Resilient Flow Regimes of the Rio Grande/Río Bravo: Implications for Water Management and Environmental Flow Restoration

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For my son, Ramon Andre Saiz

and

My wife Monica De La Teja

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ABSTRACT

Water is the most shared resource in the world, critical for shaping ecological, social, and economic systems. Yet, its availability is constrained by climate variability, human use, and historical water management frameworks. While water scarcity can lead to conflict among nations, states, or individuals, it also frequently fosters collaboration. Tensions typically arise when the resource is scarce, geographically dispersed, or tied to environmental, political, or economic interests. This study analyzes water availability and flow regimes in the Rio Grande/Rio Bravo basin to assess a resilient flow regime. I apply the principles of hydrologic variability, resilience, and functional flows to understand how the river can sustain itself under changing conditions. The research also includes an evaluation of the Pecos River's historical and contemporary flow regimes to assess human impacts and the implications of water agreements.

In this work, I introduce the concept of a resilient flow regime, a regime that includes human influences but still preserves the characteristics of the natural flow regime. I also propose a framework to evaluate water availability and the importance of period re-evaluation in basins with water agreements. Ultimately, the goal is to highlight the need to re-center riparian ecosystems in integrated water management strategies for the basin, as current approaches often fail to prioritize them. We must emphasize adaptive, science-based water management that integrates both human and ecological needs to promote sustainable and equitable water resources.

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INTRODUCTION

Water is an essential resource that sustains life, drives economic development, and supports ecosystems, influencing settlement patterns, agricultural productivity, and industrial growth (Magnuson and Stanford, 1995., Young and Lomis, 2014). At the same time, water scarcity can generate social tension, economic stress, and even conflict, particularly in regions where water resources are shared among multiple users or political jurisdictions (Westing, 1986; Gleick, 1993; Elliott, 1993; Homer-Dixon, 1994; Marty, 2001, Wolf, 2002). Across the globe, transboundary rivers and interstate water systems are governed by formal agreements, compacts, and treaties designed to allocate water equitably among stakeholders. However, many of these agreements were established under historical hydrological conditions that no longer reflect current climatic variability, growing human demand, or anthropogenic alterations of river systems. This misalignment between historical assumptions and contemporary realities creates challenges for water management, requiring adaptive strategies that integrate scientific understanding with policy and legal frameworks.

In river basins where water is shared between states or nations, such as the Pecos River Basin and the Rio Grande/Rio Bravo (RGB) Basin, formal agreements have played a central role in fostering cooperation, resolving conflicts, and establishing water allocations. The Pecos River Compact (NM Stat § 72-15-19) between Texas and New Mexico and the 1944 Treaty between the United States and Mexico are examples of these formal agreements. The Pecos River Compact was designed to ensure equitable water deliveries from New Mexico to Texas while mitigating long-standing disputes over irrigation and municipal use. Similarly, the 1944 Treaty establishes obligations for water delivery from Mexico's tributaries to the Rio Grande and from U.S. sources

and the Colorado River to Mexico, creating a foundation for binational cooperation through the International Boundary and Water Commission (IBWC). While these agreements have historically facilitated water sharing, they are increasingly challenged by extended droughts, rising water demand, and climate variability, highlighting the need for science-based reassessment and adaptive management.

Understanding the natural variability and historical flow regimes of rivers ecosystems is critical for evaluating the effectiveness of water management policies and designing resilient allocation strategies. Riparian ecosystems are adapted to the patterns of seasonal and interannual variation that support ecosystem functions (Poff et al., 1996). Human consumption, and economic activities, including the construction of reservoirs, irrigation diversions, and groundwater extraction, significantly altered these natural flow regimes (Poff and Zimmerman, 2010; Merritt et al., 2010). These alterations reduce hydrologic variability, affect low and high flow extremes, and compromise the ecological integrity of river systems, particularly in the RGB (Garcia, 2022, Wong et al. 2007) and the Pecos River (Jensen et al., 2006; Huser, 2004; Hall, 2002). Moreover, inaccurate historical estimates of water availability can misinform treaty compliance and downstream allocations, with significant implications for both human and ecological water users. This thesis integrates hydrologic analysis, ecological theory, and water policy evaluation to address three main questions: (1) How the flow regime in the RGB changed over time due to human activities? (2) To what extent have historical water agreements accurately reflected water availability, and how have they been affected by anthropogenic and climatic changes? (3) What strategies can enhance the resilience, sustainability, and equity of water sharing under contemporary and future conditions?

CHAPTER 1

Environmental Flow Assessment and Implementation strategies in the Rio Grande/Bravo

Samuel Sandoval-Solis, Ramon Saiz-Rodriguez, Gabriela Rendon-Herrera

Abstract. Water sustains life, both humans and all that in the environment. This resource is especially important in arid regions, such as the Rio Grande/ Rio Bravo (RGB) basin, a shared water resource between Mexico and the United States. The RGB headwaters run from the San Juan Mountains in Colorado, cross the Chihuahua desert, and reach the Gulf of Mexico. In this basin, water management has primarily focused on meeting human needs, leaving a river greatly altered (i.e., the regulated flow regime), causing adverse impacts on aquatic ecosystems. Riparian ecosystems are adapted to the natural seasonal and interannual variability of flows (i.e. the natural flow regime), however, in the face of human alterations, three questions arise: (1) how much disturbance can the natural flow regime absorb before riparian ecosystems are severely damaged?, (2) Is it possible to characterize a resilient flow regime that can absorb human disturbance and still have environmental functionality, (3) and how does this resilient flow regime compare to the current regulated flow regime? Thus, there is a need to characterize a resilient flow to meet environmental flow requirements that sustain healthy river ecosystems.

1 Introduction

Societies and ecosystems have evolved by adapting to the variability of climate and the water cycle. In the last two centuries, modern societies have dramatically changed rivers for developing human settlements (towns and cities), producing food, and other economic activities. As a result, rivers have experienced a profound transformation. In the RGB, current patterns of water use (e.g., river diversions and groundwater overdraft), infrastructure development (e.g., proliferation of water intakes, dams, and levees), and pollution have together greatly altered the natural flow regime, with adverse impacts on local riparian and aquatic ecosystems. While riparian ecosystems (all the organisms that live along the river) have adapted to the seasonal and interannual variability of flows (natural flow regime) two scientific questions arise: (1) how much disturbance can the natural flow regime absorb before it changes completely and the riparian ecosystem is severely damaged? and (2) Is it possible to characterize a resilient flow regime that can absorb human disturbance and still have some characteristics of the natural flow regime and how does this resilient flow regime compare with the regulated flow regime? It is critical for environmental management, understanding the occurrence and the accumulation of perturbations under which a river basin is likely to cross a threshold, including the mechanisms that underlie a regime shift behavior. In addition, the recognition of the mounting threats to freshwater and riparian species in the RGB basin has led to increased consideration of environmental flow needs within water resources management efforts. Quantifying environmental flow requirements for freshwater and riparian ecosystems is key for determining environmental flow recommendations because they define a set of initial flow targets from which flow regimes that balance human and ecosystem

water needs are derived. Determining environmental flow recommendations requires selecting appropriate estimation methods based on spatial scale, temporal resolution, data availability, technical requirements, costs, and ecological management goals. In basins where there is already human alteration, the Functional Flows Approach provides a method to determine environmental flow requirements that quantify ecologically relevant flows to sustain a healthy river ecosystem. Functional flows are those aspects of the flow regime that directly relate to ecological, geomorphic, or biogeochemical processes in a river (Figure 1-1). In other words, functional flows support foundational processes related to the ecology of the river (freshwater and riparian ecosystems), the physical habitat (geomorphology), water quality and quantity, connectivity, and in general the well-being of the biological communities.

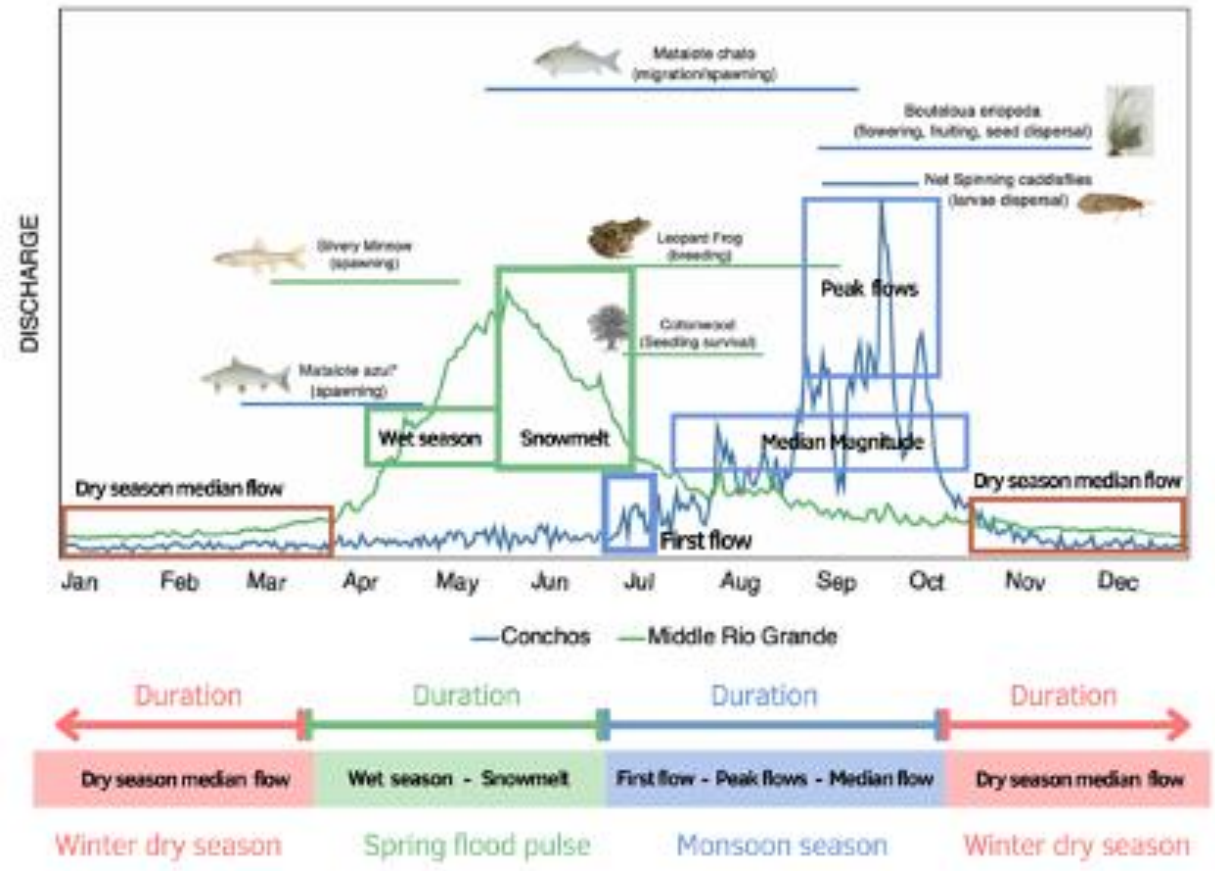


Figure 1-1. Functional flow components and example of reference hydrograph of the Rio Conchos and Middle Rio Grande-Bravo. The base flows include Winter dry season median flow, Spring flood pulse and Monsoon season median magnitude flow. Monsoon peak flows are considered events. The metrics of these components represent different flow regimes: in green is the snowmelt driven flow regime and in blue, monsoon driven flow regime. This figure also represents the component's biotic importance in riparian ecosystems.

1.1 Overall Goal and Objectives

The overall goal of this research was to determine environmental flow requirements in the RGB basin and define strategies or interventions for achieving them. An eco-hydrologic method, the functional flows approach, is used for characterizing flow regimes. Three flow regimes are analyzed in this research: (1) the natural flow regime derived from naturalized streamflow data that depicts pre-development conditions absent of human alteration, (2) the regulated flow regime which depicts the current state of the rivers, and (3) the resilient flow regime that includes human influences but still preserves the characteristics of the natural flow regime. The resilient flow regime is derived from the period when there was human alteration, but the flow regime was within the variability of the natural flow regime. The resilient period is identified by calculating breaking points, which are time thresholds when a permanent change in the flow regime occurred using resilience theory (Garza-Diaz,2022). Environmental flow requirements for 16 control points are calculated using the functional flow metrics of the resilient flow regime period. The environmental flow gap is the volume of water that is needed to meet the environmental flow requirements, it is calculated as the difference between the resilient and regulated flow regimes. Conversely, the carrying capacity of a river is the magnitude of disturbance the natural flow regime can absorb while still preserving its ecological integrity, it was estimated by comparing the natural and resilient functional flow metrics. Finally, an initial scoping of potential strategies and intervention for implementing environmental flows are presented.

The specific objectives were performed at each of the 43 streamflow gauges selected along the mainstem from the headwaters of the RGB to the Gulf of Mexico and its tributaries along the basin **(Figure 1-2)**:

1. Eco-hydrologic characterization - Estimate the Functional Flow Metrics of the Naturalized and Observed Flow Regime for 43 gauges along the RGB basin.
2. Determine breaking points to identify flow regime shifts - Calculate breaking points in time (time thresholds) when the flow regime permanently changed from an ecologically functional resilient flow regime to a regulated flow regime that is under permanently degraded conditions and has lost its ecological functionality using resilience theory through the Fisher Information Index (Garza-Diaz,2022).
3. Determine environmental flow requirements and environmental flow gaps - Determine the environmental flow requirements for every control point using the functional flow metrics of the resilient flow regime. In addition, determine the environmental flow gap, which is the volume of water needed (or streamflow re-arrangement in time) to meet the environmental flow requirements considering the current regulated flow regime. In other words, the environmental flow gap is the water needed to recover its ecological functionality. The environmental flow gap is determined by subtracting the functional flow metrics of the resilient and regulated flow regime. The carrying capacity of the river is also calculated, as the magnitude of disturbance that the natural flow regime can absorb while still preserving its ecological integrity. It is calculated by subtracting the flow metrics of the natural flow regime

and the resilient flow regime. In other words, this is the degree of hydrologic alteration that the system can absorb before changing into a different state.

4. Identify potential mitigation strategies - a list of strategies and interventions that can provide initial guidance for implementing environmental flows in the RGB.

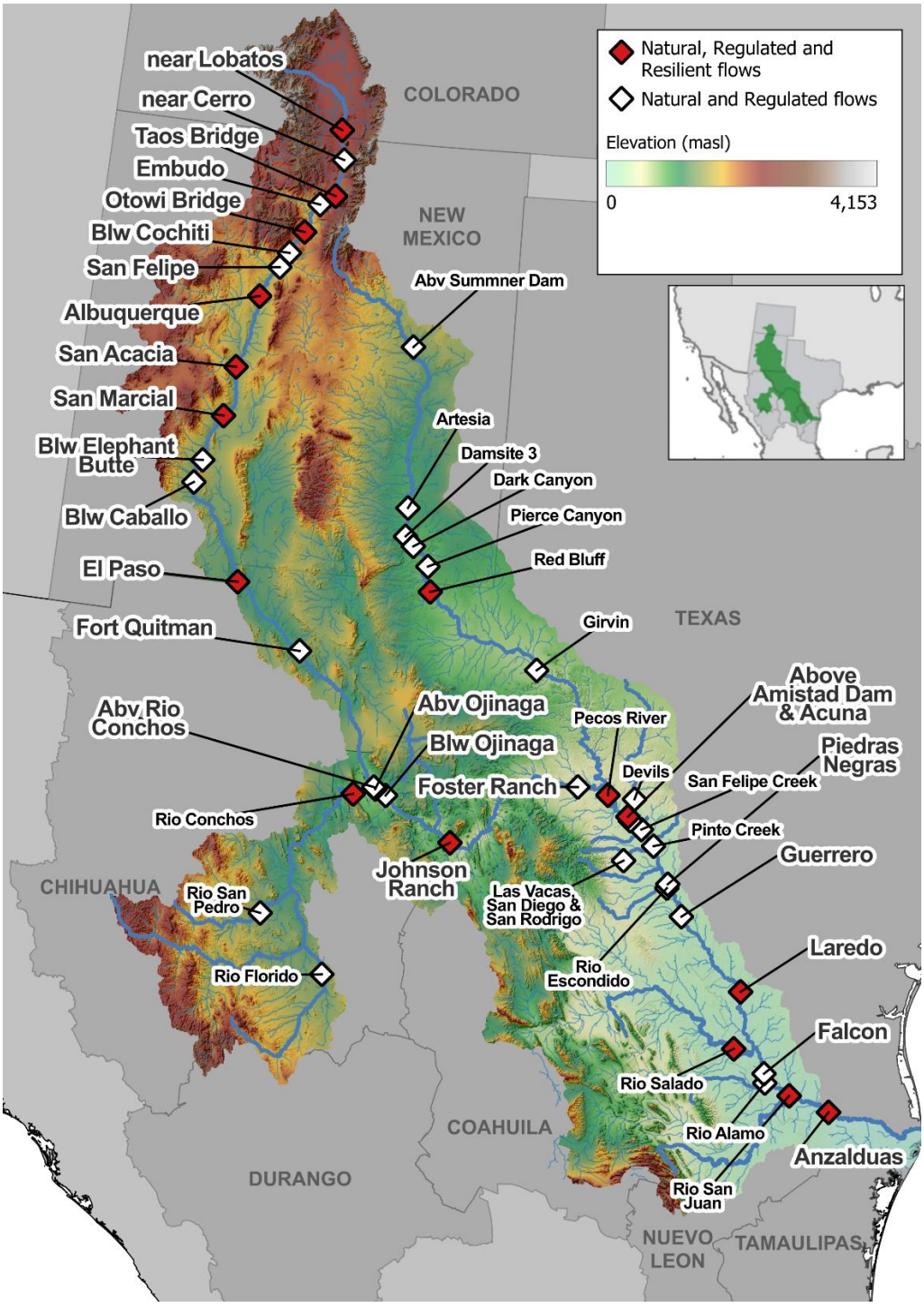


Figure 1-2. Location of the gauge stations along the RGB basin. In red, the station with natural, regulated and resilient flows and in white, the stations with Natural and Regulated flows

1.2 Rio Grande - Rio Bravo

The RGB has been listed among the world's most at-risk rivers (Wong et al. 2007), former presidents Obama and Calderon (2010) declare it a natural area of binational interest, and recently there is a large movement of initiatives implementing environmental flows in the RGB (Sandoval-Solis et al. 2021). There is an important societal and scientific movement for implementing environmental flows and restoring ecosystem functions that are beneficial for riparian ecosystems and people. The proposed research study provides key technical information for estimating environmental flow requirements beneficial for the environment and policy-relevant information for recommending mitigation strategies at different locations that can help to restore the environmental health of the RGB. These strategies could help water managers and restoration practitioners throughout the basin to design and implement restoration projects and improve water management operations.

The transboundary RGB basin is one of the three largest drainage basins in North America, it extends for approximately 557,000 km2, of which half is within the United States (U.S.) and half in Mexico. The water is shared between the states of Colorado, New Mexico, and Texas in the U.S., and the states of Durango, Chihuahua, Coahuila, Nuevo León y Tamaulipas in Mexico. The RGB has two significant headwaters – in the U.S. it is fed from snowmelt in the San Juan Mountains of Colorado and in Mexico from Rio Conchos and other tributaries whose water comes from the Mexican monsoon hitting the Sierra Madre Occidental. The river originates in the San Juan Mountains in Colorado, which drains into the southern Rocky Mountains and the western half of New Mexico. The confluence of the northern and southern branch of the RGB occurs in Presidio Texas and Ojinaga, in Chihuahua at La Junta de los Ríos, where the RGB mainstream is joined by the Rio Conchos. Historically, the Rio Conchos used to provide 54% of the water from among the 6 Mexican tributaries reaching the RGB mainstream, but current overexploitation of surface and groundwater from users in the Rio Conchos basin has significantly diminished this contribution to 35% (Garcia, 2022) (**Figure 1-3**).

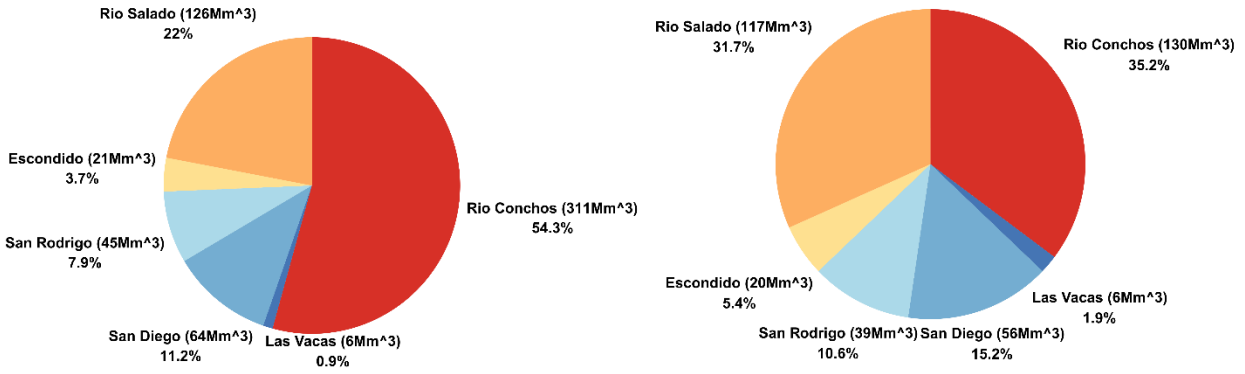


Figure 1-3. From Garcia, 2022. Water provided to the Treaty of 1954 from 1954 to 1993 (left) and from 1994 to 2019 of the six Mexican tributaries.

Approximately 530 km further downstream of La junta de los ríos, the Pecos River joins the RGB. Further downstream, the Rio Salado and the Rio San Juan are tributaries that join the RGB, until the RGB reaches its mouth flowing into the Gulf of Mexico at the Laguna Madre. Except for the snowmelt and tropical monsoons of the headwaters, most of the river flows through arid regions including the Chihuahua Desert, the third most biodiverse desert in the world and North America's largest desert. The RGB and its tributaries provide water for irrigation, rural and urban consumption, recreational and environmental use. Historically, water resources in the basin were exclusively allocated to human needs (Enríquez-Coyro, 1976) and over the past decades the variation in water distribution, precipitation, increased temperatures, and water demand have impacted the quantity and quality of the RGB as well as its riparian habitats. The importance of the basin not only lies in its natural resources and the unique species that live and migrate from, and through the basin, but also in the cultural diversity of its inhabitants and socio-economic importance of the people that live and depend on its waters.

2 Methodology

The overall methodology is shown in **Figure 1-4**. First, a set of daily naturalized (Sandoval-Solis, et al., 2023) and regulated streamflow data was used to obtain the functional flow metrics using the functional flow metrics calculator (Patterson et al., 2020). For the RGB, the functional flow components and metrics were adjusted according to previous studies (Patterson and Sandoval, 2022) and feedback provided by environmental experts in the basin. The following section describes the rationale for the functional flow components and metrics selected for the RGB. Second, the dates of the breaking point when a permanent flow regime shift occurred in the RGB were derived from Garza-Diaz and Sandoval-Solis (2022). Third, the functional flow metrics were used to estimate the functional flow hydrographs for each natural streamflow class (snowmelt driven, monsoon driven, and bimodal), streamflow condition (natural, resilient, and regulated), and water year type (dry, moderate, and wet). These hydrographs show the seasonal and interannual variability for each natural streamflow class and allow their comparison for each streamflow condition. Fourth, the functional flow metrics and hydrographs of the resilient flow regime were selected as the environmental flow requirements because these are metrics that are derived from a period when human disturbance occurred, however, they still preserve the ecological functionality because their variability falls within the natural flow regime.

Fifth, the environmental flow gaps and carrying capacity are calculated by comparing two flow conditions, resilient versus regulated flow regimes and natural versus resilient flow regime, respectively. The environmental flow gap of the RGB is determined by subtracting the functional flow metrics of the resilient and regulated flow regime; it depicts the deficit (or surplus) of streamflow volume needed to meet the environmental flow requirements. The carrying capacity of the RGB is determined by subtracting the functional flow metrics of the natural and resilient flow regime; it depicts the magnitude of disturbance that a river can absorb while still preserving its ecological integrity.

Finally, a series of mitigation strategies are discussed for implementing environmental flows in the RGB. They are divided into three main categories: systems' reoperation, water demand management, and nature-based solutions.

A total of 43 streamflow gauges were selected within the basin (**Figure 1-2**), 26 along the RGB mainstream and 17 in tributaries. Along the RGB mainstem, 15 streamflow gauges are located in the northern branch (near Lobatos, near Cerro, near Taos Bridge, Embudo, Otowi Bridge, below Cochiti dam, San Felipe, Albuquerque, San Marcial, San Acacia, below Elephant Butte, below Caballo Dam, El Paso, Fort Quitman and Above Rio Conchos), and 11 streamflow gauges are located in the southern branch (Above Ojinaga, below Ojinaga/Presidio, Johnson Ranch, Foster Ranch, Above Amistad Dam, Acuna, Piedras Negras, Laredo, Falcon, Guerrero and Anzalduas). There are 10 streamflow gauges in Mexican tributaries of which, 4 streamflow gauges are located within the Rio Conchos basin where natural flow was estimated (Granero, Burras, San Pedro, Conchos, and Florido), 1 streamflow gauge at the outlet of the Rio Conchos (at Ojinaga) that has natural and regulated streamflow, 1 streamflow gauge in that accounts for three small tributaries (Las Vacas, San Diego and San Rodrigo) and 1 streamflow gauge at the outlet of the following rivers: Rio Escondido, Rio Salado, Rio Alamo and Rio San Juan. There are 11 streamflow gauges in U.S. tributaries, of which 8 streamflow gauges are in the Pecos River basin (Above Sumner Damn, Artesia, Damsite3, Dark Canyon, Pierce Canyon Redbluff, Girvin and near Langtry), and 1 streamflow gauge at the outlet of the following rivers: Devils River, San Felipe, and Pinto Creek. Each of these streamflow gauges is described in detail in Appendix 1 and 2.

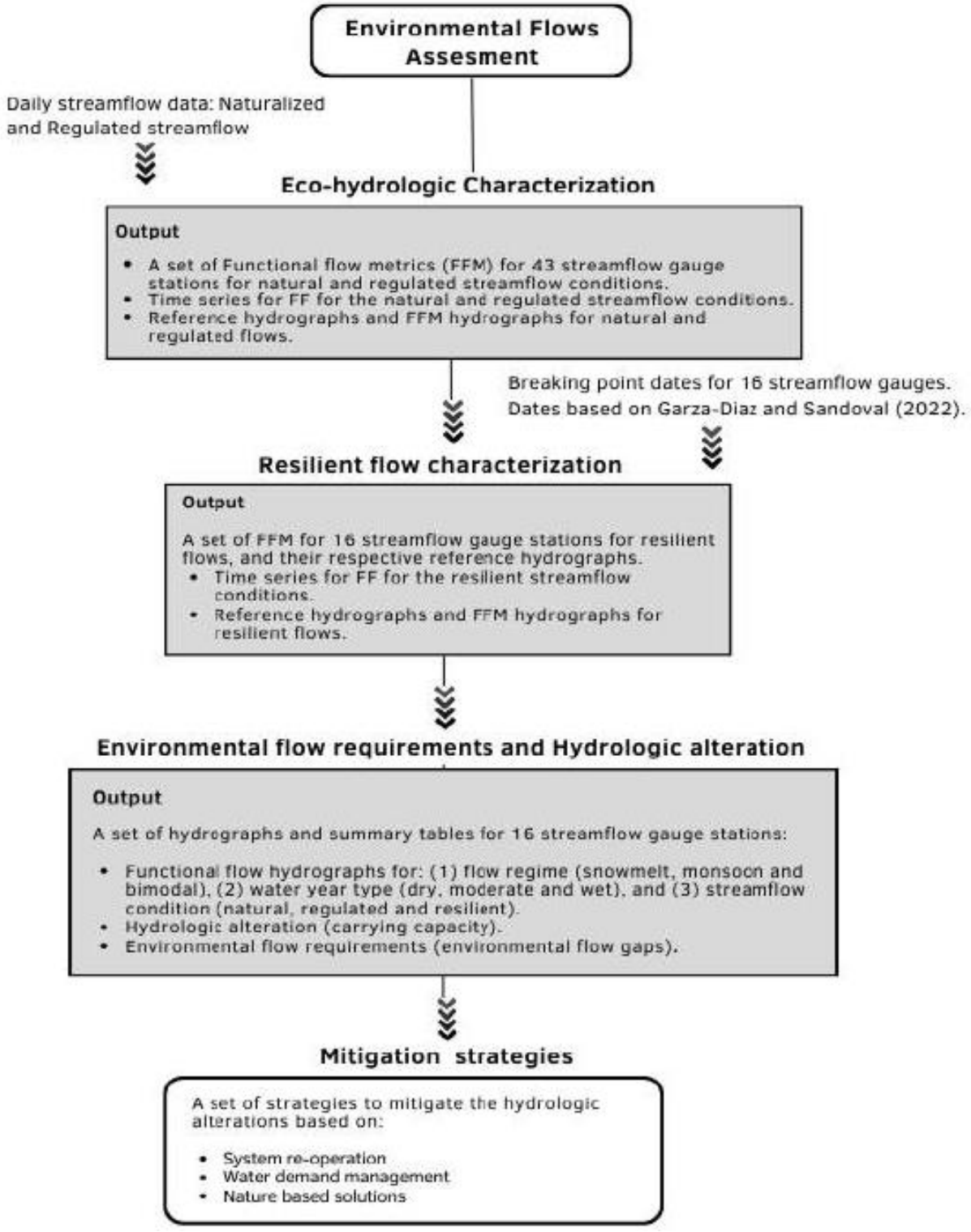


Figure 1-4. Overall methodology to estimate environmental flow requirements, environmental flow gaps and mitigation strategies in the RGB.

2.1 Functional Flows Approach

This research project used the functional flows approach as the theoretical foundation, an eco-hydrologic method. The functional flows are flow events of the natural flow regime related to the seasonal and interannual climatic variability, the physiography of the basin, the native species of the region and the hydrologic response of the basin.

The Functional Flows Approach (Yarnell et al., 2019; Yarnell et al., 2015) is a hierarchical method composed of seasonal Functional Flow Components of the natural flow regime, each of them integrated by ecologically relevant flow events and quantified by set functional flow metrics that are well-established flow characteristics (magnitude, timing, duration, frequency, and rate of change) (Poff et al., 1997) (**Figure 1-5**). This approach relates seasonal flow characteristics with ecosystem functions through biological, physical, and biogeochemical processes that are directly linked to distinctive flow events (Escobar-Arias & Pasternack, 2010; Yarnell et al., 2015). The analysis of these relationships are used to determine the ranges of flow events that are ecologically relevant for the freshwater and riparian ecosystems.

Functional flow components and flow events were defined based on previous work (Patterson and Sandoval-Solis, 2022) and expanded with consultations with experts in the basin. There are three functional flow components and six *flow events* used in the calculations of the RGB flows (**Table 1-1**).

Table 1-1. The functional flow components, events, and metrics used for the calculations of the RGB flows.

Functional flow components	Flow events	Flow metrics	Flow type
Winter Dry Season (Ds)	Winter dry season median magnitude flow	10th percentile	Low flow
		50th percentile	Median flow
		90th percentile	High flow
Spring flood pulse (Sp)	Wet season median magnitude flow	10th percentile	Low flow
		50th percentile	Median flow
		90th percentile	High flow
	Snowmelt flow	Rate of Change	Transition
Monsoon (M)	Monsoon median magnitude flow	10th percentile	Low flow
		50th percentile	Median flow
		90th percentile	High flow
	Monsoon peak flow	Peak flow magnitude	Event
	Monsoon first pulse	Flow Magnitude	Event

The Functional Flow Calculator is used to estimate the flow metrics (Patterson et al. 2020), and its parameters were adjusted to suit the natural and historical hydrology of the RGB. Both naturalized and regulated flow data are processed using the functional flow calculator to obtain a suite of

functional flow metrics, calculated for each year on record. Each metric is used to construct the Functional Flow hydrographs that depict the natural, resilient, and regulated flow regime.

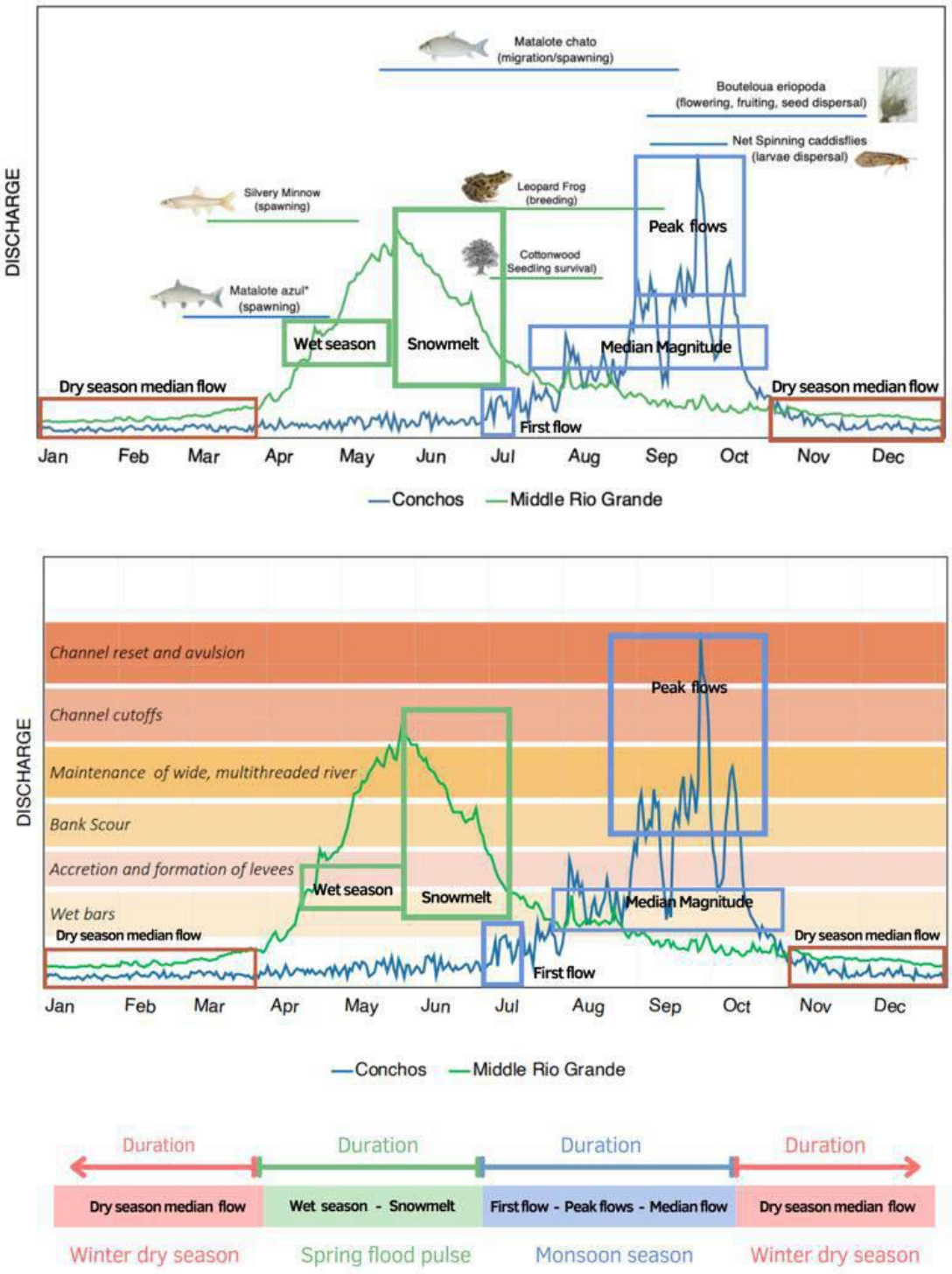


Figure 1-5. FFC and ecosystem functions in the Rio Conchos and Middle Rio Grande. Biotic (above) and abiotic (below) responses for the snowmelt flow regime of the Middle Rio Grande and for the hurricane-driven flow regime of the Conchos River.

2.2 Functional Flow Components

2.1.2. Winter Dry Season.

Dry season flow component is characterized by a low flow period with low velocities, sediment accumulation, and vegetation establishment. Low flows prevent the establishment of non-native riparian vegetation; only species adapted to these low-flow conditions can endure this period. This is a stress period for the freshwater and riparian ecosystem.

Dry season median flow: Flows sustained mostly by groundwater discharge. Dry-season median flows are important to native and endemic species that rely on dry and low flow conditions. The average duration of the dry season is about 5 to 6 months, from the end of October to the beginning of March. During this season, the steady flow provides habitat and refuge for native species, allowing them to hunt, burrow, nest, and spawn.

2.2.2. Spring flood pulse.

This flow component is characterized by the snowmelt, low water temperature and high sediment transport. These flows begin in spring around April to early May and last about 4 to 5 months. In snowmelt driven rivers, these flows contribute a large percentage to the total annual runoff in high-elevation basins where the snowmelt pulse typically corresponds to the annual peak flow.

Wet season median flow: Flows sustained by gradual snowmelt or by frequent rains caused by an early monsoon season. These flows are a key component to maintain a wide, sandy, multithreaded river, as well as maintain high groundwater levels. These flows are beneficial for riparian vegetation and seed dispersal. In bimodal rivers, the early flood pulse events and the monsoon median flow maintains a wide and shallow mainstream, preventing river incision, narrowing, and encroachment of vegetation. These flows provide adequate temperature and habitat conditions for river connectivity, fish migration, spawning, and rearing.

Snowmelt flow: The prolonged period of snowmelt runoff inundates floodplains and riverbanks. They occur around April or May, and these flows and the rate of change determines distinctive cues for reproduction. As the snowmelt runoff continues, it also has a significant impact on the river ecosystem. It scours and deposits sediment throughout the river corridor, leading to a decrease in water temperature. This change in temperature provides hydrologic signals that trigger fish-out migration, spawning, and rearing processes. These flows recharge aquifers in floodplains and riverbanks. In a snowmelt-driven river, the snowmelt flow corresponds to the largest flow event, while in monsoon-driven or bimodal streamflow classes, the peak flow event corresponds to those provoked by the monsoons.

2.3.2. Monsoon season

Monsoon season is characterized by large, sustained flows and large magnitude peak flows that occur primarily within the Mexican monsoon season. Peak flows typically occur during the late hurricane season of mid-August to September and occasionally in the early hurricane season from July to mid-August. These flow events maintain a wide, shallow, multithreaded river that provides prime habitat for riparian and riverine native species.

Monsoon median flow: Flows are sustained by prolonged rains caused by tropical depressions. These flows are instrumental in maintaining a wide, shallow, multithreaded river, they maintain high groundwater levels beneficial for riparian vegetation and create adequate conditions for seed dispersal. In bimodal rivers, this flow event acted in conjunction with the wet season median flow for maintaining a wide and shallow mainstream, preventing river incision, river narrowing and encroachment of vegetation. These flows create habitat conditions in backwaters and meanders that are adequate for fish rearing and refugia.

Monsoon peak flow: Monsoon peak flows are large-magnitude flows that occur within the monsoon season around mid-July to mid-August and end at the end of September. These flows can completely reconfigure the geomorphology of the river by resetting and re-widening the river channel and depth moving large sediments. During this period the floodplain becomes rich in organic matter and soil nutrients. The timing of the peak magnitude floods is vital for migration and spawning of native species.

Monsoon first pulse: These flow events only apply to monsoon-driven rivers because the breaking point is the period of scarce water conditions from the winter dry season. This is the first major storm event that leads to the start of the monsoon season. The transition from the dry season to the wet season begins with the monsoon's first storms typically initiating between mid-May and July. This flow event restores water quality throughout the river and introduces high loads of suspended solids and nutrients. The timing and magnitude of this flow event are essential for life-cycle cues such as migration and spawning.

2.3 Functional Flow Metrics

Table 1-2 shows the Functional Flow Metrics (FFM) and the flow characteristics calculated for each flow event. For each FFM, the 10th, 25th, 50th, 75th and 90th percentile was calculated. Reference hydrographs for the FFM for each streamflow condition (natural, resilient, and regulated) for the three water years (dry, moderate, and wet) were calculated as well. The water year conditions are derived from the 25th, 50th, and 75th percentiles of each FFM, respectively. In the Results section, a table from a sample streamflow gauge is provided to show each FFM calculated for the three natural streamflow classes of the RGB (snowmelt-driven, monsoon-driven, and bimodal) and their respective streamflow condition. Timings are the key FFM from which the rest of the calculations are derived.

2.4 Natural Streamflow Classes and Functional Flows

The flow regimes in the Rio Grande/Bravo Basin (RGB) are influenced by two primary climatic factors: (1) snowfall accumulation in the high-elevation headwaters in the San Juan mountains in Colorado, and (2) large storm events produced by the North Pacific monsoon. As a result of these climatic drivers, the RGB basin exhibits three distinct natural flow regime categories: (1) ***snowmelt driven***, registered on streamflow gauges along the RGB mainstem upstream of Ojinaga; (2) ***monsoon driven***, registered on streamflow gauges located on the tributaries, and (3) ***bimodal*** (snowmelt and monsoon driven) registered on the streamflow gauges along the RGB mainstem downstream of Ojinaga and the Pecos River basin. **Figure 1-6** shows the reference hydrographs and Functional Flow Components for the three natural streamflow classes of the RGB. **Table 1-3** shows the functional flow components and flow events calculated for each streamflow class.

Table 1-2. Functional Flow metrics obtained for each functional component in the Rio Grande-Bravo basin.

Flow Characteristics	Winter dry season	Spring flood pulse		Monsoon Season		
	Dry season median flow	Wet season median flow	Snowmelt flow	Monsoon first pulse	Monsoon peak flow	Monsoon median flow
Magnitude	X	X	X	X	X	X
Timing	X	X	X	X	X	X
Duration	X	X	X		X	X
Frequency						X
Rate of Change			X			

Table 1-3. Flow events calculated for each streamflow class.

Streamflow class	Winter dry season	Spring flood pulse		Monsoon Season		
	Dry season median flow	*Wet season median flow*	*Snowmelt flow*	*Monsoon median flow*	*Monsoon peak flow*	*Monsoon first pulse*
Snowmelt driven	X	X	X	X	X	
Monsoon driven	X			X	X	X
Bimodal	X	X	X	X	X	

For example, the gauge station RGB near Lobatos and Albuquerque is characterized by the snowmelt driven flow regime with low magnitude peak flows during the Monsoon season. The Rio Conchos, Rio Salado, and Rio San Juan are mainly influenced by the North Pacific monsoon; thus, they show a monsoon-driven natural flow regime. Finally, the RGB at Above Amistad Dam and Anzalduas, and the Pecos River are bimodal flow regimes (Figures 1-6), their flow regime is influenced by snowmelt and monsoon-driven climatic conditions.

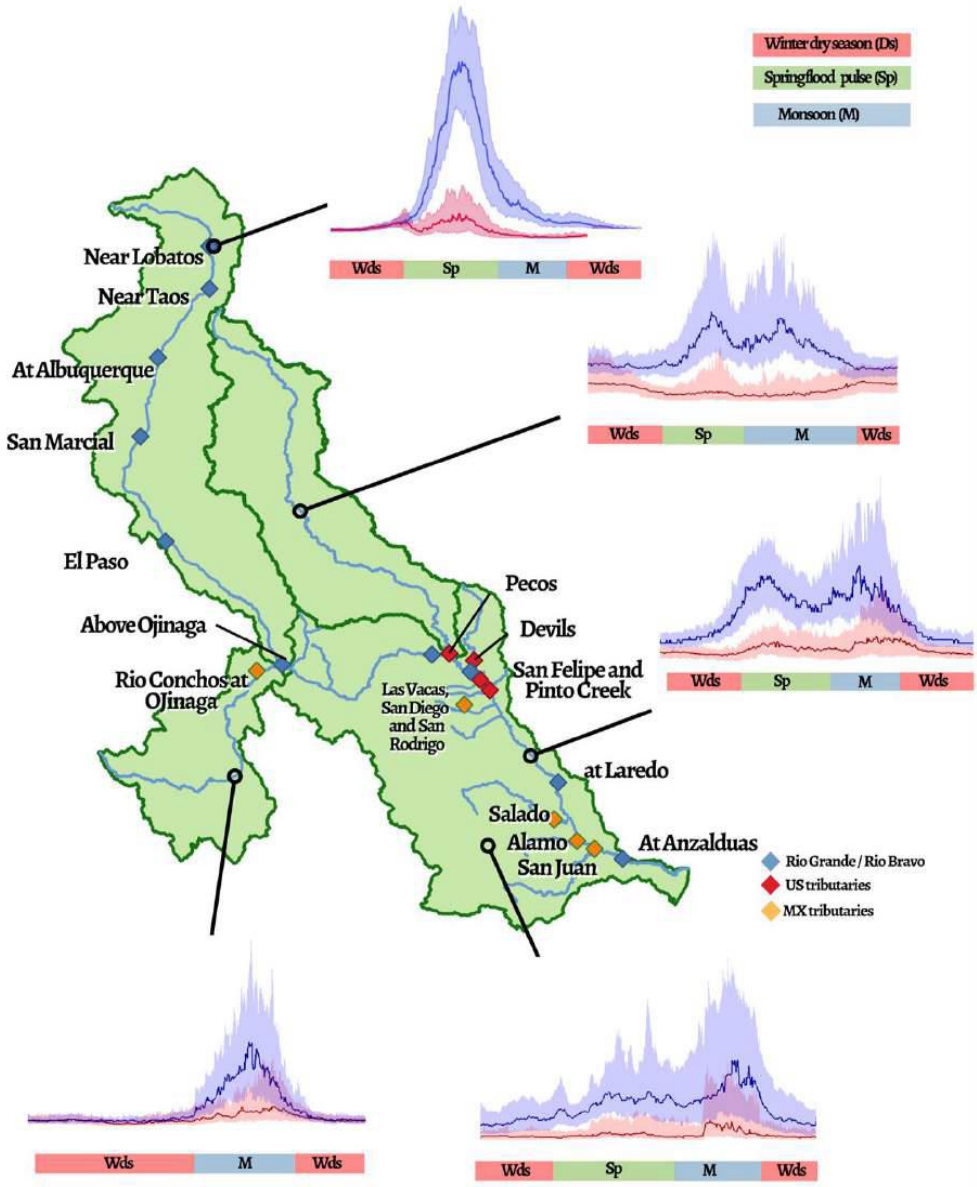
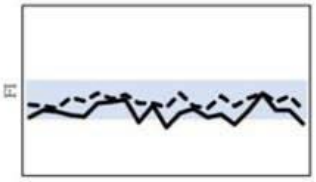


Figure 1-6. Examples of the functional flow components along the Rio Grande-Bravo basin. The Northern branch of the RGB is characterized by Winter dry season baseflow, Snowmelt flow, and Spring flood pulse; Southern Branch of RGB and Pecos River typically show the five components. Conchos, as well as most Mexican tributaries, present all except snowmelt.

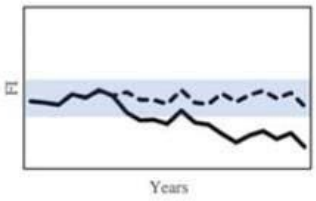
2.5 Resilient Flow Regime

5.1.2. Flow regime shifts and breaking points

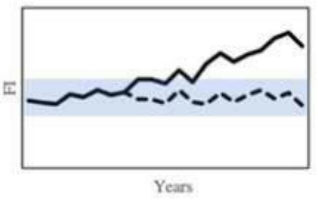
In their natural conditions, freshwater and riparian ecosystems are systems with resilience, these ecosystems absorb perturbations (e.g. droughts and floods) and they persist. Prior to European colonization, indigenous communities certainly used rivers (Gunnerson, 1969, Taylor, 1972, and Gradie 1994) but their impact was not large enough to cause a flow regime shift (Figure 1-7.1). In recent years, humans have modified rivers in such a way that they have lost their natural resilience causing a *permanent flow regime shift*, these flow regime changes can be steady (Figure 1-7.2 and 1-7.3) or abrupt (Figure 1-7.4). For the RGB, it was estimated the variability (Figure 7 dotted black line) and bounds (Figure 1-7 blue shaded area) of the natural streamflow condition using resilience theory and the Fisher Information Index (Garza and Sandoval 2022). These two reference parameters of the natural streamflow condition were used as a reference to estimate when the regulated streamflow (Figure 1-7, solid black line) went out of the bounds of the natural streamflow, and thus experienced a permanent flow regime shift. The years prior when the flow regime shift occurred are considered the resilient flow regime period, when the streamflow was altered due to human intervention, but still it was within the bounds of the natural flow regime.



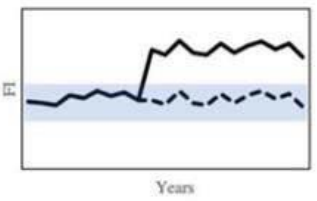
(1) A system is considered an orderly dynamic regime when a non-zero FI remains nearly constant over time (e.g., $d\langle FI\rangle/dt \approx 0$).



(2) A steady decrease in FI indicates that the system is losing its order, functionality, stability and the patterns are breaking down. This declining trend may provide warning of an imminent regime shift.



(3) A steady increase in FI indicates that the system is becoming more organized/stable.



(4) A sharp change in FI between two dynamic regimes a denotes a regime shift

Figure 1-7. From Garza-Díaz, L. E., & Sandoval-Solis, S. (2022). FI patterns of the Sustainable Regime Hypothesis.

Daily natural and regulated flows for a period of 111 years (1900 to 2010) (Sandoval et al., 2023) were estimated using historical data of streamflow, water use, return flows, temperature, evaporation, and reservoir storage. The modern hydrology of the RGB and its tributaries is different to their original natural streamflow. A combination of factors in this arid ecosystem, like rapid population growth, the increasing irrigated agriculture and infrastructure development affected the water availability in the basin. Since the 19th century the scale of irrigation in the U.S. increased significantly leading to a disproportionate expansion of agricultural land, increased water diversion for irrigation and water consumption (**Figure 1-8**).

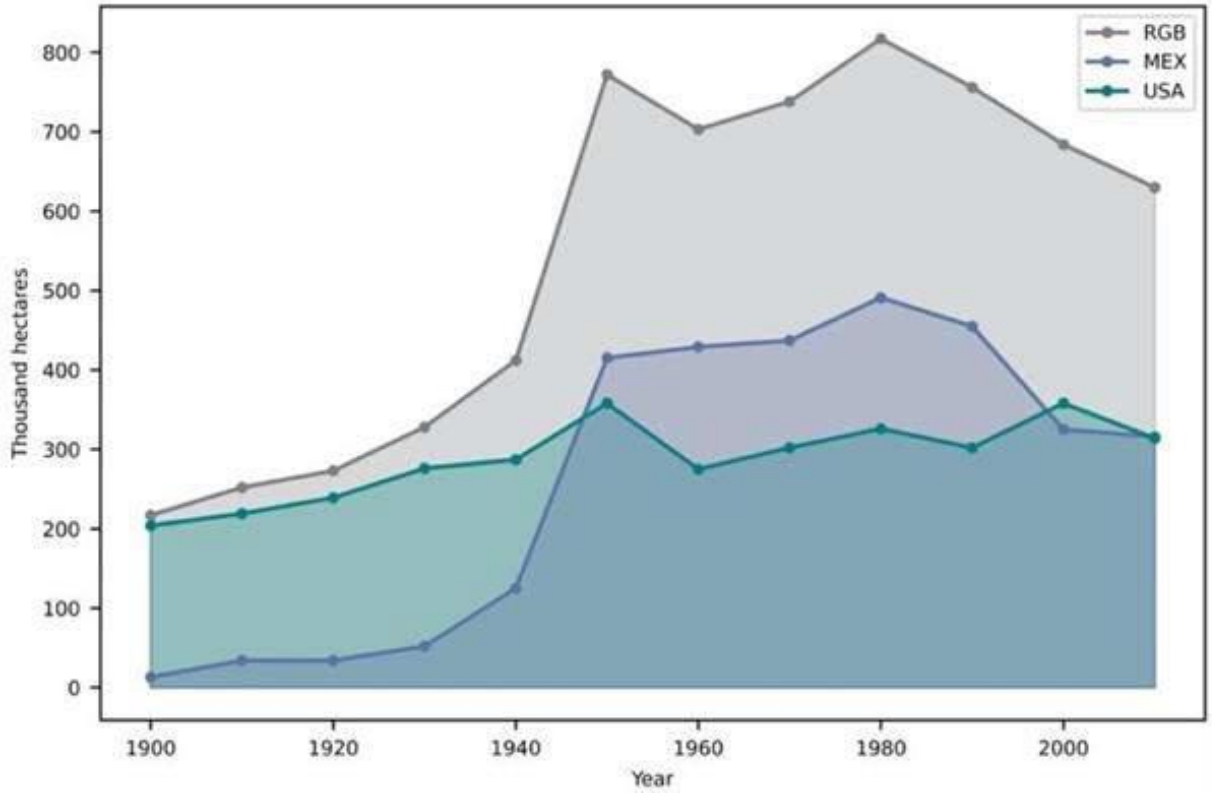


Figure 1-8. From Garza-Díaz, L. E., & Sandoval-Solis, S. (2022). Accumulated agriculture hectares (thousand hectares) in the Rio Grande–Bravo Basin (grey) and the portions of the United States (green) and Mexico (blue).

The increasing water demand for agriculture led to an increase in water storage (**Figure 1-9)** along the basin. At the same time, the establishment of irrigation districts and the development of water infrastructure allowed the growth of urban areas, industries, and rural communities within the basin. As a result, the river's natural flow was reduced more than 95% (Blythe and Schmidt 2018). Additionally, climate change has already impacted the RGB basin (Llewellyn and Vaddey 2013) and with the occurrence of human induce externalities (development of irrigation districts, reservoirs, implementation of treaties and compacts, etc.) the magnitude water available and the

natural timing changed, leading to an abrupt streamflow regime shift, changing the resilient ability of the river and its tributaries to recover and provide enough water for the ecosystem.

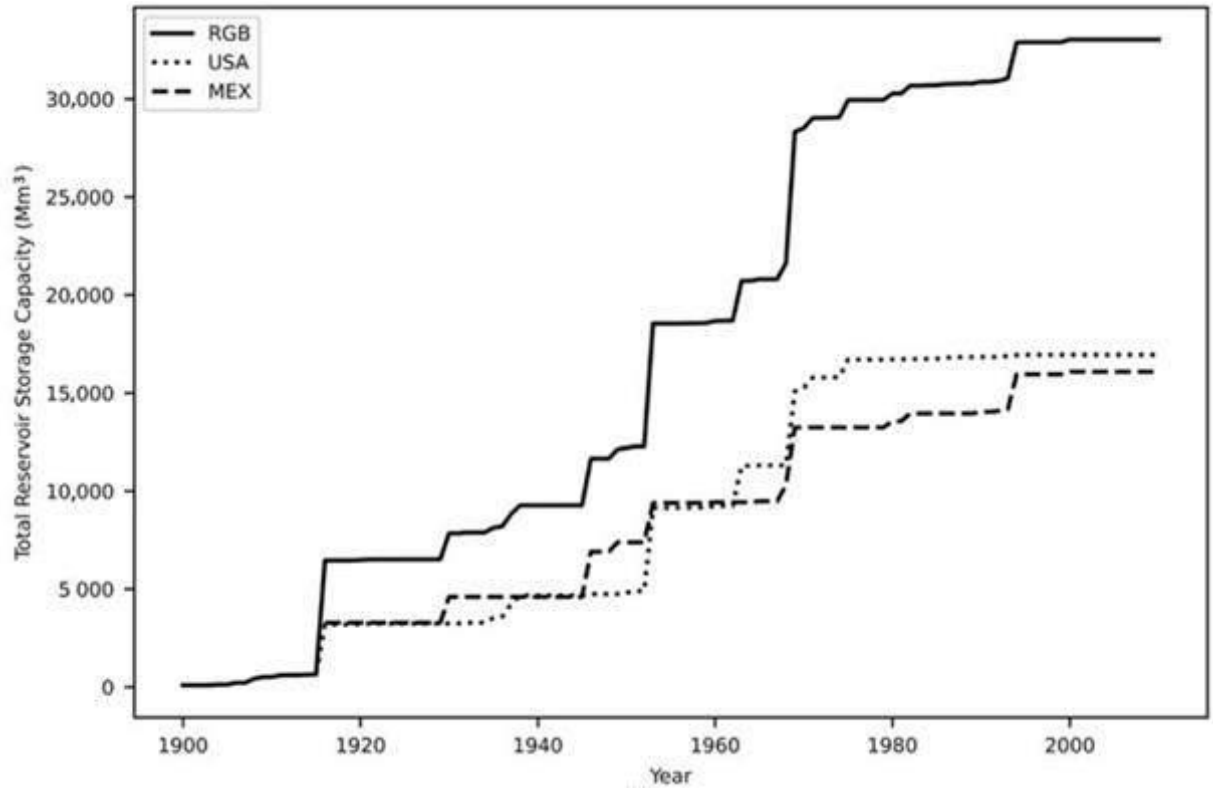


Figure 1-9. Total reservoir storage capacity (mm3) in the Rio Grande–Bravo Basin (33,037 mm3) and the portions of the United States (16,948 mm3) and Mexico (16,089 mm3).

2.6 Streamflow data

The breaking point was obtained for 16 gauge stations in the Rio Grande/Bravo basin: 11 in the RGB mainstem and 5 in tributaries. Garza and Sandoval, 2022 **(Figures 1-10** and **1-11)** published the breaking points for 8 gauge stations and shared the data to calculate the breaking points for other 8 gauge stations. Resilient flow regimes were obtained for 7 streamflow gauges in the northern branch of the RGB (Near Lobatos, Taos Bridge, Otowi Bridge, Albuquerque, San Acacia, San Marcial and El Paso), 4 streamflow gauges in the northern branch of the RGB (Johnson, Amistad, Laredo and Anzalduas), 2 streamflow gauges in the Pecos River (Red Bluff and the Outlet near Langtry), and at the outlet of 3 Mexican tributaries (Rio Conchos, Rio Salado and Rio San Juan). The resilient streamflow corresponds to the regulated records at the gauges prior the permanent regime shift occurred (i.e. breaking point). The FFM for the resilient period are referred to as resilient functional flow metrics, they are the FFM of the regulated streamflow condition prior to the breaking point years.

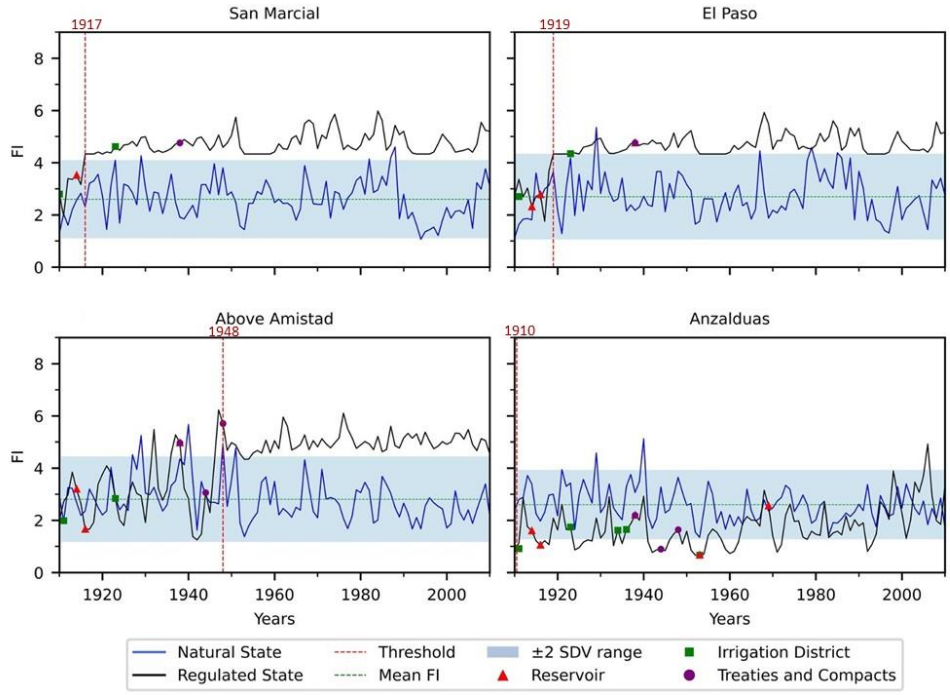


Figure 1-10. Breaking points for the upper basin gauge stations obtained from the fisher index. In blue the natural flow regime and in black the regulated.

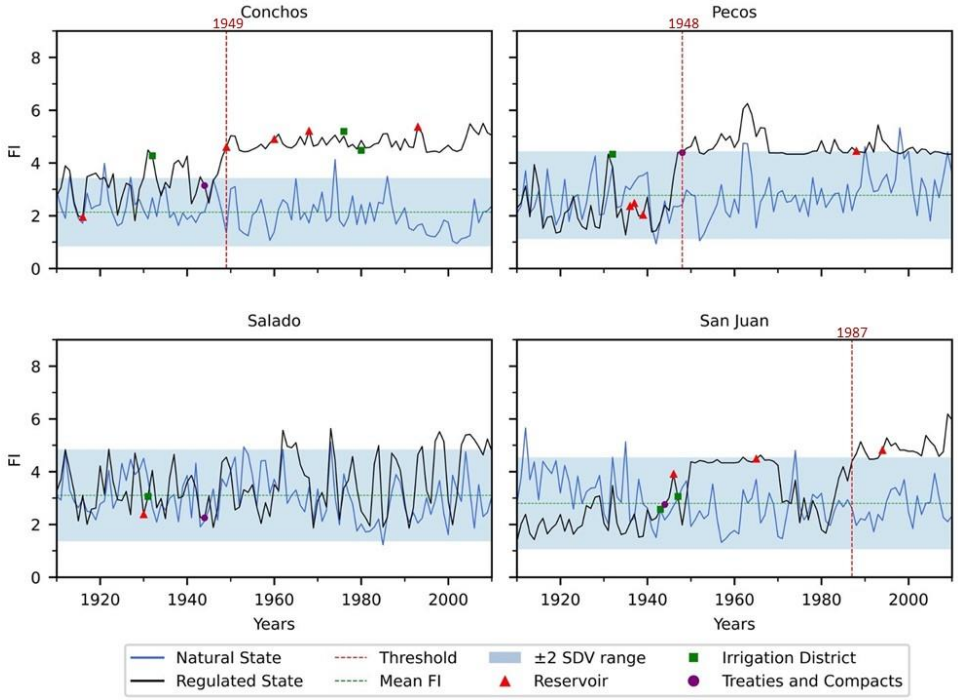


Figure 1-11. Breaking points for main tributaries obtained from the fisher index. In blue the natural flow regime and in black the regulated.

3 Results

The functional flow metrics are presented in a tabular form summarized as percentiles (10th, 25th, 50th, 75th, and 90th). At each gauge station, reference hydrographs are presented for 3 different water year types (dry, moderate, and wet) and streamflow conditions (natural, regulated, and resilient). Contact the authors or WWF to obtain the streamflow time series data and FFM for each streamflow gauge station.

The natural flow regime represents hydrology in the absence of anthropogenic impacts. Daily streamflow data from the 1900s to 2010 was used to estimate the natural flow regime (Sandoval et al., 2022). In contrast, the regulated flow regime captures the modern hydrology obtained from observed daily streamflow data at a given streamflow gauge using the period of 1975 to 2020. This period spans over the wet season of the 1970s and 1980s, the drought of the 1990s and 2000, the brief wet period of the late 2000s and early 2010s, as well as the ongoing drought since 2015. **Figure 1-12** shows an example of the reference hydrographs for natural (blue) and regulated flow (red) regimes at four streamflow gauges along the RGB mainstem, the reference hydrographs show a significant decrease in streamflow and seasonal timing alteration.

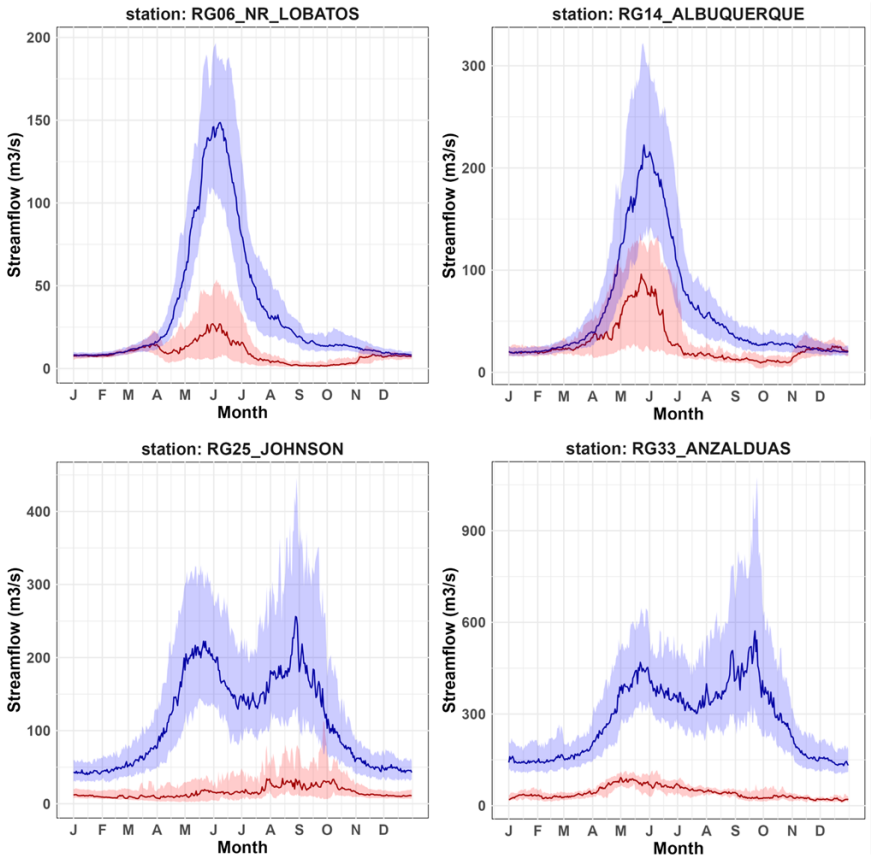


Figure 1-12. Natural (blue) and Regulated (red) flow regime. The interannual variability is shown by the upper bound, median flow and lower bound (25th, 50th and 75th percentile). Units: m3/s (cubic meters per second)

3.1 Flow Regime Types in the Rio Grande–Río Bravo Basin

The Rio Grande–Río Bravo (RGB) basin exhibits three distinct flow regime types: snowmelt-driven, monsoon-driven, and bimodal (Figure 6). Functional Flow Metrics (FFM) were calculated for naturalized and regulated daily streamflow time series at representative gauge stations, with resilient flow regimes estimated at gauges where breakpoints were identified (Figure 10 and 11).

1.1.3. Snowmelt-Driven Regime

The snowmelt-driven flow regime dominates the northern branch of the RGB (Figure 13.A), where runoff originates primarily from snowfall and spring snowmelt in the San Juan Mountains. Fifteen gauges in this region show a snowmelt signature. This regime is characterized by steady baseflows during the dry season, followed by sharp increases in discharge during spring snowmelt. Although the North American Monsoon contributes some flow, it is a secondary driver compared to snowmelt. See Appendix (1)

1.2.3. Monsoon-Driven Regime

The monsoon-driven regime is most evident in the Rio Conchos subbasin and other Mexican tributaries (Figure 13.B), where nine gauges exhibit this pattern. It features sustained baseflow through winter and spring, with sharp increases in discharge during the summer monsoon. Storms and hurricanes can further amplify peak flows. In this regime, the North American Monsoon is the dominant driver, shaping both the timing and magnitude of flows. See Appendix (2)

1.3.3. Bimodal Regime

The bimodal regime (See example in Figure 13.C), influenced by both snowmelt and monsoon rainfall, is characteristic of the Pecos River and the lower RGB (19 gauges). Streamflow in this regime rises during spring snowmelt, declines gradually, and then increases again in late summer due to monsoon rains and occasional hurricanes. This dual influence reflects contributions from both upstream snowmelt and downstream monsoon events, making it a particularly complex flow regime. See Appendix (3)

3.2 Reference Hydrographs and Flow Metrics

Reference hydrographs (**Figure 1-13**) illustrate seasonal and interannual variability under natural and regulated and resilient conditions. Shaded areas represent dry (25th percentile), normal (50th percentile), and wet (75th percentile) conditions. The functional flow metrics (**Figure 1-14**) highlight differences among water year types (dry, moderate, and wet) of functional flows. These results capture how regulation modifies the magnitude, timing, and variability of flows across the three regimes. The functional flows were obtained for the natural, regulated and resilient flow **(Figure 1-14 and 1-15)** for the three streamflow classes. **See Appendix (4).**

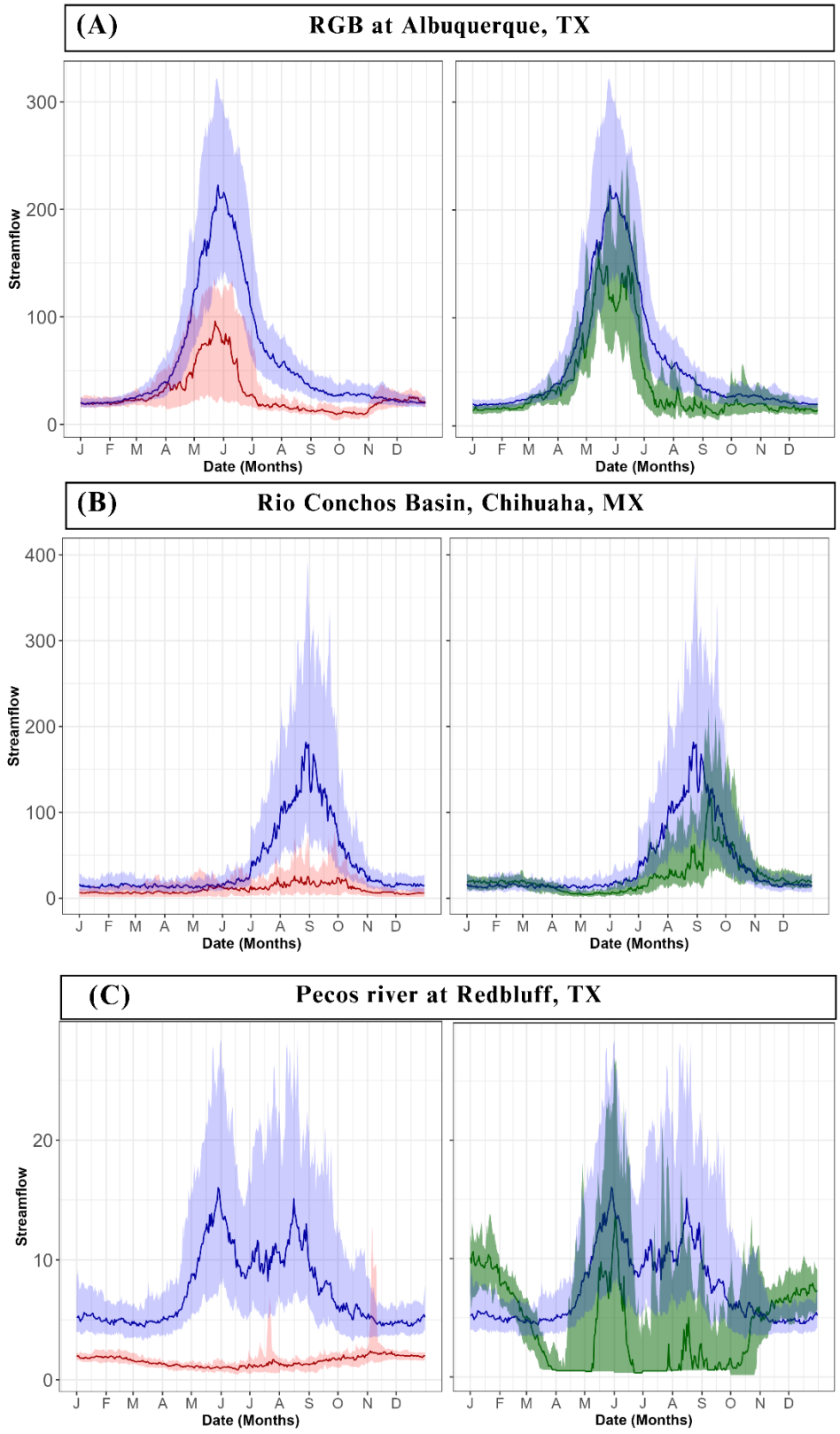


Figure 1-13. Comparison of natural (blue) and regulated (red), and natural and resiliente (green) for the three flow regimes (A) Snowmelt, (B) Monsoon-driven and (C) Bimodal (Snowmelt + Monsoon)

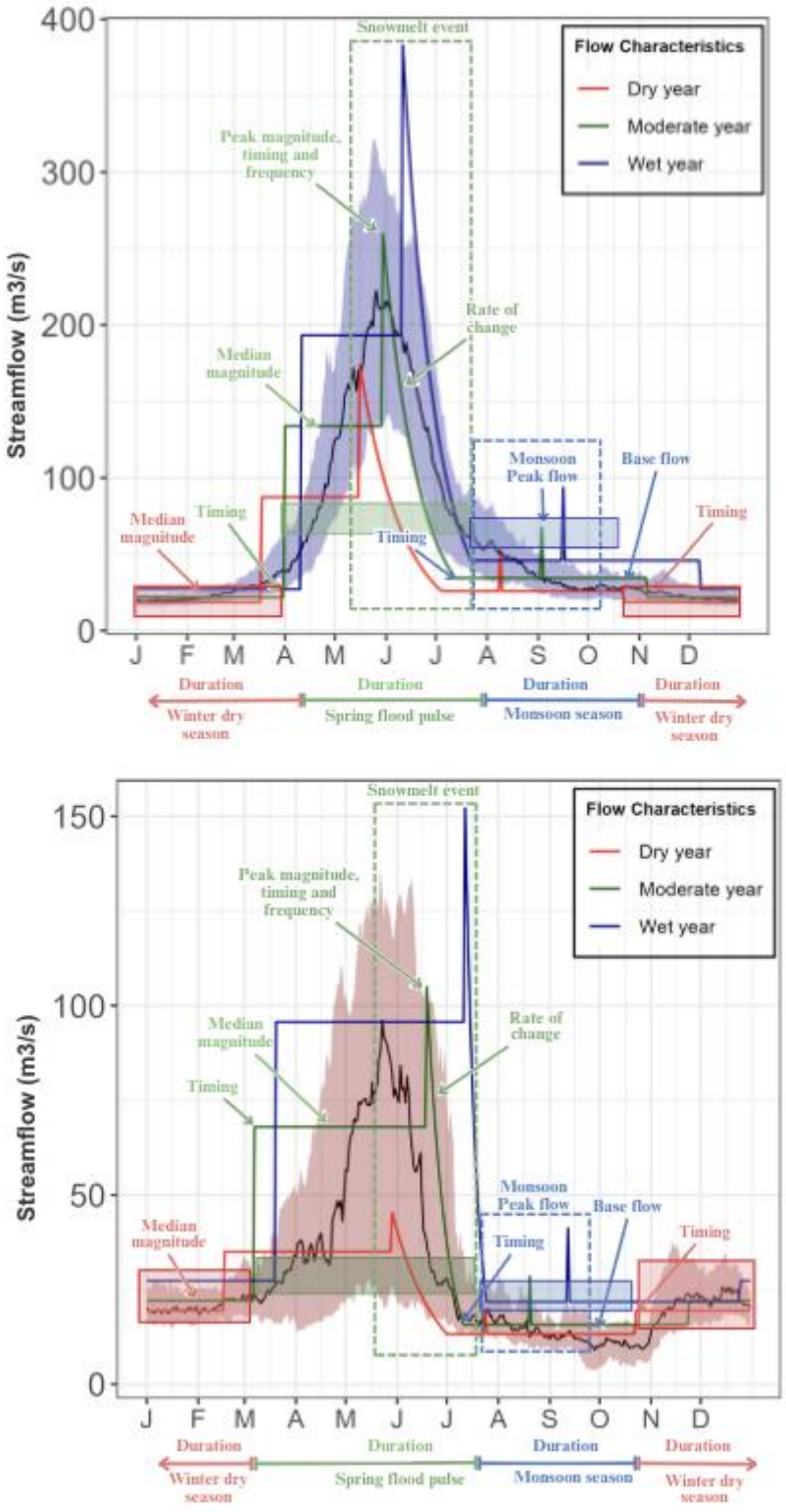


Figure 1-14. Example of the functional flow metrics for the natural (in blue) and regulated (in red) flow at the Rio Grande/Rio Bravo at Albuquerque gauge station. The thick lines (Red, Green and Blue) correspond to the water years, Dry, Moderate and Wet.

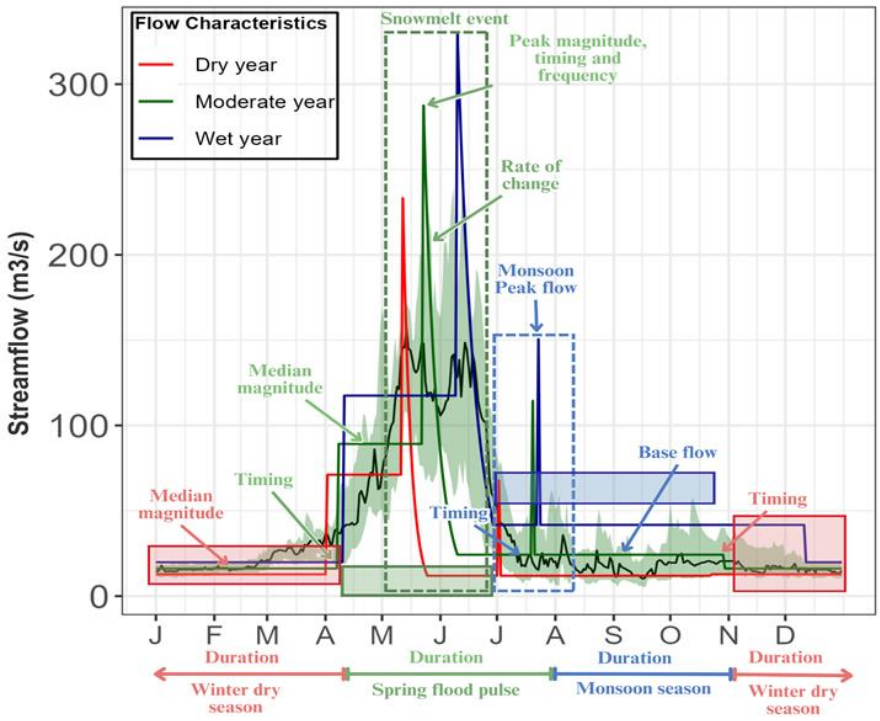


Figure 1-15. Example of the functional flow metrics for the resilient flow (green) at the Rio Grande/Rio Bravo at Albuquerque gauge station. The thick lines (Red, Green and Blue) correspond to the water years, Dry, Moderate and Wet.

3.3 Carrying Capacity and Environmental Flow Gap

There are 16 streamflow gauges that have calculated natural, regulated and resilient flow regimes to represent the overall conditions of the basin (**Figure 1-16**). The FFM of the natural streamflow condition represents the undisturbed, intrinsic flow that would have been in the absence of human intervention and works as a reference of flows that the river ecosystem adapted for thousands of years. In contrast, the FFM of the resilient streamflow condition characterizes the flow regime altered by human activities, often through water diversions, yet still preserves the functional flows that support river ecosystems. The FFMs for the resilient flow were calculated using the Functional Flow Calculator for the regulated streamflow before the breaking point (**Figure 1-14**). The difference in the volume between the natural and resilient FFM is the carrying capacity. The importance of the carrying capacity in river basin management cannot be overstated, providing the crucial framework for water management between human water needs and preservation of ecological integrity and ecosystem services.

The environmental flows gap was calculated by subtracting the functional flow metrics of the resilient and regulated flow regimes. The environmental flow gap shows the volumetric gap needed to restore the ecosystem's functionality. The resilient flow shows an alteration in magnitude and timing resulting from human activities (e.g. river diversions) but still leaving enough water for the

ecosystem. The environmental flow gap is important to understand and address health and functioning of riparian ecosystems, provide adequate flow (magnitude, timing, frequency, and rate of change), as well as preserve water quality, provide flood mitigation, groundwater recharge and cultural water use. Environmental flow gaps and carrying capacity, enhance the adaptation to climate change, and can help to promote sustainable development of human water use considering the needs of the environment.

3.1.3. Carrying capacity.

FFM of the naturalized streamflow data are used as reference conditions for a healthy and functioning ecosystem, they are compared with the FFM from the resilient period. The difference between the FFM of the natural and resilient streamflow is called hydrologic alteration (**Figure 1-17**), it describes the magnitude of disturbance that natural flow regime can absorb before changing into a different flow regime. Hydrologic alteration values were calculated for 16-gauge stations.

The 25th (dry), 50th (moderate) and 75th (wet) percentile values were taken from the 50th Percentile magnitude of the Spring flood pulse, Monsoon and Winter Dry season were compared between the natural and resilient streamflow conditions to represent dry, moderate, and wet water year types, respectively (**Table 1-4**).

Table 1-4. Example of the metrics used to build the functional flow hydrographs.

Metric	Extreme_dry_	Dry_nat	Moderate_na	Wet_nat	Extreme_Wet	station
Wet_Mag_50	1494.7775	2031.625	3127.785	4377.125	5056.375	RG06_NR_LOBATOS
Wet_Mag_90	3169.15	4321.745	5944.15	7713.225	8599.7	RG06_NR_LOBATOS
Wet_Tim	78	89	99	106	111	RG06_NR_LOBATOS
Wet_Dur	82	89.25	101	109	119.1	RG06_NR_LOBATOS
High_flow_mag	4277.66	4872.125	6487.5	8280	10340.5	RG06_NR_LOBATOS
Mons_mag_50	347.56	483.125	625.145	816.6625	1110.28	RG06_NR_LOBATOS
Mons_mag_90	617.232	1003.325	1455.4	2269.025	2871.36	RG06_NR_LOBATOS
Mons_peak_mag	599.604	903.385	1398.95	1916.57	2394.78	RG06_NR_LOBATOS
Mons_Tim	184	189	196	206	211	RG06_NR_LOBATOS
Mons_Dur	90	100	114	140	155.1	RG06_NR_LOBATOS
DS_Mag_50	224.55	274.025	335.5	399.25	459.1	RG06_NR_LOBATOS
DS_Mag_90	329.232	414.1325	525.7	688.775	869	RG06_NR_LOBATOS
DS_Tim	296	296	311	337	348	RG06_NR_LOBATOS
DS_Dur_WS	113.5	127	149.5	168	175	RG06_NR_LOBATOS
Wet_Mag_10	604.61	750.2	1124.5	1553.75	1988.728	RG06_NR_LOBATOS
Mons_mag_10	249.416	301.7375	388.44	477.98	641.196	RG06_NR_LOBATOS
DS_Mag_10	187.08	220.35	266	313.5	375	RG06_NR_LOBATOS
High_flow_tim	120	132	146	155	165	RG06_NR_LOBATOS
Mons_peak_tim	210	225	251	265	275	RG06_NR_LOBATOS
ROC	0.038346	0.039563	0.045273	0.044833	0.047554	RG06_NR_LOBATOS

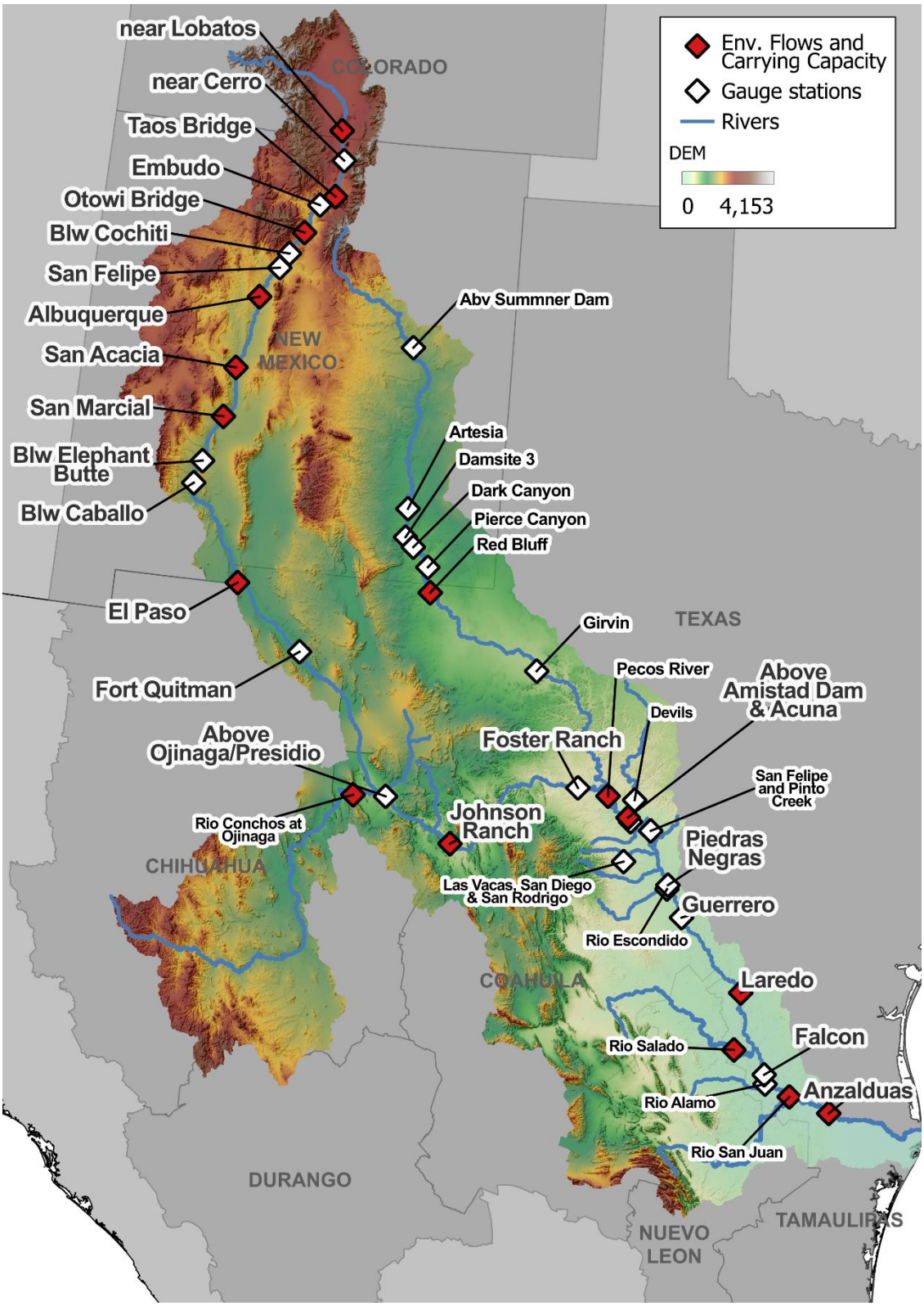


Figure 1-16. Gauge stations where environmental flow gaps and carrying capacity was calculated.

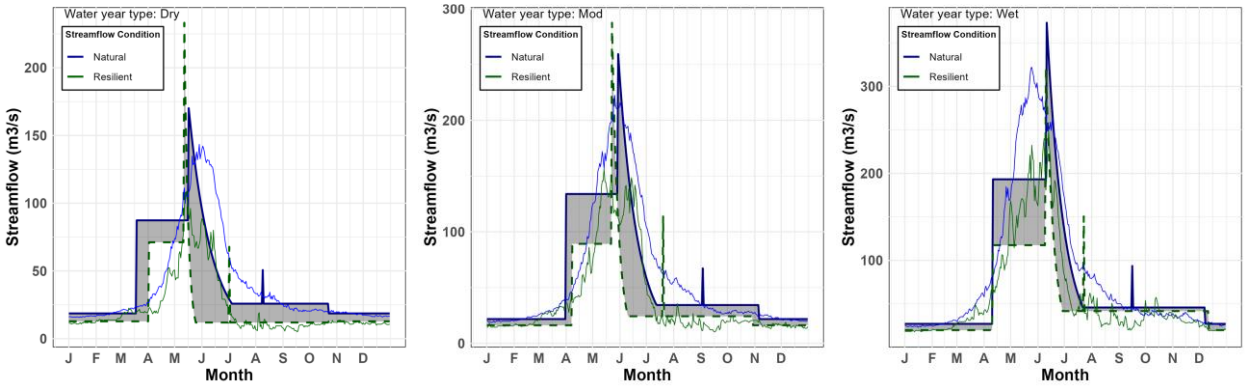


Figure 1-17. Carrying capacity for Albuquerque. In blue the natural FFM and green the resilient FFM, the shaded area represents the hydrologic alteration that can be absorbed by the system before reaching the breaking point.

Table 1-5 shows an example for estimating the carrying capacity for each functional flow components and water year types of a snowmelt streamflow class and **Table 6** shows a summary per water year type. Calculating the carrying capacity for the 16 gauge stations serves as a critical metric to evaluate the limits of water use in the RGB basin. The carrying capacity or hydrologic alteration measures the maximum level of water diversion that the ecosystem can support without compromising its ecosystem functions and causing a permanent regime shift. It is unlikely to restore the RGB to its natural state (i.e. get rid of all human interventions), however, the concept of carrying capacity is an important tool to aim for a healthier basin and serve as a guide in decision making for water allocation, ecosystem preservation, drought management and climate change adaptation.

Table 1-5. Carrying capacity for each season for Albuquerque, a snowmelt flow regime gauge station.

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(m3/s)*	*(MCM)*	*(m3/s)*	*(MCM)*	*(m3/s)*
RG14_ALBUQUERQUE	*Dry Year*	*Winter dry season*	296	91	348.1	25.2	177.8	12.9	-170	-12.3
		Spring flood pulse	92	144	448.3	99.8	339.3	75.5	-109	-3.0
		Monsoon season	145	295	470.5	36.3	173.2	13.4	-297	-6.7
	Moderate Year	*Winter dry season*	303	97	376.1	27.4	223.2	16.2	-153	-11.1
		Spring flood pulse	98	160	799.2	149.2	524.0	97.8	-275	-7.5
		Monsoon season	161	302	558.4	45.8	319.7	26.2	-239	-5.5
	Wet Year	*Winter dry season*	346	100	280.8	27.3	205.6	20.0	-75	-7.3
		Spring flood pulse	101	179	1417.4	210.3	852.2	126.5	-565	-14.8
		Monsoon season	180	345	747.5	52.4	623.0	43.7	-124	-2.7

Table 1-6. Summary of carrying capacity for three water year types for the gauge station of Albuquerque.

Streamflow Gauge	Water year type	Natural Flow	Resilient Flow	Carrying Capacity	
		(MCM)	*(MCM)*	*(MCM)*	*(%)*
RG14_ALBUQUERQUE	*Dry*	1266.9	690.3	-576.6	46%
	Moderate	1733.7	1066.9	-666.8	38%
	Wet	2445.6	1680.8	-764.9	31%

Carrying capacity results (**Annex 6**) provide the maximum sustainable water use within the basin. The results show the carrying capacity variation under different water year types and flow components. For example, RG06_NR_LOBATOS during a dry year, the carrying capacity is positive during the winter dry season but turns negative during the spring flood pulse and monsoon season. Similar patterns are observed in the other gauges on the upper. In general, the upper basin ranges from 38% to 53% carrying capacity during wet years, emphasizing the importance of sustainable water management practices to maintain ecological resilience and ensure long-term water availability. The lower basin shows varying carrying capacity percentages from 44% to 78%. This indicates that the lower basin is relatively more resilient to water use impacts during different water year types.

3.4 Recommended environmental flows and (Volume) Gaps

Determining the environmental flow gaps (Eflow Gap) in the RGB basin is important for both the ecosystem and human water use. The environmental flow gap is estimated by calculating the difference between the FFM of the resilient and the regulated streamflow, they describe the water needed to restore the functional flows at a point that resemble those of the natural flow regime, they were calculated for 16 gauge stations. These gaps represent the difference between the resilient flow and the regulated flow hydrographs resulting from human activities such as dam construction, water diversions, and irrigation (**Figure 1-18**). Resilient flows resemble the functional flows of the natural flow regime that are a time-tested recipe for a healthy freshwater and riparian ecosystem. They promote ecosystem health, preserve biodiversity, and protect water quality, which are key components of water resources management. Being able to secure the environmental flow gaps in the RGB will support resilient ecosystems by identifying locations where water can be moved in time and secured in magnitude to mimic the FFM of the resilient period. In the case of the RGB, while in some streamflow gauges the main issue is moving water in time (timing), in most of the cases the main issue is securing water (adding water to the system) to reduce the environmental flow gap. The following section describes different strategies to secure the water needed to meet the environmental flow gap.

The gaps were obtained for the three water year conditions and three seasons: Dry, snowmelt/spring and Monsoon. When calculating the environmental flow gaps water surplus and deficit can occur. A water surplus is when the regulated flow regime has a larger volume of water than the resilient flow regime. These conditions typically occur mostly below reservoirs where the flow regime follows irrigation patterns, and thus, the timing and volume has changed radically. Water deficit can occur where there is deficit in the volume to meet the resilient flow regime. These conditions typically occur because of water diversions deplete the overall volume and thus, there is a need to leave some of that water in the river to meet the resilient flow regime. In many cases, there are deficits and surpluses of water in a streamflow gauge, thus, in some cases it is a matter of moving water in time rather than increasing water volume in rivers. **Table 7** and **8** show the results for RGB at Albuquerque NM. The flow gap shows that there is enough water (volume) in

the river, the issue is timing. Results show there is a need to move water in time for dry and moderate water year types, there is no deficit in volume but a surplus of 18.7 MCM (3%) and 19.2 MCM (2%), respectively. This indicates that water can be released or move in different periods of time to mimic a more resilient streamflow.

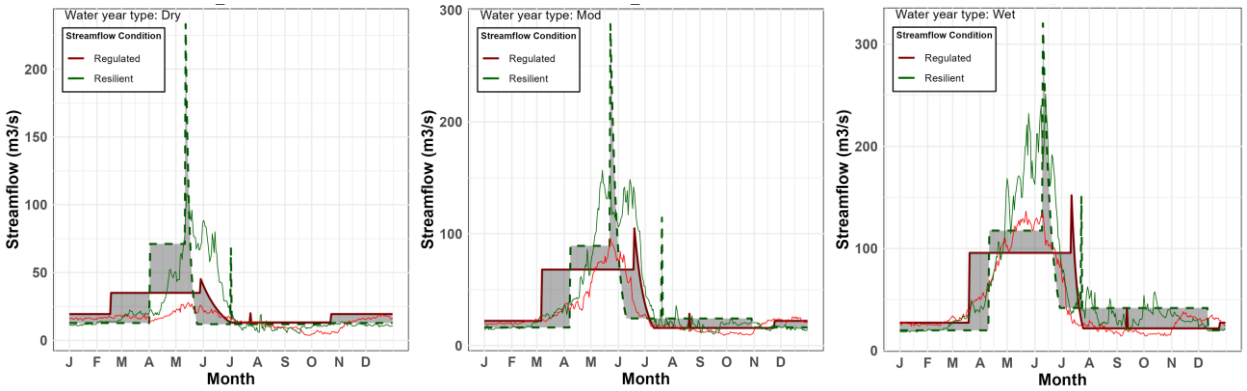


Figure 1-18. Environmental flow gap for Albuquerque. In red the regulated FFM and in green the resilient FFM, the shaded area represents the volume as a surplus or deficit from the current altered state and a resilient streamflow.

Table 1-7. Environmental flow gap for Albuquerque for each season (Dry, Snowmelt and Monsoon) for three water year types. Positive values mean deficit, negative values mean surplus. *Negative values indicate resilient flows are larger than regulated flows, showing a deficit. Positive values imply regulated flows are greater than the resilient flows in that period.

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	(MCM)	(m3/s)	(MCM)	(m3/s)	(MCM)	(m3/s)
RG14_ALBUQUERQUE	Dry Year	Winter dry season	296	91	329.6	23.8	177.8	12.9	152	11.0
		Spring flood pulse	92	144	160.5	35.7	339.3	75.5	-179	-5.0
		Monsoon season	145	295	219.0	16.9	173.2	13.4	46	1.0
	Moderate Year	Winter dry season	303	97	418.4	30.5	223.2	16.2	195	14.2
		Spring flood pulse	98	160	369.9	69.1	524.0	97.8	-154	-4.2
		Monsoon season	161	302	297.8	24.4	319.7	26.2	-22	-0.5
	Wet Year	Winter dry season	346	100	407.3	39.6	205.6	20.0	202	19.6
		Spring flood pulse	101	179	653.3	96.9	852.2	126.5	-199	-5.2
		Monsoon season	180	345	453.7	31.8	623.0	43.7	-169	-3.7

Table 1-8. Yearly environmental flow gap for Albuquerque gauge station for three water types. Negative values mean deficit, positive values mean surplus. *Negative values indicate resilient flows are larger than regulated flows, showing a deficit related to time. Positive values imply regulated flows are greater than the resilient flows in that period.

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap	
		(MCM)	(MCM)	(MCM)	(%)	(MCM)	(%)	(MCM)	(%)
RG14_ALBUQUERQUE	Dry year	709.0	690.3	197.6	29%	178.9	26%	18.7	3%
	Moderate year	1086.1	1066.9	195.2	18%	176.0	16%	19.2	2%
	Wet year	1514.2	1680.8	201.7	12%	368.2	22%	-166.5	10%

The environmental flow gaps across the Rio Grande Basin gage stations shows a significant difference between regulated and resilient flows. These gaps reflect the intricate challenges to maintaining ecologically sustainable water conditions. In the Upper Basin, deficits are evident in multiple locations, particularly during dry and wet years, with substantial gaps observed in critical points such as RG06_NR_LOBATOS and RG15_NR_SAN_ACACIA. The Lower Basin also shows deficits, more notorious in RG25_JOHNSON and RG30_LAREDO, indicating potential ecological stress. Tributaries, such as PR06_at_Redbluff, display deficits, further emphasizing the need for comprehensive water management strategies. While some surplus values exist, the overall trend suggests a vulnerability in environmental flows, thus there is a need to careful consider proactive measures to reduce those water gaps and obtain a more resilient and sustainable water ecosystem in the Rio Grande Basin.

4 Strategies and interventions for implementing environmental flows.

This section of suggested strategies is aligned and complementary to the "Assessing Climate Variability and Adaptation Strategies for the Rio Grande Basin" 2023 USGS, report, also made by the UC Davis Water Management lab team.

Three overall categories are defined to introduce a set of strategies to implement the environmental flows in the RGB: Opportunities for improving human and environmental water supply with current infrastructure, Water demand management, and Nature based solutions.

4.1 Opportunities for improving human and environmental water supply.

A reduction in water demand is necessary to mitigate the annual eco-deficits to assure that water for environmental flows. There are also system re-operations or system optimization strategies using the current infrastructure. These strategies can help move water in time for environmental purposes when is needed, such as reservoir re-operations (FIRO). In terms of environmental gaps, these strategies can help in locations that experience eco-deficits and eco-surplus, to move water from eco-surplus periods to eco-deficit periods (**Figure 1-19**). They can also help to capture and store the most amount of water to stretch this resource. Example of this strategies are groundwater recharge or conjunctive use of surface and groundwater. In terms of environmental gaps, these strategies can help both, move water in time or increase water supply sources.

4.2 Water demand management.

These strategies play a vital role in addressing the mismatch between the natural water scarcity and human water demands within the RGB basin. By implementing a range of measures regarding agriculture, domestic, and urban sectors, these strategies aim to optimize water usage and implement water conservation practices.

4.3 Nature based solutions.

Nature bases solutions are economically and environmentally desirable. They typically need low maintenance because they work integrated as part of the natural processes of the ecosystems. In terms the environmental gaps, they can enhance the habitat (geomorphology), which is an important piece besides water quantity and quality. They also can be done at the local or regional scale, which is a great advantage. As a result in the long term they provide sustained benefits.

These three main strategies are the base for a scoping process that guides the development of the specific interventions needed or that have been implemented in the RBG basin and can be applied in other sites to implement environmental flows effectively. These strategies can be achieved only by careful planning while having engagement of stakeholders.

A description of each category, the places in the RGB where they are most helpful and the environmental flow components that would benefit most from them are found in **Table 9**. The potential to implement such strategies considering the water demand, the coordination on stakeholders and the current legal framework can be found in **Table 10**. In addition, a map with the summary values of the environmental flow gaps and the carrying capacity per gauge station is provided in **Figure 1-19.** These materials were made in the hope of serve as guide to enhace the water use throughout the basin.

Table 1-9. Strategies directed to secure water resources from the Rio Bravo/Grande basing.

Category	Strategy	Description	E-flow components most benefited by the strategies	Locations benefited by the strategies
Opportunities for improving human and environmental water supply with current infrastructure	Reservoir re-operations and dam releases.	These strategies focus on maximizing the efficient use of the existing infrastructure to meet both human and environmental water needs. They focus on approaches that try to meet human and environmental water needs.	Winter dry season Monsoon season	Santa Rosa, Sumner, Red Bluff, Heron, El Vado, Abiquiu, Cochiti, Elephant Butte, Caballo, Pico del Águila, San Gabriel, Francisco I. Madero, La Boquilla, Luis L. León, Amistad, Falcon, Venustiano Carranza, El Cuchillo, Marte R. Gomez and Las Blancas.
	Forecast Informed Reservoir Operations (FIRO).		Spring flood pulse Monsoon season	Santa Rosa, Sumner, Red Bluff, Heron, El Vado, Abiquiu, Cochiti, Elephant Butte, Caballo, Pico del Águila, San Gabriel, Francisco I. Madero, La Boquilla, Luis L. León, Amistad, Falcón, Venustiano Carranza, El Cuchillo, Marte R. Gomez and Las Blancas.

	Conjunctive use of Surface water, groundwater, recycled water.		Winter dry season Monsoon season	Rio Conchos (Meoqui Aquifer, Franciso I Madero and La Boquilla dam), Lower Rio Grande (Chicot-Evangeline Aquifer and Falcon dam), San Juan Basin (Monterrey Aquifer, El Cuchillo, La Boca and Cerro Prieto Dams), Chihuahua city (Chihuahua-Sacramento aquifer, Chuviscar and El Rejon dams)
	Optimize available water sources: rainwater harvest and recycled water.		Winter dry season	Chihuahua city, Laredo, Nuevo Laredo, Monterrey, McAllen, Brownsville, Matamoros, Reynosa,
	Enforcing current regulations.		Winter dry season Monsoon season	New Mexico, Texas, Durango, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas
	Expanding new regulations-		Winter dry season Monsoon season	Rio Conchos, Arroyo las Vacas, San Diego, San Rodrigo, Rio Salado, Alamo, San Juan and the mexican portion of the basin contributing to the RGB from Fort Quitman to the Gulf of Mexico
Water demand management	Water demand management	These strategies aims to address the mismatch between the natural water scarcity of the basin and the large human water demands throughout the system, which is one of the main problems to solve. These strategies include water conservation measures for agriculture, domestic and urban sectors.	Winter dry season	Colorado, New Mexico, Texas, Durango, Chihuahua, Coahuila, Nuevo León and Tamaulipas
	Crop planting management		Winter dry season Monsoon season	All irrigation districts throughout the RGB basin
	Regulated deficit irrigation		Monsoon season	All irrigation districts throughout the RGB basin
	Buy back of water rights		Winter dry season Monsoon season	All irrigation districts throughout the RGB basin
	Land fallowing		Winter dry season Monsoon season	All irrigation districts throughout the RGB basin
	Improve water supply systems and water consumption at home (indoor and outdoor strategies).		Winter dry season Monsoon season	Albuquerque, Santa Fe, Las Cruces, Espanola, Carlsbad, El Paso, Ciudad Juárez, Chihuahua, Ojinaga, Delicias, Presidio, Eagle Pass, Laredo, Zapata, Roma, Rio Grande, Mission, McAllen, Edinburg, Weslaco, Harlingen, Brownsville, Ciudad Acuna, Piedras Negras, Monclova, Monterrey, Saltillo, Reynosa, Matamoros, Valle Hermoso, Ciudad Río Bravo.

	Conservation strategies at home		Winter dry season Spring flood pulse Monsoon season	Albuquerque, Santa Fe, Las Cruces, Espanola, Carlsbad, El Paso, Ciudad Juárez, Chihuahua, Ojinaga, Delicias, Presidio, Eagle Pass, Laredo, Zapata, Roma, Rio Grande, Mission, McAllen, Edinburg, Weslaco, Harlingen, Brownsville, Ciudad Acuna, Piedras Negras, Monclova, monterrey, Saltillo, Reynosa, Matamoros, Valle Hermoso, Ciudad Río Bravo.
Nature based solutions	Climate adapted agriculture practices	This strategy includes nature-inspired solutions to promote the ecosystem health and resilience of the riparian ecosystem, while still providing water for human water needs.	Winter dry season Monsoon season	All irrigation districts throughout the RGB basin
	Water reservoirs for protecting land and water resources.		Winter dry season Monsoon season	Janos Biosphere Reserve, Maderas del Carmen Flora and Fauna Protection Area, Big Bend National Park.
	Increasing soil health and water holding capacity.		Winter dry season	All irrigation districts throughout the RGB basin

Table 1-10. General potential for stablishing strategies directed to secure water resources from environmental flows and to restore the timing of the stream flow.

Implementation Strategies	Potential to secure water resources for environmental flow	Potential to move water in time
Reservoir re-operations and dam releases.	Medium	High
Forecast Informed Reservoir Operations (FIRO).	Medium to high	Medium
Conjunctive use of Surface water, groundwater, recycled water.	Medium to high	Medium
Optimize available water sources: rainwater harvest and recycled water.	Medium to high	Medium
Enforcing current regulations.	High	High
Expanding new regulations-	High	High

Crop planting management	High	Low to medium
Regulated deficit irrigation	Medium	Low
Buy back of water rights	High	Medium
Land fallowing	High	Low
Improve water supply systems and water consumption at home (indoor and outdoor strategies).	Medium to high	Low
Climate smart agriculture practices	Medium to high	Low
Water reservoirs for protecting land and water resources.	High	Medium
Increasing soil health and water holding capacity.	Medium to high	Medium

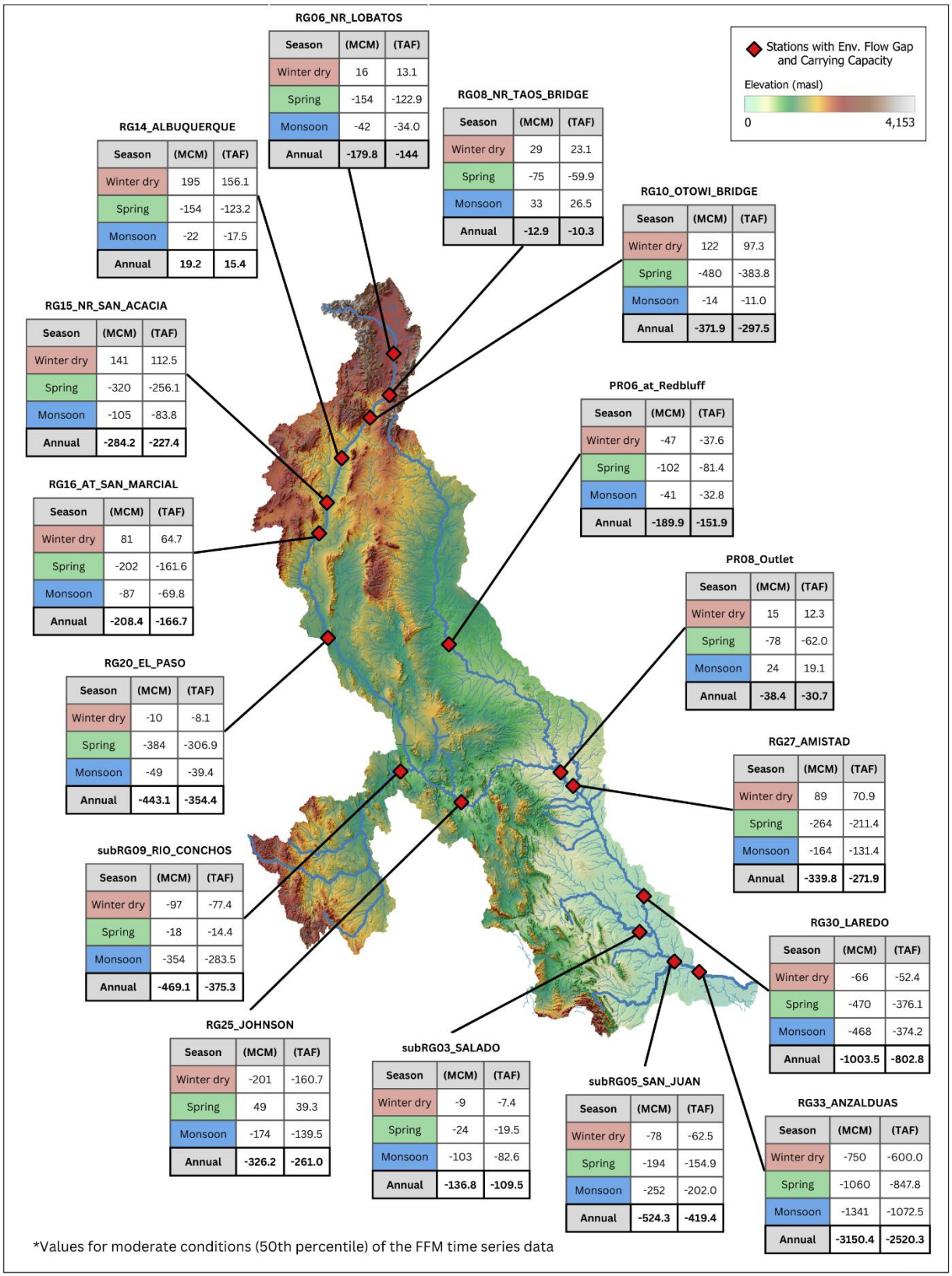


Figure 1-19. Environmental flows at each gauge station on the RGB.

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CHAPTER 2

RESILIENT FLOW REGIMES IN THE RIO GRANDE – RÍO BRAVO BASIN

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Abstract. Water is essential for human development and is an indispensable resource for economic activity and a country's growth. However, current water practices, along with increasing land-use change, climate change, and agricultural practices, have significantly altered the hydrological cycle and water availability. This study introduces the concept of a resilient flow regime—a flow regime that can absorb certain human-induced perturbations while preserving ecologically beneficial characteristics of the natural flow regime—and explores its implications for sustainable water management. Using the Rio Grande/Bravo (RGB) basin, a transboundary watershed shared by the U.S. and Mexico, as a case study, the research evaluates the similarities and differences among natural, resilient, and regulated flow regimes. The RGB faces significant water resource challenges due to extensive infrastructure development, overuse, and climate variability. The study identifies three natural streamflow classes in the basin (snowmelt-driven, monsoon-driven, and bimodal) and evaluates functional flow metrics across 16 gage stations. Results reveal strong correlations between natural and resilient flow metrics, particularly in magnitude components, while regulated flows deviate more significantly from natural conditions and the tatistical analyses shows that resilient flow regimes maintain ecological functionality and hydrological integrity, balancing human water needs and ecosystem health. By maintaining or restoring resilient flow conditions, water management strategies can mitigate the adverse impacts of human activities, preserve biodiversity, and promote the long-term sustainability of riparian ecosystems. This research provides a framework for integrating ecological considerations into water management practices, addressing the challenges of climate change, population growth, and increasing water demands.

Keywords: *Resilient streamflow, Functional Flow Metrics, time thresholds*

1 Introduction

1.1 Water crisis and the environment

Water is essential for human development and is an indispensable resource for any economic activity and country's development. Water resources provide value to lands, societies, and ecosystems (Magnuson and Stanford, 1995., Young and Lomis, 2014) and their availability is determined by geographic location, climatic conditions, environmental landscape, natural features (e.g., aquifers), manmade infrastructure (e.g., reservoirs, aqueducts), water use and governance, and other variables. However, current water practices, alongside increasing land-use change (particularly urbanization), climate change, and agriculture practices have impacted water availability (Wang et al., 2024) and altered the hydrological cycle locally (Foley, et al., 2005, Piao et al., 2007, Weather and Evans, 2009; Wisser et al., 2010; Aleksandrowicz et al., 2016), regionally, and at the continental and global scales (McAlpine et al., 2009; Sophocleous, 2004). Current water practices often prioritize human water needs over environmental conservation. However, this approach can significantly disrupt the natural flow regime that native species and riparian ecosystems have adapted to over centuries (Poff et al., 1997; Richter et al., 1996; Wohl et al.,2015). Alterations to the natural flow regime, caused by human interventions such as dam construction or excessive water extraction, negatively affect freshwater and riparian ecosystems. For instance, changes in flow patterns can disrupt the breeding and migration cycles of aquatic species, leading to population declines and loss of biodiversity (Junk, Bayley, and Sparks, 1989, Moog 1993). Moreover, riparian habitats depend on the natural flow regimes that if degraded, affect the overall ecosystem health (Poff and Zimmerman, 2010; Merritt et al., 2010). Hence, it's important to consider the conservation of some semblance of the natural flow regime when managing water resources, ensuring a sustainable balance between human needs and environmental preservation.

1.2 The RGB and its environmental crisis

The Rio Grande/Bravo (RGB) exemplifies the intricate relationship between human water needs and environmental impacts. The RGB is a transboundary basin shared between Mexico and the United States, its water is shared between the states of Colorado, New Mexico, and Texas in the U.S., and Durango, Chihuahua, Coahuila, Nuevo León, and Tamaulipas in Mexico. The RGB is North America's fifth-largest drainage basin, covering approximately 557,000 km^2.However, despite its size and ecological significance, the water flowing through the RGB and its tributaries has experienced significant changes in volume and timing, leading to a human-induced megadrought (Garza-Diaz and Sandoval-Solis,2022) primarily attributed to extensive water use and infrastructure development (Chavarria and Gutzler, 2018). These changes have led societies and the ecosystem to evolve and adapt to climate and water variability. However, in the last two centuries, these practices have placed immense pressure on the water resources in the region. The current patterns of water use (e.g., water diversions and groundwater overdraft), infrastructure development (e.g., reservoir and levees), and pollution (e.g., agrochemicals and wastewater) have

altered the natural flow regime of the river in the RGB basin to its current state (i.e., "regulated streamflow"), adding to the stress imposed by climate change effects on seasonal weather patterns (Hoegh-Guldberg et al.2018).

1.3 Flow regimes: Natural, Ecological, Environmental, and Resilient

The natural flow regime refers to the seasonal and inter-annual variability of streamflow in absence of human intervention, under which native species and riparian ecosystems have evolved for millennia. Ecological flows, also referred to as instream flows, are those that consider only the needs of freshwater and riparian ecosystems. In contrast, Environmental flows are those flows that balance the needs of water for the environment and the society, typically these are flows that came from a negotiation process that balanced human and environmental needs (Arthington 2012, Postel and Richter, 2003).

In this research, we define the concept of the resilient flow regime which is a flow regime that absorbs some perturbation by human alterations but still preserves ecologically beneficial characteristics associated with the natural flow regime. The resilient flow regime is derived from the period when there was human alteration, but the flow characteristics remained within the variability of the natural flow. The resilient period is identified using resilience theory by calculating time thresholds, which refer to a point in time (e.g. a year) when a permanent flow regime shift occurred (Garza-Diaz,2022). Within the environmental flows scientific field, the resilient flow regime is: (a) an ecological flow (instream flow) recommendation because it considers the needs of the freshwater and riparian ecosystems by preserving the key natural flow characteristics of the natural flow regime, and (b) an environmental flow recommendation because water can be used for human purposes, but the essential characteristics of the natural flow regime persists to support freshwater and riparian ecosystems.

There is a need to characterize the resilient flow regime as it is imprinted with human alterations yet retains the essential characteristics of the natural flow regime. The concept of resilient flows represents a bridge between anthropogenic water management practices and the ecological preservation of the river basins. Time thresholds can be identified as the date after human alterations to the flow regime became detectable and pushed key regime characteristics outside the bounds of natural flow variability (Garza-Diaz & Sandoval-Solis, 2022), The resilient flow regime can be characterized from regulated streamflow data preceding the time threshold date. By estimating the resilient flow regime, we can establish a framework where water can be used for human needs (e.g., industry, agriculture, human consumption, and recreation) while still providing support for freshwater ecosystems and species. With the application of resilience theory and identification of time thresholds (Garza-Diaz,2022) we can determine the periods where human alterations remained within the boundaries of natural variability, which can be used to determine strategies for sustainable water management that prioritizes both human and environmental water needs.

1.4 Overall goal and objectives

The overall goal of this research is to characterize the resilient flow regime and determine the degree of similarity with the natural flow regime. There are three specific objectives. **First**, a natural streamflow classification and flow regime characterization is determined to use it as a reference point and be compared with the regulated and resilient flow regimes. **Second**, a flow regime characterization was done for the natural, resilient, regulated streamflow regimes to evaluate the differences between the three flow regimes. **Third**, two analyses of similarity are performed between (1) the resilient versus natural flow regimes and (2) the natural versus regulated flow regimes using the functional flow metrics to evaluate if there is more similarity between resilient and natural flow regimes than between the regulated and resilient flow regimes. The RGB is used as a case study because of its ecological significance, its natural flow regime diversity, and the urgency to provide environmental flow recommendations throughout the basin.

By identifying, sustaining or restoring resilient flow conditions, we can mitigate and restore the adverse impacts of human alterations on natural flow regimes that degrade the health and integrity of freshwater ecosystems. Understanding and incorporating resilient functional flows into water management practices can be beneficial to maintaining biodiversity, ecosystem services, and the overall resilience of the basin. Moreover, by preserving aspects of the natural flow regime, resilient flows contribute to water resource sustainability and long-term viability. The resilient flow allows the implementation of an adaptive approach to water resources management, essential for addressing the multiple challenges of climate change, population growth, and increasing water demand in the basin.

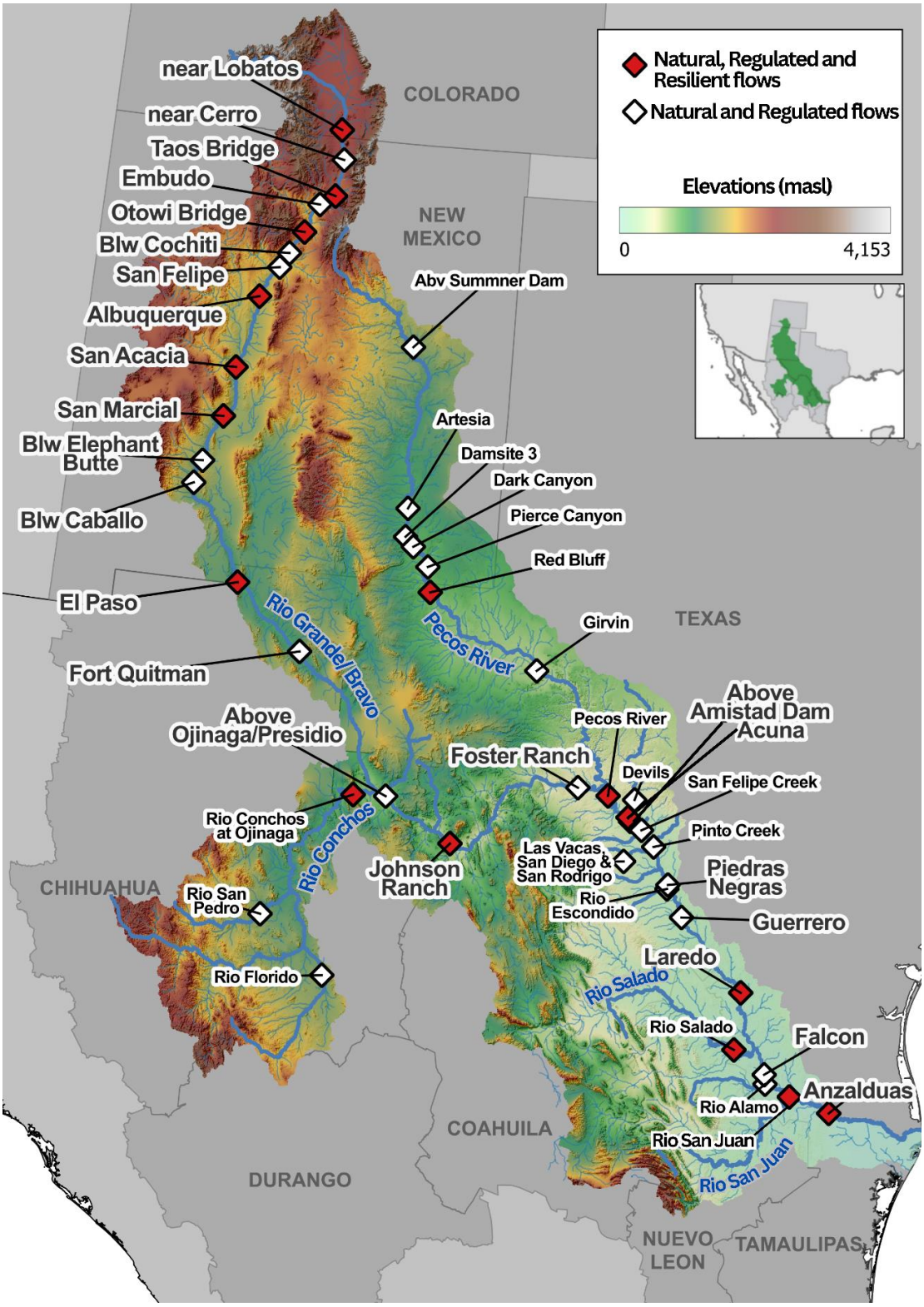

Figure 2-1. Digital elevation model of the Rio Grande/Rio Bravo basin showing the gauge stations (n=43) throughout the basin for which natural and regulated flows have been characterized (in white), and other gauges where natural, regulated, and resilient flows have been characterized (in red)

2 Literature Review

2.1 Resilience theory

Multiple definitions of resilience have been proposed and debated (**See Table 2-1**). In general, resilience has been used in two different contexts: engineering resilience and ecological resilience. Engineering Resilience is defined as the time needed for a system to return to pre-disturbance conditions once a stressor is removed or the disturbance has passed (Hashimoto, Stedinger, & Loucks, 1982; Pimm & Pimm, 1991). It assumes linear and optimal systems where the speed of return to equilibrium is used to measure the property. This definition fails to capture the nature of variability of natural systems (Holling, 1996) yet given its practical quantification, it is the most commonly used in water management, specifically in reservoir operations and water supply systems. In contrast, Ecological Resilience, initially introduced by Holling, (1973) explains the magnitude of the disturbance that a system can absorb and adapt to while maintaining its essential structure and function before it changes into an alternative regime. Ecological resilience has increasingly been recognized as an imperative aspect of sustainable development, but quantifying and applying the concept of ecological resilience has been challenging (Angeler & Allen, 2016; Webb, Watts, Allan, & Conallin, 2018). For rivers, ecological resilience can be defined as the ability of freshwater ecosystems to experience perturbations and adapt to changing environmental conditions while preserving ecological functions, species, and services (Grantham, et al. 2019). In the context of streamflow, this includes maintaining key flow regime aspects of the natural flow regime such as temporal variability, spatial heterogeneity, and hydrologic connectivity, while having water management infrastructure and decision-making actions.

Table 2-1. Resilient theory definitions

Type of Resilience	Definition	Reference
Engineering Resilience	Engineering resilience focuses on the return of structural and functional attributes of systems to pre-disturbance conditions following a disturbance. Rapid return times are interpreted as reflecting high engineering resilience	Hashimoto et al., (1982) and Pimm, (1991)
Ecological resilience	Ecological resilience is a measure of the amount of change needed to change an ecosystem from one set of processes and structures to a different set of processes and structures. Resilience is an emergent property of ecosystems and other complex systems and recognizes that systems operate in multiple basins of attraction.	Holling, (1973) and Walker, Holling, Carpenter, & Kinzig, (2004)
Ecological resilience for freshwater systems	The capacity of ecosystems to collectively adjust and adapt to shifting and potentially novel environmental conditions while preserving desired functions, species, and services	Grantham, Matthews, & Bledsoe, (2019)

2.2 Flow regimes

In natural conditions, freshwater and riparian ecosystems exhibit resilience by absorbing and adapting to natural perturbations such as droughts and floods, allowing them to persist over time. This resilience is governed by the attributes of the natural flow regime, which sustains the

ecological integrity of ecosystem structure and function through its inherent flow variability (Poff, 1997). Flow variability influences aquatic and riparian ecosystems and geomorphic processes. For instance, during dry seasons, low water flows may reduce invasive species and benefit native species adapted to drought conditions (Bunn & Arthington, 2002; Postel & Richter, 2012). Conversely, the onset of the rainy season brings high flows that counteract channel narrowing by flushing sediments, shaping physical habitats, and maintaining or widening river channels (Dean & Schmidt, 2013). These high flows also recharge the floodplain water table and trigger ecological events such as fish migration and spawning (Postel & Richter, 2012). Multiple studies have been conducted to prescribe environmental flows in different locations and reaches of the RGB (e.g. lower RGB: Matamoros and Brownsville reach, Pilon River and San Juan Tributary; middle RGB: including Big Bend region, Devils, Pecos; and Upper RGB: including Rio Chama) using a diverse array of methods including hydrologic, habitat simulation, and holistic approaches (Sandoval-Solis et. al. 2020). In addition, several other studies (Richter et al., 2024;Ortiz-Partida,2016; Lane et al., 2015; Sandoval-Solis & McKinney, 2012) have evaluated the ability to adjust existing Rio Grande/Bravo water management strategies to provide environmental flows while meeting human water management objectives, including agriculture and urban water supply, flood control, treaty obligations, and recreational and economic benefits.

The variability in river flow regimes has been characterized by using a variety of statistical parameters. One method is the Functional Flows Approach, in which flow events that are ecologically relevant in sustaining freshwater ecosystems are quantified using functional flow metrics, which in turn are key flow characteristics (magnitude, timing, duration, frequency, and rate-of-change) derived from daily streamflow records (Poff et al., 1997, Escobar-Arias & Pasternack, 2010; Yarnell et al., 2015). A group of functional flow metrics that characterize a flow event are referred to as functional flow components.

3 Data and Methodology

The 43 study gage stations used in this study are located along the mainstem from the headwaters of the RGB to the Gulf of Mexico and on various tributaries, including 16 gage stations where the time thresholds were estimated (Garza, 2022) (**Fig. 2-1**). The gage stations are distributed to represent the diversity of the hydro-climatic characteristics of the RGB basin, from the snowmelt-driven flow regime in the upper basin to the monsoon-driven flow in the lower basin and the bimodal flow regime (snowmelt and monsoon) along the mainstem in the southern portion of the RGB.

3.1 Overall Approach

First, a *natural streamflow classification* for the RGB was developed using the 43 gage stations to identify streamflow classes with a unique flow regime signature (e.g. snowmelt, monsoon, bimodal). The streamflow classification was determined using the functional flow metrics of the natural flows. **Second,** a *flow regime characterization* was done for the 16 gage stations with

natural, resilient, and regulated flows using reference hydrographs and functional flow hydrographs for dry, moderate, and wet years. **Third**, an *analysis of similarity* was performed to determine if there is a significant difference between the functional flow metrics of the natural, regulated, and resilient flow (n=16) regimes using two methods: (a) performing an ANOVA statistical test and Tukey's HSD test to identify which metrics are similar and different and (b) performing a correlation of the functional flow metrics of paired data, natural versus resilient and natural versus regulated (**Fig. 2-2**).

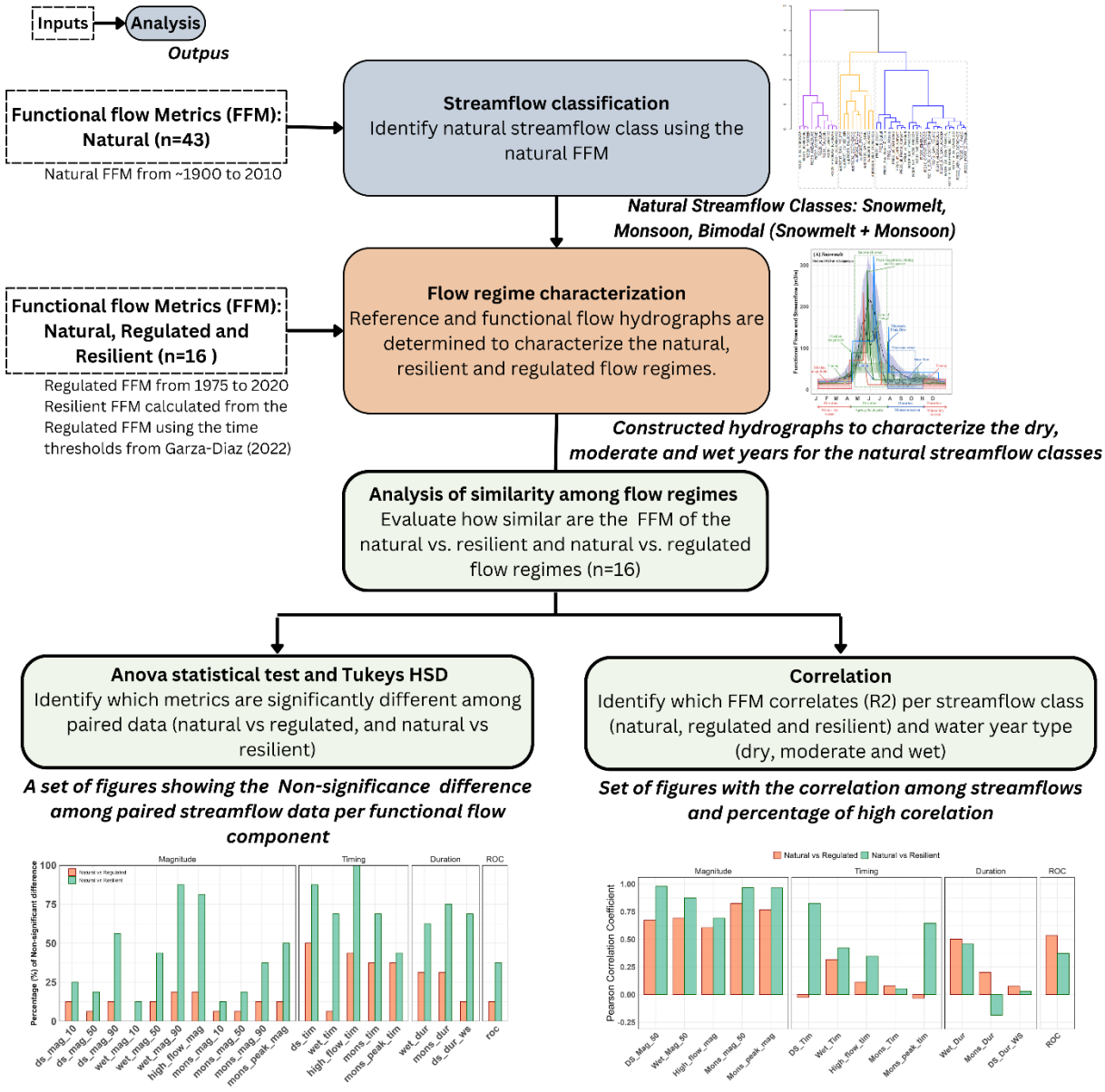

Figure 2-2. Overall methodology to determine the analysis of similarities among flow regimes. The input data corresponds to a set of FFM calculated from the streamflow data for three streamflow conditions (natural, regulated, and resilient).

1.1.3. Natural and Regulated Streamflow Data

Our dataset accounts for the daily time series data of the natural and regulated streamflow. The natural streamflow (1900 to 2010) represents the estimated hydrology unaffected by anthropogenic impacts, and the regulated streamflow (~1975-2020) represents modern hydrology and current conditions of the basin. The regulated streamflow period spans the wet season of the 1970s and 1980s, the drought of the 1990s and 2000s, the brief wet period of the late 2000s and early 2010s, and the continuous drought affecting the basin since 2015 (Sandoval Solis, et al., 2023; Harley, et al., 2018; Lehner, F., 2014; Ortega-Gaucin 2013). Garza-Diaz & Sandoval-Solis (2022) and Blythe & Schmidt (2018) describe the methods to estimate the daily natural streamflows in the southern branch and northern branch of the RGB, respectively. In summary, a gap filling and disaggregation of the regulated streamflow data was done, then to remove the river's impairment, a mass balance equation was used with climate, agriculture, and reservoir storage variables at a daily time step. These datasets have been widely used, for instance, to estimate environmental flow gaps across the basin (Patterson and Sandoval-Solis, 2022; Sandoval-Solis, Saiz-Rodriguez and Rendon-Herrera, 2024), to estimate environmental flows on the main Mexican tributaries (Sandoval-Solis, Garza-Diaz and Leal-Nares, 2019), the estimation of potential irrigation savings that were compared with our environmental flow gaps data (Richter et al., 2024).

1.2.3. Time Thresholds to Identify Change in Flow Regime

Under their natural conditions, rivers and riparian ecosystems have the capacity to absorb disturbances such as droughts and floods and still persist. However, the current water practices (e.g., river diversions and groundwater overdraft) and the infrastructure development in the basin (e.g., water intakes, dams, and reservoirs, etc.) have altered rivers significantly causing them to lose their natural resilience and shift to a permanent altered flow regime. Garza-Diaz and Sandoval-Solis (2022) used resilience theory to quantify when those changes in the flow regime of the RGB occurred. When the perturbations in the system were strong enough, they caused an abrupt change in the state of the flow regime referred to as the time threshold. The dataset used accounts for 16 control points with time thresholds (Garza, 2022). The regulated period of time and streamflow before the time threshold is defined as **resilient period and resilient streamflow, respectively;** it means that the streamflow characteristics (timing, magnitude, duration, frequency, and rate of change) are altered due to human intervention but still within the bounds of the natural flow regime.

1.3.3. Functional Flow Metrics

The Functional Flow Approach is based upon flow events and characteristics that support key ecological functions (Escobar-Arias, 2010). Streamflow characteristics can be quantified using the Functional Flow Approach (Yarnell et al., 2019; Yarnell et al., 2015) by estimating functional flow metrics (FFM) which are key ecological components relevant to freshwater and riparian ecosystems (Patterson et al., 2020). The functional flows are flow events associated with the basin's natural seasonal and interannual variability and its hydrologic and ecological characteristics (Lane

et al., 2018). The FFM of the natural flow regime represents flow ranges within streamflow that provide the necessary magnitude and timing for the ecosystem to deliver ecological services. The FFM are flow characteristics (timing, magnitude, duration, frequency and rate of change) that have been linked to the overall well-being of the ecosystem (Poff et al., 1997).

The FFM were calculated for the daily naturalized (Blythe and Schmidt, 2018; Sandoval-Solis, et al., 2023) and regulated streamflow data for 43 gage stations using the functional flow calculator (Patterson et al., 2020). Additionally, the resilient FFM values were calculated for 16 out of the 43 gage stations where the time thresholds were obtained (Garza-Diaz,2022). A series of FFMs were obtained for each year on record, and each metric is used to construct the Functional Flow Hydrographs that represent the natural, regulated, and resilient flow regime. The functional flow calculator was developed for Californian rivers to estimate environmental flow needs throughout the state (Grantham et al., 2022) and it was modified to capture the adequate metrics and components characteristic of the natural and regulated hydrology of the RGB. Appendix 1 shows the list of metrics and their rationale.

3.2 Natural Streamflow Classification and Flow Regime Characterization

The streamflow classification used similar methods described by Lane et al (2016). First, the natural FFM time series data was normalized to give equal weight to each metric. Second, to avoid redundancy in metrics, a correlation analysis was performed for each permutation of metrics; only one metric was kept out of two or more highly correlated metrics based on a Pearson correlation. Third, the gage station classification was done using Ward's hierarchical clustering (WHC) (Murtagh and Legendre, 2013; Ward, 1963) from the "hclust" function with Ward.D2 from the stats package in R. Fourth, the results obtained for the natural streamflow classification were a group of stations with similar characteristics and compared and refined with the opinions and feedback provided by environmental experts in the basin.

After obtaining the natural streamflow classification, the sixteen gages with the three functional flow conditions (natural, regulated, and resilient) were used to characterize the flow regime in the RGB. The reference hydrographs are used to represent the dry, moderate, and wet conditions of the flow (25th, 50th, and 75 percentiles of daily flows) in the basin. These gage stations are distributed in a way to represent the overall conditions of the basin and show the seasonal and interannual variation of the flow regimes. The Functional flow hydrographs were constructed using the functional flow metrics and summarized to represent different water year types (dry, moderate, and wet) that represent the seasonal variation of the functional flows for each flow condition. The database of the functional flow metrics can be downloaded from HydroShare, http://www.hydroshare.org/resource/5ca0824685ba4048bd8c5047cf6ade72

3.3 Analysis of similarity among flow regimes

3.1.3. ANOVA test and Tukey's HSD

Analysis of variance (ANOVA) is a statistical test used to compare the means of two or more groups. ANOVA determines if there is a statistical difference between the average values of the groups. The reported F value and pr(>F) on the ANOVA results indicate the significance of the test, a low pr(>F)(<0.05) suggests a difference among the compared data. The statistical analysis was performed to determine significant differences between the flow conditions (natural, regulated, and resilient) for each FFM (n=20). Then, Tukey's HSD determines which groups are statistically different (natural vs regulated and natural vs resilient). ANOVA statistical analysis and Tukey's post hoc tests were conducted using the R package Agricolae (de Mendiburu and de Mendiburu, 2019), and the data was plotted using ggplot2 (v3.4.4; Wickham, 2016).

3.2.3. Correlation

Pearson correlation was used to identify the percentage of highly correlated metrics among paired data (natural vs regulated and natural vs resilient). This first approach uses the percentiles (25th, 50th, and 75) of the time series data to represent water year types (dry, moderate, and wet conditions respectively). The natural FFM was used as a baseline to normalize the streamflow magnitudes of the regulated and resilient flows. The Pearson correlation was used to determine the degree and direction of significant correlations between pairs of flow conditions. Pearson's r correlation coefficient measures the linear correlation between two data series. The range of "r" falls between -1 to 1, where positive values closer to 1 indicate a strong correlation between the two classes and negative values show the inverse relationship.

4 Results

4.1 Natural streamflow classification and flow regime characterization

The RGB is a hydro-dynamic basin, with a diverse range of landscapes and climates. The primary water sources of the RGB are replenished by snowmelt and monsoon rains (Fig. 3 and Table 2).

The streamflow regionalization of the basin reflects the climatic and geographic diversity of the RGB. The Northern branch of the RGB and the Pecos River are primarily driven by snowmelt and the mainstem of the Southern branch of the RGB is influenced by snowmelt, monsoon, and groundwater discharge (baseflow). Three natural stream flow classes were identified across the RGB: Snowmelt-driven, Monsoon-driven, and Bimodal (snowmelt and monsoon). These natural flow classes represent the physical and dominant hydrologic regimes of the gage stations. The southern branch exhibits a unique bimodal flow regime with two peaks throughout the year, that is it is influenced by both upstream snowmelt and monsoon, meanwhile, the tributaries are only driven by the summer monsoons (Table 2-2).

Table 2-2. Summary of hydrologic characteristics for the natural streamflow classes identified in the RGB basin

Class	Name	Hydrologic Characteristics	Location
SM	Snowmelt	▪ The main driver is the snowfall and snowmelt from the San Juan Montains ▪ Steady baseflow during the winter dry season (January to March) ▪ Discharge increases (april to end of june) due to snowmelt and some peaks occuring during monsoon ▪ Discharge remains low for the rest of the year.	(A) Northern branch of the RGB and Pecos River basin
MS	Monsoon	▪ The main driver is the Monsoon ▪ Steady baseflow in winter trought spring (Jan to June) ▪ Significant increase in discharge during the monsoon season (~June to Nov). Early contribution of summer storms may occur (~june) ▪ Discharge remains low for the rest of the year	(B) Tributaries on the southern branch
BM	Bimodal (Snowmelt + Monsoon)	▪ The Main driver are spring snowmelt and the monsoon. The flow patterns have two distinct peaks throughout the year. ▪ Steady winter baseflow increases in spring with snowmelt (~april to june), then decreases. ▪ Summer monsoon brings another significant rise (~mid june to Nov). ▪ Discharge remains low for the rest of the year.	(C) Lower mainstream of the RGB

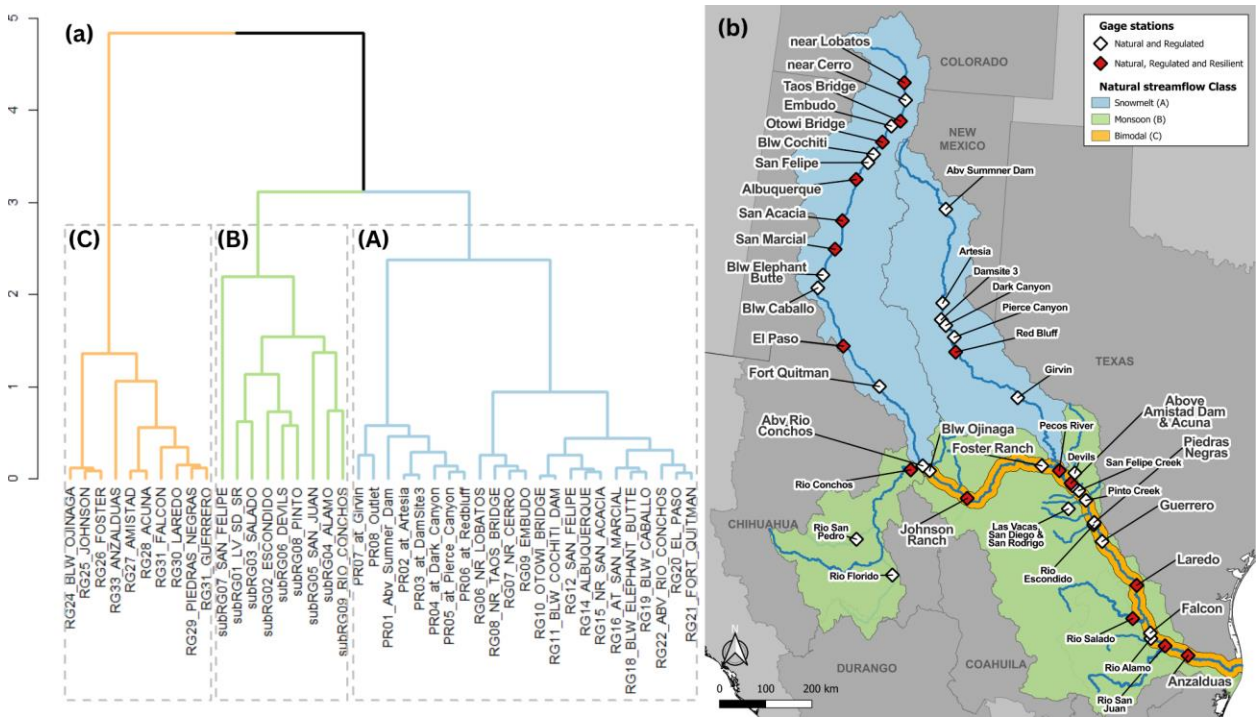

Figure 2-3. Results from (a) hierarchical clustering by Ward's algorithm analyses and (b) natural streamflow classification showing the spatial variation in the natural streamflow regimes. The streamflow differs across the basin. In the upper basin (C), snowmelt in spring is the main driver. For the tributary subbasins, the main drivers are the early summer storms and the monsoon season (B). The lower basin's mainstem (A) (from El Paso to the Gulf of Mexico) is influenced by both snowmelt and monsoon season.

Reference hydrographs characterize flow regimes, they were calculated by obtaining the 25th, 50th and 75th percentiles of daily streamflow. The reference hydrograph of the natural streamflow (Fig. 4, shaded in blue) is the flow regime to which the river basin has adapted for thousands of years, it represents the undisturbed flow that would have been in the absence of human intervention. In contrast, the resilient regime flow (**Fig. 2-4**, shaded in green) represents the flow altered by human activities while preserving the functional flows that support the river ecosystem and are within the bounds of the natural flow (**Fig. 2-4** black thick line).

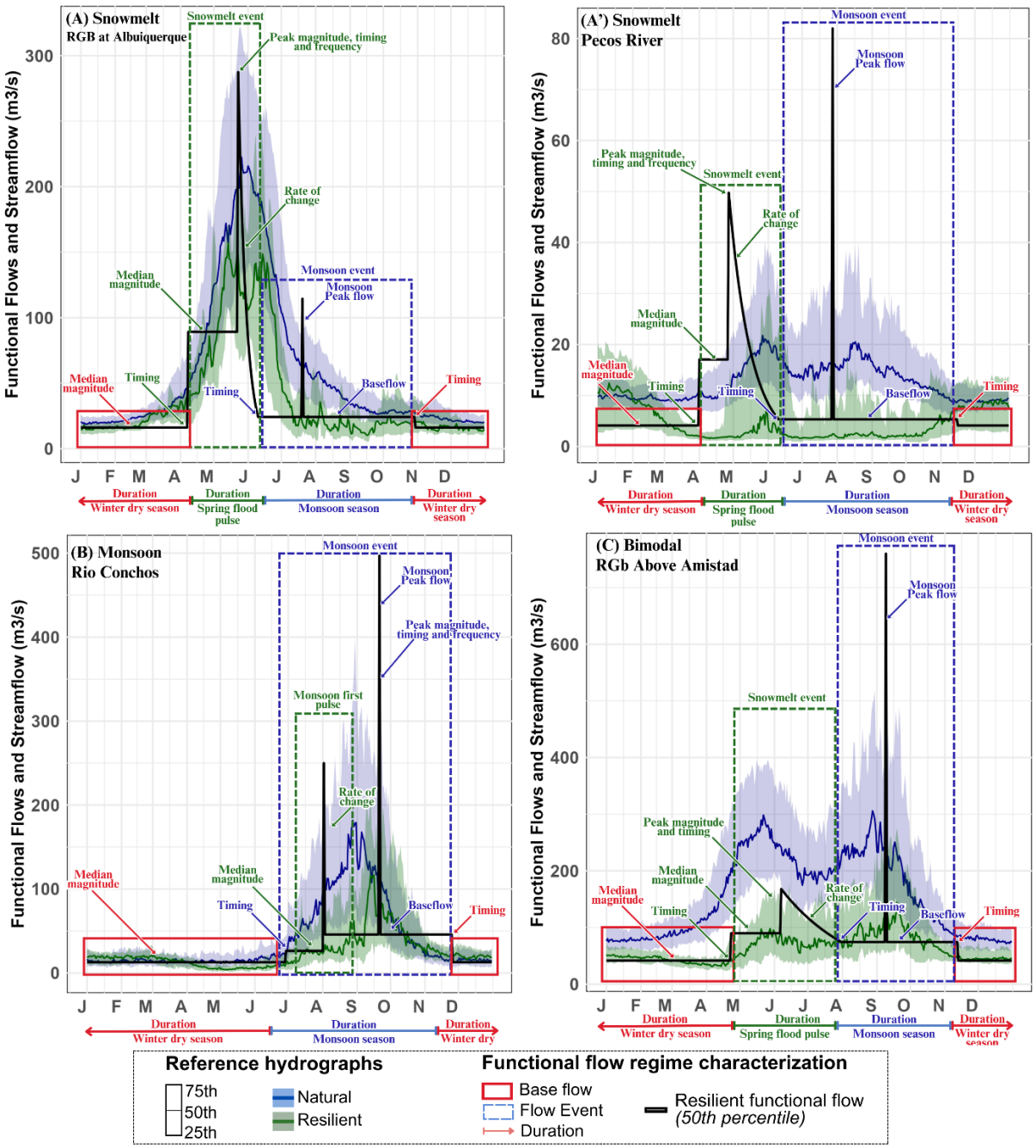

Figure 2-4. Examples of reference hydrographs for natural and resilient streamflows. Daily averages and range of flows for natural (blue line and blue shading) and resilient (green line and green shading). The lines represent the daily median flows and the shading represents the inter-quartile range of daily flows. The FFMs are represented for the moderate conditions with the black line.

4.2 Analysis of similarity

The analysis of variance (ANOVA) and Tukey's post hoc test showed a high similarity between the natural and resilient functional flow metrics while the regulated flow is significantly different. The results for the Magnitude component showed that 37 out of 80 metrics (46.2%) had no significant differences between the natural and resilient flow, compared to only 10 metrics (12.5%) of the regulated flow. For the Timing and Duration components, 61 out of 80 (76%) and 34 out of 48 metrics (71%) showed no significant difference, while the comparison with the regulated flow only accounted for 30 (38%) and 14 metrics (29%) respectively. Lastly, ROC accounted for 7 of 16 (44%) metrics that did not significantly differ between the natural and resilient flow, compared with 2 metrics (12%) of the regulated (Fig. 5). Figure 6 presents similar results for every functional flow metric; it shows that across the board all the resilient metrics have greater similarity with the natural flow regime than those from the regulated flow regime.

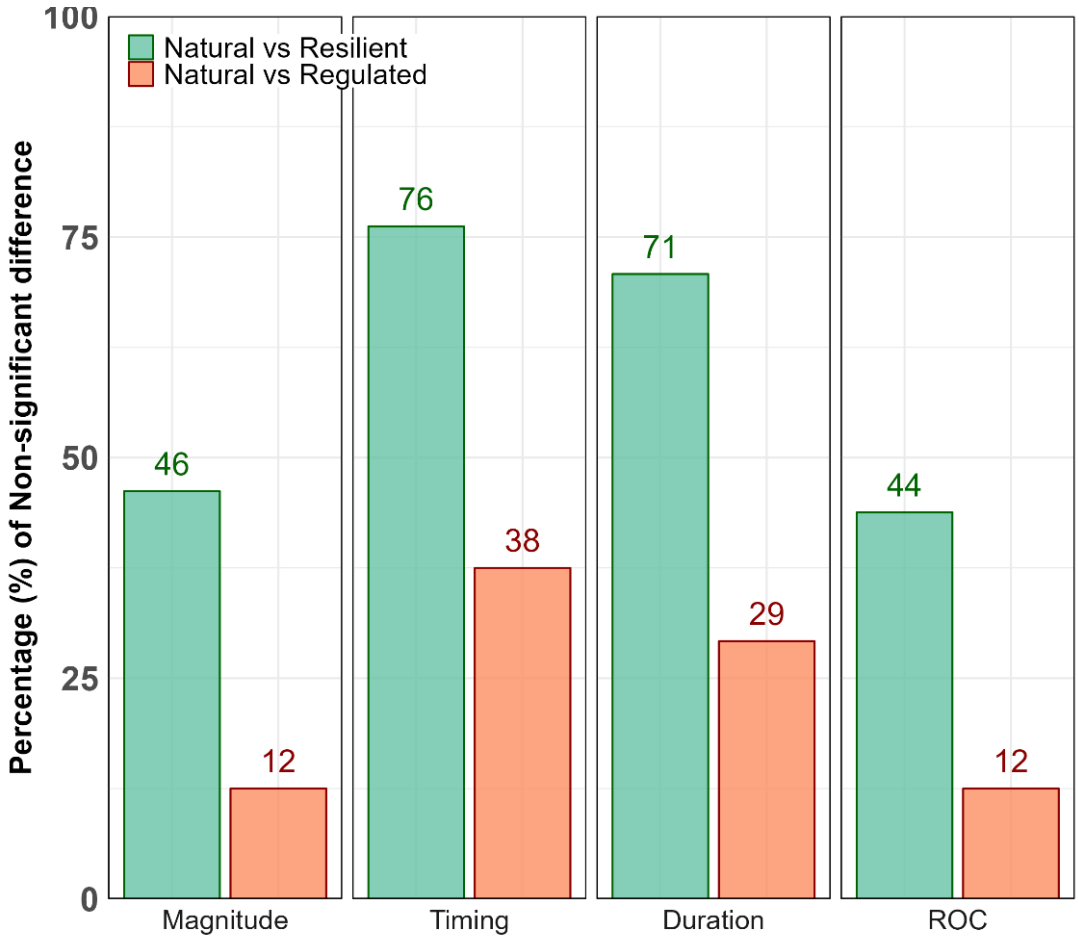

Figure 2-5. Percentage of non-significant difference (i.e. similarity) in the metrics using ANOVA and Tukey's post hoc test. The results show greater similarity between the natural and resilient FFM (green) and less similarity between the natural and regulated (orange) flow regimes.

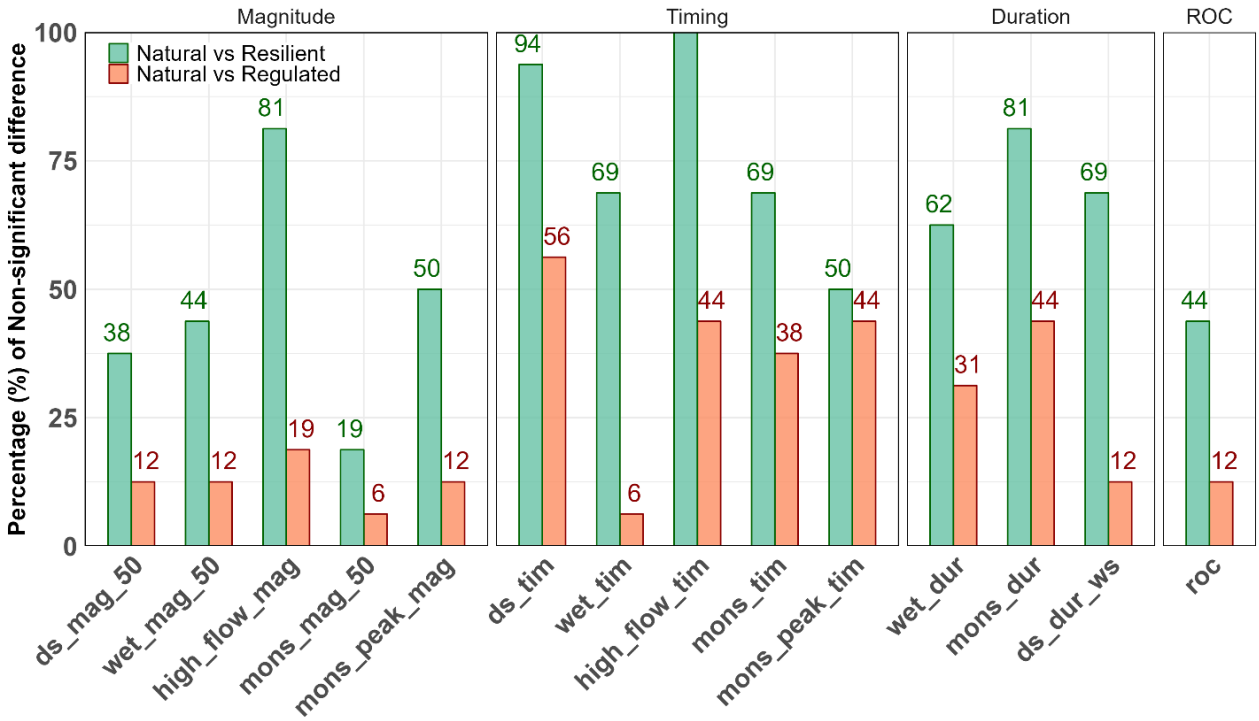

Figure 2-6. The percentage of Non-significant differences for the paired comparison (natural vs resilient in green and natural vs regulated in orange) for each functional flow metric in the RGB basin.

The analysis by natural streamflow class (Fig. 7) showed that the monsoon-driven flow regime (MS) has higher similarity among the three flow components [winter season (WSC), monsoon season (MSC), and dry season (DSC)], followed by the snowmelt-driven flow regime (SM). The winter and monsoon season components for the bimodal flow regime (BM) show a high percentage of similarity between the natural and resilient metrics (42% and 80%) while the dry season component (DSC) only 33% of the metrics of the natural and resilient are similar.

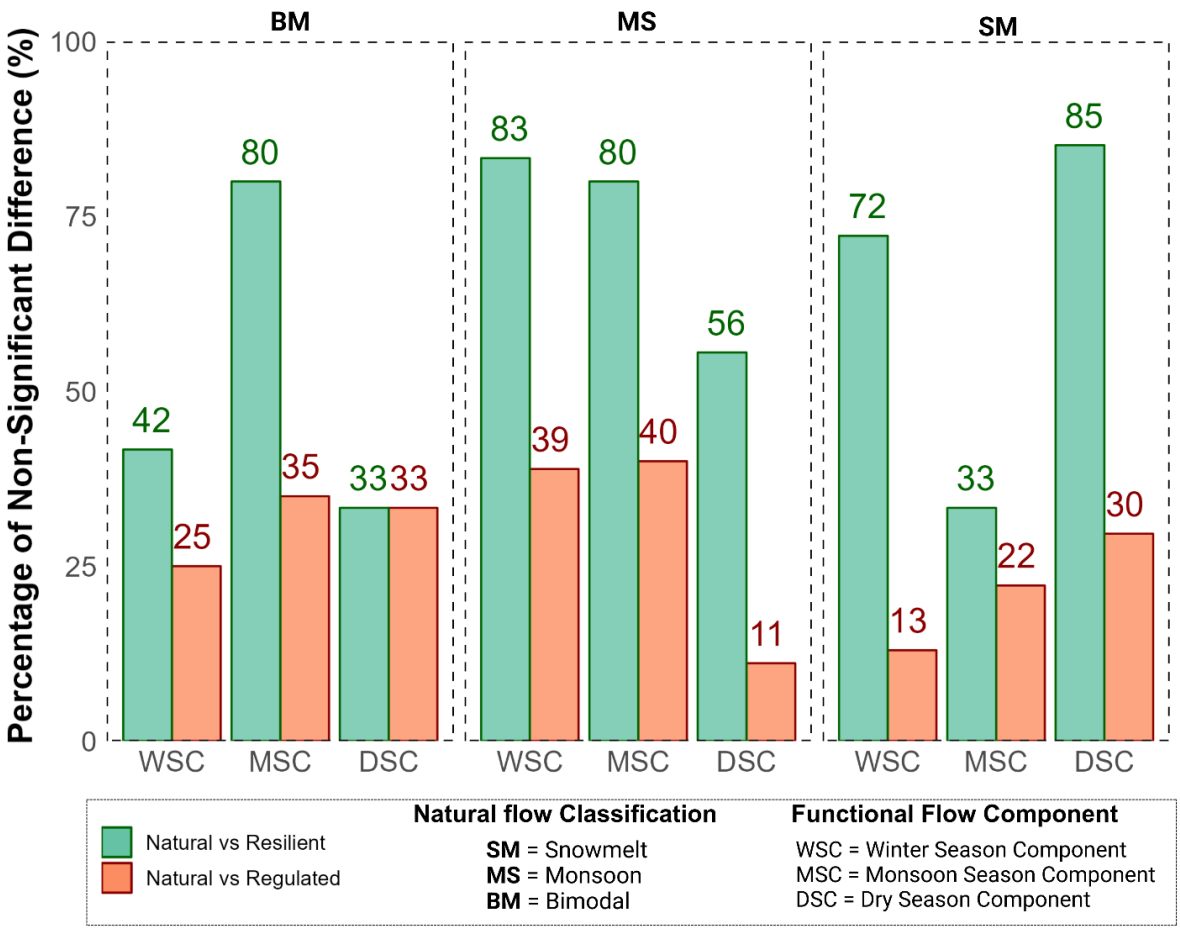

Figure 2-7. Percentage of non-significant differences for the paired comparison (natural vs resilient in green and natural vs regulated in orange) for each functional flow component and natural flow classification in the RGB basin.

4.3 Functional flow correlation for the entire RGB basin

There are 16 gauge stations with natural, regulated and resilient flow data with three streamflow classes: 9 for the Snowmelt class (Lobatos, Taos Bridge, Otowi Bridge, Albuquerque, San Acacia, San Marcial, and El Paso, Pecos River at Red Bluff and Pecos River near Langtry), 4 for Bimodal class (Johnson, Amistad, Laredo, and Anzalduas), and 3 for the Monsoon class (Salado, San Juan and Rio Conchos). The results of the correlation analysis for the entire RGB Basin show a positive correlation for all the metrics of the natural vs resilient except for the Monsoon duration which shows a negative correlation (Fig. 8). The magnitude component r^2 coefficients (from 0.69 to 0.97) suggest a notable similarity between the natural and resilient flow. Timing components correlations show a high correlation as well.

The correlations between the natural and regulated conditions are lower due to the large streamflow alteration caused by human activities, but they are still important. This implies that while regulated streamflow has alterations in the hydrological patterns, sometimes still follows some of the natural

flow dynamics, but correlations between the natural and resilient FFM show a stronger correlation than natural and regulated, indicating that the resilient flow preserves more of the natural characteristics. Duration and ROC metrics for the natural and regulated correlate more strongly than the counterpart paired data. Timing metrics are more sensitive to human alteration and as a consequence, they affect duration metrics. Grantham et al. (2022) identified similar issues when estimating the functional flows of timing and duration for the state of California, they advised using the natural duration and timing to implement environmental flows recommendations.

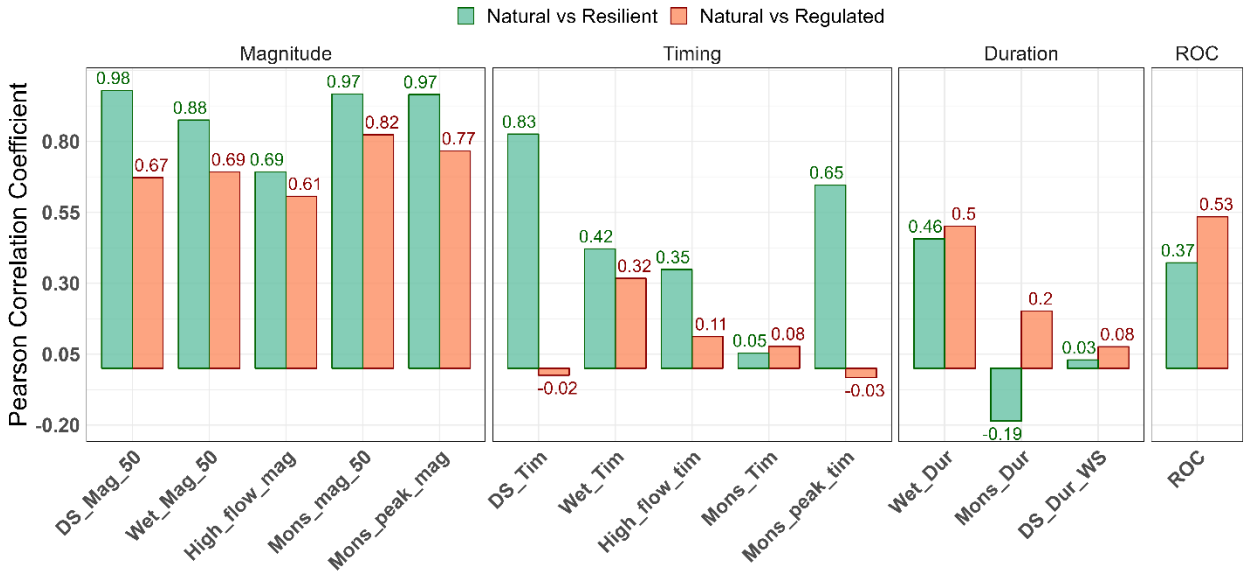

Figure 2-8. Correlation values comparing natural vs regulated (in orange) and natural vs resilient (in green) for the entire basin (n=16). Magnitude components show a strong correlation (>0.60) between the natural and resilient conditions, while similarly occurs for timing components, Monsoon timing shows a lower correlation (0.053), this is attributed to the small impact that the Monsoon season has in the upper basin.

Metrics of the resilient flows show high similarity with those of the natural flows. For r^2 values above 0.6, 50% of the metrics for the natural vs resilient fall between this range (Fig. 9). Similarly, for r^2 values between 1.0 and 0.8, 35% (5 out 14) of the metrics fall in this range for the Natural vs. Resilient, in comparison with only 7% for the natural vs regulated. In contrast, the metrics of the regulated flows are dissimilar to the natural flows, indicating flow regime alterations. For r^2 values between 0.2 and 0, only 14% (2 out 14) of the metrics fall in this range for the Natural vs. Resilient, compared with 21% for the natural vs regulated. Following this trend, for r^2 values less than 0, only 7% (1 out 14) of the metrics fall in this range for the Natural vs. Resilient, compared with 14% for the natural vs regulated. These results indicate that the resilient flow conditions preserve the natural hydrological characteristics with 50% of the metrics being higher than 0.6 r^2. These results take into consideration 16 gage stations and the characterization of the basin allowed us to address the similarities considering the different hydro-climate characteristics (flow regime drivers). The following sections show the analysis of similarities between each natural streamflow class.

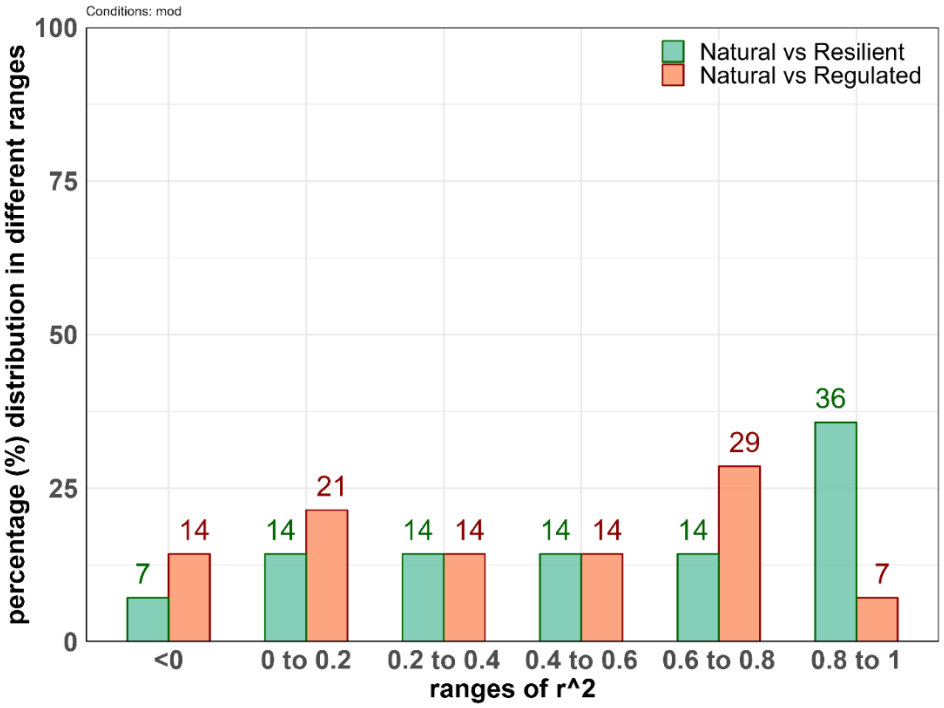

Figure 2-9. Distribution of Pearson correlation coefficients. Natural vs resilient accounts for 50% of coefficients greater than 0.6, considered a high-strong correlation.

4.4 Functional flow correlation for each natural stream flow classification

4.1.4. Snowmelt-driven flow regime

Snowmelt magnitude metrics (Fig 10), particularly Dry season base flow (DS_Mag_50), median spring baseflow (wet_mag_50), the spring high flows (high_flow_mag) and Monsoon baseflow (Monsoon_mag_50) for the resilient flow show high similarity with those of the natural flows (0.51, 0.88, 0.84 and 0.72 r^2 respectively). These metrics are the main drivers of this flow regime. However, under the regulated flow regime, the monsoon peak magnitude (Mons_peak_mag) shows a stronger correlation (0.85 r^2) with that of the natural flow regime. Timing and duration for the regulated flow show a high correlation with the natural flow. This is because the resilient flow regime was already drastically altered due to the over-allocation by the late 1800s and the extensive water infrastructure of the flow regime in this part of the river. The modern hydrology (1975 to 2020) used for this research includes influences of interstate compact water deliveries (e.g., releases of surplus water from the Cochiti Reservoir and Abiquiu Reservoir to convey water to Elephant Butte Reservoir to meet Rio Grande Compact requirements). Similarly, the strong correlation of the natural and regulated timing and duration metrics reflects the effects of the Rio Grande Compact releases from the reservoirs during October-December to release water during the fall/winter season in an attempt to reduce potential 'losses' of water to evaporation and riparian evapotranspiration.

Figure 2-10. Pearson correlation values for the snowmelt-driven class (n=9) comparing natural vs regulated (in orange) and natural vs resilient (in green).

4.2.4. Monsoon-driven flow regime

The Monsoon magnitude, timing, and duration resilient components are similar to those of the natural flows. Most metrics for the magnitude component show a strong positive correlation (r^2 > 0.79). However, the high flow magnitude (early storms before the monsoon), has a weaker correlation (0.11 ^2) but still positive (Fig. 11). Most tributaries except for the Rio Conchos, are ephemeral and not as much altered. The Rio Conchos is an important basin in both, the environment and the economy for agriculture, hydropower, and tourism of the region. These results show that before the time threshold, the Monsoon-driven rivers were within the boundaries of the natural flow.

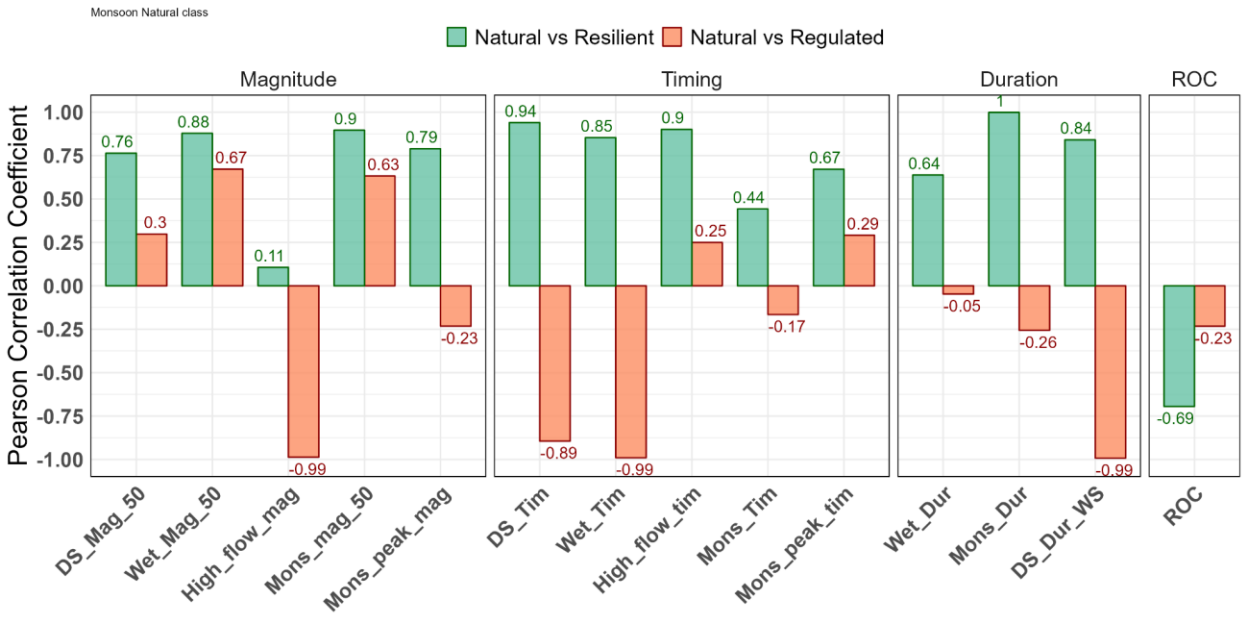

Figure 2-11. Pearson correlation values for the Monsoon-driven class (n=3) comparing natural vs regulated (in orange) and natural vs resilient (in green). All components show a strong positive correlation between the natural and resilient flows, indicating that during this period the streamflow was within the boundaries of natural variability.

4.3.4. Bimodal-driven flow regime

The magnitude components for the Bimodal-driven class show high similarity with those of the natural flows (>0.84 r^2). In contrast, timing and duration metrics show a negative correlation, suggesting a difference between the natural flow and the other flow regimes. However, there are exceptions: Monsoon peak timing (Mons_peak_tim), Dry season timing (DS_Tim), spring high flows (High_flow_tim) and Dry season duration (DS_Dur_WS) show positive correlations, indicating these specific metrics were not significantly impacted by the basin's high alteration before the time threshold (Fig 12). Similarly, as the snowmelt-driven flow regime, the early human alteration in the basin has changed the natural characteristics of the flow, being timing and duration the most affected metrics. These results highlight the importance of managing reservoir operations and water releases to mimic natural flow characteristics, such as magnitude and timing, to maintain ecological balance and ensure water resource sustainability.

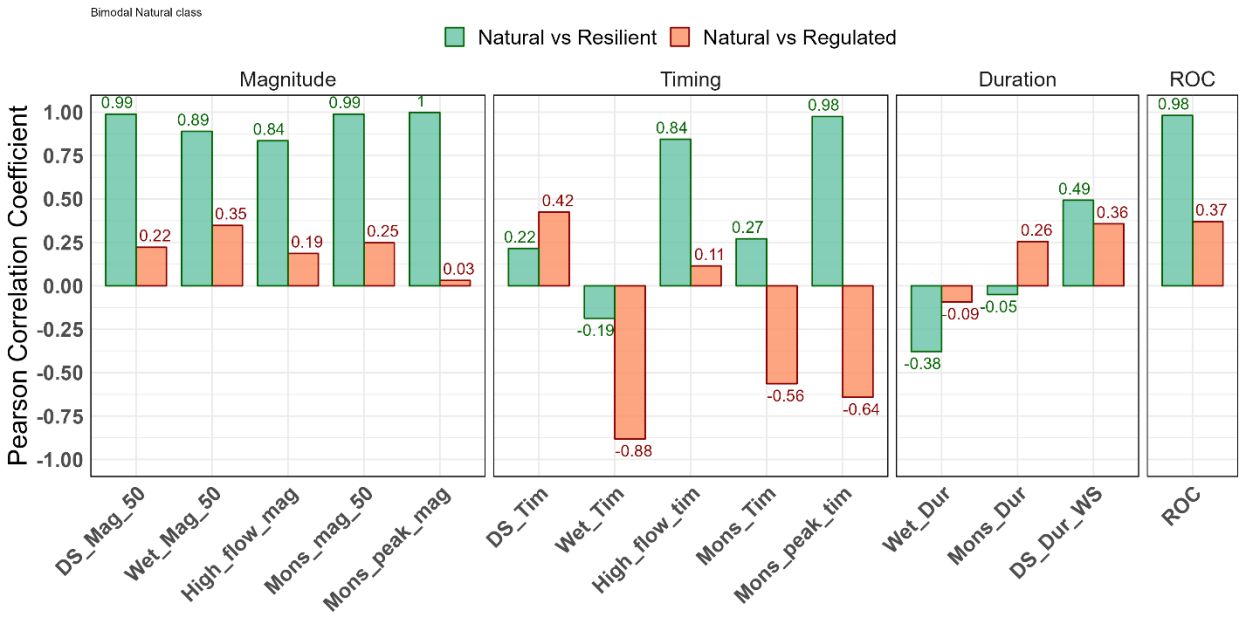

Figure 2-12. Pearson correlation values for the Bimodal-driven class (n=4) comparing natural vs regulated (in orange) and natural vs resilient (in green). The Magnitude components show a strong correlation (>0.90) between the natural and resilient conditions.

5 Discussion

In this research, we introduced the concept of resilient flow, which refers to a flow regime that can absorb human-induced alterations while maintaining the key characteristics of a natural flow regime. We classified the basin based on the natural functional flow metrics (FFM) for 43 gauge stations along the basin. Three streamflow classes were identified: Snowmelt-driven, Monsoon-driven, and Bimodal (Snowmelt and Monsoon). This classification aligns with the geographical and climatic differences across the basin (Nelson, 2021), with the northern branch of the RGB and the Pecos River primarily influenced by snowmelt, while the southern branch of the RGB mainstem shows a bimodal flow due to both snowmelt and monsoon (Blythe and Schmidt, 2018, Dean & Schmidt, 2013).

The analysis of the 16 gage stations with time thresholds in the RGB basin using the analysis of variance (ANOVA) statistical test showed a similarity between the natural and resilient flow (139 out of 224 functional flow metrics had no significant difference, 62%). Similarly, Pearson correlation showed a positive correlation between natural and resilient flow metrics, indicating that resilient flow regimes preserve key aspects of the natural hydrological characteristics (9 out of 14 resilient functional flow metrics have greater correlation with the natural functional flows metrics, 64%). The reference hydrographs for the resilient flow regime showed that the hydrologic functional flow components (magnitude, timing, duration, and ROC) overlap with the reference hydrographs of the natural flow, despite some degree of alteration due to human perturbation. All the functional flow metrics of the resilient flows showed greater similarity to the natural flow metrics, highlighting the importance of preserving natural flow dynamics for ecological and

hydrological sustainability. Thus, the resilient flow regime can be used as recommendations for ecological and environmental flows for the RGB. Long-term monitoring and adaptive management strategies are essential for making informed decisions and ensuring the sustainability of water resources in the RGB basin, promoting water management strategies that balance human needs with ecological preservation (Richter, 2024).

Interestingly, while the resilient flow regime maintains some characteristics of the natural flow, timing discrepancies are evident in our study for the RGB and in California (Grantham, et al., 2022). This finding suggests that while the magnitude of the resilient flows is relatively within the boundaries of the natural flow, the timing of these flows may not fully align with ecological requirements. Practitioners should pay attention to the timing metrics, making sure that their timing ecological and environmental flows recommendations are aligned with those of the natural flow regime. This discrepancy in flow timing shows the potential for dam reoperation as a strategy to improve environmental flows (Lane et al., 2015; Sandoval-Solis & McKinney, D.C., 2012). By reallocating the same volume of water but distributing it in a more ecologically sensitive manner, dam operations could better mimic natural flow patterns, addressing timing gaps and improving environmental flows (Lane, et al., 2015). Such adaptive management practices could bridge part of the e-flow gaps, demonstrating that operational adjustments, even without altering water availability, can provide significant ecological benefits (Richter, 2024).

Resilient flow regimes can be estimated and used as ecological and environmental flow recommendations throughout the world; it is a novel method for determining ecological and environmental flows at the same time. Worldwide, the resilient flow regime method can be used to determine tipping points for freshwater systems. It is a quantitative method to systematically identify time thresholds when the tipping point was crossed, and to determine the amount of water needed (environmental flow gap) to return to a safe operating space (Wang-Erlandsson, et al., 2022). Other methods have been developed to determine tipping points in lakes (Hessen, et al., 2023). The resilient flow regime fills the gap for determining tipping points in rivers.

While resilient flow provides a useful framework for analyzing hydrological patterns, the analysis depends on the availability of natural and regulated flow data, which is often limited by the time thresholds established for different sections of the river. These time thresholds determine how far back historical data can be used, and for many gauge stations, such data may not exist. This limitation highlights the challenges of applying resilient flow analysis in regions with incomplete or short-term datasets, emphasizing the need for improved data collection and monitoring efforts to enhance the applicability of this approach across diverse river systems.

6 Conclusion

The streamflow classification and the flow regime characterization in the RGB highlights the intricate relationships between the natural hydrological patterns and the human-induced alterations in the basin. Identifying the snowmelt-driven, monsoon-driven, and bimodal flow regimes reflects the diverse climatic and geographic influences across the basin. Resilient flows show a high

similarity with natural flows, providing a crucial framework for water management between human water needs and ecosystem integrity, allowing it to preserve and provide ecosystem services and implement environmental flow gaps. Despite alterations, the magnitude of the resilient flows remains within the ranges of natural variability, offering support for freshwater ecosystems.

The results of this research offer valuable insight into developing adaptive management strategies that support both environmental and human water needs in this complex and dynamic socio-hydrological system. In our opinion, the resilient streamflow seeks to reach a regional integrated water resources approach that accounts for the adaptation of climate change and water use practices in the RGB basin by determining (1) regional goals, (2) assessing climate vulnerability, and (3) prioritizing areas to implementing environmental flow and carrying capacity. While each restoration objective is specific to its respective gage station and varies across regions, it is essential to address goals and objectives at the basin-wide scale. Resilient flow regimes offer a critical framework for balancing human water demands with the ecological integrity of riparian ecosystems. The findings in this research highlight the need to integrate ecological considerations into water management practices to ensure the basin's resilience and sustainability against current and future challenges, including climate change and growing water demands.

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CHAPTER 3

Review of Water Availability in basins with water agreements: Implications for Climate Resilience and Treaty Management.

Ramon Saiz-Rodriguez, Samuel Sandoval-Solis, Luzma Nava

Abstract Water-sharing agreements are critical for managing transboundary and interstate river basins, yet many were designed under historical hydrological conditions that no longer reflect current climate variability or human demand. This study reviews water availability in basins with formal water agreements, using the Pecos River as a case study. We analyzed the Pecos River Basin and its link to the Pecos River and the Treaty of 1944. By reconstructing regulated streamflow and estimating natural flow using a mass balance approach we compared our data sets to historical data across key periods. Our findings show that human activities, particularly agricultural diversions and groundwater overdraft, have caused a consistent and significant reduction in the river's natural flow. Our results show that Pecos River's historical contribution was significantly overestimated to the Rio Grande. This has major implications for downstream water allocations. The study shows the critical need for periodic, science-based reassessment of transboundary water agreements as a centerpiece of water management, to ensure equitable and sustainable water sharing, and improving climate resilience in shared river basins under intensifying environmental and human pressures.

1 Introduction

Water sustains life, drives progress, and powers economies. Its availability influences social behavior and well-being, often fostering collaboration and cooperation. However, it can also lead to conflict and tension among nations, states, or individuals, particularly when resources are scarce, geographically dispersed, or tied to environmental, political, or economic interests. Conflicts over shared water resources and socio-political disagreements at national, state, and local levels have been extensively studied (Westing, 1986; Gleick, 1993; Elliott, 1993; Homer-Dixon, 1994; Marty, 2001, Wolf, 2002) and remain an area of significant interest, especially as pressing water issues related to climate change, land use, and population growth intensify. Major conflicts among co-riparian users are typically associated with water quantity and water quality (Dunca, 2018; Moore et al., 1974; Kelly, 2002), increasing population pressure (Brauman et al., 2016), unilateral economic development and infrastructure projects (Aljefri et al., 2019), and the allocation of water for environmental needs (Capon & Capon, 2017).

Among the most significant drivers of water use and potential conflicts is agriculture, which accounts for approximately 85% of global consumptive water use (Brauman et al., 2014). While

essential for food production, agriculture presents considerable challenges for water resource management. Industrial agriculture contributes to water quality degradation through the use of pesticides and fertilizers (Lim et al., 2018; Harter & Lund, 2012), while irrigation-supporting reservoirs alter the natural flow regime of rivers (Richter, 2000; Guitrón, 2020). These reservoirs reduce high flows by capturing them and increase base flows during summer to sustain crop production, shifting the timing and magnitude of streamflow events with potential ecological consequences (Sparks, 1992; Dudgeon, 2000).

Because water is one of the most widely shared natural resources, rules and frameworks for sharing it have been established through treaties, agreements, and conventions. These can occur between individuals (e.g., upstream vs. downstream riparians), municipalities (e.g., Mendocino and Sonoma counties over the Russian River in California), states (e.g., Texas and New Mexico over the Pecos River), or nations (e.g., Mexico and the U.S. for the Colorado and Rio Grande rivers; Canada and the U.S. for the Columbia River).

The Pecos River, a major tributary of the Rio Grande/Rio Bravo (RGB), is governed by the Pecos River Compact (NM Stat § 72-15-19) between Texas and New Mexico. At the same time, the RGB is regulated by the U.S.-Mexico Water Treaty, also known as the Treaty of 1944. After the construction of the Red Bluff Dam in the 1930s and multiple water conflicts between New Mexico and Texas, the Pecos River Compact was established in 1948 to ensure fair water distribution between the two states. The compact aimed to resolve longstanding disputes over water rights and water use, particularly during times of drought when water scarcity created tensions among both states.

The Treaty of 1944, formally known as the "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande," governs the distribution of shared river waters between the United States and Mexico. Under this treaty, the U.S. must deliver 1.5 million acre-feet of Colorado River water annually to Mexico, while Mexico is required to deliver 350,000 acre-feet per year from the Rio Conchos and five Mexican tributaries to the Rio Grande. The International Boundary and Water Commission (IBWC) was created to administer the treaty, resolve disputes, and coordinate binational water infrastructure, planning, and collaboration. Although the Pecos River Compact and the Treaty of 1944 were established on historical hydrological data and assumptions of

relatively stable climatic conditions, shifting precipitation patterns, recurring droughts, and rising agricultural and urban demands have tested their adaptability in recent decades. In response, supplementary agreements (minutes) have been negotiated to enhance cooperation and improve water sharing during periods of scarcity, highlighting the need for ongoing diplomatic engagement and adaptive management.

Both the Treaty of 1944 and the Pecos River Compact have long served as cornerstones of water management and cooperation between the United States and Mexico, but they now face increased pressure from climate change, population growth, and evolving water demands. Because these agreements were based on past hydrological conditions, regular reassessments of water availability, estimation of natural flow regimes, and climate impacts are necessary. The binational RGB Basin and the interstate Pecos River Basin present particularly complex management challenges. Located in an arid region, they face limited surface and groundwater availability, a rapidly growing population, and an agricultural economy heavily dependent on irrigation. The Pecos River system, in particular, has been dammed, diverted, and significantly altered for agricultural use (Jensen et al., 2006; Huser, 2004; Hall, 2002). Managing water equitably and sustainably under these conditions requires robust legal frameworks and adaptive strategies that account for both ecological and human needs.

Despite these agreements and ongoing efforts to restore the basin, the Pecos River remains significantly altered, and its water resources are still under immense pressure. The intensifying competition for water, driven by the expansion of irrigation and agriculture, has led to numerous infrastructure projects like dams and reservoirs that have further changed the river's natural flow. These developments highlight the pressing need for **a**daptive and science-based approaches to water governance. This means the frameworks established by the Pecos River Compact and the Treaty of 1944 must be re-evaluated periodically, with a particular focus on **w**ater availability under changing climatic conditions to ensure equitable and sustainable water management for both human and ecological needs.

2 Materials and Methods

2.1 Overall Approach

The overall approach of this study was structured as a four-step process to comprehensively analyze the Pecos River's flow regime and the impacts of human intervention (**Figure 1**). **First, the regulated streamflow was reconstructed** by gathering long-term historical data from the International Boundary and Water Commission (IBWC) and the U.S. Geological Survey (USGS). Missing data were filled using a combination of methods, including Mass Balance, QPPQ, regression analysis, and disaggregation from yearly and monthly data to daily values, to ensure a complete and accurate record. **Second, the natural flow was estimated** by using a mass balance approach to remove human influences such as reservoir storage, diversions, and return flows. **Third, the results were validated** by comparing the estimated natural and regulated flows with the estimations from Orive Alba (1945), and Cravioto and Lowry (YEAR), and more recent studies by Sandoval-Solis et al. (2022) and Garza-Diaz (2022). **Finally, the water availability was compared** across key periods to determine the deficit or surplus in the river's flow and assess its impact on water sharing between Mexico and the United States, as governed by the Pecos River Compact and the Treaty of 1944. This approach allowed for a robust assessment of how climate and human activities have altered the basin's hydrology over time and the implications for the Pecos River Compact and the Treaty of 1944.

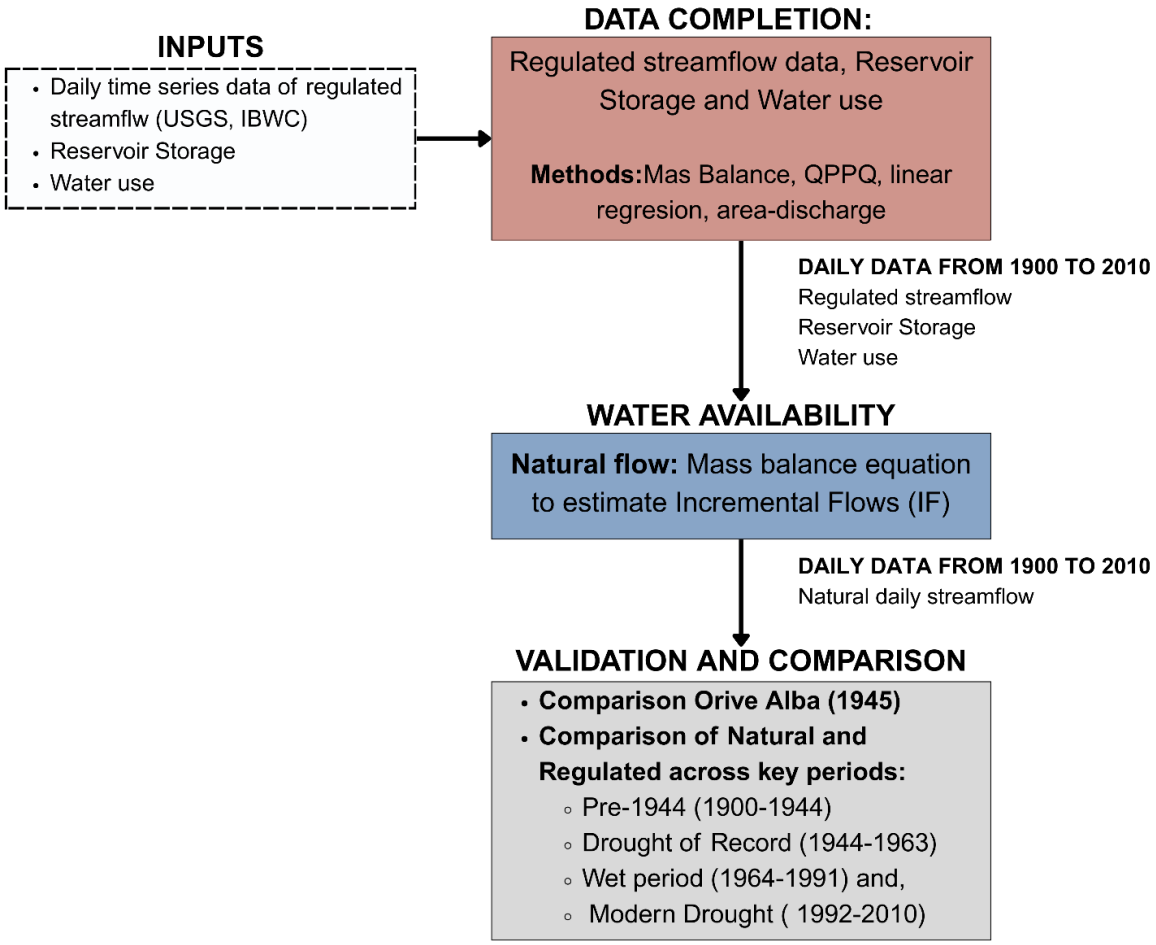


Figure 3-1. Methodology framework used to reconstruct regulated flows, estimate natural flows, validate results, and assess the impacts of human intervention on the Pecos River under the Pecos River Compact and the 1944 Treaty.

2.2 Case Study

The Pecos River Basin is a watershed shared by New Mexico and Texas in the United States, covering an area of approximately 44,402 square miles (≈115,000 square kilometers) and stretching 926 miles (≈1,490 kilometers) in length. The river originates in north-central New Mexico and flows south through the state, eventually reaching Texas, where it joins the Rio Grande/Bravo River near the town of Langtry (**Figure 2**). The Pecos River is one of the main tributaries of the Rio Grande/Bravo, contributing about 11% of its flow and providing essential water for agriculture and urban development in this semi-arid region (Jensen et al., 2006).

Over the past several decades, human activities have degraded the Pecos River's ecosystem, altered the natural flow regime, and impacted on its hydraulic characteristics, including geomorphology, hydraulic properties, and water availability (Jensen et al., 2006; Huser, 2004; Hall, 2002). Historically, water has been the most important resource in the region, sustaining Native American communities and early explorers. Since the 1800s, expanding agricultural activity has led to the development of irrigation systems. However, extended droughts have reduced water availability (Harley & Maxwell, 2018), causing the failure of some irrigation projects.

The Pecos River is a critical resource for the economic growth, ecological integrity, and social well-being of the region. It supports extensive agricultural activities that are the backbone of local economies in both New Mexico and Texas, while also sustaining rural communities that rely on it for drinking water, irrigation, and industry. Ecologically, the river corridor hosts unique riparian habitats and supports biodiversity in an otherwise arid landscape. The sustainability of water resources in the Pecos Basin is vital not only for meeting human demands but also for preserving environmental flows necessary to maintain ecosystem health. As climate variability, population growth, and competing water uses continue to challenge water availability, the Pecos River exemplifies the importance of adaptive, cooperative water management strategies that balance human and ecological needs in transboundary basins.

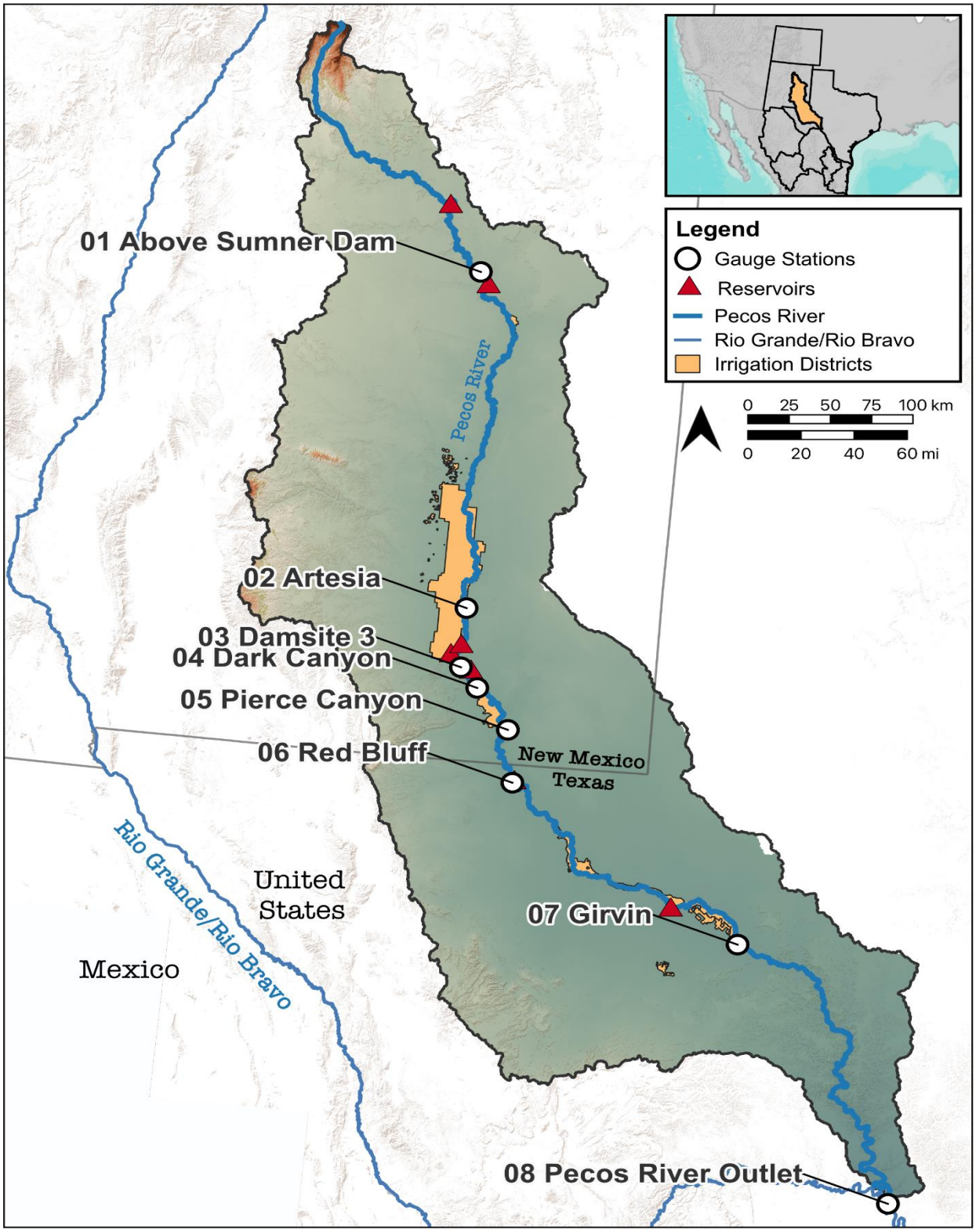
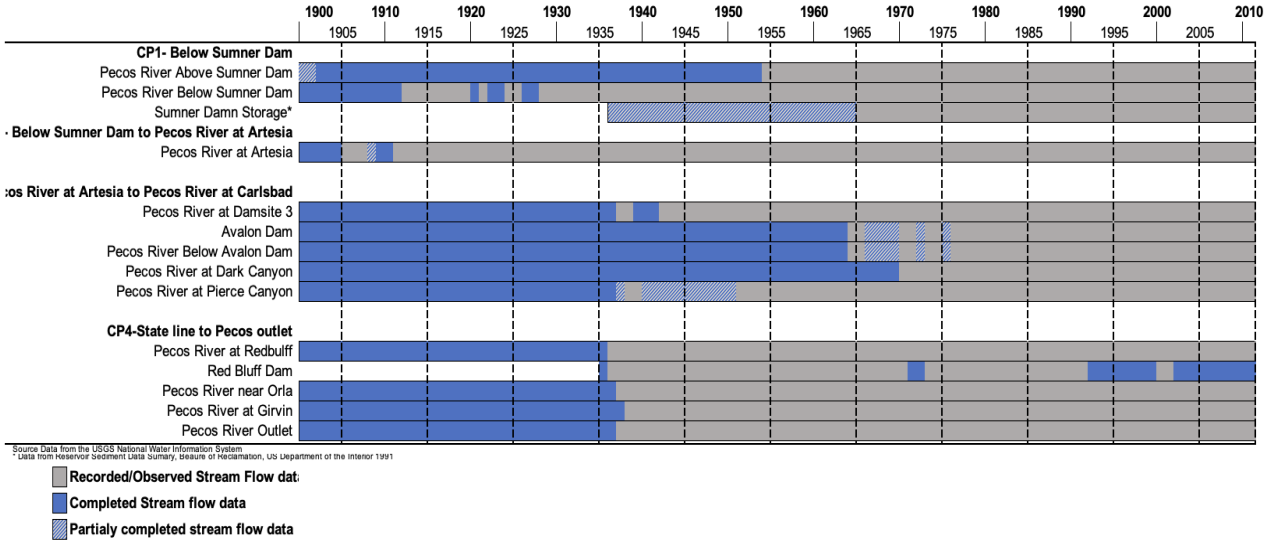


Figure 3-2. Digital elevation model of the Pecos River Basin showing the gauge stations (n=8) throughout the basin for which natural flows were estimated.

3 **Data Collection and Methodology**

To reconstruct the regulated flow and estimate the natural flow of the Pecos River, we selected a series of key gage stations throughout the basin (**Figure 1**). These stations were chosen based on the availability of long-term historical records and their ability to represent the basin's overall hydrologic and climatic conditions. While the basin was conceptually divided into four segments to guide the estimation process, our focus was on completing natural and regulated flow data at eight specific gage stations: Above Sumner Dam, Artesia, Damsite 3, Dark Canyon, Pierce Canyon, Red Bluff, Girvin, and the Pecos River outlet. The four segments included: (1) Above to below Sumner Dam, (2) Below Sumner Dam to Artesia, (3) Artesia to above Red Bluff Reservoir, and (4) From the Texas state line to the outlet. To estimate flows at the selected gage stations, we utilized data from intermediate and nearby stations within each segment. This approach allowed us to capture the spatial and temporal variability of flow along the Pecos River, even in areas with incomplete or missing data (**Table 1**).

Table 3-1. Data availability and reconstruction status for selected gage stations along the Pecos River. Grey indicates available records, solid blue indicates reconstructed flows, and dashed blue indicates partially reconstructed flows.



3.1 Regulated Streamflow

The long-term regulated streamflow data for each gage station were obtained from the International Boundary and Water Commission (IBWC) and the U.S. Geological Survey (USGS). The recorded data included multiple gaps at several stations (Table XX), and various methods were applied to estimate missing values. These included Mass Balance, QPPQ method, linear regression, precipitation and temperature correlations, and discharge–drainage area relationships.

First, when either reservoir storage, along with inflow and outflow data, is available, mass balance is used to estimate the missing streamflow values downstream. The mass balance approach is based on the principle of conservation of mass, where the change in reservoir storage over a given time equals the difference between total inflows and outflows. The general equation is expressed as: ΔS = Inflows – Outflows, where ΔS represents the change in storage, inflows include upstream river discharge and any direct precipitation, and outflows include controlled releases, evaporation losses, and downstream discharge.

When mass balance could not be applied, the QPPQ method (Fennessey, 1994; Farmer et al., 2014) was used to fill gaps in streamflow data where records were missing. This statistical method estimates missing flow data by comparing it with a nearby gauge that has continuous records and similar hydrologic conditions. It uses flow duration curves (FDCs) from both gauges, assuming that the probability of a certain flow occurring is the same at both locations. The method works best when the two sites are close together, have few changes between them (e.g., diversions or tributaries), and the reference gauge is unaltered.

Another approach applied was the drainage area ratio method, which estimates flow at ungauged or partially gauged sites based on the assumption that streamflow is proportional to the size of the contributing drainage area. This method uses a nearby reference gage with known flow data and similar watershed characteristics (precipitation, land use, geology, etc). It is most accurate when the drainage area ratio between sites is close to 1.

Finally, a monthly regression was used to estimate missing streamflow, diversion, or incremental flows between the gage station with missing data and a reference gage station with a continuous record. This method involves fitting separate linear regression models for each month to capture

seasonal variability in flow patterns and downscaled to daily values. Depending on the type, availability, and location of the gage station, the most appropriate method was selected for each site. Sites with complete reservoir operation data were suited for mass balance, while sites with missing small periods, but located near well-gauged stations, we used statistical methods such as QPPQ, drainage area ratio, or monthly regression. The selection of each method was made to ensure the most accurate and hydrologically appropriate estimation of missing streamflow values.

3.2 Natural streamflow

Natural streamflow represents the historical hydrological conditions a gage station would have in the absence of human impacts. Estimating natural flow required removing human influences, including reservoir storage and evaporation, diversions, return flows, stream losses, and interbasin imports and exports. To estimate the natural flow, a mass balance equation based on changes in storage was applied (Garza, 2022; Gonzales-Escorcia, 2017). The mass balance approach calculates natural flow as the difference between all inflows (e.g., upstream gaged flows, ungaged tributaries, and imports) and all outflows (e.g., diversions, evaporation, exports, and changes in reservoir storage). The natural flow estimation for the Pecos River followed the methodology specified in the Pecos River Master's Document, which serves as the technical basis for evaluating water availability and deliveries under the Pecos River Compact. The Master Document provides standardized equations, assumptions, and data requirements for estimating natural flow at the state line, ensuring consistency and transparency when comparing results across studies.

Natural streamflow was estimated at a daily time step from 1900 to 2010 for eight control points in the Pecos River Basin (Figure XX). For the 1900–1943 period, results were compared with the natural flow estimates reported by Orive (1945) and with the regulated flow reported by Cravioto and Lowry (1944). Figure 4 shows the reference hydrograph with the 25th, 50th, and 75th percentiles of daily streamflow over the 110-year period to show the interannual and seasonal variability. The reference hydrograph compares natural flows (blue) and regulated flows (red), in million cubic meters (1 MCM ≈ 1.23 TAF) for the eight gaging stations. Upstream stations, such as Above Sumner Dam and Artesia, show relatively minor water depletion, while downstream stations show greater deviations from natural conditions due to agricultural water use. Notably, regulated flows also show increased low flows during the dry season for the regulated conditions.

3.3 Hydrological Assessment of the Pecos River Basin: Evaluating Flow Regimes at Artesia, Red Bluff, and Pecos Outlet

The analysis of the Pecos River's flow before the Treaty of 1944 (1900 to 1943), the drought of record (1944 to 1963), the wet period (1964 to 1991), and the recent drought (1992-2010) at the Artesia, Red Bluff and Otulet is crucial to understand how the river has been altered by human activity and how the Pecos River Compact and the Treaty has been tested over time. By comparing the natural and regulated flow regimes at these key points, we determined the cumulative impact of water management and climate on the basin's hydrology. The selection of these locations and periods allowed for a comprehensive assessment of the river's historical and contemporary condition.

The Artesia gauge station, located upstream of the basin, is particularly important as it provides a baseline for the river's condition before major diversion and high consumptive use by New Mexico's irrigation districts. The Artesia site is primarily snowmelt-driven (Saiz and Sandoval, 2025). The regulated streamflow maintains similar characteristics to the natural flow before human alterations took place. Conversely, the Red Bluff Reservoir, as the first major infrastructure in Texas, is a critical point to evaluate the actual water delivered downstream under the Compact, while the Pecos Outlet reflects the river's final state before it joins the Rio Grande; it is a representative flow from the Pecos Basin to the RGB.

The analysis was structured around key management and climatic periods. The 1900-1943 (pre-treaty and compact baseline) highlights the river's hydrology before the major agreements. The 1944-1963 (drought of Record) provides a critical test of the compact's effectiveness under extreme water stress, revealing how the agreement performed during the very conditions it was designed to mitigate. In contrast, the subsequent 1964-1991 (wet period) shows how to assess management strategies when water is abundant, allowing for a clearer distinction between changes due to human activity versus natural variability. Finally, the more recent 1992-2010 drought period demonstrates the intensified pressures on the basin from climate change and growing water demands, underscoring the need for adaptive management strategies in a rapidly changing environment.

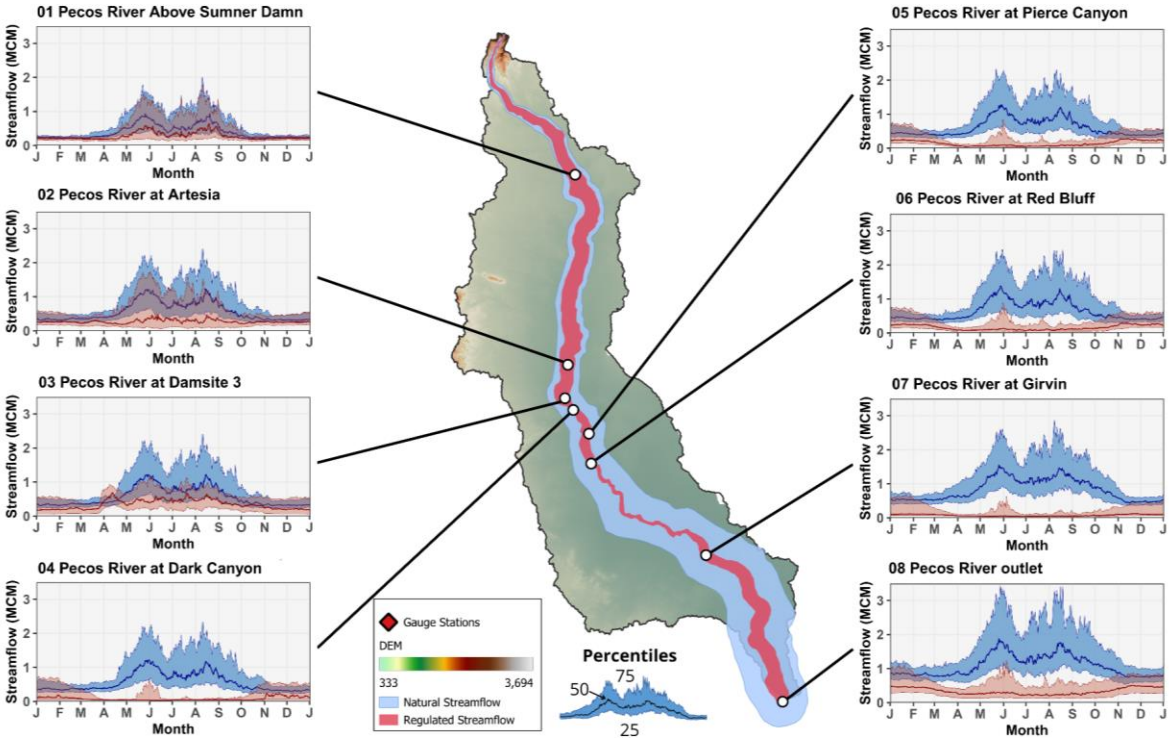


Figure 3-3. Flow regime depletion in the Pecos River basin. The reference hydrograph shows the daily median flow (line) and interquartile range (shaded area) for the Pecos River under natural (blue) and regulated (red) flow conditions.

4 **Results**

The analysis of natural and regulated streamflow shows a clear and consistent pattern of hydrologic alteration across the Pecos River basin. A comparative review of the flow across the four selected periods highlights the extensive impact of human intervention. The Annual Median Flow, which shows the overall water availability, is consistently and significantly lower under regulated conditions (Table 2 and Figure 3). The results show a substantial reduction in the overall volume of water available downstream. For example, during the "Drought of Record" (1944-1963), the regulated median flow at the Pecos Outlet was 2 CMS, an 78% reduction from the natural median of 9 CMS. The difference in total annual volume in the same period shows the severity of water depletion under regulated management, and after this period, the system's flow regime appears to have permanently shifted. As shown in **Figure 3,** the regulated becomes significantly flatter and lower than the natural, highlighting a marked loss of hydrologic variability and a reduction in the overall water volume. This observation aligns with the findings of Garza-Diaz (2022), who identified "breaking points" where the system's resilience was lost, and it irreversibly transitioned

into an anthropogenically altered state. Garza-Diaz identified an abrupt change regime in the regulated flow by 1949, a year later from the implementation of the Pecos River Compact. Although there is evidence of progressive flow degradation before the Compact due to groundwater overdraft in the groundwater basin (Bureau of Reclamation,2021).

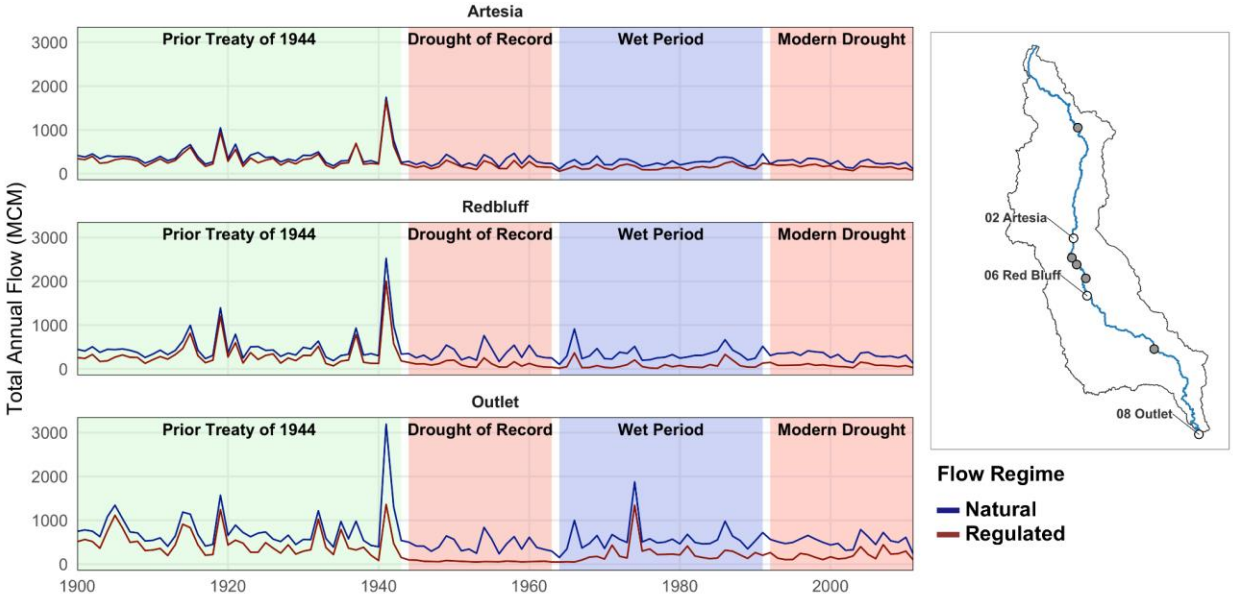


Figure 3-4. Comparison of natural (blue) and regulated (red) streamflow at representative gage stations along the Pecos River across four hydrologic periods: (1) prior to the 1944 Treaty, (2) the Drought of Record (1944–1963), (3) a subsequent Wet Period, and (4) the Modern Drought. The plot shows the reduction in overall flow volume and variability under regulated conditions.

Table 3-2. Summary of flow characteristics for natural and regulated conditions at selected Pecos River gage stations during four hydrologic periods. Metrics include total mean annual flow (in MCM), annual median flow (CMS), peak daily flow (CMS), and 7-day minimum flow (CMS).

Station	Period	Condition	Total Mean Annual Flow (MCM)	Annual Median Flow (CMS)	Peak Daily Flow (CMS)	7-Day Min. Flow (CMS)
Artesia	Treaty of 1944	Natural	424	7	1194	1.96
		Regulated	356	6	1254	0.10
	Drought of Record	Natural	284	5	607	1.05
		Regulated	182	2	606	0.02
	Wet Period	Natural	264	4	305	0.80
		Regulated	147	2	270	0.02
	Modern Drought	Natural	260	4	261	0.67
		Regulated	158	3	64	0.22
Red Bluff	Treaty of 1944	Natural	507	8	2622	1.63
		Regulated	342	5	2613	0.18
	Drought of Record	Natural	350	6	868	0.21
		Regulated	105	2	549	0.07
	Wet Period	Natural	342	5	1512	0.43
		Regulated	86	1	1436	0.01
	Modern Drought	Natural	315	6	261	1.16
		Regulated	86	2	450	0.14
Outlet	Treaty of 1944	Natural	790	14	2630	3.51
		Regulated	484	7	2655	0.03
	Drought of Record	Natural	441	9	869	2.32
		Regulated	64	2	70	0.76
	Wet Period	Natural	589	11	4516	1.96
		Regulated	241	5	4330	1.09
	Modern Drought	Natural	533	11	963	3.77
		Regulated	205	4	956	1.30

The analysis of daily streamflow data across key periods and locations reveals a consistent and significant alteration of the Pecos River's flow regime. To validate the results, the flow regimes were compared using the average annual flow of the estimations from this study with the estimations made by Orive Alba for the natural flow and with Cravioto and Lowry for the regulated flow. Other comparisons with similar methodology to estimate the natural flow that include a broad set of gauge stations (Sandoval-Solis et al., 2022) in the Rio Grande/Bravo basin have also been conducted (Garza-Diaz, 2022) to show the robustness of the findings and the consistency of the methods with other regional studies. This demonstrates that the results are not anomalous but align with broader research on the impacts of regulation on major river systems.

4.1 Streamflow validation

In the report “Runoff of the Rio Bravo at the Sites of the Proposed Dams: Current and Future Conditions” (Escurrimiento del Rio Bravo en los Sitios de las Presas Propuestas: Condiciones Actuales y Futuras) by CILA (IBWC Mexican Section), Cravioto and Lowry (1946) provide detailed estimates of water deliveries from the main tributaries of the RGB, including the Pecos River near Langtry (Outlet). We used this historical reference to compare our regulated streamflow reconstruction. The comparison shows strong statistical performance, with consistent and accurate results for the period 1900–1943. The scatter plot of the annual streamflow data aligns closely with the 1:1 reference line, indicating a strong positive correlation between the two datasets (**Figure 4**). This is quantitatively confirmed by the statistical metrics: a Pearson’s correlation coefficient (r) of 0.98 and a coefficient of determination (R^2) of 0.95. The high R^2 value indicates that 95% of the variance in the historical data is explained by our estimated flows.. The Root Mean Square Error (RMSE) of 69.89 MCM indicates a relatively small average deviation. These results validate the accuracy of our regulated flow reconstruction and reinforce the reliability of the methods used in this study.

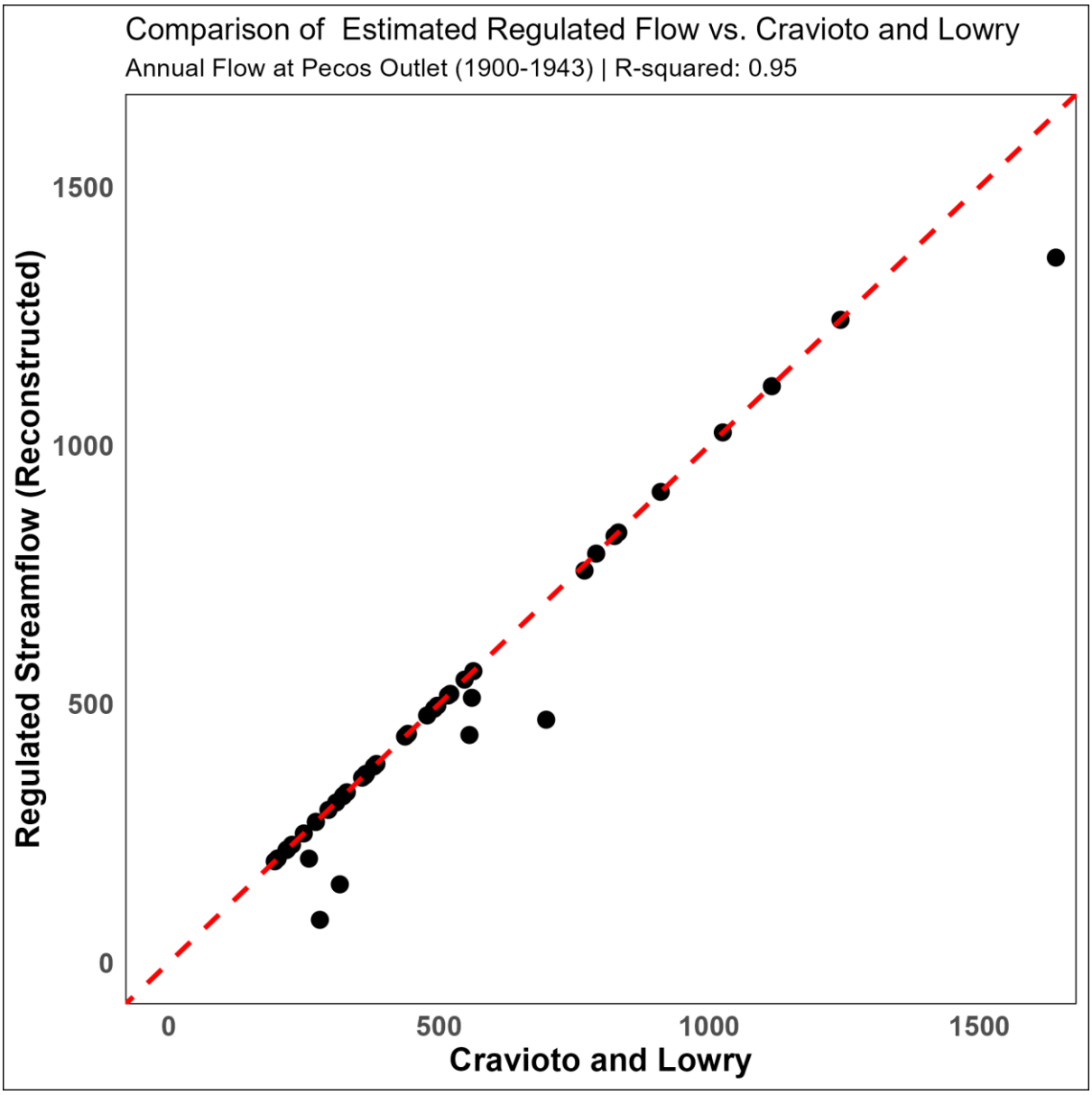


Figure 3-5. Comparison of Annual Regulated Flow: Cravioto & Lowry (1946) versus Reconstructed Flows

4.2 Comparison of the Natural Flow

Our estimated natural flows were compared with the values provided by Orive Alba in his technical report on the Treaty of 1944. Orive Alba compiled the natural flow contributions from both Mexican and US tributaries, including the Rio Conchos, Las Vacas, San Diego, San Rodrigo, Rio Escondido and Rio Salado on the Mexican side, and the Pecos River, Alamito and Terlingua, Goodenough springs, Devils River, San Felipe and Pinto Creek on the US side. Our estimated closely align with Orive Alba's estimates for most of the tributaries (See **Table 3-3**) particularly

for the Rio Conchos (2042 vs 2045 MCM) and the Rio Salado (980 vs 925 MCM). However, differences are evident for the smaller Mexican tributaries (Las Vacas, San Diego, San Rodrigo, and Rio Escondido) and the U.S. Pecos River, where our reconstructed flows are lower than Orive Alba's reported values (789 vs. 1,348 MCM for the Pecos River).

Table 3-3. Comparison of Natural Flow Contributions from Mexican and U.S. Tributaries: Orive Alba (Treaty Estimates) versus Natural Flows (this study).

		Orive Alba (1944)	Saiz (2025)
Mexico Contributions:	1. Rio Conchos	2,045	2,042
	2. Arroyo Las Vacas, Rios San Diego, San Rodrigo and Escondido	418	349
	3.Rio Salado	925	980
	I. Sum of the 6 MX Tributaries	**3,388**	**3,371**
	II. Rio Alamos and San Juan	1,557	1,814
	III. 50% IF	**867**	**528**
	TOTAL FROM MEXICO	**5,812**	**5,794**
		(66%)	*(73%)*
United States Contributions:	**1. Pecos River**	**1,348**	**789**
	2. Alamito and Terlingua (1934)	75	85
	3.Goodenough springs	126	123
	4. Devils River	546	536
	4.San Felipe and Pinto Creek	85	83
	I. Sum of the US tributaries	**2,180**	**1,616**
	II. Sum US tributaries without Pecos River	832	827
	TOTAL FROM THE UNITED STATES	**3,047**	**2,144**
		(34%)	*(27%)*
	TOTAL RIO GRANDE/RIO BRAVO	**8,859**	**7,938**

Overall, the total flow from Mexico's is similar between the two datasets (5794 vs 5812 MCM), while to total US contribution shows a large discrepancy (2144 vs 3047 MCM) (**Figure 5**). Excluding the Pecos River, the U.S. totals are nearly identical, with a difference of only 5 MCM. These differences highlight the importance of re-evaluating historical water availability using updated hydrological methods and longer-term data, particularly for tributaries with high variability or substantial human intervention. The comparison with Orive Alba's estimates suggest that the Pecos River's contribution to the basin may have been overestimated in earlier assessments, this would have major implications for downstream water allocation and Treaty compliance.

The methodology used here for estimating natural flows has also been applied to other gage stations in the RGB (Saiz and Sandoval, 2025; Garza, 2022; Sandoval, 2022). Our datasets have been widely used, for example, to estimate the resilient flow regime (Saiz and Sandoval, 2025), to estimate environmental flow gaps across the basin (Patterson and Sandoval-Solis, 2022) and Carryinc Capacityh (Sandoval-Solis, Saiz-Rodriguez, and Rendon-Herrera, 2024), to assess environmental flows on the main Mexican tributaries (Sandoval-Solis, Garza-Diaz, and Leal-Nares, 2019), and to evaluate potential irrigation savings (Richter et al., 2024). The datasets have been validated against multiple historical and modern sources (Blythe and Schmidt, 2018; Loredo-Rasgado, 2018; Gonzalez-Escorcia, 2016) and the comparisons consistently shows a strong similarity (Garza-Diaz, 2022) confirming that they provide a robust basis for analyzing the Pecos River's hydrology and its role in transboundary water allocation.

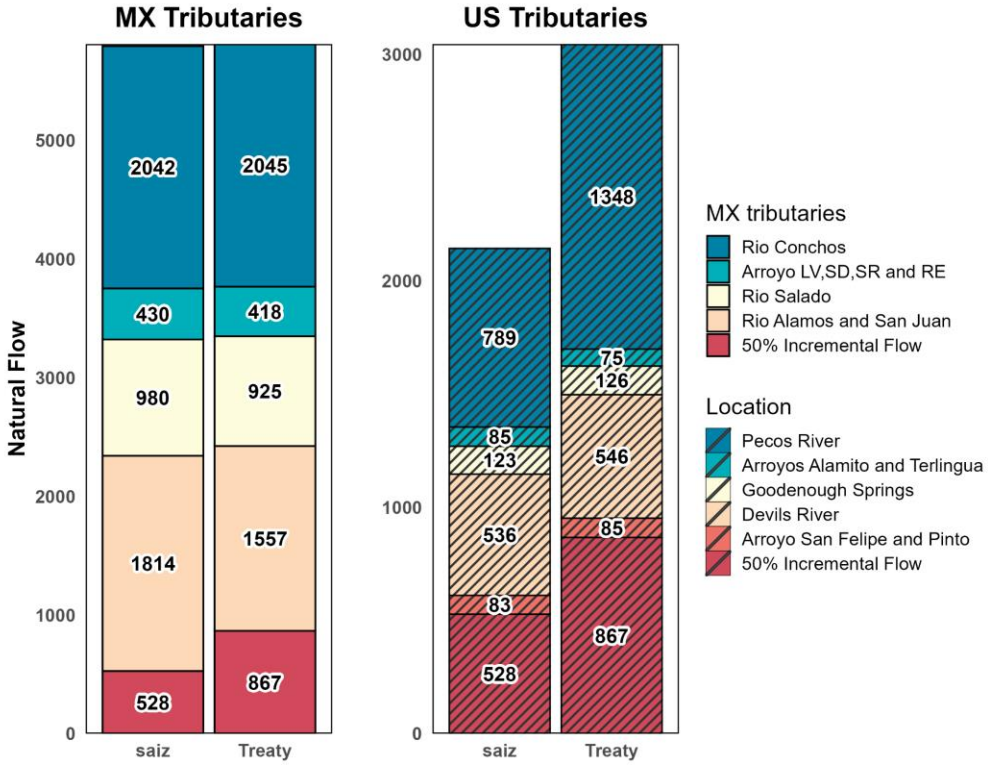


Figure 3-6. Water contribution from the Mexican and the US Tributaries to the Rio Grande/Rio Bravo.

5 Discussion

The natural water availability in the Pecos River has declined over time, directly impacting water distribution between Mexico and the United States. Water in the basin is a critical resource for regional economic activities, and downstream users are most likely to be affected by reducitons and streamflow alterations. Our analysis shows that Orive Alba (1946) overestimated the contribution of the Pecos River to the total basin flow, reporting 1,348 MCM compared to our reconstructed 789 MCM. This overestimation is significant because the Pecos River is an all-U.S. water source with limited volume, meaning U.S. water users rely heavily on water from the six main Mexican tributaries. Accurate reconstruction of the Pecos River's flow is essential for understanding historical water availability and ensuring equitable Treaty allocations.

The difference between our estimates and those of Orive Alba highlights the importance of periodically re-evaluating historical water availability using updated hydrological methods and long-term datasets. Growing population and Climate change is likely to affect water security in the basin, as shifts in precipitation, higher temperatures, and extended droughts continue to affect flows. Garza-Diaz (2022) emphasized the anthropogenic impacts on the Pecos River, identifying a "breaking point" when the system's resilience was lost due to human-induced alterations. Our results confirm that human interventions, particularly diversions and groundwater overdraft, are the primary drivers of the observed flow reductions.

Estimating water availability in transboundary basins with formal water agreements is essential for effective water resource management, conflict prevention, environmental conservation, climate resilience, infrastructure planning, agreement compliance, and long-term sustainability. Accurate assessments provide the foundation for cooperation and responsible stewardship of shared water resources, ensuring that the water users (countries, states, counties, or individuals) and the environment benefit.

In the context of the Rio Grande/Bravo basin, the Pecos River Compact and the 1944 Treaty between the United States and Mexico exemplify the role of formal agreements in promoting interstate and international collaboration. The Pecos River Compact, for instance, obligates New Mexico to deliver to Texas a quantity of water equivalent to that available to Texas under 1947 conditions. However, if those baseline conditions were miscalculated, changed over time, or

affected by human interventions or climatic variability, it becomes necessary to periodically reassess and update water deliveries through official mechanisms such as Treaty Minutes. Similarly, the 1944 Treaty establishes obligations for equitable water sharing between the two countries, and effective management depends on continuously updating hydrologic assessments to reflect actual conditions in the basin.

By combining accurate hydrologic reconstructions with long-term observations, stakeholders can ensure that water allocations are based on reliable data, improving compliance, reducing conflicts, and enhancing resilience to droughts, climate change, and other stresses. This approach is particularly critical for water sources like the Pecos River, where misestimations can have disproportionate impacts on downstream users and treaty obligations.

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CONCLUDING REMARKS

The main objective of this dissertation was to explore the complex dynamics of the Rio Grande/Rio Bravo (RGB) basin and the characterize the impacts of human alteration on its hydrological systems. This work doesn't stand alone; rather, it is a contribution to the immense effort of previous researchers and a foundational step for future scientists. My research addresses the critical need to bridge the gap between historical water management policies and the contemporary realities of a climate-stressed and human-altered river system. Ultimately, this dissertation provides a science-based framework to help navigate the basin's challenges, promoting more resilient and equitable water management for both human and ecological communities.

Chapter 1 established theoretical foundation, reviews concepts of hydrologic variability, functional flows, and river resilience. In this chapter I emphasize the importance of identifying time thresholds (Garza-Diaz, 2022) understanding the structure of flows and quantifying ecological and human needs under varying hydrological conditions. This chapter uses the Functional Flow Approach to characterize the basin's Functional Flow Metrics (FFM) for the Natural, Regulated and Resilient Flow. It also calculates Environmental Flow Requirements (environmental flow gaps) and Hydrologic Alteration (Carrying Capacity) to perform an environmental flow assessment and propose strategies to mitigate hydrologic alterations.

Chapter 2 formally introduced the Resilient Flow Regime, a flow regime that can absorb certain human-induced perturbations while preserving ecologically beneficial characteristics of the natural flow regime and explores its implications for sustainable water management. From the estimation of the natural and the reconstructed regulated streamflow from historical data, this analysis shows how human interventions have altered the river's flow regime, reduced overall

water availability, and changed the timing and magnitude of streamflow. The chapter concludes with a comparison of the natural and resilient flow regimes, determining that that the resilient flow regime can be used as recommendations for ecological and environmental flows for the RGB. Resilient flow regimes can be estimated and used as ecological and environmental flow recommendations throughout the world; it is a novel method for determining ecological and environmental flows at the same time.

Chapter 3 examined the implications of these findings for formal water agreements. The case study is the Pecos River, The Pecos River a major tributary of the RGB and the basin is governed by the Pecos River Compact (NM Stat § 72-15-19) between Texas and New Mexico. At the same time, the RGB is regulated by the U.S.-Mexico Water Treaty. This chapter compares reconstructed flows with historical estimates used in treaty formulation, highlighting discrepancies, overestimation of available water, and the potential for inequitable allocation under contemporary conditions.

Together, the three chapters underscore the importance of integrating hydrological science, historical data reconstruction, and policy analysis to support adaptive water management. By quantifying natural and altered flow regimes, evaluating historical treaty assumptions, and assessing resilience under changing climatic and human pressures, this research provides a framework for improving water allocation, treaty compliance, and sustainability in transboundary and interstate river basins. Ultimately, the findings emphasize that water management must be dynamic, informed by science, and responsive to evolving environmental and social conditions to ensure equitable and sustainable outcomes for both human and ecological communities.