Resilient Flow Regimes in the Rio Grande –RíoBravo Basin

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# Abstract

Water is essential for human development and is an indispensable resource for any economic activity and country's development. However, current water practices, increasing land-use change, climate change, and agriculture practices have significantly altered the hydrological cycle and water availability. This study defines the concept of a *resilient flow regime*—a flow regime that absorbs some perturbation by human alterations but still preserves ecologically beneficial characteristics associated with the natural flow regime—and its implications for sustainable water management. Using the Rio Grande/Bravo (RGB) basin as a case study, the research evaluates the similarities and differences between natural, resilient, and regulated flow regimes.

The RGB, a transboundary basin shared by the U.S. and Mexico, faces significant water resource challenges due to extensive infrastructure development, water overuse, and climate variability. The study identifies three natural streamflow classes in the RGB—snowmelt-driven, Monsoon-driven, and Bimodal—and evaluates functional flow metrics across 16 gage stations. Results indicate strong correlations between natural and resilient flow metrics, particularly for magnitude components, whereas regulated flows show greater differences from natural conditions.

Statistical analyses show 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 adverse impacts of human activities, preserve biodiversity, and enhance 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, Natural streamflow*

# Introduction

### 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.

### 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 one of North America's fifth largestdrainage basins covering approximately 557,000 km2. 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).

### Resilient flow regime and natural flow regime

In this research, wedefine 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 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. Under a resilient flow regime, water can be used for human purposes, but the essential characteristics of the natural flow regime persists to support freshwater and riparian ecosystems. 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).

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, recreation, etc.) 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.

### 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 regimediversity, 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.

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**Figure 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)

# Literature Review

### Resilience theory

Multiple definitions of resilience have been proposed and debated (See Table 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 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 1.**Resilient theory definitions

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### 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 prescribeenvironmental 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 (CITE)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.

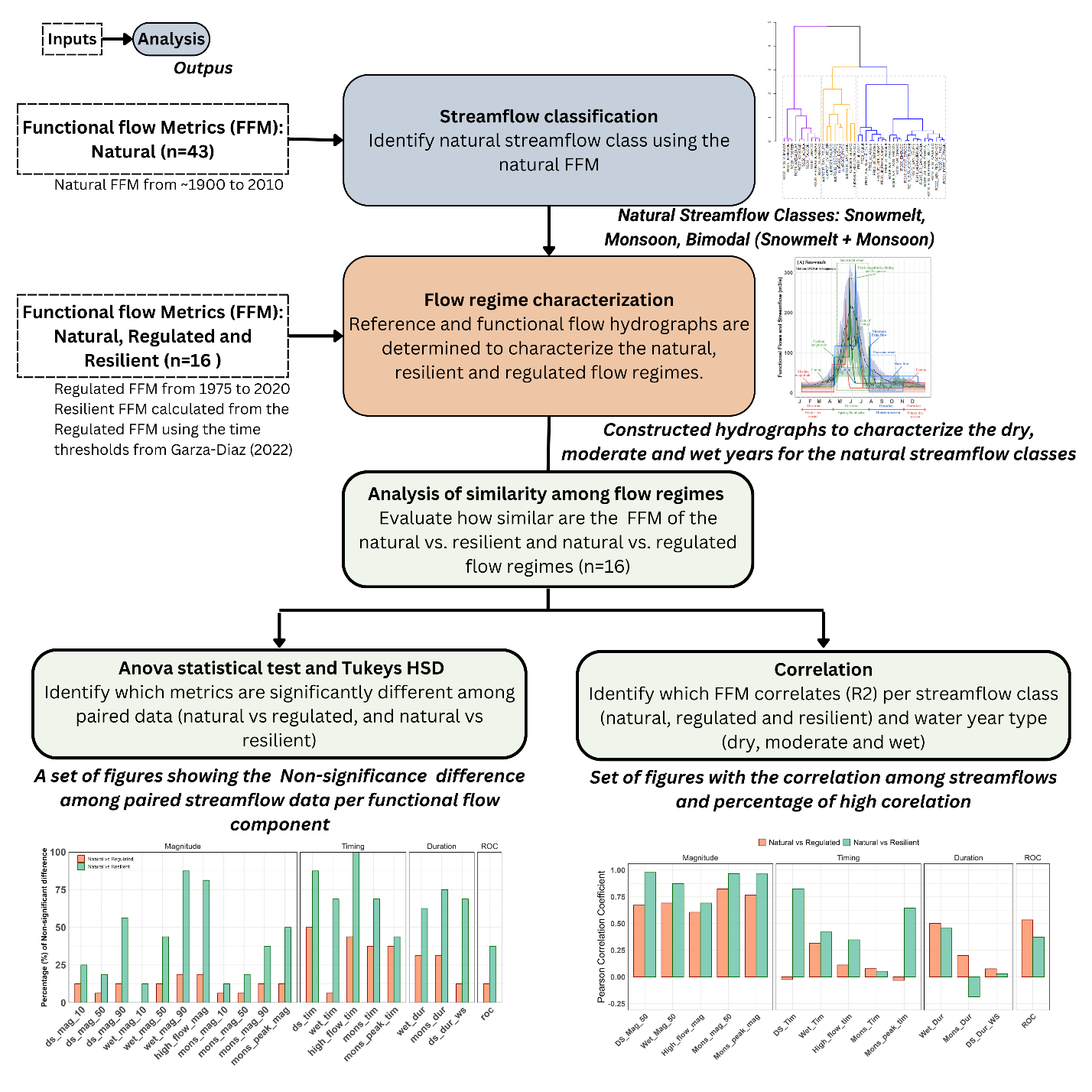
The variability in river flow regimes has been characterized using a variety of statistical parameters. One method is the Functional Flows Approach, in which flow events that are ecologically relevant in sustaining freshwater ecosystems are quantified using functional flow metrics, which in turn are 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 as functional flow components.

# 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. 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.

## Overall Approach

**First**, a *natural streamflow classification* for the RGB was developedusing 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 testand Tukey's HSD test to identify which metrics that 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).



**Figure 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).

### 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 estimatedhydrology 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. Garza-Diaz and Sandoval-Solis (2022) and Blythe and 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 they used a mass balance equation with climate, agriculture, and reservoir storage variables at a daily time step. These data 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).

### Time Thresholds to IdentifyChange 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.

### 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 are 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.

## 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

## Analysis of similarity among flow regimes

### 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).

### 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.

# Results

## Natural streamflow classification and flow regime characterization

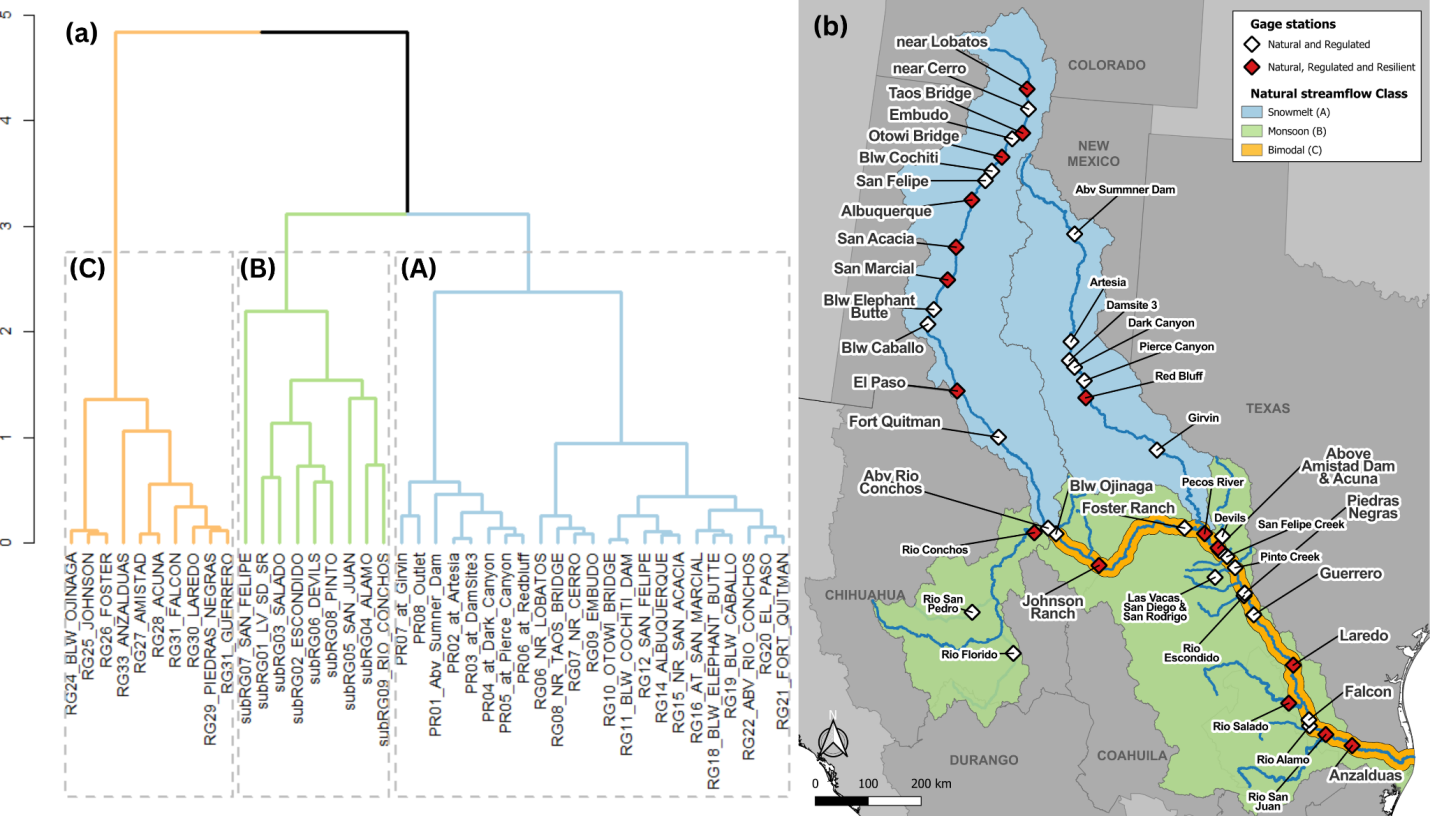
The RGB is a hydro-dynamic basin, with a diverse range of landscapes and climates. The primary water sources of the RGB are replenished by snowmelt and monsoon rains (Fig.3 and Table 2).

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 RGBis 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 andmonsoon). 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).

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

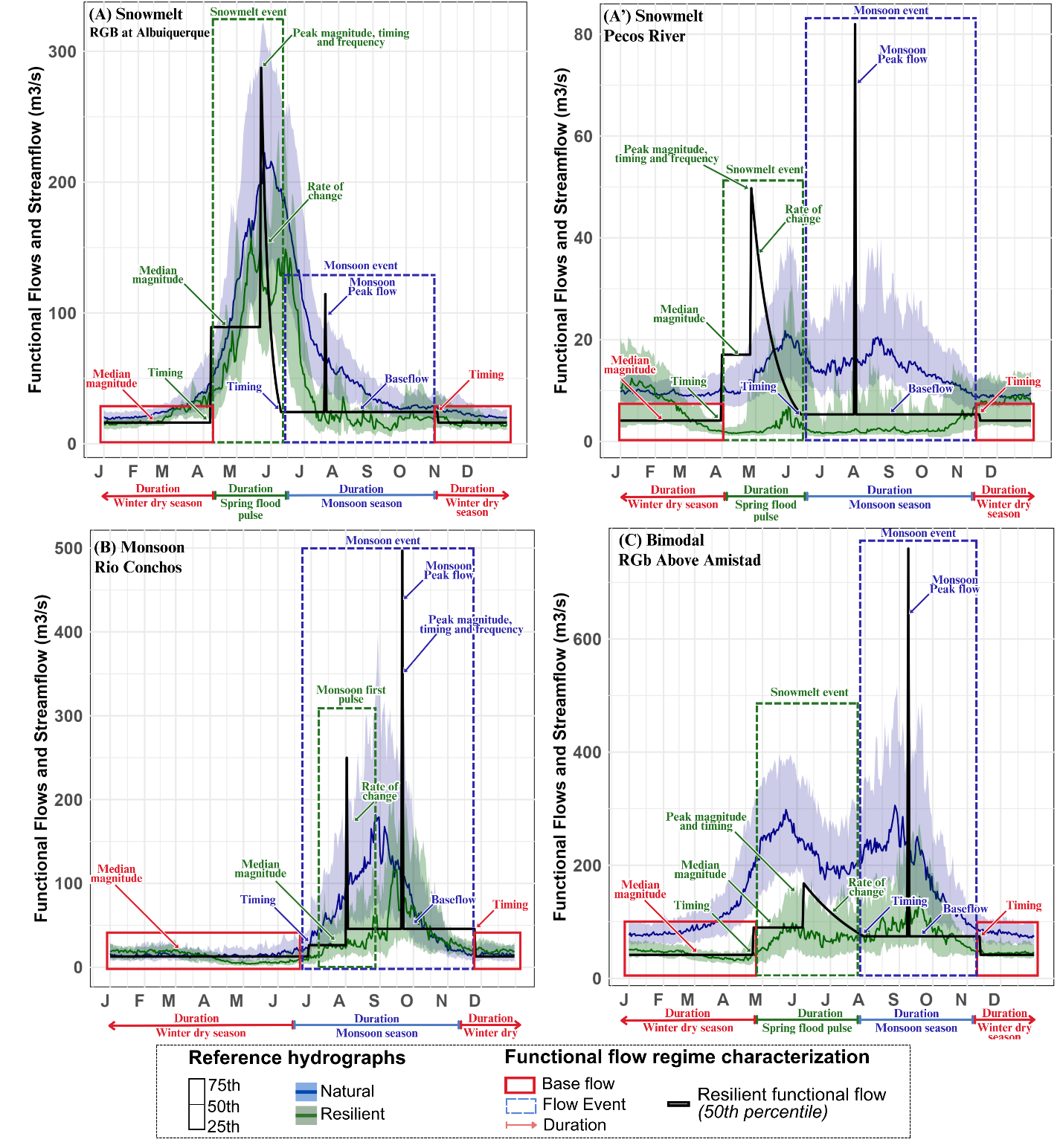
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**Figure 3.** Results from (a) hierarchical clustering by Ward’s algorithm analyses and (b) natural streamflow classification showing the spatial variation in the natural streamflow regimes. The streamflow differs across the basin. In the upper basin (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.

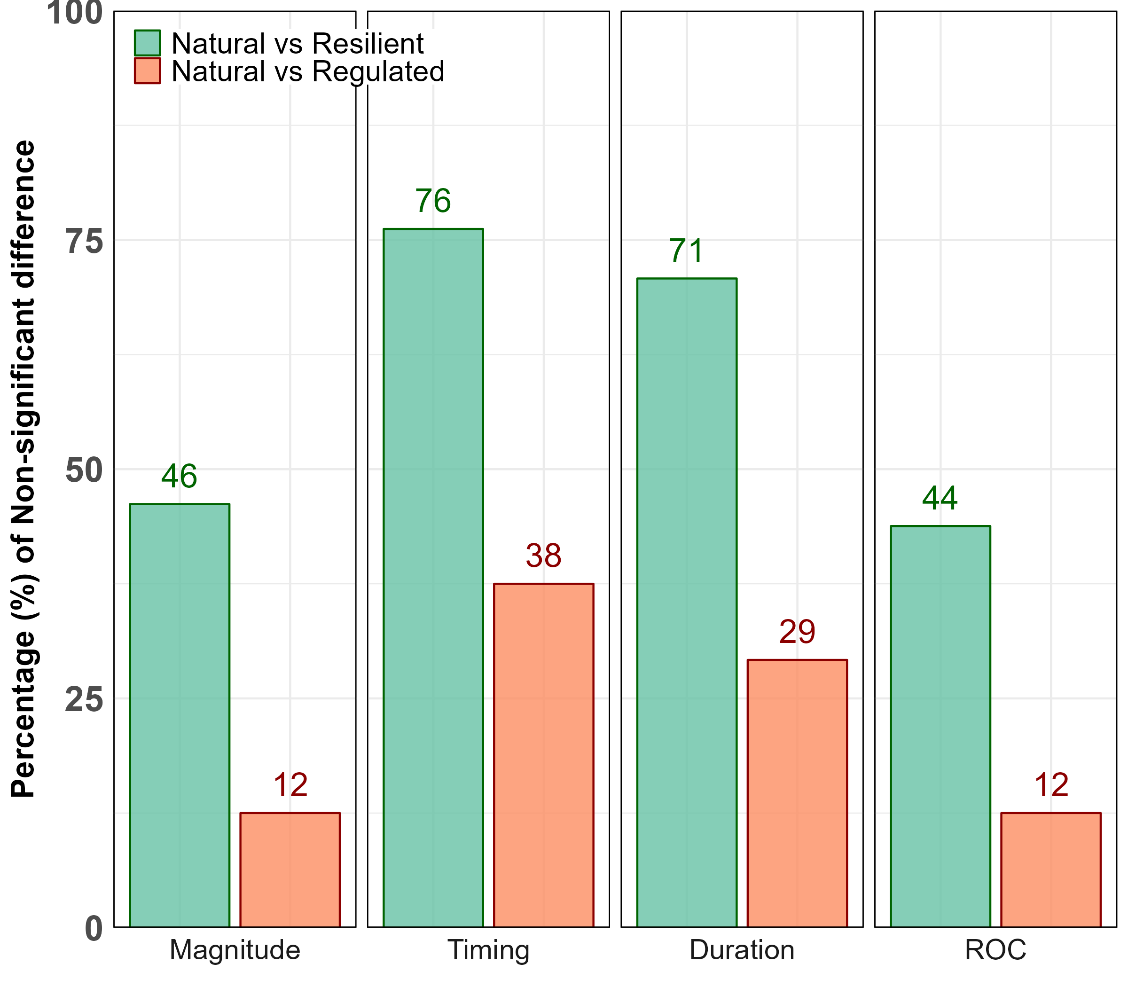
Reference hydrographscharacterize flow regimes, they are calculated by obtaining the 25th, 50th and 75th percentiles of daily streamflow. The reference hydrograph of the natural streamflow (Fig. 4, shaded in blue) is the flow regime to which the river basin has adapted for thousands of years, it represents the undisturbed flow that would have been in the absence of human intervention. In contrast, the resilient regime flow (Fig. 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. 4 black thick line).



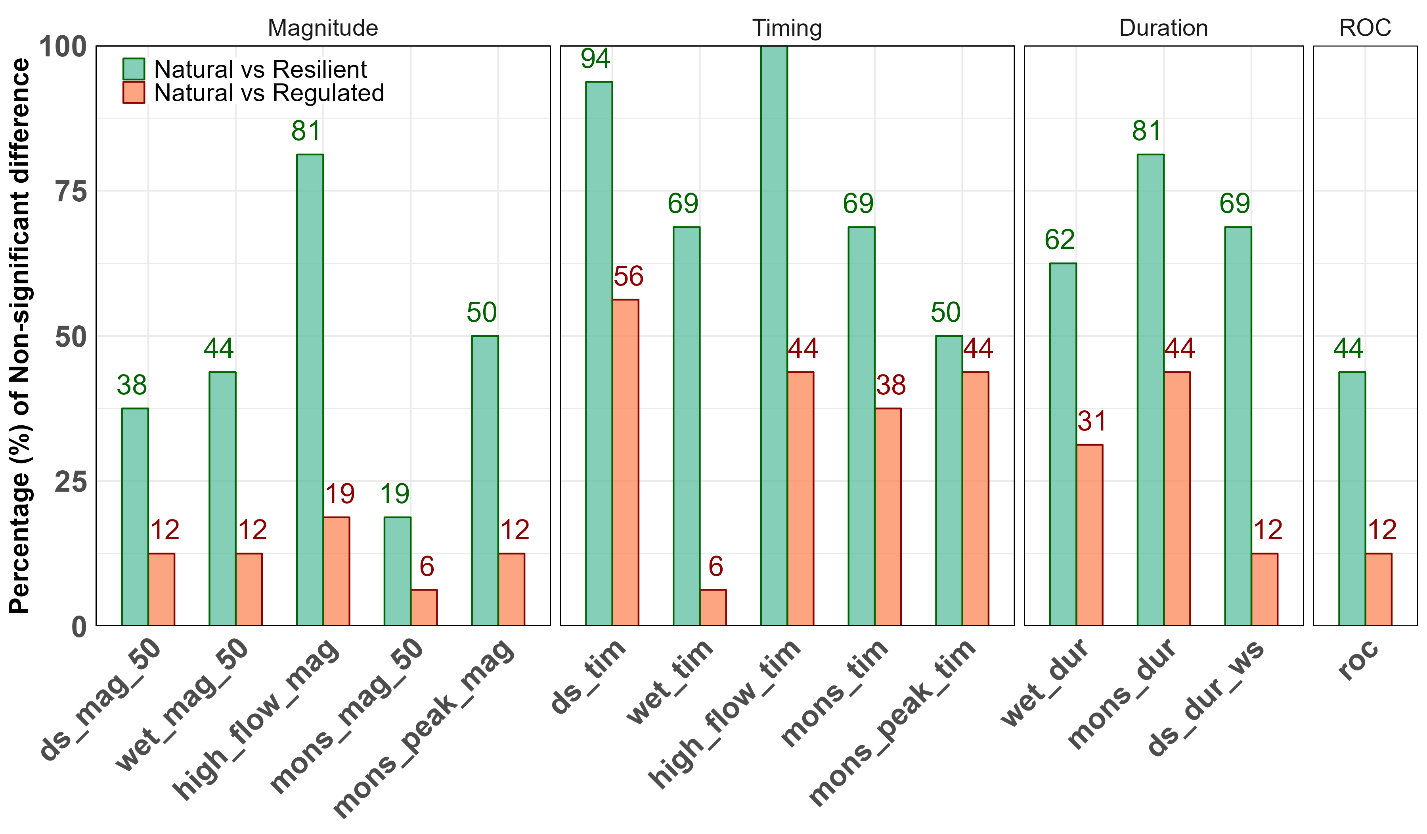
**Figure 4.** Examples of reference hydrographs for natural and resilient streamflows. Daily averages and range of flows for natural (blue line and blue shading) and resilient (green line and green shading). The lines represent the daily median flows and the shading represents the inter-quartile range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

## 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 6presents 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.

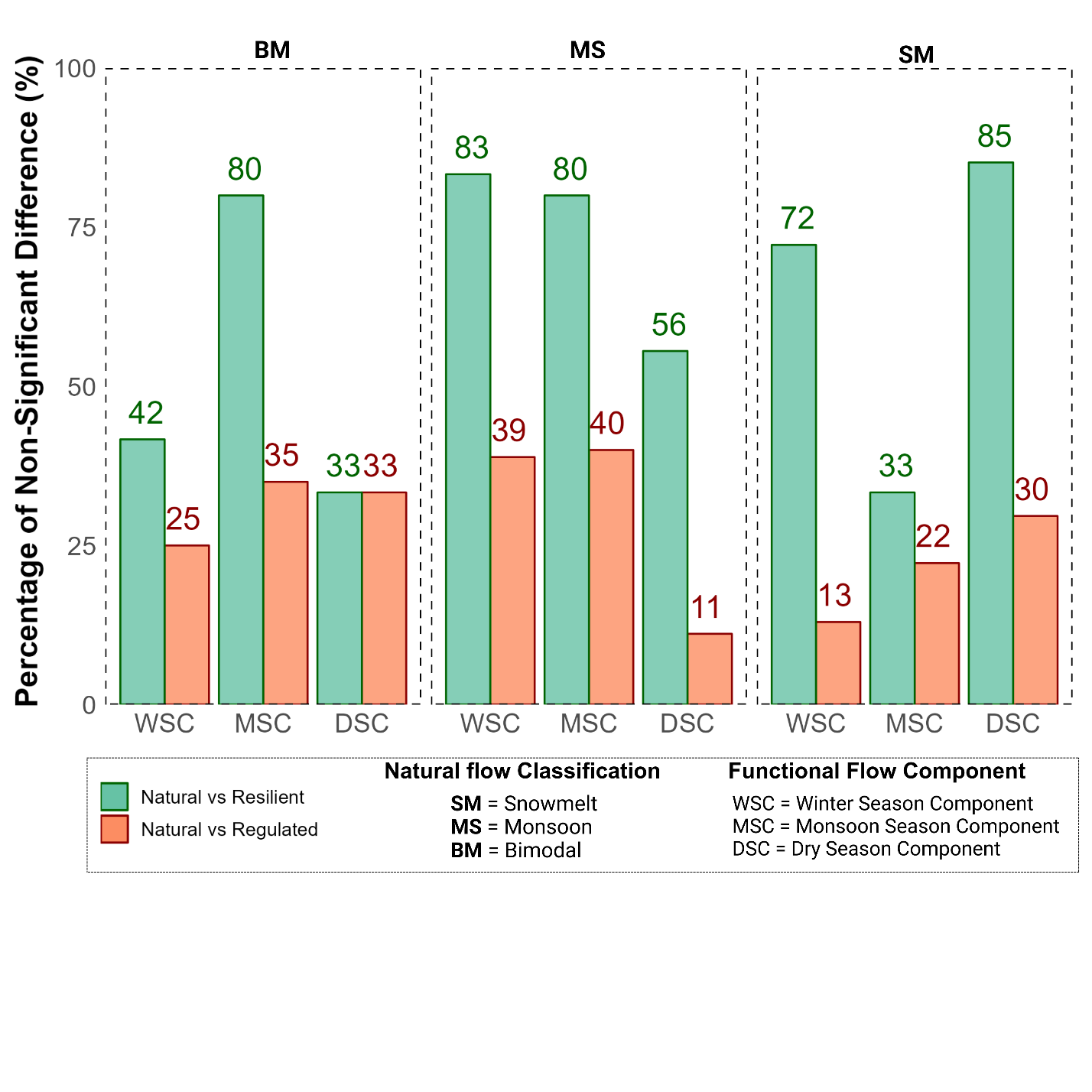


**Figure 5.** Percentage of non-significant difference (i.e. similarity) in the metrics using ANOVA and Tukey’s post hoc test. The results show greater similarity between the natural and resilient FFM (green) and less similarity between the natural and regulated (orange) flow regimes.



**Figure 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 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 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.

## 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.

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**Figure 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.

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

### Functional flow correlation for each natural stream flow classification

### 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.

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

### 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.

A screenshot of a graph

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**Figure 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.

### 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.

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**Figure 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.

## 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, 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.

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, particularly in magnitude components.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. Our evaluation showed that the resilient hydrologic functional flow components (magnitude, timing, duration, and ROC) are within the boundaries of the natural flow, despite some degree of alteration due to human perturbation. The resilient flow regimes were more aligned with natural conditions than regulated flows, highlighting the importance of preserving natural flow dynamics for ecological and hydrological sustainability. 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.

Interestingly, while the resilient flow regime maintains some characteristics of the natural flow, timing, discrepancies are evident. 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. This discrepancy in flow timing shows the potential for dam reoperation as a strategy to improve environmental flows. 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. 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.

While resilient flow provides a useful framework for analyzing hydrological patterns, the analysis depends on the availability of 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.

## 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 insightinto 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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**Data Availability Statement**

All data that supports the finding of this study are available from the corresponding author upon reasonable request.

**Appendices**