Environmental Flows Assessment and Implementation Strategies in the Rio Grande/Bravo

UC Davis, Water Management Lab

Report 2023

Prepared by:
Dr. Samuel Sandoval Solis,
M.S. Ramon Saiz,
Gabriela Rendon Herrera

Reviewers:
M.S. Enrique Prunes
M.S. Brian Richter

UC DAVIS WATER MANAGEMENT LAB

WWF

Glossary

Breaking point. An estimated year when an abrupt hydrologic regime shift occurs. The breaking point is obtained by the examination of general patterns and mechanism of regime shift streamflow that changes the carrying capacity of the river basins. The regime shift assessment is performed using resilience theory through the Fisher Information Index, to identify breaking points in time (also referred to as *time thresholds*). Before the breaking point, the resilient flow regime was providing ecological functionality even though human activities occurred. After the breaking point, the flow regime changed permanently into a regulated flow regime that is degraded and is unable to fully support a river community's composition, structure, and function.

Carrying capacity. It is the magnitude of disturbance that a river can absorb while still preserving its ecological integrity. It is determined by subtracting the flow metrics of the natural and resilient flow regimes.

Environmental flow gap. A volume of water or re-arrangement of streamflow in time to meet the environmental flow requirements considering the current regulated flow regime. It is determined by subtracting the functional flow metrics of the resilient and regulated flow regime.

Environmental flow requirements. The flow regime needed to sustain a healthy river ecosystem. This study uses the Functional Flows Approach (Escobar-Arias & Pasternack, 2010; Yarnell et al., 2015), its metrics (magnitude, timing, duration, frequency, and rate of change), and components (Winter Dry Season, Spring Flood Pulse, and Monson) to quantify the environmental flow requirements.

Environmental flows. The quantity, timing, and quality of water flows required to sustain fresh-water and estuarine ecosystems, human livelihoods, and well-being that depend upon these ecosystems (Arthington et al. 2010).

Functional flows. Distinct aspects of a natural flow regime that sustain ecological, geomorphic, or biogeochemical functions, and that support the specific life history and habitat needs of native aquatic species (Escobar-Arias and Pasternack 2010, Yarnell et al. 2015, Yarnell et al. 2019).

Functional flow hydrographs. They are constructed using the functional flow metrics. They depict an annual hydrograph that follows the calculated functional flow metrics.

Hydrologic alteration. Differences in streamflow patterns between natural pre-development conditions and human-altered conditions in a river basin, quantified by streamflow characteristics (magnitude, timing, duration, and rate of change).

Naturalized flows. Streamflow records at a gaging site that are adjusted to represent pre-development conditions absent of human alteration such as dams and diversions.

Reference hydrograph. It shows the seasonal and interannual variation of a given flow regime. It is the shaded area whose lower and upper bounds are the 25th and 75th percentiles of the daily streamflow data, and the solid line in the middle is the 50th percentile or median.

Regulated flows. Streamflow records at a gaging site that are affected by dam operation for human objectives, e.g., dam releases from reservoirs to meet specific demands for different water uses or flood control.

Resilient flow. Flow regime that occurs prior to a permanent flow regime shift (Garza-Diaz, 2022). The streamflow characteristics (timing, magnitude, duration, frequency, and rate of change) are altered due to human intervention, but still are within the bounds of the natural flow regime.

Resilient period. Period prior to the breaking point that signifies a permanent flow regime shift.

Temporal disaggregation. Statistical methods used to estimate time series streamflow data at a lower temporal scale, for example, disaggregation of monthly streamflow data into daily streamflow data.

Index

1. Executive Summary

Water sustains life, both human 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 Chihuahuan 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.

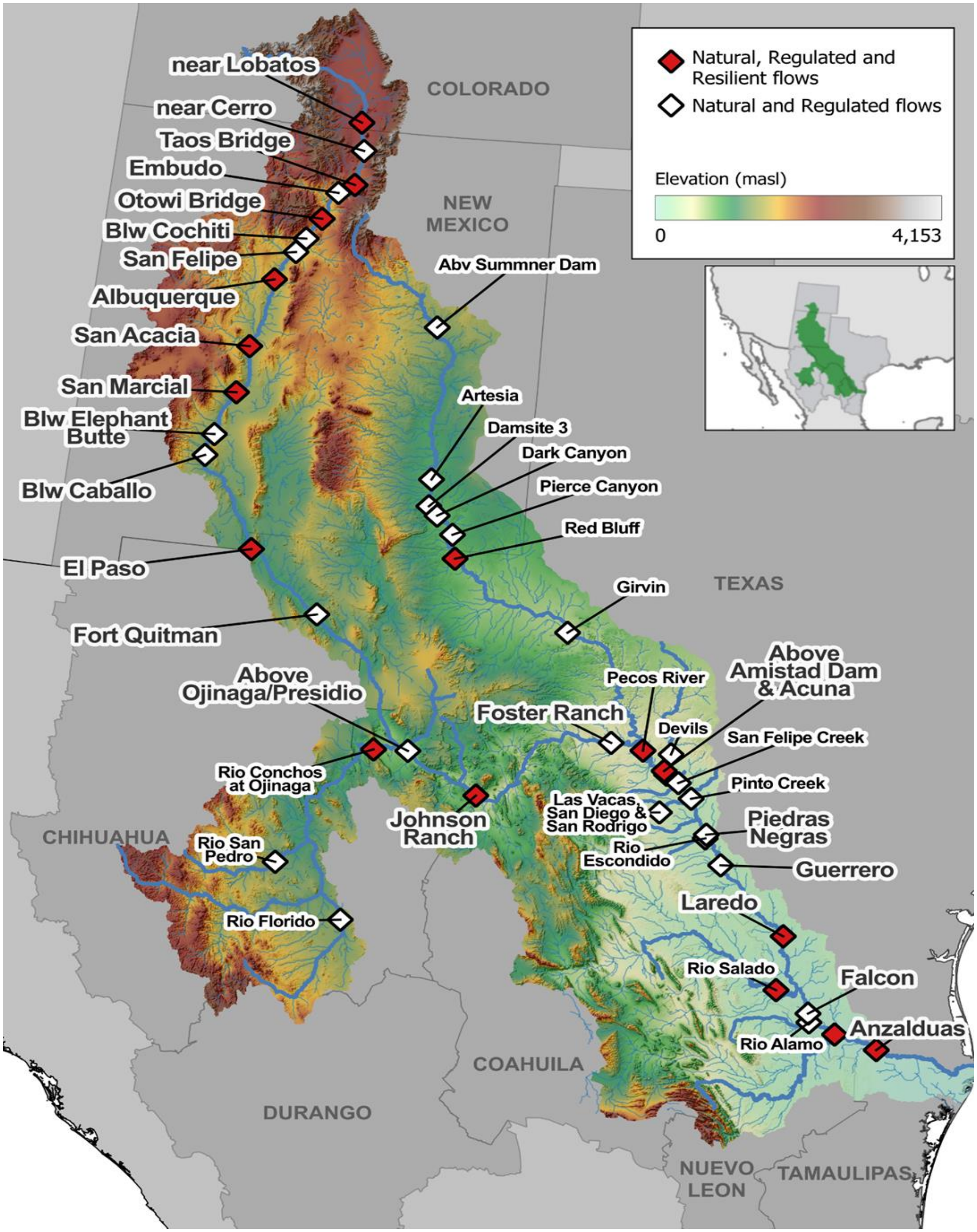


Figure ES-1. Location of 43 gauge stations analyzed, 27 gauges have natural and regulated flow regimes (white diamonds) and 16 have additionally resilient flows (red diamond).

The overall goal of this research was to determine environmental flow requirements in the RGB basin and define strategies or interventions for achieving them. The methodology carried out and its respective results were the following:

1. The functional flows approach was used for characterizing the river flow regimes. Functional flow metrics (FFMs) were calculated for daily naturalized and regulated streamflow data (1900 to 2010[1]) for 43 gauge stations (Fig. ES-1). The FFMs were adjusted to the hydrologic and climatologic conditions of the RGB based on previous studies (Patterson and Sandoval, 2022) and expert advice.

2. FFMs of the resilient flow regime were identified by selecting the metric values for years prior to breaking points. Breaking points are years when a permanent flow regime shift occurred (Garza-Diaz and Sandoval-Solis 2022).

3. Reference and functional flow hydrographs for natural, regulated, and resilient flows were estimated 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) (examples on figures ES-2 and ES-3). All the reference hydrographs of the regulated flow regimes showed a significant decrease in streamflow and seasonal timing alteration. In contrast, all the reference hydrographs of the resilient flow regime showed a great resemblance with the natural flow regime (Figure ES-2).

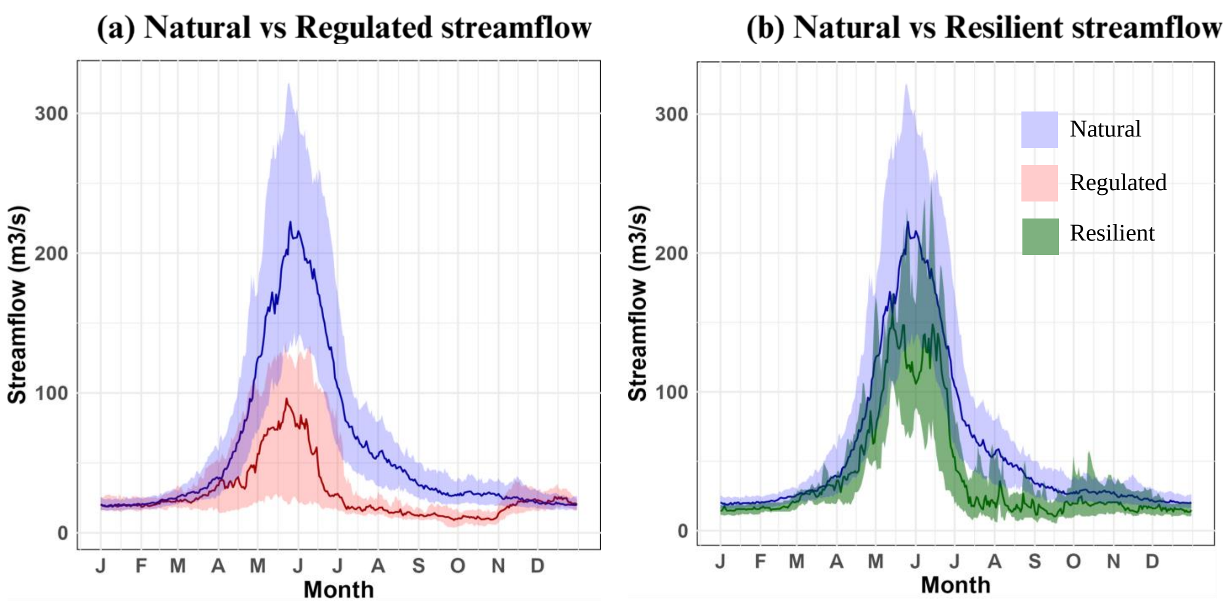


Figure ES-2. Comparison of natural versus regulated flow regimes (left) and natural versus resilient flow regimes. RGB at Albuquerque, NM.

[1] "Natural" conditions were substantially altered by 1900 (Blythe and Schmidt, 2018), to the extent that the Embudo gauge was installed in 1888 in response to Mexico's formal complaints of the dimensions of the upstream consumption.

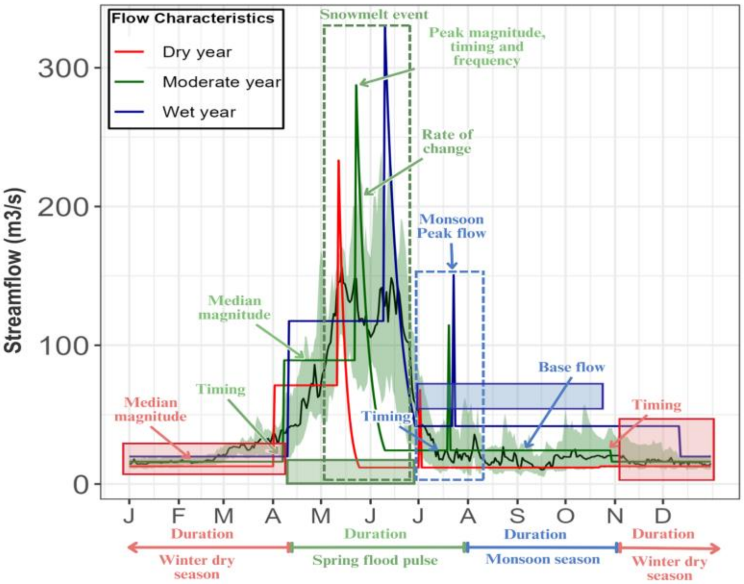


Figure ES-3. Functional flow hydrograph for the resilient streamflow, RGB at Albuquerque, NM.

4) The environmental flow requirements were calculated for 16 gauge stations (Fig. ES-1) using the FFMs of the resilient flow regime (Fig. ES-3). Subsequently, the environmental flow gaps were determined by subtracting the resilient and regulated flow regime (Figure ES-4. b). The result is the volume of water needed and/or changing in timing to restore the functional flows at a point that resemble those of the natural flow regime (Figure ES-4 a; Table ES-3 and ES-4).

5) The carrying capacity was determined by subtracting the natural and resilient flow regime. The result depicts the magnitude of disturbance that a river can absorb to preserve functional integrity of freshwater and riparian ecosystems (Figure ES-4 b).

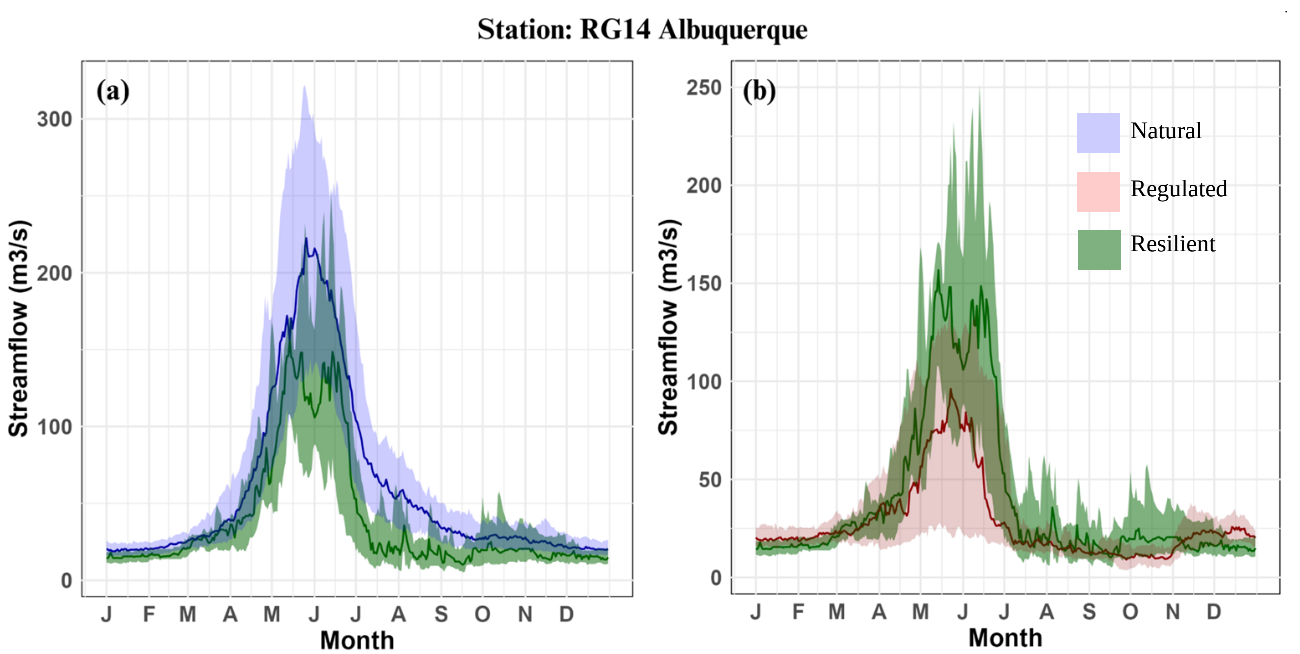


Figure ES-4. Comparison of (a) natural with resilient flow regime and (b) regulated with resilient flow regime. RGB at Albuquerque, NM.

Table ES-3 shows one of the results for the environmental flow gap, for each functional flow component and water year types at Albuquerque gauge station. For a moderate year, during the winter dry season there is a surplus of 195 million m3 needed to meet the environmental flow requirements. In spring flood pulse there is a deficit of 154 million m3, and for the monsoon season there is a deficit of 22 million m3,

This gauge station shows that in some periods of time water is needed to meet environmental requirements, and in others, there is an apparent excess of water. Thus, meeting environmental requirements for this gauge is not only a problem of volume, but also of timing, moving water from one period of the year to another to better mimic the FFM of the resilient flow regime. Table ES-4 shows a summary of the environmental flow gaps. In moderate conditions, the environmental flow gap is a surplus of 19.2 million m3 (540.5 thousand acre-feet).

Table ES-3. Environmental flow gaps for each function flow component for three water year types. RGB at Albuquerque gauge station. *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)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG14_ALBUQUERQUE	*Dry Year*	*Winter dry season*	296	91	329.6	263.7	177.8	142.2	152	121.5
		Spring flood pulse	92	144	160.5	128.4	339.3	271.5	-179	-143.1
		Monsoon season	145	295	219.0	175.2	173.2	138.5	46	36.6
	Moderate Year	*Winter dry season*	303	97	418.4	334.7	223.2	178.6	195	156.1
		Spring flood pulse	98	160	369.9	295.9	524.0	419.2	-154	-123.2
		Monsoon season	161	302	297.8	238.2	319.7	255.8	-22	-17.5
	Wet Year	*Winter dry season*	346	100	407.3	325.8	205.6	164.5	202	161.4
		Spring flood pulse	101	179	653.3	522.6	852.2	681.8	-199	-159.1
		Monsoon season	180	345	453.7	362.9	623.0	498.4	-169	-135.4

Table ES-4. Example of a summary of environmental flow gaps for each function flow component for three water year types. RGB at Albuquerque, NM. *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	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG14_ALBUQERQUE	Dry year	709.0	690.3	197.6	29%	178.9	26%	18.7	15.0	3%
	Moderate year	1086.1	1066.9	195.2	18%	176.0	16%	19.2	15.4	2%
	Wet year	1514.2	1680.8	201.7	12%	368.2	22%	-166.5	-133.2	10%

Table ES-1 shows the carrying capacity for each functional flow component and water year types at Albuquerque, New Mexico. For a moderate year it shows the different carrying capacities during the winter dry season (153 million m3), spring flood pulse (275 million m3) and monsoon season (239 million m3). Table ES-2 shows a summary for all water year types. In moderate conditions, the carrying capacity is 666.8 million m3 (540.5 thousand acre-feet), which is 38% of the natural flow regime.

Table ES-1. Carrying capacity for each function flow component three water year types. RGB at Albuquerque, NM

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG14_ALBUQUERQUE	Dry Year	Winter dry season	296	91	348.1	278.5	177.8	142.2	-170.3	-136.3
		Spring flood pulse	92	144	448.3	358.6	339.3	271.5	-109.0	-87.2
		Monsoon season	145	295	470.5	376.4	173.2	138.5	-297.3	-237.8
	Moderate Year	Winter dry season	303	97	376.1	300.9	223.2	178.6	-152.9	-122.3
		Spring flood pulse	98	160	799.2	639.4	524.0	419.2	-275.2	-220.2
		Monsoon season	161	302	558.4	446.7	319.7	255.8	-238.6	-190.9
	Wet Year	Winter dry season	346	100	280.8	224.6	205.6	164.5	-75.2	-60.2
		Spring flood pulse	101	179	1417.4	1133.9	852.2	681.8	-565.2	-452.2
		Monsoon season	180	345	747.5	598.0	623.0	498.4	-124.5	-99.6

Table ES-2. Example of a summary of carrying capacity for three water year types. RGB at Albuquerque, NM.

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG14_ALBUQUERQUE	Dry	1266.9	1013.5	690.3	552.2	0.0	0.0	576.6	461.3	-576.6	-461.3	46%
	Moderate	1733.7	1386.9	1066.9	853.5	0.0	0.0	666.8	533.4	-666.8	-533.4	38%
	Wet	2445.6	1956.5	1680.8	1344.6	0.0	0.0	764.9	611.9	-764.9	-611.9	31%

6) Finally, a set of strategies were proposed for implementing environmental flows, divided into three categories: (1) opportunities for improving human and environmental water supply with current infrastructure: these strategies aim to maximize the use of the existing infrastructure to meet both human and environmental water needs. (2) Water demand management: to address the mismatch between the natural water scarcity of the basin and the large human water demands throughout the system. (3) Nature-based solutions: proposed nature-inspired solutions to promote the ecosystem health and resilience of riparian ecosystem, while still providing water for human water needs.

2. Overview of the Research Project

Water is an important resource for everyone, including the environment. In previous research projects (Patterson and Sandoval,2022), we estimated environmental flow requirements for the Upper Rio Grande using the Functional Flows approach and developed an environmental flow indicator as part of the Rio Grande Resilient Basin Report Card Project. This report describes a research project that extends this work to estimate environmental flow requirements in the rest of the whole Rio Grande/Bravo (RGB) basin at 43 locations (gauges) in the basin **(Figure 1)**, quantify environmental flow gaps, and define strategies or interventions to implement environmental flows throughout the basin.

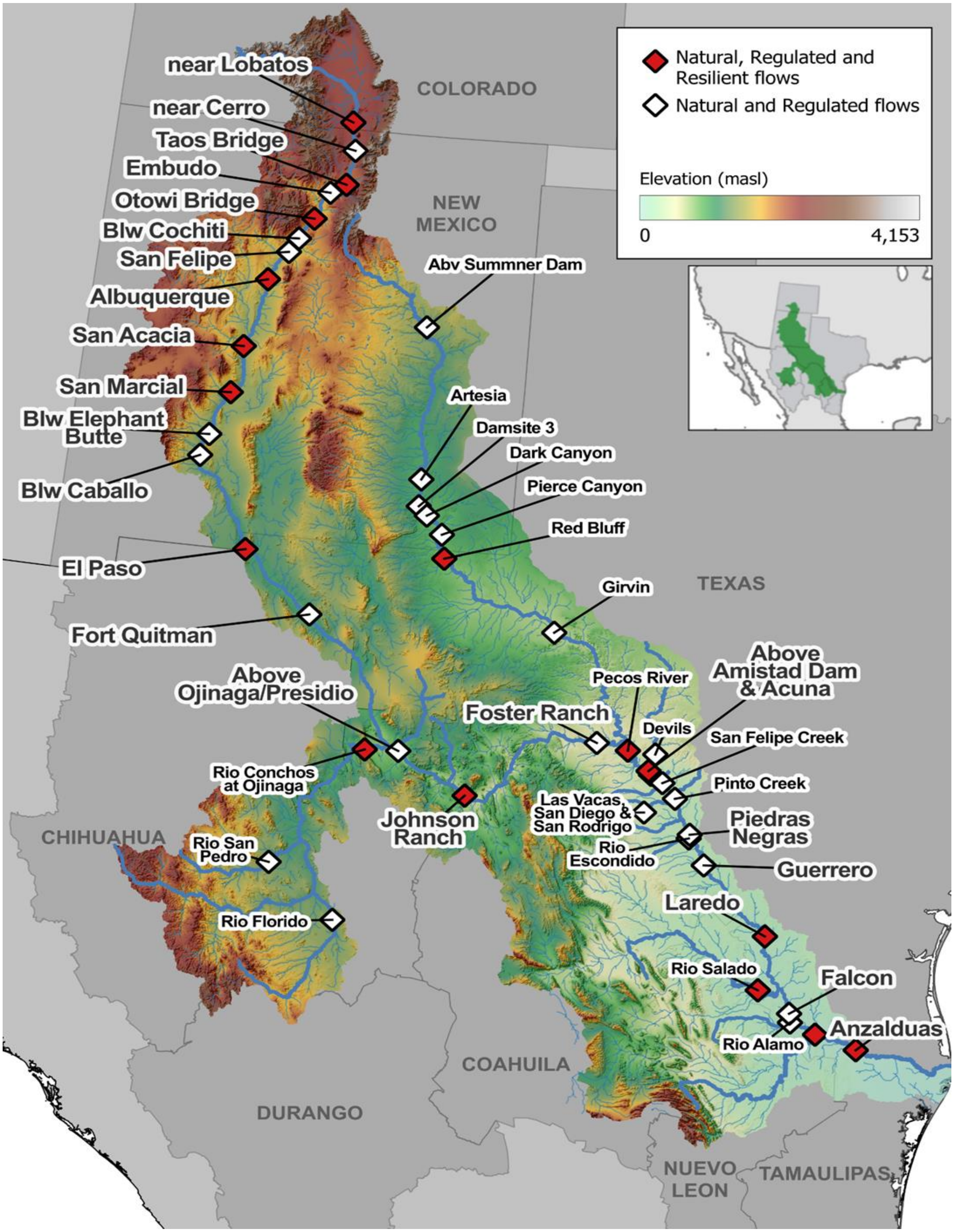


Figure 1. Location of the gauge stations along the RGB basin. In red, the station with natural, regulated and resilient flows and in white, the stations with Natural and Regulated flows

2.1 Background

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?

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 2)**. 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.

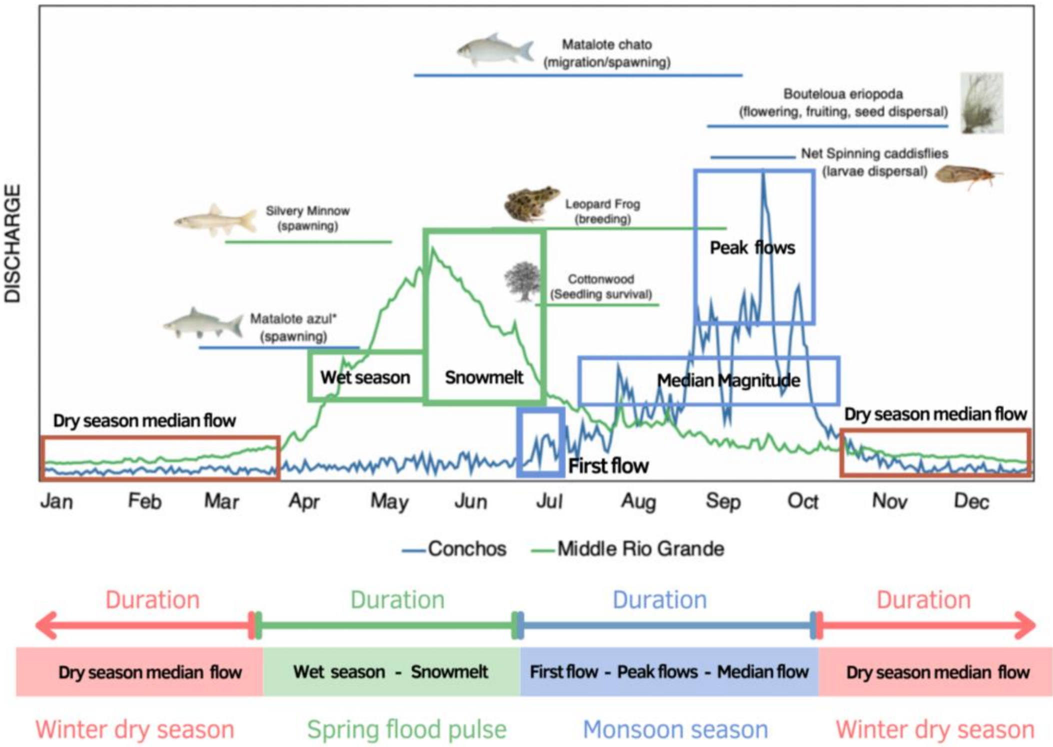


Figure 2. Functional flow components and example of reference hydrograph of the Rio Conchos and Middle Rio Grande-Bravo. The base flows include Winter dry season median flow, Spring flood pulse and Monsoon season median magnitude flow. Monsoon peak flows are considered events. The metrics of these components 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.

2.2 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)**:

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.

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

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.

2.3 Rio Grande - Rio Bravo

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 3).**

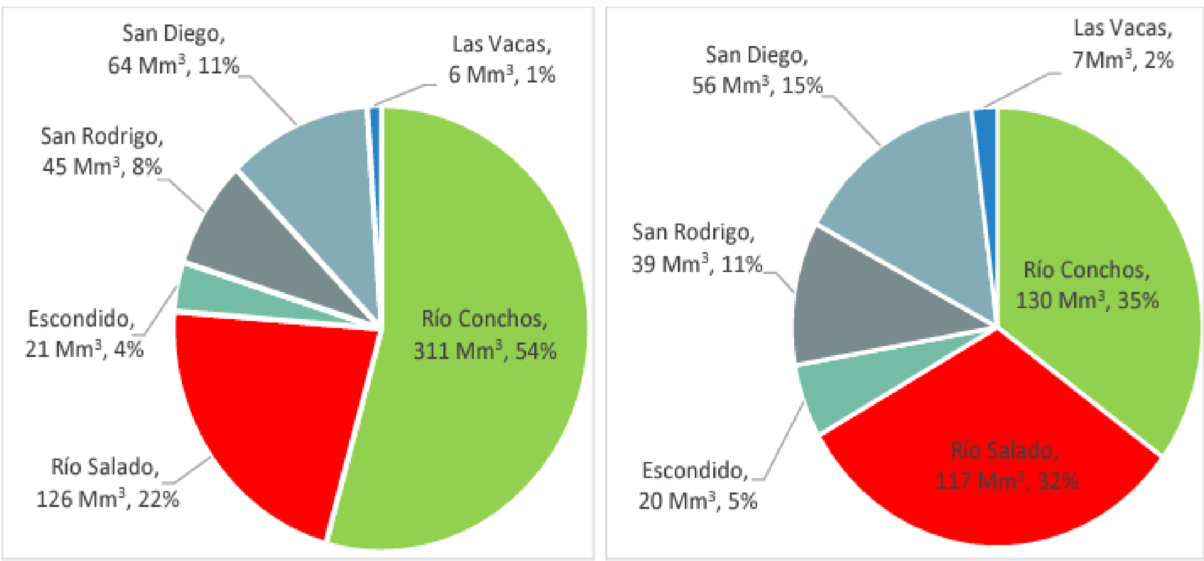


Figure 3. From Garcia, 2022. Water provided to the Treaty of 1954 from 1954 to 1933 (left) and from 1994 to 2019 of the six Mexican tributaries.

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 Chihuahuan 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,into 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.

Methodology

3. Methodology

The overall methodology is shown in **Figure 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**), 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 streamflows, 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.

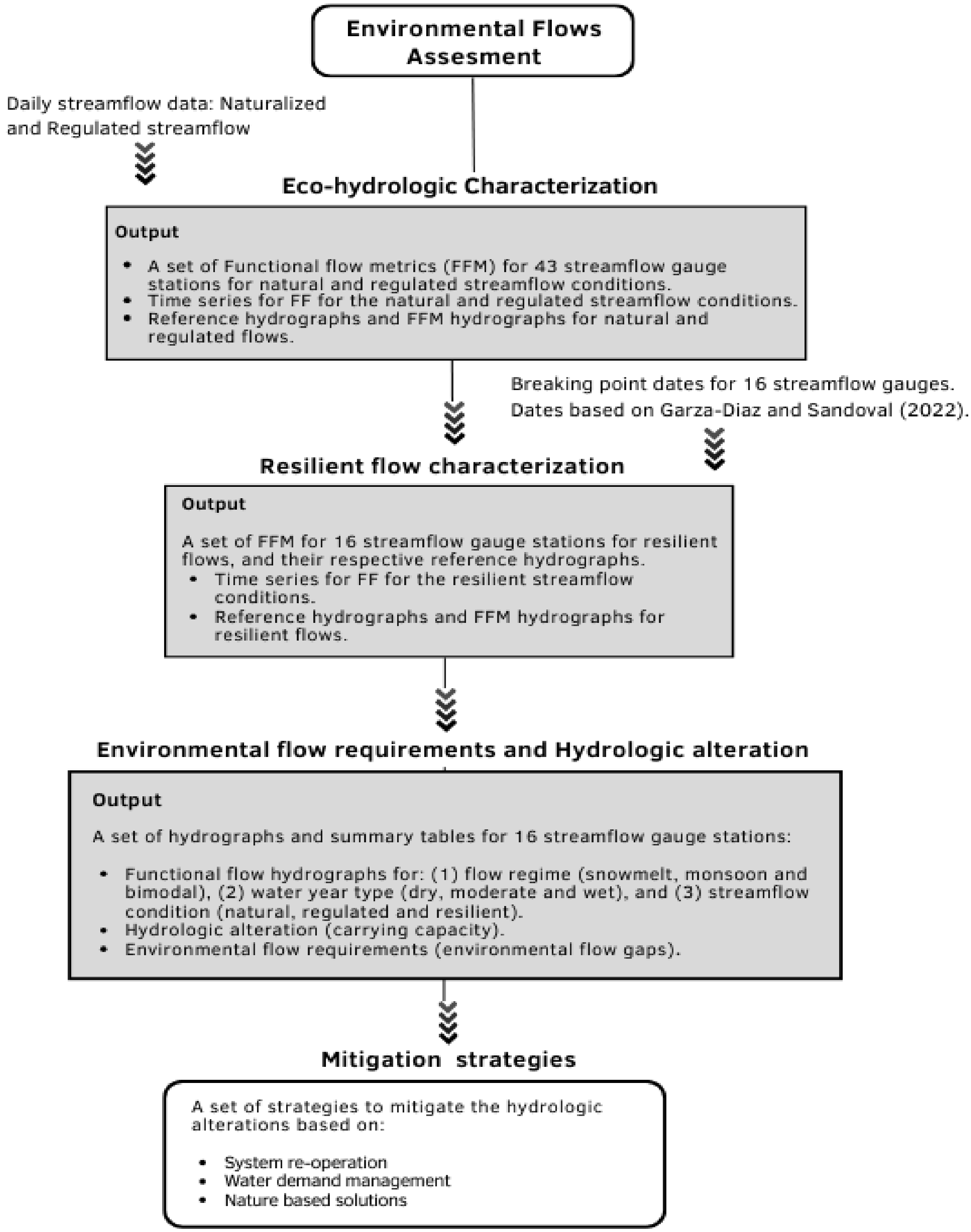


Figure 4. Overall methodology to estimate environmental flow requirements, environmental flow gaps and mitigation strategies in the RGB.

3.1 Functional Flows Approach

3.1.1 Background

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 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 analyssis of these relationships are used to determine the ranges of flow events that are ecologically relevant for the freshwater and riparian ecosystems.

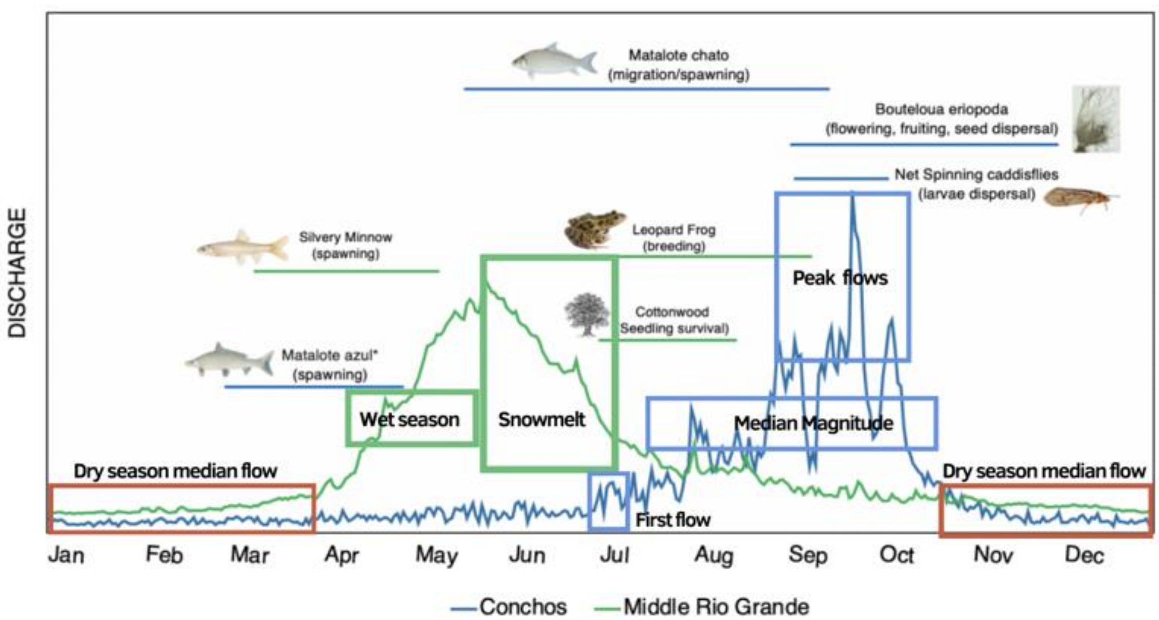
Functional flow components and flow events were defined based on previous work (Patterson and Sandoval-Solis, 2022) and expanded with consultations with experts in the basin. This study aligns with the results of Patterson and Sandoval (2022) as follows:

- Dry season median magnitude flow event here is named as dry season median flow,
- Spring flood median and spring flood peak flow events here are named as wet season median flow and snowmelt, respectively.
- Monsoon median magnitude and monsoon magnitude 90th are named as monsoon median flow and monsoon peak flow, respectively.
- Patterson and Sandoval-Solis (2022) did not consider monsoon first pulse events because their analysis was done on snowmelt. The northern branch of the RGB that has a snowmelt natural streamflow class, and the monsoon first pulse is characteristic only on monsoon driven natural streamflow classes.

There are three functional flow components and six *flow events* used in the calculations of the RGB flows (**Table A.**).

Table A. 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		
Monsoon (M)	Monsoon median magnitude flow	10th percentile	Low flow
		50th percentile	Median flow
		90th percentile	High flow
	Monsoon peak flow Monsoon first pulse		



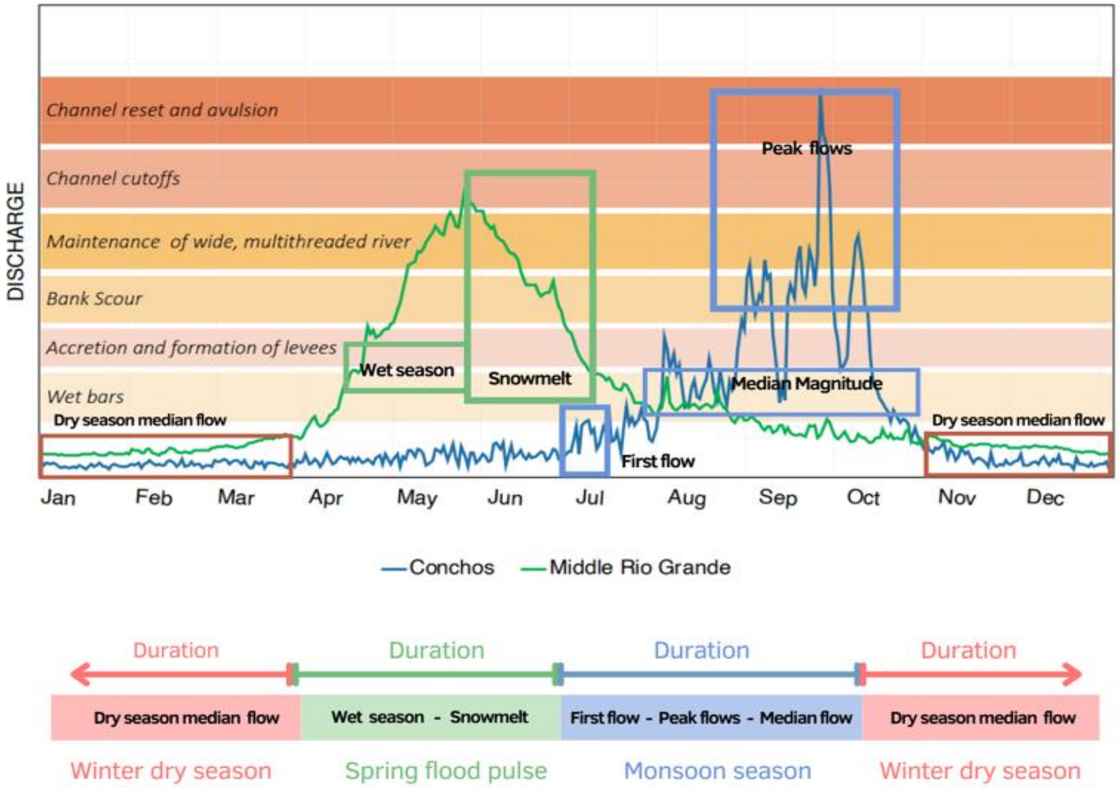


Figure 5. FFC and ecosystem functions in the Rio Conchos and Middle Rio Grande. Biotic (above) and abiotic (below) responses for the snowmelt flow regime of the Middle Rio Grande and for the hurricane-driven flow regime of the Conchos River.

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.

3.2 Functional Flow Components

This section describes each functional flow component and their respective flow events for the RGB.

3.2.1 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.

3.2.2 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.

3.2.3 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.

3.3 Functional Flow Metrics

Table 1 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.

Table 1. 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			

3.3.1 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 6** shows the reference hydrographs and Functional Flow Components for the three natural streamflow classes of the RGB. **Table 2** shows the functional flow components and flow events calculated for each streamflow class.

Table 2. 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 **(Figures 6 and 7)**. The Rio Conchos (**Figures 6 and 11)**, 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 6 and 15**), their flow regime is influenced by snowmelt and monsoon-driven climatic conditions.

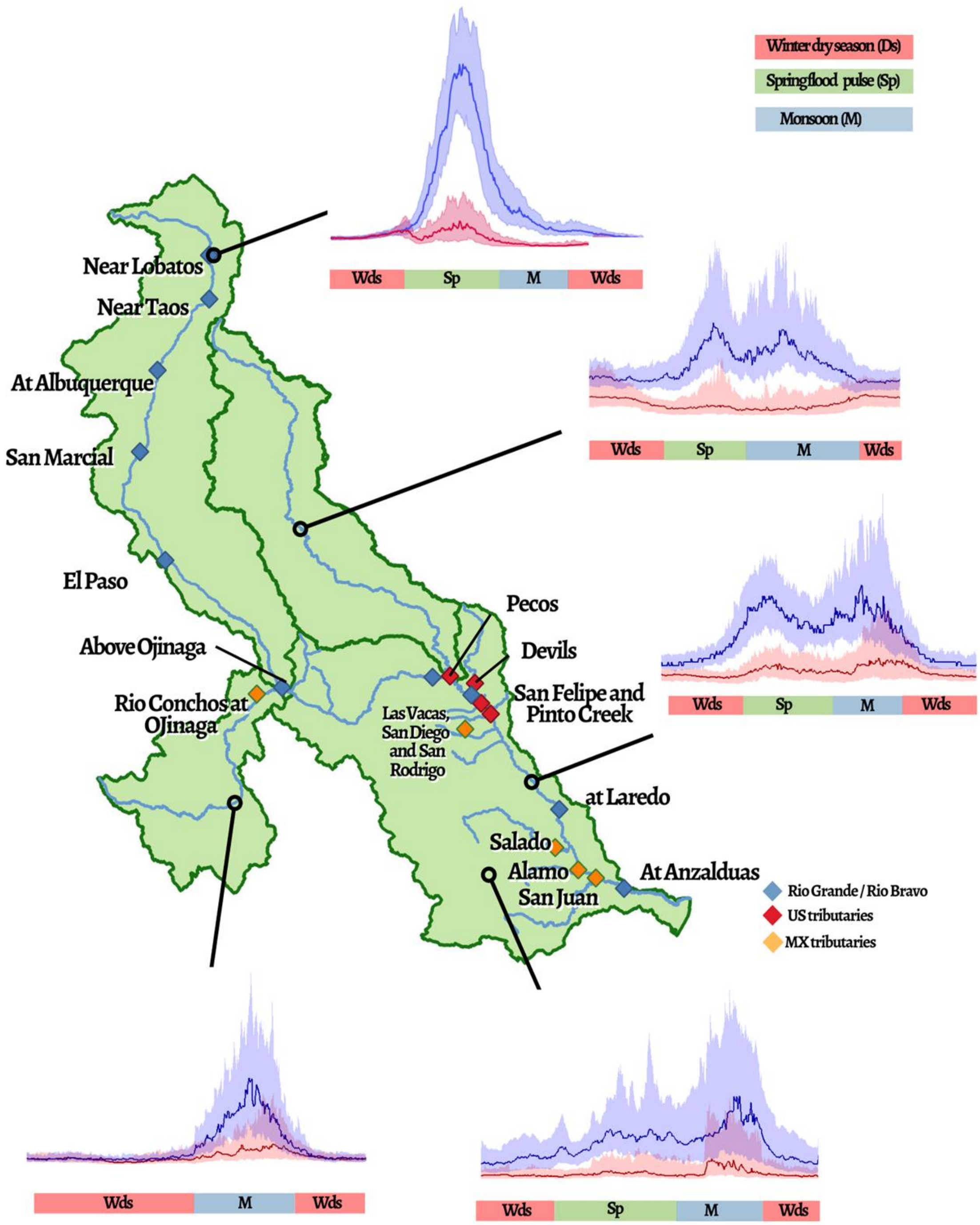


Figure 6. Examples of the functional flow components along the Rio Grande-Bravo basin. The Northern branch of the RGB is characterized by Winter dry season baseflow, Snowmelt flow, and Spring flood pulse; Southern Branch of RGB and Pecos River typically show the five components. Conchos, as well as most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

3.3.2 Ecosystem Functions

Ecosystem functions are the essential processes and activities that occur within the river ecosystem, they contribute to the health and stability of the river. Each functional flow event is related to a physical, biogeochemical, and biological ecosystem function (Table 3), and in turn, each flow event of the FFC can be associated with flow characteristic of magnitude (M), timing (T), duration (D), rate of change (R), and frequency (F). The occurrence of these flow events is often associated with specific flow characteristics, which are key parameters that describe the flow conditions.

Magnitude refers to the volume of water of an event, this associated flow characteristic allows the transport of sediment and nutrients, as well as channel shape. Timing and duration indicate when the flow occurs and the length respectively, they also refer to the annual and seasonal cycle of the flow events. Timing and Duration are crucial for the breeding and migration of different species, water availability, and germination or growth of vegetation. Frequency indicates when a flow occurs within a given time frame and it is related to processes of nutrient and sediment cycling and deposition. The rate of change measures how quickly a flow condition changes.

Table 3. Summary of the three functional flow components, their associated flow events, ecosystem functions or processes, and flow characteristics in the RGB basin.

FFC	Flow Event	Ecosystem Function Type	Ecosystem Function or Process	Associated Flow Characteristic	References
Winter dry season	**Dry season median flow**	Physical	Sediment accumulation on the channel bed	M,D	Dean et al., 2011; Escobar-Arias and Pasternack, 2010
		Physical	Maintain water table levels and soil moisture	M,D	Postel and Richter 2003
		Biogeochemical	Nutrient enrichment concentration	M,D	Ning et al., 2010
		Biogeochemical	Maintain water temperature and dissolved oxygen	M,D,T,R	Postel and Richter 2003
		Biological	Support conditions for spawning	M,D,T	Heard 2012; WWF 2009
		Biological	Enhanced growth rates of planktonic algae, followed by rapid growth and turnover of zooplankton	M,D,T	Humphries et al., 2020
		Biological	Concentration of prey for native predators	M,D,T	Ning et al., 2010
		Biological	Maintain habitat patches for reproduction of native fishes	M,D,T	Falke et al., 2010; Gido and Propst 2012
		Biological	Fish establishment and defending of nests M	M,D	WWF 2009
Monsoon	**Monsoon median flow**	Physical	Maintained a wide, sandy, multithreaded river	M,D,F	Dean and Schmidt 2013
		Physical	Scouring the channel bed of the river and offsetting the effects of sediment accumulation	M,D	Dean and Schmidt, 2011; Escobar-Arias and Pasternack, 2010
		Physical	Evacuates fine sediment	M,D,R	Dean et al., 2016
		Physical	Morpho dynamic changes of in-channel units and habitats	M,D,F	Wyrick and Pasternack, 2015; Weber and Pasternack, 2017
		Biogeochemical	Addition of organic matter and nutrient flush	M,D	Nilsson and Malm 2008
		Biogeochemical	Respiration and soil carbon dynamics in riparian plants	M,T,F	Williams et al., 2006; Maier et al., 2011
		Biogeochemical	Increase turbidity and sedimentation	M,D,R	Nilsson and Malm 2008
		Biogeochemical	Restore water quality after prolonged low flows	M,D	Postel and Richter 2003
		Biological	Flowering, fruiting, and seed dispersal	M,D,T	Simonin, 2000
		Biological	Drifting and dispersal of eggs and larvae	M,D,R	Humphries et al., 2020
		Biological	Reduction of predator density	M,D	Postel and Richter 2003

	Monsoon peak flow	Physical	Sediment deposition and construction of levees	M,D,F	Dean et al., 2011; Filgueira-Rivera et al., 2007
			Bank scouring	M,D,F	Dean et al., 2011
		Biogeochemical	Increase photosynthetic gas exchange	M,D	Fravolini et al., 2005
			Modify salinity conditions in estuaries	M,D	Postel and Richter 2003
		Biological	Provides cues for fish migration	M,D,T	WWF 2009
			Support conditions for spawning	M,D,T	Heard 2012
			Aerate eggs in spawning sites	M,D	Postel and Richter 2003
	Monsoon first Pulse	Physical	Sediment deposition and construction of levees	M,D,F	Dean et al., 2011; FilgueiraRivera et al., 2007
			Bank scouring	M,D,F	Dean et al., 2011
		Biogeochemical	Increase photosynthetic gas exchange	M,D	Fravolini et al., 2005
			Modify salinity conditions in estuaries	M,D	Postel and Richter 2003
		Biological	Provides cues for fish migration	M,D,T	WWF 2009
			Support conditions for spawning	M,D,T	Heard 2012
			Aerate eggs in spawning sites	M,D	Postel and Richter 2003
Spring flood pulse	**Wet season median flow**	Physical	Maintained a wide, sandy, multithreaded river	M,D,F	Dean and Schmidt 2013
			Scouring the channel bed of the river and offsetting the effects of sediment accumulation	M,D	Dean and Schmidt, 2011; Escobar-Arias and Pasternack, 2010
			Evacuates fine sediment	M,D,R	Dean et al., 2016
			Morpho dynamic changes of in-channel units and habitats	M,D,F	Wyrick and Pasternack, 2015; Weber and Pasternack, 2017
		Biogeochemical	Addition of organic matter and nutrient flush	M,D	Nilsson and Malm 2008
			Respiration and soil carbon dynamics in riparian plants	M,T,F	Williams et al., 2006; Maier et al., 2011
			Increase turbidity and sedimentation	M,D,R	Nilsson and Malm 2008

			Restore water quality after prolonged low flows	M,D	Postel and Richter 2003
		Biological	Flowering, fruiting and seed dispersal	M,D,T	Simonin, 2000
			Drifting and dispersal of eggs and larvae	M,D,R	Humphries et al., 2020
			Reduction of predator density	M,D	Postel and Richter 2003
	Snowmelt	Physical	Scouring and sediment deposition	M,D	Happ 1948
			Overbank floodplain inundation	M,D,T,F	Stone et al., 2017
			Recharge groundwater (floodplains)	M,D	Opperman et al 2017
		Biogeochemical	Decrease water temperature	D,R	Stacey, N. E., 1984
			Increase export of nutrients and primary producers from floodplain to channel	M,D	Bowen et al. 2003, Ward and Stanford 1995
		Biological	Provide hydrologic cues for fish out migration and spawning; rearing	M,T,R	Yarnell et al 2020
			Seedling survival	M, R, D	Bhattacharjee(2006)

4. 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.

4.1 Natural and Regulated Flow Regime

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 7 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.

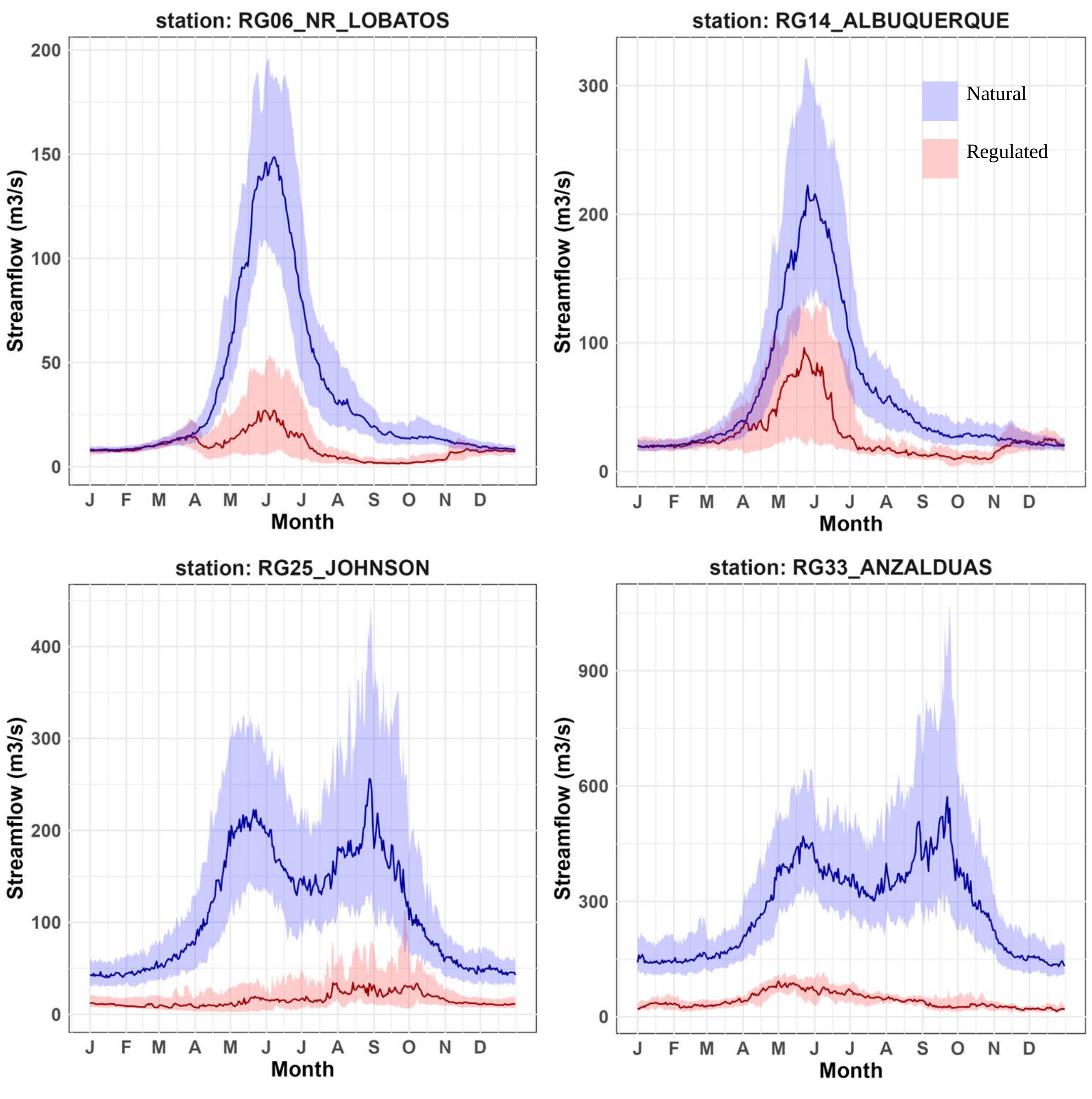


Figure 7. Natural (blue) and Regulated (red) flow regime. The interannual variability is shown by the upper bound, median flow and lower bound (25th, 50th and 75th percentile). Units: m3/s (cubic meters per second)

4.1.1 Snowmelt-driven flow regime

The snowmelt-driven flow regime is controlled by snowfall and snowmelt in the Northern branch of the RGB basin from the San Juan Mountains. There are 15 gauge stations located in the northern branch whose regime is snowmelt-driven **(Figure 8)**. FFM were calculated for 15 snowmelt-driven gauges located in the northern branch from naturalized and regulated daily streamflow time series data **(Figure 9)**. Furthermore, there are breaking points calculated for 7 streamflow gauges, thus, the resilient flow regime can be calculated prior to the breaking point (**Figure 21)**.

The snowmelt-driven regime is characterized by a steady baseflow during the dry season and a significant increase in discharge during spring due to the snowmelt. The main driver is snowfall and snowmelt. In the northern branch of the RGB, the Pacific North Monsoon is not the main driver for river streamflow, it is a component of the flow regime but is not the largest magnitude component.

Figure 9 shows the reference hydrographs in the background (shaded blue and red areas) for two flow conditions: natural and regulated flows. The shaded areas of the reference hydrographs depict the 25th percentile that represents dry conditions (lower boundary of the reference hydrograph), the median or 50th percentile flows that represent normal conditions (thick line), and the 75th percentile that represents the wet conditions (upper boundary of reference hydrograph). Reference hydrograph shows the seasonal and interannual variation of a given flow regime. **Figure 10** shows the functional flow metrics for the water year types (dry, moderate, and wet shown as red, green, and blue solid lines respectively) and the two flow conditions (natural and regulated) with the reference hydrographs as a background. The functional flow hydrographs were constructed using the FFM shown in **Table 4** and the values of **Table 5**, which is an example of the FFM calculated for each gauge station whose flow regime is snowmelt-driven.

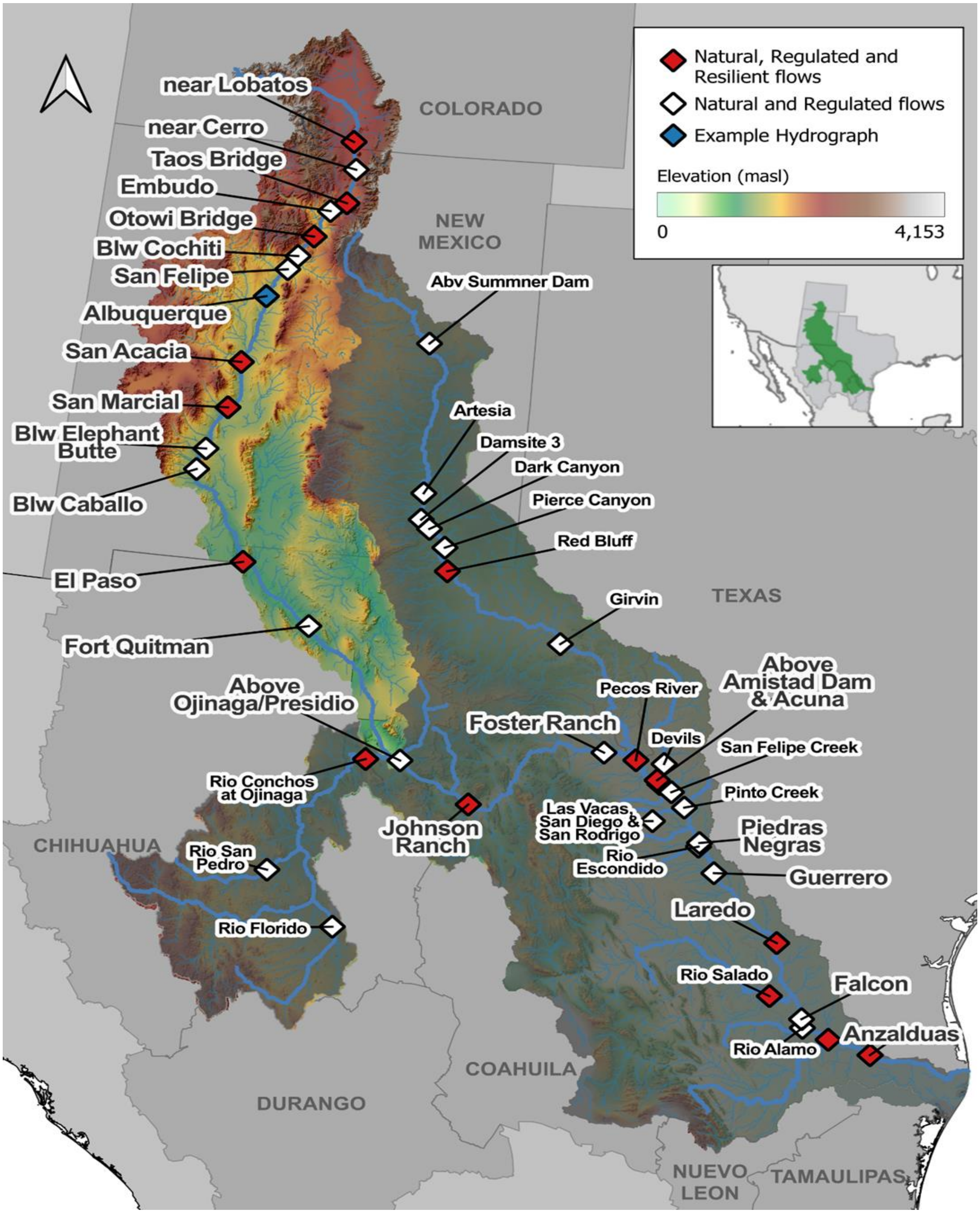


Figure 8. Gauges stations in the Northern branch of the RGB. The Functional flow regime in these stations display a Snowmelt regime behavior.

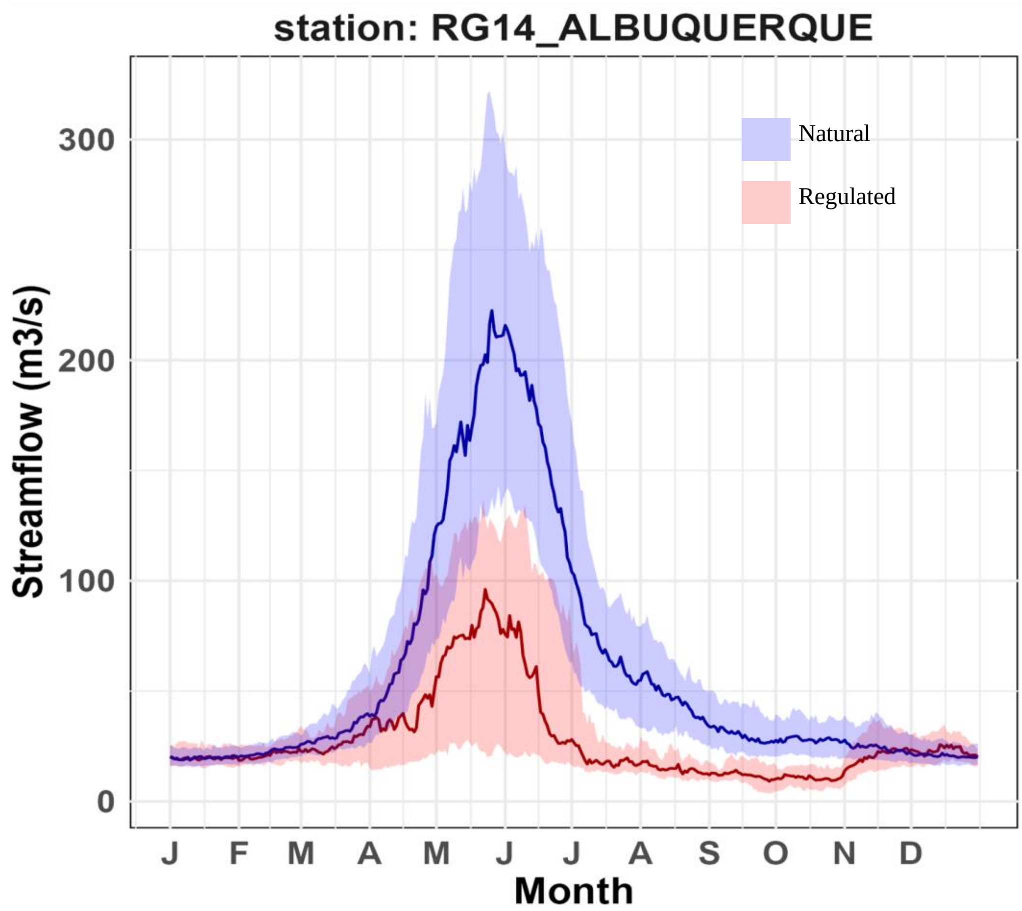


Figure 9. Comparison of natural streamflow with regulated, Rio Grande/Rio Bravo at Albuquerque, NM. Units: m3/s(cubic meters per second)

Example of a reference Hydrograph. The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

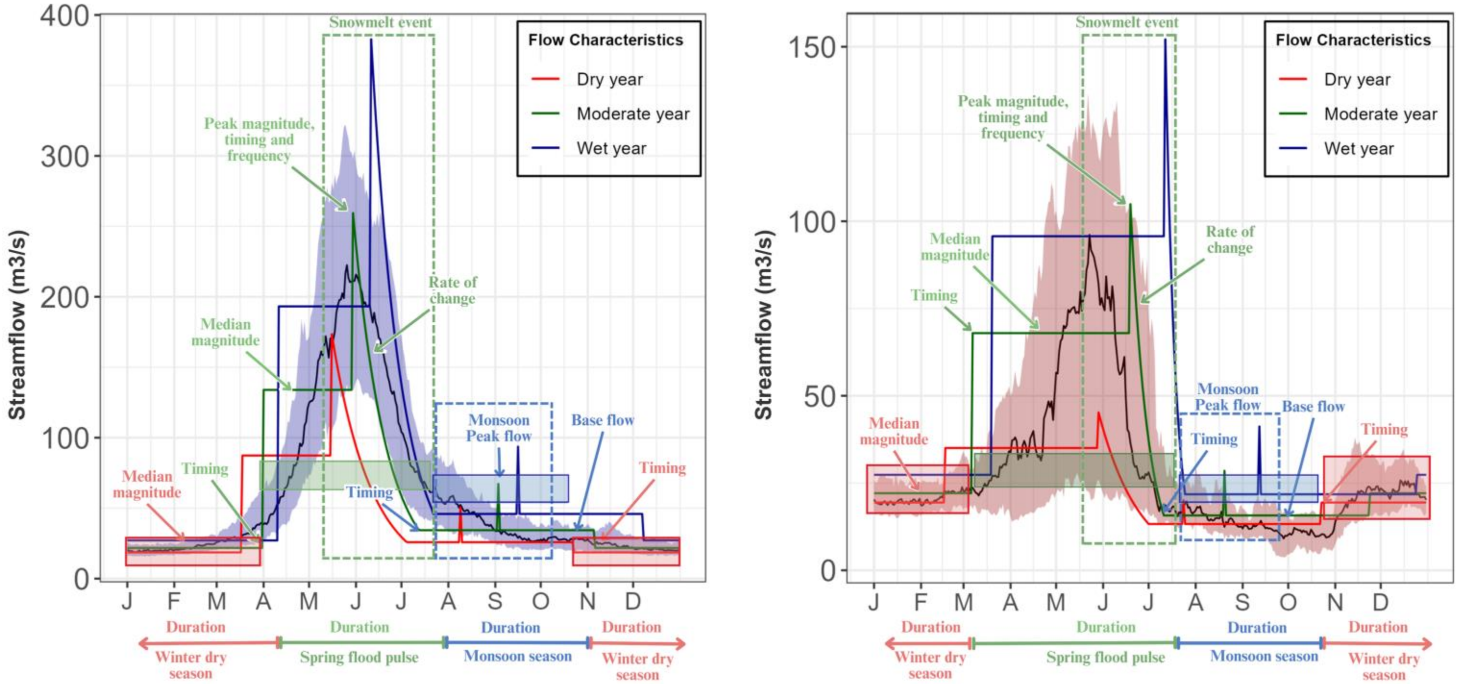


Figure 10. Functional flow metrics for the natural and regulated streamflow, Rio Grande/Rio Bravo at Albuquerque, NM. Units: m3/s (cubic meters per second)

Table 4. Albuquerque natural flow regime (above) as an example of a snowmelt driven hydrologic class and its functional flow components (below).

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

Table 5. Example of Functional Flow Components and metrics for streamflow gauges with snowmelt-driven flow regime

Gauge station : Rio Grande at Albuquerque, NM (RG14_Albuquerque)

Component/	Metric	Units	Natural flow					Regulated flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Spring Flood Pulse	Low flow: Wet season median magnitude 10th	m3/s	26	34	50	78	101	13	18	23	34	39
	Average: Wet season median magnitude 50th	m3/s	67	87	134	193	243	22	35	68	96	113
	High flow: Wet season median magnitude 90th	m3/s	125	159	254	330	431	33	72	108	146	182
	Wet season timing	DOY	69	77	91	101	105	15	48	66	79	97
	Wet season duration	Days	82	92	104	117	128	80	100	118	147	169
	Snowmelt/Highflow peak magnitude	m3/s	140	174	260	383	491	30	45	105	152	190
	Snowmelt/Highflow peak timing	Date	123	136	150	162	175	110	147	174	189	208
	Rate of Change	percent	0.0334	0.0377	0.0454	0.0498	0.0580	0.0323	0.0365	0.0827	0.1389	0.0938
Monsoon Season	Low flow: Monsoon median magnitude 10th	m3/s	13	17	22	28	35	1	4	8	11	15
	Average: Monsoon median magnitude 50th	m3/s	21	26	34	46	60	10	13	16	22	32
	High flow: Monsoon median magnitude 90th	m3/s	35	43	63	87	111	15	20	26	40	60
	Monsoon Timing	DOY	179	186	194	203	210	170	182	192	206	221
	Monsoon Peak Timing	DOY	196	221	246	259	273	170	199	243	265	283
	Monsoon Duration	Days	92	106	120	144	169	101	110	134	160	178
Winter Dry Season	Low flow: Winter dry season median magnitude 10th	m3/s	13	15	18	22	25	6	10	15	19	22
	Average: Winter dry season median magnitude 50th	m3/s	16	19	22	27	31	16	19	22	27	35
	High flow: Winter dry season median magnitude 90th	m3/s	21	26	32	42	56	19	23	29	36	43
	Winter dry season timing	DOY	296	296	310	342	358	296	296	329	359	374
	Winter dry season duration	Days	94	114	138	162	172	27	53	87	129	140

4.1.2 Monsoon driven regime.

The Monsoon-driven regime is a flow regime exclusively influenced by the North American monsoon. This regime is typical of the subbasin of the Rio Conchos (**Figure 11**) and other Mexican tributaries. FFM were calculated for 9 Monsoon gauge stations located in the tributaries' lower basin and the Rio Conchos from the natural and regulated daily streamflow time series data (**Figure 12).** There are three gauge stations with breaking points (**Figure 17)** in which the resilient flow regime can be calculated.

This flow regime exhibits distinctive features, characterized by a consistent baseflow extending from winter through spring, followed by significantly increased discharge during summer caused by the presence of storms. On multiple occasions, the presence of hurricanes increases the flow and peak discharges. The Monsoon season has a significant impact to consider environmental flows in this area, the main driver is the early heavy rains followed by the increased discharge.

Figure 12 shows the reference hydrographs, in the background (shaded blue and red areas) represents the natural and regulated flow, the lower boundary (25th percentile) represents dry conditions, the upper boundary (75th percentile) represents wet conditions, and the median or 50th percentile flows (thick line) represent normal conditions. Reference hydrograph shows the seasonal and interannual variation of the Monsoon flow regime. **Figure 13** shows the functional flow metrics for the water year types and the two flow conditions with the reference hydrographs as a background. The functional flow hydrographs were constructed using the FFM shown in **Table 6** and the values of **Table 7**, which is an example of the FFM calculated for each gauge station whose flow regime is Monsoon-driven flow regime.

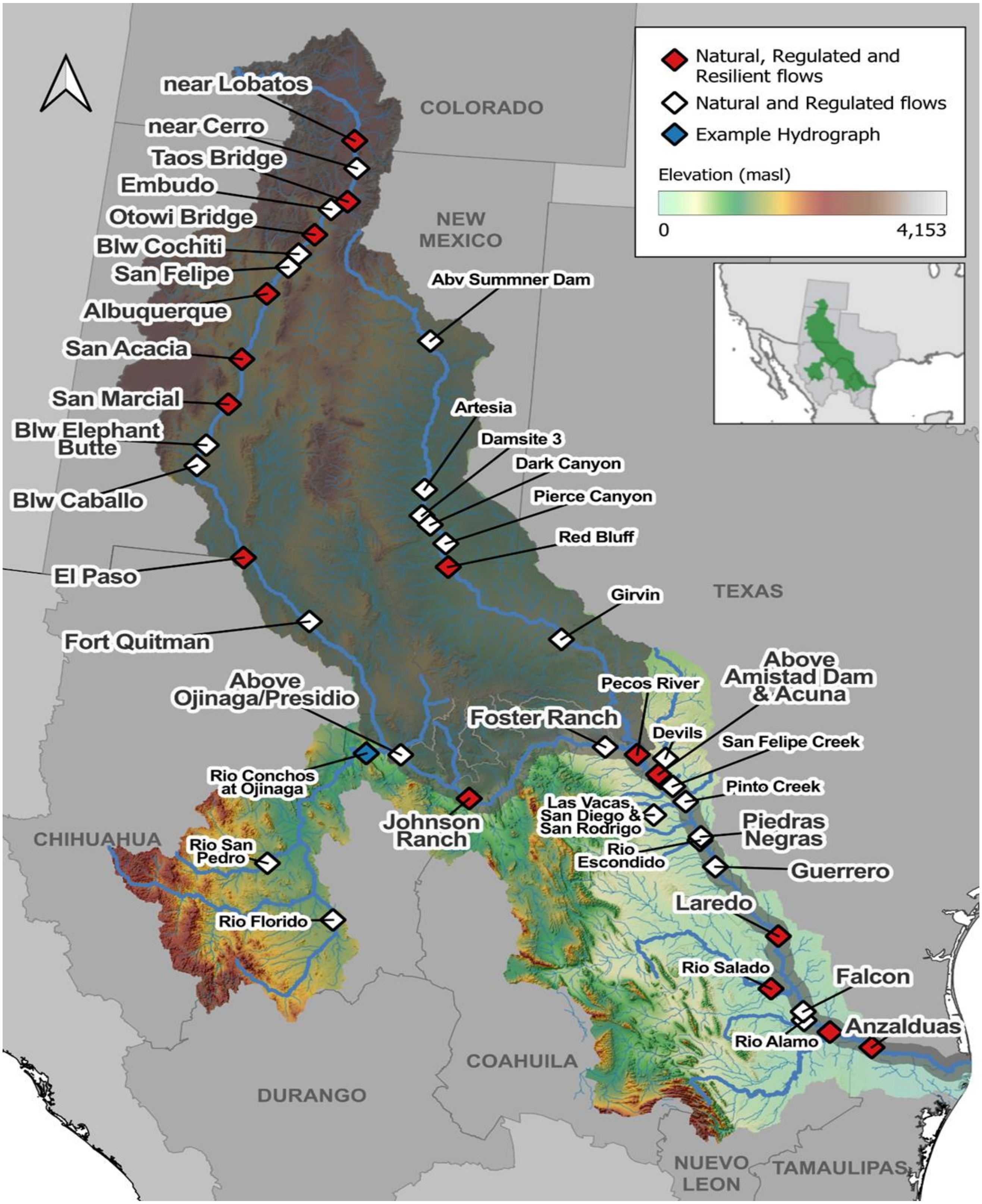


Figure 11. Station example in the outlet of the Rio Conchos subbasin. The Functional flow regime in these stations shows a Monsoon regime behavior.

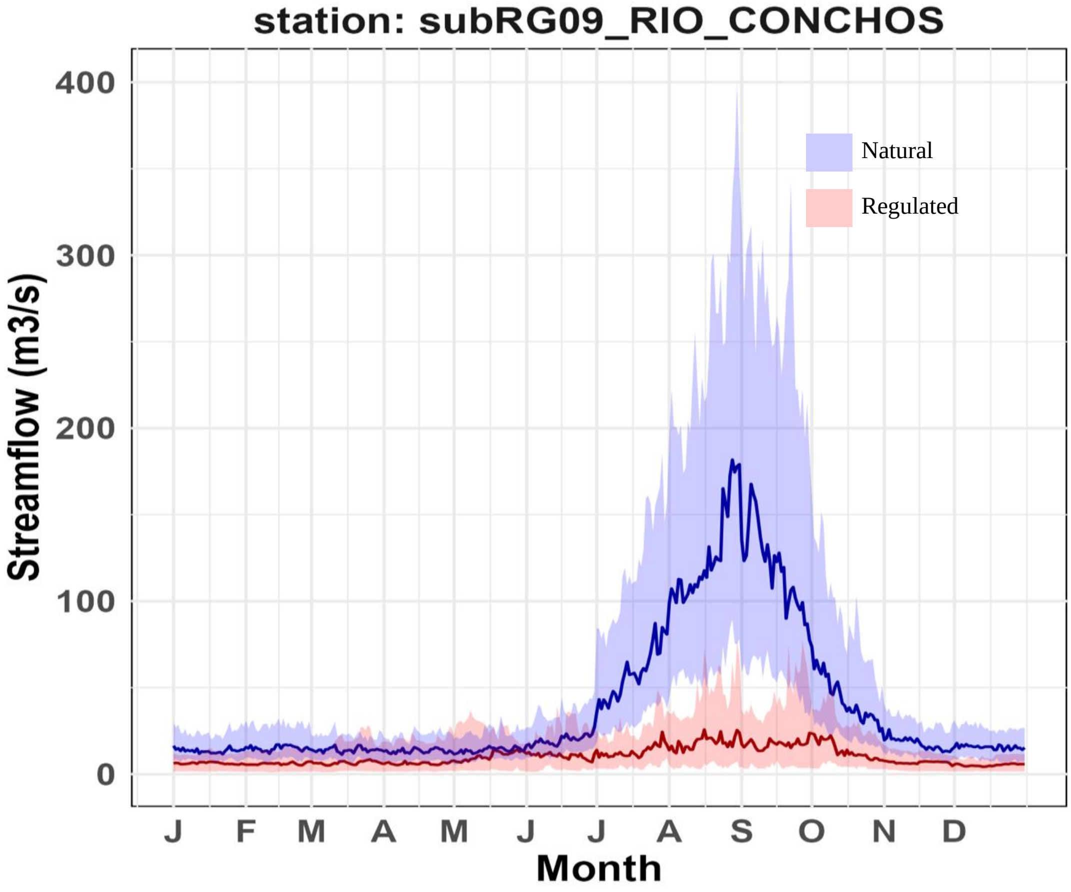


Figure 12. Comparison of natural streamflow with regulated, Rio Conchos in Mexico. Units: m3/s (cubic meters per second)

Example of a reference Hydrograph. The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

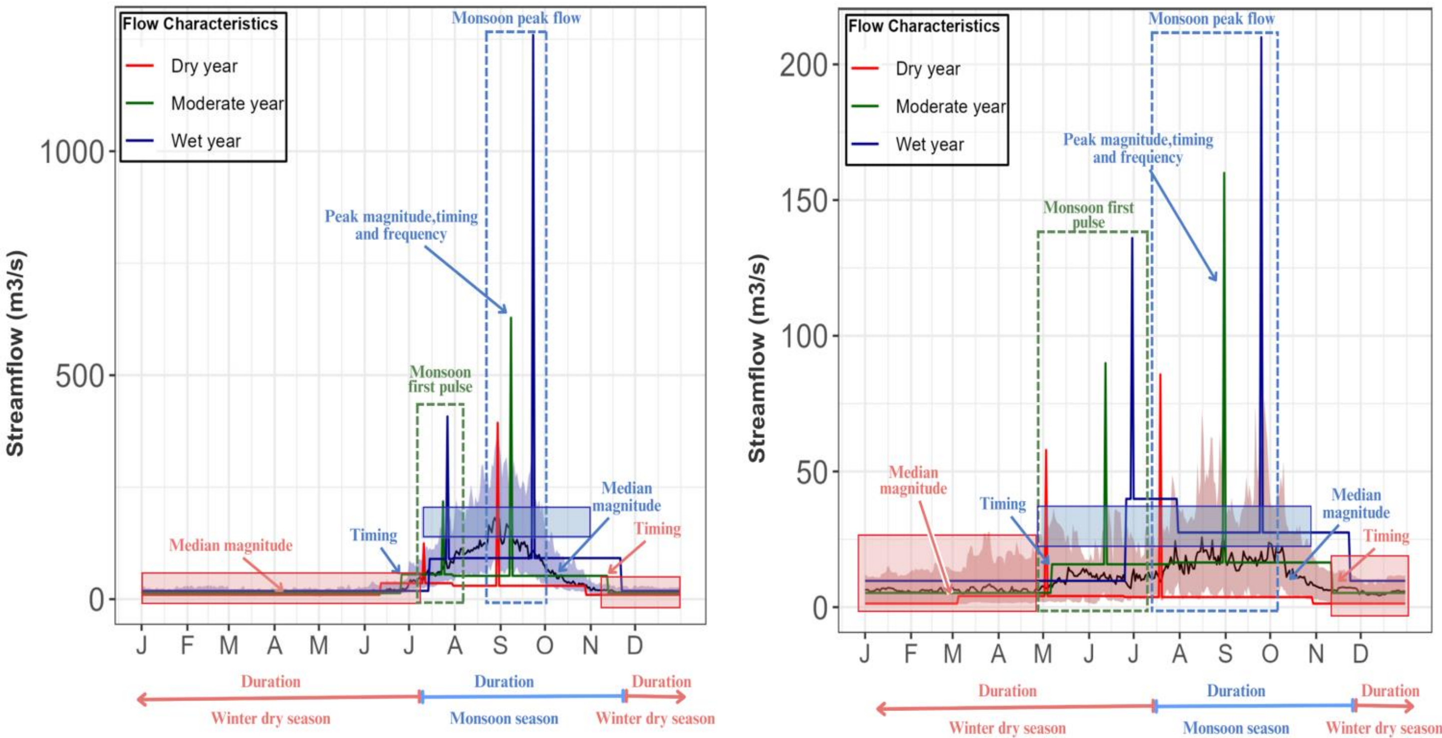


Figure 13. Functional flow metrics for the natural and regulated streamflow, Rio Conchos, Chihuahua, subbasin of the RGB. Units: m3/s (cubic meters per second)

Table 6. Conchos flow regime (above) as an example of a Monsoon driven hydrologic class and its functional flow components (below).

Flow Characteristics	Winter dry season	Monsoon Season		
	Dry season median flow	**Monsoon first pulse**	**Monsoon peak flow**	**Monsoon median flow**
Magnitude	X	X	X	X
Timing	X	X	X	X
Duration	X			X
Rate of Change				

Table 7. Example of FFC and Metrics for streamflow gauges with Monsoon driven flow regime

Gauge station: Rio Conchos Above Ojinaga (SubRGB09_Conchos)												
Components	Metric	Units	Natural flow					Regulated flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Monsoon first pulse	Low flow: Wet season median magnitude 10th	m3/s	9	14	20	31	44	1	2	9	15	26
	Average: Wet season median magnitude 50th	m3/s	23	36	55	90	151	2	4	16	40	64
	High flow: Wet season median magnitude 90th	m3/s	46	78	129	275	428	16	28	44	81	102
	Wet season timing	Date	134	163	177	196	209	43	65	127	177	215
	Wet season duration	Days	11	21	37	54	92	22	47	63	93	122
	Snowmelt/Highflow peak magnitude	m3/s	68	125	218	408	1076	21	58	90	136	253
	Snowmelt/Highflow peak timing	Date	175	192	205	208	211	83	123	163	181	206
	Rate of Change	Percent	0.10512	0.15063	0.21246	0.32708	0.38138	0.01725	0.03232	0.07922	0.16725	0.24825
Monsoon Season	Low flow: Monsoon median magnitude 10th	m3/s	5	9	15	25	32	1	2	6	12	14
	Average: Monsoon median magnitude 50th	m3/s	20	30	52	92	135	2	4	16	28	61
	High flow: Monsoon median magnitude 90th	m3/s	68	128	195	346	509	9	19	39	88	187
	Monsoon Timing	Date	212	212	212	212	212	133	176	207	212	212
	Monsoon Peak Timing	Date	228	242	251	266	275	161	200	243	269	289
	Monsoon Duration	Days	84	90	106	117	143	90	103	117	143	234
Winter Dry Season	Low flow: Winter dry season median magnitude 10th	m3/s	1	4	6	9	13	0	1	2	6	12
	Average: Winter dry season median magnitude 50th	m3/s	6	10	14	19	24	1	1	5	10	17
	High flow: Winter dry season median magnitude 90th	m3/s	15	20	34	50	63	2	3	8	17	35
	Winter dry season timing	Date	296	303	317	326	346	296	303	316	328	346
	Winter dry season duration	Days	170	204	225	244	259	87	118	173	222	278

4.1.3 Bimodal driven regime

The Bimodal driven regime is a functional flow regime influenced by both the Snowmelt and the Monsoon season. This regime is typical of the Pecos River basin and characteristic of the Lower branch of the RGB. There are 19 gauge stations, 8 located in the Pecos River and 11 in the Lower mainstream of the RGB (**Figure 14**). The FFM were calculated for the 19 gauge stations for the naturalized and regulated daily streamflow time series (**Figure 15**). Four gauge stations of the lower RGB and two gauge stations of the Pecos River have breaking points in which the resilient flow can be calculated.

This flow regime is characterized by a steady baseflow early in the year, followed by a significantly increased discharge during spring due to snowmelt that steadily decreases, and later in the year, during the summer season the monsoon presence, early storms, and some occasional hurricanes have a significant impact increasing the streamflow in these gauge stations, the lower branch of the RGB receives the water from the upper basin with snowmelt signature and the monsoon season from the Pacific North and Gulf of Mexico Monsoon. The main drivers for this flow regime are both snowmelt and monsoon.

Figure 15 shows the reference hydrograph for a gauge station characteristic of this flow regime for the natural and regulated flow and **Figure 16** shows the functional flow metrics for the water year types and the two flow conditions with the reference hydrographs as a background. The functional flow hydrographs were constructed using the FFM shown in **Table 7** and the values of **Table 8**, which is an example of the FFM calculated for each gauge station whose flow regime is Monsoon-driven flow regime.

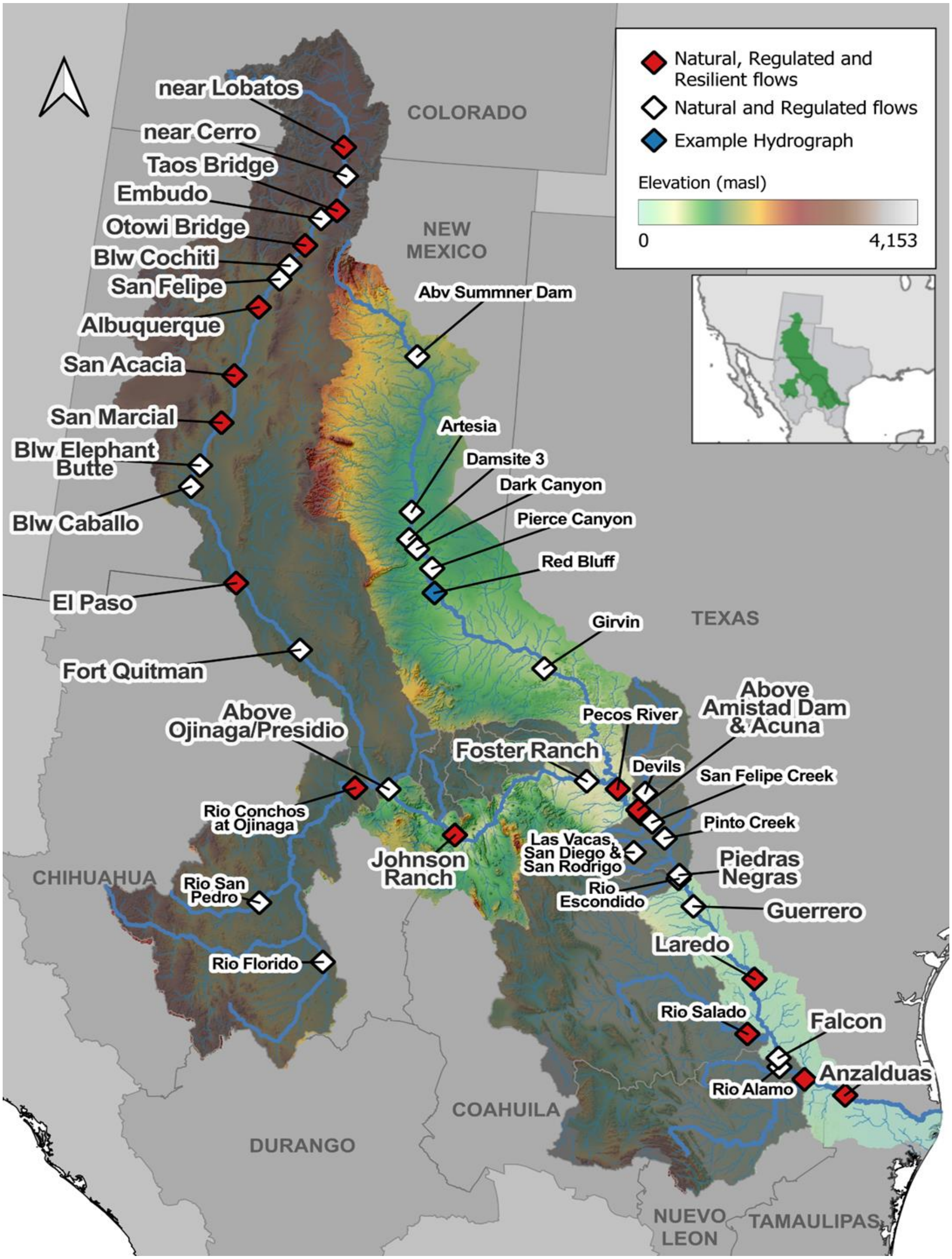


Figure 14. Gauges stations in the outlet of the Lower branch of the RGB. The Functional flow regime in these stations display a Bimodal regime behavior.

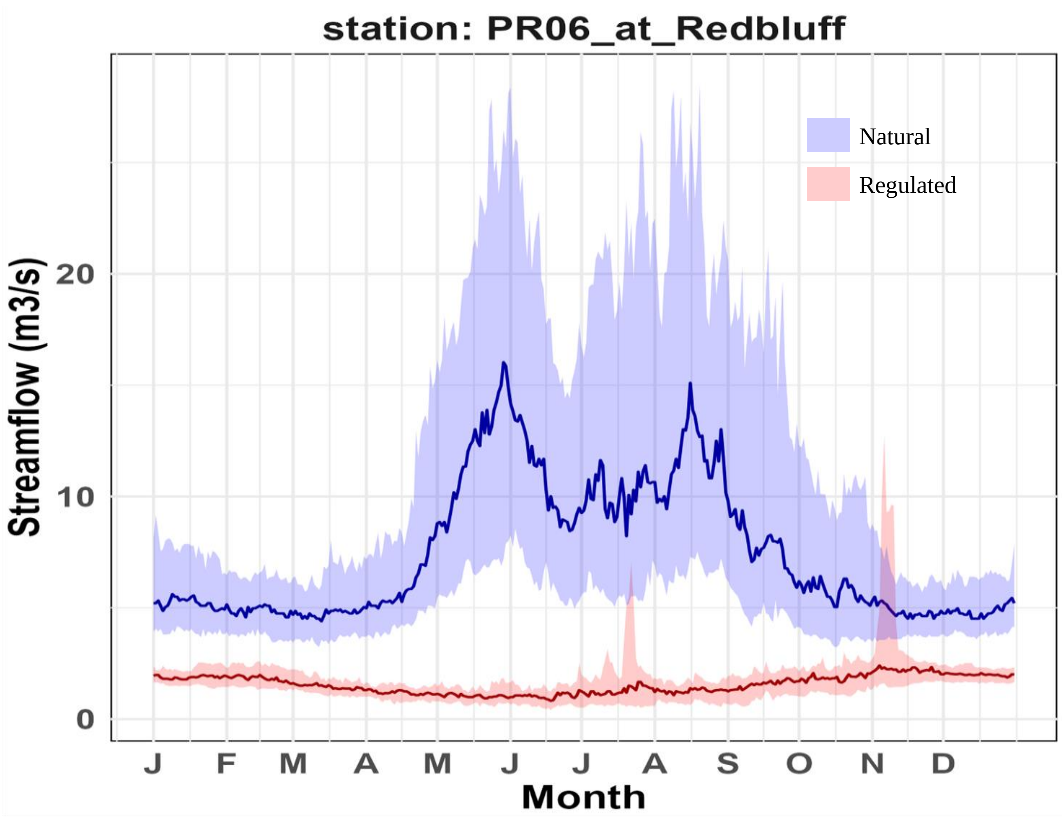


Figure 15. Comparison of natural streamflow with regulated, Pecos River, at Red Bluff,TX. Units: m3/s (cubic meters per second)

Example of a reference Hydrograph. The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

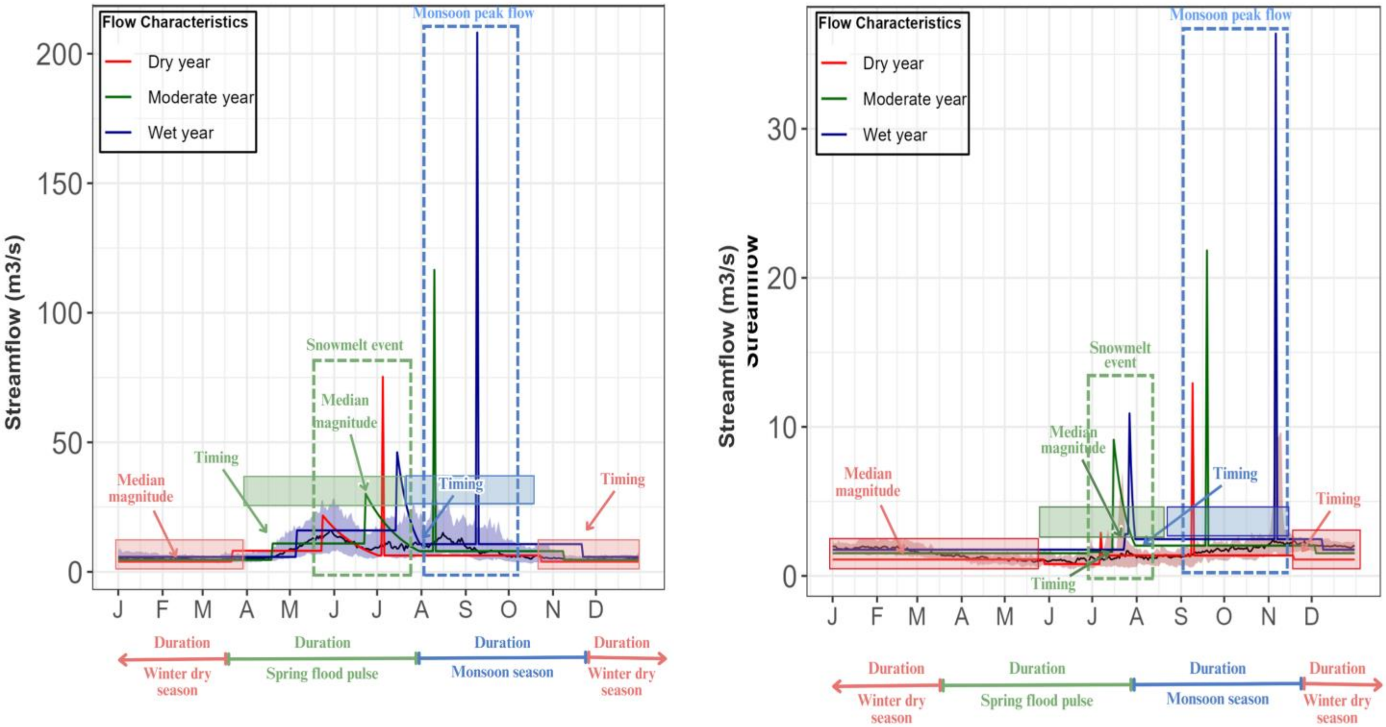


Figure 16. Functional flow metrics for the natural and regulated streamflow, Pecos River at Red Bluff, TX. Subbasin of the RGB. Units: m3/s (cubic meters per second)

Table 8. Functional flow components characteristics of a bimodal flow regime gauge station.

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

Table 9. Example of FFC and Metrics for streamflow gauges with Monsoon driven flow regime

Gauge station: Pecos River at Red bluff (PR06_at_Redbluff)												
Components	Metric	Units	Regulated flow					Resilient flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Spring Flood Pulse	Low flow: Wet season median magnitude 10th	m3/s	0.47	0.75	1.08	1.44	1.83	0.55	2.45	3.35	4.96	8.27
	Average: Wet season median magnitude 50th	m3/s	0.54	0.79	1.61	2.80	3.56	7.98	11.97	15.41	22.57	31.22
	High flow: Wet season median magnitude 90th	m3/s	1.59	9.60	14.90	52.97	379.60	33.18	61.75	119.86	945.89	1302.45
	Wet season timing	Date	37	137	165	236	282	51	81	103	134	241
	Wet season duration	Days	20	40	51	66	68	29	43	53	76	120
	Snowmelt/Highflow peak magnitude	m3/s	0.91	2.89	9.13	10.90	28.16	17.31	27.87	55.57	82.26	120.25
	Snowmelt/Highflow peak timing	Date	45	95	171	191	203	50	105	143	156	193
	Rate of Change	Percent	-0.06032	-0.04211	0.0360019	0.06838952	0.21675124	0.3954665	-0.24670085	0.0724545	0.038942743	0.107295097
Monsoon Season	Low flow: Monsoon median magnitude 10th	m3/s	0.59	0.89	1.65	2.17	2.31	0.18	0.36	0.51	0.83	7.34
	Average: Monsoon median magnitude 50th	m3/s	1.19	1.38	2.03	2.46	2.83	0.59	1.27	5.20	8.89	13.60
	High flow: Monsoon median magnitude 90th	m3/s	2.12	3.05	7.51	16.50	21.71	8.96	15.25	21.21	32.85	65.81
	Monsoon Timing	Date	50	77	212	212	212	57	91	175	212	212
	Monsoon Peak Timing	Date	95	173	262	311	323	134	160	212	248	276
	Monsoon Duration	Days	111	125	130	232	289	98	107	144	277	394
Winter Dry Season	Low flow: Winter dry season median magnitude 10th	m3/s	0.25	0.47	0.78	1.19	1.71	0.36	0.48	0.51	1.22	4.41
	Average: Winter dry season median magnitude 50th	m3/s	0.91	1.10	1.52	1.76	2.28	2.31	3.54	5.26	7.43	10.77
	High flow: Winter dry season median magnitude 90th	m3/s	1.50	1.83	2.12	2.35	2.83	4.15	6.20	10.19	11.47	15.29
	Winter dry season timing	Date	299	323	338	343	356	296	309	320	389	450
	Winter dry season duration	Days	124	178	202	276	312	70	120	150	176	217

4.2 Resilient Flow Regime

4.2.1 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 17.1). 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 17.2 and 17.3) or abrupt (Figure 17.4). For the RGB, it was estimated the variability (Figure 17 dotted black line) and bounds (Figure 17 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 17, 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.

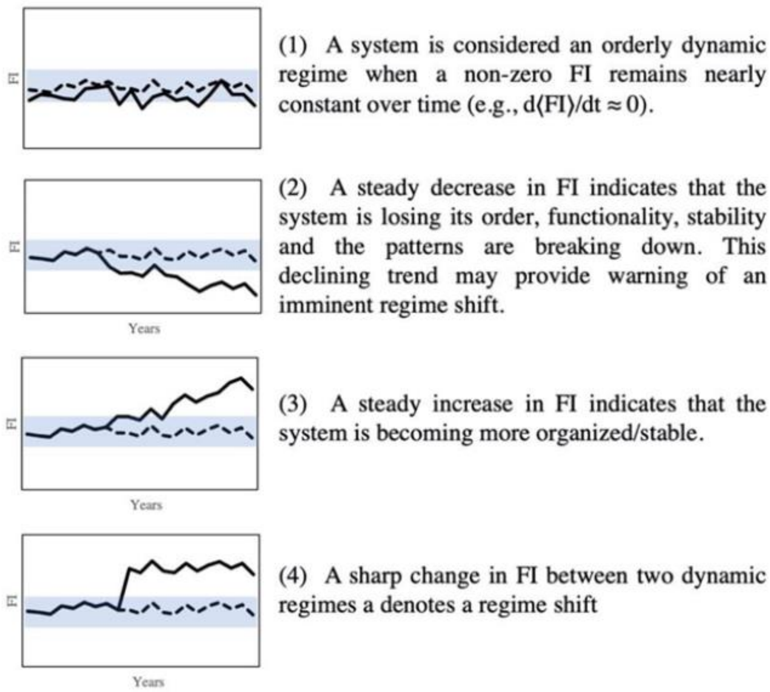


Figure 17. From Garza-Díaz, L. E., & Sandoval-Solis, S. (2022). FI patterns of the Sustainable Regime Hypothesis.

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 18**).

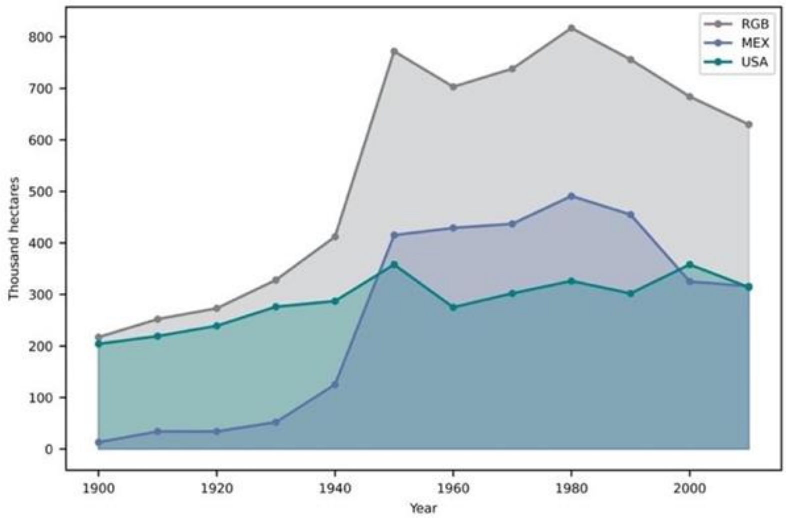


Figure 18. From [Garza-Díaz, L. E., & Sandoval-Solis, S. (2022)](). Accumulated agriculture hectares (thousand hectares) in the Rio Grande–Bravo Basin (grey)

The increasing water demand for agriculture led to an increase in water storage (**Figure 19)** 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.

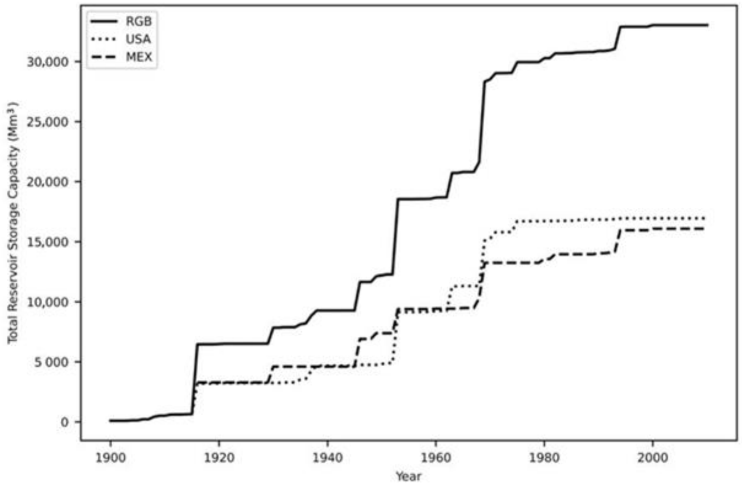


Figure 19. Total reservoir storage capacity (mm3) in the Rio Grande–Bravo Basin (33,037 mm3) and the portions of the United States (16,948 mm3) and Mexico (16,089 mm3).

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 20** and **21)** published the breaking points for 8 gauge stations and shared the data to calculate the breaking points for 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.

Breaking points for the upper basin gauge stations:

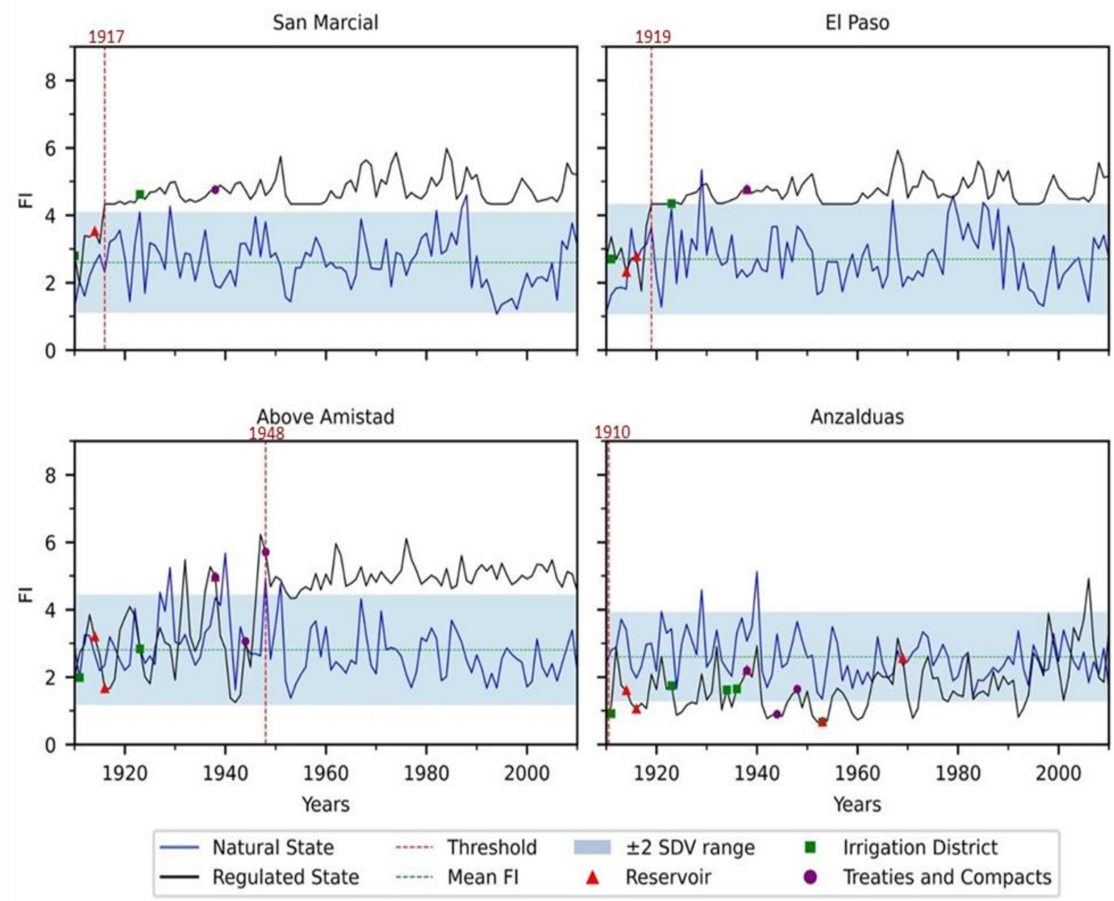


Figure 20. Breaking points obtained from the fisher index. In blue the natural flow regime and in black the regulated.

Breaking points for main tributaries:

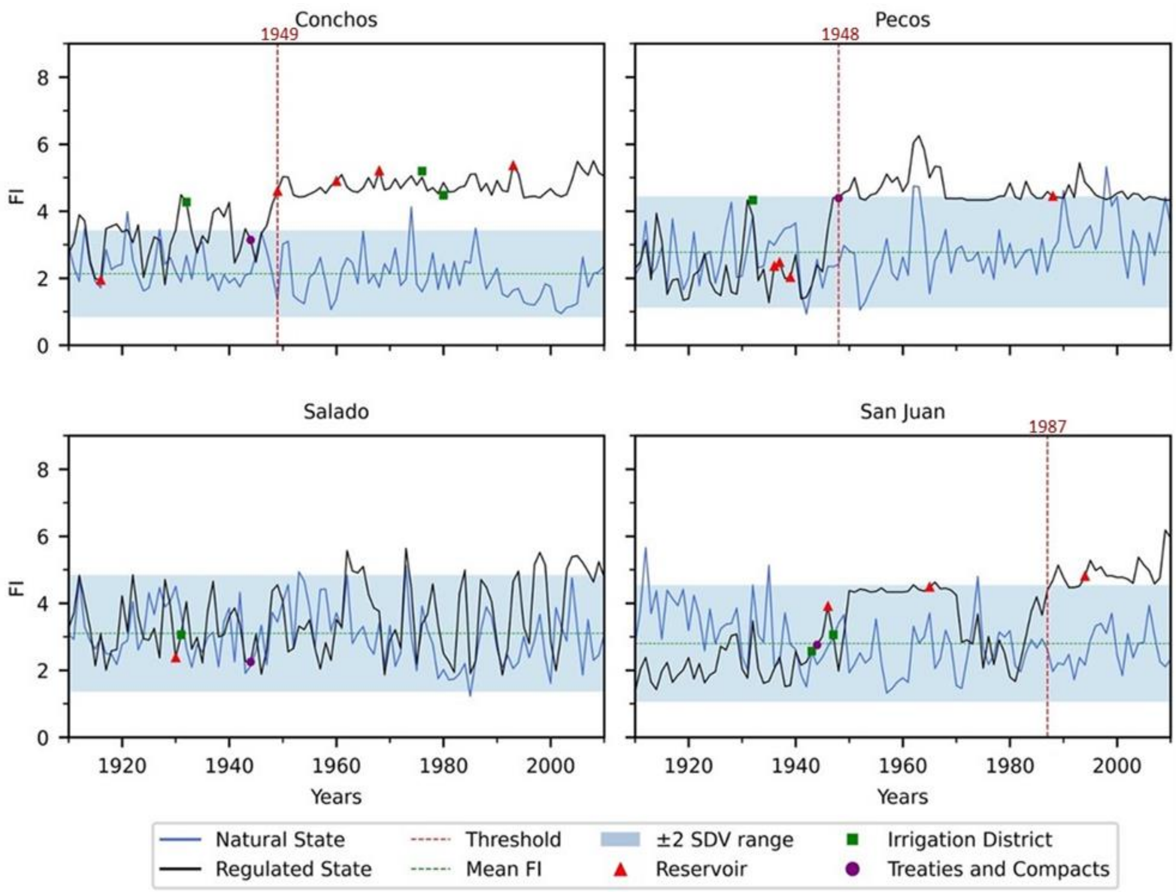


Figure 21. Breaking points obtained from the fisher index. In blue the natural flow regime and in black the regulated.

Figures 22, 23 and **25** show the reference hydrographs for the snowmelt, monsoon, and bimodal natural streamflow classes, respectively. These figures represent the interannual and seasonal hydrological variability with a closer resemblance between the natural and the resilient flow regimes as opposed to the regulated flow regime. The fundamental principle for the resilient flow regimes is to provide sustainable supply for human water needs while simultaneously providing functional flows beneficial for the ecosystem.

The FFMs for the resilient flow are calculated using the Functional Flow Calculator for the regulated streamflow before the breaking point. **Figures 22, 23** and **25** show the FFM hydrograph for all water year types during the resilient period (dry, moderate, and wet shown as red, green, and blue solid lines respectively) with the resilient reference hydrograph as a background. **Tables 10, 11 and 12** show examples of the data used to calculate the FFM hydrographs for the 16 gauge stations with breaking points.

4.2.2 Resilient snowmelt-driven regime

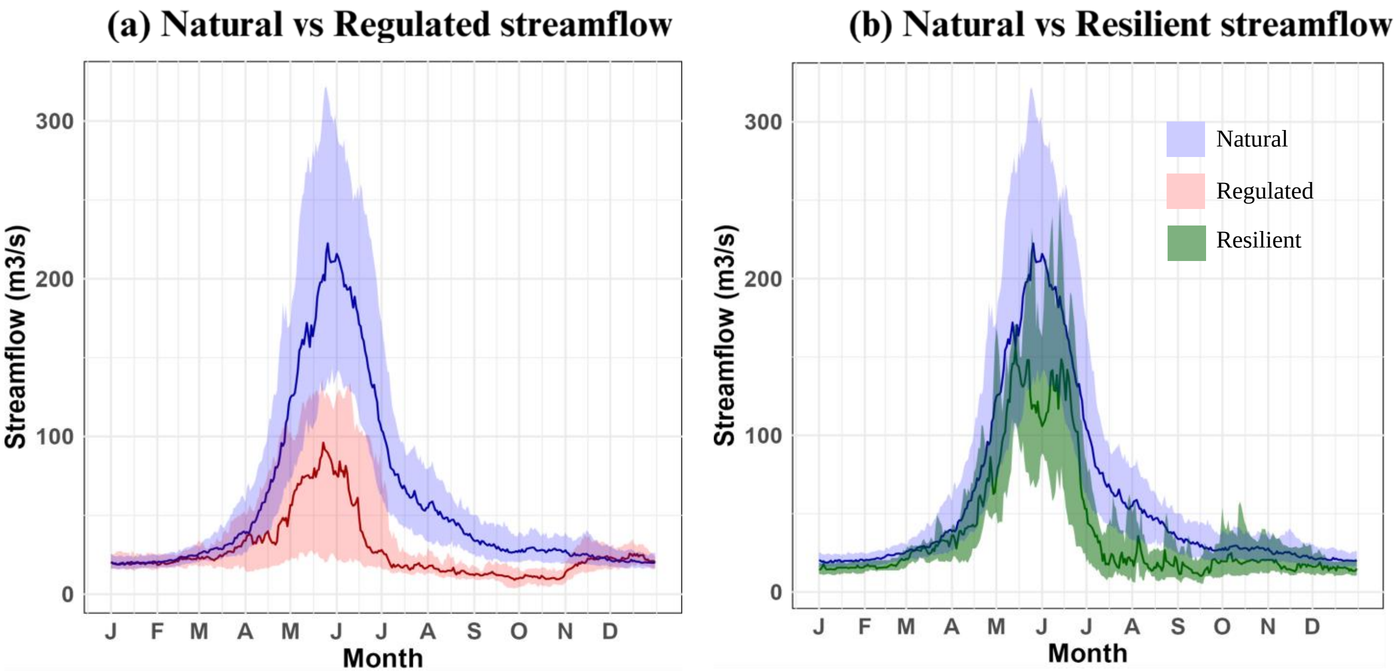


Figure 22. Comparison of natural streamflow with regulated and resilient streamflow, Rio Grande/Rio Bravo at Albuquerque, NM. Units: m3/s (cubic meters per second).

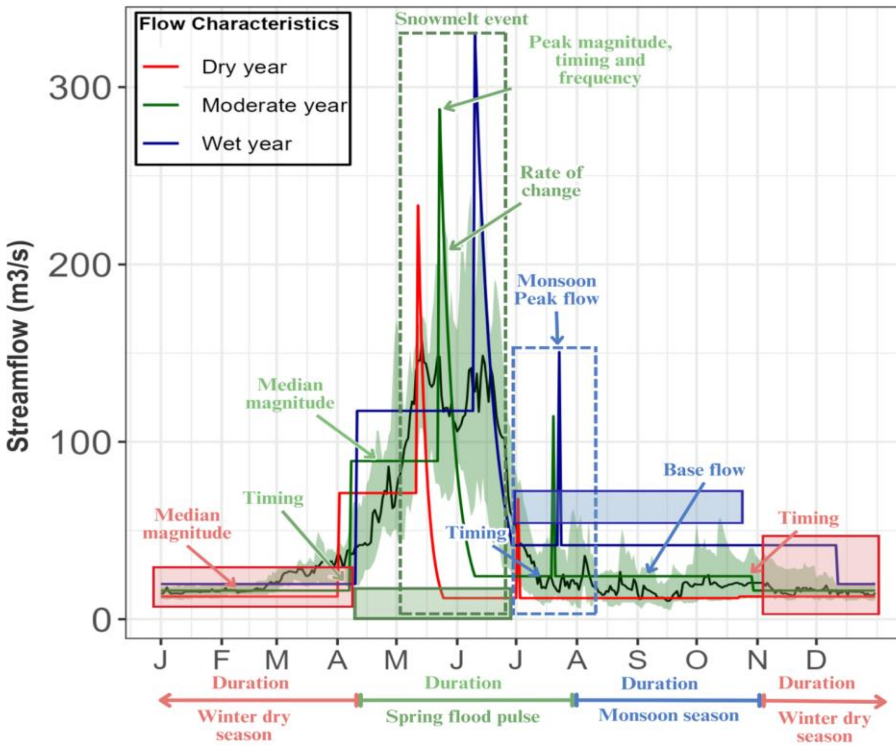


Figure 23. Functional flow metrics for the resilient streamflow. Rio Grande/Rio Bravo at Albuquerque, NM.

Table 10. Example of the Resilient FFC and Metrics for streamflow gauges with snowmelt driven flow regime

Gauge station : Rio Grande at Albuquerque, NM (RG14_Albuquerque)

Component/ Metric		Units	Regulated flow					Resilient flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Spring Flood Pulse	Low flow: Wet season median magnitude 10th	m3/s	13	18	23	34	39	16	23	26	43	50
	Average: Wet season median magnitude 50th	m3/s	22	35	68	96	113	49	71	89	118	136
	High flow: Wet season median magnitude 90th	m3/s	33	72	108	146	182	107	155	201	231	282
	Wet season timing	DOY	15	48	66	79	97	73	92	98	101	104
	Wet season duration	Days	80	100	118	147	169	81	89	104	112	127
	Snowmelt/Highflow peak magnitude	m3/s	30	45	105	152	190	145	233	288	329	347
	Snowmelt/Highflow peak timing	Date	110	147	174	189	208	120	132	143	161	166
	Rate of Change	(%)	0.0323	0.0365	0.0827	0.1389	0.0938	0.0522	0.0556	0.0707	0.1000	0.1057
Monsoon Season	Low flow: Monsoon median magnitude 10th	m3/s	1	4	8	11	15	4	5	10	21	24
	Average: Monsoon median magnitude 50th	m3/s	10	13	16	22	32	8	12	24	42	54
	High flow: Monsoon median magnitude 90th	m3/s	15	20	26	40	60	42	68	115	151	193
	Monsoon Timing	DOY	170	182	192	206	221	135	145	161	180	269
	Monsoon Peak Timing	DOY	170	199	243	265	283	177	183	201	204	210
	Monsoon Duration	Days	101	110	134	160	178	93	108	113	142	164
Winter Dry Season	Low flow: Winter dry season median magnitude 10th	m3/s	6	10	15	19	22	7	9	11	19	20
	Average: Winter dry season median magnitude 50th	m3/s	16	19	22	27	35	11	13	16	20	23
	High flow: Winter dry season median magnitude 90th	m3/s	19	23	29	36	43	19	21	29	39	51
	Winter dry season timing	DOY	296	296	329	359	374	296	296	303	346	351
	Winter dry season duration	Days	27	53	87	129	140	106	117	146	165	170

4.2.3 Resilient Monsoon-driven regime

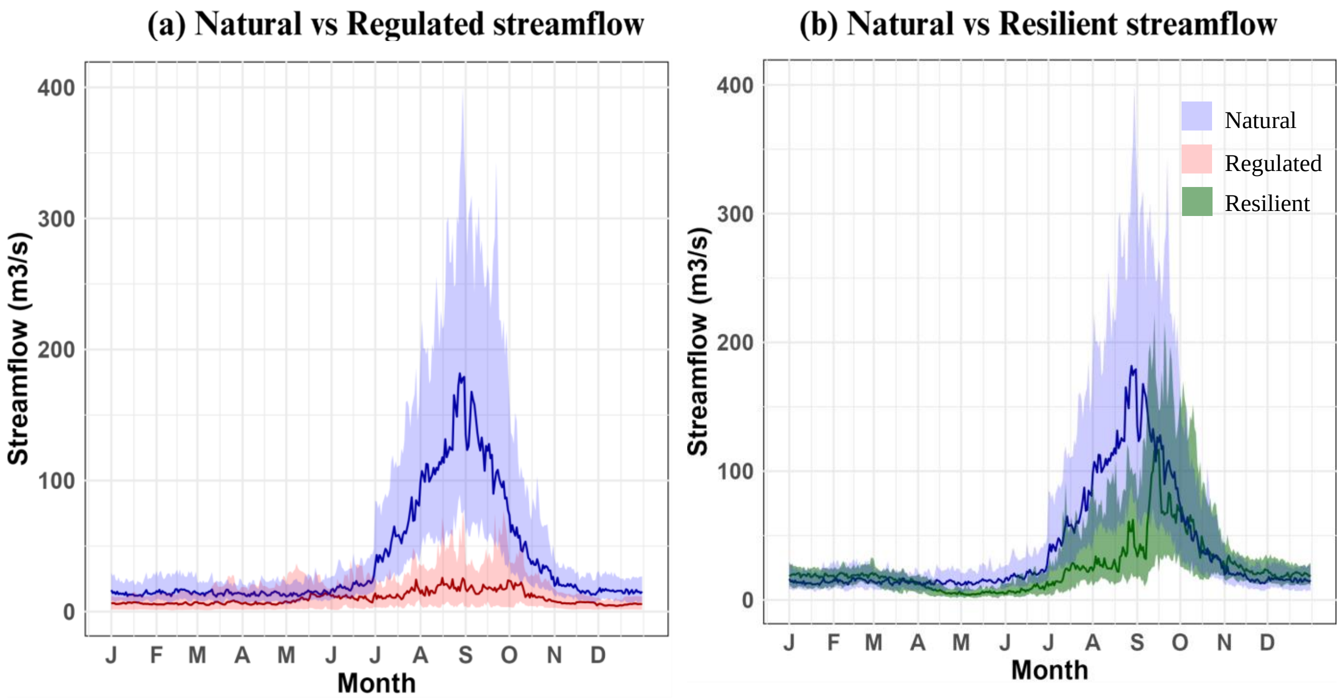


Figure 23. Comparison of natural streamflow with regulated and resilient streamflow, Rio Conchos, Chihuahua, Mexico. Units: m3/s (cubic meters per second)

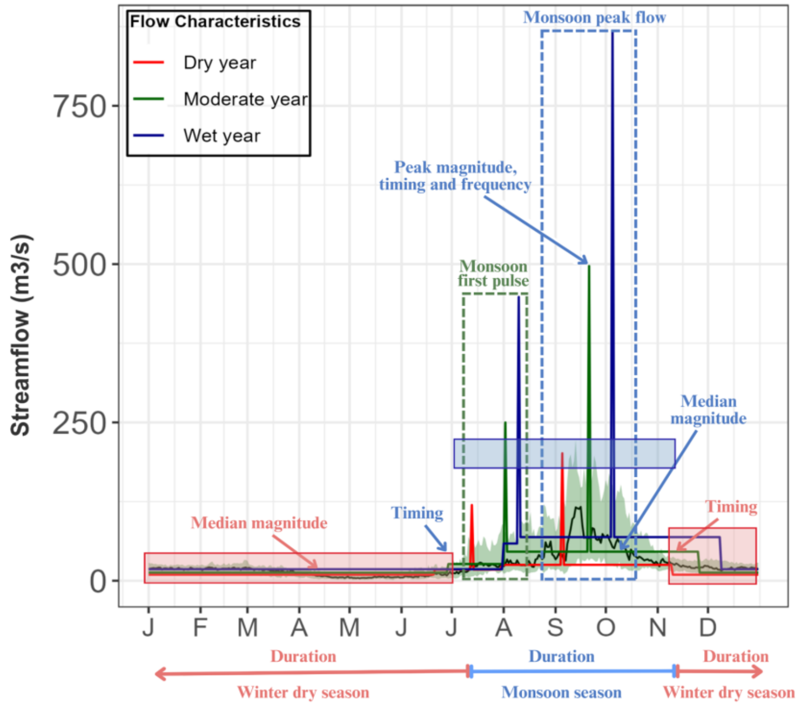


Figure 24. Functional flow metrics for the resilient streamflow, Rio Conchos, Chihuahua, Mexico

Table 11. Example of the Resilient FFC and Metrics for streamflow gauges with monsoon driven flow regime Resilient Bi-modal driven regime.

Gauge station: Rio Conchos Above Ojinaga (SubRGB09_Conchos)

Components	Metric	Units	Regulated flow					Resilient flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Spring Flood Pulse	Low flow: Wet season median magnitude 10th	m3/s	1	2	9	15	26	0	1	3	11	16
	Average: Wet season median magnitude 50th	m3/s	2	4	16	40	64	11	18	26	59	94
	High flow: Wet season median magnitude 90th	m3/s	16	28	44	81	102	36	74	119	241	325
	Wet season timing	Date	43	65	127	177	215	65	162	192	230	325
	Wet season duration	Days	22	47	63	93	122	17	32	45	66	7
	Snowmelt/Highflow peak magnitude	m3/s	21	58	90	136	253	99	120	250	448	624
	Snowmelt/Highflow peak timing	Date	83	123	163	181	206	126	163	194	207	210
	Rate of Change	Percent	0.01725	0.03232	0.07922	0.16725	0.24825	0.08642	0.11253	0.13942	0.16984	0.23857
Monsoon Season	Low flow: Monsoon median magnitude 10th	m3/s	1	2	6	12	14	6	15	18	28	37
	Average: Monsoon median magnitude 50th	m3/s	2	4	16	28	61	14	25	46	69	105
	High flow: Monsoon median magnitude 90th	m3/s	9	19	39	88	187	46	66	137	317	432
	Monsoon Timing	Date	133	176	207	212	212	105	7109	17551	30583	55714
	Monsoon Peak Timing	Date	161	200	243	269	289	234	248	264	278	294
	Monsoon Duration	Days	90	103	117	143	234	94	212	212	212	6
Winter Dry Season	Low flow: Winter dry season median magnitude 10th	m3/s	0	1	2	6	12	0	0	1	4	6
	Average: Winter dry season median magnitude 50th	m3/s	1	1	5	10	17	5	10	13	18	22
	High flow: Winter dry season median magnitude 90th	m3/s	2	3	8	17	35	16	18	25	29	34
	Winter dry season timing	Date	296	303	316	328	346	306	314	330	343	1201
	Winter dry season duration	Days	87	118	173	222	278	151	194	229	261	359

4.2.4 Resilient Bimodal-driven

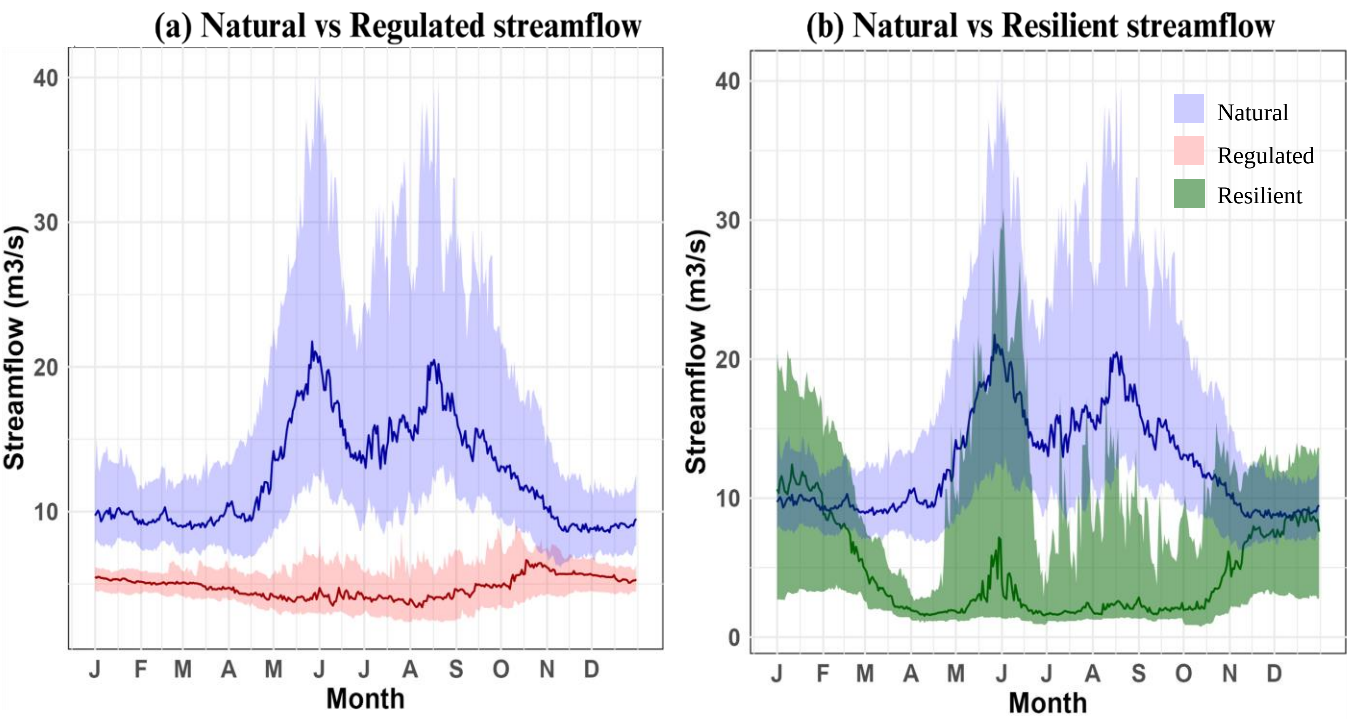


Figure 25. Comparison of natural streamflow with regulated and resilient streamflow, Pecos river at Red Bluff, NM. Units: m3/s (cubic meters per second)

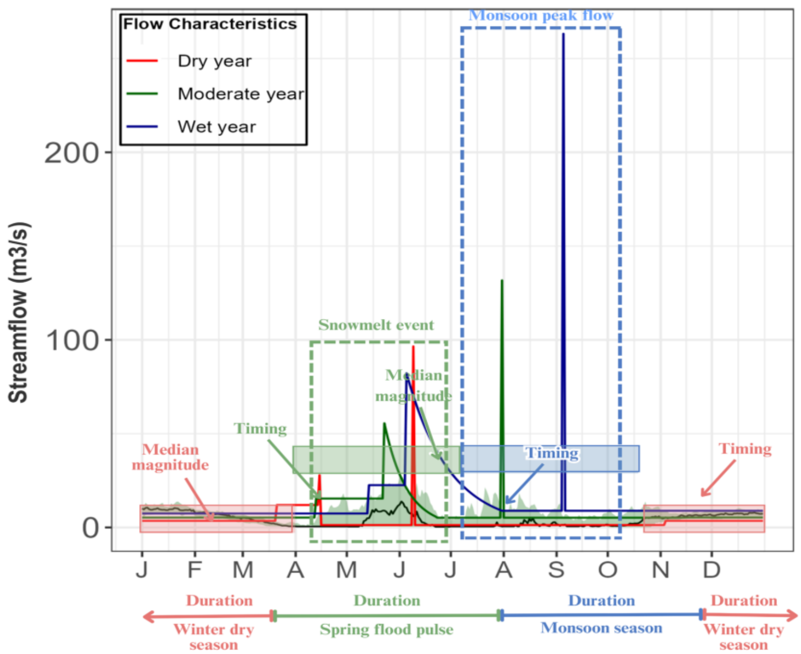


Figure 26. Functional flow metrics for the resilient streamflow, Pecos river at Red Bluff, NM.

Table 12. Example of the Resilient FFC and Metrics for streamflow gauges with bimodal driven flow regime.

Gauge station: Pecos River at Red bluff (PR06_at_Redbluff)

Components	Metric	Units	Regulated flow					Resilient flow				
			10th	25th	50th	75th	90th	10th	25th	50th	75th	90th
Spring Flood Pulse	Low flow: Wet season magnitude 10th	m3/s	0.47	0.75	1.08	1.44	1.83	0.55	2.45	3.35	4.96	8.27
	Average: Wet season median magnitude 50th	m3/s	0.54	0.79	1.61	2.80	3.56	7.98	11.97	15.41	22.57	31.22
	High flow: Wet season magnitude 90th	m3/s	1.59	9.60	14.90	52.97	379.60	33.18	61.75	119.86	945.89	1302.45
	Wet season timing	Date	37	137	165	236	282	51	81	103	134	241
	Wet season duration	Days	20	40	51	66	68	29	43	53	76	120
	Snowmelt/Highflow peak magnitude	m3/s	0.91	2.89	9.13	10.90	28.16	17.31	27.87	55.57	82.26	120.25
	Snowmelt/Highflow peak timing	Date	45	95	171	191	203	50	105	143	156	193
	Rate of Change	Percent	-0.06032	-0.04211	0.0360019	0.06838952	0.21675124	0.3954665	-0.24670085	0.0724545	0.038942743	0.107295097
Monsoon Season	Low flow: Monsoon magnitude 10th	m3/s	0.59	0.89	1.65	2.17	2.31	0.18	0.36	0.51	0.83	7.34
	Average: Monsoon median magnitude 50th	m3/s	1.19	1.38	2.03	2.46	2.83	0.59	1.27	5.20	8.89	13.60
	High flow: Monsoon magnitude 90th	m3/s	2.12	3.05	7.51	16.50	21.71	8.96	15.25	21.21	32.85	65.81
	Monsoon Timing	Date	50	77	212	212	212	57	91	175	212	212
	Monsoon Peak Timing	Date	95	173	262	311	323	134	160	212	248	276
	Monsoon Duration	Days	111	125	130	232	289	98	107	144	277	394
Winter Dry Season	Low flow: Winter dry season magnitude 10th	m3/s	0.25	0.47	0.78	1.19	1.71	0.36	0.48	0.51	1.22	4.41
	Average: Winter dry season median magnitude 50th	m3/s	0.91	1.10	1.52	1.76	2.28	2.31	3.54	5.26	7.43	10.77
	High flow: Winter dry season magnitude 90th	m3/s	1.50	1.83	2.12	2.35	2.83	4.15	6.20	10.19	11.47	15.29
	Winter dry season timing	Date	299	323	338	343	356	296	309	320	389	450
	Winter dry season duration	Days	124	178	202	276	312	70	120	150	176	217

4.3 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 27)**. 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 28)**. 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.

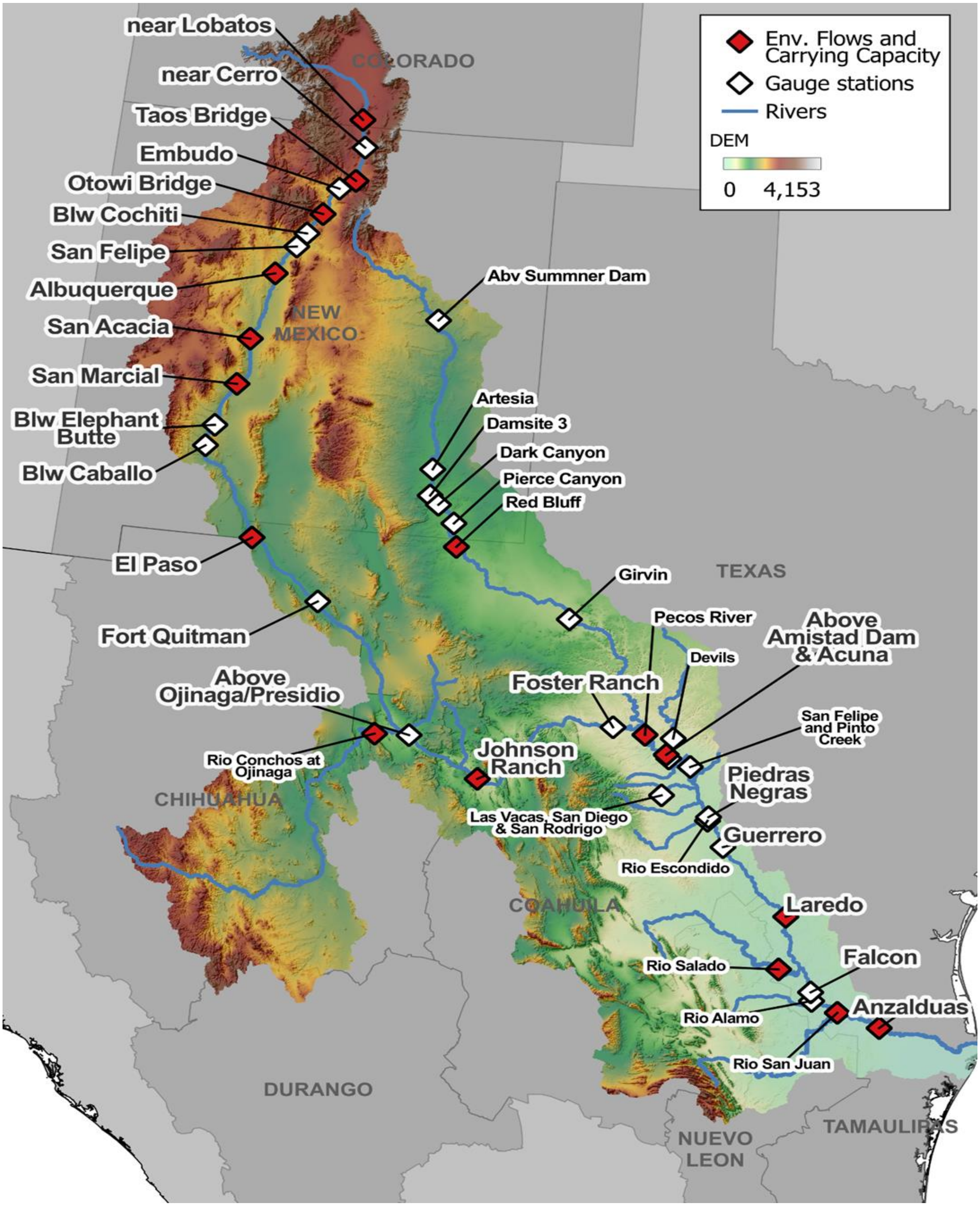


Figure 27. Gauge stations where environmental flow gaps and carrying capacity was calculated.

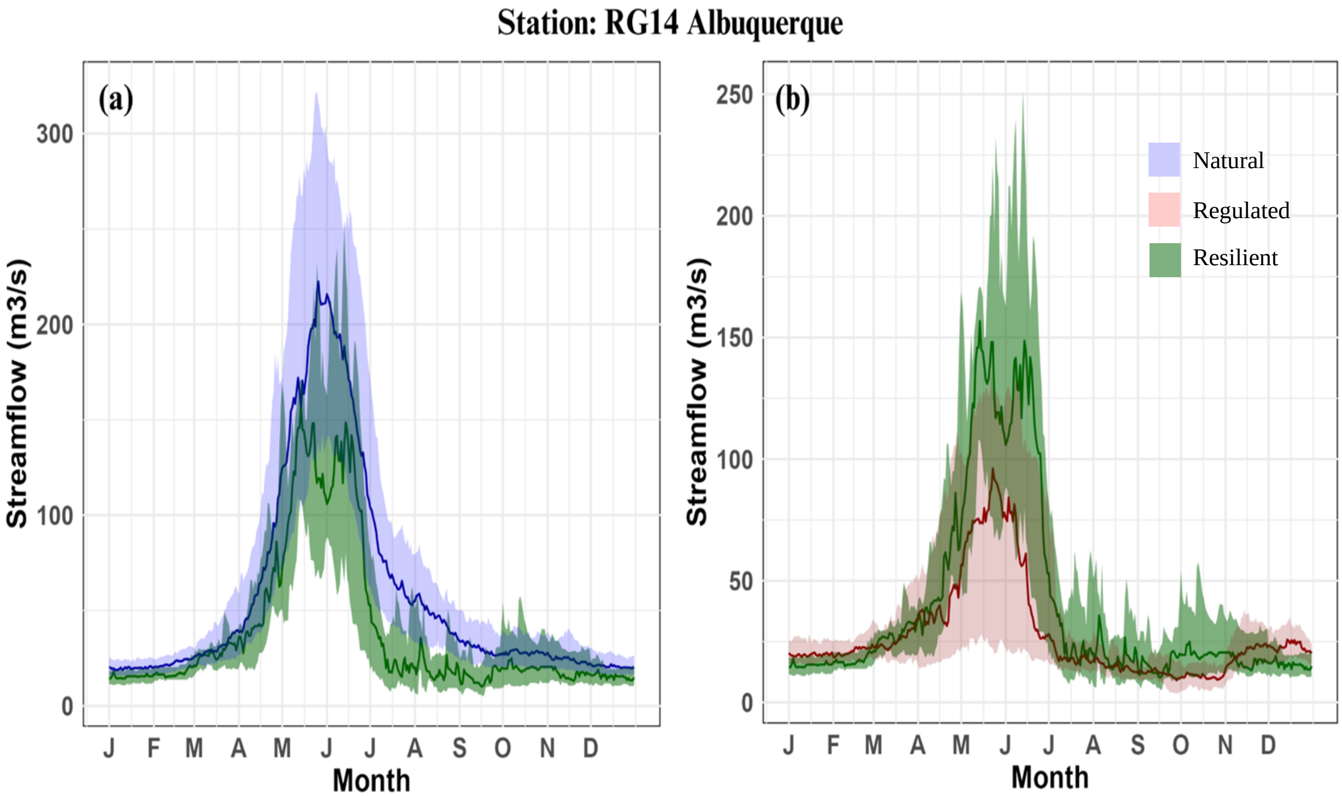


Figure 28. Comparison of (a) natural with resilient streamflow and (b) Regulated with Resilient streamflow, Rio Grande/Rio Bravo at Albuquerque, NM. Units: m3/s (cubic meters per second)

4.3.1 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 29)**, it describes the magnitude of disturbance that natural flow regime can absorb before changing into a different flow regime. Hydrologic alterarion 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 13).**

Table 13. Example of the metrics (cfs) 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	

Table 14 shows an example for estimating the carrying capacity for each functional flow components and water year types of a snowmelt streamflow class and **Table 15** 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.

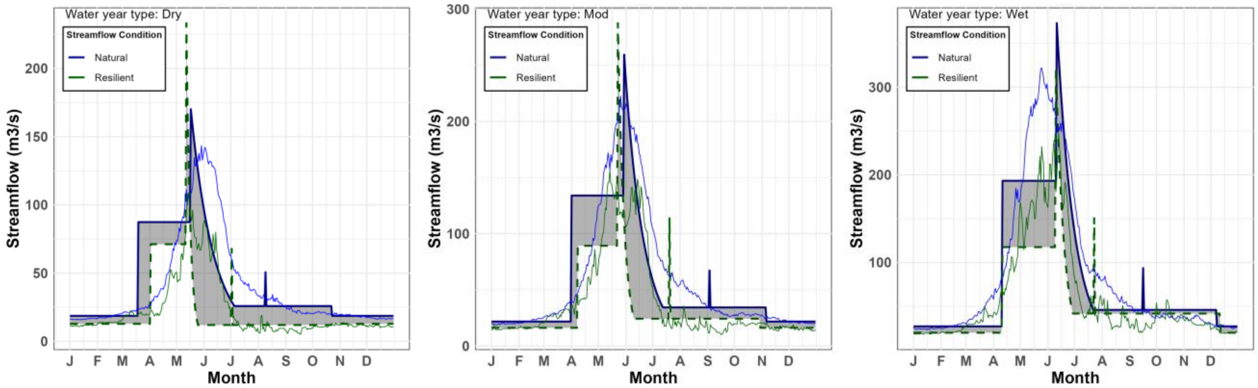


Figure 29. Carrying capacity for Albuquerque. In blue the natural FFM and green the resilient FFM, the shaded area represents the hydrologic alteration that can be absorbed by the system before reaching the breaking point.

Table 14. 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 15. 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 3**) 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.

4.4 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 30**). 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 16** and **17** 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.

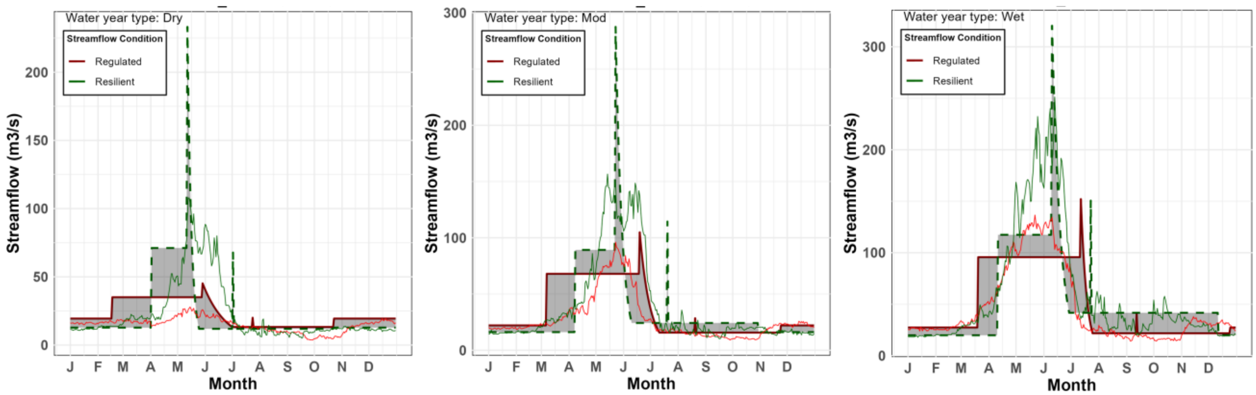


Figure 30. Environmental flow gap for Albuquerque. In red the regulated FFM and in green the resilient FFM, the shaded area represents the volume as a surplus or deficit from the current altered state and a resilient streamflow.

Table 16. 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 17. 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.

Strategies

1. 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**.**

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 31**). 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.

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 implementn water conservation practices.

Nature based solutions.

Nature bases solutions are economically and evironmentally desirable. They tipically 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 cathegory, the places in the RGB where they are most helpful and the environmental flow components that would benefited most from them are found in **Table 18**. The potential to implement such strategies considering the water demand, the coordination on stakeholders and the current legal framework can be found in **Table 19**. In addition, a map with the sumarry values of the environmental flow gaps and the carrying capacity per gauge station is provided in **Figure 31.** These materials where made in the hope of serve as guide to enhace the water use throughout the basin.

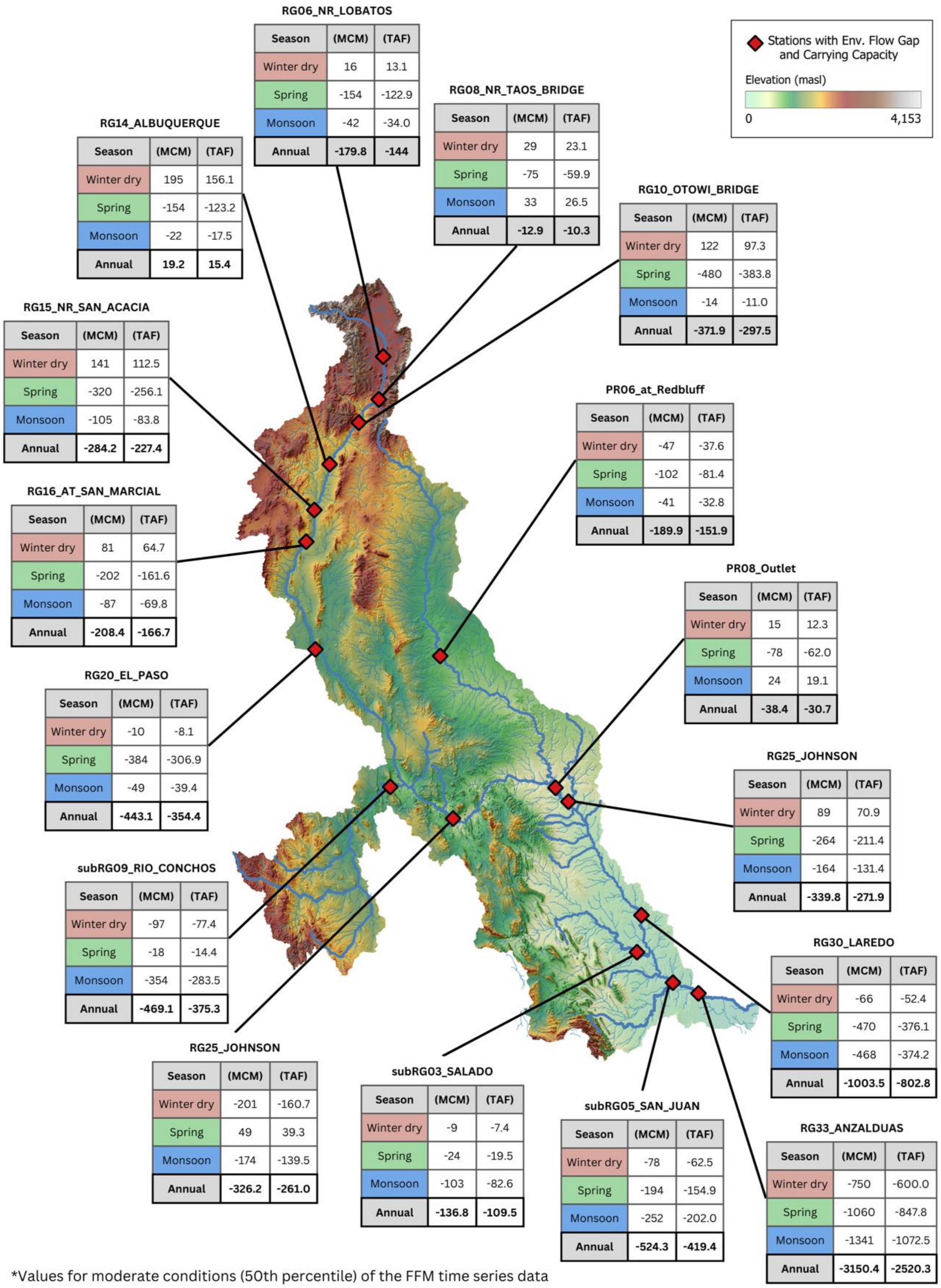
Table 18. Strategies directed to secure water resources from the Rio Bravo/Grande basing.

Cathegory	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, Francisco 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	Winter dry season	Colorado, New Mexico, Texas, Durango, Chihuahua, Coahuila, Nuevo León and Tamaulipas

	Crop planting management	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 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 19. 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



RG06_NR_LOBATOS

Season	(MCM)	(TAF)
Winter dry	16	13.1
Spring	-154	-122.9
Monsoon	-42	-34.0
Annual	**-179.8**	**-144**

RG08_NR_TAOS_BRIDGE

Season	(MCM)	(TAF)
Winter dry	29	23.1
Spring	-75	-59.9
Monsoon	33	26.5
Annual	**-12.9**	**-10.3**

RG14_ALBUQUERQUE

Season	(MCM)	(TAF)
Winter dry	195	156.1
Spring	-154	-123.2
Monsoon	-22	-17.5
Annual	**19.2**	**15.4**

RG10_OTOWI_BRIDGE

Season	(MCM)	(TAF)
Winter dry	122	97.3
Spring	-480	-383.8
Monsoon	-14	-11.0
Annual	**-371.9**	**-297.5**

RG15_NR_SAN_ACACIA

Season	(MCM)	(TAF)
Winter dry	141	112.5
Spring	-320	-256.1
Monsoon	-105	-83.8
Annual	**-284.2**	**-227.4**

PR06_at_Redbluff

Season	(MCM)	(TAF)
Winter dry	-47	-37.6
Spring	-102	-81.4
Monsoon	-41	-32.8
Annual	**-189.9**	**-151.9**

RG16_AT_SAN_MARCIAL

Season	(MCM)	(TAF)
Winter dry	81	64.7
Spring	-202	-161.6
Monsoon	-87	-69.8
Annual	**-208.4**	**-166.7**

PR08_Outlet

Season	(MCM)	(TAF)
Winter dry	15	12.3
Spring	-78	-62.0
Monsoon	24	19.1
Annual	**-38.4**	**-30.7**

RG20_EL_PASO

Season	(MCM)	(TAF)
Winter dry	-10	-8.1
Spring	-384	-306.9
Monsoon	-49	-39.4
Annual	**-443.1**	**-354.4**

RG25_JOHNSON

Season	(MCM)	(TAF)
Winter dry	89	70.9
Spring	-264	-211.4
Monsoon	-164	-131.4
Annual	**-339.8**	**-271.9**

subRG09_RIO_CONCHOS

Season	(MCM)	(TAF)
Winter dry	-97	-77.4
Spring	-18	-14.4
Monsoon	-354	-283.5
Annual	**-469.1**	**-375.3**

RG30_LAREDO

Season	(MCM)	(TAF)
Winter dry	-66	-52.4
Spring	-470	-376.1
Monsoon	-468	-374.2
Annual	**-1003.5**	**-802.8**

RG25_JOHNSON

Season	(MCM)	(TAF)
Winter dry	-201	-160.7
Spring	49	39.3
Monsoon	-174	-139.5
Annual	**-326.2**	**-261.0**

subRG03_SALADO

Season	(MCM)	(TAF)
Winter dry	-9	-7.4
Spring	-24	-19.5
Monsoon	-103	-82.6
Annual	**-136.8**	**-109.5**

subRG05_SAN_JUAN

Season	(MCM)	(TAF)
Winter dry	-78	-62.5
Spring	-194	-154.9
Monsoon	-252	-202.0
Annual	**-524.3**	**-419.4**

RG33_ANZALDUAS

Season	(MCM)	(TAF)
Winter dry	-750	-600.0
Spring	-1060	-847.8
Monsoon	-1341	-1072.5
Annual	**-3150.4**	**-2520.3**

*Values for moderate conditions (50th percentile) of the FFM time series data

Figure 31. Environmental flow gaps at each gauge station on the RGB. *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.*

Referencies

- Arthington, A. H., Naiman, R. J., McClain, M. E., & Nilsson, C. (2010). Preserving the biodiversity and ecological services of rivers: New challenges and research opportunities. Freshwater Biology, 55(1), 1-16. https://doi.org/10.1111/j.1365-2427.2009.02340.x
- Blythe, T. L., & Schmidt, J. C. (2018). Estimating the natural flow regime of rivers with long-standing development: The northern branch of the Rio Grande. Water Resources Research, 54(2), 1212–1236. https://doi.org/10.1002/2017wr021919
- Enríquez Coyro, E. 1976. El tratado entre México y los Estados Unidos de América sobre ríos internacionales. CONAGUA, Mexico City.
- Escobar-Arias, M. I., & Pasternack, G. B. (2010). A hydrogeomorphic dynamics approach to assess in-stream ecological functionality using the functional flows model, part 1—model characteristics. River research and applications, 26(9), 1103-1128.
- Garcia Pascual, L.I. (2022). Hydrologic Evaluation of Political Decisions for meeting the Treaty of 1944. Master Thesis. Instituto Politecnico Nacional and University of California, Davis. Davis, CA.
- Garza Diaz, L.E. (2022). A Quantitative Framework on Ecological Resilience for River Basins. Case Study: The Rio Grande - Rio Bravo. Ph.D. Dissertation, University of California Davis, Davis, CA.
- Gradie CM. Discovering the Chichimecas. The Americas. 1994;51(1):67-88. doi:10.2307/1008356
- Gunnerson JH. Apache Archaeology in Northeastern New Mexico. American Antiquity. 1969;34(1):23-39. doi:10.2307/278311
- Nalbantis, I.; Tsakiris, G. Assessment of Hydrological Drought Revisited. Water resources management 2009, 23, 881–897.
- Obama, B., and F. Calderón-Hinojosa. 2010. Joint Statement from President Barack Obama and President Felipe Calderón. Statements & Releases. https://obamawhitehouse.archives.gov/the-press-office/joint-statement-president-barack-obama-and-president-felipe-calder-n
- Patterson, N. and Sandoval-Solis, S. (2022). Upper Rio Grande Functional Flows Assesment. Rio Grande Resilient Basin Report Card Project. Final Report. World Wildlife Fund. Davis, California.
- Patterson, N. and Sandoval-Solis, S. (2022). Upper Rio Grande Functional Flows Assesment. Rio Grande Resilient Basin Report Card Project. Final Report. World Wildlife Fund. Davis, California.
- Patterson, N.K., Lane, B.A., Sandoval-Solis, S., Pasternack, G.B., Yarnell, S.M., Qiu, Y. (2020). A hydrologic feature detection algorithm to quantify seasonal components of flow regime. J. of Hydrology.
- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., Stromberg, J. C., Mollenhauer, R., Mouser, J. B., Roland, V. L., Brewer, S. K., Curtis, A. N., Tiemann, J. S., Douglass, S. A., Davis, M. A., Larson, E. R., Ellison, A. M., Gotelli, N. J., . . . Wolock, D. M. (1997). The Natural Flow Regime. BioScience, 47(11), 769-784. https://doi.org/1313099
- Sandoval-Solis, S., Garza-Diaz,L.E., Gomez-Quiroga, G., Saiz-Rodriguez, R., and Rendon-Herrera, G. (2023). Natural and Observed flow at gauging stations from Presidio, Texas, to the outlet of the Rio Grande/Bravo from 1900 to 2011. USGS Science Based Catalog. https://doi.org/10.21429/9h24-5g39.

- Sandoval-Solis, S.; Paladino, S.; Garza-Diaz, L.E.; Nava, L.F.; Friedman, J.R.; Ortiz-Partida, J.P.; Plassin, S.; Gomez-Quiroga, G.; Koch, J.; Fleming, J.; et al. Environmental Flows in the Rio Grande - Rio Bravo Basin. Ecology and Society 2022, 27, doi:10.5751/ES-12944-270120.
- Taylor, W. W. (1972). The Hunter-Gatherer Nomads of Northern Mexico: A Comparison of the Archival and Archaeological Records. World Archaeology, 4(2), 167–178. http://www.jstor.org/stable/123974
- Wong, C., C. Williams, J. Pittock, U. Collier, and P. Schelle. 2007. World's top 10 rivers at risk. Page 53. WWF International, Gland, Switzerland.
- Yarnell, S. M., Petts, G. E., Schmidt, J. C., Whipple, A. A., Beller, E. E., Dahm, C. N., Goodwin, P., & Viers, J. H. (2015). Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. BioScience, 65(10), 963-972. https://doi.org/10.1093/biosci/biv102
- Yarnell, S.M., Stein, E.D., Webb, J.A., Grantham, T., Lusardi, R.A., Zimmerman, J., Peek, R.A., Lane, B.A., Howard, J., Sandoval-Solis, S. (2019). A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. J. River Research and Applications, Accepted. November (2019).

Annex 1.

Table 3. gauge stations with functional flow metrics.

	Streamflow	
Location	**Natural**	**Regulated**
Northern Branch	15	15
Southern Branch	11	11
Pecos River	8	8
Devils river	1	1
San Felipe and pinto Creek	2	2
Rio Conchos*	5	1
Rio Salado	1	1
Rio Alamo	1	1
Rio San Juan	1	1
Rio Escondido	1	1
Las Vacas, San Diego and San Rodrigo	1	1
Total	**47/47**	**43/44**

Table 3. gauge stations with functional flow metrics

Annex 2.

Control Point	Control Point*	Name	Code
Northern Branch			
1	1	Rio Grande Near Lobatos CO	RG06
2	2	Rio Grande Near Cerro NM	RG07
3	3	Rio Grande Near Taos Bridge NM	RG08
4	4	Rio Grande at Embudo NM	RG09
5	5	Rio Grande at Otowi Bridge NM	RG10
6	6	Rio Grande Below Cochiti Dam NM	RG11
7	7	Rio Grande at San Felipe NM	RG12
8	8	Rio Grande at Albuquerque NM	RG14
9	9	Rio Grande at San Acacia NM	RG15
10	10	Rio Grande at San Marcial NM	RG16
11	11	Rio Grande Below Elephant Butte Dam NM	RG18
12	12	Rio Grande Below Caballo Dam NM	RG19
13	13	Rio Grande at el Paso TX	RG20
14	14	Rio grande at Fort Quitman TX	RG21
15	15	Rio Grande Above Rio Conchos, TX	RG22
Southern Branch			
16	16	Rio Grande abv Ojinaga Presidio TX	RG23
17	17	Rio Grande Blw Ojinaga	RG24
18	18	Rio grande at Johnson Ranch TX	RG25
19	19	Rio Grande at Foster Ranch nr Langtry TX	RG26
20	20	Rio Grande Above Amistad Dam	RG27
21	21	Rio Grande at Acuna	RG28
22	22	Rio Grande at Piedras negras	RG29
23	23	Rio grande at Guerrero	RG30
24	24	Rio Grande at Laredo TX	RG31
25	25	Rio Grande at Falcon	RG32
26	26	Rio Grande at Anzalduas Anzalduas	RG33
Sub-basins			
Rio Conchos Basin			
27	-	Rio Florido	subRG05
28	-	Rio Conchos	subRG06
29	-	Rio San Pedro (Villalba)	subRG07
30	-	Las Burras	subRG08
31	27	Rio Conchos Ojinaga	subRG09
Pecos River Basin			

32	28	Above Sumner Dam	PR01
33	29	At Artesia	PR02
34	30	Damsite 3	PR03
35	31	Dark Canyon	PR04
36	32	Pierce Canyon	PR05
37	33	Red Bluff	PR06
38	34	near Girvin	PR07
39	35	Pecos River Outlet	PR08
Rio Salado Basin			
40	36	Rio Salado (Outlet)	subRG03
Rio Alamo Basin			
41	37	Rio Alamo	subRG04
San Juan Basin			
42	38	Rio San Juan (Outlet)	subRG05
Other rivers			
43	39	Devil's river	subRG06
44	40	San Felipe	subRG07
45	41	Pinto Creek	subRG08
46	42	Rio Escondido	subRG02
47	43	Las Vacas, San Diego and San Rodrigo	subRG01
*** Control points with Natural and Regulated streamflow and Functional Flow Metrics**			

Annex 3. Carrying capacity tables

Upper Basin

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG06_NR_LOBATOS	*Dry Year*	*Winter dry season*	296	67	91.8	73.5	94.7	75.8	2.8	2.3
		Spring flood pulse	68	148	377.4	301.9	241.2	192.9	-136.2	-109.0
		Monsoon season	149	295	249.0	199.2	47.3	37.8	-201.7	-161.4
	Moderate Year	*Winter dry season*	300	103	176.1	140.9	136.4	109.2	-39.6	-31.7
		Spring flood pulse	104	163	519.7	415.8	258.0	206.4	-261.7	-209.4
		Monsoon season	164	299	278.7	222.9	118.7	94.9	-160.0	-128.0
	Wet Year	*Winter dry season*	333	113	224.6	179.6	167.9	134.3	-56.7	-45.3
		Spring flood pulse	114	170	674.0	539.2	367.2	293.7	-306.8	-245.5
		Monsoon season	171	332	429.8	343.8	287.9	230.3	-141.9	-113.5

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
RG06_NR_LOBATOS	*Dry*	718.3	574.6	383.1	306.5	2.8	2.3	338.0	270.4	-335.1	-268.1	47%
	Moderate	974.4	779.6	513.1	410.5	0.0	0.0	461.3	369.1	-461.3	-369.1	47%
	Wet	1328.4	1062.7	822.9	658.3	0.0	0.0	505.4	404.4	-505.4	-404.4	38%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG08_NR_TAOS_BRIDGE	*Dry Year*	*Winter dry season*	296	50	128.2	102.5	128.0	102.4	-0.1	-0.1
		Spring flood pulse	51	139	348.4	278.8	168.5	134.8	-179.9	-143.9
		Monsoon season	140	295	405.7	324.6	115.9	92.7	-289.8	-231.9
	Moderate Year	*Winter dry season*	309	83	175.5	140.4	168.2	134.6	-7.3	-5.8
		Spring flood pulse	84	156	558.1	446.5	270.5	216.4	-287.6	-230.1
		Monsoon season	157	308	444.9	355.9	155.7	124.6	-289.2	-231.4
	Wet Year	*Winter dry season*	346	105	190.1	152.1	176.5	141.2	-13.6	-10.9
		Spring flood pulse	106	169	841.4	673.1	378.4	302.7	-462.9	-370.4
		Monsoon season	170	345	566.6	453.3	273.8	219.0	-292.8	-234.3

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
RG08_NR_TAOS_BRIDGE	*Dry*	882.3	705.9	412.5	330.0	0.0	0.0	469.9	375.9	-469.9	-375.9	53%
	Moderate	1178.6	942.9	594.5	475.6	0.0	0.0	584.1	467.3	-584.1	-467.3	50%
	Wet	1598.0	1278.4	828.6	662.9	0.0	0.0	769.4	615.5	-769.4	-615.5	48%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG08_NR_TAOS_BRIDGE	*Dry Year*	*Winter dry season*	296	50	128.2	102.5	128.0	102.4	-0.1	-0.1
		Spring flood pulse	51	139	348.4	278.8	168.5	134.8	-179.9	-143.9
		Monsoon season	140	295	405.7	324.6	115.9	92.7	-289.8	-231.9
	Moderate Year	*Winter dry season*	309	83	175.5	140.4	168.2	134.6	-7.3	-5.8
		Spring flood pulse	84	156	558.1	446.5	270.5	216.4	-287.6	-230.1
		Monsoon season	157	308	444.9	355.9	155.7	124.6	-289.2	-231.4
	Wet Year	*Winter dry season*	346	105	190.1	152.1	176.5	141.2	-13.6	-10.9
		Spring flood pulse	106	169	841.4	673.1	378.4	302.7	-462.9	-370.4
		Monsoon season	170	345	566.6	453.3	273.8	219.0	-292.8	-234.3

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
RG08_NR_TAOS_BRIDGE	*Dry*	882.3	705.9	412.5	330.0	0.0	0.0	469.9	375.9	-469.9	-375.9	53%
	Moderate	1178.6	942.9	594.5	475.6	0.0	0.0	584.1	467.3	-584.1	-467.3	50%
	Wet	1598.0	1278.4	828.6	662.9	0.0	0.0	769.4	615.5	-769.4	-615.5	48%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG14_ALBUQUERQUE	Dry Year	Winter dry season	296	91	348.1	278.5	177.8	142.2	-170.3	-136.3
		Spring flood pulse	92	144	448.3	358.6	339.3	271.5	-109.0	-87.2
		Monsoon season	145	295	470.5	376.4	173.2	138.5	-297.3	-237.8
	Moderate Year	Winter dry season	303	97	376.1	300.9	223.2	178.6	-152.9	-122.3
		Spring flood pulse	98	160	799.2	639.4	524.0	419.2	-275.2	-220.2
		Monsoon season	161	302	558.4	446.7	319.7	255.8	-238.6	-190.9
	Wet Year	Winter dry season	346	100	280.8	224.6	205.6	164.5	-75.2	-60.2
		Spring flood pulse	101	179	1417.4	1133.9	852.2	681.8	-565.2	-452.2
		Monsoon season	180	345	747.5	598.0	623.0	498.4	-124.5	-99.6

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG14_ALBUQUERQUE	Dry	1266.9	1013.5	690.3	552.2	0.0	0.0	576.6	461.3	-576.6	-461.3	46%
	Moderate	1733.7	1386.9	1066.9	853.5	0.0	0.0	666.8	533.4	-666.8	-533.4	38%
	Wet	2445.6	1956.5	1680.8	1344.6	0.0	0.0	764.9	611.9	-764.9	-611.9	31%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG15_NR_SAN_ACACIA	Dry Year	Winter dry season	296	91	347.8	278.3	158.6	126.9	-189.3	-151.4
		Spring flood pulse	92	183	695.2	556.2	527.8	422.2	-167.5	-134.0
		Monsoon season	184	295	275.5	220.4	116.2	93.0	-159.2	-127.4
	Moderate Year	Winter dry season	302	97	399.1	319.3	200.6	160.5	-198.5	-158.8
		Spring flood pulse	98	199	1083.4	866.8	802.5	642.0	-280.9	-224.8
		Monsoon season	200	301	322.7	258.1	216.9	173.5	-105.7	-84.6
	Wet Year	Winter dry season	346	99	303.7	243.0	190.5	152.4	-113.2	-90.6
		Spring flood pulse	100	203	1598.4	1278.8	1064.3	851.4	-534.2	-427.3
		Monsoon season	204	345	605.2	484.2	495.9	396.7	-109.3	-87.5

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG15_NR_SAN_ACACIA	Dry	1318.5	1054.8	802.6	642.1	0.0	0.0	516.0	412.8	-516.0	-412.8	39%
	Moderate	1805.2	1444.2	1220.0	976.0	0.0	0.0	585.2	468.2	-585.2	-468.2	32%
	Wet	2507.3	2005.9	1750.6	1400.5	0.0	0.0	756.7	605.4	-756.7	-605.4	30%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG16_AT_SAN_MARCIAL	Dry Year	Winter dry season	296	68	232.7	186.1	65.8	52.7	-166.8	-133.5
		Spring flood pulse	69	175	796.0	636.8	408.5	326.8	-387.5	-310.0
		Monsoon season	176	295	305.4	244.3	48.4	38.7	-257.0	-205.6
	Moderate Year	Winter dry season	301	93	348.4	278.7	169.1	135.3	-179.3	-143.4
		Spring flood pulse	94	185	1078.0	862.4	619.6	495.7	-458.4	-366.7
		Monsoon season	186	300	380.7	304.6	132.4	105.9	-248.3	-198.7
	Wet Year	Winter dry season	328	113	551.7	441.3	259.0	207.2	-292.7	-234.2
		Spring flood pulse	114	207	1459.6	1167.7	1096.9	877.5	-362.7	-290.2
		Monsoon season	208	327	521.8	417.4	357.3	285.9	-164.5	-131.6

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG16_AT_SAN_MARCIAL	Dry	1334.0	1067.2	522.8	418.2	0.0	0.0	811.3	649.0	-811.3	-649.0	61%
	Moderate	1807.1	1445.7	921.1	736.9	0.0	0.0	886.0	708.8	-886.0	-708.8	49%
	Wet	2533.1	2026.5	1713.2	1370.5	0.0	0.0	819.9	655.9	-819.9	-655.9	32%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG20_EL_PASO	Dry Year	Winter dry season	296	54	251.2	201.0	21.4	17.1	-229.9	-183.9
		Spring flood pulse	55	186	951.4	761.1	336.5	269.2	-614.9	-491.9
		Monsoon season	187	295	337.2	269.8	35.9	28.7	-301.3	-241.0
	Moderate Year	Winter dry season	310	97	453.7	362.9	109.0	87.2	-344.7	-275.7
		Spring flood pulse	98	197	1168.8	935.1	559.5	447.6	-609.3	-487.5
		Monsoon season	198	309	447.8	358.2	174.4	139.5	-273.4	-218.8
	Wet Year	Winter dry season	344	111	509.0	407.2	165.8	132.6	-343.3	-274.6
		Spring flood pulse	112	209	1624.6	1299.7	780.8	624.6	-843.9	-675.1
		Monsoon season	210	343	704.2	563.4	307.5	246.0	-396.7	-317.4

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG20_EL_PASO	Dry	1539.9	1231.9	393.8	315.1	0.0	0.0	1146.0	916.8	-1146.0	-916.8	74%
	Moderate	2070.3	1656.3	842.9	674.3	0.0	0.0	1227.5	982.0	-1227.5	-982.0	59%
	Wet	2837.9	2270.3	1254.0	1003.2	0.0	0.0	1583.8	1267.1	-1583.8	-1267.1	56%

Lower Basin

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG25_JOHNSON	Dry Year	Winter dry season	312	135	1118.5	894.8	308	246.7	-810.2	-648.1
		Spring flood pulse	136	211	790.6	632.4	323	258.2	-467.8	-374.2
		Monsoon season	212	311	791.6	633.3	296	236.8	-495.6	-396.5
	Moderate Year	Winter dry season	322	166	1794.5	1435.6	385	307.7	-1409.9	-1127.9
		Spring flood pulse	167	215	793.9	635.1	88	70.7	-705.5	-564.4
		Monsoon season	216	321	1244.0	995.2	384	307.5	-859.7	-687.8
	Wet Year	Winter dry season	332	190	2433.0	1946.4	459	367.3	-1973.8	-1579.0
		Spring flood pulse	191	241	898.3	718.6	152	121.4	-746.5	-597.2
		Monsoon season	242	331	1383.4	1106.8	563	450.0	-820.9	-656.7

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG25_JOHNSON	Dry	2700.7	2160.5	927.1	741.7	0.0	0.0	1773.6	1418.9	-1773.6	-1418.9	66%
	Moderate	3832.4	3065.9	857.3	685.8	0.0	0.0	2975.1	2380.1	-2975.1	-2380.1	78%
	Wet	4714.7	3771.7	1173.5	938.8	0.0	0.0	3541.2	2832.9	-3541.2	-2832.9	75%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG27_AMISTAD	Dry Year	Winter dry season	302	98	1151.2	921.0	487	389.3	-664.7	-531.7
		Spring flood pulse	99	187	1417.1	1133.7	552	441.4	-865.4	-692.3
		Monsoon season	188	301	1394.9	1116.0	561	448.7	-834.0	-667.2
	Moderate Year	Winter dry season	317	112	1448.5	1158.8	580	464.0	-868.5	-694.8
		Spring flood pulse	113	211	2066.3	1653.0	889	711.6	-1176.8	-941.5
		Monsoon season	212	316	1654.1	1323.3	734	586.8	-920.5	-736.4
	Wet Year	Winter dry season	332	165	2650.2	2120.1	915	731.8	-1735.5	-1388.4
		Spring flood pulse	166	211	1341.9	1073.5	628	502.5	-713.8	-571.0
		Monsoon season	212	331	2464.1	1971.3	1414	1130.9	-1050.5	-840.4

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG27_AMISTAD	Dry	3963.3	3170.6	1599.2	1279.4	0.0	0.0	2364.1	1891.3	-2364.1	-1891.3	60%
	Moderate	5168.9	4135.1	2203.0	1762.4	0.0	0.0	2965.9	2372.7	-2965.9	-2372.7	57%
	Wet	6456.3	5165.0	2956.5	2365.2	0.0	0.0	3499.8	2799.9	-3499.8	-2799.9	54%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG30_LAREDO	Dry Year	Winter dry season	308	107	1499.0	1199.2	868	694.7	-630.6	-504.5
		Spring flood pulse	108	196	1781.1	1424.9	960	768.0	-821.1	-656.9
		Monsoon season	197	307	1540.0	1232.0	831	664.8	-709.0	-567.2
	Moderate Year	Winter dry season	320	128	1974.0	1579.2	1018	814.3	-956.1	-764.9
		Spring flood pulse	129	211	2014.8	1611.8	1148	918.0	-867.2	-693.8
		Monsoon season	212	319	2046.0	1636.8	1144	915.5	-901.6	-721.3
	Wet Year	Winter dry season	333	180	3453.1	2762.5	1460	1167.8	-1993.3	-1594.6
		Spring flood pulse	181	211	1121.2	897.0	738	590.6	-382.9	-306.3
		Monsoon season	212	332	3152.5	2522.0	2150	1719.6	-1003.0	-802.4

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG30_LAREDO	Dry	4820.1	3856.1	2659.4	2127.5	0.0	0.0	2160.7	1728.6	-2160.7	-1728.6	45%
	Moderate	6034.8	4827.8	3309.8	2647.9	0.0	0.0	2725.0	2180.0	-2725.0	-2180.0	45%
	Wet	7726.8	6181.4	4347.6	3478.1	0.0	0.0	3379.2	2703.4	-3379.2	-2703.4	44%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG30_LAREDO	Dry Year	Winter dry season	308	107	1499.0	1199.2	868	694.7	-630.6	-504.5
		Spring flood pulse	108	196	1781.1	1424.9	960	768.0	-821.1	-656.9
		Monsoon season	197	307	1540.0	1232.0	831	664.8	-709.0	-567.2
	Moderate Year	Winter dry season	320	128	1974.0	1579.2	1018	814.3	-956.1	-764.9
		Spring flood pulse	129	211	2014.8	1611.8	1148	918.0	-867.2	-693.8
		Monsoon season	212	319	2046.0	1636.8	1144	915.5	-901.6	-721.3
	Wet Year	Winter dry season	333	180	3453.1	2762.5	1460	1167.8	-1993.3	-1594.6
		Spring flood pulse	181	211	1121.2	897.0	738	590.6	-382.9	-306.3
		Monsoon season	212	332	3152.5	2522.0	2150	1719.6	-1003.0	-802.4

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG30_LAREDO	Dry	4820.1	3856.1	2659.4	2127.5	0.0	0.0	2160.7	1728.6	-2160.7	-1728.6	45%
	Moderate	6034.8	4827.8	3309.8	2647.9	0.0	0.0	2725.0	2180.0	-2725.0	-2180.0	45%
	Wet	7726.8	6181.4	4347.6	3478.1	0.0	0.0	3379.2	2703.4	-3379.2	-2703.4	44%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG33_ANZALDUAS	Dry Year	Winter dry season	314	107	2108.7	1687.0	997	798.0	-1111.2	-889.0
		Spring flood pulse	108	199	2773.0	2218.4	1234	987.0	-1539.2	-1231.4
		Monsoon season	200	313	2572.1	2057.7	1257	1005.8	-1314.8	-1051.9
	Moderate Year	Winter dry season	321	121	2665.2	2132.2	1240	992.3	-1424.9	-1139.9
		Spring flood pulse	122	211	3276.8	2621.5	1529	1223.2	-1747.9	-1398.3
		Monsoon season	212	320	3040.1	2432.1	1742	1393.6	-1298.1	-1038.5
	Wet Year	Winter dry season	337	171	4590.6	3672.5	1764	1411.4	-2826.4	-2261.1
		Spring flood pulse	172	211	2078.0	1662.4	1173	938.4	-905.1	-724.1
		Monsoon season	212	336	4747.8	3798.2	2958	2366.0	-1790.2	-1432.2

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)	(%)
RG33_ANZALDUAS	Dry	7453.8	5963.0	3488.5	2790.8	0.0	0.0	3965.3	3172.2	-3965.3	-3172.2	53%
	Moderate	8982.2	7185.7	4511.3	3609.0	0.0	0.0	4470.9	3576.7	-4470.9	-3576.7	50%
	Wet	11416.5	9133.2	5894.8	4715.8	0.0	0.0	5521.7	4417.3	-5521.7	-4417.3	48%

Tributaries

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
PR06_at_Redbluff	*Dry Year*	*Winter dry season*	309	80	46	37.0	42	33.2	-4.7	-3.8
		Spring flood pulse	81	90	7	5.6	10	8.3	3.3	2.6
		Monsoon season	91	308	152	121.4	47	37.8	-104.4	-83.6
	Moderate Year	*Winter dry season*	320	102	59	47.4	67	53.8	8.1	6.5
		Spring flood pulse	103	174	64	51.1	113	90.4	49.2	39.4
		Monsoon season	175	319	134	107.4	76	60.5	-58.6	-46.9
	Wet Year	*Winter dry season*	389	133	72	57.5	85	67.8	12.9	10.3
		Spring flood pulse	134	211	121	96.6	206	164.5	84.8	67.8
		Monsoon season	212	388	142	113.9	140	112.2	-2.1	-1.7

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
PR06_at_Redbluff	*Dry*	205.0	164.0	99.2	79.3	3.3	2.6	109.2	87.3	-105.9	-84.7	52%
	Moderate	257.2	205.8	255.9	204.7	57.3	45.8	58.6	46.9	-1.3	-1.0	1%
	Wet	335.1	268.1	430.6	344.5	97.7	78.1	2.1	1.7	95.5	76.4	29%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
PR08_Outlet	*Dry Year*	*Winter dry season*	305	62	81	64.4	23	18.2	-57.8	-46.2
		Spring flood pulse	63	70	6	5.0	6	5.0	0.1	0.0
		Monsoon season	71	304	274	219.6	51	41.1	-223.0	-178.4
	Moderate Year	*Winter dry season*	320	90	102	81.6	48	38.4	-54.0	-43.2
		Spring flood pulse	91	160	90	72.0	116	92.6	25.8	20.6
		Monsoon season	161	319	248	198.1	87	69.9	-160.3	-128.2
	Wet Year	*Winter dry season*	365	120	111	88.8	108	86.2	-3.3	-2.7
		Spring flood pulse	121	211	194	155.2	286	228.7	91.8	73.4
		Monsoon season	212	364	237	189.6	180	144.4	-56.5	-45.2

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
PR08_Outlet	*Dry*	361.2	289.0	80.4	64.4	0.1	0.0	280.8	224.7	-280.8	-224.6	78%
	Moderate	439.6	351.7	251.1	200.9	25.8	20.6	214.3	171.4	-188.5	-150.8	43%
	Wet	542.0	433.6	574.0	459.2	91.8	73.4	59.8	47.8	32.0	25.6	6%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG03_SALADO	*Dry Year*	*Winter dry season*	313	116	102.1	81.7	21	16.7	-81.2	-65.0
		Spring flood pulse	117	140	39.8	31.9	5	3.9	-35.0	-28.0
		Monsoon season	141	312	205.8	164.6	69	55.0	-136.9	-109.6
	Moderate Year	*Winter dry season*	326	147	163.2	130.6	45	35.9	-118.4	-94.7
		Spring flood pulse	148	183	87.1	69.7	32	25.4	-55.4	-44.3
		Monsoon season	184	325	296.6	237.3	147	117.8	-149.3	-119.5
	Wet Year	*Winter dry season*	345	197	371.8	297.4	98	78.6	-273.6	-218.9
		Spring flood pulse	198	246	188.2	150.5	121	96.5	-67.6	-54.1
		Monsoon season	247	344	441.0	352.8	293	234.5	-147.8	-118.3

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
subRG03_SALADO	*Dry*	347.7	278.1	94.6	75.7	0.0	0.0	253.1	202.5	-253.1	-202.5	73%
	Moderate	547.0	437.6	223.9	179.1	0.0	0.0	323.1	258.5	-323.1	-258.5	59%
	Wet	1001.0	800.8	512.0	409.6	0.0	0.0	489.0	391.2	-489.0	-391.2	49%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG05_SAN_JUAN	*Dry Year*	*Winter dry season*	314	51	91.0	72.8	36	28.8	-55.0	-44.0
		Spring flood pulse	52	168	287.5	230.0	154	123.4	-133.2	-106.6
		Monsoon season	169	313	348.0	278.4	180	143.8	-168.3	-134.7
	Moderate Year	*Winter dry season*	322	116	273.7	219.0	81	64.8	-192.7	-154.1
		Spring flood pulse	117	186	297.6	238.1	195	156.0	-102.7	-82.1
		Monsoon season	187	321	547.5	438.0	262	209.4	-285.7	-228.6
	Wet Year	*Winter dry season*	348	176	499.4	399.5	134	107.0	-365.6	-292.5
		Spring flood pulse	177	264	515.8	412.7	300	239.8	-216.1	-172.9
		Monsoon season	265	347	564.5	451.6	265	211.8	-299.7	-239.8

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
subRG05_SAN_JUAN	*Dry*	726.5	581.2	369.9	295.9	0.0	0.0	356.6	285.3	-356.6	-285.3	49%
	Moderate	1118.9	895.1	537.8	430.2	0.0	0.0	581.1	464.9	-581.1	-464.9	52%
	Wet	1579.7	1263.8	698.2	558.6	0.0	0.0	881.5	705.2	-881.5	-705.2	56%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Natural flow		Resilient flow		Carrying Capacity	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG09_RIO_CONCHOS	*Dry Year*	*Winter dry season*	314	161	177.1	141.7	175	139.9	-2.3	-1.8
		Spring flood pulse	162	211	159.5	127.6	78	62.5	-81.4	-65.1
		Monsoon season	212	313	273.2	218.6	234	187.4	-39.0	-31.2
	Moderate Year	*Winter dry season*	330	191	314.3	251.4	264	211.0	-50.5	-40.4
		Spring flood pulse	192	211	109.7	87.8	46	36.5	-64.1	-51.3
		Monsoon season	212	329	537.4	429.9	521	416.8	-16.4	-13.1
	Wet Year	*Winter dry season*	343	176	316.8	253.4	311	248.5	-6.2	-4.9
		Spring flood pulse	177	211	181.4	145.1	55	43.9	-126.5	-101.2
		Monsoon season	212	342	1031.7	825.3	869	695.1	-162.8	-130.2

Streamflow Gauge	Water year type	Natural Flow		Resilient Flow		Surplus		Deficit		Carrying Capacity		
		(MCM)	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(%)*
subRG09_RIO_CONCHOS	*Dry*	609.8	487.8	487.2	389.7	0.0	0.0	122.6	98.1	-122.6	-98.1	20%
	Moderate	961.3	769.1	830.4	664.3	0.0	0.0	131.0	104.8	-131.0	-104.8	14%
	Wet	1529.9	1223.9	1234.4	987.5	0.0	0.0	295.4	236.4	-295.4	-236.4	19%

Annex 4. Recommended environmental flows and Gaps tables.

Upper Basin

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG06_NR_LOBATOS	*Dry Year*	*Winter dry season*	296	67	91.4	73.1	94.7	75.8	-3	-2.7
		Spring flood pulse	68	148	76.7	61.4	241.2	192.9	-164	-131.6
		Monsoon season	149	295	30.4	24.3	47.3	37.8	-17	-13.5
	Moderate Year	*Winter dry season*	300	103	152.8	122.2	136.4	109.2	16	13.1
		Spring flood pulse	104	163	104.4	83.5	258.0	206.4	-154	-122.9
		Monsoon season	164	299	76.2	61.0	118.7	94.9	-42	-34.0
	Wet Year	*Winter dry season*	333	113	150.7	120.6	167.9	134.3	-17	-13.7
		Spring flood pulse	114	170	137.2	109.7	367.2	293.7	-230	-184.0
		Monsoon season	171	332	175.3	140.2	287.9	230.3	-113	-90.1

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG06_NR_LOBATOS	Dry year	198.5	383.1	0.0	0%	184.7	48%	-184.7	-148	48%
	Moderate year	333.3	513.1	16.3	3%	196.1	38%	-179.8	-144	35%
	Wet year	463.1	822.9	0.0	0%	359.8	44%	-359.8	-288	44%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG08_NR_TAOS_BRIDGE	*Dry Year*	*Winter dry season*	296	50	137.4	109.9	128.0	102.4	9	7.5
		Spring flood pulse	51	139	152.0	121.6	168.5	134.8	-17	-13.3
		Monsoon season	140	295	134.6	107.7	115.9	92.7	19	14.9
	Moderate Year	*Winter dry season*	309	83	197.2	157.7	168.2	134.6	29	23.1
		Spring flood pulse	84	156	195.6	156.5	270.5	216.4	-75	-59.9
		Monsoon season	157	308	188.8	151.1	155.7	124.6	33	26.5
	Wet Year	*Winter dry season*	346	105	189.0	151.2	176.5	141.2	13	10.0
		Spring flood pulse	106	169	273.2	218.6	378.4	302.7	-105	-84.1
		Monsoon season	170	345	300.5	240.4	273.8	219.0	27	21.4

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG08_NR_TAOS_BRIDGE	Dry year	424.0	412.5	28.1	7%	16.6	4%	11.5	9.2	3%
	Moderate year	581.6	594.5	62.0	10%	74.9	13%	-12.9	-10.3	2%
	Wet year	762.8	828.6	39.3	5%	105.2	13%	-65.9	-52.7	8%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG10_OTOWI_BRIDGE	*Dry Year*	*Winter dry season*	296	88	288.6	230.9	201.9	161.5	87	69.4
		Spring flood pulse	89	185	293.2	234.5	657.8	526.2	-365	-291.7
		Monsoon season	186	295	216.2	173.0	157.3	125.8	59	47.2
	Moderate Year	*Winter dry season*	296	97	413.8	331.0	292.1	233.7	122	97.3
		Spring flood pulse	98	200	560.4	448.3	1040.1	832.1	-480	-383.8
		Monsoon season	201	295	208.7	167.0	222.5	178.0	-14	-11.0
	Wet Year	*Winter dry season*	327	101	455.8	364.6	295.5	236.4	160	128.2
		Spring flood pulse	102	203	882.1	705.7	1305.8	1044.7	-424	-339.0
		Monsoon season	204	326	328.4	262.7	492.3	393.8	-164	-131.1

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG10_OTOWI_BRIDGE	Dry year	798.0	1016.9	145.7	14%	364.6	36%	-218.9	-175.1	22%
	Moderate year	1182.8	1554.7	121.6	8%	493.5	32%	-371.9	-297.5	24%
	Wet year	1666.2	2093.5	160.3	8%	587.6	28%	-427.3	-341.9	20%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG14_ALBUQUERQUE	*Dry Year*	*Winter dry season*	296	91	329.6	263.7	177.8	142.2	152	121.5
		Spring flood pulse	92	144	160.5	128.4	339.3	271.5	-179	-143.1
		Monsoon season	145	295	219.0	175.2	173.2	138.5	46	36.6
	Moderate Year	*Winter dry season*	303	97	418.4	334.7	223.2	178.6	195	156.1
		Spring flood pulse	98	160	369.9	295.9	524.0	419.2	-154	-123.2
		Monsoon season	161	302	297.8	238.2	319.7	255.8	-22	-17.5
	Wet Year	*Winter dry season*	346	100	407.3	325.8	205.6	164.5	202	161.4
		Spring flood pulse	101	179	653.3	522.6	852.2	681.8	-199	-159.1
		Monsoon season	180	345	453.7	362.9	623.0	498.4	-169	-135.4

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG14_ALBUQUERQUE	Dry year	709.0	690.3	197.6	29%	178.9	26%	18.7	15.0	3%
	Moderate year	1086.1	1066.9	195.2	18%	176.0	16%	19.2	15.4	2%
	Wet year	1514.2	1680.8	201.7	12%	368.2	22%	-166.5	-133.2	10%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG15_NR_SAN_ACACIA	*Dry Year*	*Winter dry season*	296	91	96.5	77.2	158.6	126.9	-62	-49.7
		Spring flood pulse	92	183	198.3	158.6	527.8	422.2	-329	-263.6
		Monsoon season	184	295	37.9	30.3	116.2	93.0	-78	-62.7
	Moderate Year	*Winter dry season*	302	97	341.2	273.0	200.6	160.5	141	112.5
		Spring flood pulse	98	199	482.4	386.0	802.5	642.0	-320	-256.1
		Monsoon season	200	301	112.2	89.7	216.9	173.5	-105	-83.8
	Wet Year	*Winter dry season*	346	99	315.7	252.6	190.5	152.4	125	100.2
		Spring flood pulse	100	203	837.0	669.6	1064.3	851.4	-227	-181.8
		Monsoon season	204	345	316.4	253.1	495.9	396.7	-179	-143.6

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG15_NR_SAN_ACACIA	Dry year	332.7	802.6	0.0	0%	469.9	59%	-469.9	-375.9	59%
	Moderate year	935.8	1220.0	140.6	12%	424.8	35%	-284.2	-227.4	23%
	Wet year	1469.1	1750.6	125.3	7%	406.8	23%	-281.5	-225.2	16%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
RG16_AT_SAN_MARCIAL	*Dry Year*	*Winter dry season*	296	68	189.2	151.4	65.8	52.7	123	98.7
		Spring flood pulse	69	175	155.8	124.6	408.5	326.8	-253	-202.2
		Monsoon season	176	295	12.3	9.9	48.4	38.7	-36	-28.9
	Moderate Year	*Winter dry season*	301	93	250.0	200.0	169.1	135.3	81	64.7
		Spring flood pulse	94	185	417.6	334.1	619.6	495.7	-202	-161.6
		Monsoon season	186	300	45.1	36.1	132.4	105.9	-87	-69.8
	Wet Year	*Winter dry season*	328	113	315.3	252.3	259.0	207.2	56	45.1
		Spring flood pulse	114	207	545.9	436.7	1096.9	877.5	-551	-440.8
		Monsoon season	208	327	170.1	136.1	357.3	285.9	-187	-149.8

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
RG16_AT_SAN_MARCIAL	Dry year	357.3	522.8	123.4	24%	288.8	55%	-165.5	-132.4	32%
	Moderate year	712.7	921.1	80.9	9%	289.3	31%	-208.4	-166.7	23%
	Wet year	1031.3	1713.2	56.4	3%	738.2	43%	-681.8	-545.5	40%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG20_EL_PASO	Dry Year	Winter dry season	296	54	19.5	15.6	21.4	17.1	-2	-1.5
		Spring flood pulse	55	186	196.2	156.9	336.5	269.2	-140	-112.3
		Monsoon season	187	295	43.9	35.2	35.9	28.7	8	6.4
	Moderate Year	Winter dry season	310	97	98.9	79.1	109.0	87.2	-10	-8.1
		Spring flood pulse	98	197	175.8	140.6	559.5	447.6	-384	-306.9
		Monsoon season	198	309	125.1	100.1	174.4	139.5	-49	-39.4
	Wet Year	Winter dry season	344	111	108.7	87.0	165.8	132.6	-57	-45.6
		Spring flood pulse	112	209	191.3	153.1	780.8	624.6	-589	-471.5
		Monsoon season	210	343	223.1	178.5	307.5	246.0	-84	-67.5

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	(MCM)	(MCM)	(%)	(MCM)	(%)	(MCM)	(TAF)	(%)
RG20_EL_PASO	Dry year	259.6	393.8	8.0	2%	142.2	36%	-134.2	-107.4	34%
	Moderate year	399.8	842.9	0.0	0%	443.1	53%	-443.1	-354.4	53%
	Wet year	523.2	1254.0	0.0	0%	730.9	58%	-730.9	-584.7	58%

Lower Basin

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG25_JOHNSON	Dry Year	Winter dry season	312	135	124.1	99.3	308.4	246.7	-184	-147.4
		Spring flood pulse	136	211	122.8	98.2	322.8	258.2	-200	-160.0
		Monsoon season	212	311	95.2	76.2	295.9	236.8	-201	-160.6
	Moderate Year	Winter dry season	322	166	183.7	147.0	384.7	307.7	-201	-160.7
		Spring flood pulse	167	215	137.4	109.9	88.3	70.7	49	39.3
		Monsoon season	216	321	210.0	168.0	384.3	307.5	-174	-139.5
	Wet Year	Winter dry season	332	190	344.9	275.9	459.2	367.3	-114	-91.4
		Spring flood pulse	191	241	190.5	152.4	151.8	121.4	39	31.0
		Monsoon season	242	331	360.2	288.2	562.5	450.0	-202	-161.9

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	(MCM)	(MCM)	(%)	(MCM)	(%)	(MCM)	(TAF)	(%)
RG25_JOHNSON	Dry year	342.1	927.1	0.0	0%	585.0	63%	-585.0	-468.0	63%
	Moderate year	531.1	857.3	49.1	6%	375.3	44%	-326.2	-261.0	38%
	Wet year	895.6	1173.5	38.7	3%	316.6	27%	-277.9	-222.3	24%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	(MCM)	(TAF)	(MCM)	(TAF)	(MCM)	(TAF)
RG27_AMISTAD	Dry Year	Winter dry season	302	98	528.6	422.9	486.6	389.3	42	33.6
		Spring flood pulse	99	187	453.0	362.4	551.7	441.4	-99	-79.0
		Monsoon season	188	301	428.4	342.7	560.9	448.7	-133	-106.0
	Moderate Year	Winter dry season	317	112	668.6	534.9	580.0	464.0	89	70.9
		Spring flood pulse	113	211	625.3	500.2	889.5	711.6	-264	-211.4
		Monsoon season	212	316	569.3	455.5	733.6	586.8	-164	-131.4
	Wet Year	Winter dry season	332	165	1117.4	894.0	914.7	731.8	203	162.2
		Spring flood pulse	166	211	475.9	380.7	628.1	502.5	-152	-121.8
		Monsoon season	212	331	1094.7	875.7	1413.6	1130.9	-319	-255.1

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	(MCM)	(MCM)	(%)	(MCM)	(%)	(MCM)	(TAF)	(%)
RG27_AMISTAD	Dry year	1410.0	1599.2	42.1	3%	231.3	14%	-189.3	-151.4	12%
	Moderate year	1863.2	2203.0	88.6	4%	428.4	19%	-339.8	-271.9	15%
	Wet year	2688.0	2956.5	202.7	7%	471.2	16%	-268.4	-214.7	9%

Streamflow Gauge	Water year type	FFComponent	Reference dates: Start Date	Reference dates: End Date	Regulated flows (MCM)	Regulated flows (TAF)	Resilient flow (MCM)	Resilient flow (TAF)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)
RG30_LAREDO	*Dry Year*	*Winter dry season*	308	107	711.3	569.1	868.4	694.7	-157	-125.7
		Spring flood pulse	108	196	441.6	353.3	960.0	768.0	-518	-414.7
		Monsoon season	197	307	398.4	318.7	831.0	664.8	-433	-346.1
	Moderate Year	*Winter dry season*	320	128	952.3	761.9	1017.9	814.3	-66	-52.4
		Spring flood pulse	129	211	677.4	541.9	1147.6	918.0	-470	-376.1
		Monsoon season	212	319	676.6	541.3	1144.4	915.5	-468	-374.2
	Wet Year	*Winter dry season*	333	180	1890.5	1512.4	1459.8	1167.8	431	344.6
		Spring flood pulse	181	211	311.1	248.9	738.3	590.6	-427	-341.7
		Monsoon season	212	332	1201.5	961.2	2149.5	1719.6	-948	-758.4

Streamflow Gauge	Water year type	Regulated flows (MCM)	Resilient flow (MCM)	Surplus (MCM)	Surplus (%)	Deficit (MCM)	Deficit (%)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)	Env. Flow Gap (%)
RG30_LAREDO	Dry year	1551.3	2659.4	0.0	0%	1108.1	42%	-1108.1	-886.5	42%
	Moderate year	2306.3	3309.8	0.0	0%	1003.5	30%	-1003.5	-802.8	30%
	Wet year	3403.1	4347.6	430.7	10%	1375.2	32%	-944.5	-755.6	22%

Streamflow Gauge	Water year type	FFComponent	Reference dates: Start Date	Reference dates: End Date	Regulated flows (MCM)	Regulated flows (TAF)	Resilient flow (MCM)	Resilient flow (TAF)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)
RG33_ANZALDUAS	*Dry Year*	*Winter dry season*	314	107	397.8	318.3	997.5	798.0	-600	-479.7
		Spring flood pulse	108	199	317.3	253.9	1233.8	987.0	-916	-733.2
		Monsoon season	200	313	303.6	242.8	1257.2	1005.8	-954	-763.0
	Moderate Year	*Winter dry season*	321	121	490.4	392.3	1240.3	992.3	-750	-600.0
		Spring flood pulse	122	211	469.1	375.3	1528.9	1223.2	-1060	-847.8
		Monsoon season	212	320	401.4	321.1	1742.0	1393.6	-1341	-1072.5
	Wet Year	*Winter dry season*	337	171	834.1	667.3	1764.3	1411.4	-930	-744.1
		Spring flood pulse	172	211	228.9	183.1	1172.9	938.4	-944	-755.2
		Monsoon season	212	336	562.0	449.6	2957.6	2366.0	-2396	-1916.5

Streamflow Gauge	Water year type	Regulated flows (MCM)	Resilient flow (MCM)	Surplus (MCM)	Surplus (%)	Deficit (MCM)	Deficit (%)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)	Env. Flow Gap (%)
RG33_ANZALDUAS	Dry year	1018.7	3488.5	0.0	0%	2469.8	71%	-2469.8	-1975.8	71%
	Moderate year	1360.9	4511.3	0.0	0%	3150.4	70%	-3150.4	-2520.3	70%
	Wet year	1625.0	5894.8	0.0	0%	4269.8	72%	-4269.8	-3415.8	72%

Tributaries

Streamflow Gauge	Water year type	FFComponent	Reference dates: Start Date	Reference dates: End Date	Regulated flows (MCM)	Regulated flows (TAF)	Resilient flow (MCM)	Resilient flow (TAF)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)
PR06_at_Redbluff	*Dry Year*	*Winter dry season*	309	80	13.2	10.6	41.5	33.2	-28	-22.6
		Spring flood pulse	81	90	0.9	0.8	10.3	8.3	-9	-7.5
		Monsoon season	91	308	25.7	20.5	47.3	37.8	-22	-17.3
	Moderate Year	*Winter dry season*	320	102	20.3	16.2	67.3	53.8	-47	-37.6
		Spring flood pulse	103	174	11.3	9.0	113.0	90.4	-102	-81.4
		Monsoon season	175	319	34.5	27.6	75.6	60.5	-41	-32.8
	Wet Year	*Winter dry season*	389	133	20.1	16.0	84.7	67.8	-65	-51.7
		Spring flood pulse	134	211	11.9	9.5	205.6	164.5	-194	-155.0
		Monsoon season	212	388	32.8	26.3	140.3	112.2	-107	-86.0

Streamflow Gauge	Water year type	Regulated flows (MCM)	Resilient flow (MCM)	Surplus (MCM)	Surplus (%)	Deficit (MCM)	Deficit (%)	Env. Flow Gap (MCM)	Env. Flow Gap (TAF)	Env. Flow Gap (%)
PR06_at_Redbluff	Dry year	39.8	99.2	0.0	0%	59.3	60%	-59.3	-47.5	60%
	Moderate year	66.1	255.9	0.0	0%	189.9	74%	-189.9	-151.9	74%
	Wet year	64.7	430.6	0.0	0%	365.8	85%	-365.8	-292.7	85%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
PR08_Outlet	*Dry Year*	*Winter dry season*	305	62	46.0	36.8	22.7	18.2	23	18.6
		Spring flood pulse	63	70	3.0	2.4	6.3	5.0	-3	-2.6
		Monsoon season	71	304	102.5	82.0	51.4	41.1	51	40.8
	Moderate Year	*Winter dry season*	320	90	63.4	50.7	48.0	38.4	15	12.3
		Spring flood pulse	91	160	38.2	30.6	115.7	92.6	-78	-62.0
		Monsoon season	161	319	111.1	88.9	87.3	69.9	24	19.1
	Wet Year	*Winter dry season*	365	120	65.3	52.2	107.7	86.2	-42	-33.9
		Spring flood pulse	121	211	69.3	55.4	285.8	228.7	-217	-173.2
		Monsoon season	212	364	132.0	105.6	180.5	144.4	-49	-38.8

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
PR08_Outlet	Dry year	151.4	80.4	74.3	92%	3.3	4%	71.0	56.8	88%
	Moderate year	212.7	251.1	39.2	16%	77.5	31%	-38.4	-30.7	15%
	Wet year	266.5	574.0	0.0	0%	307.5	54%	-307.5	-246.0	54%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG03_SALADO	*Dry Year*	*Winter dry season*	313	116	12.1	9.6	20.9	16.7	-9	-7.1
		Spring flood pulse	117	140	6.7	5.3	4.9	3.9	2	1.4
		Monsoon season	141	312	20.9	16.8	68.8	55.0	-48	-38.3
	Moderate Year	*Winter dry season*	326	147	35.6	28.5	44.8	35.9	-9	-7.4
		Spring flood pulse	148	183	7.4	5.9	31.8	25.4	-24	-19.5
		Monsoon season	184	325	44.0	35.2	147.3	117.8	-103	-82.6
	Wet Year	*Winter dry season*	345	197	57.3	45.8	98.2	78.6	-41	-32.7
		Spring flood pulse	198	246	27.7	22.2	120.6	96.5	-93	-74.3
		Monsoon season	247	344	77.6	62.1	293.2	234.5	-216	-172.4

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
subRG03_SALADO	Dry year	39.7	94.6	1.8	2%	56.7	60%	-54.9	-43.9	58%
	Moderate year	87.1	223.9	0.0	0%	136.8	61%	-136.8	-109.5	61%
	Wet year	162.7	512.0	0.0	0%	349.3	68%	-349.3	-279.5	68%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG05_SAN_JUAN	*Dry Year*	*Winter dry season*	314	51	1.2	1.0	36.0	28.8	-35	-27.8
		Spring flood pulse	52	168	3.5	2.8	154.2	123.4	-151	-120.6
		Monsoon season	169	313	3.4	2.7	179.7	143.8	-176	-141.1
	Moderate Year	*Winter dry season*	322	116	2.9	2.3	81.0	64.8	-78	-62.5
		Spring flood pulse	117	186	1.3	1.0	195.0	156.0	-194	-154.9
		Monsoon season	187	321	9.3	7.5	261.8	209.4	-252	-202.0
	Wet Year	*Winter dry season*	348	176	4.4	3.6	133.7	107.0	-129	-103.4
		Spring flood pulse	177	264	54.8	43.8	299.7	239.8	-245	-196.0
		Monsoon season	265	347	73.4	58.7	264.8	211.8	-191	-153.1

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
subRG05_SAN_JUAN	Dry year	8.1	369.9	0.0	0%	361.8	98%	-361.8	-289.5	98%
	Moderate year	13.5	537.8	0.0	0%	524.3	97%	-524.3	-419.4	97%
	Wet year	132.6	698.2	0.0	0%	565.6	81%	-565.6	-452.5	81%

Streamflow Gauge	Water year type	FFComponent	Reference dates		Regulated flows		Resilient flow		Env. Flow Gap	
			Start Date	End Date	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*	*(MCM)*	*(TAF)*
subRG09_RIO_CONCHOS	*Dry Year*	*Winter dry season*	314	161	52.1	41.7	174.8	139.9	-123	-98.2
		Spring flood pulse	162	211	23.6	18.9	78.1	62.5	-55	-43.6
		Monsoon season	212	313	30.3	24.2	234.2	187.4	-204	-163.2
	Moderate Year	*Winter dry season*	330	191	167.1	133.7	263.8	211.0	-97	-77.4
		Spring flood pulse	192	211	27.6	22.1	45.6	36.5	-18	-14.4
		Monsoon season	212	329	166.6	133.3	521.0	416.8	-354	-283.5
	Wet Year	*Winter dry season*	343	229	336.1	268.9	488.8	391.1	-153	-122.2
		Spring flood pulse	230	211	0.0	0.0	0.0	0.0	0	0.0
		Monsoon season	212	342	303.9	243.1	868.9	695.1	-565	-452.0

Streamflow Gauge	Water year type	Regulated flows	Resilient flow	Surplus		Deficit		Env. Flow Gap		
		(MCM)	*(MCM)*	*(MCM)*	*(%)*	*(MCM)*	*(%)*	*(MCM)*	(TAF)	(%)
subRG09_RIO_CONCHOS	Dry year	106.0	487.2	0.0	0%	381.2	78%	-381.2	-305.0	78%
	Moderate year	361.3	830.4	0.0	0%	469.1	56%	-469.1	-375.3	56%
	Wet year	640.0	1357.7	0.0	0%	717.7	53%	-717.7	-574.2	53%

Annex 5. Environmental flows and Gaps and carrying capacity.

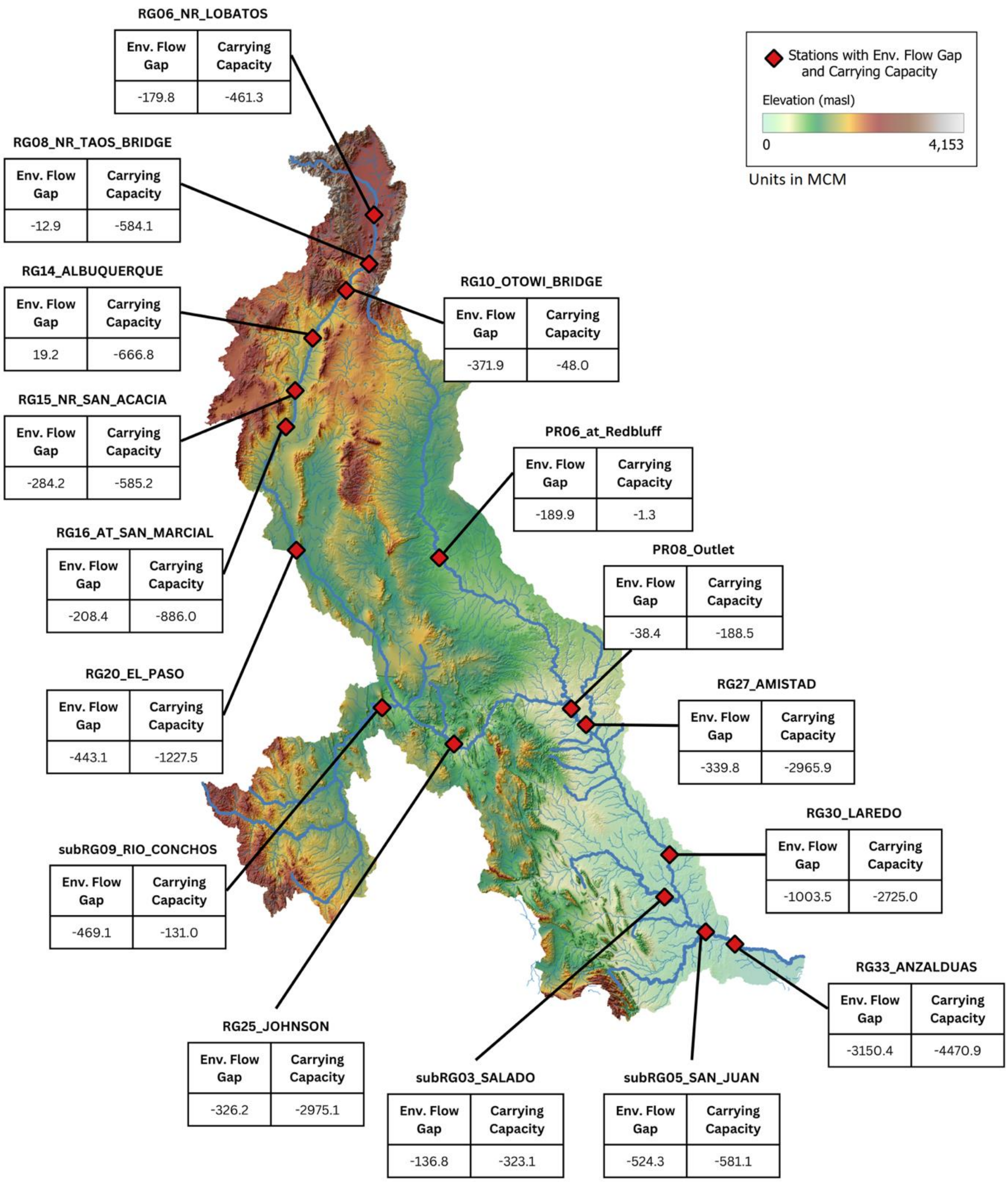


Figure 32. Summary of Carrying capacity values and recommended environmental flows at each gauge station on the RGB.

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.

The overall goal of this research was to determine environmental flow requirements in the RGB basin and define strategies or interventions for achieving them.

WWF

UC DAVIS WATER MANAGEMENT LAB