and evaluate potential impacts of reusing municipal and industrial effluent on existing water uses. The model is suitable for determining water available that could be allocated for EF or could be appropriated by environmental groups for these purposes. The model includes the available water also during extended drought scenarios.

Hathaway and Shafike (2006)

Three groundwater simulation models were developed: Upper Albuquerque (UAB) (Angostura Dam south to below Interstate 40 (I-40), Lower Albuquerque (LAB) (I-40 south to below the Bernalillo-Valencia county line. Belen (BEL) (The Bernalillo-Valencia county line to the Valencia-Socorro county line. These models can simulate surface and groundwater interactions within the floodplain of the RGB; their objective was to support the analysis of water management and restoration plans. These models had a much finer resolution (but smaller extent) than previous groundwater models developed for the area to be able to quantify water level changes in the floodplain of the RGB under different vegetation, river channel conditions, and water supplies. These models are suitable to developing and testing environmental flow objectives, and analyze system responses to drought scenarios. Results of the models show a minimal different on the water level by changing non-native to native riparian vegetation; however, the difference was considerable in areas with high salt cedar density. These models were developed as part of the Endangered Species Act Collaborative Program for the Middle Rio Grande. They have good applicability in a high scale but relatively low are coverage. Water flow targets for the silvery minnow and the southwest willow flycatcher could be developed from these models.

Keating et al. (2005)

It is a three dimensional groundwater simulation model for the Pajarito plateau in the Moddle Rio Grande Basin (also known as Albuquerque Basin). The model is useful for quantifying the magnitude of different hydrologic elements in the aquifer water budget. This model can be used to interpret contaminant transport velocities in the vadose zone. The model can be used for interpreting contaminant migration velocities in the overlying vadose zone. It considers the RGB through the Albuquerque basin, and the Santa Cruz River, Rio Chama, Santa Clara Creek, Rio Frijoles, Santa Fe, Pojoaque Creek. Results from this model suggest that about 70% of the annual recharge in the Pajarito plateau is extracted from the aquifer storage, affecting also discharge to the RGB. The model provides important insights on the effects of groundwater pumping to the aquifer storage and impacts on the RGB flow; however, the extent of the model is not sufficient to consider it for testing EF.

Booker et al. (2005)

It is a non-linear programming optimization model for the New Mexico Upper Rio Grande. The model is developed to maximize total economic benefits from water resources allocation to test if institutional adjustments can reduce damages caused by drought. It considers the mainstem of the RGB and main tributaries. By incorporating more environmental constraints to the model could be applicable to test EF and evaluate their economic effects; so far it only incorporates minimum flow constraint for the Silvery Minnow. The model is also suitable to evaluate drought scenarios as it is its main focus; however, it considers drought scenarios in a simplified way by reducing the inflow in a certain percentage.

Teasley and McKinney (2005)

It is a mass balance simulation model of the Forgotten Reach of the RGB, from Fort Quitman to Ojinaga, above the Rio Conchos. The model was developed to determine effects on streamflow from restoration work along the river, and to recommends restoration hydrographs for the reach. Despite having uncertainty and limitation because of data availability, it might be possible to couple the recommended hydrograph from this document with other proposes hydrograph for environmental restoration, for example, the models developed by Lane et al. (2014); Sandoval-Solis and McKinney (2014). This model is useful for providing insights on the feasibility of EF in the area; however, the monthly time step is insufficient to develop EF targets as it would not be possible to evaluate the inundation plain and flow relationships, duration of floodplain inundation, water temperature, and flow recession.

MacClune et al. (2006)

Five groundwater simulation models were developed for Middle Rio Grande in New Mexico from the Angostura Diversion Dam to the northern edge of Bosque del Apache National Wildlife Refuge. The models goal was to simulate shallow riparian environments to develop restoration projects and river management strategies along the Rio Grande in New Mexico. The models seems to follow the same characteristics as the ones developed by Hathaway and Shafike (2006). Similarly, these models could have important consideration for assessing the impacts of environmental flow in riparian areas along the Rio Grande in Middle New Mexico. These models were developed as part of the Endangered Species Act Collaborative Program for the Middle Rio Grande.

Novak (2006)

It is a two dimensional hydraulic water routing for the Middle Rio Grande, from Cochiti Dam to Galisteo Creek. It was developed to measure spatial and temporal changes in channel geometry, discharge, and sediment in Cochiti Dam reach. The purpose was to estimates future potential conditions of the reach to help developing restoration projects for endangered species. This hydraulic model could help to evaluate the inundation plain and flow relationships, duration of floodplain inundation, and flow recession, as specific parameters to support silvery minnow habitat in the area, which is included in the current extent of the endangered fish. The reduced extent of the model, however, makes it difficult to consider for a basin wide tool.

Amato et al. (2006)

It is a hydrologic model for the Río Conchos basin that uses the rainfall runoff soil moisture method. It includes the Río Conchos, Río Sacramento, Río San Pedro, Río Balleza, Arroyo el Parral, and Río Florido. The model was constructed to explore the hydrologic capabilities of the Water Evaluation and Planning Platform (WEAP) (Yates et al. 2005). Results show a good approximation to both annual and monthly flows. Hydrologic models allow inputs from climate change models, as they consider precipitation, temperature and other climate variables as part of the inputs. The model could be useful to evaluate systems response under climate change scenarios. An updated version of this model developed by Ingol-Blanco and McKinney (2009) is considered for testing EFs.

Ho et al. (2006)

It is a physical and 2D hydraulic model for the Rio Grande Diversion Structure at Albuquerque. It's downscaled representation of 305m upstream and 152m downstream of the diversion structure. The purpose was to construct physical model to test gates operation over different flow rates, flow transitions and sediment. This model considers a fish bypass for fish protection but fish was not part of the tests. The model may not be available anymore.

Chowdhury and Mace (2007)

It is a three dimensional groundwater simulation model for the Gulf Coast Aquifer in the Lower Rio Grande Valley. The system is composed of the Jasper, Evangeline and Chicot aquifers, which are an important groundwater resource for municipal and agricultural uses. The purpose was to evaluate the feasibility of groundwater desalination as an option for water supply in the future. It also improved the understanding of groundwater flow in the region and evaluated potential water level declines due to pumping. If pumping continues at current levels, a considerable decline in the water table is expected. The monthly time-step of the model could help evaluating system response under environmental flow scenarios; however, drought scenarios were considered in future predictions, which makes it suitable to evaluate responses under a changing climate.

Passell et al. (2007)

It is systems dynamic model for water quality, specifically for dissolved un-ionized ammonia, NH_3. The model is for the New Mexico Upper Rio Grande, near Albuquerque. The purpose was to address impacts of ammonium in fish population. The study concludes that NH3 toxicity must be seriously considered as a potential ecological impact in the River, especially for the silvery minnow. This model could be useful for identifying the maximum level of ammonia instream before it represents high risk for the silvery minnow and other species. Ammonia concentrations during drought conditions are not part of the model and should be considered for future evaluations and policy development as the study concludes that it has impacted on silvery minnow population decline.

Ward and Pulido-Velázquez (2008)

It is a deterministic, dynamic, non-linear optimization model. It optimizes the net present value of the basin totals economic benefits subject to constraints on equity, sustainability, hydrology, and institutions. It analyzed a two tire drinking water pricing of urban water supply; results suggest that the proposed water pricing could improve efficiency, equity and sustainability in the system. It included the Middle Rio Grande Conservancy District, Elephant Butte Irrigation District, and El Paso County Water Improvement District, in addition to the most populated cities in the basin, Albuquerque, NM and El Paso, TX. The model is not considered suitable for developing or testing EF or analyzing drought scenarios because it has a yearly time-step and it assumes that hydrologic conditions produce constant inflow level to the basin for twenty consecutive future years (2006-2020). In addition, the study has limitations for implanting the value of aquatic ecosystem and services.

Stone (2008)

It is a two dimensional hydraulic model of habitat evaluation for the Middle Rio Grande, from Alameda Boulevard bridge to the Paseo Del Norte bridge in Albuquerque, NM. The model was developed to evaluate silvery minnow habitat suitability under unsteady flow conditions; it provides valuable information for targeting restoration sites. Despite not considering drought or climate change scenarios, it provides interesting data for habitat restoration. Nevertheless, the applicability on testing EF is limited due to its scale. Model outputs showed that habitat for the silvery minnow highly depends on the flow.

Danner et al. (2006 Revised 2008)

It is a mass balance simulation model for the Middle and Lower Rio Grande, from above Elephant Butte (San Marcial gage) to the Gulf of Mexico. It includes the mainstem and main tributaries in U.S. (Pecos, Devils, Alamito, Terlingua, San Felipe, Pinto Creek) and Mexico (Conchos, San Diego, San Rodrigo, Escondido, Salado, San Juan, Alamo, Arroyo las Vacas). It addresses all the inputs for demands and supplies for the Rio Grande/ Bravo Basin to import water allocation in the basin. The model was developed as part of the Physical Assessment Project, which objective as "examine the hydro-physical opportunities for expanding the beneficial uses of the fixed water supply in the Rio Grande/Bravo to better satisfy an array of possible water management objectives, including meeting currently unmet needs in all sectors (agricultural, urban, and environmental), all segments, and both nations". Because of its monthly time-step it is only a useful as a tool for planning for developing and testing EF. Climate change projections cannot be directly applied to model because it does not incorporate climatic data; however hypothetical drought scenarios could be developed for drought and climate change scenarios.

Molotch (2009)

It is a Distributed Snow Water Equivalent (SWE) simulation model for the Rio Grande Headwaters. The purpose of the model is to resolve the spatial and temporal variability of SWE in the Rio Grande headwaters at high resolution by incorporating remote sensing analysis. It considers the RGB from its headwaters to the Del Norte gage station. It only considers a drought year (2002) and a normal year (2001) for the analysis, however, there seems to be application for real-time estimates of SWR that could help on different water management objectives, including the development of environmental flow targets based on streamflow estimates from the headwaters.

Cañón et al. (2009)

It is an optimization model developed for the Río Conchos basin. The purpose is to minimize water deficits and maximize net crop benefits in irrigation districts during drought periods through reservoir operations and water allocation objectives, using the Drought Frequency Index (DFI). The DFI is a stochastic index that modifies a parameter (i.e. precipitation) towards its lowest value based on a probability density function. The index allows measuring the severity and duration of a drought in each time step relatively to its probability of occurrence. It considers the Rio Conchos, Rio Florido, and Rio San Pedro. Results from the model suggest an improvement on reservoir operation when considering the DFI, which increases the net economic benefits in the basin. It does not consider the environment as an independent element in the system.

Oad et al. (2009)

It is an optimization model developed for the Middle Rio Grande Basin from Cochiti reservoir to the Bosque del Apache National Wildlife Refuge. The purpose of the model was to assist implementation of scheduled water delivery in the Middle Rio Grande Conservation District (MRGCD) service area. It is of relevancy for environmental flow because the objective is to divert the minimum amount of water from the mainstem, so more water can be maintained in the river, which ultimately benefits the aquatic and riparian ecosystems. The model has a considerable extent and a sufficient time-step to help on testing EF. Regarding to its application for drought or climate change, it does not implicitly consider such scenarios, but drought scenarios could potentially be evaluated as it uses climate data.

Gastélum et al. (2009)

It is a semi-distribution model based on systems dynamics for the Rio Conchos Basin. It includes the Rio Conchos, Río Florido, Río San Pedro, and Río Chuviscar. The purpose was to improve water resources management in the Basin and to evaluate temporary water transfers in the Río Conchos Basin. The model does not consider any water for environmental purposes.

Teasley (2009)

This was a modification of Danner et al. (2006 Revised 2008) simulation model for the Middle and Lower Rio Grande, from above Elephant Butte (San Marcial gage) to the Gulf of Mexico. Its application was on calculating characteristic functions for a cooperative game analysis to determine if cooperation can exist across individuals along the river. It concluded that there might be not enough water (due to system losses) to downstream “players” to induce cooperation. The updated version of the model can be applicable for the same purposes as Danner et al. (2006 Revised 2008) model.

Sandoval-Solis et al. (2010)

It is a statistical analyses of river flow that identified a considerable hydrograph change pre-1946 and post-1946 at Johnson Ranch. It then proposes a new hydrograph to try to mimic the pre-1946 conditions to revert the channel width loss and the environmental impacts from human infrastructure. It includes the Rio Conchos from LLL, downstream to its confluences with the RGB mainstem and continues until Amistad Dam. Despite not being a simulation or optimization model, it is highly applicable for EF, because it is one of the focus of the research. It shows a hydrograph that can be considered as pre-alteration of the Rio Grande Bravo.

Bestgen et al. (2010)

It was a fishway physical model to assess Rio Grande silvery minnow swimming performance under different flows, temperatures, and fishway substrates. The experiment site was the Aquatic Research Laboratory at Colorado State University. Results showed that the endurance of the silvery minnow dramatically declines when the flow is higher than 60cms; the endurance of the fish positively correlates with temperature; and a rock channel seems to be the best substrate to increase silvery minnow passage success. Outcomes from this experiment helped decision regarding fishways characteristics and information developed from this research need to be considered when developing environmental flow targets.

Yalcinkaya and McKinney (2011)

It is a hydrologic model for the Pecos River that uses the soil moisture method. The purpose of the model is to developed water availability simulations in the Pecos River Basin considering climate change effects. It considers the Pecos River from Red Bluff Reservoir to Rio Grande/Bravo near Langtry. Despite having a monthly time-step, the model is highly relevant for developing EF in the Pecos River, because there are no other comprehensive models in the area. In addition, the model directly considers climate change effects, which makes it suitable to address future drought scenarios.

Sandoval-Solis (2011)

It is a mass balance simulation model for the Middle and Lower Rio Grande, from above Elephant Butte to the Gulf of Mexico. It includes the mainstem of the RGB, the Río Conchos, Pecos River, Devils River, Arroyo las Vacas, Rio San Diego, San Rodrigo, Río Escondido, Rio Alamo, Río Salado, and Rio San Juan. The goal of the research was to develop a methodology to evaluate different water management policies in a large scale transboundary river basin. The evaluation was made in terms of performance criteria such as reliability, vulnerability, and resilience. Results were later summarized in the Sustainability Index, which is summary index that measures the sustainability of water resources systems. The model is very applicable as a planning tool for developing environmental flow scenarios and address the question of how new operation policies could affect water allocation for individual users in the basin.

Ingol-Blanco and McKinney (2012)

It is an update for the Amato et al. (2006) hydrologic model using the rainfall runoff soil moisture method for the Rio Conchos Basin. It includes the Río Conchos, Río Sacramento, Río San Pedro, Río Baleza, Arroyo el Parral, Río Florido. The purpose of the model was to evaluate the effects of climate change on hydrology and water resources with emphasis on the water treaty of 1944. The Calibration and Validation was extended to a 10-year period in comparison with its previous version, instead of 1 with the appropriate adjustments to model parameters. This model is highly applicable for testing environmental flow target and can be useful for evaluating climate change in the Rio Conchos basin, which ultimately affects the RGB.

USDOI et al. (2013) The Upper Rio Grande Simulation Model (URGSiM)

It is a suite of tools to “better understand, predict, plan, and account for surface water movement through the Rio Grande system in New Mexico”. URGSiM was developed closely following the Upper Rio Grande Water Operations Model (URGWOM). It includes the RGB from its headwaters to below Caballo reservoir, and 20 rivers reaches, including the Rio Chama, Jemez River, Rio Puerco, Rio San Jose, Rio Salado. The model also incorporates temperatures and precipitation data, which makes is suitable for evaluating climate change scenarios. This model is very relevant as it one of the models that are currently in use by governmental agencies in the basin. It is suitable for analyzing effects of EF in the water allocation of the Upper Rio Grande Basin.

Nuñez-Lopez et al. (2013)

It is a spatial precipitation model for the RGB in the side of Mexico. The purpose of the model was to represent the spatial variability of monthly average precipitation in Rio Grande/Bravo basin. Results from this model are not suitable for developing environmental flow targets or evaluating drought scenarios because it shows static monthly average precipitation from 1970-2004. It is a statistical model, not a simulation or optimization model.

USACE (2014) Upper Rio Grande Water Operation Model (URGWOM)

It is a simulation model that accounts for year to date water allocation for individual water users, streamflow, and reservoir operations in the Upper Rio Grande, in New Mexico. It includes the mainstem of the RGB between Lobatos, CO and El Paso, TX; Willow Creek, Rio Chama, and the lower reach of the Jemez River. Like URGSiM, this model is currently in use by governmental agencies in the basin. It would be useful to address effects of environmental flow policies on water users in the basin.

Sandoval-Solis and McKinney (2014)

It is a water allocation simulation model for the Big Bend Reach (BBR) of the RGB. It Includes the Rio Conchos from LLL reservoir and the mainstem of the RGB from above the Rio Conchos to Amistad Dam. The purpose was to estimate the maximum volume of water available for EF without affecting human and international water requirements, and without increasing the flood risk in Presidio and Ojinaga. The model objective was to meet the flow targets proposed by Sandoval-Solis et al. (2010) in Foster Ranch. This model was updated by Lane (2014) and is highly applicable for evaluating environmental flow policies at a planning time scale.

Lane et al. (2014)

It is a modification from Sandoval-Solis and McKinney (2014) model. Similar to Sandoval-Solis and McKinney (2014) model, the purpose of this model was to estimate the maximum volume of water available for EF without affecting human and international water requirements, and without increasing the flood risk in Presidio and Ojinaga. The update of this model was on estimating the reliability, vulnerability, and resilience on achieving environmental flow targets at three different locations along the RGB. It also incorporated the environmental flow targets developed by Upper Rio Grande Bay Expert Science Team (2012). The model proposed a reoperation policy for LLL reservoir, which increased water supply reliability and resilience with respect to the baseline water management while reducing the systems vulnerability in both countries. These results are highly significant because suggest the hydrologic feasibility of meeting environmental flow demands without affecting human water uses in the BBR. Efforts are undergoing to downscale the time step to better represent streamflow need of the aquatic and riparian ecosystems.

Sayto-Corona (2015)

It is hydrologic and hydraulic model currently under development for the Lower Rio Conchos, from LLL reservoir to Presidio-Ojinaga Valley. It is a model that determines river channel capacity and flood prone areas with the purpose of modifying a reservoir operation policy to reduce flood risk from tropical storms. Models like this are very important for testing and developing environmental flow targets, however the extent is small when compared to the basin. The model does not directly considerer environmental objectives, however, it could be used for evaluating drought scenarios as it includes climate date as inputs.

Porse et al. (2015)

It is a linear programming optimization and water planning model for the BBR of the RGB. It Includes the Rio Conchos from LLL reservoir and the mainstem of the RGB from above the Rio Conchos to Amistad Dam. The purpose of the model was to perform an analysis of reservoir operation strategies to integrate EF into existing management objectives considering five EF regimes. Results suggest that there is enough water to increase EF allocation without affecting water deliveries or international treaty allocations. Such finding add up to the previously stablish hydrologic feasibility by Lane et al. (2015) of providing EF in the BBR.

Gómez-Martinez (2015)

It is a water allocation simulation model for the San Juan Basin that includes the Río San Juan, Río Salinas, Río Pesquería, and Río Pablillo Camacho. The purpose of the model was to develop water supply and demand evaluation for Monterrey Metropolitan Area (Mexico) under different future alternatives. It focused attention into a water supply alternative named Monterrey VI, which is a controversial water project to construct a channel to divert water from a different watershed in Mexico. The model does not consider EF or drought scenarios, but could be potentially added.

RGBRT & Dinatale Water Consultants (2015)

It is a surface water simulation model for the Upper Rio Grande Basin, which includes the RGB and the Conejos River system in Colorado. The model was developed to identify projects and methods to meet basin specific municipal, industrial, agricultural, recreational, and environmental water needs. The model allows assessment of current and future conditions considering climate change, wildfires, dust on snow, infrastructure, water rights, and administrative policies. This model is relevant for testing outcomes of environmental flow policies in Colorado as the model includes some parameter for environmental purposes. Also, it includes possible future scenarios under climate change.

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5.3 Appendix

This appendix contains a description of the applied performance criteria, model equations, parameters, and data specific to the area of application.

5.3.1 Performance criteria

Four performance criteria were used to evaluate observed data and model results under the different models: (i) time-based reliability; (ii) volumetric reliability; (iii) resilience; and (iv) vulnerability (Sandoval-Solis et al. 2011). Here, water demand reliability is the probability of meeting water demands over the period of simulation (Hashimoto et al. 1982). A common practice of water managers is to measure the reliability of water allocation systems in terms of volume or timing of water supplied. Volumetric reliability quantifies the total volume of water supplied divided by the total water demand for each user on each time step during the simulation period (n is the total number of steps) (McMahon et al. 2006) (Equation (A5-1)).

$$Rel_{vol}^{i} = \frac{\sum_{t=1}^{t=n} Supplied_{t}^{i}}{\sum_{t=1}^{t=n} Demand_{t}^{i}} \qquad \textbf{(A5-1)}$$

Water deficits $Deficit_{t}^{i}$ for each user i over a period t are the difference between water demands ($Demand_{t}^{i}$) and water supplied ($Supplied_{t}^{i}$); when the $Demand_{t}^{i}$ is higher than the $Supplied_{t}^{i}$, the deficit is positive; otherwise the deficit is zero (Equation (A5-2)). Time-base reliability is the probability to fulfill water demands over the period of simulation (Equation (A5-3)) (Loucks 1997; Sandoval-Solis et al. 2011).

$$Deficit_t^i = \begin{cases} Demand_t^i - Supplied_t^i \ \ if \ \ Demand_t^i < Supplied_t^i \\ 0 \qquad\qquad\qquad if \ Demand_t^i > Supplied_t^i \end{cases} \tag{A5-2}$$

$$Rel_{time}^i = \frac{No. of\ times\ Deficit_t^i = 0}{n} \tag{A5-3}$$

Resilience is a measure of the ability of the system to recover after a failure (Hashimoto et al. 1982). Here, we consider resilience as the probability of the successful deficit control after a period of failure (Equation (A5-4)). Long periods of deficit may contribute to lower agriculture productivity, and thus, a system performance increases with its resilience.

$$Res^i = \frac{No. of\ times\ Deficit_t^i = 0\ follows\ Deficit_t^i > 0}{No. of\ times\ Deficit_t^i > 0\ occurred} \tag{A5-4}$$

Not all the periods of deficit have the same impact in the system; therefore, vulnerability is a measure of severity of a deficit. There are at least three different ways to express vulnerability, as the average failure, the average of maximum shortfalls over continuous failure periods, or as the probability of exceeding a certain deficit threshold (Sandoval-Solis et al. 2011). Here we consider the first approach, which is the sum of the deficits divided by the number of times that the system was in deficit. For a dimensionless value of vulnerability, we then divide it by the corresponding water demand (Equation (A5-5)) (Sandoval-Solis et al. 2011).

$$Vul^i = \frac{\dfrac{(\sum_{t=0}^{t=n} D_t^i)}{No. of\ times\ Deficit_t^i > 0\ occurred}}{Water\ demand^i} \tag{A5-5}$$

To avoid any potential overlaps among these indicators, we combined them into the *sustainability index* that considers each of the criteria and creates a rank that summarizes the performance of alternative policies based on the calculated criteria. Such approach facilitates decision-making process (Loucks 1997). Since it was introduced by Loucks (1997), numerous studies have used the sustainability index to evaluate water system performance, including applications to groundwater management (Mays 2013), water use under changing climate and irrigation management (Santikayasa et al. 2014), and water distribution systems (Dziedzic and Karney 2014). In this study, we used the sustainability index as adapted by Sandoval-Solis et al. (2011), referring to the geometric average of M performance criteria for each water user i (Equation (A5-6)) (Sandoval-Solis et al. 2011). Vulnerability becomes a similar measure to reliability and resilience (higher values are preferred) when subtracted from 1.

$$SI^i = \left[Rel_{vol}^i * Rel_{time}^i * Res^i * (1 - Vul^i)\right]^{\frac{1}{4}} \tag{A5-6}$$

5.3.2 Model parameters and variables

Stochastic model equations, parameters, and data specific to the area of application (Figure A5-1) are presented in the following sections. Table A5-1. Model parameters and variables as declared in the model for the Rio Conchos (m = month, and s = scenario, i= water users). provides a list of the empirical model parameters and variables used to calculate historical economic cost and benefits as well as for the deterministic and stochastic models.

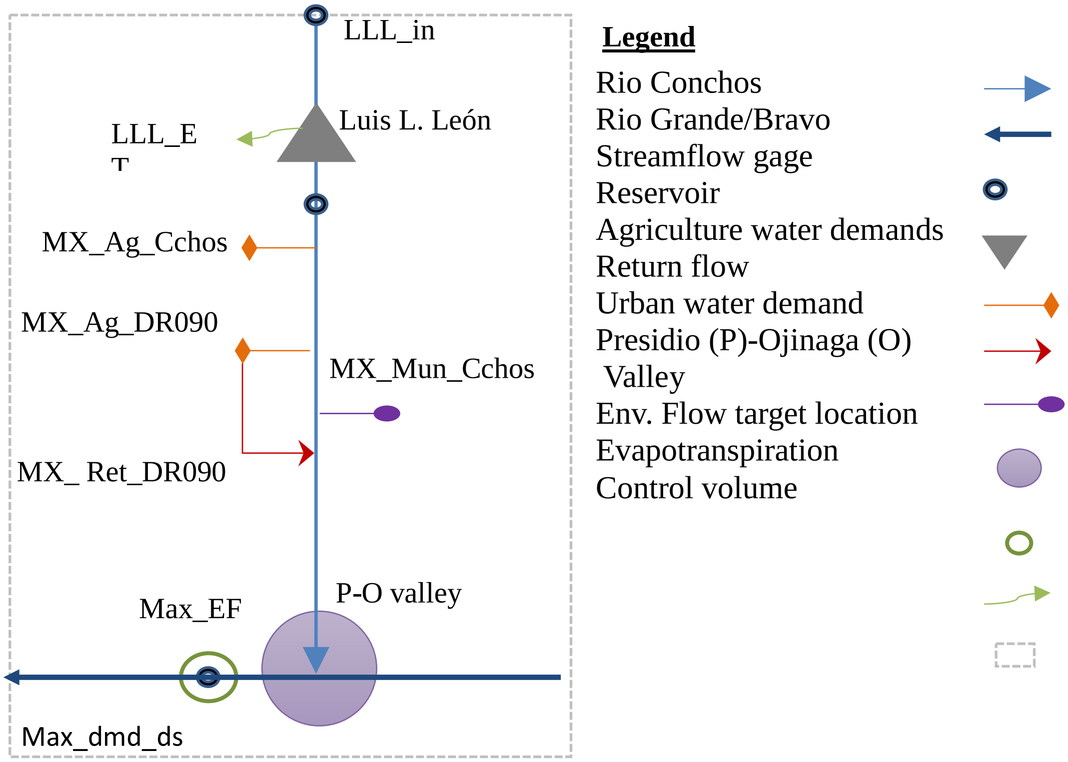

Figure A5-1. Rio Conchos below Luis L. León (LLL) schematic with variables names used in the models.

Table A5-1. Model parameters and variables as declared in the model for the Rio Conchos (m = month, and s = scenario, i= water users).

Parameters	Description	Value
$Max\_dmd_{i,m}$	Maximum water allocation per user, including environmental flow requirements at Presidio and downstream Maximum water allocation for users downstream of the confluence with the RG	Appendix 5.3.4
$LLL\_in_{m,s}$	Inflow to LLL reservoir (42 years of historical records)	Appendix 5.3.5
$LLL\_ET_{m,s}$	LLL evaporation losses (42 years of historical records)	Appendix 5.3.6
$Water\_price_{i,m}$	Cost of water deficit by user per unit of water	0.05 $M/Mm^3
$Cost_m$	Cost of water deficit in the system per unit of water	0.05 $M/Mm^3
$Cost\_flood_m$	Median cost of flood per Mm^3 above threshold	0.02 $M per Mm^3 above threshold
Z_0	Initial storage of LLL reservoir	196 Mm^3
Zmax	Reservoir capacity	832 Mm^3
Zmin	Dead storage plus two times annual municipal demand	55.2 Mm^3
Z_{12}	Minimum storage at the end of period	196 Mm^3

5.3.3 Model applied to the area of study

The objective function Equation (3-4) applied to this system and including also a cost related to floods damages changes as follows:

$$\begin{aligned} Objective = {} & \sum_{i}\sum_{m} Benefits_{i,m} \cdot iDeliveries_{i,m} - \sum_{s=1}^{S}\sum_{m} Cost\_flood_{m} \\ & \cdot Cchos\_flow_{m,s} \\ & - \frac{1}{S}\sum_{s=1}^{S}\sum_{m}\sum_{i} de\_Cost_{i,m} \cdot iDeficit_{i,m,s} - \\ & - \frac{1}{S}\sum_{s=1}^{S}\sum_{m} su\_Cost_{m} \cdot Surplus_{m,s} \end{aligned} \tag{A5-7}$$

subject to:

$$Release_{m} = \sum_{i} iDeliveries_{i,m} \tag{A5-8}$$

$$\begin{aligned} Z_{m,s} = {} & Z_{m-1,s} + LLL\_in_{m,s} - LLL\_E_{m,s} - Release_{m} - Surplus_{m,s} \\ & + Deficit_{m,s} \end{aligned} \tag{A5-9}$$

$$iDeficit_{i,m,s} = \; Max\_dmd_{i,m} - iDeliveries_{i,m} \tag{A5-10}$$

$$Deficit_{m,s} = \sum_{i}^{I} iDeficit_{i,m,s} \tag{A5-11}$$

$$Surplus_{m,s} \geq Releases_{m} - \sum_{i} Max\_dmd_{i,m} \tag{A5-12}$$

$$\underline{Z}_{m,s} \leq Z_{m,s} \leq \overline{Z}_{m,s} \,, Z_{1,s} = Z_{0} \text{ and } Z_{12,s} \geq Z_{12} \tag{A5-13}$$

This objective function (A5-7) is maximized subject to several constraints (equations (A5-8) to (A5-13)). Equation (A5-8) defines that the sum of reservoir releases for each user must be equal to the total release from the reservoir. Equation (A5-9) includes the reservoir water balance for the storage $Z_{m,s}$ in each time-step including $Surplus$ and $Deficit$ variables. Equation (A5-10) limits the deficits to the amount of maximum allocation for each user. Equation (A5-11) limits the whole system deficit to the sum of individual deficits. Equation (A5-12) quantify the surplus and allow high inflows to be released to avoid or reduce overtopping. Equation (A5-13) defines the minimum and maximum reservoir storage allowed in each month and year as well as the initial and end of period storage. Another term to account for return flows (A5-14) from the Irrigation district Mx_Ag_DR090 is included in the optimization:

$$Return\_\mathrm{DR090}_{m,s} = iDeliveries_{Mx\_Ag\_DR090,m} \cdot 0.25 \qquad \text{(A5-14)}$$

The flow at the Rio Conchos at P-O valley (A5-15), an area prone to flood events is calculated as the sum of the deliveries for EF ($iDeliveries_{Mx\_EF\_Cchos\_f,m}$) plus the spilled water from the reservoir $Surplus_{m,s}$ and the return flows ($Return\_\mathrm{DR090}_{m,s}$):

$$\begin{aligned} &Cchos\_flow_{m,s} \\ &\quad = iDeliveries\_EF_m + Surplus_m \qquad \text{(A5-15)} \\ &\quad + Return\_\mathrm{DR090}_{m,s} \end{aligned}$$

5.3.4 Maximum water demands, and benefits per unit of water delivered

Table A5-2. Maximum water demand (Mm^3) per month for water users.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
MX_Ag_Cchos	1.22	1.34	1.81	2.63	2.84	3.06	3.32	2.80	3.40	3.30	2.69	1.60
MX_Ag_DR090	3.46	3.80	5.12	7.46	8.05	8.66	9.41	7.63	9.62	9.35	7.61	4.53
MX_Mun_Cchos	0.22	0.21	0.22	0.22	0.20	0.22	0.21	0.22	0.21	0.22	0.22	0.21
Max_dmd_ds	4.51	2.59	2.25	2.51	2.92	6.66	5.32	5.98	7.32	7.90	7.46	6.28
Max_EF	40.73	43.30	44.75	44.75	40.42	26.39	25.54	26.39	25.54	40.73	40.73	39.41

The following values were derived from Ortiz-Partida et al (2016).

Table A5-3. Benefits per unit of water volume delivered to users ($M per Mm^3).

	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
MX_Ag_Cchos_f	0.091	0.078	0.091	0.094	0.105	0.108	0.121	0.102	0.121	0.119	0.101	0.078
MX_Ag_DR090_f	0.091	0.078	0.091	0.094	0.105	0.108	0.121	0.102	0.121	0.119	0.101	0.078
MX_Mun_Cchos_f	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Max_dmd_ds	0.091	0.078	0.091	0.094	0.105	0.108	0.121	0.102	0.121	0.119	0.101	0.078
Max_EF*	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

***EF Economic benefits are quantified as costs from restoration actions that could be avoided by improving environmental flow allocation**

5.3.5 Inflows to Luis L. León reservoir

Monthly inflows in million cubic meters for 42 historic scenarios. S1 correspond to 1969, S2 to 1970 and so on.

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Oct	142.00	152.60	166.20	71.80	68.90	165.20	116.30	82.50	95.50	362.70
Nov	63.00	64.20	47.70	50.30	56.90	70.80	103.20	67.30	44.60	87.40
Dec	44.00	41.50	45.60	42.60	47.90	49.60	74.00	50.20	37.90	48.70
Jan	70.10	50.80	34.40	47.00	43.40	45.70	46.30	83.10	40.70	29.50
Feb	56.60	44.80	35.50	33.30	65.60	48.50	82.80	82.20	47.20	27.00
Mar	65.30	44.70	36.50	44.00	57.30	53.20	121.60	61.90	60.50	24.40
Apr	61.00	26.50	30.60	30.90	48.40	48.20	71.90	72.70	54.90	27.70
May	52.30	29.10	35.90	40.00	49.30	86.90	62.90	97.70	54.60	28.70
Jun	47.90	46.60	32.30	66.90	55.10	60.00	61.40	77.20	60.90	16.20
Jul	81.20	60.10	45.60	82.80	134.30	83.60	95.70	193.40	98.60	38.10
Aug	47.10	56.70	116.30	110.40	369.30	68.20	90.30	90.90	63.30	222.20
Sep	62.90	110.40	84.30	317.40	215.50	605.00	91.60	156.20	48.30	1075.10

s11	s12	s13	s14	s15	s16	s17	s18	s19	s20	s21
56.90	149.20	534.10	58.20	73.40	59.40	63.70	79.00	99.40	99.00	72.40
40.40	62.80	65.80	44.20	53.50	42.50	38.40	45.00	50.80	45.90	38.50
36.10	62.60	50.90	42.30	37.30	39.00	32.50	43.10	47.40	38.20	31.50
35.80	32.90	47.50	42.80	36.80	37.00	36.80	27.20	42.10	39.90	42.20
35.40	35.40	35.40	40.00	31.20	41.00	40.80	31.20	50.80	56.10	53.00
52.40	42.20	37.50	48.10	38.30	41.60	47.30	33.60	54.10	54.40	64.60

54.80	33.20	56.00	43.50	30.30	32.00	45.50	32.20	82.70	55.20	52.00
59.80	47.10	47.40	53.00	32.50	47.40	49.40	47.90	91.10	68.50	55.40
83.20	42.10	43.70	41.40	38.90	129.80	61.40	58.80	120.50	80.90	51.70
74.80	30.40	56.30	70.10	46.00	86.60	93.10	82.80	107.10	112.70	50.90
105.20	110.20	104.10	64.20	63.60	197.60	69.70	75.30	101.80	114.10	60.30
63.00	190.00	293.80	53.90	48.10	69.10	87.00	346.70	86.70	87.10	58.90

s22	s23	s24	s25	s26	s27	s28	s29	s30	s31	s32
348.32	254.77	95.80	70.10	28.46	5.16	24.04	29.44	36.49	5.41	31.37
34.60	73.64	70.80	55.89	24.70	5.20	8.46	25.60	28.96	11.45	20.40
33.73	69.06	49.80	43.06	27.26	5.58	8.86	21.07	19.04	10.90	19.91
32.80	45.19	220.80	43.98	38.30	28.78	7.16	11.31	20.11	18.53	12.51
35.80	53.70	176.90	54.08	36.30	10.95	5.45	8.06	7.27	9.04	7.32
43.00	63.11	102.50	57.38	45.40	8.95	3.48	10.14	9.48	6.25	4.38
33.00	65.90	92.40	58.29	37.25	4.83	2.38	13.30	8.39	5.55	2.97
38.30	62.91	126.50	63.08	39.98	8.02	2.82	39.20	8.20	3.57	6.57
48.10	35.74	104.50	76.14	28.00	11.82	5.21	11.78	6.85	3.68	22.26
34.10	212.61	93.50	120.15	30.07	13.63	5.06	37.97	31.06	34.94	23.56
344.32	386.31	102.90	69.53	14.36	12.51	66.43	38.59	33.12	15.07	17.91
145.98	1607.04	105.40	121.04	22.20	38.37	317.16	23.76	18.98	12.17	13.81

s33	s34	s35	s36	s37	s38	s39	s40	s41	s42
3.51	5.23	66.05	23.28	18.69	26.01	16.70	326.28	48.35	118.80
6.59	4.76	9.70	41.97	4.72	18.80	0.00	42.60	23.15	21.90
12.10	12.50	10.40	22.13	10.84	23.24	0.00	31.81	25.98	24.30
18.47	7.25	13.09	18.23	19.42	11.44	28.77	14.84	24.60	22.48
10.41	4.03	5.92	8.02	17.04	6.37	14.84	76.02	18.57	18.98
3.79	2.84	3.02	15.61	9.10	5.12	4.88	7.63	15.66	10.17
6.70	1.78	2.64	4.54	5.25	3.08	12.64	5.29	9.44	14.41
1.76	2.34	3.10	5.37	4.35	4.90	13.77	7.87	51.42	12.70
1.46	11.45	9.04	10.27	1.78	2.23	12.12	10.44	27.60	21.40
19.60	41.90	12.90	42.28	4.38	9.56	47.07	41.46	32.51	87.50
8.70	25.14	5.00	42.05	19.79	80.40	39.90	41.92	45.72	133.00
3.99	3.63	5.78	23.21	4.12	413.98	42.54	2405.89	43.88	137.30

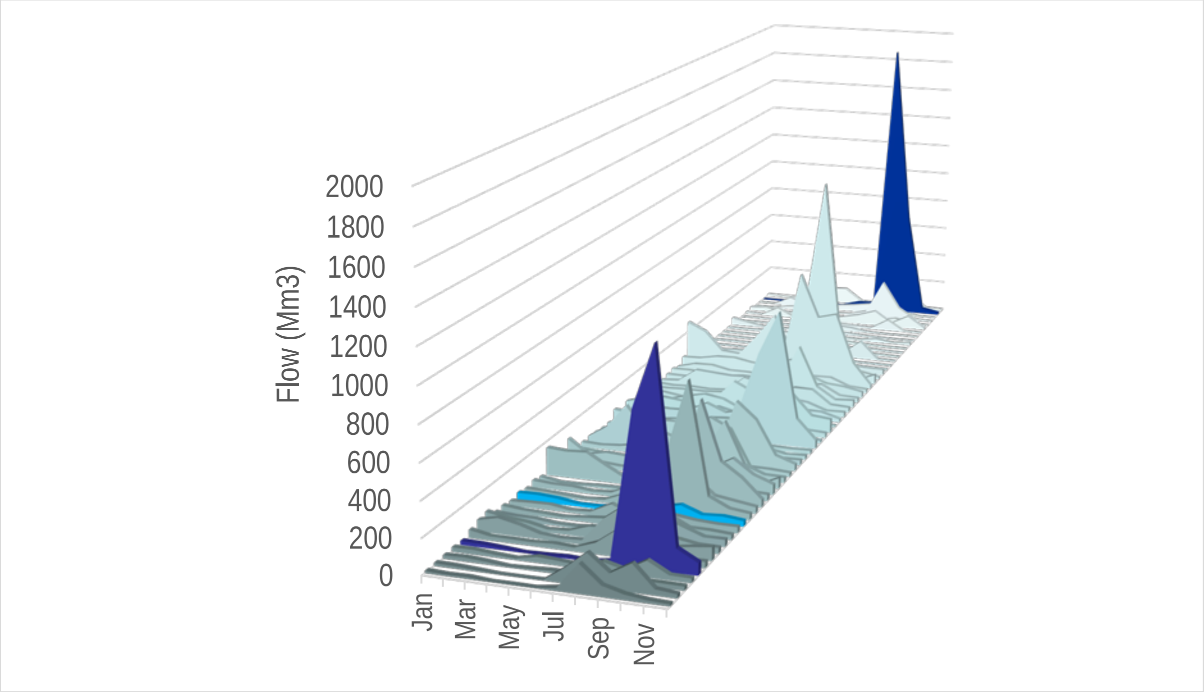

Figure A5-2. Streamflow variability above Luis L. Leon reservoir

5.3.6 Evaporation losses from Luis L. León reservoir

Monthly evaporation (m1:m12) in million cubic meters for 42 historical observation. The evaporation is in water year, m1 corresponds to October.

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
Oct	7.5	5.3	6.4	3.7	6.2	5.4	6.4	6.7	4.8	3.9	4.2	3.3
Nov	4.7	5.3	7.8	3.8	6	2.7	6.3	6.5	3.3	2.3	2.6	1.9
Dec	3.6	5	7.3	4.4	6.7	2.3	6.4	2.7	2.7	2.5	1.9	2.3
Jan	3	2.4	5	6.9	3.4	6.9	2.5	6.6	2.4	2.1	2.7	2.2
Feb	3.8	2.5	4.3	3.9	2.4	7	3.1	6.9	3.7	2.9	3.6	3.4
Mar	5.3	3.7	5.1	5.3	5.1	8.1	4.7	7.6	5.7	4.7	5.5	4.4
Apr	5.7	4.2	5.2	6.6	7.1	8.3	5.6	7.5	6.5	6.9	7	5.9
May	7.1	5.5	7.2	6.4	7.4	7.8	6.4	8.2	7.7	6.4	7.3	6.9
Jun	7.3	5.6	6.4	7.4	7.8	6.3	6.4	7.7	7.2	7.1	7	8.4
Jul	5.6	5.9	6.9	6.4	6.8	5.9	6.2	6.6	6.7	6.1	6.1	7.1
Aug	6.2	5.8	5.8	6.2	7.8	4.8	6.1	6.9	6.6	5	4.3	5.8
Sep	5.2	4.6	5.4	5	6.2	4.6	5.8	5.9	6.6	4	4.2	2.9

s13	s14	s15	s16	s17	s18	s19	s20	s21	s22	s23	s24	s25
3.3	4.1	3.2	3.3	3.2	2.8	3.2	3.7	4	5.1	4.8	4.1	5.1
3.3	1.9	2	2.7	2.3	2.9	3.2	3	2.4	2.5	2.8	3	3.3
2.8	1.5	1.8	1.6	2.1	1.5	2.3	2.5	2.7	2.1	2.7	2.9	3
1.5	2.6	1.5	1.5	1.5	1.6	1.8	1.5	2.1	2.5	2.5	1.9	2.5
2.8	3	2.7	2.5	2.2	2.7	2.5	2.2	2.6	3.2	3.2	3.2	3.3
4.3	5.5	4.3	4.3	4.1	4.3	3.1	4	4.3	2.8	4.7	6.1	6.1
3.7	6.1	5.8	6.1	4.8	5.7	4.7	2.5	5.4	6.3	5.9	8.6	7.9
6.8	5.4	6.7	5.7	6.1	6.4	4.5	7.2	6.8	7.5	6.3	8.3	9.8
5.6	6.7	6.4	4.6	6	13	5.1	5.1	6.9	7.6	7	9	9.8
5.3	5	6.3	4.9	5.3	4.2	4.8	6.3	7.5	5.2	4.1	6	6.6
4.3	5	4.7	3.8	5.3	4.8	3	5.3	7.2	3.8	4	5.3	6.7
3.7	4.8	4.4	4.2	4	3.7	3.5	4.3	6.4	3.1	3.8	2.6	4.9

s26	s27	s28	s29	s30	s31	s32	s33	s34	s35	s36	s37
3.4	3.6	5.3	3.5	3.2	3.5	2.5	2.1	2.1	2.0	2.8	2.7
2.9	2.5	3	1.9	1.8	2.4	2.0	1.4	1.6	1.8	1.9	2.3
1.7	1.7	2.7	1.6	1.6	1.3	2.0	1.2	1.2	1.5	1.5	1.6
2.7	1.8	1.9	3.1	2.5	2.2	2.0	1.7	1.5	1.4	0.8	1.7
3.2	2.6	2.7	2.7	3.0	2.6	2.5	2.2	1.5	1.5	1.7	1.7
5.2	3.7	3.5	3.9	4.3	3.4	3.5	2.9	2.6	2.8	2.7	3.7
7	4.6	3.2	5.7	5.2	4.9	4.2	3.5	2.8	3.3	3.4	5.1
6.6	5	4.2	6.2	6.4	5.7	4.9	3.9	3.1	4.0	4.7	5.7
6.3	4.8	4	5.5	6.1	5.2	3.6	4.1	3.0	3.9	4.5	6.3
6.6	4.7	3.9	3.6	5.1	3.7	3.9	3.3	2.5	3.4	4.1	5.9
5.8	4.3	3	3	2.4	4.5	3.4	3.4	2.8	3.4	3.7	4.6
4.2	3.7	4.6	4.2	4.1	3.6	3.5	2.9	3.2	2.6	3.6	4.3

s38	s39	s40	s41	s42
3.4	3.7	3.9	4.0	4.8
2.6	2.2	2.7	2.4	3.3
1.9	2.0	2.8	1.7	2.4
2.0	1.6	2.0	2.7	2.0
2.3	2.8	2.8	3.9	2.0
4.0	4.5	3.9	5.2	3.6
4.3	4.7	4.2	6.8	4.5
4.9	5.4	6.0	7.0	5.7
4.5	5.5	6.6	5.8	5.4
3.7	5.1	4.4	6.1	4.6
2.4	4.7	3.9	5.0	5.6
3.8	3.5	4.5	4.6	4.2

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