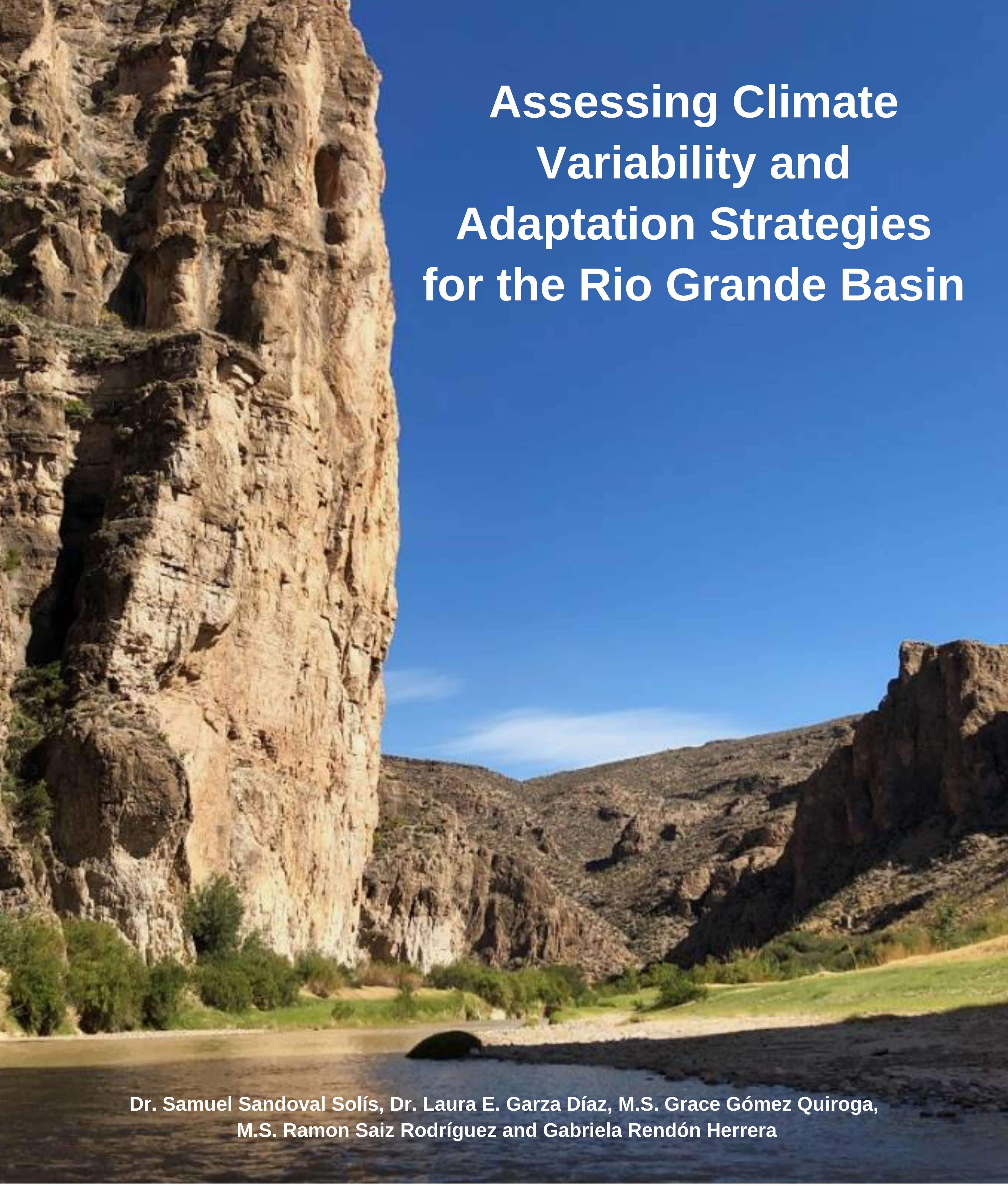

Assessing Climate Variability and Adaptation Strategies for the Rio Grande Basin

Dr. Samuel Sandoval Solís, Dr. Laura E. Garza Díaz, M.S. Grace Gómez Quiroga,
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Abstract

The Rio Grande/Bravo (RGB) is a basin full of extreme climate conditions. The overall goal of this study was the estimation of climate variability on the southern branch of the RGB basin (from Presidio Texas to the outlet of the river in the Gulf of Mexico) and the characterization of the periods of drought and water abundance for 110 years [1900 – 2010]. This study focused on the natural streamflow variability as a proxy for climate variability, and for extreme drought and flood events. Specifically, on the estimation of daily natural water availability for the RGB along the border, comparing the long-term water availability with drought periods. This research aimed to help in the understanding of extreme climatic events and support the formulation of adaptation strategies relevant for agriculture, urban and rural communities, water management agencies, flood protection, and environmental restoration activities. The findings of this study present the role of climate variation over time was significant under natural conditions; however, its current human-centered water management use and regulations are the main drivers of floods patterns and the present anthropogenic megadrought that has lasted more than 100 years in the RGB. In addition, there is evidence that the basin is less resilient, the present anthropogenic megadrought impedes the natural fluctuation of wet and dry periods keeping the basin in a perennial and severe drought state. This report also provides management strategies of climate adaptation considering the flood and drought characterization of the RGB basin, as well as the prediction in the context of climate change. The results also included a communication campaign developed with stakeholders explaining results and adaptation strategies for public outreach.

January ,2023
Davis, California, U.S.

Index

Introduction

The transboundary Rio Grande/Bravo (RGB) basin is a water-scarce basin full of extreme climate conditions, from heavy snowfall and tropical storms to prolonged minimal precipitation, which ranges from 190 to 2250 mm per year and an average temperature range of -2°C to 25°C. As one of the largest drainage basins in North America, the RGB extends approximately 557,000 km^2 between the United States of America (US) and Mexico. The RGB provides water to eight states, three in the US (Colorado, New Mexico, and Texas) and five in Mexico (Chihuahua, Coahuila, Durango, Nuevo León, and Tamaulipas). Snowmelt from the Rocky Mountains and monsoon runoff from the Sierra Madre Occidental flows mostly through arid regions, including the Chihuahuan Desert, North America's largest desert.

The volume of water allocated in the RGB basin is greater than the volume of water available. The majority of the RGB basin is a desert; it is a water-scarce basin prone to severe and extended drought events. Even though water availability can be stretched to some extent through water storage and imports, it is currently impossible to meet present water demands, let alone future demands. All cities in the basin are experiencing water limitations, and to meet increasing water demands many of them have been over drafting groundwater for decades. In agriculture, farmers are changing from annual crops (e.g. cotton) to perennial crops (e.g. pecans), reducing their inter-annual flexibility to adjust their production acreage according to the water availability. There is a need for policies that incentivize water conservation, such as water rights buybacks, planting less water intensive and seasonal crops, improving irrigation efficiencies (e.g., Minute 309), increasing aquifer recharge and water reuse, among other activities. Severe and persistent droughts in the RGB basin reduce water availability, which triggers economic, environmental, and social impacts, difficult the water supply for different water users and the compliance with interstate compacts and international treaty commitments. In contrast, the RGB basin is also affected by floods events that result in major economic and life losses. Projected increases in temperature and population growth in the basin will continue to increase the gap between water supply and demand [1]. Increasing temperatures are expected to shift the timing of water supply earlier in the year, drive more extreme high and low flow events, and augment irrigation needs through increases in agricultural evapotranspiration. One study estimates that climate change could reduce RGB mainstem streamflow by 4–14 percent by 2030 and 8-28 percent by 2080 [2], further limiting already over-allocated basin water resources.

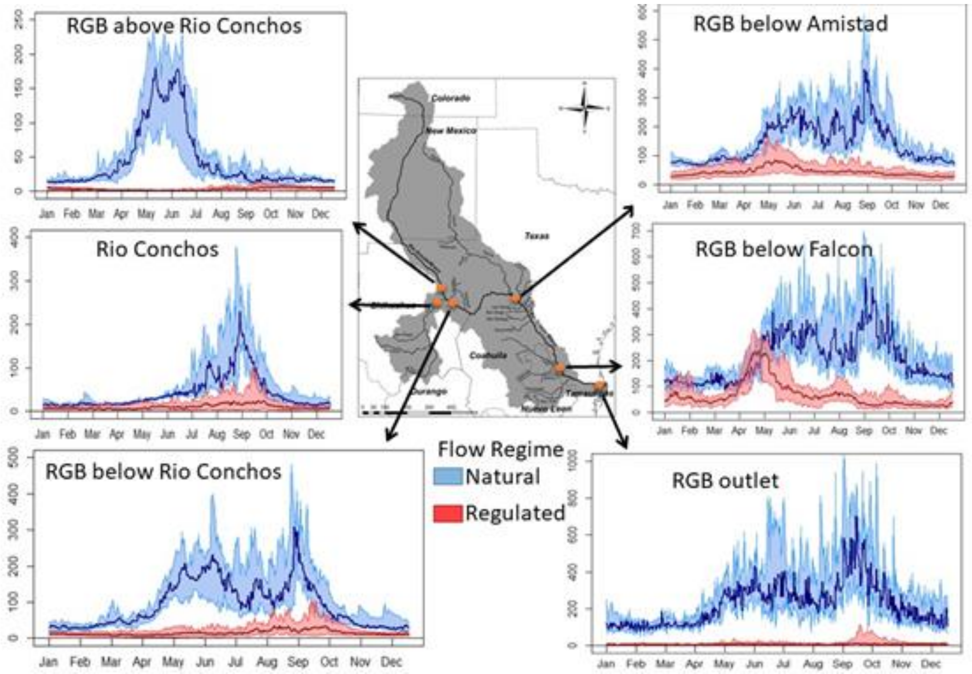

Figure 1. Natural and regulated streamflow for 6 gauge stations along the main stem of the southern branch of the Rio Grande/Rio Bravo (RGB) from 1901 to 1913.

The previous information was documented in the Rio Grande Atlas, which was a project funded by the USGS South Central Climate Science Center. This project became the foundation for collecting and organizing data relevant to water management models, analysis and key information that will be relevant for the proposed research study [3]. Furthermore, in a collaboration with researchers from Utah State University [16] and the National Polytechnic Institute in Mexico [15], the daily natural flow regime was estimated for the southern branch from 1901 to 1913 (Figure 5). This analysis shows the proof concept for calculating the natural flow regime in the southern branch of the RGB; it also shows the high variability of flows in that short period of time, demonstrating the need to further expand the calculation of the natural availability for a longer period that include the extended and severe droughts and floods that are characteristic of the RGB.

There are several opportunities to improve water management resilience through the development of adaptation strategies in the face of limited and increasingly uncertain water resources. To develop such strategies, it is vital that we characterize the climate variability and quantify the natural water availability during periods of droughts and floods. Coping with extreme climate events is not simply a matter of infrastructure or scientific knowledge; it is an issue that must be addressed by decision-makers with a regulatory framework and political willingness.

Currently, the Rio Grande Water Master Program is a successful example of an adaptive water allocation system capable of allocating surplus water during wet periods and reducing diversions during drought periods. Such an approach allows individual water rights holders to determine their water withdrawals over time while managing water at the larger scale. This allocation system can be replicated in other parts of the basin and other strategies can be developed with the aid of this research.

Geographic Scope

The geographic scope of this project was the southern branch of the RGB, which is the watershed that contributes to the mainstem of the RGB below its confluence with the Rio Conchos.

Justification

The economic development of 14 million people and the survival of the Chihuahuan desert ecosystems are at risk due to the climate variability produced by droughts and floods in the Rio Grande (RGB) Basin. The RGB is a basin with extreme climate conditions, from heavy snowfall in the San Juan Mountains of Colorado and tropical storms impacting the basin from the Pacific Ocean and the Gulf of Mexico, all the way to having minimal precipitation for several years in West Texas. In terms of droughts, there have been five droughts in the recent history of the basin: 1892 to 1904, 1930 to 1940, the drought of record from 1942 to 1956, 1962 to 1967, and 1994 to 2007. These droughts have severely affected the communities and economic activities that depend on water. The economic impact of drought is significant, for the 2011 drought it has been estimated at $7.62 billion only in the agricultural sector [4], and at $16.9 billion in the Texas economy [5]. Furthermore, each of these droughts triggered a change on strategies to manage water in the RGB, from international agreements (Convention of 1906) after the drought of 1892 to 1904, all the way to changes in water allocation systems in Texas (Texas Administrative Code 303) after the drought of 1942 to 1956.

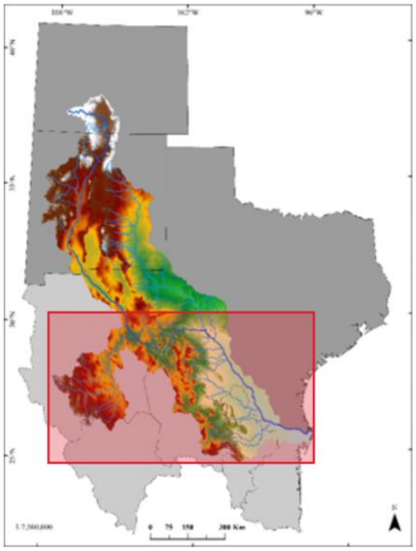

Figure 2. Geographic scope of the project

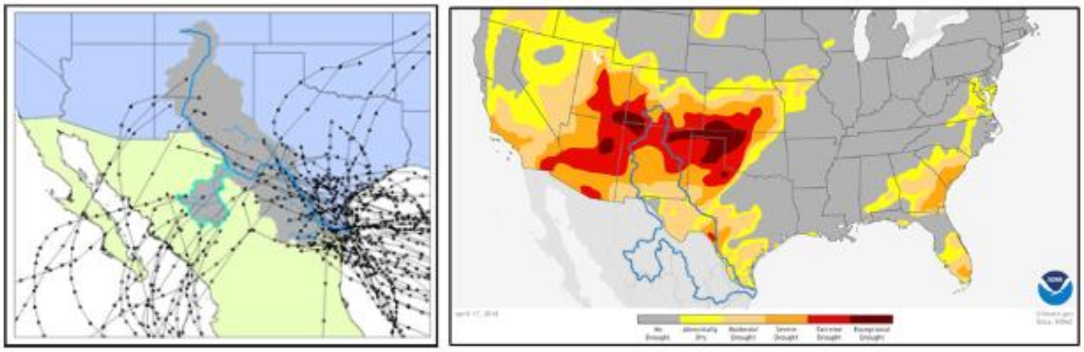

Figure 3. Climate dichotomy of the RGB basin. On the left, the trajectories of tropical storms that have impacted the basin from the Pacific and Atlantic oceans. On the right, the drought monitors shows that the entire basin is in extreme or severe drought along the southern border in Texas.

In contrast, heavy rain events and floods occurred due to the influence of hurricanes and tropical storms coming from the Pacific and Atlantic oceans. Tropical storms bring heavy rainfall in short periods of time, saturating the soil and making some reaches prone to flood, such as Presidio, McAllen and Brownsville, Texas. Extreme climate events are highly unpredictable, and their intensity and frequency have augmented in the last years, having devastating consequences. Thus, there is a need to characterize extreme climatic events of floods and drought and estimate recent trends to predict near future conditions of drought and floods.

This study is crucial for stakeholders and the society because the economic and environmental sustainability of the communities living in the basin depend on the actions to cope with the climate variability produced by droughts and floods. The water availability characterization provides insights for water managers and decision makers to decide what actions can be taken given the reduced water availability during drought periods. Estimating the variability of natural water availability has the potential to improve the water management in the basin and reduce the basin vulnerability during drought periods. Besides, the water availability will allow characterizing the natural flow regime of the RGB, this knowledge is fundamental to understand the flow regime in which the native riparian and aquatic ecosystems evolved. As of today, there is no study that has estimated the daily natural water availability for such a long period in the southern branch of the RGB and compared it during drought periods.

Understanding each of these periods of scarcity and water abundance can help to design adaptation strategies that cope with these two extremes while still supporting human and environmental water management needs. Adaptation strategies based on scientific research will provide specific actions to reduce the consequences of being underprepared to deal with major droughts or flood events.

Objectives and overall methodology

The overall goal of this study is to estimate the climate variability of the southern branch of the RGB basin (from Presidio Texas to the Gulf of Mexico) and characterize the periods of drought and water abundance for 110 years (1900 – 2010). Explicitly, this research (1) assessed the climate variability in the RGB by estimating the daily natural flows, water availability and extreme flow events, (2) characterized droughts and floods in the lower branch of the RGB, and (3) proposed and designed climate adaptation strategies for droughts and floods in the lower branch of the RGB.

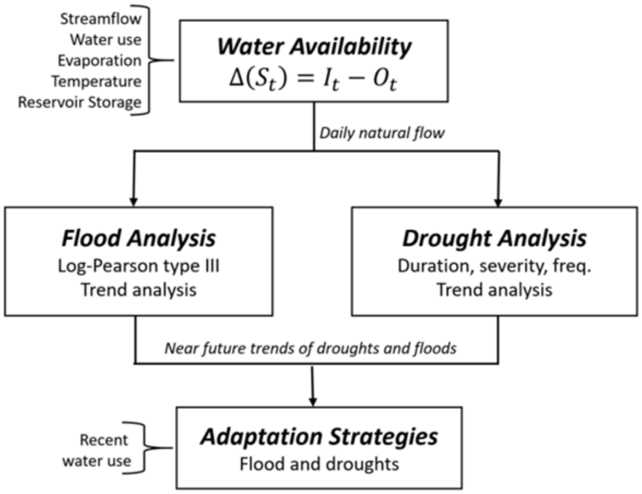

Figure 4. Schematic of Methods

For this project, long-term streamflow data was required to represent specific conditions of river basins, including the dynamics and behaviors of hydrologic, climatic, anthropogenic, and seasonal variables over extended periods in a river basin. The analysis presented in this report required two streamflow datasets:

(1) Observed flow regimes, which represent a clear manifestation of the Anthropocene, including water diversions, withdrawals, and reservoir operations, among others. Observed flow data were obtained from the Mexican National Water Commission (Comisión Nacional del Agua [CONAGUA]), the International Boundary and Water Commission (IBWC), and the U.S. Geological Survey (USGS).

(2) Natural flow regimes represent streamflow without anthropogenic impacts, removing the impacts of reservoirs, diversions, return flows, groundwater sources, and any other water management practice and assuming to capture the relevant characteristics of climate and natural river basin hydrology [6]. Naturalized streamflow data sources were retrieved from previous studies, including the Upper RGB at Rio Grande Del Norte, Colorado, to the Rio Grande Above Presidio, Texas [7]. Then for the Lower RGB, daily and monthly naturalized data was retrieved from below Presidio/Ojinaga to Anzalduas, Tamaulipas from 1900-1943 [23,24], and from 1950 to 2008 [8]. For this research data gaps in the regulated streamflow dataset were calculated as well using streamflow naturalization.

Streamflow Naturalization

Streamflow naturalization was used in observed flow regimes for removing anthropogenic influence disturbances such as impoundments of rivers, land-use changes, water extractions, return flows, and other factors from streamflow time series. As the influence of humans continues to have a direct impact on river flows, the natural and anthropogenic parts of observed flows need to be distinguished [9,10]. The method used to naturalize flow is a water balance, which is the most widely used, despite the fact that it is primarily governed by data availability. This approach consists of decomposing flow into a natural part and an influenced part by removing the volume variation induced by the source of influence (e.g., reservoirs) [11] by accounting for the system's gains and losses for the desired time frame [6]. The mass water balance equation (Eq. 1) is the following:

$$Q_t^{nat} = GF_t + O_t - I_t + \Delta S_t \quad (1)$$

Where Q_t^{nat} is the natural flow, GF_t is the observed/gauged flows, O_t is the outflows, I_t is the inflows, and ΔS_t is the change of reservoir storage at a given daily time step t.

Outflows include evaporation losses from the reservoir and streamflow losses, obtained from the Mexican National Data Bank for Superficial Waters (Banco Nacional de Datos de Aguas Superficiales [BANDAS]) and IBWC. Moreover, any consumptive use, including agriculture diversions retrieved by the Agricultural Statistics of the Irrigation Districts in Mexico (Estadísticas Agrícolas de los Distritos de Riego), domestic and industrial water uses obtained by CONAGUA. Inflow data include agriculture and urban returns, flows, precipitation in the reservoir, and streamflow gains obtained by BANDAS and CONAGUA. Furthermore, the change of storage was obtained from BANDAS and IBWC. Lastly, to validate our results, we performed a statistical analysis comparison between our results and available research including the studies of Orive de Alba [12] and Blythe and Schmidt [13]. The goodness of fit criteria used from Moriasi et al. [14] were the coefficient of determination (R2), index of agreement (d), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS).

Flood events characterization and trend analysis

This section analyzes natural and regulated flood events in the Lower RGB Basin using 110 years of streamflow from 1900 to 2010 at five control points: (1) Below Ojinaga, (2) Foster Ranch, (3) Amistad, (4) Laredo, and (5) Anzalduas. Flood timing was described with central metrics and measures of spread, which were also used to compare differences between natural and regulated floods. Flood magnitude and frequency were analyzed using flood frequency analysis and magnitude prediction of the 2-, 5-, and 10-year floods. To compare magnitude and frequency of natural and regulated floods, two indexes were developed. The natural and regulated annual flood series were obtained for 110 years on a daily scale to perform the flood event characterization of the southern branch of the RGB.

Drought's characterization

The streamflow drought index (SDI) was determined to explore the drought properties of the RGB. To analyze the basin-wide dynamics, this study uses 110 years of monthly streamflow from 1900 to 2010 at eight control points (i.e. hydrologic gauge stations) to portray the natural and anthropogenic states of the RGB. Four control points are selected in the mainstem of the river basin: San Marcial, El Paso, Above Amistad Dam, and Anzalduas. In addition, four control points are selected at the outlet of the main sub-basins: Rio Conchos, Pecos River, Rio Salado, and Rio San Juan. The natural and regulated annual flood series were obtained for a 110 years in a daily scale to perform a hydrologic drought assessment for the observed and naturalized flows to identify the hydrologic variability of the river basin.

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Objective 1: Assessing Climate Variability

The climate variability in the RGB was estimated by calculating the daily natural flows through a water mass balance for 110 years. This approach required historic data of streamflow, water use, return flows, temperature, evaporation, and reservoir storage. Regulated streamflow data was collected from IBWC [8] the national institute of water technology (ERIC), water bulletin data (Follansbee et al. 1915) and the irrigation commission of water [2]. Water use and return flows were compiled from historic water use described in reports from the irrigation [2]. water availability studies from CONAGUA [5], irrigation district reports [3], and water diversion data [7]. Weather parameters (Temperature and evaporation) were obtained from databases available along the border (e.g., PRISM, ERIC). Reservoir storage was collected from the water agencies responsible for their operation [2,3,6,7] A mass balance approach was used to complete the proposed period of hydrologic analysis (from 1900 to 2010) on a daily scale. The results were compared with different studies of that time [1] to verify their validity.

Data Validation

Results of the analysis comparison between the streamflow estimations from the period of record of 1900-1943 from Orive de Alba [2] were R2=0.9, d=0.9, NSE=0.9, and PBIAS=3.6. In addition, the comparison between Blythe and Schmidt [9] with a period of record is 1900-2010 are R2=0.9, d=0.9, NSE=0.9, and PBIAS=1.8. The statistical performance for both comparisons was very good according to the criteria of da Silva et al. [6].

Products

(a) A time series data of the daily natural flow for five gauge stations [June/20] (RGB below Presidio Texas, RGB at Foster Ranch, RGB above Amistad reservoir, RGB at Laredo Texas and RGB at Anzalduas).

- Folder that contains the results of the daily natural flow for five gage stations: https://drive.google.com/drive/u/0/folders/1PKCGrOzxUGRt1J_63pDkDv0uxCd6viiQ

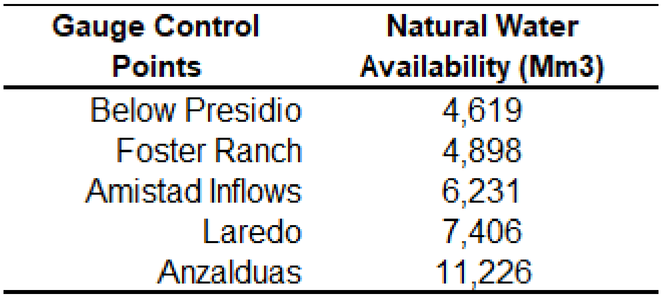
(b) One presentation with stakeholders to share the results and data on Feb/1/2022 titled:

- CCAST Webinar: Environmental Flows in the Rio Grande-Rio Bravo Basin (https://www.drought.gov/events/environmental-flows-rio-grande-rio-bravo-basin)
- Link for webinar recording: https://youtu. be/5I-prBCOjTs

(c) a map of the natural water availability for the southern branch of the RGB [Aug/20].

- **Link for the map figure in .png format:** OBJ1_map_Natural_Water_Availability_Southern-Branch-RGB.png

Table **RGB**



Gauge Control Points	Natural Water Availability (Mm3)
Below Presidio	4,619
Foster Ranch	4,898
Amistad Inflows	6,231
Laredo	7,406
Anzalduas	11,226

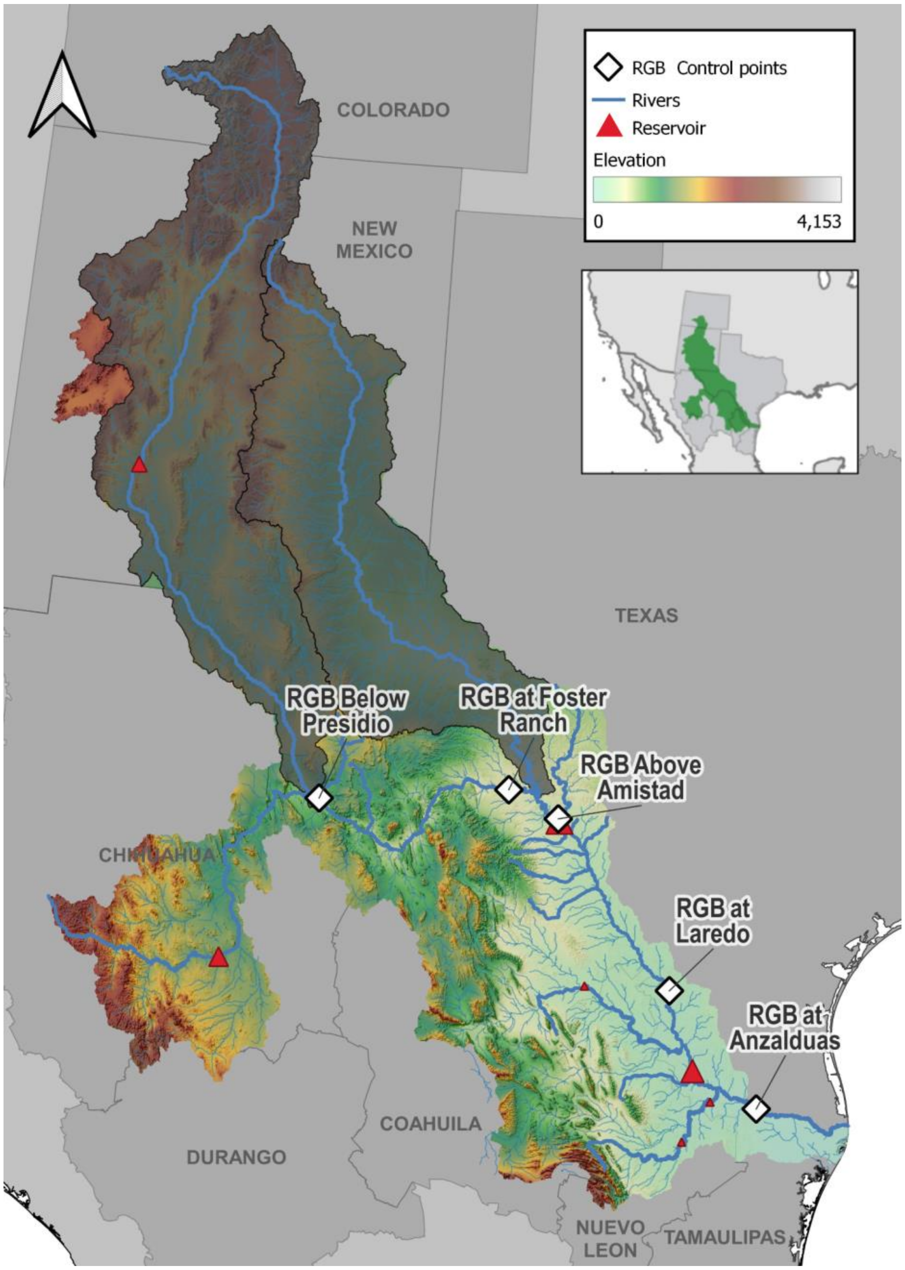


Figure 1. Streamflow gauge station in the southern RGB

Objective 2: Characterize droughts and floods in the lower branch of the RGB

Droughts and floods occur periodically as extreme events that can have a catastrophic impact for the ecosystem and society if they last for a long period of time. Historic cycles of flooding and drought in the natural flow regime are integral components of most intact running water ecosystems [4] as these exert dominant controls on ecosystem structure and function [10]. As water resources are well into the era of the Anthropocene, climate change and human dominance pose pressing challenges to the hydrologic cycle and its components, putting the integrity and resilience of river basins at higher risk.

In semi-arid basins like the RGB, floods are an important component that allows change after annual and interannual periods of droughts. But long periods of low flows in rivers habitats, leads to isolated water bodies, discontinuity and water shortages. By comparing the natural and regulated flow regimes using long-term streamflow data (110 years) we analyzed the hydrologic variability (floods and droughts) of the RGB system.

Products

(a) A report that describes the statistical analysis, trend analysis and results [Dec/20]

- **Section I. Report for Floods**
    - **Background.-** This section provides an overview of floods in the Rio Grande. Analysis of floods timing, magnitude-frequency. It also includes two indices one for change in magnitude and another for the change in frequency.
    - **Methods.-** This section describes the methods used for flood analysis, including Exceedance probability curves, Log-Pearson Type III, and a trend analysis.
    - **Results.-** The analysis identifies spatial trends in the probability of floods and how change in these weather patterns could influence the occurrence of large flow events in the basin.
- **Section II. Report for Drought**
    - **Background.-** This section presents evidence that anthropogenic drought in river basins has caused changes in the timing and duration of wet and dry periods in the RGB basin using a comparison between its current and natural state. **Methods.-** This section describes the characterization of drought events by estimating the SDI and determining the dry and wet periods that occur naturally through the basin. The analysis included Streamflow Drought Index and a Computation of stability landscapes.
    - **Results.-** The findings indicate the permanent presence of an anthropogenic megadrought in the RGB. In addition, with changes in the stability landscape of the river basin.

(b) one presentation to explain the droughts and floods analysis and what to expect in the future [Dec/20].

- CCAST Webinar: Environmental Flows in the Rio Grande-Rio Bravo Basin (https://www.drought.gov/events/environmental-flows-rio-grande-rio-bravo-basin)
- Link for webinar recording: https://youtu.be/5I-prBCOjTs
- Folder that contains the presentation slides: Dissertation_LEGARZA.pptx

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Section I. Floods Report

Background

Even though floods are usually associated with risks to human lives and infrastructure, they play a vital role in river and riparian ecosystem health. High flows and large floods drive changes in streamflow quality, habitat, and connectivity, which have a direct impact in the life cycle of river and riparian organisms [1]. Flood pulses maintain the ecosystem in a dynamic equilibrium, in which organisms and natural processes respond to the change of amplitude, duration, frequency, of the flood pulses [1].

Floods occur when water rises to overflow land that is not usually submerged [2]. More specifically, river floods arise when a flow is too large to be contained within the natural channel network [2]. A flood may occur depending on multiple factors, including the catchment state (i.e. how much moisture is stored in the basin), catchment dynamics (i.e. how fast runoff occurs), and atmospheric inputs (i.e. increasing precipitation and high water depth) [3]. During flooding, high habitat diversity on the inundated floodplain is coupled with massive increases in aquatic habitat, nutrient regeneration, and increased primary and secondary productivity [1].

In semi-arid basins floods play a crucial role for river and riparian ecosystem health [1]. These basins are characterized by a high level of climate variability; they experience consistent, year-long dry periods marked by punctuated precipitation events, which vary greatly from year to year [4]. Long periods of low flows dehydrate channel habitats and isolate water bodies, which are filled and reconnected during infrequent and low predictable high flows and floods [1]. Additionally, nutrients are replenished, fish reproduction and dispersal become possible on a grand scale, and fisheries productivity of inundated floodplains reaches “boom” proportions" [5, 6]. These processes "maximize the chances of floodplain and channel water bodies starting the dry season with a diverse, abundant, and healthy fish assemblage immediately after flood recession, and this ultimately enhances the survival of fish and other biota through prolonged periods of adverse conditions” [7, 8].

Floods in the Lower RGB play a vital role in sustaining riparian and river health. The Big Bend Region illustrates the importance of annual and interannual floods. This region is an environmentally protected area, located downstream the confluence of the Rio Grande mainstem and Rio Conchos, the main tributary. Before widespread human intervention altered the hydrology of the RGB, the Big Bend Region received two large pulses, one in spring and another one in summer or fall, similar in magnitude [9]. In areas where the river flowed through valleys, flood pulses created multiple channels and sudden changes in its course. These pulses achieved several functions: they flushed sediments carried by tributaries; they controlled riparian vegetation, preventing the formation of floodplains; and they created wide channels with slow-moving water, which provided habitat for rearing and growth of native and endangered fish [9].

Water diversions, reservoir operation and management, and river channelization have heavily altered the magnitude, frequency, duration, timing, and variability of high flows and floods, especially since the 1940s [9]. As a result, many sections of the RGB have experienced channel narrowing and floodplain disconnection. In the Big Bend Region, this has resulted in a "laterally stable river with one channel and dense riverside vegetation", which reduces habitat for native and endangered species [9]. Historic flood management, including river channelization and reservoir operation, and land-use change have caused increased flooding risk in human settlements adjacent to the river, like the Presidio and Ojinaga communities, resulting in human, infrastructure, and economic losses. On some occasions, extreme, large floods have reset the river channel for brief periods.

Justification and objectives

Previously, estimation of natural water availability has been obtained in a coarse time step, either yearly or monthly. However, sub-monthly natural streamflow data was estimated recently in the Upper RGB [10]. In this project, 110 years of daily streamflow data were obtained for the Lower RGB. The streamflow records for the complete RGB span from the late 1880s until 2015. This new dataset presents an opportunity to describe naturally-occurring floods in the Lower RGB during the last 110 years. This characterization would provide a clearer picture of recent natural flood events characteristics and how they have changed in the regulated basin. Additionally, it would be possible to understand the relationship between floods and climate variability in the last century, considering the natural streamflow as a proxy for climate.

The trend analysis can inform decision makers and the society in general what are the expected changes in flood events in the near future in the southern branch of the RGB. The analysis was performed at 5 gauge stations along the RGB mainstem: (1) below Presidio Texas, (2) at Foster Ranch, (3) above Amistad reservoir, (4) at Laredo Texas and (5) at Anzalduas.

The specific objectives of this section are to describe 1-day annual peak flows for natural and regulated hydrology in terms of magnitude, frequency, and timing, and to compare the natural and regulated peak flow characteristics (quantitative).

Methods

Overview

The methods are grouped in two steps: flood event characterization and trend analysis. First, the natural and regulated annual flood series were obtained from the daily streamflow time series. Then, annual flood data were used to estimate flood timing, magnitude, and frequency through different statistical analyses. Finally, these three characteristics of natural and regulated flood events were compared with population metrics and indexes, to understand spatial and temporal trends.

Flood event characteristics

Timing

Flood or peak flow timing refers to the day of the calendar year in which the annual maximum streamflow occurs. The annual peak flow and its ordinal date of occurrence (i.e. day of the year, ranging between 1 and 366) were computed from the daily natural and daily regulated streamflow series. Next, descriptive statistics were computed, including central metrics (average and median), measures of spread (standard deviation, interquartile range), and maxima and minima. Then, peak flow timing was plotted in violin plots in different time windows: the complete 110-year series and periods of 25 years.

Magnitude and frequency

Flood or peak flow magnitude is simply the value of the maximum streamflow that occurs in one day in a given calendar year, expressed in cubic meters per second. Frequency refers to the probability with which a peak flow of a certain magnitude occurs. Two methods were used to estimate natural and regulated flood magnitude and frequency: flood frequency analysis and flood magnitude prediction.

Flood frequency analysis - Exceedance probability curves

First, exceedance probability curves were drawn by plotting cumulative frequency against streamflow magnitude. To construct these plots, the one-day annual peak flow data were ranked from smallest (i = 1) to largest (i = n, where n = sample size). Next, plotting positions were computed as a function of rank *i* and sample size *n*, where (Cunnane, 1978):

$$P(Q^i)=\frac{(i-0.4)}{(n+0.2)} \quad (1)$$

Thus, exceedance probability curves were plotted for the complete 110-year data set, with peak flow magnitude in the horizontal axis and cumulative frequency in the vertical axis.

Flood magnitude prediction - Log-Pearson Type III

Flood magnitude estimates were predicted by fitting a Log-Pearson Type III (LP3) distribution to the logarithm of the annual peak flow dataset, using the mean, standard deviation and skew coefficient of the data, and the method of moments. This fitting was performed for (1) the complete 110-year time series to obtain the cumulative distribution function, and (2) in consecutive windows of 20 years (i.e. 1900 - 1920, 1901 - 1921, …, 1994 - 2014) to obtain the 2-, 5-, 10-year annual peak flow estimates. Mean, standard deviation, and skew coefficient (X, S_x, G_x) were computed as follows:

$$\underline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i\ ; \qquad S_x = \left[\frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \underline{X}\right)^2\right]^{1/2}; \qquad G_x = \frac{N}{(N-1)(N-2)S^3}\sum_{i=1}^{N}\left(X_i - \underline{X}\right)^3 \quad (3)$$

The parameters of the Pearson Type III distribution (α, β, τ) were obtained by:

$$\hat{\alpha} = \frac{4}{G_x^2}; \qquad \hat{\beta} = \frac{S_x G_x}{2}; \qquad \hat{\tau} = \underline{X} - \hat{\alpha}\hat{\beta} = \underline{X} - 2\frac{S_x}{G_x} \quad (4)$$

To assess the goodness of fit of the distribution to the sample data, two techniques were used: probability versus quantile plots with 5% and 95% confidence intervals and the probability plot correlation coefficient (PPCC) with its graphical analog, the quantile-quantile plot. The quantile-quantile plot graphs observed quantiles in the y-axis versus theoretical quantiles in the y-axis.

Trend analysis: comparison of natural and regulated peak flows

Change in timing

To compare the differences in flood timing between natural and regulated flows, two techniques were used: estimating differences in the central metrics (average, median), and computing differences in measures of spread (standard deviation and IQR).

Change in magnitude

To assess the change in magnitude, the 10-year estimate of regulated peak flow of a determined year was divided by the 10-year estimate of the natural peak flow of the same year. The 10-year estimates were obtained with the LP3 function in windows of 20-years. The index (Equation 5) defines the proportion between the regulated and the natural flood magnitude estimate for a given year.

$$Index\ 1 = \frac{Flood\ Magnitude_{regulated}^{T=10}}{Flood\ Magnitude_{natural}^{T=10}} \quad (5)$$

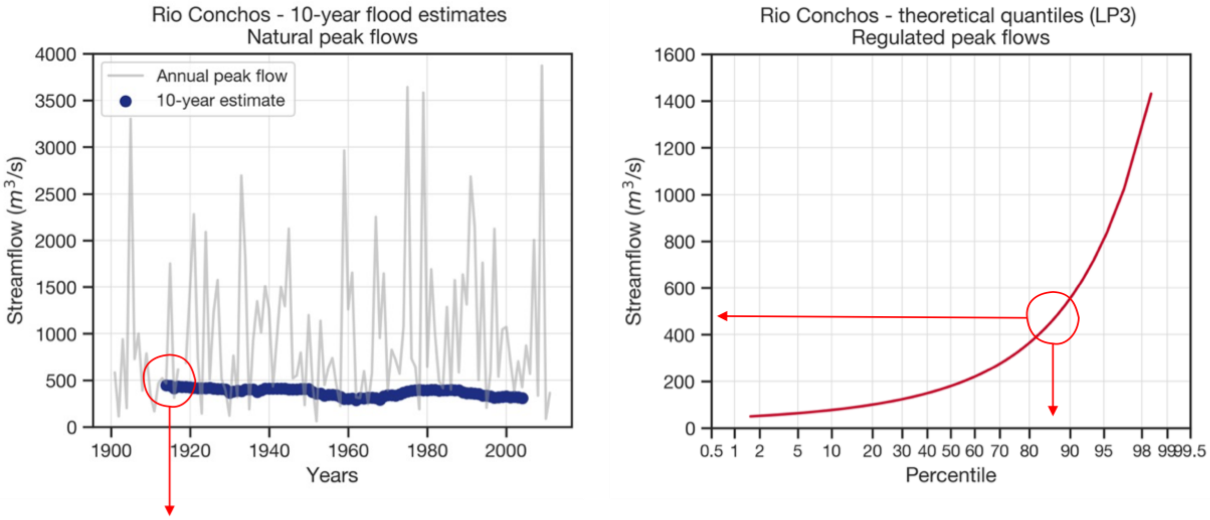
Change in frequency

To assess the change in frequency, two steps were involved. First, the magnitude of the natural flood with a 10-year return period was obtained for each year. As mentioned earlier, this value was obtained with the LP3 function and the natural flood timeseries in windows of 20 years. Then, the estimates of the regulated flood magnitude were computed with the LP3 function, and the 110 year regulated flood data. The value of the natural flood magnitude was looked up in the 110 year regulated estimates, and the frequency of the regulated estimate was obtained. For example, for a given station, from 1900 to 1920, the natural peak flow estimate with a 10-year return period is 300 m^3/s. This value, 300 m^3/s, was looked up in the quantiles obtained with the LP3 function of the 110-year regulated peak flow data. The frequency of the 300 m^3/s in the regulated flood estimates is a return period of 50 years. The questions this index seeks to answer are: how often do natural flood magnitudes occur in the regulated hydrology? and how does this frequency compare to the frequency of natural floods?

$$Index\ 2 = \frac{P(Q_{nat\ (T=10)}) \in TS_{natural, t = 20\ years}}{P(Q_{nat\ (T=10)}) \in TS_{regulated, t = 110\ years}} = \frac{F_{natural}}{F_{regulated}} \quad (6)$$

Frequency is obtained as follows, where F is frequency, P is percentile, and T is return period. Figure 1 presents a conceptual model that illustrates how to obtain the frequencies to compute Index 2. Index 2 is a multiplier to obtain the frequency of natural peak flows based on the frequency of the regulated flows.

$$F = \frac{P}{100} = 1 - \frac{1}{T} \quad (7)$$


Rio Conchos - 10-year flood estimates
Natural peak flows

Rio Conchos - theoretical quantiles (LP3)
Regulated peak flows

Using natural, annual peak flow data from 1904 to 1924, we fit the LP3 model and obtain a peak flow estimate with a 10-year return period of 443 m^3/s. A 10-year return period corresponds to a frequency of 0.90.

Using regulated, annual peak flow data from 1900 to 2010, we fit the LP3 model and obtain theoretical quantiles. Here, a peak flow of 443 m^3/s is positioned in the 85th percentile, which corresponds to a 7-year return period and frequency of 0.85.

Figure 1. Calculation of Index 2

Results

Flood characteristics

Timing

At all RGB stations of the southern branch, the natural, median peak flow timing is between late August and early September, with very little variation between stations (Figure 2). At Rio Conchos, half of flood events are distributed between one month, from late August to late September. In the RGB Below Ojinaga and Foster Ranch, half of flood events are distributed between two months, from late July until late September. This changes at Amistad, Laredo, and Anzalduas, half of flood events are distributed between three months, from late June until late September. Additionally, in these three stations the timing presents a bimodal distribution, which is incrementally marked in each subsequent downstream station.

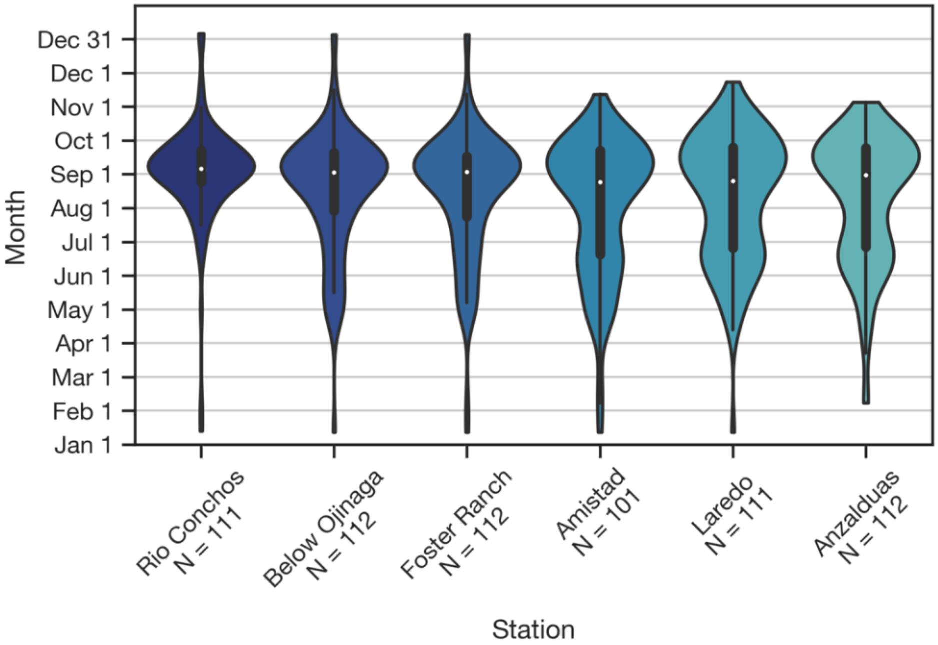


Figure 2. Timing of the annual peak flows in the RGB Natural streamflow

This corresponds with what is known about the natural flow regime in the lower branch of the RGB. The flow regime of the Rio Conchos is dominated by rainfall events caused, in most part, by the North American monsoon [11], with additional flows resulting from tropical storms that either impact directly or approximate the Rio Conchos basin from both the Pacific and Atlantic Oceans [12]. At downstream stations, particularly at Laredo and Anzalduas, peak flow timing reflects the influence of two climatically-different headwaters [13]: the snow-melt driven peaks that occur from late April to mid-June [10] and the rainfall-dominated flows from Rio Conchos presented from late July to late September. Indeed, navigation reports (Blythe and Schmidt 2018) describe how annual high flows entered the Gulf of Mexico from April until August.

Figure 3 shows flood timing in four different time periods. The main differences between these four periods are several. First, some outlier values are found; several peak flows occur much earlier in the periods from 1930 to 1959 from Rio Conchos to Laredo, and in the period from 1990 to 2015, in Foster Ranch, Amistad, and Anzalduas. Second, there is slightly more variation in the median between periods, especially in 1930-1959 and 1990-2015 in Amistad, Laredo, and Anzalduas, with the median peak flow occurring up to a month earlier. Lastly, the bimodal distribution is not as marked in all periods; the interquartile range is much shorter in Amistad from 1960 to 1989, and at Laredo and Anzalduas from 1990 to 2015. Otherwise, the values of median and the interquartile range are similar to the values of the 100-year timing timeseries.

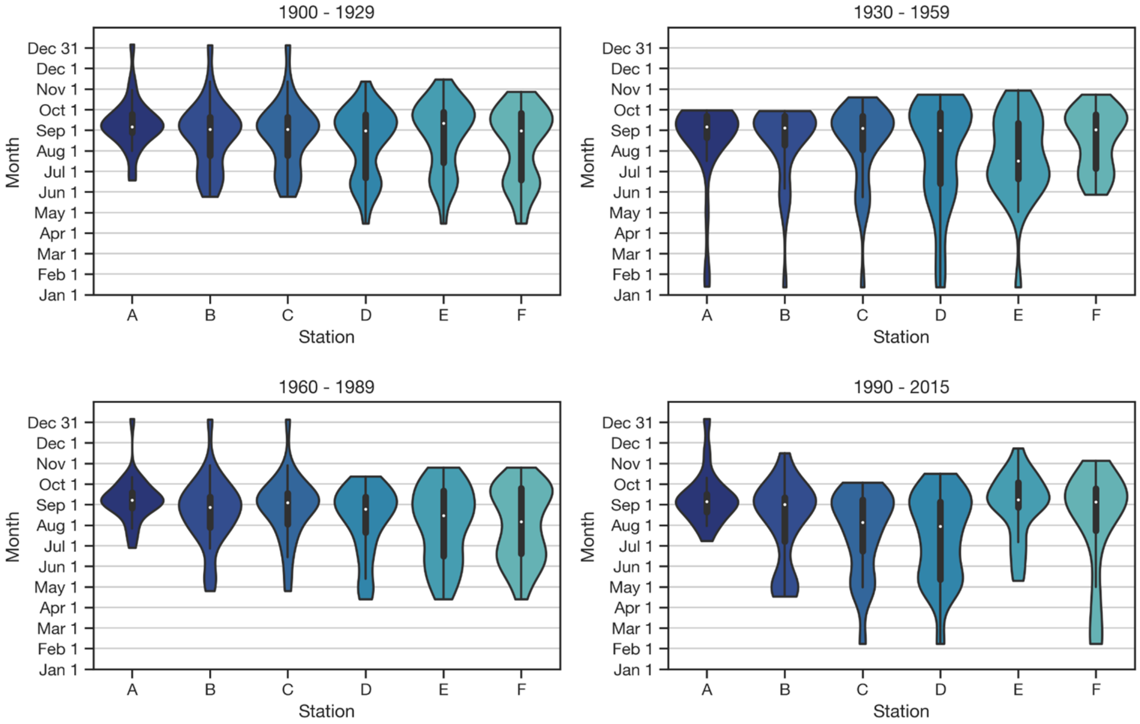


Figure 3. Flood timing in four different periods in the RGB Natural Flow. Station nomenclature: **A** - Rio Conchos, **B** - Below Ojinaga, **C** - Foster Ranch, **D** - Amistad, **E** - Laredo and **F** - Anzalduas

Similarly, Figure 4 presents peak flow timing of the regulated streamflow, and Figure 5 presents flood timing for the regulated streamflow in four different time periods. The changes in timing between natural and regulated streamflow are discussed later in the Trend Analysis section.

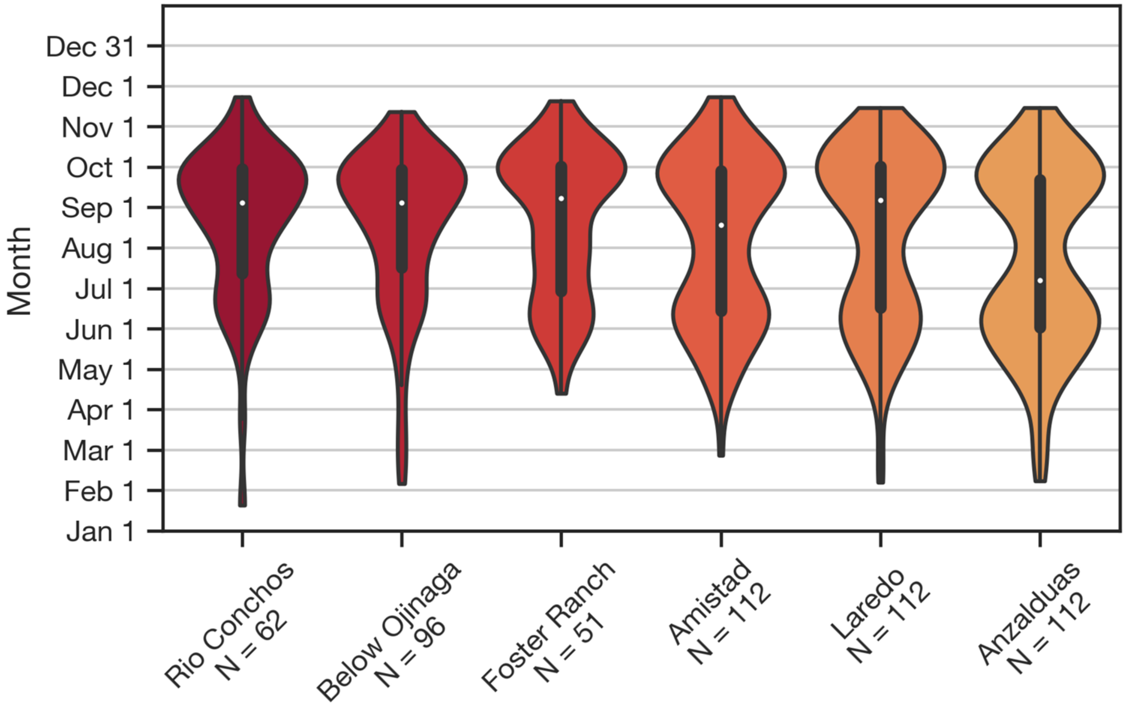


Figure 4. Timing of the annual peak flows in the RGB regulated streamflow

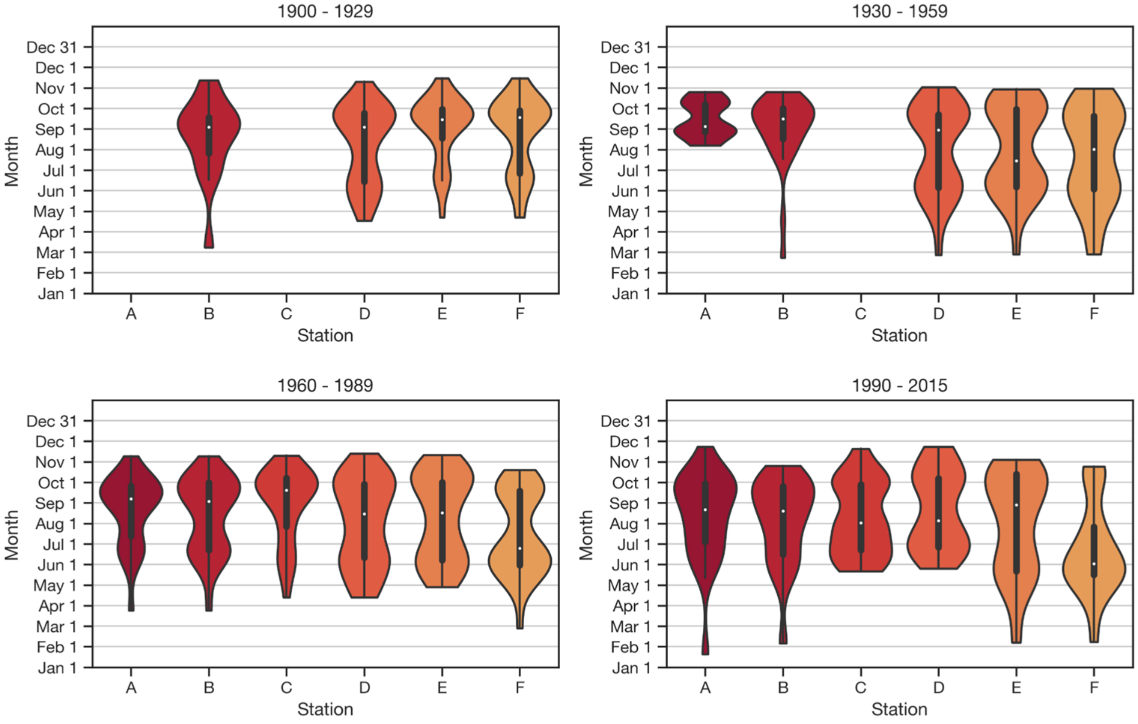


Figure 5. Flood timing in four different time periods in the RGB regulated streamflow. Station nomenclature: **A** - Rio Conchos, **B** - Below Ojinaga, **C** - Foster Ranch, **D** - Amistad, **E** - Laredo and **F** - Anzalduas

Magnitude and frequency

Flood frequency analysis

Natural, median peak flow magnitude ranges from 720 m^3/s at Rio Conchos to 2,250 m^3/s in RGB at Anzalduas. The minimum peak flow ranges from 59 to 440 m^3/s, while the maximum from 16,808 to 19,522 m^3/s. Downstream from Rio Conchos, in RGB below Ojinaga and at Foster Ranch, the median peak flow increases in increments of less than 10% in each station, while in downstream stations, the median peak flow increases in increments from 20% to 35%. In the regulated basin, median peak flow magnitude ranges from 199 m^3/s at Rio Conchos to 648 m^3/s in RGB at Anzalduas, while the minimum ranges from 44 to 82 m^3/s, while the maximum from 1,490 to 7,203 m^3/s. The difference in the metrics of natural and regulated flows are stunning; the median of regulated peak flows at the upstream and downstream stations decreases 70% (see Table 1), while minima and maxima at two stations show up to 90% reduction.

Table 1. Metrics of the natural and regulated annual peak flow magnitudes.

Annual peak flow magnitude (m^3/s)									
Metric	**Rio Conchos**			**Below Ojinaga**			**Foster Ranch**		
	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change
Minimum	59	44	-26%	200	14	-93%	202	70	-66%
Average	1,134	281	-75%	1,219	449	-63%	1,275	508	-60%
Median	720	199	-72%	799	251	-69%	837	306	-63%
Maximum	16,808	1,490	-91%	16,830	4,220	-75%	17,496	2,440	-86%
SD	1,707	315	-82%	1,689	591	-65%	1,741	548	-69%
IQR	889	140	-84%	906	346	-62%	957	401	-58%
Metric	**Amistad**			**Laredo**			**Anzaldúas**		
	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change
Minimum	260	117	-55%	359	156	-57%	440	82	-81%
Average	1,812	1,406	-22%	2,296	1,500	-35%	3,181	1,225	-61%
Median	1,293	778	-40%	1,725	840	-51%	2,258	648	-71%
Maximum	17,516	11,672	-33%	19,479	16,300	-16%	19,522	7,023	-64%
SD	2,014	1,698	-16%	2,225	1,935	-13%	2,856	1,471	-49%
IQR	1,438	1,165	-19%	2,002	1,108	-45%	2,397	1,587	-34%

Figure 6 presents exceedance probability curves of peak flows at all stations, for natural and regulated streamflow. In the natural hydrology, above 60% probability of occurrence, peak flow magnitudes at Rio Conchos, RGB below Ojinaga, and RGB at Foster Ranch are very similar, while greater differences in magnitude can be observed between RGB at Amistad, Laredo, and Anzalduas. Below 20% probability of occurrence, all stations, except for Rio Conchos, present peak flow magnitudes above 200 m^3/s. The curves of natural peak flows barely overlap below 90% of occurrence, which shows that peak flows of all magnitudes increase proportionally as the river travels downstream, which is expected in the natural hydrology of the basin.

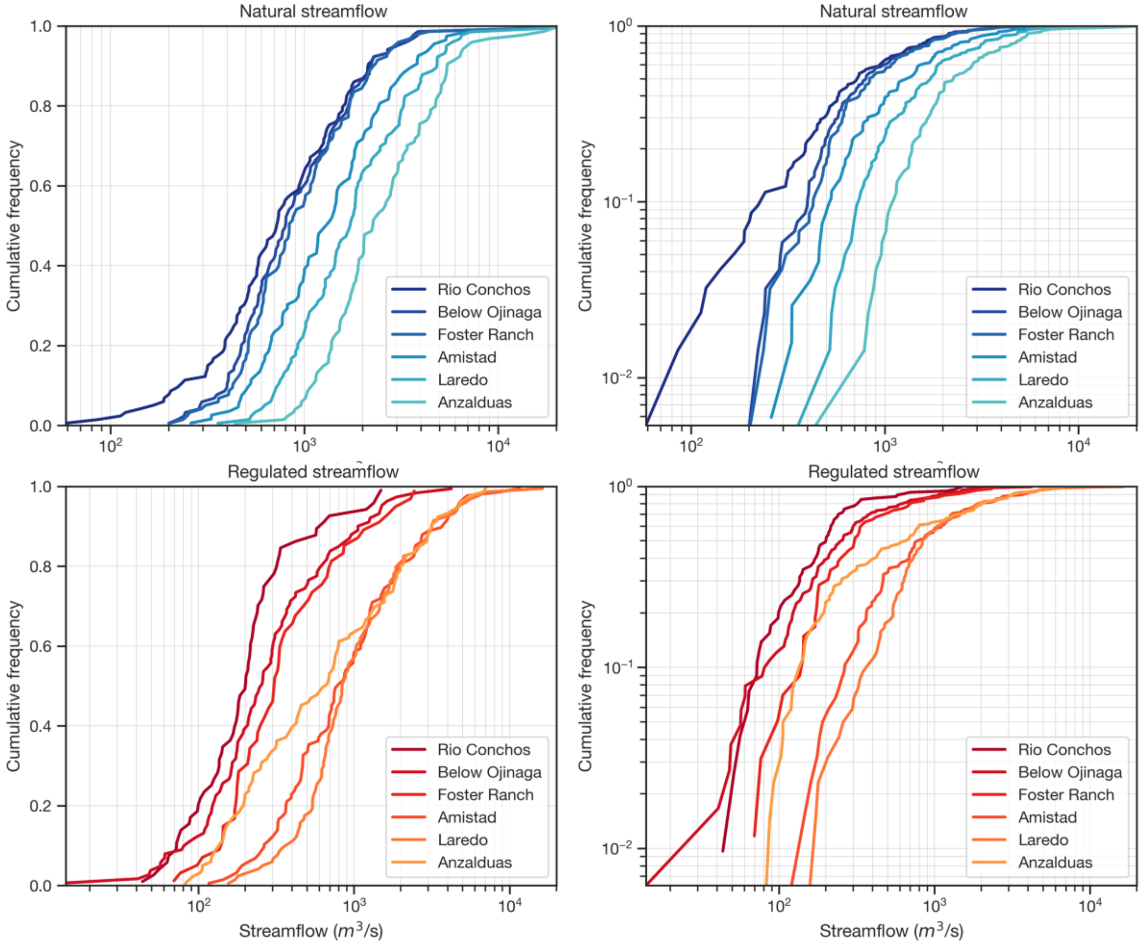


Figure 6. Cumulative frequency of annual peak flows in the RGB for the natural and regulated streamflow

In contrast, the curves of the regulated peak flows overlap. For instance, below 70% of occurrence in RGB at Amistad and Laredo, peak flow magnitudes are larger than in RGB at Anzalduas, which is located downstream from these two stations. Similarly, below 20% of occurrence in RGB below Ojinaga, peak flows fall below 40 m^3/s, while Rio Conchos, located upstream from RGB below Ojinaga, experiences peak flows of at least 40 m^3/s. This illustrates how peak flow magnitude does not increase proportionally as the river travels downstream.

Table 1 presents metrics of the natural and regulated peak flows. Median peak flow magnitude presents significant decreases, above 60%, at Rio Conchos, at RGB below Ojinaga, at Foster Ranch, and Anzalduas. Rio Conchos is the station where most metrics show the largest difference between natural and regulated peak flows, while Amistad is the station with the smallest difference. This is presented visually in Figure 7, which compares the exceedance probability curves of natural and regulated hydrology in each station. Most notably, at RGB in Anzalduas, there is a significant difference in natural and regulated magnitudes below 70% probability of occurrence.

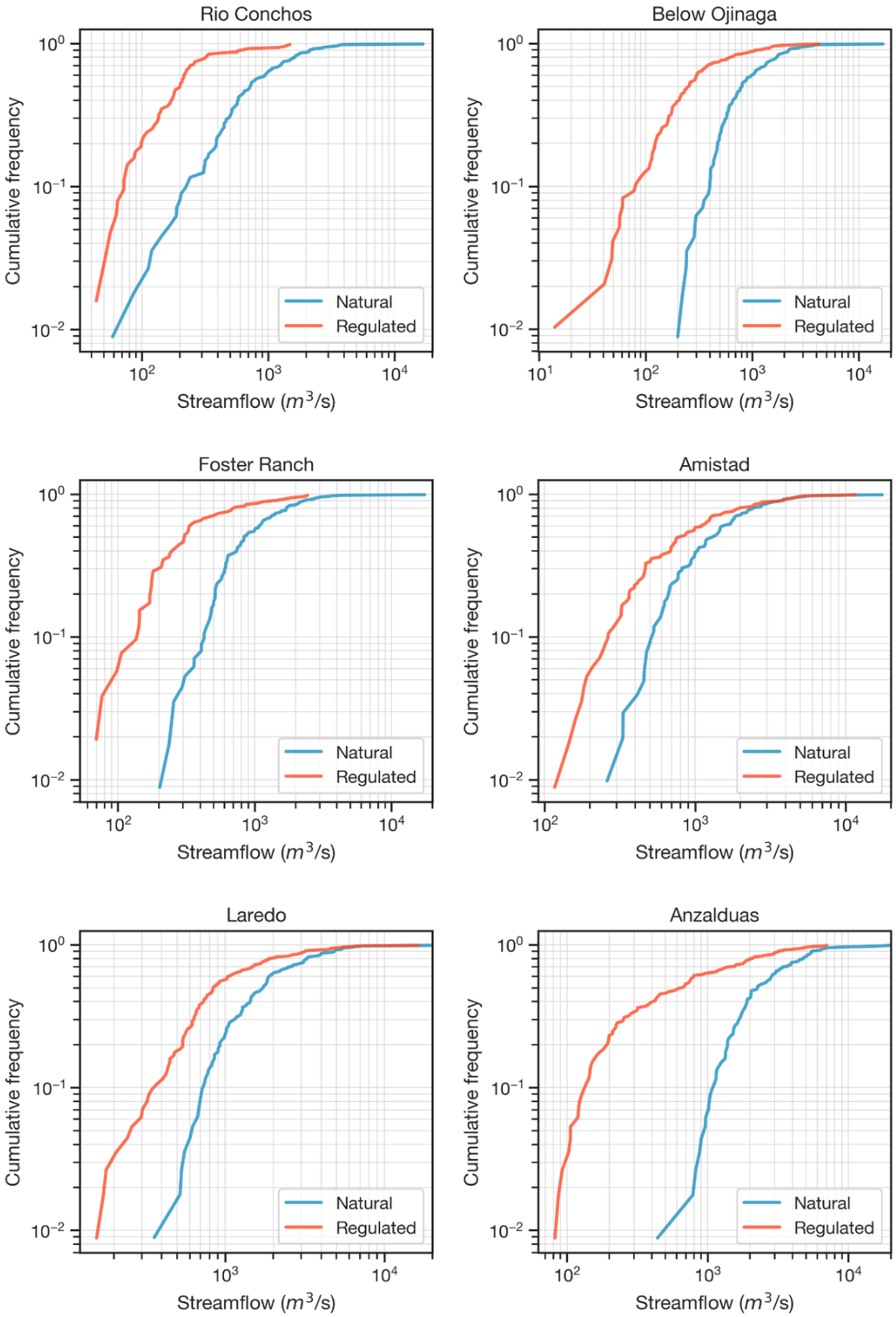


Figure 7. Comparison of exceedance probability curves of the natural and regulated flow

Flood magnitude prediction

Table 2 presents the median magnitude of estimated annual peak flows of different return periods: 2, 5 and 10 years, which correspond to the 50th, 80th and 90th percentiles, respectively.

Estimated magnitudes were obtained using the 110-year time series in windows of 20 years and the cumulative distribution function of the LP3 fitting shown in Figures 8.a and 8.b for Natural and Regulated streamflow, respectively. In natural hydrology, the 2-year peak flow estimate ranges from 750 m^3/s at Rio Conchos to 2,372 m^3/s in RGB at Anzalduas, while the 10-year estimate ranges from 2,055 m^3/s to 6,083 m^3/s. In the regulated hydrology, the 2-year peak flow estimate ranges from 179 m^3/s at Rio Conchos to 616 m^3/s in RGB at Anzalduas, while the 10-year estimate ranges from 576 m^3/s to 3,002 m^3/s. The largest changes in the median between natural and regulated hydrology are observed in Rio Conchos, at RGB below Ojinaga, RGB at Foster Ranch, and RGB at Anzalduas, where the relative reduction of from 50% to 76%.

Table 2. Estimated peak flow magnitude for return periods of 2, 5 and 10 years.

Estimated peak flow magnitude (m^3/s)									
Metric	**Rio Conchos**			**Below Ojinaga**			**Foster Ranch**		
	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change
Median (observed)	720	199	-72%	799	251	-69%	837	306	-63%
T = 2	758	179	-76%	833	264	-68%	893	316	-65%
T = 5	1,482	360	-76%	1,508	619	-59%	1,582	693	-56%
T = 10	2,055	576	-72%	2,072	948	-54%	2,141	1,074	-50%
Metric	**Amistad**			**Laredo**			**Anzaldúas**		
	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change	Natural	Regulated	Rel. change
Median (observed)	1,293	778	-40%	1,725	840	-51%	2,258	648	-71%
T = 2	1,283	838	-35%	1,700	931	-45%	2,372	616	-74%
T = 5	2,336	1,945	-17%	2,996	2,006	-33%	4,334	1,733	-60%
T = 10	3,224	3,082	-4%	4,069	3,097	-24%	6,083	3,002	-51%

Overall, the LP3 function proved a good fit to the annual peak flow data, both for the natural and the regulated streamflow records. Figure 8a and 8b presents the cumulative distribution function of the LP3 fit and the 110-year annual peak flow data and Figure 9a and Figure 9b presents the Quantile-Quantile plots and the PPCC.

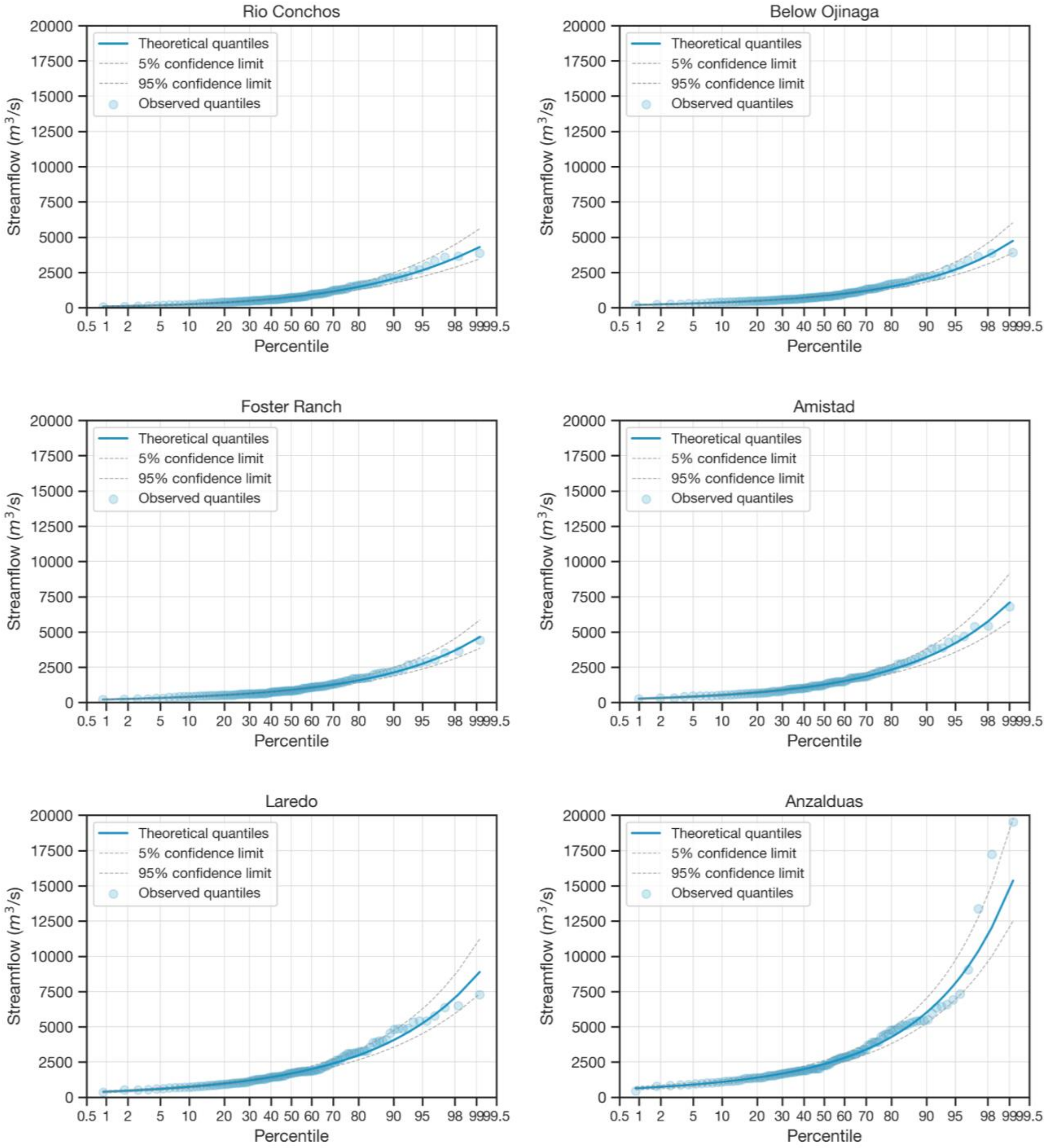


Figure 8a. Cumulative distribution function of the LP3 fit and the 110-year annual peak flow

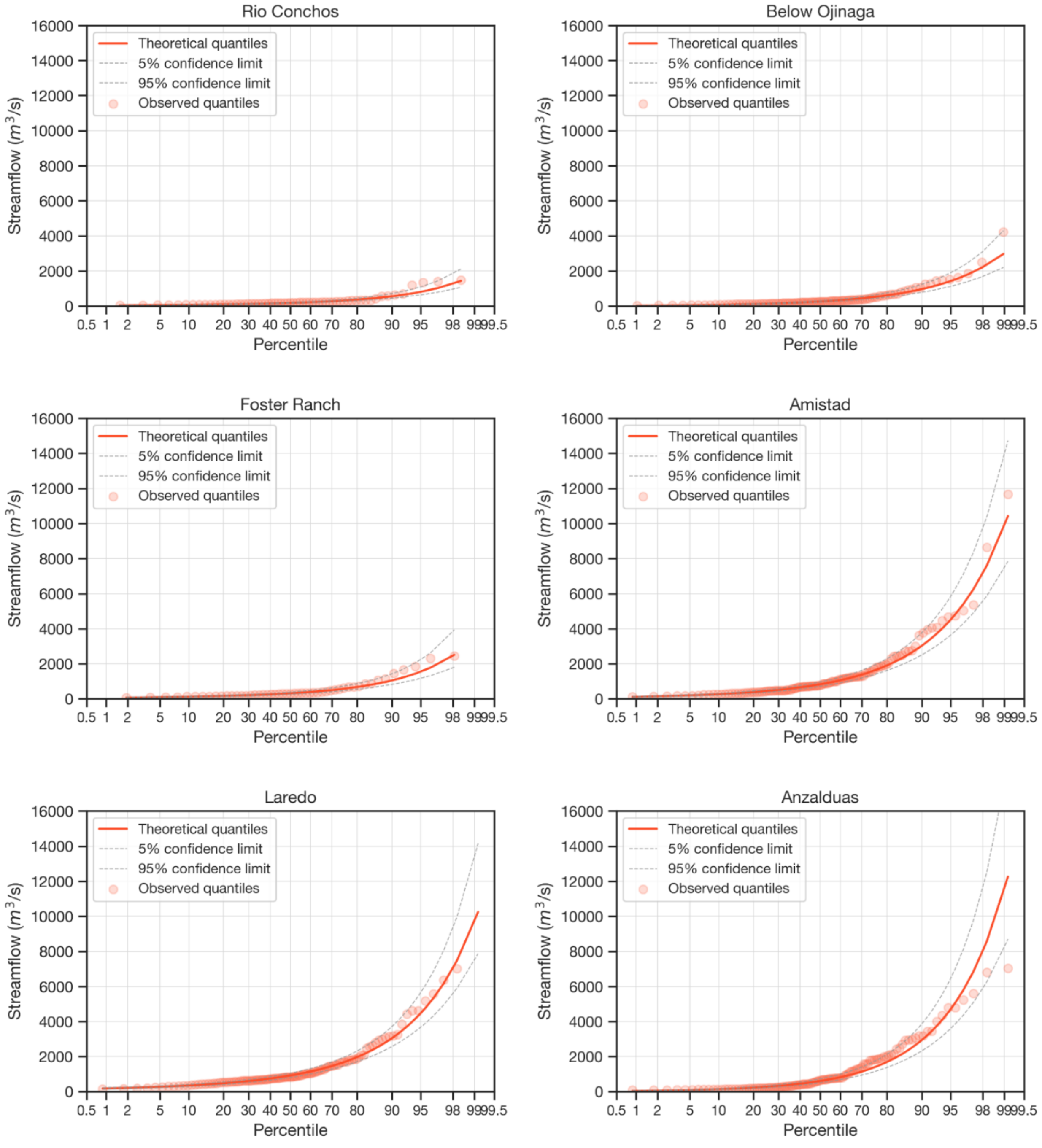


Figure 8b. Cumulative distribution function of the LP3 fit and the 110-year annual peak flow

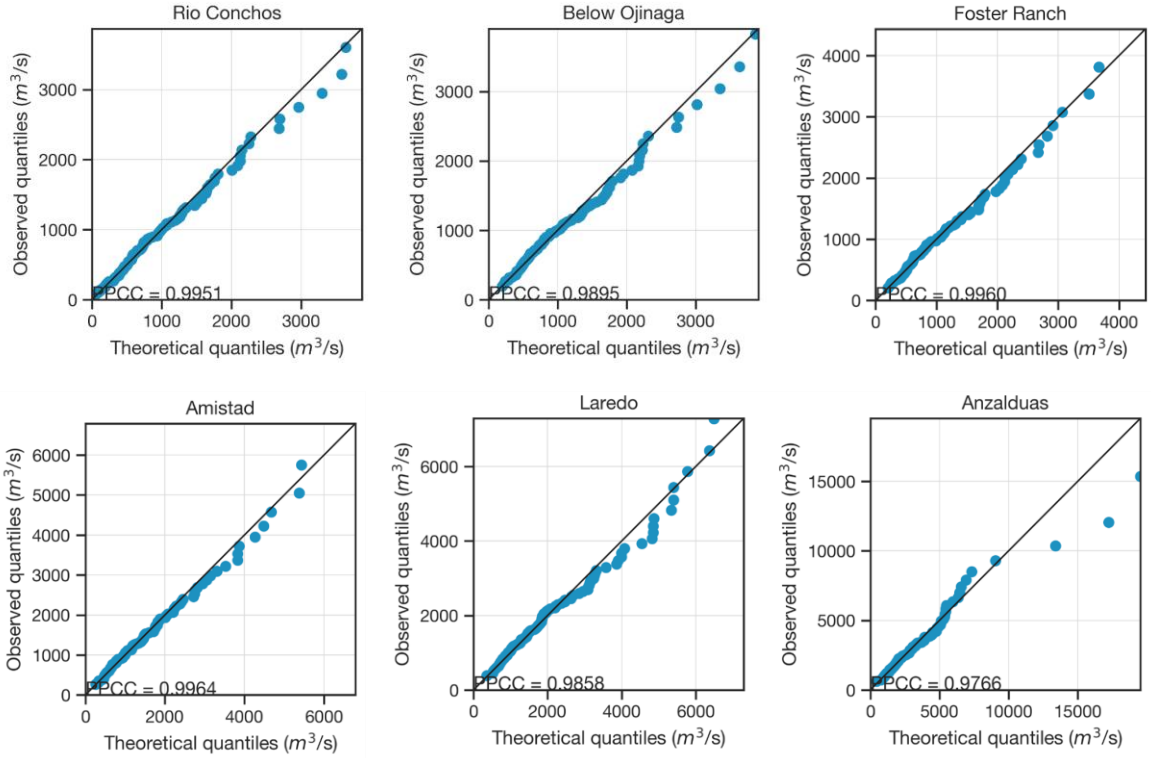


Figure 9a. Quantile-Quantile plots and the probability plot correlation coefficient (PPCC)

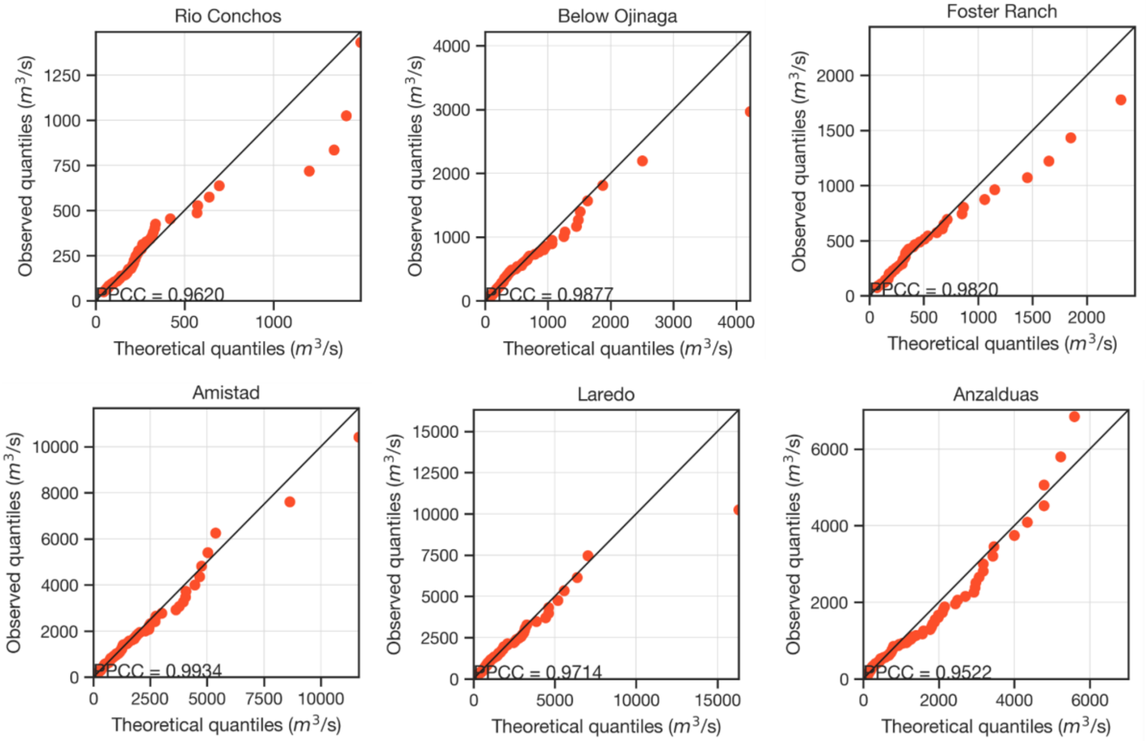


Figure 9b. Quantile-Quantile plots and the probability plot correlation coefficient (PPCC)

Figures 10a, and 10b, show the estimated annual peak flows for natural and regulated streamflow from 1900 to 2010 respectively. Figure 11 shows the natural and estimated 10-year return period peak flows for the Natural and Regulated streamflow in a single plot for comparison. Regarding the 10-year magnitude estimate, from 1920 to 2000, in Rio Conchos, RGB below Ojinaga, and RGB at Foster Ranch, there is little variation in peak flow magnitudes, ranging from 1,500 to 3,000 m^3/s. However, in RGB at Laredo and RGB at Anzalduas, magnitude estimates present larger changes across time. In RGB at Laredo, from 1920 to 1960 magnitudes range from 4,000 to 6,000 m^3/s, decreasing to below 4,000 m^3/s after 1960. In RGB at Anzalduas, from 1920 to 1960 magnitudes range from 4,000 to 8,000 m^3/s, with the lowest values occurring in 1940, this pattern is repeated from 1960 to 2000, with the lowest values occurring in 1980.

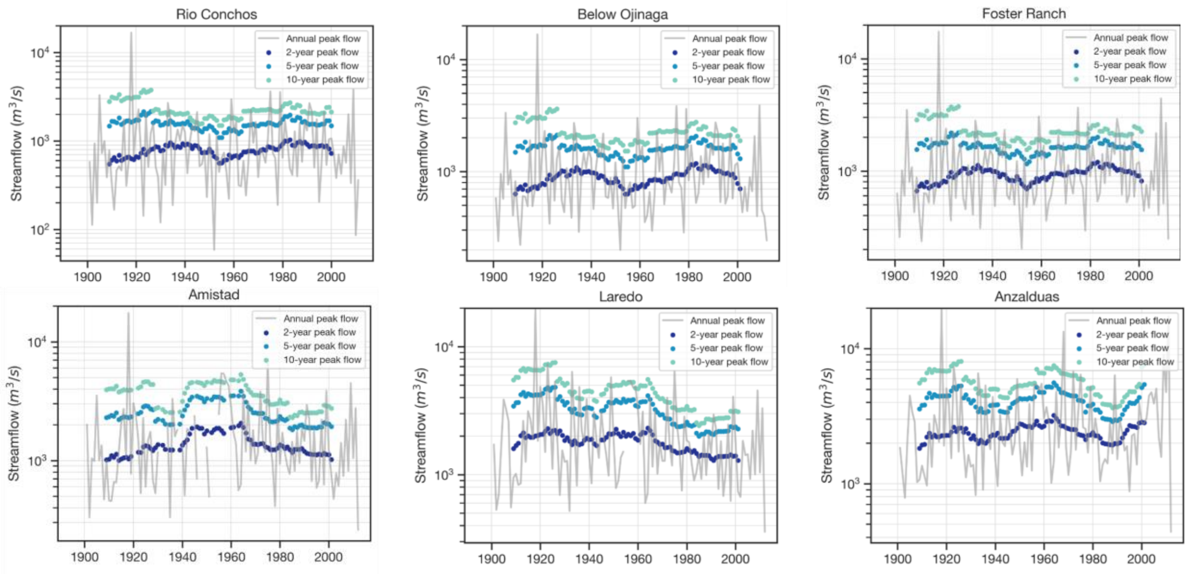


Figure 10a. . Estimated annual peak flows for natural streamflow from 1900 to 2010

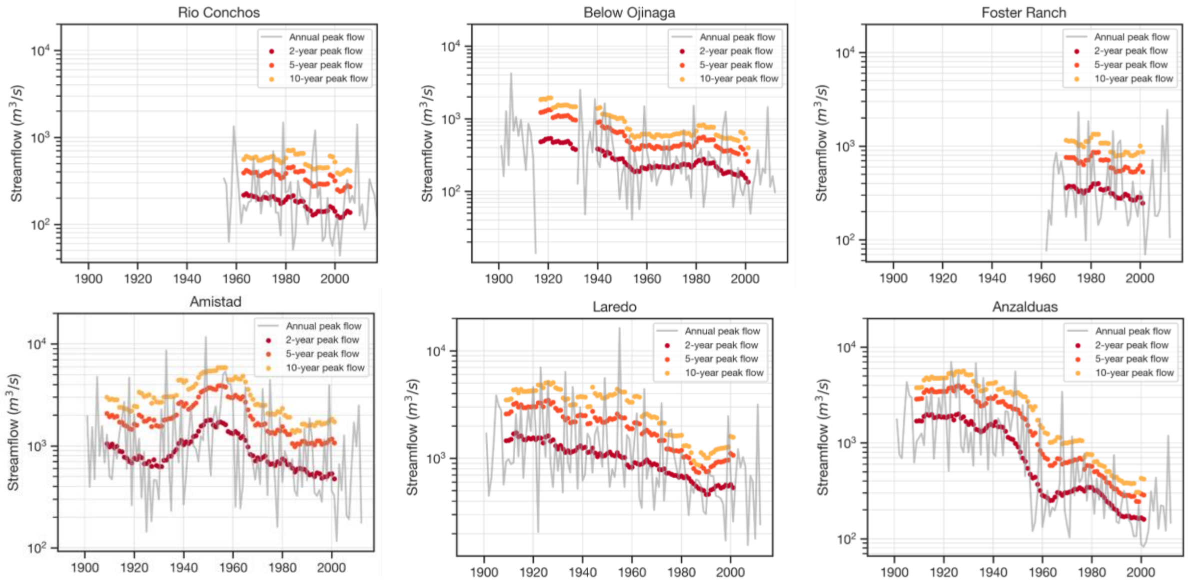


Figure 10b. Estimated annual peak flows for regulated streamflow from 1900 to 2010

Changes between natural and regulated 10-year magnitude estimates across time are more noticeable at RGB below Ojinaga, RGB at Laredo, and RGB at Anzalduas, where regulated streamflow records are longer. In RGB below Ojinaga and RGB at Anzalduas, there is a marked decrease in estimated regulated peak flows from 1940 onwards, with Anzalduas presenting the starkest differences between natural and regulated floods. in RGB at Laredo, regulated floods start decreasing from 1960.

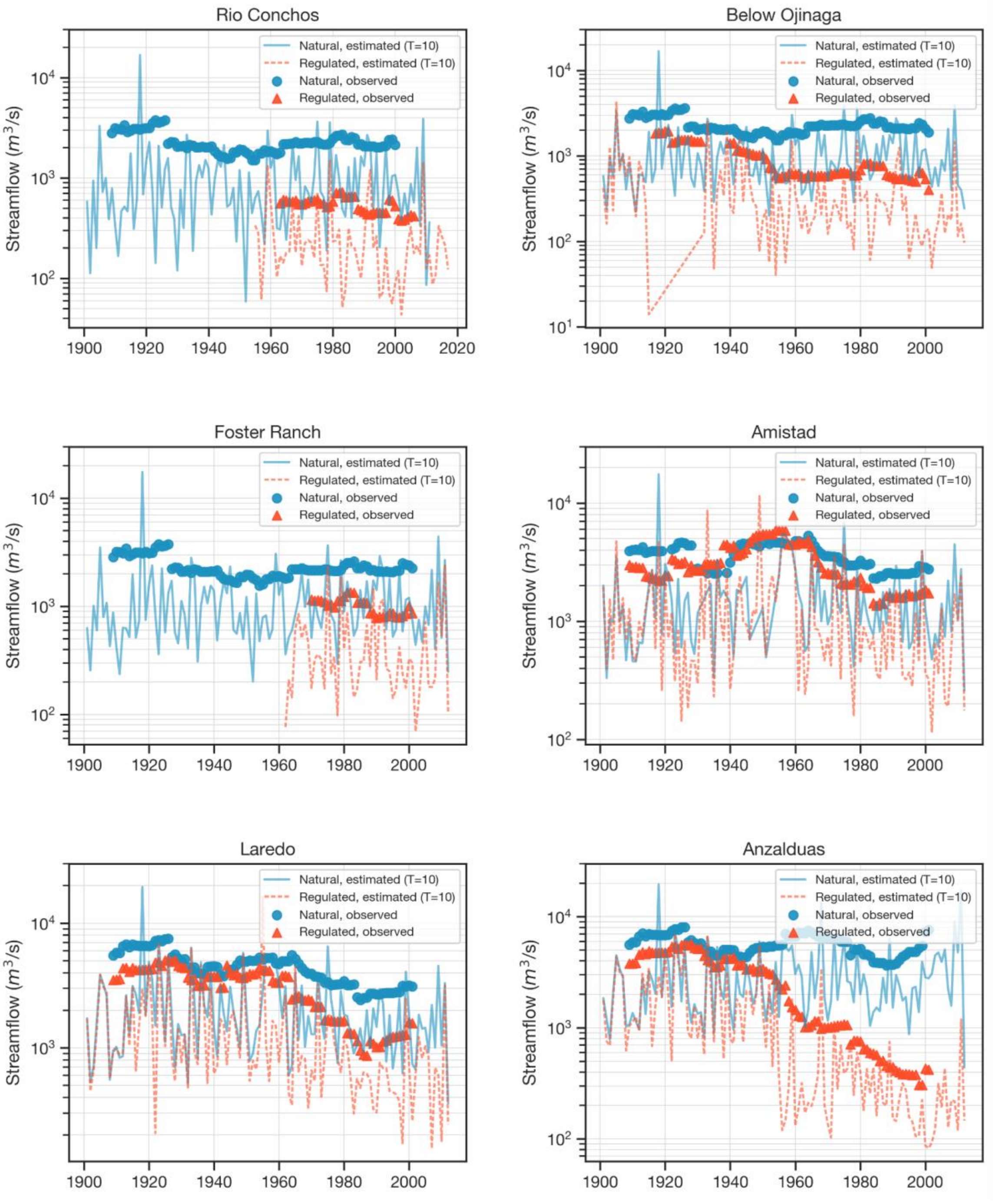


Figure 11. Estimated annual peak flows for natural and regulated streamflow from 1900 to 2010

Trend analysis

Change in timing

At all stations except RGB at Anzalduas, regulated median peak flows occur within 14 days in relation to the natural median peak flows. In RGB at Anzalduas, median peak flows occur over two months earlier. At Rio Conchos and RGB at Foster Ranch, the IQR is larger compared to the natural timing; half of flood events occur within almost two months and over three months, respectively, instead of one month and two months. At Rio Conchos, in RGB below Ojinaga, and in RGB at Foster Ranch, maximum peak flows occur between 1.5 months and 2 months earlier in the year.

Table 3. Annual peak flow timing

Metric	Rio Conchos			Below Ojinaga			Foster Ranch		
	Natural	Regulated	Difference (days)	Natural	Regulated	Difference (days)	Natural	Regulated	Difference (days)
Minimum	Jan 11	Jan 18	7	Jan 10	Feb 3	24	Jan 10	Apr 11	91
Average	Aug 29	Aug 15	-13	Aug 13	Aug 13	0	Aug 11	Aug 16	5
Median	Sep 1	Aug 30	-2	Aug 28	Aug 30	2	Aug 29	Sep 3	5
Maximum	Dec 30	Nov 17	-43	Dec 29	Nov 6	-53	Dec 29	Nov 14	-45
SD	45	56	11	53	57	4	55	55	0
IQR	28	78	50	52	73	21	54	93	39

Metric	Amistad			Laredo			Anzaldúas		
	Natural	Regulated	Difference (days)	Natural	Regulated	Difference (days)	Natural	Regulated	Difference (days)
Minimum	Jan 10	Feb 24	45	Jan 10	Feb 4	25	Feb 5	Feb 5	0
Average	Jul 29	Aug 3	4	Aug 7	Aug 6	0	Aug 5	Jul 19	-17
Median	Aug 20	Aug 14	-6	Aug 21	Sep 1	12	Aug 26	Jul 4	-54
Maximum	Nov 6	Nov 17	11	Nov 17	Nov 9	-8	Oct 30	Nov 9	10
SD	61	61	1	56	64	7	57	66	9
IQR	92	104	12	90	105	15	88	110	22

Figure 12 presents the violin plots of both natural and regulated peak flows and Table 3 shows compares the statistics of the Natural and Regulated timing. Compared to the natural peak flows, all stations in the regulated hydrology present two periods of peak flows, one between late spring and early summer, and another one between late summer and early fall. In contrast, the natural peak flows, especially at Rio Conchos, RGB below Ojinaga, and RGB at Foster Ranch, concentrate between late summer and early fall. This bimodal distribution is more marked in the downstream stations. Even though in RGB at Anzalduas the median peak flow occurs much earlier, it maintains the bimodal distribution.

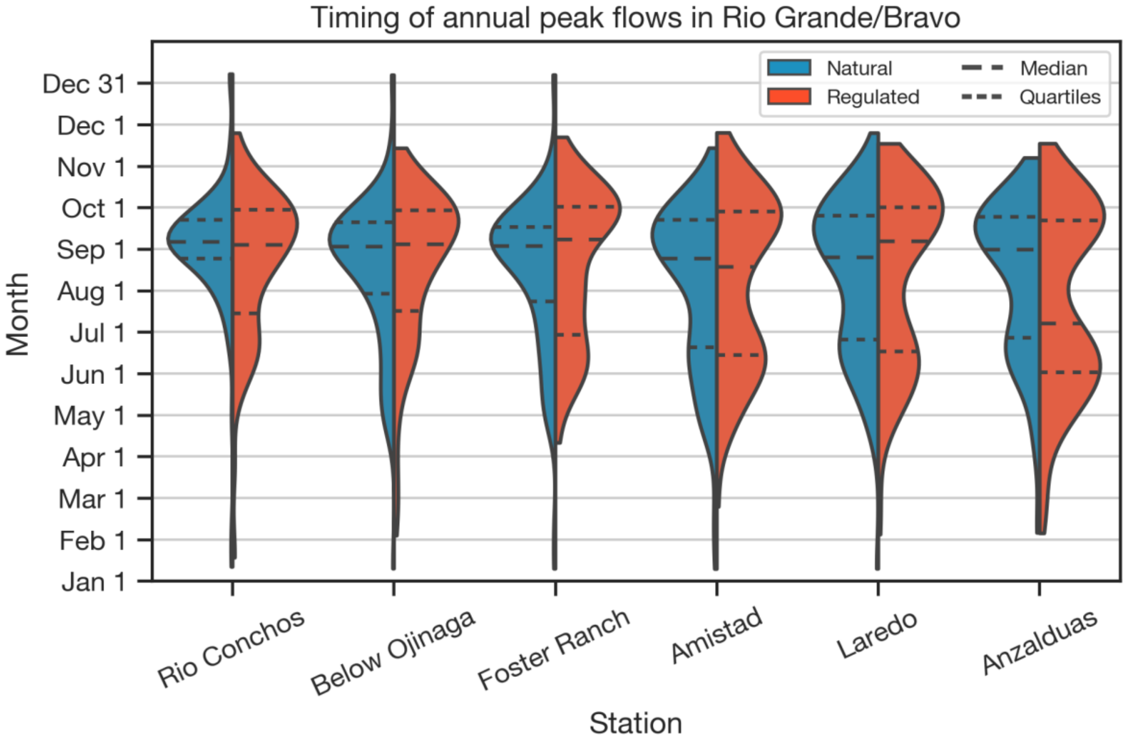


Figure 12. Timing of annual peak flows for natural (in blue) and regulated (in orange)

Change in magnitude

Index 1 describes how peak flow magnitude has changed over time. It compares the 10-year estimated natural and 10-year estimated regulated peak flows, dividing the regulated estimate by the natural estimate. The question this index seeks to answer is: what is the proportion between the regulated and the natural flood magnitude estimate for a given year?

At all stations except RGB at Amistad, the proportion between regulated and natural floods is less than 1.0, meaning peak flow magnitudes have been reduced for the same return period. At stations with more data availability, RGB below Ojinaga, RGB at Laredo, and RGB at Anzalduas, Index 1 has values above 0.5 before 1960, which means that the magnitude of regulated peak flows represents around 50% of the natural peak flows. However, after the 1960s, Index 1 decreased, most notably in RGB at Anzalduas, where it ranged around 0.25 until the 1990s, and dropped to less than 0.15 by the 2000s (Figure 13). This indicates that regulated peak flows represent around 25% and 15% of the natural peak flows. In RGB at Amistad, Index 1 reached values higher than 1.0, up to 1.75, between 1930 and 1960. This means that the magnitude of regulated floods is larger than that of natural floods, which might be due to the operation of Amistad Dam in the regulated hydrology during those 30 years. In Rio Conchos and RGB at Foster Ranch, Index 1 has values around 0.25 and 0.5, respectively, from 1960 and 1970 onwards.

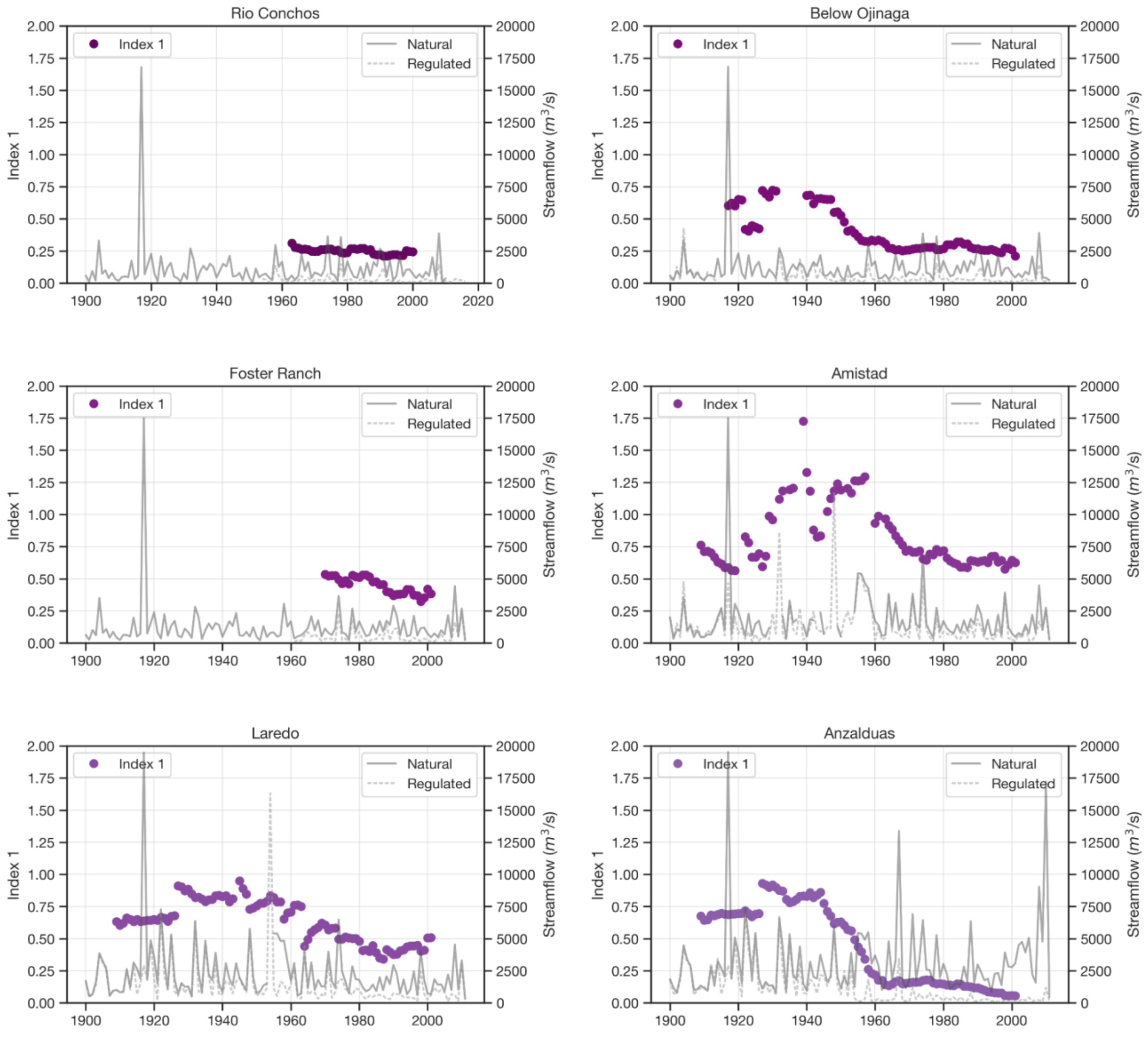


Figure 13. Index 1. Flow magnitude change over time.
Comparison of 10-year estimated natural and 10-year estimated regulated peak flows

Change in frequency

Index 2 presents the frequency with which the magnitude of 10-year natural floods occurs in the regulated hydrology (Figure 14). At stations with more data availability, RGB below Ojinaga, RGB at Laredo, RGB at Amistad, and RGB at Anzalduas, Index 2 has values below 2, with some values under 1, before 1960, which means that the frequency with which 10-year natural floods occur is roughly the same or twice as often as that of regulated floods. After 1960, these stations presented values over 2 and up to 5 in RGB at Laredo and up to 7 in RGB at Anzalduas. This means that the frequency with which 10-year natural floods occur is up to 5 or 7 times the frequency of regulated flows. In RGB at Laredo and RGB at Anzalduas, floods with magnitudes comparable to the natural hydrology do not occur with the same frequency. In Rio Conchos and RGB at Foster Ranch, Index 2 has values below 2 from 1960 onwards.

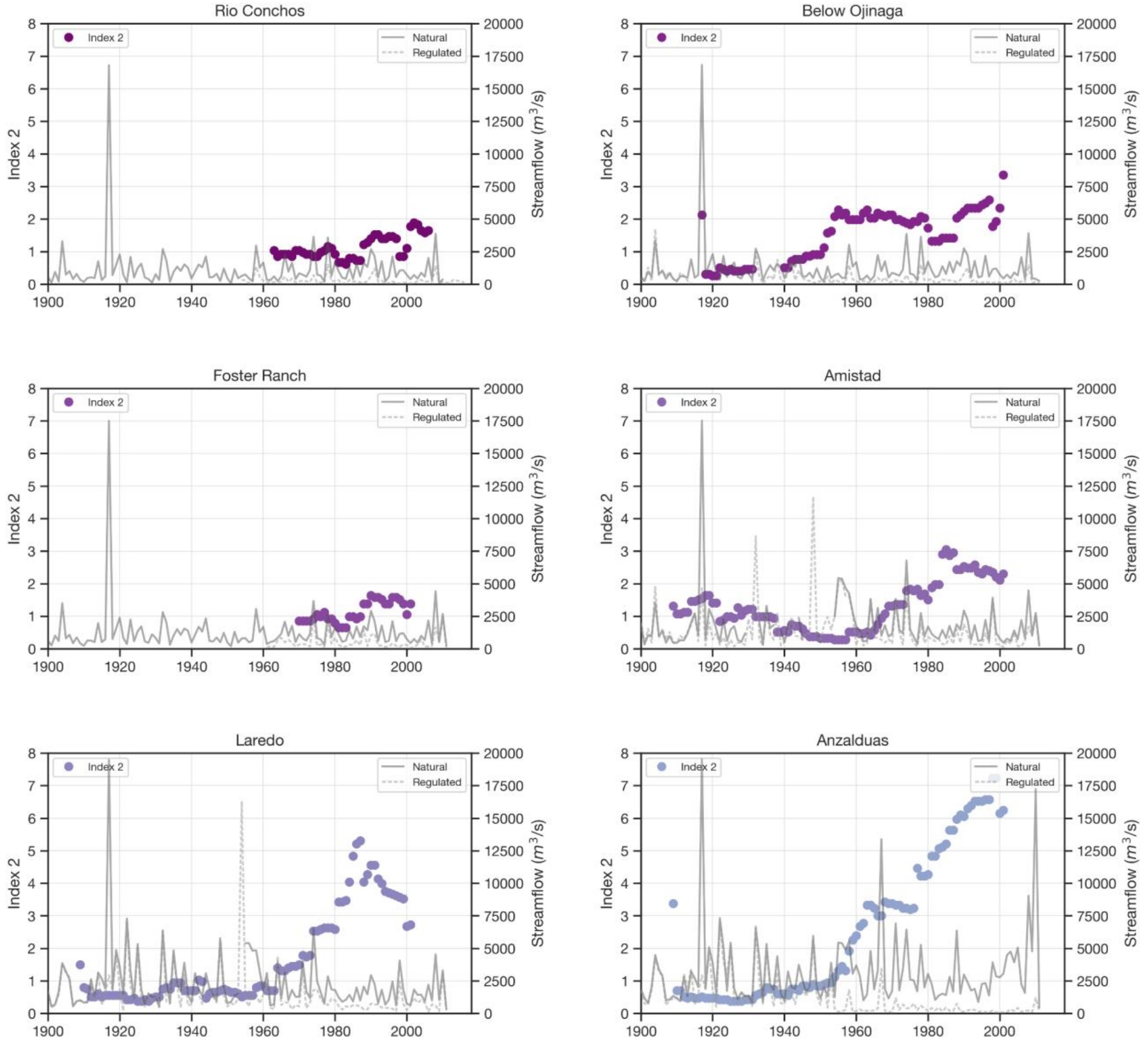


Figure 14. Index 2 showing the frequency of occurrence for the 10-year natural flow floods within the regulated hydrology

Conclusions

The results of this chapter show significant changes in timing, magnitude and frequency of peak flows. The station RGB at Anzalduas, located in the outlet at the Gulf of Mexico shows the most significant changes in terms of magnitude, frequency and timing. This change in flow patterns has significant implications for the riparian ecosystem along the RGB and the estuarian ecosystem near the outlet. In the regulated flow, the gauge stations Rio Conchos, RGB below Ojinaga, RGB at Foster Ranch, and RGB at Amistad show fewer floods events occur during the late summer, those flood events are shifted to late spring indicating that snowmelts in the upper basin are more frequent and monsoon peak flows are less common compared with the natural flow. The distribution of half of the flood events is longer in Rio Conchos and RGB at Foster Ranch, with a higher incidence of summer pulses in Rio Conchos, and more frequent summer pulses and snowmelt floods in RGB at Foster Ranch. Finally, the results show that natural median floods range from 720 m^3/s at the headwaters to 2,250 m^3/s at the basin outlet while regulated median flood magnitudes decreased by about 70% in four stations, with larger floods occurring in stations located upstream of the river outlet.

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Section II. Droughts Report

Background

The complex and interrelated processes between natural and human-induced changes drive the development of anthropogenic droughts [1–6]; a compound multidimensional and multiscale phenomenon governed by the combination of natural water variability, climate change, human decisions and activities, and altered microclimate conditions due to changes in land and water management [3]. The growing frequency of precipitation extremes, especially droughts, will have profound consequences on the hydrologic variability of the streamflow systems and the natural flow regime, creating selective pressures in the environment and society. In return, this will affect the resilience of river basins and the capacity of systems to withstand shocks and perturbations without modifying their functional identity and adapting to changing conditions [7].

Resilience theory applied to water systems can offer a perspective on the understanding of anthropogenic droughts as one of the central disturbances of streamflow dynamics and the potential changes in hydrological resilience across all scales, from local watersheds to regional and transboundary basins. Catastrophic disturbances such as anthropogenic megadroughts can cause shifts in ecosystems into alternative states, through which many ecosystems can lose their functionality and identity.

This phenomenon can be assessed by determining the relationships between natural drivers and processes that allow for ecosystem functioning (e.g., streamflow) and the anthropogenic pressures (e.g., water use, land use change, and management practices. To see how resilience is affected by changes in hydrologic conditions, we may construct stability landscapes [8] which are good approximations for understanding resilience concepts [9].

The metaphor of stability landscapes in resilience theory depicts the various stable states of a system as a series of "basins of attraction," which are regions in state space in which a system tends to remain (Figure 1 – Retrieved from Dakos and Kefi, 2002 [10]) and have been used to explain the dynamics of several ecosystems and the components of resilience including resistance, latitude, precariousness, and panarchy [11]. Stability landscapes help understand the properties of dynamical systems and have been used to represent resilience characteristics of shallow lakes [12], urban water systems [13], tropical forest and savanna [14], climate states [15], plant patterns in drylands [16,17] and river management [18].

A stability landscape with several basins of attraction corresponds to the various stable states in which a system will exist. As streamflow in river basins is modified by exogenous drivers (precipitation, exchange rates) and endogenous processes (infrastructure, management practices), the streamflow system may move from one basin of attraction to another when substantial disturbances occur (e.g., hurricanes, dry spells, ENSO patterns, management practices) and affect the state variables.

State variables include temporal or spatial characteristics, and when these occur, the set of variables will persist in one of many possible configurations, which may shift to a different configuration or equilibrium after a perturbation [9]. However, changes in environmental conditions that affect processes between state variables, such as river fragmentation or changes in the natural flow regime, will alter the shape of the stability landscape as these pressures directly affect state variables.

Justification, hypothesis, and objective

The hypothesis held there is evidence that anthropogenic drought in river basins caused changes in the timing and duration of wet and dry periods in the RGB basin. The general objective was to identify the current anthropogenic state of a transboundary basin in comparison to its natural state and approximates the metaphor of stability landscapes and basins of attraction using streamflow as a representation of the resilience conditions of river basins which can be used in any local, regional, or international scale worldwide. The specific objectives included 1) analyze the hydrologic variability (floods and droughts) of a river system by comparing the natural and regulated flow regimes using long-term streamflow data, and 2) construct stability landscapes and explore properties of resilience in terms of changes in the basins of attraction of the natural and anthropogenic state.

Methods

Overview

We characterized drought events by estimating the SDI and determining the dry and wet periods that occur naturally through the basin (at the 5 control points). Then we use the SDI values of the natural flow as a template to characterize the regulated system. Initially, we proposed to characterize the drought events by performing a 20-year running period of analysis calculation of the frequency, severity, length of droughts. However, when analyzing the results for the regulated period, we identified that the current regulated flow regime is in a perennial man-made megadrought and thus, the running 20-year period of analysis was not adequate because for the hundred years of regulated streamflow analysis, all that time the system was in a perennial anthropogenic megadrought [69].

To analyze the basin-wide dynamics, this study used 110 years of monthly streamflow from 1900 to 2010 at eight control points (i.e. hydrologic gauge stations) to portray the natural and anthropogenic states of the RGB. Four control points were selected in the mainstem of the river basin (San Marcial, El Paso, Above Amistad Dam, and Anzalduas) and four at the outlet of the main sub-basins (Rio Conchos, Pecos River, Rio Salado, and Rio San Juan) see Figure 2.

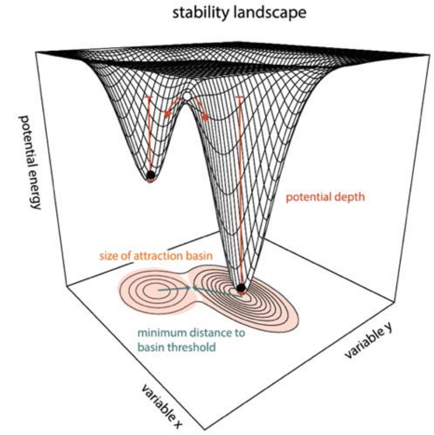


Figure 1. A (hypothetical) stability landscape of a two-dimensional system with hilltops and valleys, also known as a marble-in-a-cup or balls-and-cups landscape. Black balls are found at the bottom of the valley and represent stable states. Retrieved from Dakos and Kefi, 2020 [10].

Furthermore, we performed a Bayesian analysis in the natural flow regime to determine what was the probability to move from drought state to a wet state to quantify the stability landscapes. When performing the same analysis for the regulated stream flows, results showed that there is a higher probability for the system to remain in a drought state. These results reinforce the previous analysis that shows the perennial and severe anthropogenic megadrought that the southern branch of the RGB that has been experiencing since the 1920s.

The methodology included:

1) Data collection of historical streamflow data, including inflows and outflows of the river system.
2) Converting gaged or observed flows to naturalized flows using a water mass balance.
3) Performing a hydrologic drought assessment for the observed and naturalized flows to observe the hydrologic variability of the river basin.
4) Developing stability landscapes to compare resilience attributes between the naturalized and anthropogenic states of the river basin.

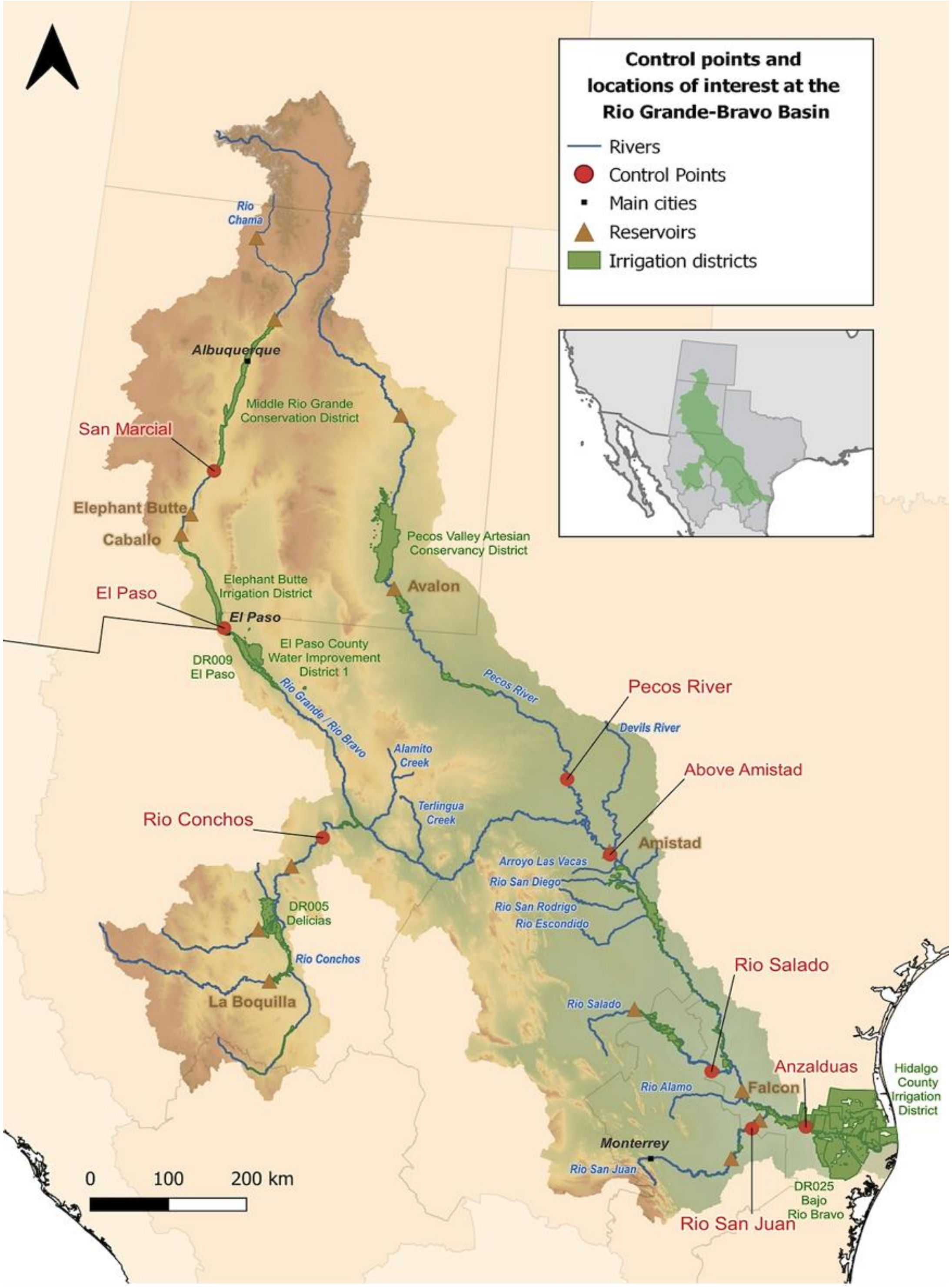


Figure 1. Control points and locations of interest at the Rio Grande-Bravo Basin.

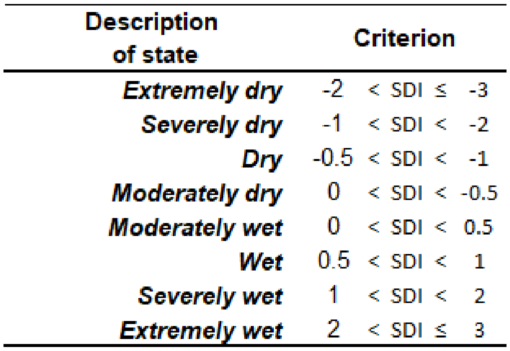
Streamflow Drought Index

The Streamflow Drought Index (SDI) developed by Nalbantis and Tsakiris [31] is used to characterize the severity of hydrological droughts. To capture decadal changes and long-term droughts in the basin for each control point. First, the cumulative streamflow of the naturalized streamflow data was estimated in a time window of 120-months. Then, the aggregated time series were fitted to probability distribution functions (normal, log-normal, and gamma) using the Kolmogorov-Smirnov (K-S) test; the log-normal distribution function (*p-value* less than 0.5) was selected based on the goodness of fit at a 95 percent confidence level and the least sum squared error between each probability distribution function. The software used to test and select the best probability distribution function was the Python package: fitter [32]. At last, the estimation of the cumulative probability is transformed into a standard normal random variable with a mean zero and standard deviation of one, resulting in the values of the naturalized SDI (Eq. 1).

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{S_k} \qquad (1)$$

Where $SDI_{j,k}$ is the standard drought index value, $V_{j,k}$ is the cumulative streamflow volume, $\overline{V}_k$ is the mean, and S_k is the standard deviation of the cumulative streamflow volume for an *i -th* hydrological year with a period length of *k*. Consecutively, the observed streamflow data is evaluated by correlating the cumulative observed streamflow volumes with the closest aggregated naturalized volume; then, its corresponding SDI value is assigned. Hydrologic wet states are values between 0 and 3, and dry states between 0 and -3. For this study, eight states of hydrological droughts representing different severities are used (Table 1), which is the criterion of Nalbantis & Tsakiris [31] modified by Garza-Díaz and Sandoval-Solis [33]

Table 1. Description of hydrologic states based on a modified Streamflow Drought Index (SDI) criterion by Garza-Díaz and Sandoval-Solis [33].



Description of state	Criterion
Extremely dry	-2 < SDI ≤ -3
Severely dry	-1 < SDI < -2
Dry	-0.5 < SDI < -1
Moderately dry	0 < SDI < -0.5
Moderately wet	0 < SDI < 0.5
Wet	0.5 < SDI < 1
Severely wet	1 < SDI < 2
Extremely wet	2 < SDI ≤ 3

Computation of Stability Landscapes

Properties of the stability landscape in environmental systems are commonly linked to the geometric properties of a potential function [10]. Where minima and maxima respectively correspond to stable and unstable equilibria of the basins of attraction, the slopes of the potential surface are proportional to the rates of change in the system [10]. Even if this method is widely used, finding a potential function for systems with more than one dimension can be difficult [34]. Alternative measures have been applied to other systems, including the use of probability distribution functions (pdf) as it is closely related to the potential function where local minima of the potential function correspond to local maxima in the pdf [35]. Hypothetical three-dimensional stability landscapes for the river basin were computed directly from the probability distribution function (pdf) of the natural and regulated SDI values. These figures depict the conditional probability of a given SDI value (SDI_t) given a previous SDI value (SDI_{t-1}). For instance, given that the system had an SDI of -3 in the previous year (SDI_{t-1}= -3), what is the probability of having an SDI value of X in the present year? The pdfs dominant modes serve as proxies of the shape of the basins of attraction and are used to reflect the stability landscape properties and how they change over time.

Results

Hydrologic variability of the natural state of a river basin

The RGB basin spans a climatic gradient from semi-arid to subhumid; its environment is vulnerable to extreme hydroclimatic events [37]; and to investigate its dichotomy, the hydrologic variability of the natural state of the RGB is depicted in a 120-month SDI analysis (Figure 3) which allowed identification of hydrologic drought and flood events.

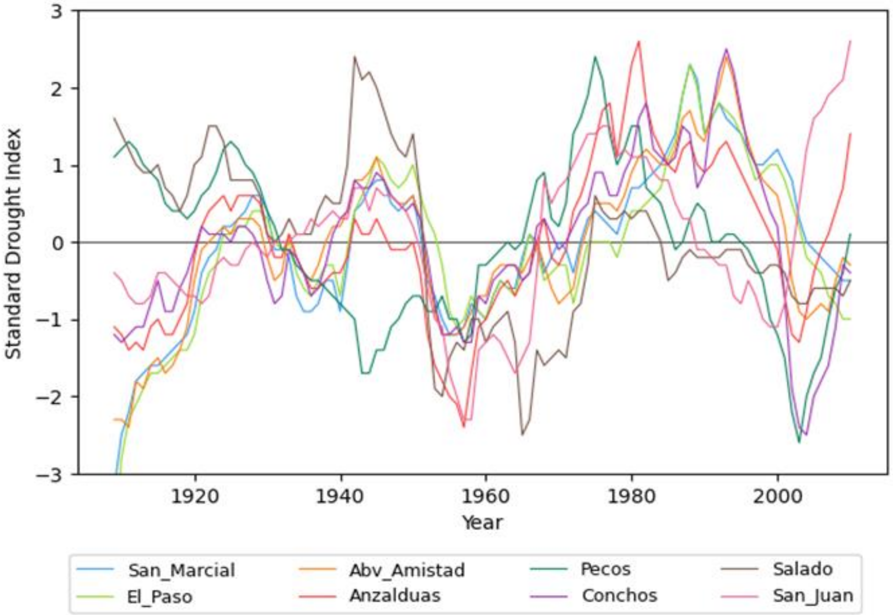


Figure 3. Streamflow Drought Index of the naturalized control points of the Rio Grande-Bravo Basin

Overall, the hydrological behavior of the basin indicates recurrent periods of water stress (Table 2). Droughts in this basin are common and, on average, can span from 10 to 25 years, including consecutive extremely and severely dry periods ranging between 5 to 9 years. In contrast, wet periods tend to be shorter, from 11 to 16 years; extremely and severely wet periods could typically last between 2 to 4 years. Alternating dry and wet cycles could last 24 years in the mainstem of the RGB; these cycles are correlated with ocean-atmosphere climate variability [38].

Table 2. Hydrologic periods of the Rio Grande – Bravo basin. Each hydrologic period is the average of the consecutive number of years that ranges from specific SDI values. [1] Streamflow Drought Index (SDI)

Control Point	Hydrologic Period *(average of consecutive years)*			
	Dry (-3 to -0.5)[1]	Extremely Dry (-3 to -2)[1]	Wet (0.5 to 4)[1]	Extremely Wet (2 to 4)[1]
San Marcial	10	8	11	2
El Paso	13	8	15	2
Above Amistad	13	9	16	3
Anzalduas	13	6	12	2
Rio Conchos	12	6	16	3
Pecos River	25	2	16	4
Rio Salado	23	5	13	2
Rio San Juan	18	4	15	3
Average	**16**	**6**	**14**	**3**
Median	**13**	**6**	**15**	**3**

values

Synchronous and Asynchronous wet and dry periods

Synchronous and asynchronous wet and dry periods occurred along the RGB mainstem due to the difference in physiographic and climatic main controls in the RGB, snowmelt runoff in the headwaters of the San Juan Mountains, and the strong influence of the North American monsoon gives rise to two different hydroclimate regions: the hydroclimatic snowmelt variability in the headwaters of the RGB (the northern branch, including: San Marcial, El Paso, and Pecos River) and the North American monsoon variability experienced downstream of its confluence with the RGB (the southern branch, including Above Amistad, Anzalduas, Rio Conchos, Rio Salado, and Rio San Juan). This can be shown in the overlap and out of phase of droughts and wet periods that are concurrent in specific decades and regions, and other times are out of phase and independent. For example: synchronous wet periods occurred in the late 70s and the 80s, which were the wettest of the century, and matching droughts years include 1909-1920, the 1930s, 1950s, and 2005-2010. Although in some of these periods, the severity was not as extreme as in other regions. For example, the drought experienced in 1910 by the Rio Conchos was less severe than those in San Marcial or El Paso, or the wettest period was more severe for Anzalduas than El Paso. On the contrary, asynchronous wet and dry periods can also occur; for example: the beginning of the twentieth century was particularly wet for the Pecos River and the Rio Salado, which showed positive SDI values from 1900-1930. After this wet period, these rivers exhibit contrasting dry/wet periods between 1940 to 1950, where the Pecos River has the second driest period on record while the Rio Salado shows its wettest period. In addition, all control points exhibit differences in severities and durations, even if these overlap, indicating that one or more underlying circulation mechanisms influence the entire basin [39].

Occurrence of droughts

The RGB is vulnerable to extreme hydroclimatic events, especially droughts, which are expected to become more severe in this region by the end of the 21st century. Paleoclimate reconstructions using tree rings have been used in the RGB to reconstruct streamflow. For the Pecos River, a 700-year paleoclimate reconstruction estimated streamflow declines in a multi-century context, setting the drought of 1950-1957 as one of the highest ranked based on magnitude and intensity, slightly less severe as the 11-year drought of 1772-1782 [40]. For the RGB near Del Norte [39] and the Rio Conchos [41], a 344-year (1749-1933) reconstruction of seasonal precipitation and a 243-year (1775-2015) reconstruction of streamflow volume reported an extraordinary drought from 1950 to 1957 and from 1948 to 1958, respectively. These studies coincide with our research where the severely dry period for the natural streamflow system is estimated, from 1950 to 1965, for several control points, including Pecos River and Rio San Juan. The drought of the 1950s has been well documented in rainfall, discharge, and dendro–chronological data and is consistent with drought spells in northern Mexico [42]. However, in our records, the most severe drought in the Rio Conchos was in 2005 and the second driest in the 1950s. Nonetheless, the study of Ortega-Gaucin [43], reports from 1997 to 2008 as an extraordinarily hydrological dry period for the portion of the RGB located in Mexican territory, specifically the severe and extremely dry period from 2000 – 2008 in the control points of Rio Conchos. Moreover, San Marcial and El Paso experienced extreme and severe drought in the early 1900s, a decade distinguished by predominantly below-average flows in the northern branch of the RGB [39].

Occurrence of Snowfall and Hurricanes

Snowfall and hurricanes significantly affect the water availability throughout the basin. The RGB (San Marcial and El Paso) and Rio Conchos showed an exceptionally wet decade between the 1980s - 1990s, as reported by the northern branch using a 445-year streamflow reconstruction forecast [44] and streamflow data along the RGB mainstem (at Johnson Ranch) and the Rio Conchos [45]. The Rio Salado shows its wettest period in the 1970s, which coincides with estimates of Ortiz-Aguilar [46]. Then the 1900s was extraordinarily wet within the context of the Pecos basin, only broken by the widespread 1950s drought, which was ended by the 1980s wet event. In addition, the 20th century was the wettest in the Pecos basin over the past 700 years [40]. Heavy rains, influenced by tropical storms and hurricanes that hit the RGB from the Pacific and Atlantic Oceans, have increased in frequency. These storms, concentrated in short periods, are responsible for high annual discharge in the RGB. In Rio Salado and Rio San Juan, the hurricanes Beulah, 1967; Allen, 1980; Barry, 1983; and Gilbert, 1988 [47] resulted in an extremely wet and wet period, respectively. In the 2000s, hurricanes Emily, 2005; Dean, 2007; Dolly, 2008; and Alex, 2010 [47] resulted in a severely wet period for the Rio San Juan basin and in Anzalduas, the outlet of the RGB.

Impacts of climate change

Effects of climate change are already altering the RGB streamflow timing and volume through changes in rainfall, snowfall and snowpack, and increased temperatures and evapotranspiration rates [48]. Despite that this study did not distinguish the effects of climate change and human impacts separately. Climate and hydrologic forced models (e.g., rainfall-runoff models) are needed as additional research to distinguish the impact of climate change in the natural streamflow. The intensity and frequency of dry and wet conditions for the natural system in Figure 3 have increased since 1950. Extreme hydroclimatic events, such as intense precipitation and drought, are expected to increase in this region by the end of the 21st century [49,50]. For example, streamflow declines are occurring in tributaries upstream of Albuquerque between 1980 and 2016 [51]. In addition, in the past 40 years, snow drought has impacted the RGB headwaters in Colorado and New Mexico [52]. Moreover, elevated evapotranspiration rates since 1980 in the Rio Conchos, Rio Salado, and Rio San Juan are affecting crop production [53] and changes in air temperature exacerbate water quality issues in border cities of the southern branch of the RGB [54]. Furthermore, there has been an increase in the frequency of tropical cyclones and hurricanes since 1950 generated in the Pacific Ocean [55] resulting in economic losses by flooding and crop destruction.

The modern hydrology: a perennial human-induced extreme drought

A comparison between the natural and modern streamflow variability in the mainstem of the RGB is shown in Figure 4 and the subbasin control points in Figure 5. The natural hydrology of the RGB exhibits a strong hydrologic variability with alternating dry and wet periods. In contrast, the regulated hydrology lacks the cyclical wet and dry periods highlighted in the natural system; it shows a permanent state of human-induced extreme drought in the basin. The lack of hydrologic variability intensifies the dry states' severity and frequency, shifting from a possible wet or moderately wet to a dry, moderately dry, or even extremely dry period that could last several years.

The loss of this dynamism puts the system in a perennial and extreme dry state for most of the sites for decades, in some regions more severe than others, yet the magnitude and extent of the dry state permeate all regions of the RGB. In the RGB mainstem, perennial extreme dry periods started in San Marcial and El Paso in 1920 (for 90 years), above Amistad in 1939 (for 71 years), and in Anzalduas since the beginning of the 20th century (for 110 years). Anzalduas represents the response of the entire RGB basin given its location near the outlet; it shows that since the early 1900s, water diversions and flow regimes modified the basin as if it was in a perennial drought. For the main tributaries of the RGB, perennial extreme dry periods started in the Pecos River in 1945 (for 65 years) and the Rio Conchos in 1960 (50 years). In the San Juan and Rio Salado basins, they appear to have periods of extreme drought that are separated by periods of dry and moderately dry periods; these can be explained by the1980s wet period in the San Juan and the severely and extremely wet period in the 1970s in the Salado basin.

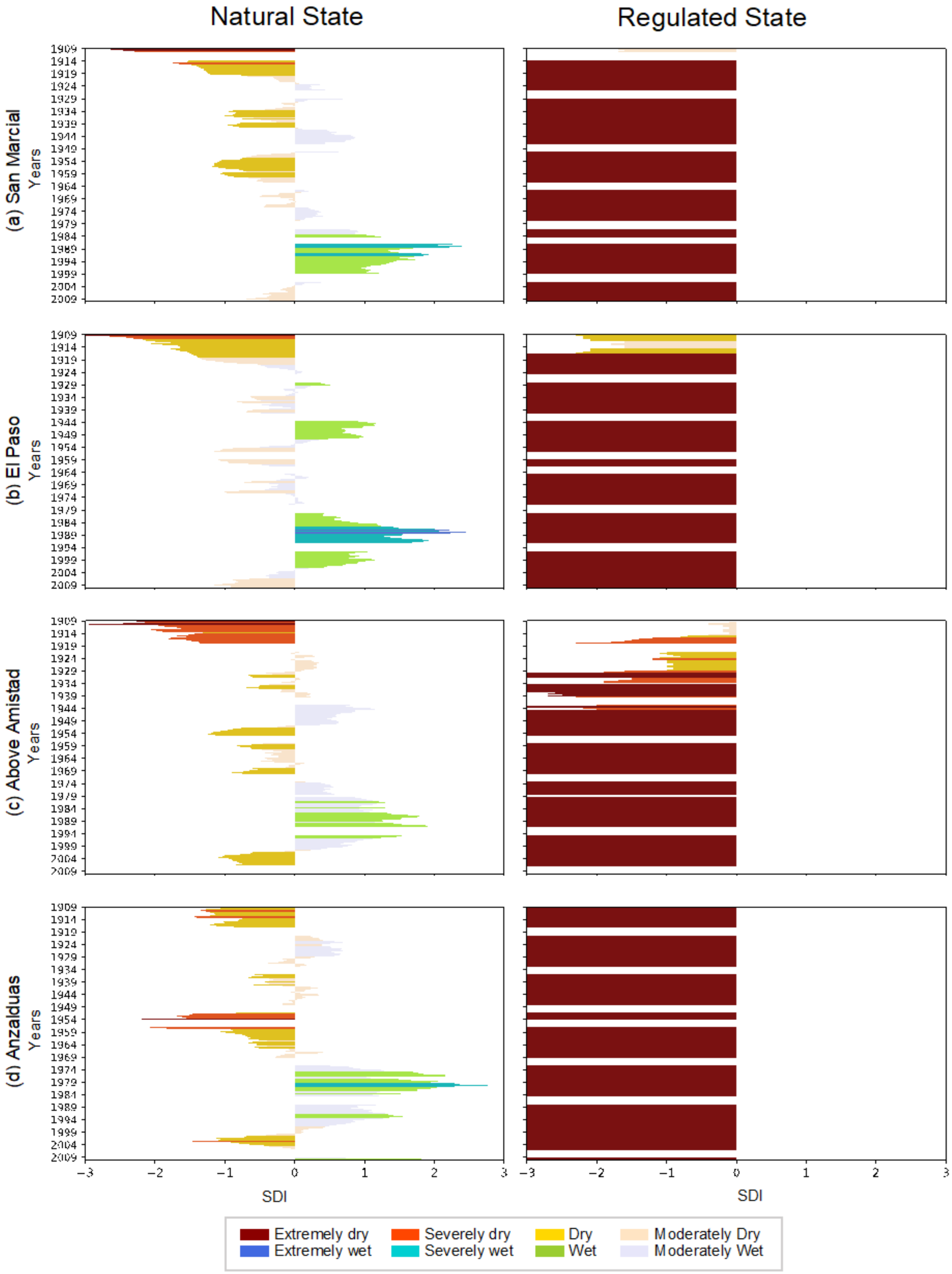


Figure 4. Streamflow Drought Index (SDI) indicating the hydrologic variability of the natural (left) and the regulated (right) state of four mainstem control points of the Rio Grande-Bravo Basin at (a) San Marcial, (b) El Paso, (c) Above Amistad, and (d) Anzalduas

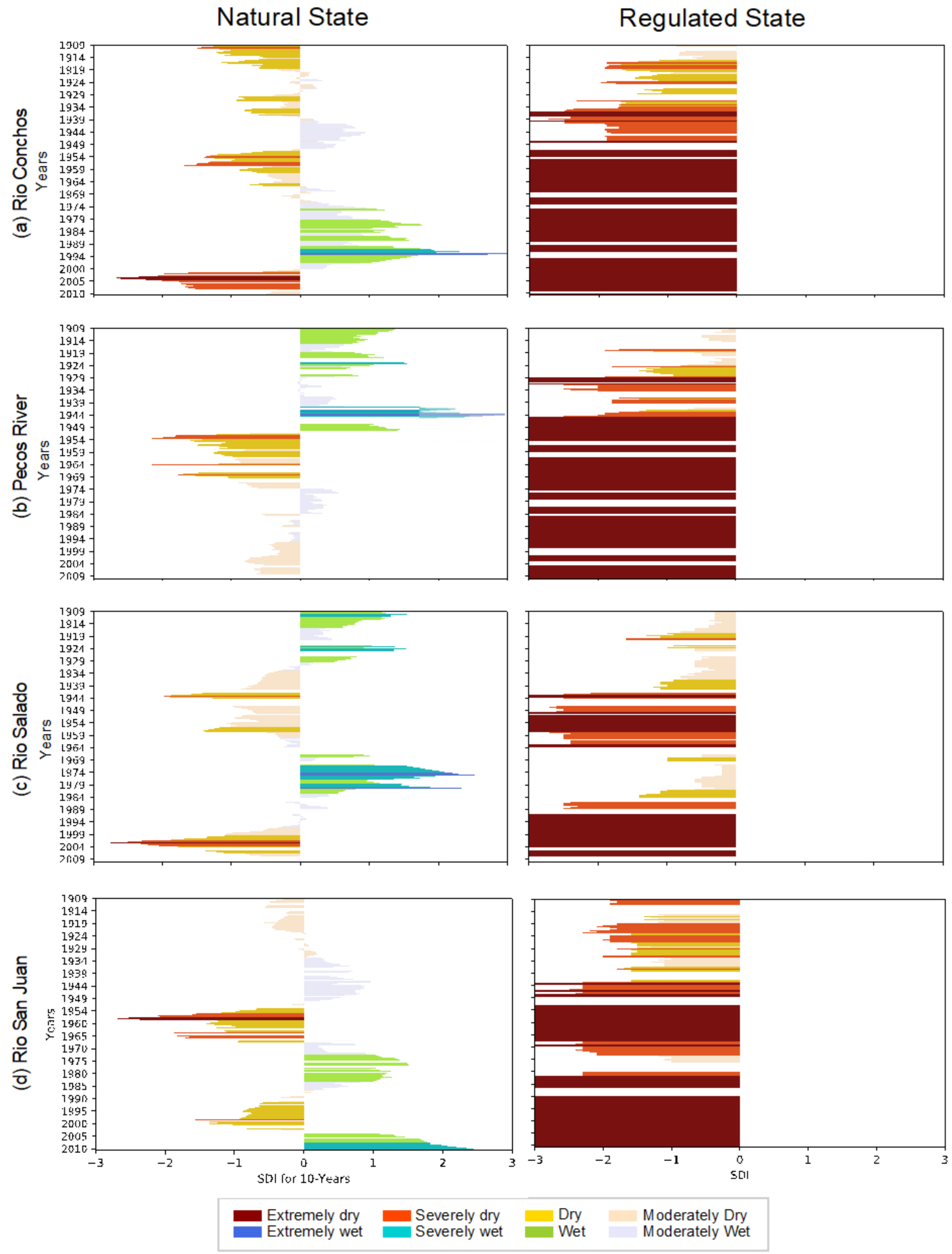


Figure 5. Streamflow Drought Index (SDI) indicating the hydrologic variability of the natural (left) and the regulated (right) state of four subbasin control points of the Rio Grande-Bravo Basin at (a) Rio Conchos, (b) Pecos River, (c) Rio Salado, and (d) Rio San Juan.

Causes of the perennial human-induced drought

Since the 1870s, the RGB has been subject to a long history of human manipulation [20]. The present perennial drought state is the result of increased water demands (for agriculture, municipal, and industrial), water agreements (at the international, interstate, regional and local scales), water overallocation, and the construction of large water infrastructure (reservoirs, canals, levees) [33,37]. Water resources are often insufficient to meet human and environmental requirements due to the natural water scarcity in the basin and the increased human water demand. The RBG basin provides water for more than 10.4 million inhabitants. Moreover, the basin supports extensive irrigated agriculture, comprising approximately 780 thousand hectares of irrigated land [33] and accounting for 83% of water withdrawals in the RGB [37]. In the U.S., the extent of irrigation activities expanded during the 19th century after the Desert Land Act of 1877 [56,57], prompting a disproportionate expansion of agricultural land, water diversions for irrigation, and water consumption. In the U.S., irrigated agriculture accounts for 80 to 90% of the overall water use. The main crops are forage, cotton, pecans, and vegetables [58]. In contrast, as a result of the Mexican Revolution in 1917, the Mexican Agrarian Reform implemented a prolonged distribution of land, where more than half of the Mexican territory was assigned to farmers [59]. A total of 11 irrigation districts were created, totaling 458 thousand hectares of irrigated land [33], where the states of Chihuahua and Tamaulipas account for 87% of the total irrigated areas. In both countries, the large-scale farming systems require large reservoir projects and extensive channelization, which started in 1916 with Elephant Butte in New Mexico and La Boquilla in Chihuahua. Since then, 27 large dams (greater than 16,000 Mm3 of storage capacity) have been built in the basin, including two international dams: Amistad and Falcon.

As streamflow is reduced by overconsumption and climate change, access to water is becoming a looming crisis, and droughts have become more devastating due to increased use of water resources for human purposes, changes in regulations for water allocation between users, states, or countries. Management actions for concealing water shortages and increasing water supply through more river engineering in one area certainly affect downstream communities. For example, the construction of El Cuchillo Dam in the Rio San Juan during the drought of 1990 aimed to supply water for the city of Monterrey in Nuevo Leon. However, this action led to a diminishing water supply for farmers in Tamaulipas. Droughts have also triggered a change in regulations for water allocation, whether in international agreements or state water allocation systems [37].

For instance, the Pecos River Compact [60] between New Mexico and Texas promotes collaboration and sharing of water resources. However, constraining surface water use created an increase in groundwater use that ultimately ended up in groundwater overdraft that diminished base flows that downstream users depended on. Droughts have also triggered conflicts among water users, states, and countries. For example, the drought in the late 1990s triggered disputes between farmers and the federal government in Mexico. From 1997 to 2002, Mexico incurred a substantial water debt to the U.S.

The Rio Conchos basin was not able to deliver water to U.S. and Mexican downstream water users due to drought and increased water use in the Rio Conchos basin. At that time, the Mexican government solved this conflict by delivering water to the U.S. from other tributaries and from Mexican water stored in the international reservoirs, leaving without downstream water users in Tamaulipas. The imbalance between supply and demand creates a complex web of governance structure, infrastructure, and user conflicts, which translate into compounding effects for anthropogenic droughts.

The degradation toll of the environment due to human activities

Land use change, reservoir development, straightening of the main river, and over-extraction of water have a high degradation toll on ecosystems by altering the river's natural flow pattern, timing, temperature, and quantity of river flows. By changing the temporal variation of streamflow in river basins, assemblages of riparian species are profoundly transformed because their life cycle is synchronized with the timing, magnitude, duration, and rate of change of the natural flow regime. For example, lack of fall monsoonal flooding facilitates the invasion by non-native organisms by shifting regionally endemic species (e.g., generalist red shiner; *Cyprinella lutrensis*) to dominant generalist fish species (e.g., endemic Tamaulipas shiner; *Notropis braytoni*) [61]. In addition, other native species have gone locally extinct in some areas of the RGB (e.g., the Rio Grande Monkeyface mollusk; *Quadruka couchiana*), while others have been listed as endangered species (e.g., the Rio Grande silvery minnow; *Hybognathus amarus*). In addition, reduced flood flow frequency has enhanced invasive vegetation encroachment and caused channel incision and narrowing [37]. Native ecosystems are adapted to droughts; however the level and persistence of the current human-induced drought are severely affecting river ecosystems and species throughout the basin. In the 20th century, the flow of the RGB had been reduced by nearly 95% of its natural flow [22,23], and at least 30 springs have gone dry in the states of Chihuahua and Coahuila [62,63].

The human-induced megadrought

The perennial drought state of the RGB can be better described as an anthropogenic megadrought; a compound multidimensional and multiscale phenomenon governed by the combination of natural water variability, human decisions, increased water use for human activities, climate change, and altered microclimate conditions due to changes in land and water management [3]. Since the early 2000s, the Rio Grande/ Bravo has been listed among the most at-risk rivers in the world [64]. Other regions in the world are experiencing anthropogenic megadrought, for instance, across Canada, the United States, and Mexico [5], and in South America, a multi-year dry spell has been referred to as the Central Chile Mega Drought [65]. These examples point out that anthropogenic forcing is critical to explain the perennial dry states of regions, given its capability of transforming a dry spell into a full-blown multiyear megadrought [4]. The regulated state in Figures 4 and 5 show that the human-induced megadrought has become the new normal in the RGB, posing environmental and socioeconomic hardship, including the unwanted anthropogenic consequences of altering natural systems beyond their resilience carrying capacity. Prolonged droughts cause major fluctuations in the structure and functioning of the RGB; resilience erosion can trigger changes in the stability landscape of the system or even changes in regimes.

Stability landscape metaphor: resistance, latitude, precariousness, and panarchy

The resilience of a system can be described using the stability landscape metaphor [11] by characterizing the components that govern a system's dynamics: resistance, latitude, precariousness, and panarchy. A three-dimensional stability landscape is used to estimate, visualize, and compare the resilience attributes of the natural and regulated flow regimes as shown in Figure 6. The topology of the stability landscape is portrayed by the occurring valleys and hilltops [11] that delineate the boundaries between the basins of attraction and represent the states where the system exists for a determined period. The resistance indicates how easy or difficult the system can be changed between states; it is expressed by the depth of the basin. The latitude is the maximum amount the system can be changed and is depicted as the width of the basin of attraction. Wide basins mean a greater number of system states can be experienced without crossing a threshold, while deep basins indicate greater perturbations are required to change the current state of the system away from the attractor [66]. The precariousness indicates the trajectory of the system at a given time within the stability landscape and how close it is to crossing it. Finally, panarchy acknowledges that systems are dynamic and continually passing through "adaptive cycles" at various scales [67]. Like any metaphor, there are limitations to using stability landscapes as a decision-making tool. Nonetheless, it is a valuable resilience concept that helps us to think about ecosystem dynamics and how human management might affect resilience properties.

The dynamic RGB natural stability landscape

In the natural flow regime (Figure 6A), two states are identified: (1) a dry state portrayed as a constricted-deep basin of attraction located in the persistent dry zone; and (2) a wet state portrayed as a shallow-wide basin located in the persistent wet zone. Valley bottoms correspond to the highest likelihood value of the system to remain in a given state; they are the modes of the probability density distribution [10]. At a given time, if the system is in a dry state~~,~~ the system will remain in this state between 15 to 20 years, or if the system has transitioned to a wet state it will remain in this state between 2 to 5 years. Based on the duration and frequency of both states, the basins of attraction differ in width, depth, and the number of valleys. In general, the RGB basin will tend to remain in a dry state, and greater perturbations are needed to move the system out of the persistent dry zone. In contrast, the RGB basin will remain less time in a wet state, and smaller perturbations will likely move the system away from the persistent wet zone. In essence, the stability landscape of the natural flow regime incorporates a diverse topography with different shapes and valleys where environmental stochasticity in the form of perturbations, such as hurricanes, droughts, tropical depressions, ENSO events, among others, will expose the system to a wide range of dynamics under the two stable states: dry and wet.

The precarious RGB regulated stability landscape

In contrast, the regulated flow regime (Figure 6B) has only a dry state depicted as a single wide-deep basin of attraction located in the persistent dry zone. Anthropogenic forcing (e.g., increased water use for agriculture) has altered the dynamics of river basins and changed the behavior and functionality of the natural ecosystem and causing alterations in the topology of the stability landscape. In the absence of environmental stochasticity due to the water regulations and streamflow diminishment, the resilience of the natural system erodes, and precariousness increases, moving the system closer to crossing a threshold. Precariousness is the result of management actions under historical conditions that have transformed the system and as a result, the number of states [68]. The anthropogenic megadrought in the RGB is likely the driver that transformed the stability landscape, reducing and shrinking the two states (dry and wet) of the natural stability landscape into the one state (dry) of the regulated system.

The human-environmental systems and the adaptive cycles of panarchy in the RGB basin modified the stability landscape eroding its resilience. There is a higher resistance (depth of the basin) in the regulated system (Figure 6B) in comparison with the natural system (Figure 6A), indicating that greater forces and perturbations are required to move the system out of the current dry state.

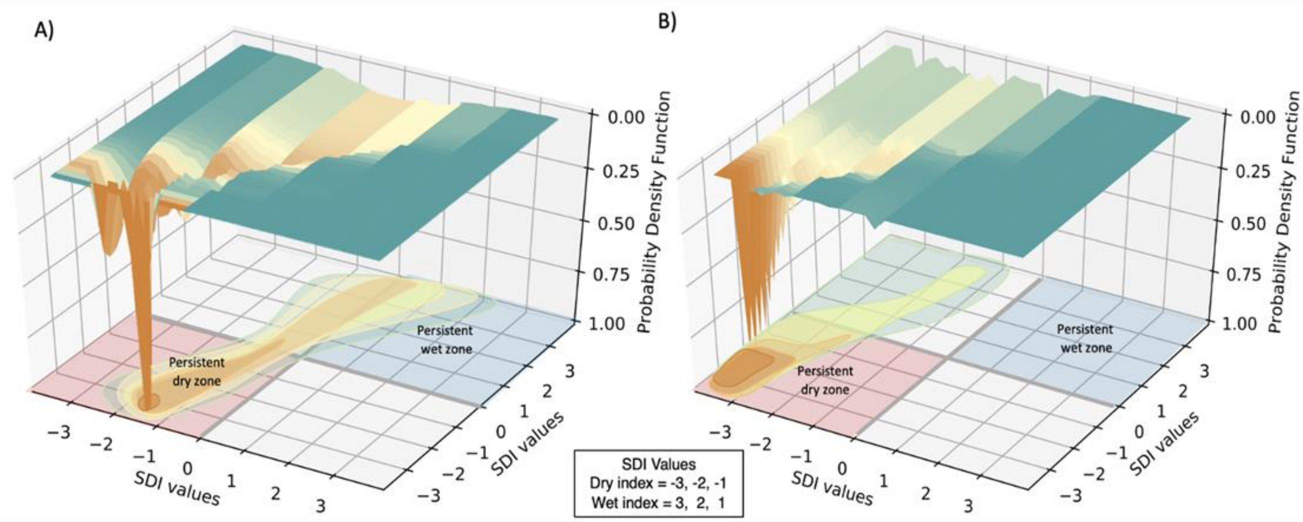


Figure 6. Stability Landscapes of the Rio Grande-Rio Bravo at Above Amistad control point. (A) Natural flow regime (Figure 5A), two states are identified: (1) a persistent dry zone, characterized by a constricted-deep basin of attraction; and (2) a persistent wet zone, portrayed as one shallow-wide basin. (B) The regulated flow regime shows a single wide-deep basin of attraction pertaining to the persistent dry zone.

Conclusion

The results of this study demonstrated how human development and human-centered water management regulations are the main drivers of the anthropogenic megadrought in the RGB. The present perennial drought state is the result of increased water demands (for agriculture, municipal, and industrial), water agreements (at the international, interstate, regional and local scales), water overallocation, and the construction of large water infrastructure (reservoirs, canals, levees). Water resources are often insufficient to meet human and environmental requirements due to the natural water scarcity in the basin and the increased human water demand. As streamflow is reduced by overconsumption and climate change, access to water is becoming a looming crisis, and droughts have become more devastating due to increased use of water resources for human purposes, changes in regulations for water allocation between users, states, or countries. Management actions for concealing water shortages and increasing water supply through more river engineering in one area certainly affect downstream communities, and most likely been counterproductive.

In addition, these drivers have produced changes in the stability landscape of the river basins, including changes in the topology (resistance and latitude), the trajectory (precariousness), and the dynamic processes of a natural system (panarchy). The stability landscape alteration is depicted as the modification of two basins of attraction, which represent the natural wet and dry hydrologic states, into a single basin of attraction representing a permanent dry state. The implication of the resilience erosion in the RGB indicates that streamflow conditions have changed sufficiently to provide early warning signals of crossing a resilience threshold, meaning that the system could suffer consequences.

As a society, we are already experiencing the effects of a water crisis, and current management practices and policies are beginning to migrate into placing aspects of social-ecological resilience analysis at the core of integrated water resources management. Aside from the limitations to operationalizing the concept of stability landscapes, the broader impact of this study is that it sheds light on quantifying ecological resilience attributes in river basins.

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Objective 3. Design climate adaptation strategies for droughts and floods in the lower branch of the RGB

This section describes some overall adaptation strategies that can be applied in the future or that have been applied and can be expanded or implemented in other parts of the RGB basin. The strategies are divided into four main categories:

Regulatory strategies that are economically attractive since they do not need the construction, expansion, or investment of new infrastructure, however, they need the political will of the regulatory institutions. These are important strategies because they regulatory tools for an improved administration of the water resources.

Water conservation strategies that reduce the water demand. These are very important strategies that go to the root of the problem in the basin: there is more water used than the natural availability in the RGB basin. The RGB is a n overallocated basin where all surface water is used and allocated and groundwater resources are over drafted, thus a reduction of water demand is the one and only starting point for a sustainable water resource use in the future.

Improved water storage strategies that increase the amount of water stored in surface water reservoirs and aquifers, without the construction of reservoirs. These are important strategies that can mitigate the current water crisis in the basin, but they can not solve the root of the problem, which is excessive water use.

Increased water supply strategies can slightly increase the water availability in the RGB, but they require that all the previous strategies are implemented for them to function. These strategies are discussed as a last resource because they can create the false sense of water supply reliability, however, they will not work unless the rest of the aforementioned strategies are implemented before.

Regulatory Strategies

The regulatory strategies presented in this section describe how current or new regulations can improve the water resources management in the basin. While the RGB is an over-regulated basin, paradoxically, there is not enough regulation or the regulations is not comprehensive, so there are legal gaps that has been taken advantage by water users to overexploit water resources. While this is not a comprehensive list, it highlights some challenges and opportunities in the basin.

Law Enforcement

There is a lack of enforcement in several regions of the basin, where the problem is not the lack of regulation but the enforcement of the law. These are some examples:

Unlawful diversion of surface and groundwater

There is a widespread diversion of water from users that do not have water rights in Mexico. According to some personal communications with local users, it is considered to be 20% to 30% of the lawfully regulated diversions. These unlawful diversions are not for domestic or municipal use; mostly they are for agricultural production. In this case, satellite data and land use change can document the locations where the agricultural land has been expanded. Local authorities at the municipal and state level are aware of the change in land use, as well as the suspicion that the owners of these properties are diverting water without a water right, however they may be dissuaded not implement the law because of blackmailing, corruption, or personal benefit. Federal authorities may or may not be aware of these unlawful diversions, however they may decide not to implement the law to avoid political conflicts between federal and state/local jurisdictions. While unfortunately this is a common practice in surface water (rivers), it is more common in groundwater because people do not require to get a permit to drill a well. Applying the National Water Law (Ley de Aguas Nacionales) may be the first step to reducing the water demand that is affecting law abiding water users.

Water use priority

According to Mexico’s constitution, Article 133, international agreements have higher priority than federal, state, or municipal regulations. Thus, meeting the water deliveries established in the Treaty of 1944 are of higher priority than state or municipal agreements. While in practice this is not the case, meeting the water deliveries according to the Treaty must be the highest priority in the basin. This change of mindset not only can improve water resources access and management for Texan water users, but also to Mexican water users along the border.

Irrational groundwater use

Groundwater has been overused and abused throughout the basin. For instance, water users in Mesilla Valley (New Mexico), Delicias (Rio Conchos) and Lower Rio Grande Valley (Texas), just to mention a few, have extracted more groundwater than what is naturally replenished leading to groundwater overdraft. In each case, this has been possible due to a gap in regulation. For instance, water users in the Mesilla Valley are taking water from wells that are hydrologically connected with the RGB main steam, depleting in fact both, surface, and groundwater resources. This is possible because of the law regulates separately surface and groundwater, and until is proved that both resources are connected, which all water resources are, well owners are taking advantage of this distinction in the law to over extract water for a short-term economic profit that will certainly affect the long-term sustainability of water resources in the basin. In other cases, such as in the Meoqui aquifer in Delicias or in the Evangeline aquifer in the Lower Rio Grande Valley, surface water users have increased their supply by extracting groundwater because they have increased their agricultural acreage or converted to more water demanding and profitable crops (e.g. pecans). These actions are for pure economic profit. This has led to groundwater overdraft in these aquifers that are been depleted. Lack of regulation or lack of law enforcement are jeopardizing groundwater resources throughout the basin, these are just a few examples.

Water diversion monitoring

Regardless of the water source (surface water, groundwater, recycled water, rainfall), there is a lack of water monitoring and water use metering throughout the basin. There are few gauge stations and monitoring wells for the entire basin. It is very difficult to manage what is not measured. Lack of water monitoring hides the over all challenges that the basin is suffering, including water quality problems.

New regulations

Reglamento de distribución de aguas del Rio Bravo

The water user’s agreement has been on the make for more than 15 years. This water user’s agreement is a document that will lay out the procedures to allocate surface water for each Mexican user in the RGB basin. It is intended to define how much water will be diverted from dams and allocated to cities, irrigation districts and small water users throughout the basin. It also considers water releases from reservoirs to meet the water volumes agreed on the Treaty of 1944. While this regulation will not solve all the problems related to water supply in the basin, is a very good first step towards an organized and transparent system to allocate water among Mexican users and to meet the agreements established in the Treaty of 1944.

Integrated Land and Water Management

There is a disconnect between land use ordinance and water plans. Land use ordinance rarely look at natural water availability to define and approve land use zoning and change. This has become an important problem because while land use zoning may be approved for activities that require more water, on the water right registry (e.g. water comptroller office in Texas or the Registro Publico de Derechos de Agua (REPDA) in Mexico) there may not be water available to provide a new water right. What is approved in the land use zoning directly affects water use and the way these activities (e.g. new residential zones or increased agricultural areas) increased their water use by buying, transferring, borrowing or illegally diverting water to these areas.

Incentives

Conjunctive Use Incentives

There should be economic and legal incentives for water users that promote conjunctive use of water. Water users that wisely manage different water sources should be rewarded, by using (or coordinating) the water source according to their natural water availability. For instance, during wet periods, use exclusively surface water (e.g. from reservoir) and let aquifers rest by not extracting water from, them. During dry periods, use both, surface and groundwater to meet water demands. This is the “in lieu” managed aquifer recharge that do not require the construction of more infrastructure, but the coordination of surface and groundwater users to use water wisely. This type of coordination and practices should be economically and legally incentivized.

Water Conservation Strategies

Water conservation strategies are aimed to address the root of the problem: reducing the water demand. Currently, there is more water demands than water available; this is possible because surface water and groundwater is been over drafted to meet larger water demands. All water plans in the RGB must start with water conservation strategies that will reduce the overall water demand in the basin.

Agriculture

Crop planting management

Current and future agriculture operations must re-evaluate their spatial extent and crop selection. They should consider the following:

- Selection of crop that are suitable for the climate. Crops must be selected according to their climate and soils suitability. Some of the native crops in the RGB basin include corn (*Zea mays*), cockscomb (*Amaranthus cruentus*), grain amaranth (*Amaranthus hypochondriacus*), calabasa verde (*Cucurbita mixta*), pumpkin (*Cucurbita pepo*), bottle gourd *(Lagenaria siceraria*), common bean (*Phaseolus vulgaris*), lima bean (*Phaseolus lunatus*), wild potato (*Solanum spp*.), zuni tomatillo (Physalis philadelphica), goosefoot (Chenopodium spp.), rocky mountain beeweed (Cleome serrulata), and common sunflower (*Helianthus annuus*) [2].

- Spatial extension of annual and perennial crops. Water must be one of the constrains to be considered is determining the extent of perennial and annual crops. For perennial crops, a firm water yield should be determined to estimate the spatial extent of this crop for which water is mostly secured. Annual crops must be considered as supplemental income and used as a buffer when excess water is available during wet years.
- Economic feasibility. The previous two factors should be considered to determine the economic feasibility of a given agricultural enterprise (ranch, finca, land property).

Reduction of non-beneficial agricultural water irrigation efficiencies

In the current irrigation system is possible to reduce the non-beneficial uses: soil evaporation, sprinkler evaporation, deep percolation due to low distribution uniformities. The following actions address this issue:

- Increased in distribution uniformity. This is a wide-known procedure to determine the distribution uniformity of irrigation systems and improve the location where irrigation is deficient. Greater distribution uniformities lead to less water use.
- Irrigation scheduling. This is a calculation that can help to determine when and for how long irrigation events are needed to minimize the over application of water.
- Irrigation monitoring. This is a best practice that should be implemented in all irrigation systems to estimate the amount of water used in given spatial extent. Water metering is needed to monitor water use and adjust irrigation practices, leaks and system malfunctions.

Regulated Deficit Irrigation

This is practice reduce the applied water from irrigation to a percentage that will not meet the full crop evapotranspiration needs, but still will maintain crop yields for economic feasibility.

Buy-back of water rights

This practice retires water rights from the water system, reducing the users that would want to permanently be foregone their water rights for an economic incentive. The PADUA program [1] was implemented in Mexico for 3 years and retired an important amount of water rights in the basin.

Land Fallowing and Rotation

This is a last resource practice, but sometimes needed, that retires land out of production because there is no other alternative to supply water to these areas. This practice not only reduces the economic income for growers, but also leave without jobs to agricultural laborers and the communities that depend on those jobs.

Municipal and Urban Use

Improve Water Supply Systems

Improved urban water networks require real-time monitoring, segmentation of the network, maintenance, replacement of old piping and infrastructure and trained human resources. Reduction of water loses through evaporation., leaks, and system malfunctions can be avoided by implementing procedures that describes the operation, repair, and maintenance of water supply systems. Cities and rural communities can reduce water losses by contemplating a mix of local and distant water supply sources, giving preference to local water sources

Indoor strategies

Human behavior. The greatest water saving can occur by changing individual human behavior. Day to day habits generate a consistent water use at individual levels. Modifying day to day habits such as taking shorter showers, using the dishwasher, collecting and re-using the water from the shower while hot water comes out, closing the faucet while brushing out teeth are key and economic practices that everyone can do but are difficult to implement because they are daily habits. These are simple strategies that are difficult to establish consistently because they require repetition, family education, and discipline for everyone. However, if they are achieved, permanent and long-lasting water conservation can be achieved.

- High water efficiency appliances. These are practices that are typically sought by public utilities. Providing rebates for changing head showers, faucets, dish washer, laundry machines, are common practices that reduce the water use while obtaining the same service.
- Tier price charges. This practice is used by public utilities to reduce the use of medium and large water users by incrementing the price of unit of water in the medium and high end. This practice also may affect low income large families that by nature use a medium to large amount of water, but do not have the economic affluence to pay for increased water prices.

Outdoor

- Low water-use landscaping. In the United States (US), half of the water used goes to landscaping. Utilizing native plants or xeriscaping can help to significantly and permanently save water. This is not the case in Mexico, where most of the water use goes for indoor use, and thus, water conservation policies oriented towards landscaping may benefit, but not to the extent as in the US.

- Irrigation monitoring. Timers or irrigation schedulers are recommended for watering outdoor landscapes. These devices not only help with the irrigation scheduling but also in monitoring when and how much water is applied to plants.

Environmental Water Use

Unfortunately, water for the environment typically is an afterthought rather than an essential and first step requirement for water planning and management. Environmental flows, water intended to benefit freshwater ecosystems while meeting human needs, provide ecosystem services that are beneficial for the society, such as aquifer recharge, improved water quality, transport of sediment and nutrients, reduction of invasive species, among others. The lack of environmental flows typically creates environmental degradation, affecting freshwater ecosystems, such as the endangerment of key species, channel entrenchment, increase in flood risk, etc. Once environmental degradation occurs, government and institutions decide to develop riparian restoration projects, regulations and bureaucracy that are costly. All these expenses could have been avoided if environmental flow practices have been putted first in place. A full list of strategies for environmental flow in the RGB is listed by Sandoval-Solis et al. 2022.

Reservoir re-operations and dam releases

In the RGB, reservoirs have been a main contributor of environmental degradation; however, they can be used also as a solution. Water releases from reservoir that mimic the natural flow regime, or releases that follow environmental flow recommendation can help to improve the wellbeing of freshwater ecosystem, while still serving human needs. Water releases for environmental purposes are not a consumptive use, meaning, that water can later be stored in a downstream reservoir. These can be scheduled releases that can be planned to benefit the environment, while still be caught in downstream reservoirs.

Surface water and groundwater protection

Water for the environment is not only about quantity but also quality. While the environment can be sustained with a reduction in water, it is needed to protect the water quality and volume required to maintain adequate freshwater conditions. Programs such as water reserves that explicitly secure water volumes for environmental purposes are key for protecting freshwater ecosystems. These strategies are not only environmentally desirable but also economically feasible.

Improved Water Storage Strategies

Improved water storage strategies are aimed to better utilize the natural and current manmade storages, they look at the basin as a system and consider all the water stores on and under the landscape. Their main objective is to maximize the overall water storage of the current manmade infrastructure through system re-operation.

Increased soil water holding capacity

Soil is the most overlooked storage in the water cycle, and yet, the only storage that every property owner has control of it. In terms of agriculture, soil goes beyond the plant structure, it is the main provider of nutrients, water, microbes that are needed to grow food, and soils are the medium to retain and capture storm water for storage and aquifer recharge, they are a key element in the water cycle to improve water resources management. There are different strategies to increase water holding capacity which in turn, increase the amount of water stored in the soil layer.

- Cover crops. Cover crops is a non-cash crop grown during the off-growing season (typically winter). Cover crop is a vegetation on top of the soil (it can be grass, legumes, or any other vegetation) that protect the soil from erosion, produce roots that increase soil organic matter and macrobacteria, increase nutrients, that are highly beneficial for the cash crop. While cover crops have evapotranspiration, the amount of evapotranspiration is similar to the evaporation of bare ground soils, and thus, cover crops do not reduce the water content in the soil layer, while increasing water percolation to aquifers and providing benefits to the soil.
- Low tillage. Agricultural fields that do not experience tillage or low tillage have a larger water holding capacity than fields tilled. Low or no tillage is a practice that requires increased labor time for any agronomic practice, however, it has shown increase crop yields and reduction in fertilizer applications.
- Mulching. This practice is widely used in landscaping and in orchards, it reduces the evaporation of water from the soil, and thus, retain water moisture for longer period in the ground.

Forecast Informed Reservoir Operations (FIRO)

This strategy use weather forecast to estimate a series of reservoir inflows that are used in reservoir model to determine the dam releases that are needed to maximize the storage while not increasing the risk of flooding or compromising the safety of the reservoir. These reservoir re-operation strategies have been proved to be successful in maximizing reservoir storage and water supply while do not compromising the dam safety and protecting for floods.

Conjunctive Use of Water

This is a technique that utilize all available water sources to maximize the water stored. Traditionally, conjunctive use referred to surface and groundwater joint operation, but recently it also includes recycled water, storm water, rainwater harvest, fog, and snow.

Managed Aquifer Recharge (MAR)

Managed aquifer recharge is the intentional recharge and storage of water in aquifers for the purpose to increase water stored in those. There are different methods of MAR.

- In lieu. This is a method that during periods of surface water abundancy, there is no water extractions from aquifers through wells, and thus the aquifer storage increases. In drought periods where surface water is scarce, surface and groundwater are used to meet water supply demands. This is a MAR method that do not require increased manmade infrastructure, only coordination between surface water and groundwater users.
- MAR on large spaces. MAR can occur in large spaces, in floodplains where water naturally use to overflow, and alternatively in agricultural fields that have a large extension and can hold a lot of water diversion. In both cases, water must have access to this large spaces where it will be standing for certain period of time, ideally less than a week. Water will infiltrate through the soil into the aquifers that will be recharged with important volumes of water. These large spaces are not bought for MAR purposes, in contrast they are only used temporally for recharge purposes. This make this alternative very affordable and opportunistic.
- MAR on dedicated infrastructure. Facilities can be built for MAR purposes; however, these strategies will require larger investment, maintenance and operation. For instance, recharge ponds (also referred as infiltration basins) can be constructed in key places, where a property is bought, an unlined pond is constructed and diversion infrastructures are built, such as turn outs and gates. Other type of facilities are dry wells and injection wells. Dry wells are wells where water is conducted and let it infiltrate through an abandoned or dry well. The main idea is to simply let water get into the well and by gravity recharge water into the aquifer. Injection well are wells with pumps that rather than extract water from aquifer, they use the pump to inject water into the aquifer. The main difference between dry and injection wells is the recharge rate, injection wells have a higher rate of recharge because water is injected into the aquifer using a pump that increase the recharge rate. Dry wells have a lower recharge rate, they only rely on gravity for recharge water into the aquifer.

Increased Water Supply Strategies

The following strategies are listed as a last resource for improving water management. They should be implemented and considered as last options because they are costly and do not address the key problem of the RGB, greater water demands than natural water availability. Also, these strategies may provide relief for a given period, but the problem of water overallocation remain the same or may worsen.

Rainwater harvest

This is a strategy that can be implemented at the household level. It requires the construction of a system of pipes and tanks that collect storm water from the roof into tanks, where water is stored for later use, typically, for landscaping. This is a de-centralized strategy that make people aware and involved into their own water use and water supply. At a larger scale, (e.g. neighborhood) this strategy can be implemented in detention ponds, which are areas where the stormwater sewer discharge water for temporary storage to do not crowd the stormwater drainage system. These detention ponds can be repurposed for water storage and later re-use. The main draw back is that standing water can create adequate habitat for mosquitos and other undesirable fauna that are vectors for diseases such as the Dengue or Nile fever.

Recycled water

This is the most affordable increased water supply because water typically has already been treated. It requires increased wastewater treatment, typically to tertiary (bacterial) treatment, so water can be reused for agriculture.

Increased current storage capacity

This strategy consists of adding height to the already constructed reservoirs. This can be done with plastic or wood structures. This strategy is not recommended without a safety and geologic analysis of the dam, because it can severely compromise the safety of the reservoir and highly increase the risk of catastrophic flood for human settlements downstream of the reservoir.

Construction of new storage capacity

This strategy considers the construction of new reservoir for water storage and flood mitigation; however, these is a very environmental costly strategy because it will degrade the environment, it will require mitigation and restoration strategies that may end up been more economically costly than the reservoir itself. In the RGB there storage capacity is 3.5 times the average annual flow, meaning that it is possible to store 3.5 times the average annual runoff. All the locations where there was needed a reservoir for water supply has already been built. The current proposed locations will store water not so often, and thus this reservoir will be very costly to store a very small amount of water.

Water importation

This strategy requires to import water from other basins into the RGB. This is a costly strategy that will affect the water availability on the basin where water is been imported, and typically requires a lot of energy to move the water and the construction of massive infrastructure that require important economic investment.

Desalination plants

This is the costliest strategy, economically and environmentally. Economically, it requires important quantities of energy and thus of economic resources to desalinate water. Environmentally, typically the by-product of desalination, called brine, is a highly saline residue that is dumped back into the ocean. This action creates hypersaline zones where everything that lives there is killed.

References

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