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Publication Date

2022

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A Quantitative Framework on Ecological Resilience for River Basins
Case Study: The Rio Grande – Rio Bravo

By

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DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Hydrologic Sciences

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2022

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ACKNOWLEDGEMENTS | AGRADECIMIENTOS

"*Como agua entre las grietas*"

Al gran amigo, mentor y asesor que me inculcó el amor por el estudio del agua, Sam Sandoval. Gracias por dejarme explorar la metáfora de resiliencia, llevaré por siempre conmigo las ideas en garabatos, las grandes enseñanzas y las tardes de trabajo merecedoras del té mexicano. Tu apertura, confianza y maravillosa amistad hicieron que el camino fuera extraordinariamente grato. Por las incontables veces que me dijiste —creo en ti. ¡Salud, lo logramos Sam!

A mis profesores de hidrología, en especial a Carlos Puente, por su humilad y compleja sencillez de ver el mundo; tus campanitas, que llegaban siempre en el momento correcto, me sanaron más de una vez. A Majdi Abou Najm por su apoyo y reciptividad en este último esfuerzo del doctorado. A Belize Lane, Mark Lubell y Greg Pasternack por sus comentarios reflectivos que me llevaron a experimentar el significado personal de resiliencia. A Nancy Aceves, del Tec de Monterrey, quien me dio la plataforma para conversar con agricultores, diseñar una clase de verano y soltarme en el desierto con veinte alumnos. A Oscar Leal de Pronatura Noreste, mi gran admiración por tu lucha por preservar el oasis de Cuatrociénegas y brindarme un espacio para ser vocera del río en el Consejo de Cuenca del Río Bravo. Además, a los más de cien alumnos que tuve el placer de enseñarles una que otra cosa sobre hidrología.

Mi eterno agradecimiento para mis mejores amigas Alyssa DeVincentis, Helaine Berries, Katie von der Lieth y Silvia Almaraz. Ustedes hicieron que Davis se sintiera como un hogar y siempre les agradeceré sus consejos de vida, las risas eternas, los fun cocktails y su extraordinaria amistad. A Pablo Ortiz, que ha sido un gran amigo y hermano a lo largo del doctorado. Al equipo de amigos del Río Bravo: Ramón Saiz, Gaby Rendón y Grace Quiroga además del Water Management Lab; Hervé Guillon, Noelle Patterson, Leo Qiu, Romina Díaz, Paulina Rojas, Daisy Guitron y Sloane Rice, por nuestras aventuras por México, los parish announcements y el legendario Open Mic.

Por último y más grande agradecimiento es a mi familia. A mis padres Sergio y Yolanda quienes me dieron la oportunidad y libertad de volar lejos gracias a su gran esfuerzo y a mi hermano Checo por siempre unir a la familia con nuevos viajes y experiencias. Su amor incondicional lo he sentido en todo momento, aún y cuando estemos a la distancia. A mi abuelo Ricardo, quien a sus 93 años me sigue haciendo reir a carcajadas. Voy atesorar el momento cuando te platiqué sobre el Río Bravo, este trabajo te lo dedico con todo mi amor.

Y a mi Dany, mi compañero de vida, quien ha estado a mi lado por el mundo incluso antes de conocernos. Por sostenerme y apoyarme en los últimos años, no pudiera haberlo logrado sin ti. Gracias por tu paciencia, por escucharme y por el amor infinito que me das. Esto es para ti.

ABSTRACT

River basins are unique dynamic systems that depend on their natural hydrologic variability and streamflow diversity to provide a wide range of ecosystem services. However, on a global scale, the fragmentation of river networks and the dampening of environmental variability are increasing by the unforeseen pressures of climate change and anthropogenic disturbances, including unsustainable water withdrawals, dam constructions, and land-use change. These disturbances can accumulate, pushing the system beyond a threshold, inducing a regime shift, and leading the system to an alternative state. But how much forcing a river basin can take until the system undergoes a regime shift and into an alternative state? And how to assess ecological resilience of a river basin from anthropogenic and climatic disturbances? A resilience approach seeks to explain these dynamics, including understanding the ecosystem organization and functional flow traits that are inherently bound to the system's adaptive capacity to maintain critical functions and processes during changing environmental conditions. In this work, I propose a tractable framework to evaluate the ecological resilience of river basins by assessing three measurable resilience attributes: alternative regimes, thresholds, and adaptive capacity using the transboundary Rio Grande-Bravo basin as a case study. The broader impact of this work is to advance into the general endeavor of moving forward from the theoretical understanding of resilience into a more tangible and quantifiable measure to assess it. But most importantly is the strong potential that this framework has to support conservation efforts, ecosystem management and inform current policy of river basins to understand and incorporate the inherent dynamism of ecosystems into water management.

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INTRODUCTION

As the centerpiece of the evolution of ecosystems and human societies, river basins are unique dynamic systems that depend on their natural hydrologic variability to provide a wide range of ecosystem services. However, accumulating anthropogenic disturbances and climate change risks in river basins contribute to a long-lasting problem that involves multiple domains, dimensions, and scales of analysis (Vitousek, Mooney, Lubchenco, & Melillo, 1997) altering ecosystem functions and limiting the river basin's ability to respond, absorb and adapt to changing conditions. While scientific knowledge to explain systems and their intrinsic pressures is accumulating, traditional approaches to river basin problems have tended to be tackled from a single disciplinary perspective or assuming static states, and conventional linear methods (Cumming, 2011) while trying to reach optimal and increasing yields. As freshwater pressures amplify, alternative approaches to explore ecosystem needs are growing and the term **resilience** has become increasingly recognizable in environmental sciences and water management policies.

Multiple definitions of resilience have been proposed and debated (See Glossary). In general, resilience has been used in two different contexts: 1) Engineering resilience, defined as the time needed for a system to return to pre-disturbance conditions (Hashimoto, Stedinger, & Loucks, 1982; Pimm & Pimm, 1991). It assumes linear and optimal systems where the speed of return to equilibrium is used to measure the property. This definition fails to capture the nature of variability of natural systems (Holling, 1996) yet given its practical quantification, it is the most commonly used in water management, specifically in reservoir operations. In contrast, ecological resilience, initially introduced by Holling, (1973) explains the magnitude of the disturbance that a system can absorb and adapt while maintaining its essential structure and function before it changes into an alternative regime. Ecological resilience has increasingly recognized as an imperative aspect of sustainable development, but quantifying and applying the concept of ecological resilience has been challenging (Angeler & Allen, 2016; Webb, Watts, Allan, & Conallin, 2018).

Water managers and ecologists are aware that the carrying capacity of ecosystems to adapt to environmental change may be exhausted in the future. This may lead to a widespread erosion of ecosystem resilience and, ultimately, to regime shifts and reorganization in distinct, alternative, undesirable and potentially stable regimes on local, regional and planetary scales (Hughes et al. 2013). It is clear that current problems related to the operationalization of resilience theory and although the metaphorical concept of resilience has the power to inspire useful analyses of socioecological systems, much more insight could be

gained from empirical analyses, which would require an operational, measurable concept of resilience (Carpenter, 2001). Therefore, the motivation and question for this research is:

how to assess ecological resilience of a river basin from anthropogenic and climatic disturbances?

Recently, ecological resilience principles to assess social ecological systems rely on considering ecological resilience as an emergent property of a complex systems that can be decomposed into attributes or surrogates of resilience: alternative regimes, thresholds, scales, and adaptive capacity. These surrogates are described by Baho et al., (2017) as:

- Alternative regimes: based on the ecological theory that natural systems can exist in alternative stable states (Lewontin, 1969), meaning that a potential alternative configuration of a system can exist in terms of abundance, composition, function and process of a system. E.g. Transitions of tree cover between tropical forest and savanna in response to rainfall (Hirota, 2011).
- Thresholds: defined as the point at which there is an abrupt change in a quality, property or phenomenon or where small changes in a driver may produce large responses in the ecosystem (Groffman, 2006). E.g. thresholds responses of riverine fish communities to flow changes.
- Scales: the organization of ecosystems wherein structures, functions, and processes are compartmentalized by distinct scales of space and time. Related to the spatial heterogeneity and temporal variability of a system.
- Adaptive capacity: Refers to the functional traits of an ecosystem which provides the ability to maintain critical functions and processes during changing environmental conditions.

In this dissertation, **I suggest a simple and tractable framework (Figure 0), using three measurable resilience attributes, to evaluate the ecological resilience of river basins using well-known methods and streamflow data as the main input.** This framework will offer the opportunity to assess ecological resilience broadly in a local and regional scale, bridging gaps between science and policy in water resources management.
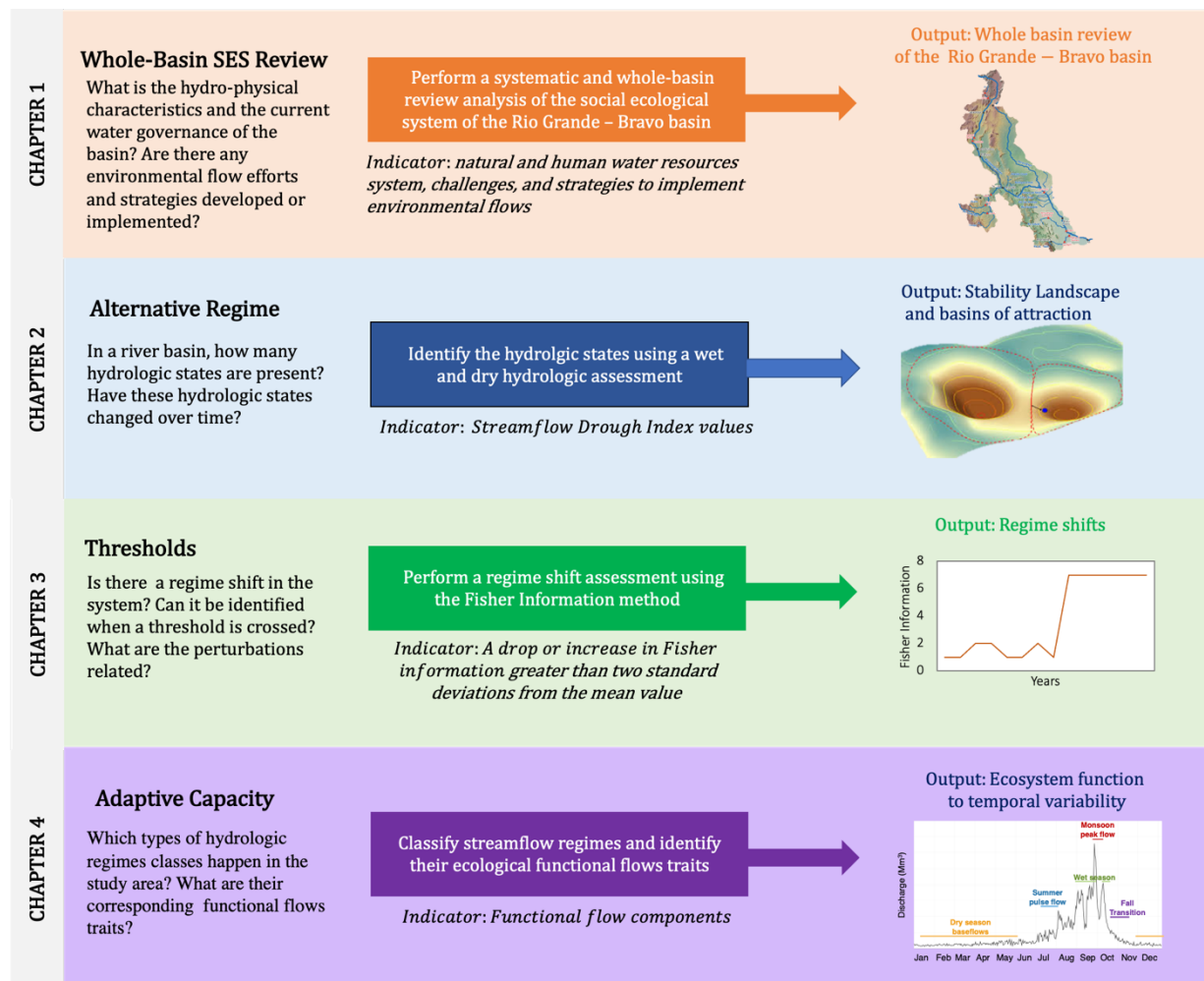
Figure 0. Dissertation schematic.

The dissertation includes four chapters designed to stand alone and therefore each contains its own abstract, introduction, methods, results, discussion, and conclusions. The first chapter provides a review of the study area, the transboundary Rio Grande-Bravo (RGB) basin, followed by three chapters that explores three ecological resilience surrogates of alternative regimes, thresholds, and adaptive capacity.

Chapter I performs a **systematic and whole-basin review analysis of the Rio Grande – Bravo basin** by analyzing the efforts of implementing environmental flows (flows necessary to sustain riparian and aquatic ecosystems and human activities). This chapter introduces the physical characteristics, the water governance, the different environmental flows legal frameworks of the basin and several success stories for implementing environmental flows in the RGB. Chapter I was a collaborative research between 15 authors, were I was co-leading the hydro-physical science research and supported the social science research, water governance policies, and success stories for the Mexican section of the scientific article.

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Chapter II explores the resilience surrogate of **alternative regimes** by analyzing how anthropogenic droughts can lead to changes in the resilience properties of the stability landscape of the RGB. This chapter analyses the modern hydrology of the RGB, a perennial human-induced extreme drought and the ecological resilience of the RGB using the stability landscape metaphor. The main finding is the evidence of resilience erosion and alterations to the properties of the stability landscape by the human-induced megadrought in the, which resulted from extensive anthropogenic alteration and fragmentation of the RGB system.

Chapter III explores the resilience surrogate of **resilience thresholds** by evaluating the carrying capacity of the RGB through the identification of ecological resilience thresholds, regime shifts, and early warning signals. This chapters identifies when a regime shift occurred and discusses how depending on resilience safeguards, crossing thresholds might suffer abrupt or delayed regime shifts at different times. In addition, different mechanisms of regime shifts were identified including abrupt, cascading, and gradual shifts, and early warning signals such as flickering and critical slowing down.

Chapter IV explores the resilience surrogate of **adaptive capacity** by estimating one hundred years of daily natural streamflow and proposing six functional flows for the RGB: dry season baseflows, summer pulses, monsoon peak flows, wet season, and snowmelt flows. Additionally, the functional flows were quantified using flow metrics such as magnitude, timing, frequency, duration, and rate of change. These provide a baseline to propose instream flows in the RGB.

Together, these chapters expand the research and application of ecological resilience in in river systems and challenges the outdated vision of highly manipulated systems to obtain maximum yields for a foundational understanding of river basins as dynamic and variable systems. In addition, the unique combination of methods used in these chapters lays the foundation for future research focused on a whole-basin thinking, the integration of ecological resilience theory, and the adoption of resilience analysis and adaptive water resources management strategies in transboundary river basins across the world.

CHAPTER 1

ENVIRONMENTAL FLOWS IN THE RIO GRANDE – BRAVO BASIN

Samuel Sandoval-Solis, Stephanie Paladino, **Laura E. Garza-Diaz**, Luzma F. Nava, Jack R. Friedman, J. Pablo Ortiz-Partida, Sophie Plassin, Grace Gomez-Quiroga, Jennifer Koch, Jeri Fleming, Belize A. Lane, Sean Wineland, Ali Mirchi, Ramon Saiz-Rodriguez, and Thomas M. Neeson (DOI: https://doi.org/10.5751/ES-12944-270120)

ABSTRACT. The Rio Grande/Bravo is an arid river basin shared by the United States and Mexico, the fifth-longest river in North America, and home to more than 10.4 million people. By crossing landscapes and political boundaries,

the Rio Grande/Bravo brings together cultures, societies, ecosystems, and economies, thereby forming a complex social-ecological system. The Rio Grande/Bravo supplies water for the human activities that take place within its territory. While there have been efforts to implement environmental flows (flows necessary to sustain riparian and aquatic ecosystems and human activities), a systematic and whole-basin analysis of these efforts that conceptualizes the Rio Grande/Bravo as a single, complex social-ecological system is missing. Our objective is to address this research and policy gap and shed light on challenges, opportunities, and success stories for implementing environmental flows in the Rio Grande/Bravo. We introduce the physical characteristics of the basin and summarize the environmental flows studies already done. We also describe its water governance framework and argue it is a distributed and nested governance system across multiple political jurisdictions and spatial scales. We describe the environmental flows legal framework and argue that the authority over different aspects of environmental flows is divided across different agencies and institutions. We discuss the prioritization of agricultural use within the governance structure without significant provisions for environmental flows. We introduce success stories for implementing environmental flows that include leasing of water rights or voluntary releases for environmental flow purposes, municipal ordinances to secure water for environmental flows, nongovernmental organizations representing the environment in decision-making processes, and acquiring water rights for environmental flows, among others initiatives. We conclude that environmental flows are possible and have been implemented but their implementation has not been systematic and permanent. There is an emerging whole-basin thinking among scientists, managers, and citizens that is helping find common-ground solutions to implementing environmental flows in the Rio Grande/Bravo basin.

1. Introduction

1.1 The RGB as a Social-Ecological System

The Rio Grande/Bravo (RGB) is a transboundary river basin shared by the United States (U.S.) and Mexico, and is home to over 10.4 million people. It is the fifth-longest river in North America with a length of about 3,000 km, two-thirds of which delimit the border between the two countries. The RGB has a drainage area of approximately 557,000 km2 and extends over three states in the U.S. (Colorado, New Mexico, and Texas) and five states in Mexico (Durango, Chihuahua, Coahuila, Nuevo León, and Tamaulipas). The main tributaries of the RGB are the Rio Conchos, Rio Salado, Rio San Juan, Rio Chama and the Pecos River (Figure 1). By crossing landscapes and political boundaries, the RGB brings together cultures, societies, ecosystems, and economies forming a complex social-ecological system (SES) (Koch et al. 2019, Plassin et al. 2020). Understanding the relationships and feedback between people and water is a prerequisite to understand the long-term dynamics of a region's hydrology (Sivapalan et al. 2011). According to Ostrom (2009), all resources used by humans - including water - are intrinsic components of SES. Finding sustainable solutions for the use of these resources requires the identification and analysis of the relationships between different social and ecological components of SES across spatial and temporal scales (Ostrom 2009). The RGB is an arid, water-limited, and drought-prone basin that supplies water for all of the economic activities that take place within its territory. However, environmental flows - streamflows necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being (Arthington et al. 2018) - have not been addressed within the water governance and allocation institutions of the basin (Nava et al. 2016) similar to other water-scarce areas (King and Brown 2006). This paper examines environmental flows within the context of the RGB as a complex SES, where it is not possible to decouple the social, political, economic, hydrological, and ecological aspects from each other. Approaching the RGB basin as SES allows the framing of challenges and opportunities for implementing environmental flows that are not only technically and legally sound and socio-environmentally needed but necessary to sustain ecosystem functions and the ecological goods and services provided to people (Balvanera et al. 2006). Through this exercise, we highlight some of the key socio-political-legal challenges to integrating environmental flows into existing water governance and management practices within the RGB. We also describe several initiatives that represent innovative attempts to implement or facilitate environmental flows within this challenging context. The authors recognize the RGB basin as a river basin with shared common-pool resources; therefore, managing

common-pool resources in a transboundary SES requires understanding both the natural and social systems.

Main rivers, reservoirs, and cities in the Rio Grande/Bravo Basin
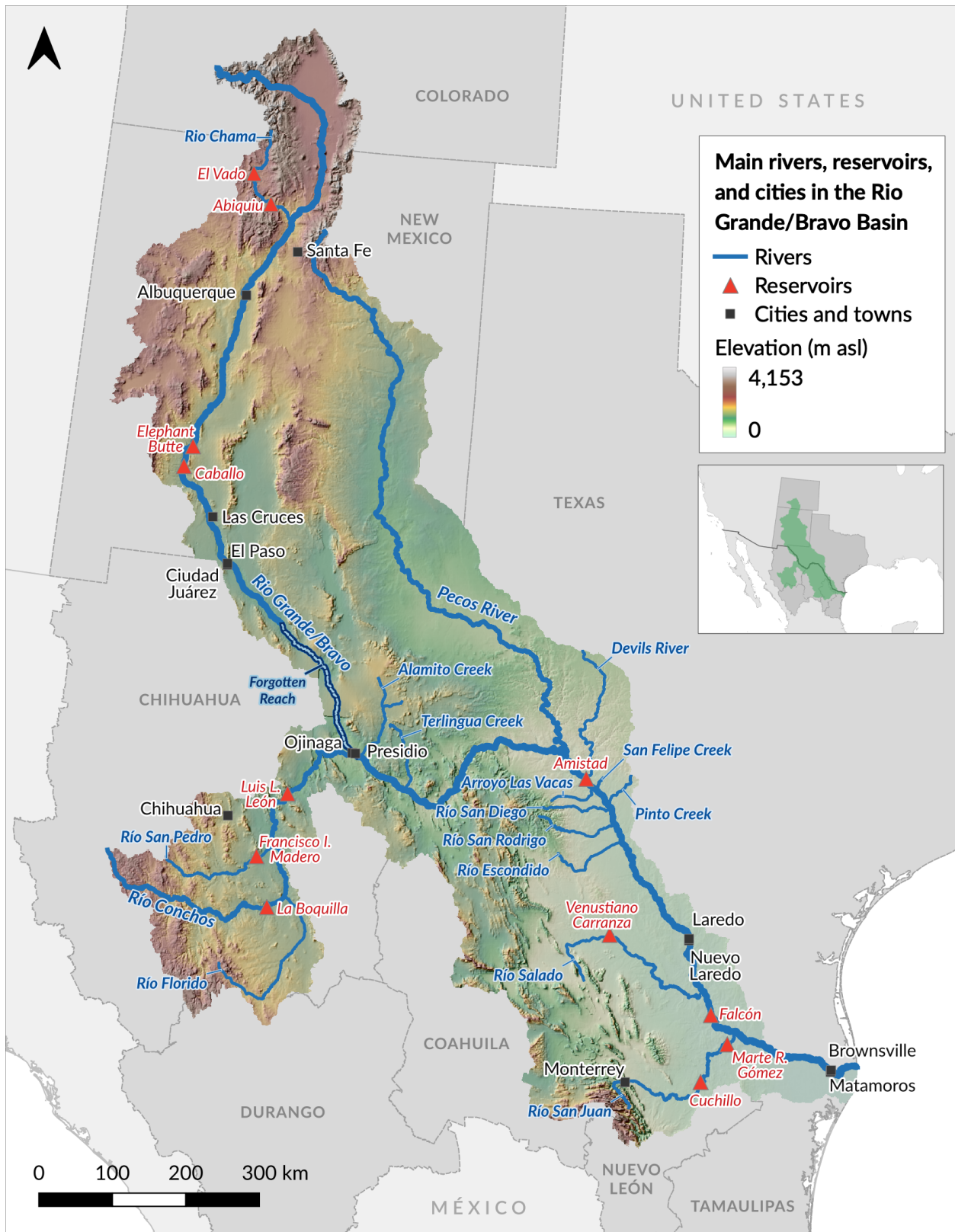
Figure 1.- Main rivers, reservoirs, cities and population settlements in the Rio Grande/Bravo (RGB) basin.

Since the 1870s, the RGB basin has experienced a long history of human manipulation (Enríquez Coyro 1976, Horgan 1984). Economic and agricultural development has resulted in severe impacts on river ecosystems, and hydraulic infrastructure has considerably altered the basin's natural flow regime (Blythe and Schmidt 2018). The extent of environmental degradation can be seen most drastically along a 240-km stretch of the river, called the *Forgotten Reach* (Figure 1), that is at times completely dry due to upstream diversions (Everitt 1993). The river corridor itself has also been heavily modified, including the human-engineered straightening of the mainstem in some areas for conveyance and flood protection (e.g. in Presidio/Ojinaga and El Paso/Cd. Juarez), as well as channel narrowing and incision caused by reduced frequency of flood flows and encroachment of invasive vegetation (e.g. in the Big Bend Reach). These physical changes make it harder for the river to access its floodplains, reducing availability of the shallow and low-velocity spawning habitat (the preferred conditions for the endangered Rio Grande Silvery Minnow (USFWS 2010)) and promoting recruitment of invasive species (e.g. *Tamarix spp.* and *Arundo donax*). Furthermore, the basin is experiencing increasing threats from climate change (Hurd and Coonrod 2012, Elias et al. 2015) that are affecting water availability (Utton 1999, Kelly 2002), changing the timing and volume of snowmelt in the basin's headwaters (Rango 2006) and the frequency of tropical storm events in tributaries (Sayto-Corona et al. 2017). There is a need to provide environmental flows in order to maintain both river ecosystems and water provision for human needs. While there have been recent efforts to implement environmental flow agreements at various locations throughout the basin, a systematic and integrated analysis of these efforts that conceptualizes the RGB as a single, complex socio-ecological system is missing.

Our objective is to address this research and policy gap and shed light on challenges, opportunities, and success stories for implementing environmental flows in the Rio Grande/Bravo. Our methodology combines a literature review with the bilingual, multidisciplinary, and topical expertise of the authors, which includes social, political, legal, environmental, and hydrological research in the basin. We focused on three questions: (1) What is the current status of knowledge about environmental flows and their relation to ecosystem and human water needs in the Rio Grande/Bravo? (2) In what ways do current water governance frameworks in the basin appear to support or hinder the establishment of environmental flows? (3) Are there policies or practices that have implemented environmental flows, and what lessons can be learned from those experiences for a more widespread implementation in the basin? We address these questions by considering the Rio Grande/Bravo as a whole basin. The target audience for this research study is scientists, natural resources managers, decision-makers, and land, water, and environmental advocates who are interested in better understanding both technical and socio-political conditions for integrating environmental flows into existing water governance and management practices. While the focus is the Rio Grande/Bravo, we believe there are many dynamics represented that are relevant to other areas of the North American arid west, as well as to arid lands elsewhere. Fig. 2 provides an overview of the topics discussed in this research study. We have created a repository of the geographic information presented in this study (Sandoval- Solis and Lane 2021).

Introduction
The Rio Grande – Rio Bravo as a socio-ecological system
  • Objective of this research synthesis
Basin characteristics and natural flow regime
Water competition and climate change

Environmental Flows Studies
The need for environmental flows
Instream and environmental flow studies

Water Governance, Water Rights, and Environmental Flows
Overview
In the United States
In Mexico

Challenges and Opportunities
Paradoxes in social perceptions: the challenge of managing for the commons
The central place of agriculture
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Conclusions
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Figure 2. Overview of the topics discussed

1.2 Basin Characteristics

The RGB's biological richness is embodied in the basin's diverse topography (with elevations ranging from 4,365 m to sea level), climatology (snow and hurricane driven precipitation ranging from 2,260 to 190 mm/year), hydrology (including diverse streamflow regimes), and ecoregions (crossing five continental ecoregions). These characteristics shape a diverse environment with climatic and hydrologic contrasts, from high mountain terrain to desert landscapes, river canyons, and a wide deltaic floodplain creating exceptionally high diversity of plant and animal life. The climatic and topographic diversity also affects the flow regime of the RGB; its principal streamflow sources are (1) snowmelt from the San Juan Mountains and mountains of northern New Mexico, (2) monsoon-driven flows during the hurricane season from the

Pacific and Atlantic oceans, and (3) groundwater inflow to streams throughout the basin. These streamflow sources shape the features of its riverine ecosystems and its natural flow regime.

1.3 Natural Flow Regime

Prior to substantial human impacts on the river, starting in the 1870s, the natural flow regime of the RGB evolved along its mainstem. A large spring snowmelt pulse was the dominant signal upstream of Ojinaga/Presidio (Figure 1) (hereafter referred to as the northern branch; (Blythe and Schmidt 2018)); and a bi-modal snowmelt and monsoonal rain flow regime occurred downstream of Ojinaga/Presidio (hereafter referred to as the southern branch). In the main tributaries of the southern branch, the flow regime was dominated by a seasonal monsoonal rainfall-driven signal from July to September, and a stable groundwater-fed baseflow during the dry months. Flash-floods in small ephemeral tributaries contributed infrequent large flow and sediment pulses (Schmidt et al. 2003, Dean and Schmidt 2013). These distinctive streamflow signatures provided the dynamic natural processes that the river ecosystems depend on (Poff et al. 1997). For example, many riparian plant species (e.g., Rio Grande cottonwood) are evolutionarily adapted to germinate after predictable, annual, snowmelt-driven high flows (Bhattacharjee et al. 2009). Flood flows from heavy rains provide migration and spawning cues for native fish such as the Rio Grande cutthroat trout (Young 1995), as well as restore water quality conditions by flushing sediment accumulated over the dry season and contributing cool, oxygenated water (Postel et al. 2003). Management, maintenance, and restoration of a healthy river involves more than maintaining a constant minimum flow; it requires maintaining or restoring key aspects of this dynamic flow regime specifically intended to sustain critical ecological functions while continuing to meet human water management objectives.

1.4 Water competition and Climate Change

Today, the RGB bears little resemblance to its pre-1870s conditions. Increased water use and hydraulic infrastructure (Sandoval-Solis et al. 2011) have significantly altered the natural flow (Gonzalez-Escorcia 2017, Blythe and Schmidt 2018) and sediment regimes (Dean and Schmidt 2011). In 2007, the World Wildlife Fund (WWF) listed the RGB among the world's most at-risk rivers (Wong et al. 2007). Soon afterwards, Presidents Obama and Calderón (2010) of the U.S. and Mexico, respectively, declared the Big Bend region of the RGB as a natural area of binational interest. Agriculture, municipal and domestic uses, industries, hydroelectric power, and recreational activities compete for water. The extent of irrigation activities has steadily expanded during the 19th century, especially after the Desert Land Act of 1877 (Scurlock 1998, Wozniak 1998). Currently, agriculture accounts for 83% of water withdrawals in the RGB, while covering less than 5% of the basin area (U.S. Geological Survey, 2010; National Water Commission of Mexico, 2010; Canada Centre for Remote Sensing et al., 2017). Major irrigated crops include alfalfa, sorghum and other hay crops, corn, cotton, pecans, wine grapes, chile, onions, melons, potatoes, barley, sugar cane, and citrus. In addition, continued water use from growing cities has intensified the pressure on already scarce, freshwater resources. For example, the population of El Paso County rose by 150% between 1960 and 2010 (U.S. Census Bureau 2010), and the four counties that compose the Lower Rio Grande Valley in Texas (Cameron, Hidalgo, Starr, and Willacy) have recorded a population growth of over 342% during the same period. Overall, during the latter half of the 20th century (1950 - 2010), these water demands have reduced the natural flow of the river by over 95% in the forgotten reach from 2,507 million m3 to 125 million m3 (Blythe and Schmidt 2018). The pressure on this over-allocated system is such that agricultural land fallowing has been practiced across the basin to reduce irrigation withdrawals and respond to additional water demands.

Climate change is expected to affect the RGB streamflow timing and volume through changes in air temperature, snowfall and snowpack, rainfall, and increased evapotranspiration rates (Llewellyn and Vaddey 2013), with some of these changes already underway. The RGB basin spans a climatic gradient from semi-arid to sub-humid; its environment is vulnerable to extreme hydroclimatic events and especially to droughts that are expected to become more severe in this region by the end of the 21st century (Cayan

et al. 2010, Cook et al. 2015). In contrast, large rain events, influenced by tropical storms and hurricanes that impact the RGB from the Pacific and Atlantic oceans, have increased their frequency (Sayto-Corona et al. 2017), resulting in flooding of towns and cities, crop destruction, waterborne diseases, significant economic losses, and human fatalities. According to Rumsey et al. (2020), streamflow decreased at 9 of 12 sites upstream of Albuquerque, NM between 1980 and 2015. In almost all cases, the decrease was associated with decreases in baseflow and snowmelt rates. Moreover, Lehner et al. (2017) showed that the current decreasing trend in the fraction of runoff produced from precipitation is unprecedented in the last 445 years. Several studies have predicted substantial climate impacts on the RGB by the end of the 21st century. Elias et al. (2015) estimated runoff volume will range from +7% to -18%, and the timing of 7-day peak runoff will range from 14 to 24 days earlier upstream of Albuquerque. Samimi et al. (2020) evaluated the effects of four carbon emission scenarios in the water availability upstream of Elephant butte; the majority of the projections showed a declining annual streamflow, about -1 m3/s across all projections (Townsend and Gutzler 2020). Ingol-Blanco and McKinney (Ingol-Blanco and McKinney 2010) projected a streamflow decline of the Rio Conchos at the confluence with the Rio Grande of 18% by the end of the century. Changes in air temperature are also expected to exacerbate water quality issues, especially in the border cities of the southern branch (Duran-Encalada et al. 2017). Changes in volume and timing of streamflow could have substantial implications for aquatic and riparian ecosystems, agriculture, recreational activities, municipalities, and industries, resulting in alterations of existing patterns of water use, timing of water storage, and release from reservoirs. These changes will create additional challenges and opportunities to coordinate releases with environmental flow needs in given locations.

2. Environmental Flow Studies

2.1 The need for Environmental Flows

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 water regime, with adverse impacts on local riparian and aquatic ecosystems. Recognition of the mounting threats to riparian and aquatic species in the RGB basin has led to increased consideration of environmental flow needs within water resources management efforts. *Instream flows*, flow requirements that only consider ecological water needs, are key for determining environmental flows because they define a set of initial flow targets from which flow regimes that balance human and ecosystem water needs are derived. Fundamentally, determining *instream flows* requires selecting appropriate estimation methods based on spatial scale, temporal resolution, data availability, technical requirements, costs, and ecological management goals (Tharme 1996, Arthington and Zalucki 1998, Arthington 2012). More than 200 methodologies exist for estimating instream flows (Tharme 2003), the majority of which fall into three distinct categories: hydrologic, habitat simulation, and holistic. Hydrologic methods focus on the analysis of streamflow data. Traditionally these methods estimate instream flow requirements as a certain percentage/percentile of the natural flow regime (e.g. Tennant 1976, Richter et al. 2012), and more recently, by estimating ecologically relevant flows (e.g. Escobar-Arias and Pasternack 2010, Yarnell et al. 2015, 2020) using key flow regime characteristics (Poff et al. 1997, Patterson et al. 2020). Habitat simulation methods are based on the relationships between flow, hydraulic variables (e.g. water velocity, water depth), and target species or life-stage observed suitability for those hydraulic conditions (Tharme 2003, Arthington 2012). Expert-driven holistic methodologies combine the local expertise of scientists and stakeholders with hydrologic and/or hydraulic methods, and have the goal of restoring or conserving entire river ecosystems. This approach is often used in large scale projects to protect rivers of high strategic and conservation importance (Poff et al. 2017).

2.2 Instream and Environmental Flows for the RGB

In the last fifteen years, multiple studies have been conducted to estimate instream flows in different locations and sections of the RGB basin, using several methods. Table 1 presents a brief overview of some

of these studies. Starting with a holistic study in the Rio Conchos by the World Wildlife Foundation (WWF) in 2006, these studies have mostly relied on hydrologic (Sandoval-Solis and McKinney 2009, Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team for the Lower Rio Grande Basin, 2012) and habitat simulation methods (e.g., Mussetter et al. 2004, Stone 2008, Trungale Engineering & Science 2012, Horner 2016) from which ecosystem water needs have been recommended. Table 2 lists several studies that evaluate the ability to adjust existing RGB water management strategies to provide instream flows while meeting human water management objectives, including: agriculture and urban water supply (Sandoval-Solis and McKinney 2009, Sisto 2009, Porse et al. 2015); flood control (Lane et al. 2015); treaty obligations (Sandoval-Solis and McKinney 2014, Lane et al. 2015); and recreational and economic benefits (Ortiz-Partida et al. 2016, 2019).

Two key insights emerge from a review of these studies. First, there are several locations and reaches (Figure 2) that already have estimated instream flows from which environmental flows can be derived. Second, and notably, past studies indicate that, even though the RGB is a heavily managed and allocated basin, it is feasible to provide environmental flows intended to maintain or restore aquatic and riparian ecosystems while still supplying agricultural water needs (Sisto 2009, Sandoval-Solis and McKinney 2011) and meeting treaty obligations (Lane et al. 2015). Furthermore, these water management changes are hydrologically (Lane et al. 2015) and economically viable (Ward et al. 2006, Ortiz-Partida et al. 2016). These findings indicate that the focus must turn to addressing how the complex and nested water governance framework in the RGB can be harnessed or modified to achieve these outcomes.

Table 1. Examples of instream flow studies in the Rio Grande/Bravo.

Location	Instream flow method		Results	Reference
Lower RGB Matamoros and Brownsville reach	Hydrological	Percentage of average annual runoff	Estimations of a minimum seasonal environmental flow for the lower RGB due to the high anthropogenic demand.	(de la Lanza Espino et al. 2018)
Pilón River and San Juan tributary to the lower RGB	Hydrological	Percentage of average annual runoff and Modified Tennant method	Estimations of the minimum flow for the Pilon and San Juan river.	(Zepeda-Martínez 2012, Vidales-Contreras et al. 2014)
Big Bend region and the tributaries Rio Salado, Rio Escondido, Rio Alamo, and Rio San Juan	Hydrological	Percent Flow	Estimation of maintenance and dry season instream flows.	(Sandoval-Solis et al. 2019)
Middle RG at San Acacia reach	Hydrological	Minimum flow	A biological opinion issued that the minnow requires continuous minimum streamflow of at least 50 cubic feet per second over the San Acacia Diversion Dam.	(USDOI and USFWS 2003)

Independence Creek, Devils River and Pecos River	Habitat Simulation	Physical Habitat Simulation Model	A habitat-simulation model was built considering a one-dimensional hydraulic model and a habitat suitability criteria for certain species to estimate the weighted usable area (WUA) for each species over a range of flows at all cross sections.	(Trungale Engineering & Science 2012)
Middle RG (Espanola, Pena Blanca, Bernalillo, Central Ave, Bernardo, Bosque del Apache, San Marcial, and Lower Rio Chama downstream from Abiquiu Reservoir	Habitat Simulation	2-D Hydrodynamic Model	A habitat-simulation model was built for several sites along the Middle Rio Grande and lower Rio Chama to support efforts to protect and enhance Rio Grande. This model simulates flow, hydraulic variables, sediment transport, vegetation, water quality and the ecology of the aquatic systems.	(Mussetter et al. 2004, Stone 2008)
Middle RG (Bernalillo and Escondida)	Habitat Simulation	Hydraulic Criteria	Three habitat suitability curves were estimated using key variables (flow velocity, water depth, and substrate type) for mature and juvenile Rio Grande silvery minnow. Results show the lack of adequate habitat for the Rio Grande silvery minnow within the main channel and highlight the importance of floodplain connection, where most of the appropriate mesohabitat resides.	(Horner 2016)
Rio Chama tributary to the Upper Rio Grande	Habitat Simulation	System dynamics modelling	A one-dimensional hydraulic model was developed using the recruitment box model (Mahoney and Rood, 1998) to develop stage-discharge curves for cottonwood establishment and to determine the discharge at which overbank flooding occurs.	(Morrison and Stone 2015)
Rio Chama tributary to the Upper Rio Grande	Habitat Simulation	1-D and 2-D Hydrodynamic Model	A 1D and 2D hydrodynamic modeling was used within a collaborative process with the aim to improve spawning habitat for brown trout by flushing fine sediments from gravel features.	(Gregory et al. 2018)

Rio Grande basin upstream of Amistad Reservoir and below Presidio, including the Pecos and Devils river basins.	Holistic	Physical and Water Quality Habitat Simulation Model	This study emphasized the relationship of high flow pulses with sediment transport and channel geomorphology. Also, it evaluated water quality and biological overlay consisting of flow-instream habitat modeling for ten focal fish species for base flows and subsistence flow.	(Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Team for the Lower Rio Grande Basin, 2012)
Rio Conchos tributary to the Rio Grande	Holistic	Building Block Method	Estimation of instream flows considering geomorphology, flora, and fauna (fish and invertebrates) to determine the maintenance and drought flows necessary to sustain the river ecosystems for seven sites in the Conchos River.	(WWF 2006)

Table 2. Examples of studies that have proposed environmental flows in the Rio Grande/Bravo.

Location	Reference of instream flow study(s) based of	Water management strategy	Results	Reference
Rio Conchos in Chihuahua and the RGB downstream of Fort Quitman	WWF, 2006	Reservoir-reoperation	Provide environmental flows in the Rio Conchos basin while meeting treaty obligations and water supply for users located in the lower RGB basin, such as irrigation district 025 Bajo Rio Bravo but affecting upstream irrigation district 005 Delicias in Chihuahua.	(Sandoval-Solis and McKinney 2009)
RGB in the Big Bend Region	WWF (2006) and Upper Rio Grande Basin and Bay Expert Science Team (2012)	Reservoir-reoperation	An alternative reservoir operation policy maximized environmental flows to sustain key ecological and geomorphic functions in Big Bend without significantly impacting current water management objectives. The proposed policy also improved water supply provisions, reduced average annual flood risk, and maintained historical treaty provisions.	(Sandoval-Solis and McKinney 2014, Porse et al. 2015, Lane et al. 2015, Ortiz-Partida et al. 2016)

Rio Conchos tributary to the Rio Grande	WWF, 2006	Agro-economic model	Provides a proposal to restore and maintain ecosystems on a stretch of the Rio Conchos in northern Mexico, downstream from a large irrigation district that consumes nearly all local flows. The study provides estimates of environmental flow requirements for these ecosystems and computes compensation figures for irrigators.	(Sisto 2009)
Rio Chama tributary to the Upper Rio Grande	Morrison and Stone, 2014	System dynamics modelling	Examined the influence of flow regimes on cottonwood recruitment and reservoir storage, and investigated the impact of three alternatives on cottonwood recruitment within the project reach. The model attributes seedling survival to floodplain elevation, annual timing of peak flows and river stage declines that match seedling root growth.	(Morrison and Stone 2015)
Upper RGB at San Acacia Reach	U.S. Department of Interior, 2001	Integrated simulation model	This study estimates economic impacts associated with one strategy for increasing instream flows to protect critical habitat requirements of the endangered Rio Grande Silvery Minnow. Using an integrated hydrologic, economics, and allocation model of the Rio Grande Basin, a 44-year simulation of future inflows to the basin was conducted to estimate economic impacts of providing minimum acceptable flows for the minnow.	(Ward et al. 2007)
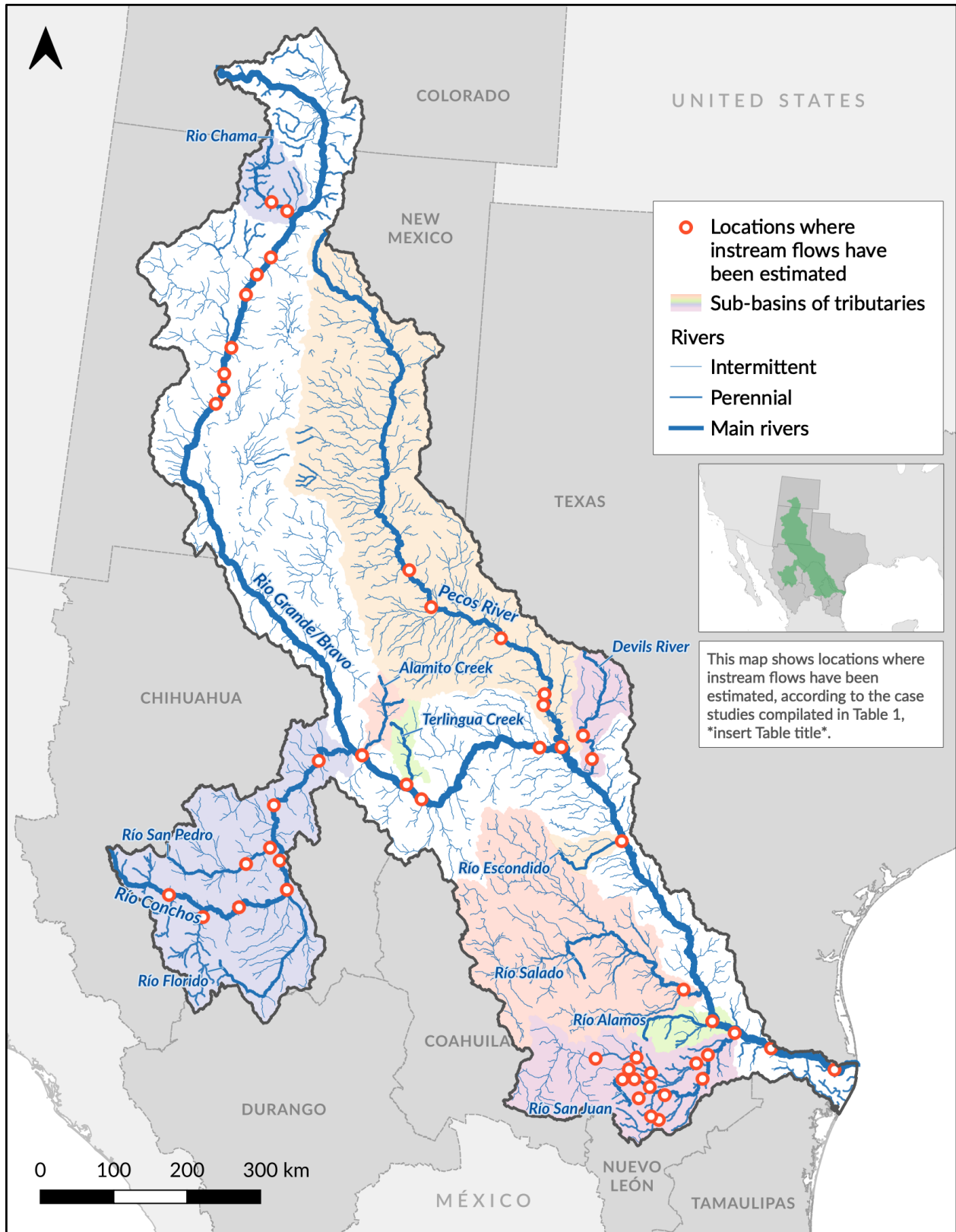
Figure 3.- Locations in the Rio Grande/Bravo (RGB) basin where instream flows have been estimated. The locations are derived from Table 2, which is not an exhaustive list.

3. Water Governance and Environmental Flows

3.1 Overview

3.1.1   Polycentric and Fragmented Water Governance

The process of incorporating environmental flow recommendations into water management regulations and policies is a complex undertaking. Water governance in the RGB is characterized by a mosaic of institutions and regulations for water and land management that either have a direct or indirect impact on the establishment of environmental flows (Groenfeldt and Schmidt 2013, Poff and Matthews 2013, Nava and Solis 2014). One challenge to coordinating environmental flows derives from the multi-layered and varied systems of water governance that have developed over the last two centuries within and between both countries. Governance of the basin, riparian ecosystems, and associated lands is also divided according to the different functions, services, or utilities its human inhabitants have defined for them. Key characteristics of water governance affecting the establishment of environmental flows are: (a) authority over water is distributed and nested across multiple political jurisdictions and spatial scales, with the addition that in the U.S. it tends to be more decentralized, while in Mexico it is more centralized; (b) authority over different aspects of environmental flows (e.g. water quantity, water quality, surface water and groundwater sources) that sustain river ecosystems are divided across different agencies and institutions; (c) there is a prioritization of agricultural use within the governance structures of both countries; (d) inter-state and inter-country treaties and compacts for basin water-sharing have been developed around existing patterns of water use, without significant provisions for environmental flows; and (e) groundwater and surface water have been effectively governed as separate bodies of water, even when hydrologically connected.

3.1.2   Distributed and Divided Governance

Water governance in the U.S. related to water rights, domestic and agricultural water supply, water quality, water flow, surface water, and groundwater, are typically managed by different institutions and/or under different sets of regulations and policies. This is less true in Mexico, where most of these water functions come under the jurisdiction of the Mexican National Water Commission (Comisión Nacional del Agua, CONAGUA). However, in both countries, there is a prevalent separation between domestic and agricultural water supply governance, and between surface water and groundwater governance. It is only recently, in Mexico, that CONAGUA has begun efforts to regulate and manage surface water and groundwater use conjunctively to mitigate impacts on both surface flows and aquifers. In the U.S. portion of the RGB, efforts to more closely link groundwater and surface water governance are localized and geographically dispersed, and also are relatively recent initiatives. Furthermore, policies shaping land, water, and species governance are similarly divided across institutions in both countries. The management of forests, rangelands, protected areas and parks, agricultural lands, water supply, biodiversity protection, hunting and fishing, all tend to fall under the mandates of different institutions and policies, with different if sometimes related, conflicting, or overlapping missions. In both countries, there are also a variety of forms of land ownership, each with their own implications for land and water management objectives, policies, and regulations. In addition to private landholdings, in the U.S., a substantial amount of land in the RGB is owned and managed by federal and state agencies and Native American tribal governments. In Mexico, ejidos and comunidades represent a distinctive category of land ownership that combine elements of both common property and private property.

Attempts to establish environmental flows can thus find themselves at the crosshairs of competing governance policies, mandates, and interests, even within the same political jurisdictions. In the U.S., the Endangered Species Act (ESA) is a federal law that can override other governance objectives to mandate the restoration of ecological conditions, including environmental flows, but only when a species meets the criteria of the Act. In Mexico, in July 2000, the Wildlife Act (Ley General de la Vida Silvestre) was established, which is similar to the ESA in that it also protects endangered species and habitats.

3.1.3 Dominance of Agricultural Water Rights

An estimated 83% of the surface water in the basin is allocated to agricultural use (Sandoval-Solis and McKinney 2011). Complicating this, surface water rights in both countries are over-appropriated: there are more rights to water than is normally available. Surface water rights in both countries are thus precious commodities, in high demand, increasingly sought by non-agricultural interests, and only reluctantly relinquished by farmers and landowners. Yet surface water-sharing agreements among U.S. states and between the two countries are formulated primarily on the basis of water that has been allocated to agricultural use rights (although urban centers, especially in southern Texas below the Conchos, have increasingly acquired surface water rights). For instance, the water stored in Elephant Butte Reservoir is distributed by the Rio Grande Project according to a set of specific allocation rules to the irrigation districts of Elephant Butte Irrigation District (EBID), El Paso County Water Improvement District #1 (EPCWID#1), and Irrigation District 009 Valle de Juárez (DR-009). Representatives from each irrigation district, along with representatives of the International Boundary and Water Commission (IBWC) from both countries and personnel of the Bureau of Reclamation (BOR), meet monthly to discuss water releases and allocations, which is almost exclusively destined for agricultural rights holders. Thus, the introduction of environmental flows is challenged by the dominance of agricultural use rights and the water-sharing agreements based on them, and can be seen by farmers as competing with their own water needs.

3.1.4 Interstate compacts and international treaties

The RGB water sharing legal framework is based on two binational agreements between the U.S. and Mexico (the 1906 Convention and the 1944 Water Treaty), and two compacts among the U.S. states (the Rio Grande Compact and the Pecos River Compact) (Nava and Solis 2014, Nava et al. 2016, Nava 2020) (Nava, 2020; Nava, et al. 2016; Nava & Sandoval-Solis, 2014). The 1906 Convention is a binational instrument which defines the amount of water to be delivered by the U.S. to Mexico for the primary purpose of irrigation; it establishes the distribution of surface waters of the RGB at the international border between El Paso and Ciudad Juarez. The second instrument is the Rio Grande Compact (RGC). Signed in 1929 and revised in 1939, the RGC provides for the allocation of the RGB waters between the states of Colorado, New Mexico, and Texas at a level intended to protect water use as it existed from 1928 to 1937. The 1944 Water Treaty, signed in 1944 and ratified in 1945, sought satisfactory utilization of shared surface waters based on equitable distribution between the two countries; it established water allocations for the U.S. and Mexico and joint use of its international waters. The Treaty recommended three reservoirs for water storage along the mainstem of the RGB of which two were constructed: Amistad and Falcon. The Treaty allocates one-third of the water reaching the RGB mainstem from 6 tributaries originating in Mexico to the U.S. and two-thirds to Mexico. The U.S. third shall not be less than 350,000 acre-feet/year (432 million m3/year), calculated as an average over a treaty cycle of five consecutive years. The water of the Pecos River, the largest U.S. tributary of the RGB, is allocated between New Mexico and Texas through the Pecos River Compact (PRC) signed in 1948. Its purpose is to promote inter-state collaboration and remove the causes of current and future water resources controversies. Thus, the structures of water governance that have evolved in the RGB have diminished, fragmented and disconnected the RGB throughout the Basin. It is worth noting that droughts have triggered a change in regulations for water allocation, whether in international agreements (Convention of 1906 after the drought of 1892 to 1904, the binational water crisis of 2001 during the 1992 - 2007 drought) or in state water allocation systems (Texas Administrative Code 303 after the drought of 1942 to 1956). Historically, periods of drought have also resulted in more engineering of the river system, e.g. construction of reservoirs for water storage or increased groundwater use for agriculture.

3.2 Water Governance and Environmental Flows in the United States

3.2.1 Water Rights

In the U.S., water rights are established at the state level of government. Surface water rights can be transferred among individuals, and under certain conditions can be separated from the land they are originally attached to. Changes in the uses of water rights (e.g., from agriculture to urban) must be petitioned for and adjudicated at the state level; however this additional judicial process offers one challenge to the establishment of environmental flows. All three RGB states follow a "first in time, first in right" principle of surface water rights, where the earliest users of water have priority rights to water flow over those with later claims. The exception to this rule is the water allocation system below Amistad Dam to the Gulf of Mexico, where domestic, municipal and industrial water right holders have priority rights from the water stored in Amistad and Falcon reservoirs over agriculture water right holders according to rules established for each water user type (Office of the Secretary of State). The majority of surface water rights in New Mexico have never been fully adjudicated, making precise calculation and enforcement of surface water volume usage challenging.

3.2.2 Western U.S. Water Governance

In regards to water rights, the federal government's role is limited. In 1935, the court confirmed the Desert Land Act of 1877 conveyed the land, but gave "no common law right to the water flowing through or bordering upon the lands conveyed" (California Oregon Power Co. v. Beaver Portland Cement Co. et al. 1935). The Court went on to hold that after the 1877 act, "all non-navigable waters that are part of the public domain became publici juris, subject to the plenary control of the designated states," thus each state has the power to enact the type of water law it deemed appropriate. However, the court later recognized two limitations on state power (United States v. Rio Grande Dam & Irrigation Co. et al. 1899): (a) a state can not destroy the U.S.'s right to the continued flow of a stream bordering government property if it is needed for a beneficial use on the property, and (b) ensuring "the uninterrupted navigability of all the navigable streams within the limits of the U.S." (Tarlock et al. 2002). Additionally, the federal government has the responsibility for location, construction, and management of federally funded reservoirs.

In the RGB, each state makes its own water laws and policy, and has specific state institutions that register, monitor and enforce water rights and withdrawals, maintain water flow and use databases, initiate planning and projections for future water supply/demand, and represent the states in inter-state compacts and agreements. Within the states, there is also a considerable amount of water governance and management authority distributed amongst a multitude of nested, and sometimes spatially overlapping, sub-regional and local institutions with different purposes, including: various kinds of water management and conservancy districts, sub-basin councils, planning districts, irrigation districts, irrigation companies, acequias and community ditch organizations, well-user groups, groundwater management districts, counties, and incorporated towns and cities. While these institutions operate within the framework of state-established water use rights and regulations, they have considerable autonomy and authority in establishing and enforcing local regulations, researching, monitoring, and planning for local/sub-regional water conditions, shaping local/subregional water practices, and entering into collaborations and agreements with other institutions.

3.2.3 Environmental Flows

3.2.4 Colorado

In 1973, Colorado enacted the Instream Flow Act (ISF) to preserve water in natural streams and lakes to help preserve freshwater environments in the face of many competing demands. It allows the Colorado Water Conservation Board to appropriate new water rights and acquire existing water rights, on a temporary (such as leasing) to permanent basis through: "(1) new appropriations requiring detailed analyses of recommendations, processing, and adjudications of new ISFs; (2) acquisitions by analyzing,

processing, and approvals of short-term, long-term, and permanent acquisitions of water rights and interests in water; (3) physical protection, such as stream gaging and requesting administration; and (4) legal protection, such as water court resume review, opposition, negotiation of decree terms, and litigation when needed" (Bassi et al. 2018). The rights are administered within the state's water right priority system.

3.2.5   New Mexico

Prior to 1998, New Mexico had no mechanism to implement environmental flows; in fact the belief has been that to perfect a water right in New Mexico, the law required a diversion, so leaving water in the stream would not result in a perfected right. Previous attempts to implement environmental flows through legislation had all failed, but in 1984, an informal letter from the Attorney General's office suggested that under state law, instream flows were a beneficial use and a diversion was likely not required for instream flows (Fort 2000). However, in 1998, then Attorney General, Tom Udall, issued Opinion 98-01 addressing the question of whether the New Mexico state engineer had the authority to "afford legal protection to instream flows for recreational, fish or wildlife or ecological purposes." The opinion stated that the state engineer had the authority to grant a change in use to an instream flow use and approve installation of gauges "to measure the instream flow beneficially used." The opinion did not address the question of new diversions as New Mexico's rivers are fully appropriated (Udall 1998). The reality of implementing an environmental flow program is still a challenge, but through agreements, federal reserved rights for endangered species and as a result of compact requirements New Mexico is making strides in implementing environmental flows. In 2005 the New Mexico legislature enacted the Strategic Water Reserve which "allows water or water rights to be designated for public purposes." (State of New Mexico Office of the State Engineer) The Reserve has two purposes "to comply with interstate river compacts; and to assist the state and water users in efforts to benefit threatened and endangered species." (State of New Mexico Office of the State Engineer). New Mexico also established the River Stewardship Program that grants funds to river restoration projects that enhance water quality and stream habitat implemented by Irrigation Districts, Soil and Water Conservation Districts, municipalities, Pueblos, NGOs, etc. (Szeptycki et al. 2015).

3.2.6   Texas

In Texas, Senate Bill 2 (2001) required the implementation of an instream flow program, which is carried out by the Texas Water Development Board (TWDB), the Texas Parks and Wildlife Board (TPWD) and the Texas Commission on Environmental Quality (TCEQ). The agencies developed a Programmatic Work Plan (PWP) and the Technical Overview Document (TOD). The instream flow study goals identified in the PWP are to "determine an appropriate flow regime (quantity and timing of water in a stream or river) that conserves fish and wildlife resources while providing sustained benefits for other human uses of water resources" (Rivers, Committee On Review Of Methods For Establishing Instream Flows for Texas). In addition to the development of instream flow program, Chapter 15 Section 7031 established the Texas Water Trust under the Texas Water Bank to "hold water rights dedicated to environmental needs, including instream flows, water quality, fish and wildlife habitat, or bay and estuary inflows."

3.3 Water Governance and Environmental Flows in Mexico

3.3.1   Water Rights

In Mexico, water is owned by the nation. Water is managed by the federal branch in a single centralized national institution: CONAGUA. Water policy in Mexico is based on one single legal instrument, the National Waters Law (Ley de Aguas Nacionales, LAN) that applies for the entire country and has three main purposes: (a) specifies the federal ownership of all national waters (based on article 27 of Mexico's Constitution); (b) defines thirteen basins as the spatial jurisdiction for water management and establishes water administration through basin councils; and (c) sets the rules for obtaining a water

concession, defines the responsibilities, rights and penalties of a water concession holder. The priority of water use specified in the LAN is assigned according to the type of use. Of the eleven water use types, the top five priorities are: (1) domestic, (2) urban, (3) livestock, (4) agriculture, and (5) wildlife conservation and environmental use. CONAGUA is in charge of granting water rights as concessions to individuals or entities, monitoring, enforcement, planning and policy. By means of the National Registry of Water Rights (Registro Público de Derechos de Agua, REPDA), CONAGUA authorizes, and keeps a record of water allocations for agricultural water use from surface water and groundwater sources and among a diversity of users.

3.3.2   Water Governance

CONAGUA manages national waters by means of river basin councils. The Consejo de Cuenca del Río Bravo (CCRB, Rio Bravo Basin Council) acts as a multi-stakeholder consultative and planning body across the five Mexican states in the RGB. CONAGUA maintains its directive role through a network of state and municipal offices, personnel from these offices engage in water planning, infrastructure operation, and maintenance, since they have the constitutional responsibility to ensure domestic water supply and water quality. Since the 1990s, increasing responsibilities for the internal operation and management of *Distritos de Riego* (DR) (federally-established Irrigation Districts) have been transferred from CONAGUA to the irrigator members of the DRs. However, CONAGUA retains the authority for operation and management of reservoirs, dams, and water releases, as well as of water allocation for agricultural use. The LAN describes the legal mechanisms for transfers of water concessions among irrigators within DRs, as well as for water concessions to be bought back from irrigators by the government and retired from use.

3.3.3   Environmental Flows

In 2012, the federal government published the guidelines for estimating environmental flows at the national level. The Mexican Environmental Flows Norm (NMX-AA-159-SCFI-2012) establishes the procedure and technical standards to determine the instream flow required for sustaining river ecosystems. The norm aims to find a balance between human water use and water conservation for the environment, it provides a standardized approach for conducting environmental flow assessments, which consists of: (a) providing guidelines for determining the current condition and degree of alteration of a given basin, (b) setting water conservation objectives for the environment in light of current and future human water demands, (c) assessing environmental flows requirements based on the analysis of the intra and interannual variability of the natural and current flow regime, and (d) recommending methods for delivering science-based outcomes to decision makers to determine the amount of water to be allocated as an environmental reserve volume, which should be linked to back to the water conservation objectives to maintain or improve the current environmental condition of the basin.These guidelines specify that any instream flow methodology is acceptable as long as it considers the natural flow regime and seeks to restore (partially or fully) components of the natural flow regime to provide instream flows that directly benefit river and estuary ecosystems. The guidelines outline a method for determining the degree of alteration and recommend four methods for developing instream flow requirements: two hydrologic methods based on unimpaired hydrology (Tennant and Modified Percent of Flow); one habitat simulation method based on hydraulic habitat (Instream Flow Incremental Methodology), and one holistic method based on expert understanding and available literature (Building Blocks Method).

In 2015 the federal government established the water reserve zones program, which is a legal instrument (federal decree) to secure a volume of water for drinking water consumption and wildlife protection above any other water use. In 2018, 10 water reserves were established in Mexico, none of them in the RGB. In 2019, the WWF identified 189 additional zones to be added into this program (WWF 2019), however these zones have not yet been approved.
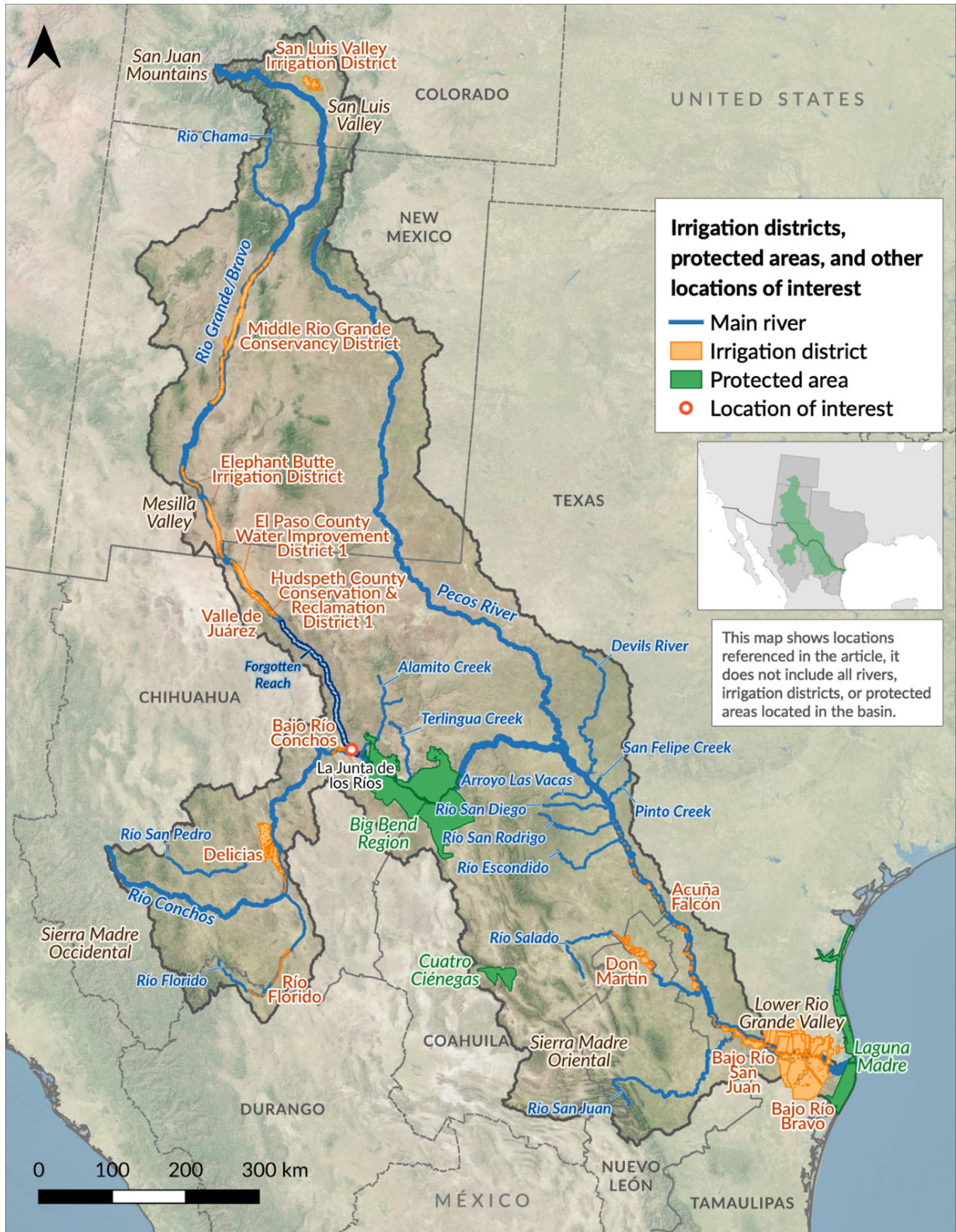
Figure 4.- Location of major irrigation districts, national and state parks, natural protected areas, and location of interest. This is not an exhaustive list.

4. Challenges and opportunities: A complex landscape

Given the spatial scale of the basin and the biophysical, social, political, cultural, and economic heterogeneity that co-exists across it, there are many factors that influence the success of attempts to establish environmental flows, and these vary greatly across localities, regions, and countries, as well as across different sectors and water use interests. There are some common threads across the basin, but also much variation; absolute statements are difficult to make. We here highlight some significant challenges and opportunities in the basin for establishing environmental flows.

4.1 Paradoxes in the Social Perceptions of and Practices Associated with the RGB: The Challenge of Managing for the Commons

The interdependence of society and river ecosystems across the whole basin on scarce surface water sources that interact with groundwater, plus the large-scale challenges posed by climate change, mean that whole-basin thinking and planning are critical to sustaining human-natural systems going forward. Yet the abilities of the basin's residents to interact with the river on a whole-basin basis, to effectively plan for and manage it as a common pool resource, are hampered by several factors.

We describe above and below many factors that contribute to the hydraulic and social fragmentation of the river system: (a) varied and distributed governance and legal frameworks; (b) re-engineering of the river course, damming and extensive water extraction; (c) locally varying histories of water use and management; competition for water resources amongst water users, sectors, and political jurisdictions; and (d) varying objectives and interests at national, binational, state, and local levels, including along the border between the U.S. and Mexico. Many stakeholders find initiating change overwhelming, due to the nature of water rights and the scale of many of the problems facing the region. These kinds of dynamics have shaped social, cultural, political, legal, and economic understandings of the river that have a primarily local or sub-basin focus. This has led to planning and management strategies that focus on one portion of the river and neglect a broader, sustainable, whole-basin thinking that could treat the RGB as a commons. Effectively and practically, the river system is perceived and interacted with as if fragmented into many rivers, rather than one, with some notable exceptions.

For instance, Koch, et al. (2019) coined the term "compact cognition" to highlight how the distributed, multi-level governance systems, as well as compacts and treaties defending different jurisdictions' water access across the basin, not only contribute to but end up reinforcing the fragmented quality of the basin as immutable and normal. In conducting several years of ethnographic fieldwork across the basin, the authors note how this normalization of fragmentation can become almost invisible to people who use, manage, or advocate for the river, that unfortunately has become the customary law when managing the river (cf. Tidwell et al. 2004, Nava and Solis 2014, Nava et al. 2016, Duran-Encalada et al. 2017, Broadbent et al. 2017).

Competition for limited water resources across the arid/semi-arid basin (Phillips et al. 2011) can reinforce both perceptions and practices that treat the river as fragmented. In many cases, "the river" becomes reduced to the water that can be drawn from it, while the river itself is perceived as a means of conveyance for transporting that "good" from upstream to the ultimate water rights holder. Disputes over how water is allocated among individuals, organizations, sectors, and political jurisdictions are constant, and at least in the U.S., make litigation over water rights and allocations a permanent feature of the social and hydrological landscape. At the same time, the compacts and treaties governing bi-national and inter-state water sharing constitute the few institutional and political mechanisms that exist for constituting the RGB basin as a functional commons across so many jurisdictions and such a large spatial scale. While these legal agreements defend the participating jurisdictions' water interests, they also force them to monitor, estimate, maintain records for, plan for, communicate about, and take action based on real-time hydrological and social conditions across the basin.

Similarly, conservation and sustainability narratives exist in the basin that build connections between different regions of the RGB, although their sometimes localized focus still has the potential to negatively affect both upstream and downstream conditions . The river is seen as a critical connection between different communities that has led to efforts to find common ground in managing the river's resources. There are community-based efforts throughout the RGB committed to protecting the river or rewriting the extractive narrative of the river — NGO-farmer partnerships to restore the river in Colorado; joint efforts between federal, state, and NGOs actors to protect habitat for endangered or threatened wildlife in New Mexico's Middle Rio Grande; transborder community efforts to clean debris from and conduct citizen science species surveys around Laredo-Nuevo Laredo. However, each of these projects, programs, or arrangements is, in general, an ad hoc effort implemented to combat the normalization of fragmentation, so it remains unclear whether or not they are sustainable.

Individual actors recognize that their past, current and future well-being is closely tied to the sustainable management of the RGB (including surface water, ground water, and land management decisions), both upstream and downstream of their immediate management and decision making area. This understanding reflects a sense of the river as a commons, as well as values that deeply entwine the health and function of natural systems with the continuing florescence of people and their communities. Nevertheless, structural constraints, cognitive factors, and socio-economic-cultural dynamics (e.g. market forces, "use-it-or-lose-it" laws, or value systems) create a confluence of factors that often cause actual river management and water practices to undermine the shared health of the RGB commons.

4.2 The Central Role of Agricultural Water Rights

Agricultural water rights holders understandably tend to put high priority on the preservation of their water rights. However this can be true even when agriculture may no longer be a primary or viable source of livelihood, especially among populations that have been historically dispossessed of land rights in the past, e.g. Native Americans, Pueblos Indigenas, as well as Hispanos in northern New Mexico and the San Luis Valley in Colorado. Throughout the RGB basin, allocating water rights to environmental flows can be perceived as competing with scarce water resources for agriculture. In addition, use-it-or-lose-it water rights laws in the U.S. states mean that water rights holders often feel strong pressures to exercise their water rights in order to preserve them. Once lost or separated from agricultural land, water rights are difficult to replace, given the over-appropriated nature of the basin. In addition, many landowners who are unable to farm temporarily or permanently nevertheless do not want to relinquish the water rights attached to their land. As a result, it is common for irrigation organizations (e.g., acequias, ditch companies, unidades de riego, irrigation districts) to have mechanisms that allow some form of water banking or temporary/permanent water transfer among members to preserve water rights and use. In order to reconcile pressures to preserve agricultural water rights with those of river preservation, various versions of temporary or conditioned agricultural water rights transfers are being experimented with (selected examples provided in the following section), that keep water rights intact and attached to land while at the same time supporting environmental flows and ecological restoration.

In both countries, farming systems range on a spectrum from smaller-scale, river-fed, floodplain irrigation, with Native American and Spanish colonial-era origins; to larger-scale farming operations, originating in the 20th century, that cultivate substantially larger acreages and broader extensions of the river valleys - made possible only by water storage in large reservoirs and its distribution through extensive canal systems. The latter tend to be organized into some form of irrigation district, federally decreed or recognized as having rights to the water within the federally constructed and managed reservoirs. These irrigation districts often subsumed earlier small-scale, river-fed irrigation operations and organizations, in addition to adding vast new extensions of irrigable land (e.g. EBID, EPCWID#1 and DR-009 with origins around the 1906 Convention).

Where agriculture is or was river-fed, knowledge of and an expressed relationship to the river tends to be strongest. In many cases, there is multi-generational knowledge of environmental change in the river ecosystem, and a strong sense of place that includes the river and streams, as well as associated wetlands, terraces, and floodplains, as part of the socio-ecological and cultural landscape — including local efforts to reinforce or revitalize that cultural-natural landscape through river restoration and species preservation. Some river-fed agriculturalists (e.g. DR-090 Bajo Río Conchos) have advocated for environmental flows to be restored, since stream flows dominated by reservoir releases have reshaped the river channel and interfered with their irrigation systems. On the other end of the spectrum, in areas where farming developed more recently (20th century) as a direct result of reservoir and canal distribution system development, farming can also be multi-generational (albeit within a shorter time horizon), but farmers often have relatively less relationship to and long-term knowledge of the river: their access to irrigation water has almost always been mediated by large-scale, reservoir storage and extensive distribution canal networks. This kind of farming has developed in greater isolation from the river as an ecosystem, and the river ecosystem has been more transformed in order to serve it, likely causing more decoupling between the two. However, there have been growing efforts to find ways to accommodate the allocation of water flows specifically to river ecosystem needs, without jeopardizing agricultural water use rights.

4.3 The River as Shared Waters and as Political Boundary

The binational sharing of waters, and the critical function of the river as a political border, mean that management of stream flow, river channel, and the river ecosystem in the border region serves multiple objectives, many of which are disconnected from or in conflict with the maintenance of river ecosystem function (or even agriculture and water supply), and serve wider political, economic, and other shifting agendas, e.g., the need for security and control the border.

The construction of fences and other barriers, increasingly built-up border crossings, and the management of river vegetation (through herbicides that are washed out into the river) with the aim of controlling the crossing of people and goods, both legal and illegal, are some important features of the politicization of the river. Political tensions, law enforcement activities, and chronic violence associated with immigration, drugs, and cartel activities have combined to transform some areas of the border section of the RGB into a kind of no-man's land (Massey 2016), described by Roland (2020) as "the most militarized peacetime border in the world," where increasing number of human lives are put at risk and the imposition of national-level and organized crime agendas disrupt centuries-long social, cultural, and economic relationships among communities on both sides of the border and their relationship with the river as a source of livelihood and well-being. These tensions at the border are nothing new; however, since 2001, border security has increasingly driven U.S. national policy and action at the border, resulting in increased barrier construction and mobilization of border patrol forces, further putting at risk the environmental protection of riparian boundary areas.

At the same time, there are multiple initiatives in the border region working to counter the alienation of border communities from each other and from the river system. For example, the maquiladora system along the Mexico-U.S. border has mobilized Mexicans living near the border to organize around environmental deterioration and social and economic problems in the region (Moure-Eraso et al. 1994). The increasing focus on landscapes and watersheds as the objects of conservation has resulted in multiple projects, many of them cross-border, that approach the region as more of a socio-ecological entity. For instance, there are active calls among ecosystem restoration and recreational water interests below la Junta de los Ríos, in both countries, to find ways for releases from Luis L. Leon reservoir in the Rio Conchos to better serve environmental flow purposes (Bennett et al. 2008). There have been localized initiatives to build on long-standing socio-environmental traditions that include restoration or preservation of river-centered ecosystems. And, recent intensification of U.S. policies to expand border wall construction and increase militarization of the border have produced new socio-environmental movements to protect the river and associated lands, together with long-standing socio-cultural relationships.

5. Meeting Environmental Flow Needs: Examples of Initiatives in the RGB

The previous sections described several challenges to establishing environmental flows in the RGB and discussed ways in which the biophysical heterogeneity, data limitations, water governance structures, political interests, and historical, social, cognitive, and economic factors contribute to prevent the whole-basin thinking needed to integrate environmental flows into existing water management policies and practices. Similarly, we have described the technical, governance, and socio-political frameworks on which the integration of environmental flows could be built, considering existing and new legal space within and across political jurisdictions to support environmental flows and related river restoration actions; as well as long-standing and emergent social foundations for merging social and ecological objectives for the river.

In this section, we highlight several examples (Table 3 and Figure 4) in which environmental flows have begun to be implemented or supported in various locations throughout the RGB. Each example takes a different approach to address the challenges aforementioned and draws on some combination of either existing forms of support for environmental flows or builds new ones. These examples operate at different spatial scales and timelines and involve different kinds of collaborations among institutions and sectors, and they are not intended to be a comprehensive list of environmental flow initiatives in the RGB. These examples are potential models for integrating environmental flows in the RGB, and by extension, in other arid zones of North America. They are meant to be followed, watched, analyzed, and learned from.

Table 3. Summary table of projects where environmental flows have been implemented

Related Section	Strategy	Geographic extent	When	Key actors and institutions	Reference
A	Representative for environmental flows added to multi-state, basin planning council	Area of the RGB basin located in Mexico (Durango, Chihuahua, Nuevo León, Coahuila, Tamaulipas)	2017	Rio Bravo Basin Council and Pronatura Noreste	(CCRB 2018a)
B.1	5-year lease of agricultural water rights for environmental flows	New Mexico, U.S.: Rio Gallinas, upstream of the confluence with Rio Chama, New Mexico	2019	NMOSE, Audubon New Mexico, and Farmers	(Tashjian 2019, Chamberlain 2019)
B.2	Leasing of agricultural water rights for environmental flows to preserve native trout	Gallinas creek (tributary of the Pecos River) in northern New Mexico	2019	Trout Unlimited, private landowner	(Peterson 2020)
B.3	Strategic water reserve that provides funding to lease or purchase environmental flow water	New Mexico, U.S.: the RGB above Elephant Butte and the Pecos River	Since 2005	New Mexico Legislature	(OSE 2020)

	rights in the state of New Mexico				
C.1	Voluntary releases of unused water in reservoirs for environmental flow	Rio Chama downstream El Vado Reservoir (New Mexico)	2016	NM Audubon, Sandia Pueblo	(Paskus 2015)
C.2	Voluntary releases of water in reservoirs for environmental flow	34-mile reach of the Rio Grande downstream of Isleta Diversion Dam and through isleta Pueblo, Los Lunas, and Belen (New Mexico)	2018	NM Audubon, Middle Rio Grande Conservancy District, Bureau of Reclamation, Pueblo of Isleta, Albuquerque Bernalillo County Water Utility Authority	(Audubon 2018)
D.1	Municipal ordinance to to provide environmental flows	Santa Fe City and Santa Fe river	2012	City of Santa Fe Environmental advocacy groups (e.g. Santa Fe Watershed Association)	(City of Santa Fe 2013)
D.2	Municipal ordinances to ensure environmental flows for fishway pass and sediment movement	Albuquerque City and RGB mainstem	2016	City of Albuquerque	(Water Utility Authority 2016)
E	First environmental water right in Mexico	Coahuila, México: Cuatro Ciénegas	2014-present	CONAGUA, Pronatura Noreste	(Pronatura Noreste 2019)
F	Cross-sectoral,cross-jurisdictional and cross-boundary collaboration in forest management for water quality and flow: the Rio Grande Water Fund	Rio Blanco, Rio Navajo in the Colorado River Basin and Rio Chama in the RGB basin	2016	The Nature Conservancy, state agencies, local municipalities, community-level donors across NM	(Hartwell et al. 2016)

G.	Adapting irrigation district policy to accommodate river restoration with agricultural water rights	Southern New Mexico: Elephant Butte reservoir to Texas border	2013	Elephant Butte Irrigation District, International Boundary and Water Commission, Audubon New Mexico, US Fish and Wildlife Service	(Stevens 2013, IBWC 2015, n.d.)
H	Scientist advisory groups determining environmental flows	Rio Grande mainstem from Presidio to Amistad dam, from Falcon dam to the estuary and the Laguna Madre (Texas)	2011	Basin and Bay Area Expert Science Teams, Basin and Bay Area Stakeholder Committee	(TCEQ 2012)
I	Nongovernmental organizations promoting socio-ecologically based land and water management for conservation	Alamito Creek and Matonoso Creek (Texas)	2003	Dixon Water Foundation and Trans Pecos Water and Land Trust (TPWT)	(Desert Fish Habitat Partnership 2016)
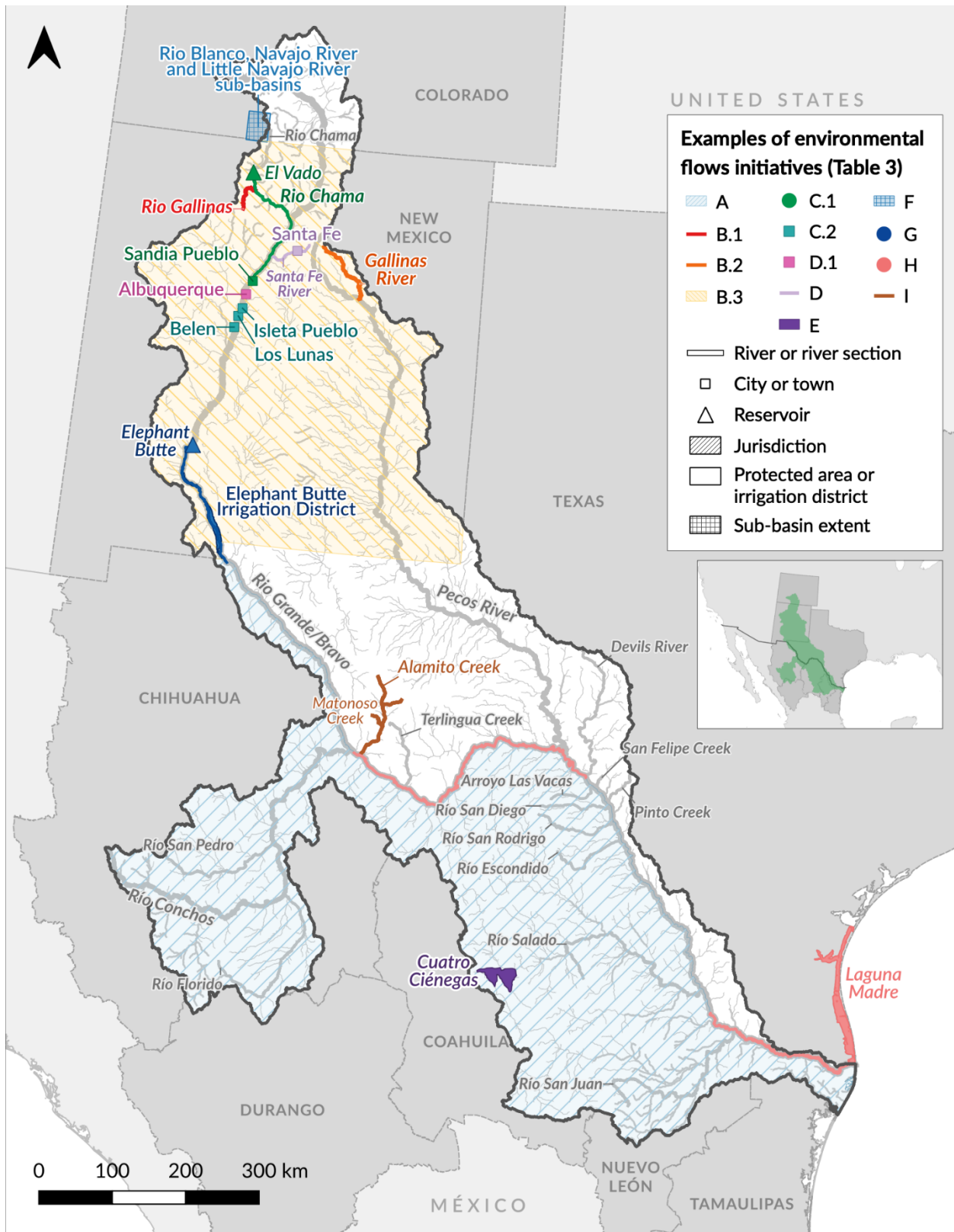
Figure 5. Examples of environmental flows initiatives

5.1 (A) The Rio Bravo Basin Council - Consejo de Cuenca del Río Bravo (CCRB): México

The CCRB has served as a public and organized venue for discussing challenges and reaching agreements related to water management in the Mexican portion of the RGB (Table 3 and Figure 4: Example A). The CCRB stands out because of its trust, engagement, cooperation and discussions among stakeholders (water users, NGOs, community organizations and citizens), water advisors (academics, scholars, researchers) and technical advisory committees. Since its inception in 1999, two technical advisory committees (the Specialized Modelling Group and the Legal Working Group) met regularly to define water allocation rules using a human-centric vision of the basin. After the first water concession title was awarded for environmental flows, a new water representative was added: the environmental water user voting member represented by the NGO Pronatura Noreste. The CCRB is the only river basin council in Mexico to include an environmental figure in its structure, and it is known to be the most specialized and proactive council in Mexico. Since the inclusion of an environmental representative in 2017 and the determination of environmental flow throughout the basin (Bennett et al. 2008, Sandoval-Solis et al. 2019) the CCRB is now considering environmental flows as an integral part of a new regulatory framework for allocating water to the Mexican water users of the RGB.

Including environmental flows as part of the proposed rules for water allocation and water transfers between reservoirs was not an easy task and required a change in the mindset of stakeholders. Currently, the top four water use priorities in the basin (domestic, urban, livestock and agriculture) already account for more than 95% of the consumptive water use in the Mexican portion of the RGB. A key argument was used by explaining to the basin stakeholders that environmental flows are not adding another consumptive use, environmental flows can be supplied by transferring water from upstream to downstream reservoirs in an environmental friendly pattern, which is a similar argument used in Rio Chama for Heron, Vado and Abiquiu reservoirs (Table 3 and Figure 4: Example C.1 and C.2). While the volume of water for environmental flows can be small compared to the natural flow regime, including environmental flow in the regulatory framework opens the door for managing water for environmental objectives. In the specialized modeling group, environmental flows are now considered as a definitive attribute on the water allocation of the RGB, shifting to a human-environmental perspective. In the last decade, the council promoted the creation of the Specialized Group on Wetlands, Water Education and Culture, Payment for Environmental Services, Strategic Planning, and Treaty Deliveries (CCRB 2018b). These efforts have a position to positively influence water policy on the implementation of environmental flows and the establishment of priority wetlands along the basin.

5.2 (B) Leasing of Agricultural Water Rights for Environmental Flows: New Mexico

Example B.1

In November 2019, the New Mexico Office of the State Engineer (NMOSE) issued the first state in-stream-flow water permit for a stretch of the Rio Gallinas (Table 3 and Figure 4: Example B.1), just upstream of its confluence with the Rio Chama, a tributary of the RGB. NMOSE granted the permit to the NGO Audubon. The permit allows the water right holder to leave water in the river rather than diverting it. Generally, water use permits are forfeited if they are not withdrawn within a certain time period. Audubon's permit allows for a 5-year lease of an agricultural water right for environmental flows. It provides an opportunity for farmers to derive some economic benefit during times when farming might not be cost-effective or they do not want to farm (Tashjian 2019, Chamberlain 2019).

Example B.2

Trout Unlimited, another NGO, secured the second New Mexico permit to lease agricultural water rights (5 acre-feet per year) for instream flow to preserve native cutthroat trout on Gallinas Creek in San Miguel County (Pecos River sub-basin) (Table 3 and Figure 4: Example B.2). Accomplished in collaboration

with a local, landowning family, this kind of arrangement allows local landowners to preserve the active use of their water rights, keep them connected to family land, and at the same time, help preserve riparian ecosystems, meeting several environmental and social objectives at the same time (Peterson 2020). Very recently, The Nature Conservancy (TNC) included the Pecos River in the list of advancing projects in their sustainable rivers program (TNC 2020).

Example B.3

In 2005, the New Mexico legislature enacted the Strategic Water Reserve (OSE 2020) which "allows water or water rights to be designated for public purposes" (Table 3 and Figure 4: Example B.3). It also provided funding to lease or purchase water rights. As of January 2018, three leases had been signed and four purchase agreements had been executed for a total of 1,099 acre-feet of water for the RGB above Elephant Butte and 1,583 acre-feet for the Pecos River (OSE 2018). The purchases and leases were to protect endangered species and to meet compact requirements. In March 2020, the New Mexico Legislature appropriated $750,535 to the Strategic Water Reserve to purchase additional water rights (New Mexico Legislature 2020).

5.3 (C) Voluntary Eeleases of Unused Water in Reservoirs for Environmental Flows: New Mexico

Example C.1

Examples of voluntary implementation include the New Mexico Audubon Society working with the Pueblo of Sandia to restore flows in the Rio Grande, the Audubon offered to buy water rights from the Pueblo, but instead the Pueblo did a one-time donation of 101 acre-feet stored in the El Vado Reservoir which were released in 2016 to help restore the river's ecosystem (Audubon 2015, Paskus 2015) (Table 3 and Figure 4: Example C.1). This was the first, but not last donation of its kind.

Example C.2

In July 2018, while the Rio Grande was experiencing severe dry conditions, the New Mexico Audubon Society formed a partnership with the Middle Rio Grande Conservancy District, the U.S. BOR, the Pueblo of Isleta and the Albuquerque Bernalillo County Water Utility Authority to release 994 acre-feet into a 34-mile reach of the Middle Rio Grande, downstream of the Isleta Diversion dam to sustain wetlands, riparian habitats, birds and wildlife through Isleta Pueblo and the towns of Los Lunas and Belen (Table 3 and Figure 4: Example C.2) (Audubon 2018).

5.4 (D) Municipal ordinances to establish environmental flows: Santa Fe and Albuquerque, New Mexico

Example D.1

In 2012, the city of Santa Fe passed a Living River ordinance that allows up to 1,000 acre feet of water per year to flow down the stream in normal and wet years, purely to maintain the river ecosystem (Table 3 and Figure 4: Example D.1). The Santa Fe River target flows can be revised downward in drier years when the forecast for the runoff from mountain snows is 75% or less of the thirty-year annual average (City of Santa Fe 2013).

Example D.2

Similarly, the city of Albuquerque has restructured its water supply to ensure a minimum flow of 70 cfs (50cfs for fishway bypass and 20 cfs for sediment movement) below the city's central stream gauge

which contributes to the maintenance of downstream riparian and riverine habitats (Table 3 and Figure 4: Example D.2) (Water Utility Authority 2016).

5.5 (E) First Environmental Water Right: Cuatro Ciénegas, México

In an important historic event, in 2014 CONAGUA awarded for the first time in the entire country, surface water rights for environmental use to the NGO Pronatura Noreste and applied in Cuatro Ciénegas Valley, one of the most important wetlands in the Chihuahuan desert and the RGB (Table 3 and Figure 4: Example E). Cuatro Ciénegas is a protected area recognized for its exceptional biodiversity, including the greatest number of endemic species of any place in North America (Stein et al., 2000) that has been affected greatly by the intensification of high-water demand crops and water exports outside the basin. This environmental water right will facilitate the path towards the conservation of water resources in Mexico by: (1) promoting environmental water use titles, based on the human right to a healthy environment (CNDH 2014), (2) providing to the environment, through the legal figure of and organization, the capacity (for legitimate interest) to oppose third parties, against threats to the ecological balance of hydrological basins; and (3) the possibility of rescuing water for the environment in overallocated watersheds through the transfer of rights and the conversion from agricultural to environmental use in the form of water reserves for the environment (CONAGUA 2004).

The key figure of Pronatura Noreste has been of pivotal importance in the efforts towards introducing environmental water rights in the Mexican legislation and in representing the environment as a water user in the RGB. However, the acquisition of ecological water rights remains challenging as there is more water in paper than physically in the basin. In addition, the transfer of water rights also poses additional layers of complexity to the acquisition of environmental water use. Nonetheless, this unprecedented event's success lies in recognizing the legitimacy of public environmental water rights for environmental preservation as a beneficial use. The recognition of this ecological water rights serves as a vehicle to create awareness about the urgency for allocating water to the environment and mobilizing stakeholders into discussing potential environmental flow policies.

5.6 (F) Cross-sectoral, Cross-jurisdictional and Cross-boundary Collaboration in Forest Management for Water Quality and Flow: Colorado and New Mexico

Some of the structural challenges that make it difficult to introduce successful, conservation-focused management in the RGB — especially, challenges associated with fragmented water rights and basinwide obligations to pay water from one region to another — have also resulted in innovative and unexpected approaches to protecting the river. TNC in New Mexico saw the damage caused to water quality that resulted from a number of wildfires that occurred near riparian forest zones in southwest Colorado in 2011. Though these forests are in areas that are under the management of the US Forest Service, there were few resources available to ensure the forest thinning that would be necessary to reduce the risk of wildfire impacts in runoff, such as ash, soil, and trees/debris that impacted the water quality of the Rio Chama that feeds into the RGB, clogging the river and impacting dam operations in New Mexico. TNC worked with state agencies, local municipalities, and community-level donors across New Mexico in order to create the Rio Grande Water Fund to contribute to thinning and better managing forests in southwest Colorado, despite the fact that these forests are outside of the Rio Grande basin (they are located in Rio Blanco and Navajo River basins which are river exporting their waters into the RGB) and they are located in the state of Colorado (Hartwell et al. 2016). In other words, TNC demonstrated the kind of whole-basin thinking (as opposed to compact cognition) that is both rare and required to improve the sustainability of the RGB as a whole (Table 3 and Figure 4: Example F).

5.7 (G) Adapting Irrigation District Policy to Accommodate River Restoration and Agricultural Water Rights below Elephant Butte: New Mexico

The section of the RGB from Elephant Butte Reservoir to El Paso Texas was significantly channelized beginning in the first half of the 20th century, disrupting normal flows and meander patterns that supported local species and habitat. Yet this segment of the river includes areas that could be considered critical habitat under the ESA for species such as the Southwester Willow Flycatcher. In addition, the IBWC (US Section) began efforts in 2009 to support habitat restoration at several sections of the river here and in West Texas. However, all surface water available in this section of New Mexico is already designated for agricultural use within the Rio Grande Project, which oversees allocation of the waters stored in Elephant Butte Reservoir to New Mexico, Texas and Mexico water users. Changing water rights from agricultural to other uses here would require going through an extensive legal process. In 2013, EBID, which administers and distributes irrigation waters to southern New Mexico farmers, adapted its internal policy to make it possible for member irrigators to temporarily or permanently transfer some or all of their agricultural water rights to environmental use within EBID's area of operation (Table 3 and Figure 4: Example G). Any such transfers are still subject to the same conditions as irrigation water: the amounts allocated per water right each year will be decreased or increased (within the maximum allowable) in the same proportions as for all agricultural water rights holders, based on conditions in Elephant Butte Reservoir, and they must be applied to lands within the EBID's area of jurisdiction. The Environmental Water Transaction Program was developed in conjunction with the IBWC-US, allowing the IBWC to lease, buy, or receive donations of agricultural water rights to apply to environmental flows for habitat restoration. By recognizing that watering native species is also a form of irrigation, EBID made it possible for water not needed by member farmers to be used towards environmental flows, without having to legally change its beneficial use designation.

5.8 (H) Environmental Flows Science Advisory Group in Texas

In 2007, the Texas legislature passed the House and Senate Bill 3 Environmental Flow Program (TWDB 2020) to develop environmental flow recommendations based on the best available science and stakeholder involvement. The Bill established Environmental Flows Advisory Groups and Science Advisory Committees, allowing diverse interest groups to discuss the costs and benefits incurred by environmental flows scenarios (Roach 2013). For the RGB, two expert teams were formed to estimate instream flows in the Big Bend area (from Presidio to Amistad dam) nd at the RGB estuary (From Falcon Dam to the Gulf of Mexico): the Upper and Lower Rio Grande Basin and Bay Expert Science Teams (BBEST) (Table 3 and Figure 4: Example H.1 and H.2) (TCEQ 2012). The outcome from the BBESTs are key reports that determine instream flows along the border and in the estuary of the RGB (TCEQ 2012).

In addition, the coalition of regional public participation, statewide supervision, and a state agency action provide the assistance to recommend and implement environmental flows through the Texas Environmental Flows Science Advisory Committee and the Basin and Bay Area Stakeholders Committees (TCEQ 2020). This scheme was created by the 80th Texas Legislature to recognize the ecosystem services that the ecological integrity of riverine, bay, riparian, and estuarine ecosystems provide to social-ecological systems. The consensus is based on local stakeholders and technical expert environmental flow recommendations. The environmental flow process in Texas through expert teams is fortunately bridging the best available science and public input under the development of water management policies that guide state agencies in managing and conserving human and environmental needs.

5.9 (I) Nongovernmental Organizations Promoting Socio-ecologically Based Land and Water Management for Conservation: West Texas

In 2003, a rancher in Hudspeth county granted 1,236 acre-ft per year to provide water for fish and wildlife in the RGB, this is the first water rights donation in Texas to the RGB through the Texas Water Trust (TWDB 2006). This donation sets a precedent for other water users to follow in the state of Texas. In addition to the state's water trust, a regional water trust, the Trans-Pecos Water and Land Trust (TPWLT) is the state's first private water trust. The TPWLT collaborates with the Dixon Water Foundation NGO to preserve almost 1400 acres of Alamito Creek watershed, designated as the Alamito Creek Preserve (Table 3 and Figure 4: Example I). The area includes a 3.5-mile riparian zone of Alamito Creek and a shorter segment of Matonoso Creek. The segment of Alamito Creek within the Preserve boundary is recommended by the Far West Texas Regional Water Planning Group as an "Ecologically Unique River and Stream Segment" (TCEQ 2012). Building partnerships between private landowners and conservation organizations is critical in conserving riparian ecosystems mainly because large portions of tributaries such as Terlingua and Alamito creek are privately owned. Water rights donations and conservation projects aimed to improve instream flows and habitat, water quantity and quality, and removal of exotic species will contribute to native species' persistence and a healthy river (Desert Fish Habitat Partnership 2016).

6. Conclusions

6.1 Initiatives Discussion

This study examined the natural and human water resources system, challenges, and strategies to implement environmental flows, stressing the importance of treating the RGB as a continuous, dynamic, and complex socio-ecological system. The environmental flows initiatives documented in this paper suggest that it is possible to implement environmental flows in the basin despite the formidable physical, socio-economic, and institutional challenges facing the RGB, its large spatial scale, and its transboundary nature. These initiatives show some creative ways in which agricultural, municipal and environmental flow needs have begun to be addressed conjunctively and how multiple actors have designed local or sub-regional approaches to provide environmental flows that do not require major structural changes. Many of them are in early stages of implementation, they are to be watched, analyzed, learned from, and built upon. These initiatives highlight key partnerships, trust building and empathy among diverse groups of individuals, stakeholders, and NGOs that have innovatively navigated difficult regulatory frameworks and sociopolitical challenges to support the implementation of environmental flows. Nonetheless, current policies, regulations and water governance frameworks are trapped in the inertia and legacy of the last two centuries and have not, in most cases, made the formal, long-term changes in the regulatory framework that would ensure environmental flows are maintained as an integral part of water resources management into the future. Recent efforts have suggested a number of viable and sustainable ways to integrate environmental flows into the future management and governance frameworks of the RGB. The years to come will reveal if there is enough political will and societal pressure to pass these regulations and change the ways we are managing water today.

6.2 Whole-Basin Thinking

The dependence of the entire basin on a few and remote sources of surface water requires a whole-basin thinking and coordination. In the last few decades, there have been increasing efforts among scientists, water resource managers, citizens, and decision-makers to approach the RGB with a whole-basin thinking. Recognizing the complexity of the challenges in the RGB has meant that more actors are seeing it as a complex socio-ecological system. These trends, we believe, are critical for finding common ground and designing solutions to ensure environmental flows across the RGB Basin, recognizing its shared nature and the need to supply water to all users, including the environment.

6.3 Including Social, Governance and Political Aspects in EF Strategies

A considerable number of studies have determined instream flows and proposed water management strategies for implementing environmental flows that consider both, human and ecosystem water needs. They have advanced our understanding of the RGB. Instream flow studies can be used as a starting point for proposing ecosystem water needs, and to test innovative water management strategies to implement environmental flows. Technical solutions are important; however, any environmental flow study must include an understanding of the social, water governance, and political aspects. As we have shown, it is not possible to decouple the social, political, economic, hydrological, and ecological aspects from each other in the RGB and, thus, environmental flow policies must consider the RGB as a complex, dynamic, and socio-ecologically constituted system. Failing to do so will generate many fine technical studies, but they will likely remain infeasible or not implemented. Restoring the RGB flow regime to predating small-scale human settlement conditions is unrealistic, given the substantial engineering of the river, extensive biophysical changes, increasing anthropogenic water demands, and the effects of climate change. However, we see many opportunities for strategies that can begin to re-establish and/or maintain environmental flows within the current socio-ecological dynamics of the basin.

6.4 Water Management Strategies into the Future

One win-win environmental flow strategy can be envisioned by rethinking surface water storage and reservoir operations. For instance, the current infrastructure of the RGB present opportunities for updating reservoir operations to maximize beneficial use by providing environmental flows for river connectivity and maintaining native vegetation (cf. Fuchs et al. 2018, Ahn et al. 2018) while reducing evaporative losses from reservoirs (cf. Eichinger et al. 2003), especially during wet years. Water transfers among reservoirs are occurring with or without environmental flows policies, here we are proposing to advocate for the exact same amount of water releases from reservoirs but in an environmental friendly pattern. This approach can be augmented by riparian vegetation management to remove high water use species (e.g., saltcedar) to create a mosaic of riparian habitat that requires less water (Fullerton and Batts 2003). Furthermore, coupling these strategies with local restoration projects may create sequential pockets of native riparian habitat (i.e., "string of pearls" Stanford and Ward 1993) that will extend the impact of environmental flow strategies. There is a need for a system-wide information exchange and knowledge sharing about localized and regional restoration efforts and other innovative measures to support environmental flows (Fullerton and Batts 2003). Coordinated restoration efforts founded on strong public awareness campaigns can facilitate dissemination of knowledge, data, best practices, and environmental flow schemes that benefit different stakeholder groups along the river (e.g., in-stream and downstream uses).

In addition, another technical option is to support the development of improved methods for reducing agricultural water use, with the ultimate goal of re-establishing a more natural flow hydrograph. In fact, adoption of many water-conserving technologies and practices is already underway in the basin, including increasing microbial activity, organic matter, and water retention in soils, increasing the precision and efficiency of irrigation equipment and practices, modifying cropping systems and crops grown, and increasing the efficiency of water distribution infrastructure. Yet the agricultural sector's water needs remain formidable, and heavily limit the possibilities for securing sustainable environmental flows.

Data Availability

The data and files for the maps that support the findings of this study are available in HydroShare at: Sandoval-Solis, S., and B. A. Lane. 2021. Rio Grande - Río Bravo environmental flows database. Data and tools. https://doi.org/10.4211/hs.76bd2b2e36aa4f23920b20e5a5accb2a These data were derived from the following resources available in the public domain:

https://www.sciencebase.gov/catalog/item/58e52181e4b09da679997bed

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CHAPTER 2

CHANGES IN THE STABILITY LANDSCAPE
OF A RIVER BASIN BY ANTHROPOGENIC DROUGHTS

Laura E. Garza-Díaz and Samuel Sandoval-Solis (DOI: https://doi.org/10.3390/w14182835)

Abstract: As water resources enter the era of the Anthropocene, the process of anthropogenic droughts arises as the interplay between climate cycles and human-centered water management in rivers. In their natural conditions, rivers exhibit a natural hydrologic variability, wet and dry cycles, that are a vital property for promoting ecological resilience. Human activities alter the temporal variability of streamflow, a resilience property of river systems. We argue that anthropogenic droughts in river basins can lead to changes in the resilience properties of the system depicted in stability landscapes. This study aims to analyze anthropogenic droughts and the changes provoked to the stability landscapes of the streamflow system of a river basin. We use 110 years of regulated and naturalized streamflow data to analyze the hydrologic variability (wet periods and droughts) of a river system. First, we determined the Streamflow Drought Index (SDI), and the results were assessed using probability distribution functions to construct stability landscapes and explore the resilience properties of the system. The transboundary basin of the the Rio Grande / Rio Bravo (RGB) is used as a case study. Our main findings include evidence of resilience erosion and alterations to the properties of the stability landscape by the human-induced megadrought in the RGB, which resulted from extensive anthropogenic alteration and fragmentation of the river system. The novelty of this research is to provide a baseline and move forward into quantifying ecological resilience attributes of river basins in water resources planning and management.

Keywords: anthropogenic drought; ecological resilience; river basin; stability landscape

1. Introduction

As social-ecological systems (SES), river basins are inherently bound to a fundamental property of ecological resilience: dynamism, expressed by the temporal variability of the natural flow regime. Historic cycles of flooding and drought in the natural flow regime are integral components of most intact running water ecosystems [1] as these exert dominant controls on ecosystem structure and function [2]. As water resources are well into the era of the Anthropocene, climate change and human dominance pose pressing challenges to the hydrologic cycle and its components, putting the integrity and resilience of river basins at higher risk. The human influence on the global hydrological cycle is now the dominant force behind changes in water variability across the world and in regulating and triggering hydrologic resilience changes in the Earth system. Globally, extreme weather or climate events are expected to become more frequent and increase in intensity and duration, due to climate change and largely exacerbated by the persistent pressures of human water demands in creating such extreme environmental conditions. The complex and interrelated processes between natural and human-induced changes drive the development of anthropogenic droughts [3–6]; a compound multidimensional and multiscale phenomenon governed by the combination of natural water variability, climate change, human decisions and activities, and altered micro-climate conditions due to changes in land and water management [3]. The growing frequency of precipitation extremes, especially droughts, will have profound consequences on the hydrologic variability of the streamflow systems and the natural flow regime, creating selective pressures in the environment and

society. In return, this will affect the resilience of river basins and the capacity of systems to withstand shocks and perturbations without modifying their functional identity and adapting to changing conditions [7].

Resilience theory applied to water systems can offer a perspective on the understanding of anthropogenic droughts as one of the central disturbances of streamflow dynamics and the potential changes in hydrological resilience across all scales, from local watersheds to regional and transboundary basins. Catastrophic disturbances such as anthropogenic megadroughts can cause shifts in ecosystems into alternative states, through which many ecosystems can lose their functionality and identity. This phenomenon can be assessed by determining the relationships between natural drivers and processes that allow for ecosystem functioning (e.g., streamflow) and the anthropogenic pressures (e.g., water use, land use change, and management practices). To see how resilience is affected by changes in hydrologic conditions, we may construct stability landscapes [8] which are good approximations for understanding resilience concepts [9]. The metaphor of stability landscapes in resilience theory depicts the various stable states of a system as a series of "basins of attraction," which are regions in state space in which a system tends to remain (Figure 1 – Retrieved from Dakos and Kefi, 2002 [10]) and have been used to explain the dynamics of several ecosystems and the components of resilience including resistance, latitude, precariousness, and panarchy [11]. Stability landscapes help understand the properties of dynamical systems and have been used to represent resilience characteristics of shallow lakes [12], urban water systems [13], tropical forest and savanna [14], climate states [15], plant patterns in drylands [16,17] and river management [18].

A stability landscape with several basins of attraction corresponds to the various stable states in which a system will exist. As streamflow in river basins is modified by exogenous drivers (precipitation, exchange rates) and endogenous processes (infrastructure, management practices), the streamflow system may move from one basin of attraction to another when substantial disturbances occur (e.g., hurricanes, dry spells, ENSO patterns, management practices) and affect the state variables. State variables include temporal or spatial characteristics, and when these occur, the set of variables will persist in one of many possible configurations, which may shift to a different configuration or equilibrium after a perturbation [9]. However, changes in environmental conditions that affect processes between state variables, such as river fragmentation or changes in the natural flow regime, will alter the shape of the stability landscape as these pressures directly affect state variables.

We argue that the evidence of anthropogenic drought in river basins can lead to changes in the stability landscape, such as changes in position, width, depth, and configuration of the basins of attraction. The
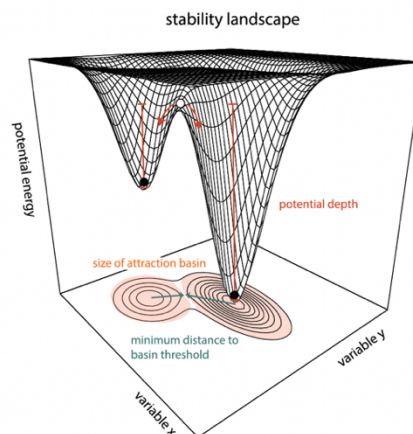
Figure 3. A (hypothetical) stability landscape of a two-dimensional system with hilltops and valleys, also known as a marble-in-a-cup or balls-and-cups landscape. Black balls are found at the bottom of the valley and represent stable states. Retrieved from Dakos and Kefi, 2020 [10]

problem is that, for most systems, its quantification is challenging to operationalize, and we usually do not know the shape of the stability landscape, but in principle, we could derive their shapes [10,19] to assess

the resilience properties of resistance, latitude, precariousness, and panarchy. The objective of this study is to assess anthropogenic droughts and the changes provoked to the stability landscapes of the streamflow system of a river basin. This study assessment is twofold: (1) analyze the hydrologic variability (floods and droughts) of a river system by comparing the natural and regulated flow regimes using long-term streamflow data, and (2) construct stability landscapes and explore properties of resilience in terms of changes in the basins of attraction of the natural and anthropogenic state. The transboundary basin of the Rio Grande / Rio Bravo, located half in the United States (U.S.) and the other half in Mexico, will be used as a case study given its arid, water-limited, and drought-prone landscape, its binational context, and its long history of human manipulation. This research identifies the current anthropogenic state of a transboundary basin in comparison to its natural state and approximates the metaphor of stability landscapes and basins of attraction using streamflow as a representation of the resilience conditions of river basins which can be used in any local, regional, or international scale worldwide.

2. Materials and Methods

To analyze the basin-wide dynamics, this study uses 110 years of monthly streamflow from 1900 to 2010 at eight control points (i.e. hydrologic gauge stations) to portray the natural and anthropogenic states of the RGB. Four control points are selected in the mainstem of the river basin: San Marcial, El Paso, Above Amistad Dam, and Anzalduas. And four at the outlet of the main sub-basins: Rio Conchos, Pecos River, Rio Salado, and Rio San Juan (**Figure 2**). The overall methodology includes (1) data collection of historical streamflow data, including inflows and outflows of the river system; (2) converting gaged or observed flows to naturalized flows using a water mass balance; (3) performing a hydrologic drought assessment for the observed and naturalized flows to observe the hydrologic variability of the river basin; and (4) developing of stability landscapes to compare resilience attributes between the naturalized and anthropogenic states of the river basin.

2.1. Case Study

The transboundary Rio Grande/Bravo (RGB) basin is a water-scarce basin full of extreme climate conditions, from heavy snowfall and tropical storms to prolonged minimal precipitation, which ranges from 190 to 2250mm per year and an average temperature range of -2°C to 25°C. As one of the largest drainage basins in North America, the Rio Grande-Rio Bravo (RGB) extends approximately 557,000 km^2 between the United States of America (U.S.) and Mexico. The RGB provides water to eight states, three in the U.S. (Colorado, New Mexico, and Texas) and five in Mexico (Chihuahua, Coahuila, Durango, Nuevo León, and Tamaulipas). Snowmelt from the Rocky Mountains and monsoon runoff from the Sierra Madre Occidental flows mostly through arid regions, including the Chihuahuan Desert, North America's largest desert. The northern branch of the RGB joins the Rio Conchos at La Junta de los Rios near Ojinaga (Chihuahua) / Presidio (Texas) to form the mainstem river. Several other tributaries contribute to streamflow, including but not limited to the Pecos River, which originates in New Mexico and flows through Texas until the mainstem, and other Mexican tributaries such as the Rio Salado and the Rio San Juan, which originate in the states of Coahuila and Nuevo León, respectively. The annual average natural supply of the Rio Grande delivered to the Gulf of Mexico was between 10 and 12 km3 [20].

Figure 4. Control points and locations of interest at the Rio Grande-Bravo Basin.

2.2. Data Collection

Long-term streamflow data is required to represent specific conditions of river basins, including the dynamics and behaviors of hydrologic, climatic, anthropogenic, and seasonal variables over extended periods in a river basin. This analysis requires two streamflow datasets: (1) Observed flow regimes, which represent a clear manifestation of the Anthropocene, including water diversions, withdrawals, and reservoir operations, among others. Observed flow data were obtained from the Mexican National Water Commission (Comisión Nacional del Agua [CONAGUA]), the International Boundary and Water Commission (IBWC), and the U.S. Geological Survey (USGS). (2) Natural flow regimes represent streamflow without anthropogenic impacts, removing the impacts of reservoirs, diversions, return flows, groundwater sources, and any other water management practice and assuming to capture the relevant characteristics of climate and natural river basin hydrology [21]. Naturalized streamflow data sources were retrieved from previous studies, including the Upper RGB at Rio Grande Del Norte, Colorado, to the Rio Grande Above Presidio, Texas [22]. Then for the Lower RGB, daily and monthly naturalized data was retrieved from below Presidio/Ojinaga to Anzalduas, Tamaulipas from 1900-1943 [23,24], and from 1950 to 2008 [25]. Data gaps were calculated using streamflow naturalization.

2.3. Streamflow Naturalization

Streamflow naturalization is used in observed flow regimes for removing anthropogenic influence disturbances such as impoundments of rivers, land-use changes, water extractions, return flows, and other factors from streamflow time series. As the influence of humans continues to have a direct impact on river flows, the natural and anthropogenic parts of observed flows need to be distinguished [26,27]. The method used to naturalize flow is the water balance, which is the most widely used, despite the fact that it is primarily governed by data availability. This approach consists of decomposing flow into a natural part and an influenced part by removing the volume variation induced by the source of influence (e.g., reservoirs) [28] by accounting for the system's gains and losses for the desired time frame [21]. The mass water balance equation (**Eq. 1**) is the following:

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

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

Outflows include evaporation losses from the reservoir and streamflow losses, obtained from the Mexican National Data Bank for Superficial Waters (Banco Nacional de Datos de Aguas Superficiales [BANDAS]) and IBWC. Moreover, any consumptive use, including agriculture diversions retrieved by the Agricultural Statistics of the Irrigation Districts in Mexico (Estadísticas Agrícolas de los Distritos de Riego), domestic and industrial water uses obtained by CONAGUA. Inflow data include agriculture and urban returns, flows, precipitation in the reservoir, and streamflow gains obtained by BANDAS and CONAGUA. Furthermore, the change of storage was obtained from BANDAS and IBWC. Lastly, to validate our results, we performed a statistical analysis comparison between our results and available research including the studies of Orive de Alba [29] and Blythe and Schmidt [22]. The goodness of fit criteria used from Moriasi et al. [30] were the coefficient of determination (R2), index of agreement (d), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS).

2.4. Streamflow Drought Index

The Streamflow Drought Index (SDI) developed by Nalbantis and Tsakiris [31] is used to characterize the severity of hydrological droughts. To capture decadal changes and long-term droughts in the basin for each control point. First, the cumulative streamflow of the naturalized streamflow data was estimated in a time window of 120-months. Then, the aggregated time series were fitted to probability distribution functions (normal, log-normal, and gamma) using the Kolmogorov-Smirnov (K-S) test; the log-normal distribution function (*p-value* less than 0.5) was selected based on the goodness of fit at a 95 percent

confidence level and the least sum squared error between each probability distribution function (See supplemental materials). The software used to test and select the best probability distribution function was the Python package: fitter [32]. At last, the estimation of the cumulative probability is transformed into a standard normal random variable with a mean zero and standard deviation of one, resulting in the values of the naturalized SDI.

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{S_k} \tag{2}$$

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

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

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

2.5 Computation of Stability Landscapes

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

3. Results and Discussion

3.1. Data Validation

Results of the analysis comparison between the streamflow estimations from the period of record of 1900-1943 from Orive de Alba [29] were $R^2=0.9$, d=0.9, NSE=0.9, and PBIAS=3.6. In addition, the comparison between Blythe and Schmidt [22] with a period of record is 1900-2010 are $R^2=0.9$, d=0.9, NSE=0.9, and PBIAS=1.8. The statistical performance for both comparisons was *very good* according to the criteria of da Silva *et al.* [36].

3.2. Hydrologic variability of the natural state of a river basin

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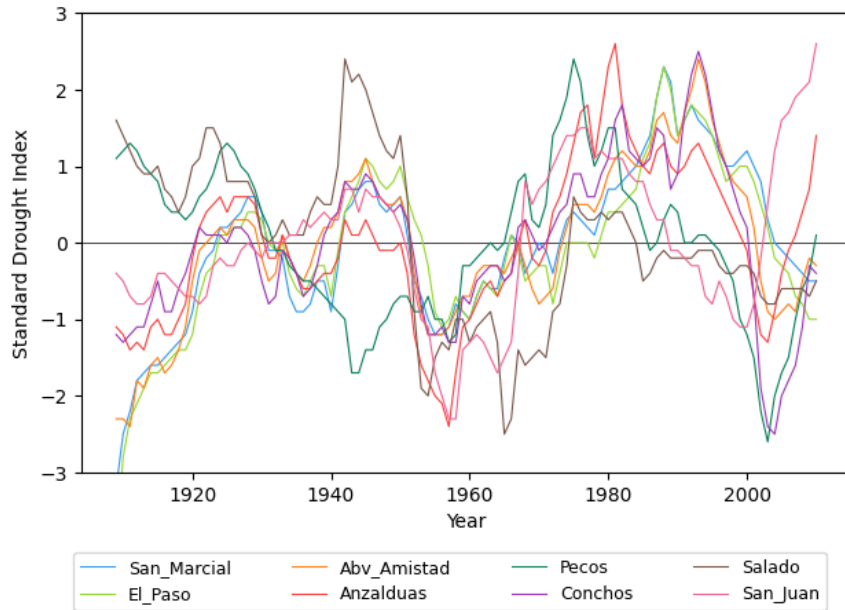
Figure 3. Streamflow Drought Index of the naturalized control points of the Rio Grande-Bravo Basin

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

Table 2. Hydrologic periods of the Rio Grande – Bravo basin. Each hydrologic period is the average of the consecutive number of years that ranges from specific SDI values.

Control Point	Hydrologic Period (average of consecutive years)			
	Dry (-3 to -0.5)[1]	Extremely Dry (-3 to -2)[1]	Wet (0.5 to 4)[1]	Extremely Wet (2 to 4)[1]
San Marcial	10	8	11	2
El Paso	13	8	15	2
Above Amistad	13	9	16	3

Anzalduas	13	6	12	2
Rio Conchos	12	6	16	3
Pecos River	25	2	16	4
Rio Salado	23	5	13	2
Rio San Juan	18	4	15	3
Average	16	6	14	3
Median	13	6	15	3

[1] Streamflow Drought Index (SDI) values

3.2.1 Synchronous and Asynchronous wet and dry periods

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

3.2.2 Occurrence of droughts

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

3.2.3 Occurrence of Snowfall and Hurricanes

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

3.2.4 Impacts of climate change

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

3.3 The modern hydrology: a perennial human-induced extreme drought

A comparison between the natural and modern streamflow variability in the mainstem of the RGB is shown in **Figure 4** and the subbasin control points in **Figure 5.** The natural hydrology of the RGB exhibits a strong hydrologic variability with alternating dry and wet periods. In contrast, the regulated hydrology lacks the cyclical periods of wet and dry periods highlighted in the natural system; it shows a permanent state of human-induced extreme drought in the basin. The lack of hydrologic variability intensifies the dry states' severity and frequency, shifting from a possible wet or moderately wet to a dry, moderately dry, or even extremely dry period that could last several years. The loss of this dynamism puts the system in a perennial and extreme dry state for most of the sites for decades, in some regions more severe than others, yet the magnitude and extent of the dry state permeate all regions of the RGB. In the RGB mainstem, perennial extreme dry periods started in San Marcial and El Paso in 1920 (for 90 years), above Amistad in 1939 (for 71 years), and in Anzalduas since the beginning of the 20th century (for 110 years). Anzalduas represents the response of the entire RGB basin given its location near the outlet; it shows that since the early 1900s, water diversions and flow regimes modified the basin as if it was in a perennial drought. For the main tributaries of the RGB, perennial extreme dry periods started in the Pecos river in 1945 (for 65 years) and the Rio Conchos in 1960 (50 years). In the San Juan and Rio Salado basins, they appear to have periods of extreme drought that are separated by periods of dry and moderately dry periods; these can be

explained by the1980s wet period in the San Juan and the severely and extremely wet period in the 1970s in the Salado basin.

3.3.1 Causes of the perennial human-induced drought

At the core of this permanent state of human-induced drought is the interplay of human development and climate. Since the 1870s, the RGB has been subject to a long history of human manipulation [20]. The present perennial drought state is the result of increased water demands (for agriculture, municipal, and industrial), water agreements (at the international, interstate, regional and local scales), water overallocation, and the construction of large water infrastructure (reservoirs, canals, levees) [33,37]. Water resources are often insufficient to meet human and environmental requirements due to the natural water scarcity in the basin and the increased human water demand. The RBG basin provides water for more than 10.4 million inhabitants. Moreover, the basin supports extensive irrigated agriculture, comprising approximately 780 thousand hectares of irrigated land [33] and accounting for 83% of water withdrawals in the RGB [37]. In the U.S., the extent of irrigation activities expanded during the 19th century after the Desert Land Act of 1877 [56,57], prompting a disproportionate expansion of agricultural land, water diversions for irrigation, and water consumption. In the U.S., irrigated agriculture accounts for 80 to 90% of the overall water use. The main crops are forage, cotton, pecans, and vegetables [58]. In contrast, as a result of the Mexican Revolution in 1917, the Mexican Agrarian Reform implemented a prolonged distribution of land, where more than half of the Mexican territory was assigned to farmers [59]. A total of 11 irrigation districts were created, totaling 458 thousand hectares of irrigated land [33], where the states of Chihuahua and Tamaulipas account for 87% of the total irrigated areas. In both countries, the large-scale farming systems require large reservoir projects and extensive channelization, which started in 1916 with Elephant Butte in New Mexico and La Boquilla in Chihuahua. Since then, 27 large dams (greater than 16,000 Mm^3 of storage capacity) have been built in the basin, including two international dams: Amistad and Falcon.

As streamflow is reduced by overconsumption and climate change, access to water is becoming a looming crisis, and droughts have become more devastating due to increased use of water resources for human purposes, changes in regulations for water allocation between users, states, or countries. Management actions for concealing water shortages and increasing water supply through more river engineering in one area certainly affect downstream communities. For example, the construction of El Cuchillo Dam in the Rio San Juan during the drought of 1990 aimed to supply water for the city of Monterrey in Nuevo Leon. However, this action led to a diminishing water supply for farmers in Tamaulipas. Droughts have also triggered a change in regulations for water allocation, whether in international agreements or state water allocation systems [37]. For instance, the Pecos River Compact [60] between New Mexico and Texas promotes collaboration and sharing of water resources. However, constraining surface water use created an increase in groundwater use, that ultimately ended up in groundwater overdraft that diminished baseflows that downstream users depended on. Droughts have also triggered conflicts among water users, states, and countries. For example, the drought in the late 1990s triggered disputes between farmers and the federal government in Mexico. From 1997 to 2002, Mexico incurred a substantial water debt to the U.S. The Rio Conchos basin was not able to deliver water to U.S. and Mexican downstream water users due to drought and increased water use in the Rio Conchos basin. At that time, the Mexican government resolved this conflict by delivering water to the U.S. from other tributaries and from Mexican water stored in the international reservoirs, leaving without downstream water users in Tamaulipas. The imbalance between supply and demand creates a complex web of governance structure, infrastructure, and user conflicts, which translate into compounding effects for anthropogenic droughts.

3.3.2 The degradation toll of the environment due to human activities

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

3.3.3 The human-induced megadrought

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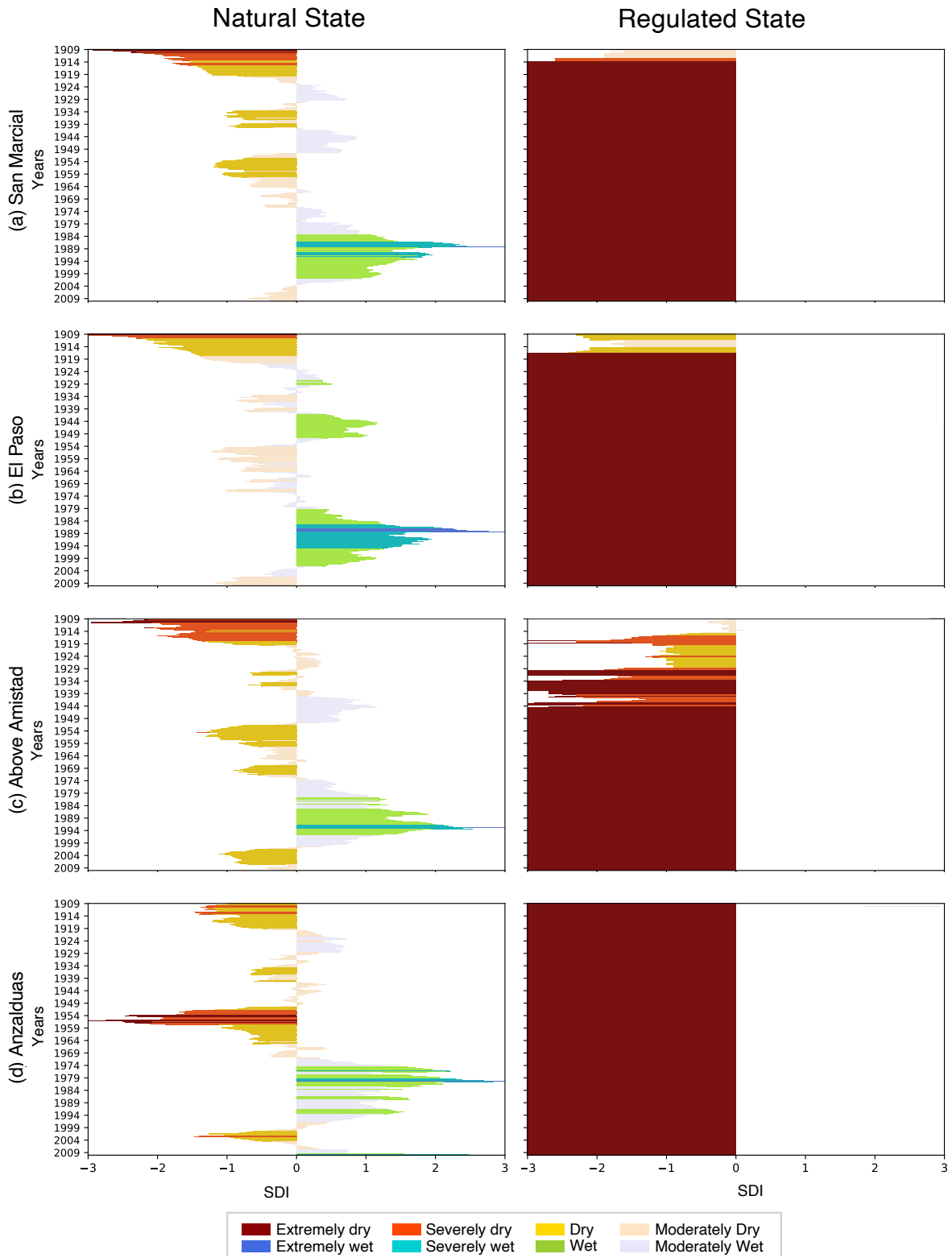
Figure 4. Streamflow Drought Index (SDI) indicating the hydrologic variability of the natural (left) and the regulated (right) state of four mainstem control points of the Rio Grande-Bravo Basin at (a) San Marcial, (b) El Paso, (c) Above Amistad, and (d) Anzalduas
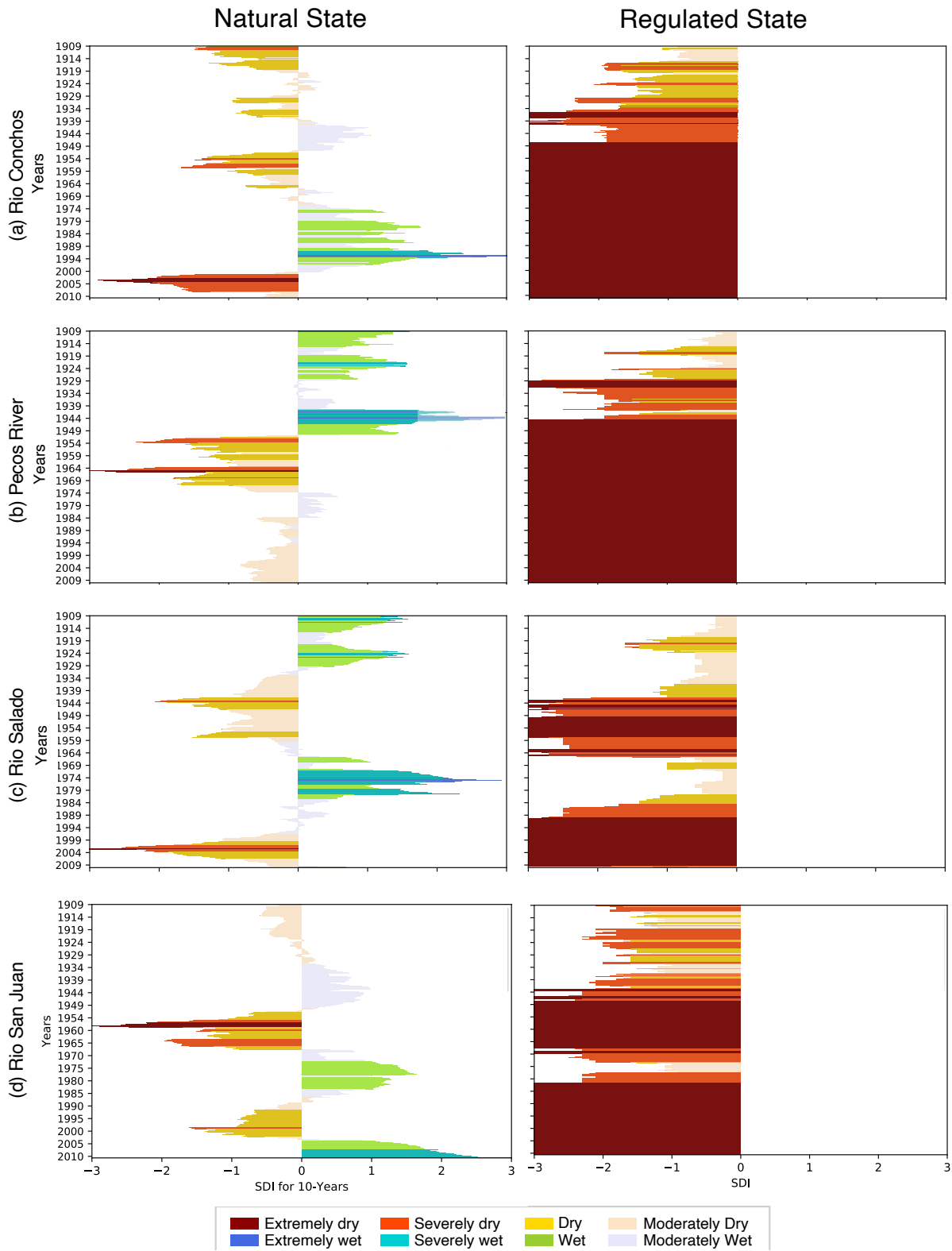
Figure 5. Streamflow Drought Index (SDI) indicating the hydrologic variability of the natural (left) and the regulated (right) state of four subbasin control points of the Rio Grande-Bravo Basin at (a) Rio Conchos, (b) Pecos River, (c) Rio Salado, and (d) Rio San Juan.

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

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

3.4.1 The dynamic RGB natural stability landscape

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

3.4.2 The precarious RGB regulated stability landscape

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

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

state. Even if the critically endangered RGB is trapped in an undesirable and unsustainable human-induced megadrought state, our society have the ability to modify the current stability landscape through transformability –the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable [11]. The challenge is to reduce or avoid the human activities (e.g., modification of flow regime due to water storage in reservoirs that only meet human water needs) that create undesirable basins of attractions and move toward stability landscapes that resemble the natural state (e.g., implementation of environmental flows through dem releases mimicking the natural flow regime). "Different management actions would be required to initiate a transformative change that envisions and restores natural dynamic processes. Reservoir re-operation and environmental flows are strategies targeted to minimize hydrologic alteration by incorporating water releases that include functional flow metrics such as timing, frequency, magnitude, duration, and rate of change of the natural flow regime. Other management actions include environmentally, socially, and climate responsible agriculture, such as adequate selection of crops, deficit irrigation, and the implementation of cover crops which are measures to reduce consumptive water use."
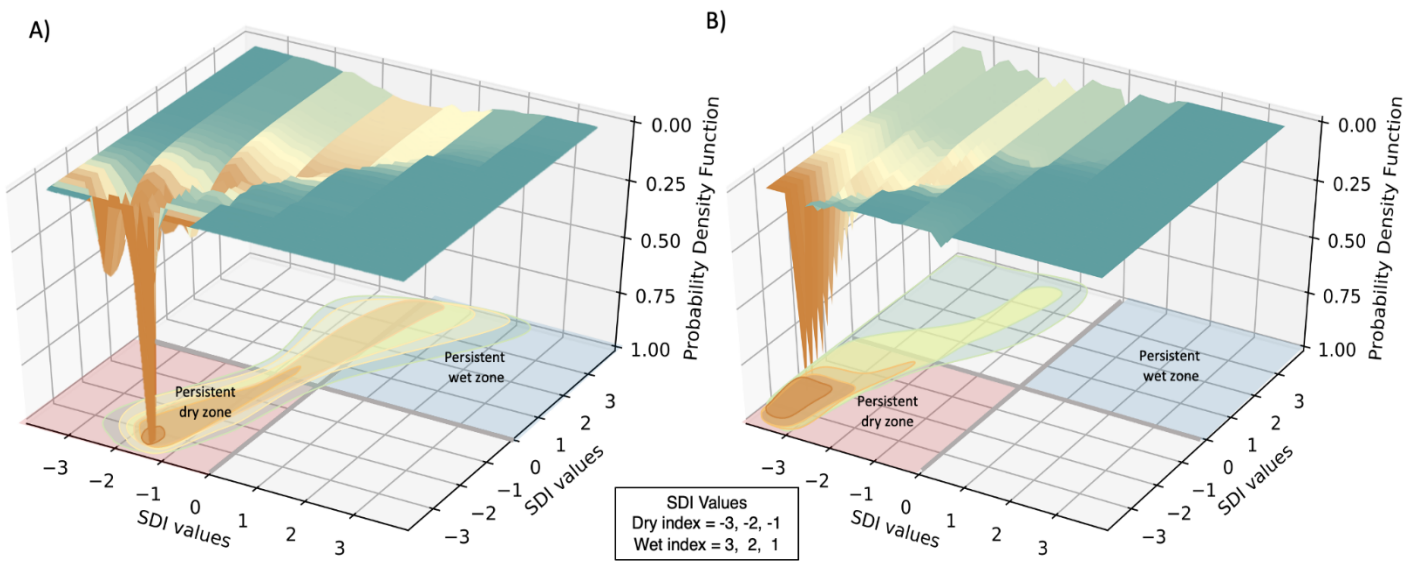
Figure 6. Stability Landscapes of the Rio Grande-Rio Bravo at Above Amistad control point. (A) Natural flow regime (Figure 5A), two states are identified: (1) a persistent dry zone, characterized by a constricted-deep basin of attraction; and (2) a persistent wet zone, portrayed as one shallow-wide basin. (B) The regulated flow regime shows a single wide-deep basin of attraction pertaining to the persistent dry zone.

4. Conclusions

Natural hydrologic variability is vital for promoting ecological resilience, as it governs the water quantity, quality, habitat, and health of riverine ecosystems. In the Anthropocene, the alteration of natural flow variation by human-induced changes is the dominant force in social-ecological systems, causing changes in flow regimes and the resilience properties of river basins. This study demonstrates how human development and human-centered water management regulations are the main drivers of the anthropogenic megadrought in the Rio Grande. In addition, we demonstrate how this process has produced changes in the stability landscape of these river basins, including changes in the topology (resistance and latitude), the trajectory (precariousness), and the dynamic processes of a natural system (panarchy). The stability landscape alteration is depicted as the modification of two basins of attraction, which represent the natural wet and dry hydrologic states, into a single basin of attraction representing a

permanent dry state. The implication of the resilience erosion in the RGB indicates that streamflow conditions have changed sufficiently to provide early warning signals of crossing a resilience threshold, meaning that the system could suffer consequences. As a society, we are already experiencing the effects of a water crisis, and current management practices and policies are beginning to migrate into placing aspects of social-ecological resilience analysis at the core of integrated water resources management. Aside from the limitations to operationalizing the concept of stability landscapes, the broader impact of this study is that it sheds light on quantifying ecological resilience attributes in river basins. We believe that a shift toward addressing resilience in river basins is a prerequisite to understanding current systems and reconnecting our societies with adaptable strategies aimed to be in sync with the dynamics of natural resources. Scenario planning and adaptive management are also necessary to overcome undesirable systems and foster flexibility and adaptability. Our ability to understand the dynamic processes of the natural system and modify our outdated vision of highly manipulated systems to obtain maximum yields is the most effective way to manage sustainable, resilient river basins in the face of increasing environmental and social change.

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CHAPTER 3

IDENTIFYING THRESHOLDS, REGIME SHIFTS, AND EARLY WARNING SIGNALS USING LONG-TERM STREAMFLOW DATA IN THE TRANSBOUNDARY RIO GRANDE–RIO BRAVO BASIN

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Abstract: As the centerpiece of ecosystems and human societies, river basins are complex social–ecological systems (SESs) that depend on the natural flow regime and the hydrologic variability to adapt to changes and absorb disturbances. Anthropogenic and climate change disturbances destabilize river systems. Therefore, a resilience question arises: What is the carrying capacity of a river basin, i.e., how much disturbance can a river basin take until the system undergoes a regime shift? To answer this question, this study aims to identify regime shifts, thresholds, and the carrying capacity of the transboundary Rio Grande–Rio Bravo (RGB) basin using 110 years of monthly streamflow data. To address this research question, first, gauged (regulated) and naturalized streamflow data is collected; if naturalized flows are not available, they are calculated through streamflow naturalization. Second, streamflow standardization is estimated using the streamflow drought index. Third, a regime shift assessment is performed using Fisher Index, and fourth, the nonparametric Mann-Kendall test is used to assess the Sustainable Regime Hypothesis which evaluates regime shifts and alternative regimes. Results demonstrate that resilience thresholds are surpassed, and regime shifts, including early warning signals, occurred in multiple locations of a transboundary basin. The present study highlights the importance of assessing the carrying capacity of a river basin; hence, evaluating regime transitions, including identifying early warning signals and thresholds, is critical in managing for sustainability and ecological resilience of SESs. Looking ahead, the integration of ecological resilience theory into water management has the potential to recognize the sustainable carrying capacity of river basins at the local, regional, and international scale.

Keywords: carrying capacity; ecological resilience; early warning signals; regime shifts; resilient flow regime; river basins; thresholds

1. Introduction

River basins are resilient and dynamic social–ecological systems (SESs) defined by the natural flow regime paradigm. This concept recognizes the attribute of flow variability as the master variable that sustains the ecological integrity of ecosystem structure and functions [1]. The temporal variability of the natural flow regime underpins ecological resilience [2,3] by providing riverine systems with the capacity to adapt and thrive, absorb perturbations, reorganize, and retain its identity to flow-related disturbances. However, the near-ubiquitous anthropogenic activities in river systems (e.g., reservoirs, agricultural expansion, land-use change, water compacts, and treaties) and the accelerated climate changing conditions (e.g., extreme events such as droughts and floods) cause severe consequences in the variability of the natural flow regime [4]. When environmental variation is lost, ecological resilience erodes, and the capacity of rivers to support biological, biogeochemical, and geomorphic processes declines [3]. For example, flow releases from reservoirs that suit the agricultural growing season or comply with water treaties do not always correspond with the timing of the natural flow regime. These flow disturbances will modify the quantity and timing of flows, which are vital flow attributes for the lifecycle of native species [5,6] (e.g., fish spawning and vegetation recruitment), including floodplain connectivity, channel morphology, water quality, and nutrient cycling[7]. The persistent anthropogenic forcing can lead to hydrological consequences, destabilizing river basins worldwide and bringing the system to the point of an ecological threshold. A

point at which, if crossed, an abrupt change in an ecosystem quality, property, or processes occurs [8]. Studies suggest that once a threshold is attained, stream ecological health may decline precipitously [9]. The ecological attributes that confer resilience to a system depend on the magnitude of the disturbance, the temporal and spatial scale where it occurs, and the resilience safeguards that it possesses.

In hydrology, identifying thresholds in rivers would provide relevant information about the sustainable carrying capacity of river basins, the maximum number of anthropogenic disturbances that a hydrologic area can withstand before shifting to an unattainable state. Depending on the relative strength and severity of disturbances, a stressed system may respond by remaining in the current state or shifting (smoothly or abruptly) to a new state if a threshold is crossed. This new potential state, a long-term system reorganization, is known as a regime shift [10,11]. The mechanisms that cause regime shifts, including the types of regime shifts in a system, are useful evidence of the relationship between the response (e.g., flow regime) and control variables (e.g., flow regulation) [12]. For instance, abrupt regime shifts will a exhibit nonlinear relationship or positive feedbacks between the response and the control variables, while cascading regime shifts happen when a regime shift in a system changes key variables that make another system undergo a regime shift [13]. Adapting to a new state following a regime shift means that variables in the systems will likely undergo significant change, tipping into a new equilibrium. As resilience of natural ecosystems research continues to unfold, understanding and identifying regime shifts and the capacity of a river basin to absorb and recover from perturbations has become a critical topic in river basin resilience, conservation, and management [14,15].

Numerous studies have strived to improve our understanding of regime shifts in river basins—for example, the conceptualization of alternate regimes in a large floodplain-river ecosystem [16] or the long-term hydrological regime shifts under climatic and anthropogenic pressures, including tropical cyclone flooding [17] and experimental floods on regulated rivers for improving the ecological integrity [18,19]. These studies support the need to broaden our conceptualization of river basin ecosystem dynamics, resilience, and regime shifts. Moreover, recent research has focused on devising early warning signals for anticipating such abrupt ecological transitions and the evidence of early warning signals before regime shifts signal for systems approaching a tipping point [20] due to critical slowing down or a flickering phenomenon. Resilience theory predicts that approaching critical thresholds in natural systems may result in an increasingly slow recovery from small perturbations, a phenomenon called critical slowing down [21], which provides signals for loss of resilience before the occurrence of regime shifts. Strong perturbations may cause the system to "flicker" [22,23], occurring when a complex system starts moving back and forth between two alternative attractors. Long time series and high resolution are required to capture the internal dynamics of early warning signals in systems [20,23]. Understanding the conditions under which critical thresholds are approaching and likely to be crossed and the mechanisms that underlie threshold behavior and regime shifts are critical given the significant effects on ecosystem functions and services in freshwater systems [24]. Quantitative approaches to identify early warning signals, thresholds, and regime shifts require a strong focus on ecological resilience assessments. In hydrology, ecological resilience principles to assess freshwater systems [3] include key aspects to assess resilience, such as temporal variability, spatial heterogeneity, hydrologic connectivity, and decision-making actions. Other measures rely on considering ecological resilience as an emergent property of complex systems that decompose into attributes or surrogates of resilience: alternative regimes, thresholds, scales, and adaptive capacity [25]. However, quantifying and applying the concept of resilience has been challenging, and current approaches are correlative and limited to the local scale of ecosystems [15,26,27], or the qualitative treatment of resilience rather than quantitative facets has limited its applicability [25].

To advance in closing knowledge gaps of freshwater resilience, this study evaluates thresholds, early warning signals, and regime shifts of a transboundary river basin, using streamflow. The novelty of this study is that it uses a simple and reproducible assessment that can be applied to river basins at multispatial scales—including at the transboundary, sub-basin and basin wide scales—for quantifying and characterizing the resilience surrogates of thresholds and regime shifts through the lens of temporal variability using long-term streamflow data. The assessment includes five steps. First, gauged data is

collected for desired control points in a river basin. Second, naturalized streamflow data is calculated from the collected gauged data using a mass water balance. Third, naturalized and gauged (regulated) streamflow data is standardized using the Streamflow Drought Index (SDI). Fourth, regime shifts are detected through the Fisher information (FI) method. Fifth, FI results are evaluated using the nonparametric Mann-Kendall test and the Sustainable Regime Hypothesis. To the knowledge of the authors, this is the first study that tests the suitability of FI in identifying regime shifts, early warning signals, and critical slowing down for river basin flow regimes.

The case study is the Rio Grande/Rio Bravo (RGB) basin given its social–ecological complexity. Its binational character includes two countries and eight states with distinctive political, institutional, and legal frameworks which account for the growing water demand and economic development. The region also possesses a mosaic of unique ecosystem landscapes, which makes it an ideal study area to perform this analysis. Under this premise, interesting research questions arise: (1) Can we quantify how many anthropogenic disturbances a river basin can absorb until reaching a resilience threshold? (2) If a threshold is crossed and a regime shift occurs, can we identify when it happened? and (3) Can we recognize early warning signals for potential regime shifts and/or the mechanism under which a regime shift occurred? Overall, this study is intended to serve as a baseline for evaluating thresholds and regime shifts in any river basin worldwide, at the local, regional, and international scale.

2. Materials and Methods

2.1. Case Study

The transboundary Rio Grande–Rio Bravo (RGB) basin is one of the three largest drainage basins in North America. It is the fifth longest river in North America (2830 km), and it extends for approximately 557,000 km^2, half of which is located in the United States and the other half is in Mexico. The richness of the RGB is bound to the basin's climate, topography, and hydrology. Snow and hurricane-driven precipitation range from 190 to 2250 mm/year, the average temperature ranges between −2 °C and 25 °C, and in some areas the annual evapotranspiration can range between 400 and 2400 mm. The topography varies significantly from the mountains and gorges of the headwaters to deserts and subtropical terrain in the lower basin. The annual average, natural supply of the Rio Grande delivered to the Gulf of Mexico was between 10 and 12 km^3, and the runoff coefficient varies from 0.05 to 0.5 in the Colorado headwaters to 0.05 to 0.15 in the Rio Conchos Basin headwaters. Its diverse hydrologic regime flows result from the snowmelt signature, late summer floods from the Rio Conchos, moderate magnitude floods, and some flash floods from ephemeral tributaries. The region includes forest and desert, migratory birds, vast areas of grasslands and arid shrubland, rare desert plants, springs, rivers, streams, and endemic species that support a rich diversity of species. The water is shared between the states of Colorado, New Mexico, and Texas in the U.S., and Durango, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas in Mexico. The RGB has two significant headwaters; in the U.S., they are fed from snowmelt in the San Juan Mountains of Colorado, and in Mexico, from the tropical monsoons hitting the Sierra Madre Occidental of Chihuahua (Figure 1). The river originates in the San Juan Mountains in Colorado, draining into the southern Rocky Mountains and the western half of New Mexico. When the upper RGB basin reaches the city of Presidio, Texas, it is joined by the Rio Conchos in Mexico at La Junta de los Rios, which nowadays provides up to 75 percent of the flow at its confluence with the RGB. Approximately 530 km further downstream, the Pecos River flows into the RGB. Further downstream, the Rio Salado and the Rio San Juan contribute streamflow from the south until flowing into the Gulf of Mexico. Except for the snowmelt and tropical monsoons of the headwaters, most of the river flows through arid regions, including the Chihuahuan Desert, North America's largest desert.
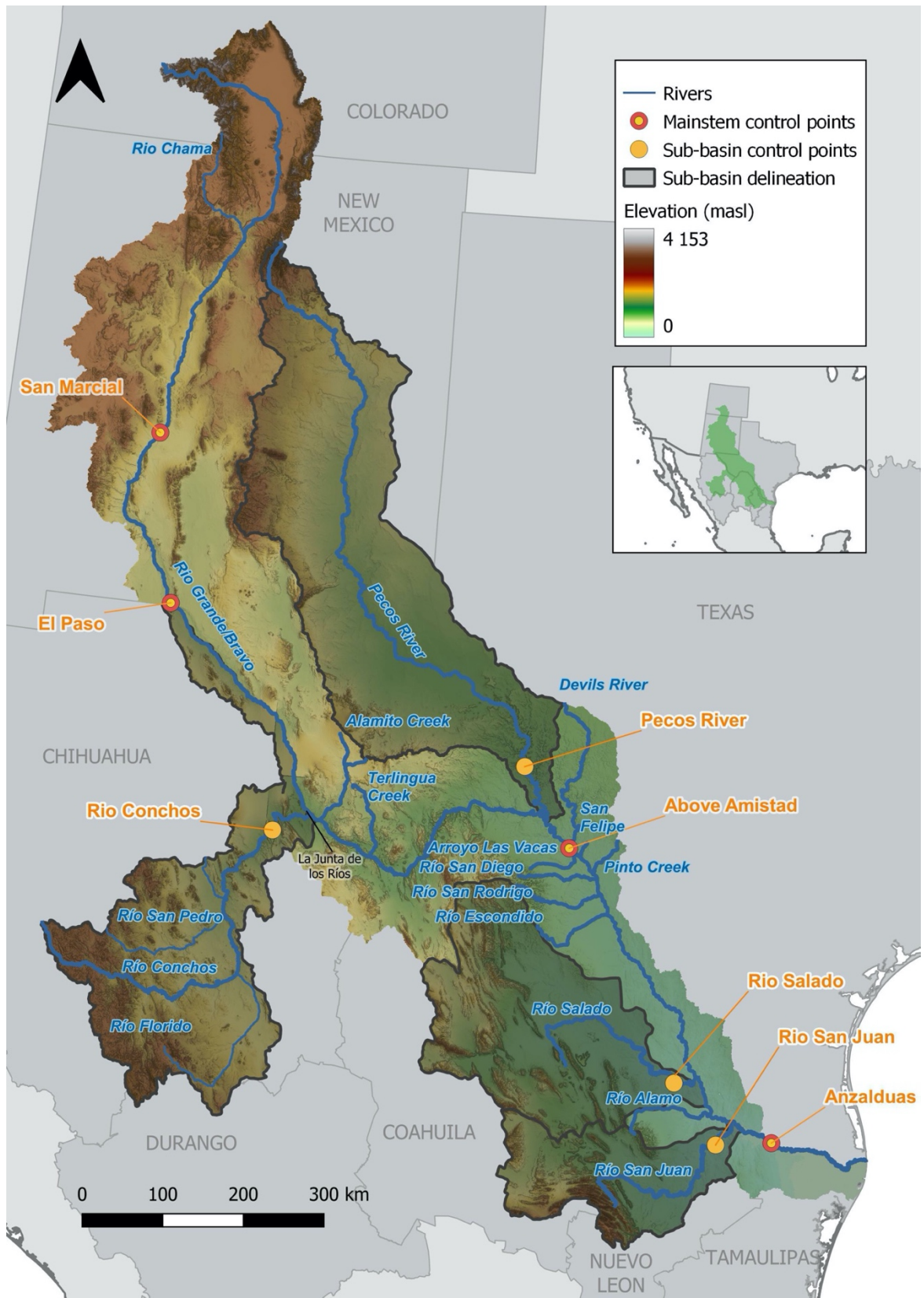
Figure 1. Mainstem and Subbasin control points, sub-basin delineations and main rivers of the Rio Grande–Bravo basin.

2.2. The Anthropocene of the Rio Grande-Bravo

The modern RGB and its streams hardly resemble the original watercourse or abundance of native species. The collective features of an arid ecosystem, rapid population growth, a landscape dominated by irrigated agriculture, and infrastructure development are pushing the limits of environmental sustainability and present a significant challenge in managing this transboundary basin (Figure 2). The alteration of the natural flow regime and degradation of these riparian ecosystems had a tremendous toll on the river. The extent of environmental degradation can be seen most drastically along the forgotten reach, a 240-km stretch of the river that at times is completely dry due to upstream diversions. The river corridor has been heavily modified, including the human-engineered straightening of the mainstem for conveyance and flood protection (e.g., in Presidio/Ojinaga and El Paso/Cd. Juarez). Channel narrowing and incisions emerged by the reduced flood flows and encroachment of invasive vegetation (e.g., Big Bend Reach). Historically, water resources in the basin have been planned to meet human needs. Irrigation practices introduced by Spanish explorers in the 1600s supplanted pre-Hispanic flood irrigation [28]. In the U.S., the extent of irrigation activities expanded during the 19th century after the Desert Land Act of 1877 [29,30], prompting a disproportionate expansion of agricultural land, water diversions for irrigation and water consumption. Main irrigation districts include Elephant Butte Irrigation District (36,681 hectares), the Middle Rio Grande Conservation District (36,281 hectares), and the Lower Rio Grande Valley (300,000 hectares), among others. In contrast, as a result of the Mexican Revolution in 1917, the Agrarian Reform implemented a prolonged distribution of land, where more than half of the Mexican territory was assigned to farmers. There are 11 irrigation districts (ID) in the Mexican area of the RGB; the main ones include DR005 Delicias (73,002 hectares) and DR025 Bajo Rio Bravo (201,291 hectares). The total irrigation area for the RGB comprises approximately 780 thousand hectares (Figure 3), which accounts for 83% of the surface water in the basin allocated to agricultural use [31].

Figure 2. Irrigation districts, main cities, and reservoirs of the Rio Grande–Bravo basin.
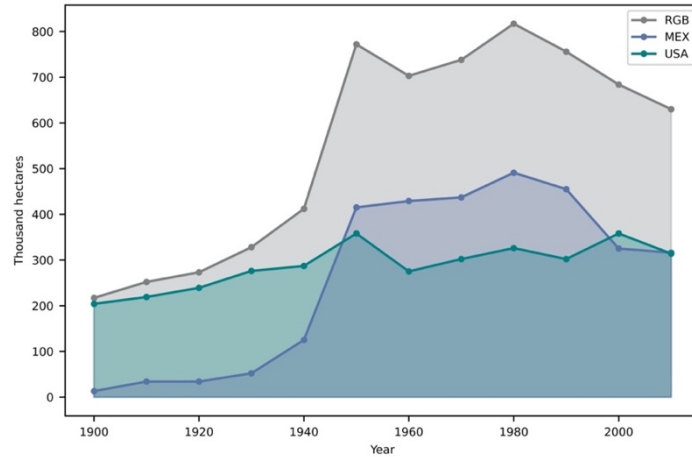
Figure 3. Accumulated agriculture hectares (thousand hectares) in the Rio Grande–Bravo Basin (grey) and the portions of the United States (green) and Mexico (blue).

To impulse the agriculture sector, the proliferation of dams in the RGB reached a maximum capacity of 33,037 million cubic meters (Mm³) shared almost equally among both countries; the U.S. reached a total reservoir capacity of 16,948 Mm³ and Mexico 16,089 Mm³ (Figure 4). The first large reservoirs started in 1916 with Elephant Butte (capacity 6455 Mm³) and La Boquilla (capacity 3177 Mm³). Since then, 27 big dams have been constructed in the basin, including two international dams: Amistad (capacity 2926 Mm³) and Falcon (capacity 2013 Mm³). The development of irrigation districts and water infrastructure has fostered the growth of important cities, industries, and rural areas in the basin. Today an estimated 10.4 million people inhabit the RGB. For instance, surface water rights in both countries are over-appropriated: there are more rights to water than is normally available [32]. All of these anthropogenic pressures have reduced the natural flow of the river by over 95% [33]. Furthermore, climate change is already affecting the RGB streamflow timing and volume through changes in air temperature, snowfall and snowpack, rainfall, and increased evapotranspiration rates [34], adding pressures on water availability and threatening the environment, society, and the economy of the RGB.
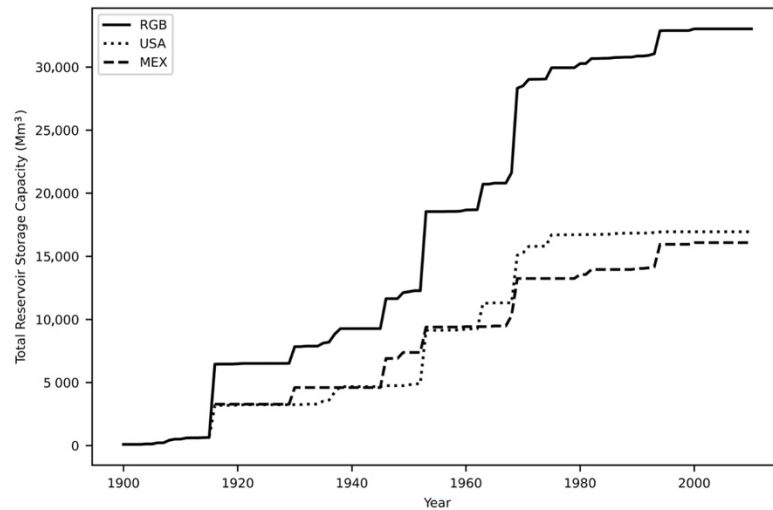
Figure 4. Total reservoir storage capacity (Mm³) in the Rio Grande–Bravo Basin (33,037 Mm³) and the portions of the United States (16,948 Mm³) and Mexico (16,089 Mm³).

2.3. Methodology Overview

The methodology to evaluate thresholds, early warning signals, and regime shifts of a river basin using streamflow includes five steps: (1) data collection, (2) streamflow naturalization, (3) streamflow standardization, (4) regime shift assessment and (5) testing of the Sustainable Regime Hypothesis. See methodology flowchart in Figure 5 and used software in Supplementary Materials.
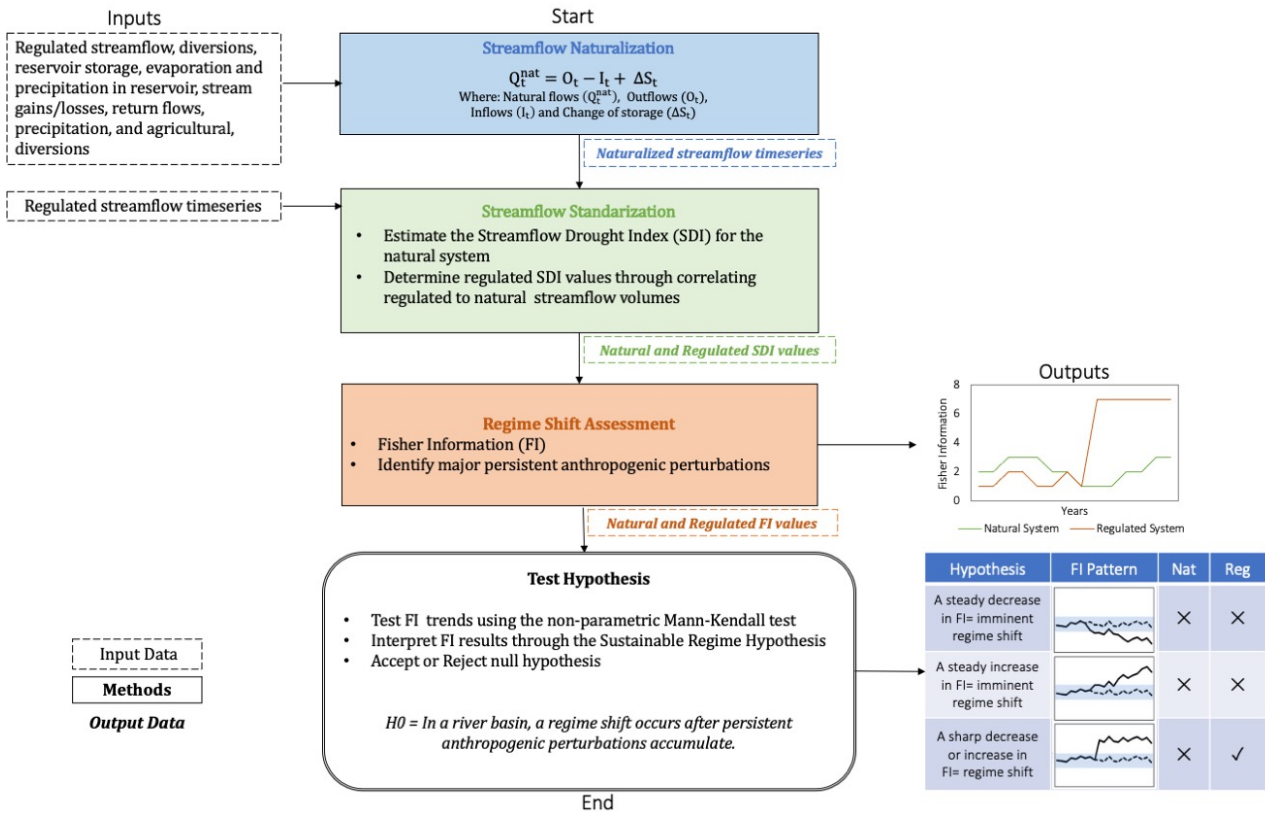
Figure 5. Methodology flowchart to assess thresholds, regime shifts, and early warning signals in a river basin.

2.3.1. Streamflow Data Collection

Eight control points are selected for this case study, four located in the mainstem of the RGB, namely San Marcial, El Paso, Above Amistad, and Anzalduas, and four located at the outlets of the sub-basins of the Rio Conchos, Pecos River, Rio Salado, and Rio San Juan. We considered that these control points represent the overall condition of the whole RGB basin (Figure 1). For each control point, gauged streamflow data (referred as regulated streamflow in this study) was retrieved from 1900 to 2010 at a daily and monthly scale. Depending on the location of the control point, regulated streamflow data was collected from the Mexican National Water Commission (Comisión Nacional del Agua [CONAGUA]), the International Boundary and Water Commission (IBWC), and the US Geological Survey (USGS) gauge station data. Naturalized flows from 1900 to 1943 and from 1950 to 2008 were obtained from several research studies, including [33,35–38]. Period gaps for naturalized flows were estimated using the streamflow naturalization method.

2.3.2. Streamflow Naturalization

Naturalized streamflows represent historical natural hydrology that would have occurred in the absence of anthropogenic impacts. In this study, estimating daily naturalized flow consists of removing anthropogenic impairment such as reservoir development, water supply diversions, return flows, stream losses, water imports and exports, and other factors from regulated streamflow [39]. Streamflow naturalization uses a mass balance Equation (1) to estimate the natural flow by accounting for the system's inflows, outflows, and change of reservoir storage for the desired time frame. Outflows were estimated using Equation (2) and include consumptive losses involving agricultural water demands obtained by the Agricultural Statistics of the Irrigation Districts in Mexico (Estadísticas Agrícolas de los Distritos de Riego), urban and industrial water uses obtained by CONAGUA. Evaporation and stream losses were retrieved by the Mexican National Data Bank for Superficial Waters (Banco Nacional de Datos de Aguas Superficiales (BANDAS)) and IBWC. Then, inflows were estimated using Equation (3), and data sources include return flows, precipitation in the reservoir, and streamflow gains obtained by IBWC. Finally, for the change of reservoir storage in Equation (4), data was retrieved by BANDAS and IBWC.

$$Q_{tj}^{nat} = GF_{tj} + O_{tj} - I_{tj} + \Delta S_{tj} \qquad (1)$$

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

$$O_t = AD_t + UD_t + ID_t + SL_t + Ev_t \qquad (2)$$

where O_t is the outflows, AD_t is the agriculture diversions, UD_t is the urban diversions, AI is the industrial diversions, SL_t is the streamflow losses, and Ev_t is the reservoir evaporation at a given monthly time step t.

$$I_t = R_t + P_t + SG_t \qquad (3)$$

where I_t is the inflows, R_t is the return flows from agriculture, urban, and industrial diversions, P_t is the reservoir precipitation, and SG_t is the streamflow gains at a given monthly time step t.

$$\Delta S_t = S_t - S_{t-1} \qquad (4)$$

where ΔS_t is the change of reservoir storage and S_t is the reservoir storage at a given monthly time step t.

Natural streamflow completion techniques such as the QPPQ method [40] were used to fill gaps when ungagged data was incomplete for specific periods. Gaps were estimated by transferring streamflow data at reference gauges with complete data to ungauged or incomplete gauges. The reference gauge should be unaltered and similar to the incomplete gauge location. The QPPQ method uses flow duration curves and relies on the assumption that exceedance probabilities are equivalent between the reference gauge and the incomplete data gauge, and then it transfers the flow at the incomplete control point using the estimated flow-duration curves. Lastly, a comparison of the average estimated natural flows and the available studies of Orive de Alba [38], Loredo-Rasgado [37], and Blythe and Schmidt [33] were assessed using the statistical analysis from Moriasi et al. [41] to validate our calculations. The goodness of fit criteria used in this study were the coefficient of determination (R2), index of agreement (d), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS). In addition, the statistical performance was evaluated using the criteria in the study of da Silva et al. [42]

2.3.3. Streamflow Standardization

Once the naturalized and regulated streamflow time series were available, the Streamflow Drought Index (SDI), an approach that characterizes the severity of hydrological events [43], was used for two objectives: (1) to normalize streamflow across the basin and allow adaquate comparisons of the naturalized and regulated hydrologic conditions; (2) to evaluate and illustrate the hydrologic extremes of the basin from 1900 to 2010. For the SDI computations, first, the natural streamflow datasets were aggregated into a 120-month time window as it represents the system's memory and captures decadal changes and

characteristic long-term droughts of the RGB. Then, a normality test was performed in the aggregated natural streamflow using the Kolmogorov–Smirnov (K-S) test at a 0.05 significance level. To decrease the skewness of the data series, log-normal distributions were used. After the transformation, the cumulative probability is then transformed to the standard normal variable with mean zero and standard deviation, which resulted in the SDI values for each window. Next, to calculate the regulated SDI, each regulated streamflow was aggregated using the same window size (120-months); finally, these volumes were cross-referenced with the closest aggregated naturalized volume and assigned with its corresponding SDI value. Hydrologic dry states are values between 0 and −3, and wet states between 0 and 3. [43] Eight hydrologic SDI states are considered in this study, defined 0 to −0.5 as moderately dry, −0.5 to −1 as dry, −1 to −2 as severe drought, and from −2 to −3 as extreme drought. While wet states are values between 0 and 3, classes range from 0 to 0.5 as moderately wet, 0.5 to 1 as wet, 1 to 2 as severe wet, and 2 to 3 as extremely wet.

2.3.4. Regime Shift Analysis

The quantitative indicator Fisher information (FI) was used to identify regime shifts and detect early warning signals that capture shifting dynamics. FI is a key method in information theory developed by Fisher [44] that offers a means of measuring the amount of information about an unknown parameter based on current observations [45]. This approach collapses the behavior of one or multiple variables of a complex system into an index, showing the overall system dynamics, regimes, and regime shifts [10,46]. FI is a well-established indicator that has been applied extensively to social–ecological systems [47] including analysis of regime shifts in the sustainability of a regional system [48–51], in water supply systems [52], and recently to detect precipitation and streamflow changes contributed by climate change and land management practices in agricultural watersheds [53]. This study takes a step forward into testing the suitability of FI of social–ecological systems by presenting the first application of FI for assessing river basin flow regimes.

To calculate FI values, we used the python package csunlab/fisher-information [54] and the natural and regulated SDI values as the input data. The general methodology to compute FI follows four steps: (1) create time series windows, using two parameters to move through the data: time windows and a window step; (2) bin points into states within each window by establishing a level of uncertainty for each variable using a size of state, which establishes the size of the area used to bin points into states; (3) generate probability density functions for each time window using the binned points; and (4) calculate FI values as the amplitude of the probabilities for each state [49]. For this analysis we used a window of 12 (twelve calendar months), a window increment of 1 month, and a size of the state of 3. Then, smoothed annual FI values are presented to focus on dynamic order trends and not monthly or seasonal fluctuations. Lastly, to find an increasing or decreasing trend, the nonparametric Mann-Kendall test uses equation (5) with a confidence level of 95%. This nonparametric test has been used to detect FI patterns [45] and changes in climatic and hydrologic time series. Therefore, this test was applied to the natural and regulated FI values and to find if the natural system has remained time invariant or changed over time due to climatic pressures in the natural flow regime.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \qquad (5)$$

where the X_j are the sequential data values, n is the length of the data set, and

$$sgn(\theta) \begin{cases} 1 \; if \; \theta > 0 \\ 0 \; if \; \theta = 0 \\ -1 \; if \; \theta < 0 \end{cases}$$

Finally, to evaluate regime shifts in the RGB, the FI results and the Mann-Kendall trends were assessed using the Sustainable Regime Hypothesis [10,55] patterns summarized in Figure 6.

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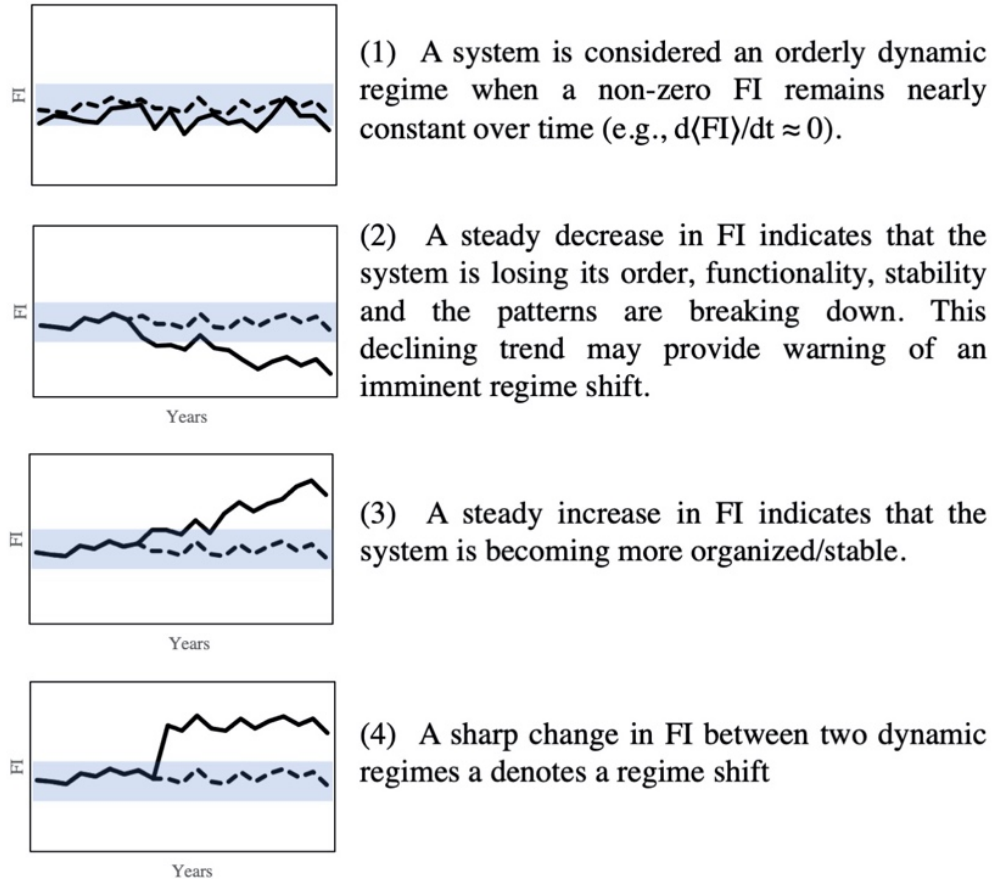
Figure 6. F1 patterns of the Sustainable Regime Hypothesis. The dotted line indicates a natural system's regime, and the solid line indicates a regulated system's regime. The blue shaded region denotes the boundaries for a regime shift, estimated as the two-standard deviation from the natural system's mean FI [56]. The subfigure (1) indicates an oderly dynamic system, (2) a steady decrease in FI of the regulated system, (3) a steady increase in the regulated system, and (4) a sharp increase in the regulated system.

Overall, FI values can increase, decrease, or remain stable over a time period. It can also undergo a sharp decrease or increase, indicating a regime shift. In this study, the boundaries to detect regime shifts are two standard deviations from the mean FI for the entire time period, a criteria established by Gonzalez-Mejía et al. [56]. These limits define the ranges to distinguish a stable regime (within the boundary) from a regime shift (relatively stable trend outside of the boundary) for both natural and regulated systems. In addition, early warning signals such as flickering and critical slowing down are typically evaluated using measures such as lag-1 autocorrelation and variance [26,57], but in this study, FI was able to detect such evidence.

3. Results

3.1. Streamflow Naturalization Validation

A statistical comparison between the average annual natural flow estimations of our study and three available studies is shown in Table 1. For the study of Orive de Alba [38], we compared the period of 1900 to 1943, for the control points of Rio Conchos, Rio Salado, Rio San Juan, and Anzalduas. Then, we compared the period of 1900–1944 of the control points of Rio Conchos, Pecos River, Above Anzalduas, Rio Salado, Rio San Juan and Anzalduas from Loredo-Rasgado [37]. Lastly, we compared the period of 1900–2010 of the control points of Rio Conchos, Pecos River, Rio San Juan and Anazalduas with Blythe and Schmidt [33].

Results indicate a very good statistical performance for R^2, NSE, d ($\geq$ 0.9) and for PBIAS ($<\pm$10). These values are considered indicative of acceptable estimations of the natural flow.

Table 1. Statistical comparison of the estimated natural flows and the available studies of Orive de Alba [38], Loredo-Rasgado [37], and Blythe and Schmidt [33].

Goodness of Fit Criteria	Orive-Alba 1900–1943	Loredo-Rasgado 1900–1944	Blythe and Schmidt 1900–2010
Pearson's Correlation	0.990	0.995	0.996
Coefficient of Determination (R^2)	0.995	0.998	0.998
Index of Agreement (Willmott-d)	0.995	0.995	0.995
Coefficient of Efficiency (Nash-NSE)	0.979	0.979	0.979
Percent bias (PBIAS)	3.589	7.131	1.881

3.2. Regime Shifts of the Natural and Regulated Systems

FI results are shown in Figure 7 for the sub-basin control points: (Figure 7a) Rio Conchos, (Figure 7b) Pecos River, (Figure 7c) Rio Salado, and (Figure 7d) Rio San Juan. Figure 8 shows the control points located in the mainstem of the RGB: (Figure 8a) San Marcial, (Figure 8b) El Paso, (Figure 8c) Above Amistad, and (Figure 8d) Anzalduas. Both figures depict the FI values for the natural (blue line) and regulated (black line) streamflow systems. The establishment of reservoirs, irrigation districts, and implementation of management policies (e.g., treaties and compacts) are visualized using distinctive symbols under the regulated streamflow and the dates of anthropogenic pressures help to associate them with regime shifts. The ±2 standard deviation (SDV) range (light blue area) from the mean value (green dashed line) of the natural system indicates the boundaries to distinguish a stable regime (within the boundary) from a regime shift (relatively stable trend outside of the boundary) for both natural and regulated systems. The ±2SDV sets the baseline limits and helps to detect when regime shifts occurred (dashed red). In addition, results to examine the Sustainable Regime Hypothesis and the FI trends from the nonparametric Mann-Kendall test are shown in Table 2.
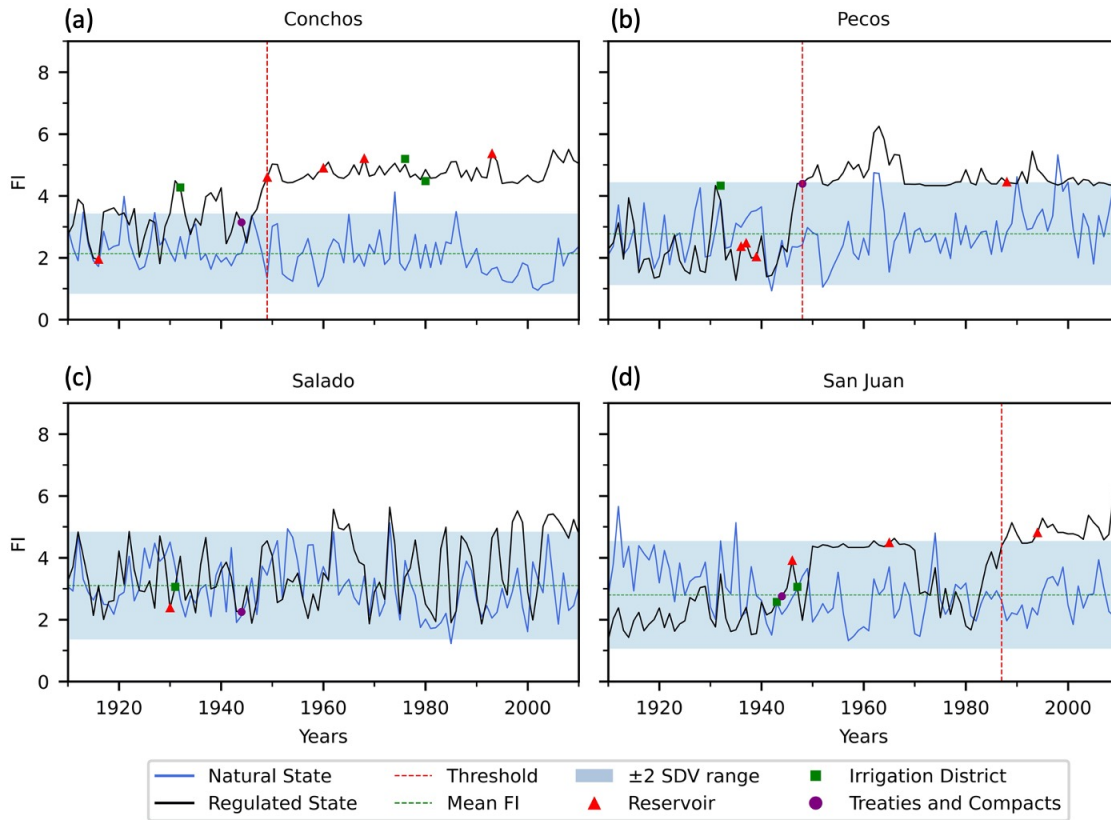
Figure 7. Analysis of regime shifts using Fisher Index (FI) in four sub-basins of the Rio Grande-Bravo basin including the control points of (a) Rio Conchos, (b) Pecos River, (c) Rio Salado, and (d) Rio San Juan. FI scores of the subfigures scores are shown for the natural (blue line) and regulated (black line) states, and the thresholds (dashed red line) indicate the year of a regime shift occurrence. The regulated state includes accumulated perturbations such as reservoirs, irrigation districts, and treaties and compacts. The ±2 standard deviation (SDV) range (blue area) including the mean FI value (dashed green) indicate the baseline limits to detect regime shifts.

Figure 8. Analysis of regime shifts using Fisher Index (FI) in the mainstem of the Rio Grande–Bravo Basin including the control points of (a) San Marcial, (b) El Paso, (c) Above Amistad , and (d) Anzalduas. FI scores of the subfigures are shown for the natural (blue line) and regulated (black line) states, and the thresholds (dashed red line) indicate the year of a regime shift occurrence. The regulated state includes accumulated perturbations such as reservoirs, irrigation districts, and treaties and compacts. The ±2 standard deviation (SDV) range (blue area) including the mean FI value (dashed green) indicate the baseline limits to detect regime shifts for the regulated system.

Table 2. Sustainable regime null hypothesis evaluation defined by the dynamics of the natural flow regime.

Sustainable Regime Null Hypothesis	Control Gauge Station	Naturalized Streamflow System	Regulated Streamflow System
A system is considered in an orderly dynamic regime when a nonzero FI remains nearly constant over time (i.e., d⟨FI⟩/dt ≈ 0).	Rio Conchos Pecos River Rio Salado Rio San Juan San Marcial El Paso Above Amistad Anzalduas	Accept	Accept
A steady decrease[1] in FI indicates that the system is	Rio Conchos Pecos River	Accept Reject	Reject

losing its order, functionality, stability, and the patterns are breaking down. This declining trend may provide warning of an imminent regime shift.	Rio Salado	Accept	
	Rio San Juan	Accept	
	San Marcial	No trend	
	El Paso	No trend	
	Above Amistad	Accept	
	Anzalduas	Accept	
A steady increase[1] in FI indicates that the system is becoming more stable and organized.	Rio Conchos	Reject	
	Pecos River	Accept	
	Rio Salado	Reject	
	Rio San Juan	Reject	Accept
	San Marcial	No trend	
	El Paso	No trend	
	Above Amistad	Reject	
	Anzalduas	Reject	
A sharp decrease or increase in FI indicates a regime shift	Rio Conchos		Accept
	Pecos River		Accept
	Rio Salado		Reject
	Rio San Juan	Reject	Accept
	San Marcial		Accept
	El Paso		Accept
	Above Amistad		Accept
	Anzalduas		Reject

[1] The decrease or increase must be greater than two standard deviations from the mean FI for the entire time period [50]. Mann-Kendall decrease/Increase.

3.2.1. Natural System

The natural system of the RGB remains in an orderly dynamic system with no regime shifts, denoting stability and equilibrium in the system. The FI values of the natural state for all control points remained between the ±2SDV limit and range between ~1 to 4.5 depending on the control point. The natural system of all control points are resembled in Figure 6(1), in which a system is considered an orderly dynamic regime with no steady or sharp change. There are few instances where the natural system goes out of bounds and surpasses the ±2SDV limit; however, the FI values return and stabilize within the ±2SDV boundaries. These occurrences appear in the control points of Above Amistad and Anzalduas (Figure 8a,d, respectively), between 1930 to 1950 and in the (Figure 7d) at Rio San Juan sub-basin between 1900 to the 1930s. In addition, from 1990 to 2010, in the control points of Rio Conchos, San Marcial, and El Paso (Figures 7a and 8a,b, respectively) a U-shape form is shown which might indicate a climate perturbation such as an extreme wet or dry period. As for the nonparametric Mann-Kendall test (Table 2), San Marcial and El Paso show no trends. Meanwhile, Above Amistad, Anzalduas, Rio Conchos, Rio Salado, and Rio San Juan indicate decreasing trends, similar to Figure 6(2), which denotes warnings for an upcoming regime shift given that the system's instability is increasing. Meanwhile, the Pecos River displays an increasing trend, similar to Figure 6(3), indicative of the system's growing stability.

3.2.2. Regulated System

Several regime shifts and early warning signals occurred in the regulated state in which FI values surpass and remain outside of the ±2SDV range. In the six control points of San Marcial, El Paso, Above Amistad, Rio Conchos, Pecos River and Rio San Juan (Figures 7a,b,d and 8a–c, respectively), sudden regime

shifts with no rebounds took place at different times and anthropogenic pressures. Despite the contrasting conditions, the results from these six control points follow the pattern of Figure 6(4) which denotes a sharp increase in FI. Some control points experience two or three anthropogenic disturbances, including reservoirs and development of irrigation districts, before having a regime shift (e.g, San Marcial in 1916 and El Paso in 1923), while others need four to seven disturbances, including several reservoirs, irrigation districts, and treaties and compacts, prior to a regime shift (e.g., Above Amistad in 1947, the Pecos River in 1949, Rio Conchos in 1947 and Rio San Juan in 1987). A common aspect of the regulated state is that regime shifts move the system to an alternative state with higher FI values ranging between 4 and 6 and that additional disturbances keep the systems in this new regime. Rio San Juan and Above Amistad showed early warning signals before experiencing a regime shift. For instance, the Rio San Juan sub-basin underwent a stability period from 1951 to 1970 within the ±2SDV range, then moved within the ±2SDV range for a few years until a regime shift happened by 1987. Two control points showed different behavior from the rest: Rio Salado and Anzalduas (Figures 7c and 8d respectively). The Rio Salado sub-basin crosses eight times the ±2SDV range starting in 1962, despite having three anthropogenic disturbances; however, no regime shift takes place. Nonetheless, after the late 1960s, the system appears to have larger fluctuations that reach both ±2SDV limits, indicating early warning signals for an upcoming regime shift. The Anzalduas control point shows a particular behavior that differs from the other locations. First, it has been consistently low since the 1900s, (−2SDV), and it has been high since the 2000s (+2SDV); it is the only control point to surpass the lower and upper boundaries. The differences in occurrence of regime shifts and early warning signals imply that several factors, conditions, and mechanisms affect differently the resilience thresholds of the control points. In addition, results from the nonparametric Mann-Kendall test reveals an increasing trend in all control points, implying a greater degree of dynamic order.

3.2.3. Sustainable Regime Hypothesis Evaluation

The interpretation of Fisher Information through the Sustainable Regime Hypothesis (Table 2) exhibits that both natural and regulated systems for all control points are considered in a dynamic regime. At last, a sharp decrease or increase indicating regime shifts is not observed in the natural system of any control point, but it did in six control points in the regulated state. However, the natural system of the Rio Conchos, Rio Salado, Rio San Juan, Above Amistad, and Anzalduas (Figures 7a,c,d, and 8c,d, respectively) shows decreasing patterns which may exhibit a warning for an upcoming regime shift because uncertainty in the system is increasing. In contrast, increasing patterns are present in all control points of the regulated system, indicating that the system is becoming more stable and organized.

4. Discussion

Persistent forcing of anthropogenic development, and resource management have a strong influence on the hydrologic variability of flow regimes and the ecological resilience of river basins. These interactions can lead to flow disturbances, pushing the system toward ecological thresholds, and once they are transgressed, regime shifts occur. Identifying critical aspects of thresholds (e.g., how many anthropogenic disturbances a river basin can absorb before reaching a resilience threshold) and the mechanisms that cause regime shifts (e.g., recognition of early warning signals) in rivers would provide relevant information about the number of shocks and perturbations that a river basin can cope with before it shifts into a different flow regime. The proposed assessment of this study was able to detect thresholds, early warning signals, and regime shifts at different control points using the SDI and the Fisher Information by comparing natural and regulated streamflow data. The advantages of the proposed assessment rely on the well-established hydrologic and statistical methods used in water resources management and the use of streamflow as the main input data. Streamflow regimes, either natural or regulated, reflect the hydrologic variability patterns that are determinant to the quality and quantity of ecosystem services, and the ecological resilience of river basins. Nonetheless, a limitation of this methodology relies on the availability of complete long-term streamflow data which can be difficult to obtain in under-monitored river basins. However, several methodologies can be included in this assessment to reconstruct long term data, including tree-ring data

and stochastic modeling. Despite this, long-term river flow is acknowledged as the accumulated representation of upstream seasonal variability and the natural or anthropogenic disturbances suffered by upstream subcatchments [58]. In this study, all of the identified regime shifts and early warning signals occurred in the regulated streamflow system; therefore, underlying anthropogenic pressures can be explored to determine or compare the condition of the system in its new state.

4.1. Occurrence of Regime Shifts

The examination of general patterns and mechanisms of regime shifts streamflow data is key to reveal intrinsic factors of environmental changes that drive the sustainable carrying capacity of river basins. Focusing on these mechanisms could provide potential management actions at preventing or reverting such abrupt responses [59]. In this case of study, we identified three types of regime shifts in the regulated system: (1) *abrupt regime shifts*, triggered by human development (e.g., reservoirs, agriculture development, treaties and compacts, groundwater overdraft, population growth) and by climatic effects (e.g., extended drought periods); (2) regime shifts delayed by *resilience safeguards*, traits that confer resilience to the system and serve as a buffer to disturbances; and (3) *cascading regime shifts*, regime shifts caused by a domino effect when systems are dependent on one another.

4.1.1. Abrupt Regime Shifts

The abrupt nature of change produced by ecological thresholds in systems is commonly explained by the nonlinear behaviour of an affected ecosystem attribute. However, abrupt regime shifts are also induced by positive feedback mechanisms, in which a perturbation in one component of the system causes a change in a second component, leading to additional changes in the first component [59]. These feedbacks are commonly triggered by environmental changes which amplify the system responses and unleash abrupt shifts. In this study, two scenarios showcasing abrupt regime shifts by positive feedbacks are distinguished: San Marcial and El Paso.

The San Marcial control point (Figure 8a) suffered an abrupt regime shift in 1917 by the development of reservoirs and agricultural development which are subject to produce abrupt regime changes due to the underlying instability and the reduction of dynamism in a system [53,60]. Extensive irrigation developed in the San Luis Valley, at the upper RGB in Colorado where, initially, 150,000 acres were irrigated in 1880. Later, by 1915, expansion of irrigated land reached 550,000 acres with continuous growth over the next decades. To supply the demand, a large network of ditches and canals was built in 1880–1890 [61]. However, as water demand increased by the expansion of agriculture and population growth in the San Luis Valley, water supply diminished. As the river became drier and drier prior to 1904, a plan to compensate for the reduced flows included the construction of the Rio Grande Reservoir (capacity 64 Mm^3) built in 1914, which resulted in a dramatic decline in the nonflood flows of the Rio Grande that formerly reached the Mesilla and El Paso valleys. The accumulation of anthropogenic pressures above San Marcial induced the abrupt regime shift of 1916, triggered by the positive feedbacks of supply–demand cycles, where increasing water supply enabled higher water demand which quickly counterbalanced the initial benefits of the reservoir. In addition, the establishment of the irrigation district the Middle Rio Grande Conservation District in 1923 (upstream of San Marcial) created a new level of order that is retained throughout the rest of the time period. While additional anthropogenic pressures came in 1935 (e.g., the construction of El Vado dam and the diversion dams at Cochiti, Angostura, Isleta, and San Acacia in several tributaries), the system retained this new regime state after 1916. The underlying instability and the reduction of dynamism in a system triggered an alternative stable state to the system.

Other drivers to induce abrupt regime shifts are water resource regulations by treaties and compacts, as they play important roles in shaping policy and management actions that influence the trajectory of ecosystem health and resilient systems. The implementation of treaties could promote ecological resilience or exacerbate pressures, inducing positive feedbacks and finally causing regime shifts. For example, the Pecos River experienced an abrupt regime shift in the regulated state by 1949 (Figure 7b), a year later from the establishment of the Pecos River Compact (U.S. Congress, 1949) between New Mexico and Texas. The

Pecos River Compact purpose is to promote interstate collaboration and remove the causes of current and future water resources controversies, yet this water agreement also addresses unappropriated or uncontrolled water uses, conflicts among water users, and damages to the environment [62]. Under the compact, New Mexico must deliver to Texas a quantity of water equal to that available to Texas under 1947 conditions, later identified as a dry year event [63]. Although the Pecos River Compact sets the 1947 conditions as the beginning of a new era in the basin, clear evidence of the progressive streamflow depletion was already experienced due to groundwater overdraft in the Roswell groundwater basin for irrigation purposes. In a 25-year period, the use of groundwater in this basin increased from 197 Mm^3 (2225 hectares) in 1930 to 555 Mm^3 (308,882 hectares) in 1954, reaching a maximum irrigated land of 390,427 hectares in 1955. Increased pumping in the basin caused a marked decline in groundwater levels and a corresponding decrease in artesian flows and baseflows [64]. The Pecos River Compact mandated water deliveries to downstream users in Texas; this action led the over extraction of groundwater resources from upstream users in New Mexico, causing surface water depletion. The intensive use of water resources in the basins combined with the Pecos River Compact delivery conditions created positive feedback in the hydrologic pressures of the basin that provoked the system's abrupt regime shift.

4.1.2. Resilience Safeguards: A Buffer to Regime Shifts

Resilience safeguards in this study are seen as natural features or management practices that confer resilience by counteracting events that affect the integrity of a system and prevent or delay regime shifts. Two control points, El Paso and the Rio Conchos (Figures 7a and 8b, respectively), show delayed regime shifts by resilience safeguards.

Treaties, regulations and low diversions can help a system remain in a certain state until further anthropogenic perturbations cause a regime shift. For example, upstream of El Paso is the San Marcial control point, which suffered an abrupt regime shift by 1916 from the accumulation of irrigation and reservoir development. The RGB streamflow at these two control points (San Marcial and El Paso) is a relatively linear course, largely due to the structural geographic control of the Rio Grande rift. This means that the river has no further significant tributaries to join the river. Therefore, it was expected to observe a regime shift in El Paso in 1916, at the same time as the San Maricial and Elephant butte dam (capacity 6455 Mm^3) was built. Two reasons delayed the regime shift of the RGB at El Paso until 1924 (Figure 8b). First, the creation of the Convention of 1906 supported flow variability at El Paso, this agreement stipulates that the U.S. must deliver 74 Mm^3/year to Mexico at the Acequia Madre to support irrigation at El Valle de Juárez region. Second, flow variability still occurred in El Paso before the establishment of the Middle Rio Grande Conservation District in 1923, but one year after this irrigation district was established, the RGB in El Paso experienced a regime shift.

In a river basin, flow regime connectivity and river networks pose another important natural resilience safeguard to anthropogenic perturbations, as they contribute significantly to shape the hydrological response of catchments [65] and mediating recovery processes. The control point of the Rio Conchos (Figure 7a) is an example of how unaltered tributaries contribute to the ecosystem functions and processes, retaining riverine functionality and acting as natural resilience safeguard. In 1916, La Boquilla dam (2903 Mm^3) was built to provide hydroelectricity, irrigation, flood control, and later deliver water for the international Treaty of 1944. Even though La Boquilla is one of the largest reservoirs in the RGB, the Rio Florido and the Rio San Pedro tributaries counteracted the flow reduction of the Rio Conchos' main tributary. These tributaries supported ecosystem functions that allowed the system to remain in the natural regime resilient boundaries. However, fragmentation of tributaries and streamflow networks due to reservoirs and agricultural development provoked imminent abrupt regime shifts.

In the Rio Conchos (Figure 7a), two additional disturbances accumulated, causing a regime shift in the regulated state of this control point. First, the establishment (in 1932) and expansion of the irrigation district DR005 Delicias in the Rio Conchos and San Pedro rivers went from approximately 8000 hectares to 22,000 hectares in 1934, 40,000 hectares in 1938 and 79,555 hectares in 1941 [66]. This agriculture expansion period aligns with sharp increases of FI values that surpassed the +2SDV range (FI value 3.43). At this point, the

FI values are increasing and moving upward from the mean FI value of 2.1. Second, the construction of the Francisco I. Madero dam, built in 1948 in the Rio San Pedro, to deliver water to the expanded irrigation district caused the regime shift of the Rio Conchos sub-basin to a new regime. By this point, the main tributaries which served as natural resilience safeguards were altered and modified, losing their functionality to absorb shocks and disturbances. After the regime shift, several other anthropogenic perturbations maintained the system in this new regime including the construction of three more reservoirs: Luis L. Leon (capacity 832 Mm^3 in 1968), Pico del Aguila (capacity 86 Mm^3 in 1993), and Chihuahua (capacity 37.8 Mm^3 in 1960), and the development of two irrigation districts DR103 Rio Florido (in 1952), and DR090 Bajo Rio Conchos (in 1955). Compared to the other control points, the Rio Conchos shows the highest degree of shift from the respective mean FI values. Higher FI values are generally associated with a greater degree of dynamic order [67], yet the increase is not an indication that the system is moving toward a more humanly preferable state [10,56]. In the RGB, the Rio Conchos is one of the most disturbed systems, and in this case, this new order is not a desirable one, as the hydrologic variability of the system is imperiled by the multiple diversions and impoundments.

4.1.3. Cascading Regime Shifts

A cascading regime shift can occur through a domino effect, when feedback processes of one regime shift affect the drivers of another regime shift [13,68], propagating to larger scales and creating a one-way dependency between systems [68]. This mechanism is shown in the control point of Above Amistad dam (Figure 8c), located in the mainstem of the RGB, which suffered a regime shift in 1948. The main difference between Above Amistad and the early regime shift behavior of San Marcial (Figure 8a) and El Paso (Figure 8b) is the influence of two important tributaries that feed the RGB, the Rio Conchos and the Pecos River. These tributaries provide natural safeguards to anthropogenic changes upstream of Above Amistad. When San Marcial and El Paso control points experienced regime shifts before 1920, Above Amistad remained between the +2SDV range. By 1948, three regulations were passed: the Rio Grande Compact of 1938, the Binational Treaty of 1944, and the Pecos River Compact in 1948. One hypothesis can be that the regime shift in Pecos River caused the Above Amistad regime shift. However, the Rio Conchos also experienced a regime shift in 1948, and it is well documented that the Rio Conchos delivers approximately 70% of its streamflow by this time [69]. The regime shift of Above Amistad is most likely influenced by Rio Conchos, given that the Rio Conchos is three times larger in terms of volume than the Pecos River. Local regime shifts can propagate to larger scales, creating a domino effect and dependency between tributaries given that regional ecosystems can be transformed by water management policies applied to distinctive regions; local management decisions could have extensive consequences elsewhere, especially in river systems.

4.2. Early Warning Signs for Regime Shifts

Because regime shifts occur in a variety of mechanisms, detecting early signals indicating that a system is approaching resilience thresholds would be highly valuable for researchers and managers to predict events before devastating regime shifts. This case study provides evidence to observe two signaling patterns of early warning signals: (1) critical slowing down and (2) flickering. Early warning signals such as flickering and critical slowing down is typically evaluated using measures such as lag-1 autocorrelation and variance, but in this study, FI was able to detect such evidence.

4.2.1. Critical Slowing Down

Critical slowing down is an indicator of early warning for regime shifts, and this occurs when a system approaches a threshold and becomes increasingly slow in recovering from disturbances. This pattern shows as a decrease in rates of change of a system, and an increase in short-term autocorrelations [20,70]. The sub-basin of the Rio San Juan (Figure 7d) shows two behaviors that portray signals of critical slowing down. First, a stable period characterized by lack of variability and dynamism between 1951 to 1970 occurred after three anthropogenic and climatic pressures: (1) the development of the irrigation districts Las Lajas DR031 in 1947, and part of Bajo Rio San Juan DR026 in 1943; (2) the construction of the Marte R.

Gómez reservoir (capacity 2304 Mm^3) in 1946; and (3) the 1950s decadal drought spell, where discharge was reduced by 52 percent [71]. During the stable period, an additional reservoir, La Boca reservoir (capacity 42.6 Mm^3), was built in 1965 to provide water to the increasing population of the Metropolitan Area of Monterrey. In addition, this sub-basin is the largest domestic water user in the RGB and between the 1950s and the 2010s the water supply of the Metropolitan Area of Monterrey, one of the three largest metropolis in Mexico, grew almost 14-fold from 25.3 Mm^3 to 347.0 Mm^3 [72].

This stable period reveals an increasing trend in short-term autocorrelation before the shift. The slowing down causes the intrinsic rates of change in the system to decrease, the state of the system at any given moment becomes more and more like the past state [73]. In addition, this period is characterized by relatively high FI values, which in this case ranged between 4.3–4.5, almost reaching the upper boundary of the +2SDV range. Ultimately, after 19 years of the stability, FI values declined to previous levels in 1971.The impending transition occurred in 1987, when the regulated state shifted to new dynamics after moving upwards from the regime boundary established. After the shift, El Cuchillo reservoir (capacity 1784 Mm^3) was built in 1996, likely impeding the already fragmented system to return within the natural system mean FI range values.

4.2.2. Flickering

Another phenomenon that identifies the vicinity of regime shifts is flickering. This occurs when a strong disturbance move the system back and forth between two alternative attractors [73]. Evidence of flickering is shown in the Rio Salado and in the control point Anzalduas.

In the Rio Salado sub-basin (Figure 7c), flickering was observed from 1960 to 2010, where the regulated system peaked eight times above the +2SDV range. The main anthropogenic perturbations of this sub-basin are (1) the construction of the reservoir Venustiano Carranza (storage capacity 1313 Mm^3) in 1930, which main use is for mining and irrigation practices; (2) the development of 30,000 hectares in irrigation district DR004 Don Martin; and (3) the 1944 International Treaty between U.S. and Mexico. Even with these perturbations, the sub-basin appears to be functioning within the natural system. However, climate-driven pressures are common in this basin; for example, an extraordinary drought period occurred between 1950 and 1957, and a twelve-year drought spell occurred between 1994 and 2006 [74]. The summing of the anthropogenic disturbances and the drought event most likely induced the system to show increased variance and flickering activity. This period shows amplitude of fluctuation, causing an increase in the distribution variance and the skewness. As the system is driven closer to the FI ranges, the persisting behavior is indicative of an early warning for regime shift, given that the system may shift to an alternative state if this condition persisted.

In the case of Anzalduas control point, found at the outlet of the RGB, FI results (Figure 8d) show how the regulated system starts outside of the lower boundaries of the -2SDV range and remains under the mean FI value of the ±2SDV resilient range, but it never shows a complete shift outside the resilient range. Lower FI values signify unstable dynamics and loss of resilience, which aligns with the compounding upstream events of increasing depletion of surface water through impoundments, agriculture, and human-oriented water management. The upstream–downstream processes are concentrated at the mouth of a river basin and can provide an overall overview of the entire dynamics of a river basin. Instead of an imminent regime shift (e.g., the Rio Conchos and the Rio San Juan subasins), the RGB shows characteristics of flickering due to the propagation of a perturbation beyond its original extent in spatially extended ecosystems. This is not an unexpected result, given that the basin has been modified and exploited prior to the 1900s in several locations of the RGB. Understanding the upstream–downstream processes in river basins is essential for water management and planning [75]. It is particularly important in basins where climatic, geological, and political conditions differ among regional locations within a river basin; such cases often occur in transboundary basin configurations. Flickering in this modern system can be considered as a direct warning that the system is in a vulnerable yet redeemable state, and measures to mitigate future disturbances and transformation to undesirable transformation pose complex management challenges that must be addressed promptly.

5. Conclusions

This study demonstrates the power and utility of the approach for examining aspects of the ecological resilience of river basins through the assessment of streamflow. Three research questions are addressed. (1) Depending on the location of the control point within the river basin, we can quantify the amount of anthropogenic disturbance to be absorbed until reaching a resilience threshold. (2) Our approach identifies when a regime shift occurred using long-term natural and regulated streamflow data, the SDI, and the Fisher Information index. However, depending on resilience safeguards, crossing thresholds might suffer abrupt or delayed regime shifts at different times, depending on the amount of accumulated disturbance and the regional location of the control point. (3) Different mechanisms of regime shifts were identified, including abrupt, cascading, gradual regime shifts. In addition, early warning signals such as flickering and critical slowing down were detected using the FI. While the evaluation at each control point provides an overall assessment of the basin or sub-basin, there may be portions of the basin that may be (semi-)pristine or intact—mostly areas upstream from major human alteration (e.g., reservoirs or irrigation districts) or disturbance (land use change).

In terms of future research, the integration of ecological resilience theory into water management has the potential to recognize the sustainable carrying capacity of river basins and aim for adaptive management strategies. As river basins cross or approach critical tipping points, our goals and management strategies should aim to restore or preserve natural freshwater characteristics while providing ecosystem services for society. Interesting questions arise that await further investigation. For example, how are ecological and economic consequences, which have been documented in the RGB, linked to regime shifts, crossing thresholds, and early warning signals in river basins? There is a need to further investigate the relationships between regime shifts and ecological–economic consequences. In addition to assessing natural and regulated streamflow, supplemental ecological indicators such as functional flow metrics or indicators of hydrologic alteration can provide important information on functional flow regime components; therefore, we can identify key flow metrics to support ecological resilience. Moreover, we can further investigate if regime shifts are reversible and, if so, which management practices (e.g., instream flows, environmental flows, key flow metrics) can shift the system into a resilient flow regime. Evidence of regime shifts and thresholds in river basins due to increasing interactions of the Anthropocene requires finding common ground to design a standard assessment for regime shifts in river basins. We propose that this assessment be further explored and used in different river basins as a leading effort to include in water management strategies and policy instruments to support and monitor complex and dynamic social–ecological river basins worldwide.

6. References

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CHAPTER 4

FUNCTIONAL FLOWS OF THE RIO GRANDE – BRAVO BASIN

Abstract: The integrity of riverine ecosystems reflects the dynamic interaction of hydrologic processes and ecosystemic functions which are central in the ecological resilience of river basins. The property of ecosystems comprised of understanding the components that refer to the functional responses and ecosystem patterns, structure, function, and processes with the capacity to modify resilience is adaptive capacity, a surrogate of ecological resilience. This chapter investigates the adaptive capacity of the Rio Grande – Bravo (RGB) basin through the estimation of 110 years of daily natural flows, the visual classification of three hydrologic classes (snowmelt flow, monsoon flow, and bimodal snowmelt-monsoon flow), the proposition of five functional flow components for the RGB: the dry-season baseflows, the wet season, the summer pulse, the monsoon peak flows, and the snowmelt flow, the quantification of functional flow metrics which describe the magnitude, timing, duration, frequency, and/or rate of change of flow for each of the functional flow components and lastly, descriptions of the biological, physical, and biogeochemical ecosystem functions that are supported by each of the five components of functional flows. With the overarching goal of assessing the adaptive capacity of the RGB, this chapter provides instream flows following a whole-basin thinking, which can be used as a water management strategy to modify the resilience, or basins of attraction of the system.

1. Introduction

The ecological integrity of the riverine ecosystems depends on the natural dynamic character and functional diversity of hydrologic regimes. Hydrological regimes are essential to understand critical functions and processes of riverine ecosystems (Zeiringer, Seliger, Greimel, & Schmutz, 2018) as they are central in supporting biodiversity and ecosystem processes. Hydrologic variability, and spatial heterogeneity are some key principles to ecological resilience – the capacity of ecosystems to adapt to shocks and shifts while preserving desired functions and services. For freshwater ecosystems, which are inherently dynamic, temporal variability is expressed by the natural flow regime paradigm, which postulates that the structure and function of riverine ecosystems, and the adaptation of native species, are dictated by the patterns of natural variation in river flows (Lytle & Poff, 2004).

Flow variability has strong influence on aquatic and riparian ecosystems, and geomorphic processes. For example, during the dry season, low flows purge invasive species and support native species well adapted to extremely dry conditions (Bunn & Arthington, 2002; S Postel & Richter, 2012). Then, as the rainy season begins, high flows reset rivers from progressive channel narrowing, by flushing sediments, shaping physical habitat formation, and maintaining or rewidening channels (Dean & Schmidt, 2013). In addition, these flows recharge the floodplain water table and provide ecological cues such as fish migration and spawning (S Postel & Richter, 2012). This flow regime variability enhances a mosaic of ecological functions of riverine ecosystems, which, depending on the spatiotemporal conditions within the basin, a diverse portfolio or functional flow components may arise. A functional flow approach is at the core of evaluating the third resilient surrogate of this dissertation, the adaptive capacity of riverine systems. In an ecosystem context, adaptive capacity is a system property that has the capacity to modify ecological resilience (or basins of attraction) to cope with disturbances. Adaptive capacity as a latent potential of ecosystems is comprised of components that are dynamically interlinked so only partially lend themselves to being organized in discrete categories. Among these components are cross-scale interactions, which means that ecosystems are hierarchically organized and have distinct patterns of structure, function, and processes that are compartmentalized by spatiotemporal scales; and ecological functioning, which refer to the diversity of functional responses and traits to which ecosystems react to disturbances (Angeler, 2019).

In this study, this ecology theory is modified to hydrology in the sense that the adaptive capacity of a river basin is referred to the cross-scale interactions of the natural flow regimes and the functional flow

functions as the ecological functioning. The functional flow components of the natural flow regime are discrete aspects of a natural flow regime that links seasonal flow characteristics with ecological functions, and geomorphic and biogeochemical processes (Escobar-Arias & Pasternack, 2010; Yarnell et al., 2015). Collectively, the discrete set of functional flow metrics provides the means to focus on maintaining river ecosystem dynamism, structure, and function. In addition, this approach provides an environmental assessment for instream flows and environmental flows.

In the last 15 years, multiple studies have been conducted to estimate instream flows in different locations and sections of the Rio Grande/Bravo basin (See Table X of Chapter 1) which use varying instream flow methods and from which ecosystem water needs have been recommended. In addition, several other studies, listed in Table 2 of Chapter 1, evaluate the ability to adjust existing Rio Grande/Bravo water management strategies to provide instream flows while meeting human water management objectives, including agriculture and urban water supply, flood control, treaty obligations, and recreational and economic benefits. As today, and to the author's knowledge the functional flow components of the RGB haven't been determined, nor instream flows for the entire basin.

Therefore, this chapter's objective is two-fold. The first one is to determine the functional flow components of the Rio Grande-Bravo basin to assess the resilient surrogate of adaptive capacity in the river system. And the second, is to provide instream flows for the river basin following a whole-basin thinking which can be use as a water management strategy to modify the resilience, or basins of attraction of the system. To achieve these goals a series steps are used: First, the daily natural flows for 110 years is estimated for eight control points. Second, the natural functional flows components are identified based on the physical, biogeochemical, and biological functions linked to distinctive flows. Third, each flow component is described by parameters of the natural flow regime: magnitude, duration, frequency, timing and rate of change (Poff et al., 1997) quantified by flow metrics (e.g., number of days, start-day, rate of decrease, the peak of flushing flow etc.).

2. Materials and Methods

2.1. Estimating daily natural flows

2.1.1 Data Collection

A total of 70 gauge stations were selected for this case study.

For each control point, gauged streamflow data (referred as regulated streamflow in this study) was retrieved from 1900 to 2010 at a daily and monthly scale. Depending on the location of the control point, regulated streamflow data was collected from the Mexican National Water Commission (Comisión Nacional del Agua [CONAGUA]), the International Boundary and Water Commission (IBWC), and the US Geological Survey (USGS) gauge station data. Naturalized flows from 1900 to 1943 and from 1950 to 2008 were obtained from several research studies, including [33,35–38], additionally 110 daily natural flows for the Pecos River was obtained from the on-going thesis work of Saiz-Rodíguez (in prep). Period gaps for naturalized flows were estimated using the streamflow naturalization method.

2.1.2. Streamflow Naturalization

Naturalized streamflows represent historical natural hydrology that would have occurred in the absence of anthropogenic impacts. In this study, estimating daily naturalized flow consists of removing anthropogenic impairment such as reservoir development, water supply diversions, return flows, stream losses, water imports and exports, and other factors from regulated streamflow [39]. Streamflow naturalization uses a mass balance Equation (1) to estimate the natural flow by accounting for the system's inflows, outflows, and change of reservoir storage for the desired time frame. Outflows were estimated using Equation (2) and include consumptive losses involving agricultural water demands obtained by the Agricultural Statistics of the Irrigation Districts in Mexico (Estadísticas Agrícolas de los Distritos de Riego), urban and industrial water uses obtained by CONAGUA. Evaporation and stream losses were retrieved by the Mexican National Data Bank for Superficial Waters (Banco Nacional de Datos de Aguas Superficiales

(BANDAS)) and IBWC. Then, inflows were estimated using Equation (3), and data sources include return flows, precipitation in the reservoir, and streamflow gains obtained by IBWC. Finally, for the change of reservoir storage in Equation (4), data was retrieved by BANDAS and IBWC.

$$Q_{tj}^{nat} = GF_{tj} + O_{tj} - I_{tj} + \Delta S_{tj} \tag{6}$$

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

$$O_t = AD_t + UD_t + ID_t + SL_t + Ev_t \tag{7}$$

where O_t is the outflows, AD_t is the agriculture diversions, UD_t is the urban diversions, AI is the industrial diversions, SL_t is the streamflow losses, and Ev_t is the reservoir evaporation at a given monthly time step t.

$$I_t = R_t + P_t + SG_t \tag{8}$$

where I_t is the inflows, R_t is the return flows from agriculture, urban, and industrial diversions, P_t is the reservoir precipitation, and SG_t is the streamflow gains at a given monthly time step t.

$$\Delta S_t = S_t - S_{t-1} \tag{9}$$

where ΔS_t is the change of reservoir storage and S_t is the reservoir storage at a given monthly time step t.

Table 2. Input data to estimate daily natural flows for the Rio Grande – Bravo basin

Inputs	Source	Control Points (CP)	Period of record	Time Step	Unit
Natural Streamflow	• Blythe & Schmidt (2018)	33 CP of the northern branch	1900 – 2010	D	
	• Gonzalez-Escorcia (2016)	13 CP mainstem of the lower branch	1900 – 1913	D	Mm³
	• Loredo-Rasgado (2018)	13 CP mainstem of the lower branch	1900 – 1943	M	
	• Silva Hidalgo (2010)	37 CP for the lower branch	1950 – 2008	M	
Regulated Streamflow	• IBWC, CILA, CONAGUA	37 CP for the lower branch	1900 – 1913 1934 – 2010	D	
	• Orive-Alba (1945)	8 CP for the lower branch	1900 – 1943	M	Mm³
	• Lowry & Cravioto (1944)	18 CP for the lower branch	1900 – 1943	M	
	• Silva Hidalgo (2010)	37 CP for the lower branch	1950 – 2008	M	
Diversions	• Gonzalez-Escorcia (2016)	13 CP mainstem of the lower branch	1900 – 1913	D	
	• Loredo-Rasgado (2018)	13 CP mainstem of the lower branch	1900 – 1943	M	Mm³
	• Silva Hidalgo (2010)	37 CP for the lower branch	1950 – 2008	M	
Return Flows	• Gonzalez-Escorcia (2016)	13 CP mainstem of the lower branch	1900 – 1913	-	%
	• Loredo-Rasgado (2018)	13 CP mainstem of the lower branch	1900 – 1943	-	%
	• Silva, H. (2008)	37 CP for the lower branch	1950 – 2008	M	Mm³
Temperature	• PRISM	13 CP mainstem of the lower branch	1900 – 2010	M	°C
	• ERIC	13 CP mainstem of the lower branch	1935 – 2010	M	
Evaporation	• IBWC/CILA/CONAGUA	14 reservoirs and 2 international	1935 – 2010	D	Mm³
	• Loredo-Rasgado (2018)	reservoirs	1916 – 1943	M	
Precipitation	• PRISM	13 CP mainstem of the lower branch	1900 – 2010	M	Mm³
	• ERIC	13 CP mainstem of the lower branch	1935 – 2010	M	
Latitudes	CONAGUA		-	-	degrees
Reservoir Storage	• IBWC/CILA/CONAGUA	14 reservoirs and two international	1916 – 2010	D	Mm³
	• Loredo-Rasgado (2018)	reservoirs	1916 – 1943	M	

D – Daily, M – Monthly, Mm³– Million cubic meters

2.1.3. Streamflow Completion Techniques

a) QPPQ

Natural streamflow completion techniques such as the QPPQ method [40] were used to fill gaps when ungagged data was incomplete for specific periods for control points located in series. Gaps were estimated by transferring streamflow data at reference gauges with complete data to ungauged or incomplete gauges.

The reference gauge should be unaltered and similar to the incomplete gauge location. The QPPQ method uses flow duration curves and relies on the assumption that exceedance probabilities are equivalent between the reference gauge and the incomplete data gauge, and then it transfers the flow at the incomplete control point using the estimated flow-duration curves.

b) Temporal Downscaling

A deterministic fractal-multifractal (FM) method is used for the temporal downscaling of monthly natural streamflow to daily time series. The FM method relies on finding a set of parameters that accurately represent the geometry of complex natural patterns (Maskey, Puente, & Sivakumar, 2016; Puente, 2004) generating daily time series over a monthly accumulated information, while preserving key statistical measures. The FM method has been used to model and downscale streamflow (Mahesh L Maskey, Puente, & Sivakumar, 2016), temperature (Mahesh Lal Maskey et al., 2016), rainfall (Maskey, Puente, Sivakumar, & Cortis, 2016) and groundwater movement (C E Puente, Robayo, Diaz, & Sivakumar, 2001) . In this study, the FM method is used in streamflow gauges. The process for temporal downscaling consists of two steps: (1) fitting FM models to obtain a portfolio of parameters that adequately represent the geometry of a given year, and (2) temporal downscaling of monthly data into daily streamflow data using the closest geometry between the naturalized streamflow data and the FM simulations.

In the first step, a single gauge station is selected. Then for each year containing daily data of naturalized flows available, a FM model is fitted to obtain a collection of 100 FM parameters that resembles the geometry of the normalized natural streamflow data. The model uses 365 or 366 bins for computing the output measure, a smoothing parameter, and two penalties in the monsoon months of June and September. The penalties ensure that the model matches the cumulative volume of the estimated naturalized flows on those months to guarantee that the FM solutions share similar geometric features with the estimated data set. Each FM simulation is evaluated using a scoring method that ranges from 1 to 4, with 1 being the best score possible. The scoring method includes (1) statistical indices including the annual volume, the median of dry months, and the timing and magnitude of peak flows and (2) a visual inspection of the magnitude and timing of baseflows and peak flows. In the second step, a nested RMSE analysis is performed to disaggregate monthly to daily data. The first RMSE analysis compares the cumulative curves between a year with monthly data to every year with daily data. The daily year that results with the smallest RMSE solution is selected as the template to disaggregate. After the pair of the daily and monthly years is identified, a second RMSE is performed between the cumulative curve between the year with the monthly data and the 100 FM parameters of the selected year. The FM parameter with the smallest RMSE solution is selected as the geometry of the hydrograph and the monthly data is disaggregated. Statistical measures were calculated to validate this approach and select the most adequate streamflow geometry.

2.1.3. Data Validation and Selection

Lastly, a comparison of the average estimated natural flows and the available studies of Orive de Alba [38], Loredo-Rasgado [37], and Blythe and Schmidt [33] were assessed using the statistical analysis from Moriasi et al. [41] to validate our calculations. The goodness of fit criteria used in this study were the coefficient of determination (R2), index of agreement (d), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS). In addition, the statistical performance was evaluated using the criteria in the study of da Silva et al. [42].

2.2. Determination of Functional Flow Components

The determination of functional flow components applied a signaling processing method to identify ecological flow transitions that support key biological, geomorphic, and biogeochemical processes in riverine systems (Escobar-Arias and Pasternack 2010; Yarnell et al. 2015). Eight control points are selected for this section of the case study, four located in the mainstem of the RGB, namely San Marcial, El Paso, Above Amistad, and Anzalduas, and four located at the outlets of the sub-basins of the Rio Conchos, Pecos

River, Rio Salado, and Rio San Juan. We considered that these control points represent the overall condition of the whole RGB basin (Figure 1). To identify ecological significant flow transitions from the annual hydrograph, this study applied the Functional Flow Calculator which is a signal processing approach to identify functional flows found in the highly seasonal Mediterranean streams of California, USA. The Functional Flow Calculator code was developed by Patterson et al. (2020) and it identifies four functional flow components applicable to California's natural streamflow regimes: fall pulse flow, wet season flow (encompassing both wet season baseflow and peak flow conditions), spring recession, and dry season baseflow (Fig. 1). Once the timings of functional flow transitions are identified from the annual hydrograph, each functional flow component can be further quantified using additional flow metrics such as magnitude, timing, frequency, duration, or rate of change, and can be used to design functional flow regimes in managed river systems (Yarnell et al. 2020). In this study, the code was modified for parameters to suit the hydrology of the RGB, specifically the timing of the functional flow components of the dry season baseflow and the wet season, and two components were included: a summer pulse and monsoon peak flows. Lastly, any existing flow criteria and data from previous studies that might provide insights into flow-ecology relationships for the study area was collected.

3. Results

3.1. Natural Streamflow estimations

3.1.1. Streamflow completion techniques - Temporal downscaling

Monthly to daily temporal downscaling from 1900 to 2010 has been completed for the Ojinaga gauge station of the Conchos basin. The additional gauge stations of San Pedro, Granero, Florido, Burras, and Conchos are still post processing. The FM approach showed different performance rates for each gauge and year, ranging from 10% to 85% of acceptance rate. Years with a high acceptance rate (Good runs >34%) are mostly related to normal years; in contrast, erratic or extremely wet or dry years will most likely show lower acceptance rates. The average acceptance rate was 24%. **Figure 1** illustrates results obtained from a single gauge station for two distinctive years, 1944 (top row) and 1930 (low row). The observed data are plotted in black, and the best FM fits in red. The data of 1944 had available daily records, which were used to "train" the FM model to get 100 different FM parameters. One of the 100 FM parameters for a year with daily data is used to downscale the year 1930, which only had monthly natural streamflow data. The goodness of fit criteria between observed daily data and the FM representation is the Pearson's Correlation (r), coefficient of determination (R2), index of agreement (d), and the Root Mean Squared Error (RMSE). The performance for the year 1944 and 1930 were very good $r = 0.99$ and 0.85; $R2 = 0.99$ and 0.92; $d = 0.99$ and 0.71, and satisfactory for the $NRMSE = 0.51$ and 0.22, respectively.
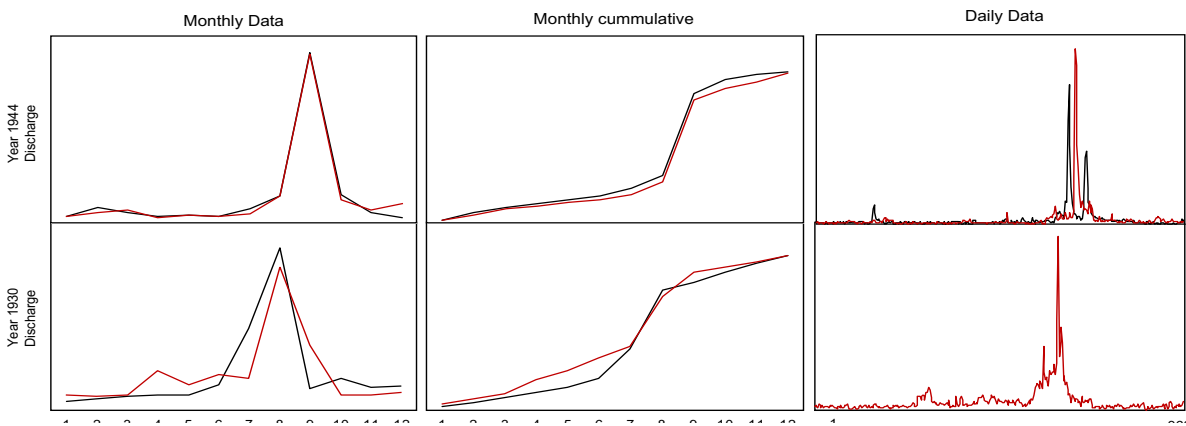

Figure 1. Monthly, monthly cumulative and daily streamflow records at the Ojinaga station for the years 1944 (top row) and 1930 (low row). Observed data is depicted in black and FM representations in red.

3.1.2. Daily Natural Flows for the Rio Grande – Bravo Basin and Natural Streamflow Validation

A comparison between the average annual natural flow estimations of this study (Garza-Diaz) and three available studies is observed in Table 2. For the study of Orive de Alba [38], we compared the period of 1900 to 1943, for the control points of Rio Conchos, Rio Salado, Rio San Juan, and Anzalduas. Then, we compared the period of 1900–1944 of the control points of Rio Conchos, Pecos River, Above Anzalduas, Rio Salado, Rio San Juan and Anzalduas from Loredo-Rasgado [37]. Lastly, we compared the period of 1900–2010 of the control points of Rio Conchos, Pecos River, Rio San Juan and Anazalduas with Blythe and Schmidt [33]. Results indicate a very good statistical performance for R^2, NSE, d (≥ 0.9) and for PBIAS ($<\pm10$). These values are considered indicative of acceptable estimations of the natural flow. Overall, and according to this study the total natural flow availability of the RGB between 1900 to 2010 is 11,226 Mm^3.

Table 2. Average annual natural flow estimation from 1900 to 2010 of the Rio Grande-Bravo basin, a comparison between available studies.

CONTROL POINTS	GARZA-DIAZ 1900-2010	BLYTHE 1900-2010	GARZA-DIAZ 1900-1943	ORIVE 1900-1943	LOREDO 1900-1943
Above Presidio	2406	2507	2070		2323
Rio Conchos	2149	2043	2042	2045	2050
Below Presidio	4619	4584	4249		
Alamito (1934)	17		34		
Terlingua (1934)	48		51		
Alamito and Terlinuga					75
Johnson	4611		4189		
Foster	4898		4446		
Manantiales	245		123		126
Pecos River	632	1500	789		1054
Devils	452	492	536		541
Amistad Inflows	6231		5895		
Acuña	6371		6108		
San Felipe	74		61		
Pinto Creek	19		22		
San Felipe and Pinto Creek	93		83		85
Las Vacas, San Diego, and San Rodrigo	354		349		555
Piedras Negras	7143		7343		
Escondido	69		81		92
Las Vacas, San Diego, San Rodrigo, and Escondido	423		430	418	647
Nuevo Laredo	7406	7407	7625		
Salado	974	1212	980	925	859
Sum Afluentes USA (Pecos, Devils, Manantiales, Terlingua, Alamito, San Felipe and Pinto Creek)	1487		1616	2180	1806
Sum 6 Afluentes Mx (Conchos, Las Vacas, San Diego, and San Rodrigo, Escondido, Salado)	3546		3452	3388	3556
Falcon Inflows	8399		8445	9809	

Alamo	176		188		216
San Juan	2009	1075	1626		1523
Alamo and San Juan	2185		1814	1557	1739
Rio Grande City at Camargo	10607		10418		
Anzalduas	11226	11243	10418	11366	
Incremental Flows	1179		528	867	1290
Total RGB	**11226**	**11243**	**10418**	**11366**	**10789**

3.2. Determination of Functional Flow Components and Functional Flow Metrics

Five functional flow components were identified for the RGB (Figure 2): dry season baseflows, a wet season, snowmelt flow, summer pulse, and monsoon peak flows. This particular flow regime is driven by the snowmelt of high elevation snowpack headwaters and the North Pacific monsoon. However, depending in the location of the RGB, some tributaries might lack the snowmelt or the monsoon signature. San Marcial and El Paso are strongly influenced by the snowpack headwaters and only show results for dry season baseflows, wet season, and snowmelt flow. The Rio Conchos, Pecos River, Rio Salado, and Rio San Juan are influenced by the North Pacific monsoon, therefore results include dry season baseflows, wet season, summer pulse and the monsoon peak flow. Then, the control points of Above Amistad Dam and Anzalduas, which are at the mainstem below Rio Conchos have a bimodal river flow signature, which are a mix between snowmelt and monsoon driven tributaries showing the six functional flow components.
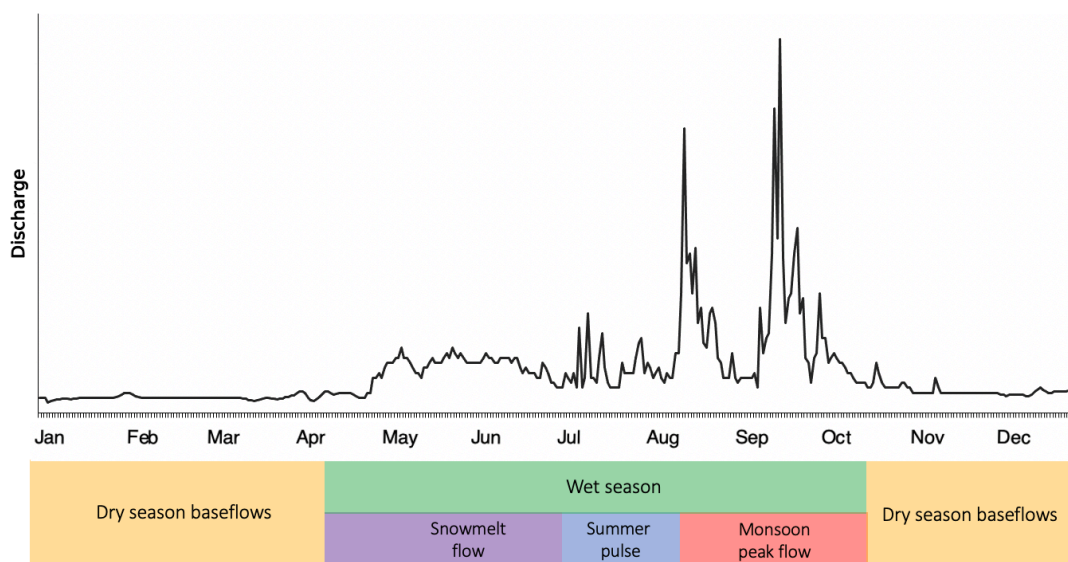

Figure 2. Functional flows components and reference flow characteristics of the Rio Grande-Bravo basin (Above Amistad reference hydrograph).

Then, for each functional flow component, the functional flow metrics based on the magnitude, timing, duration, rate of change, and frequency are observed in Table 3 and vary between components based on the importance of the metrics. Dry season baseflows metrics include magnitude 50 and 90, timing and duration. The summer pulse metrics include magnitude and timing. Monsoon peak flows metrics include peak magnitude, peak timing, timing, and duration. Wet season metrics include magnitude 10, 50, and 90, timing, and duration. And, snowmelt flow metrics include magnitude 50, timing, duration, peak magnitude, and rate of change.

Table 3. Functional flow metrics of the Rio Grande – Bravo basin for eight control points.

Functional Flow Component	Functional Flow Metric	San Marcial	El Paso	Above Amistad	Anzalduas	Rio Conchos	Pecos River	Rio Salado	Rio San Juan
Dry season baseflows	Magnitude 50	2	3	7	13	1	1	1	1
	Magnitude 90	3	4	10	21	3	1	2	3
	Timing	315	318	319	327	320	322	337	334
	Duration	135	133	136	139	212	153	149	133
Summer pulse	Magnitude	0	0	90	168	8	2	3	6
	Timing	0	0	151	154	166	107	116	100
Monsoon peak flow	Peak Magnitude	0	0	157	255	94	31	40	106
	Peak Timing	0	0	228	230	249	217	212	232
	Timing	0	0	195	196	237	185	179	187
	Duration	0	0	123	131	206	194	188	194
Wet season	Magnitude 10	1	1	11	19	2	1	1	2
	Magnitude 50	3	4	21	34	8	2	3	6
	Magnitude 90	7	8	35	66	31	5	9	20
	Timing	197	199	89	99	166	107	116	100
	Duration	124	124	230	228	153	213	217	235
Snowmelt flow	Magnitude 50	13	13	21	34	0	0	0	0
	Timing	91	91	89	99	0	0	0	0
	Duration	106	109	109	107	0	0	0	0
	Peak Magnitude	27	28	0	0	0	0	0	0
	Rate of Change	0.07	0.06	0.2	0.1	0	0	0	0
	Avg	6	7	17	31	6	2	3	6
	CV	1	1	1	1	2	1	2	2

Lastly, Table 4 and Figure 3 and Figure 4 includes results of the physical, biogeochemical, and biological ecosystem functions and processes per functional flow components. Data and information were collected from literature review and expert opinions including the associated flow characteristic of magnitude, timing, duration, rate of change and frequency.

Table 4. Summary of the five functional flow components, their associated ecosystem functions and processes, and corresponding flow metric indicator of the Rio Grande – Bravo basin.

| Functional Flow Component	Ecosystem Function Type	Function/ Process	Associated Flow Characteristic	References
Dry-season baseflow	Physical	Sediment accumulation on the channel bed	M, D	Dean et al., 2011; Escobar-Arias and Pasternack, 2010
		Maintain water table levels and soil moisture	M, D	Postel and Richter 2003
	Biogeochemical	Nutrient enrichment concentration	M, D	Ning et al., 2010
		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
		Enhanced growth rates of planktonic algae, followed by rapid growth and turnover of zooplankton	M, D, T	Humphries et al., 2020
		Concentration of prey for native predators	M, D, T	Ning et al., 2010
		Maintain habitat patches for reproduction of native fishes	M, D, T	Falke et al., 2010; Gido and Propst 2012
		Fish establishment and defending of nests	M, D	WWF 2009
Summer pulse 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 peak flows	Physical	Channel reset, avulsions, and braiding	M, D, F	Ashworth et al., 2004; Harrison et al., 2011; Swartz et al., 2020
		Meander migration and cutoffs	M, D, F	
	Biogeochemical	Increase in soil microbial response and flux of carbon and nitrogen pools	M, T, F	Austin et al., 2004
		Deposit nutrients on floodplain	M, D	Postel and Richter 2003
	Biological	Growing period for riparian plants	M, D, T, R	Williams et al., 2006
		Removal of generalists and survival of native species	M, D	Heard 2012
		Insect larvae coloniztion	M, D	Kimura 2011
Wet season high flows	Physical	Mainteined 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 large quantities of fine sediment	M, D, R	Dean et al., 2016
		Morphodynamic 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 prolongued low flows	M, D	Postel and Richter 2003
	Biological	Flowering, fruting and seed dispersal	M, D, T	Simonin, 2000
		Drifting and dispersal of eggs and laevae	M, D, R	Humphries et al., 2020
		Reduction of predator density	M, D	Postel and Richter 2003
Snowmelt flows	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 outmigration and spawning; rearing	M,T,R	Yarnell et al 2020
		Seedling survival	M, R, D	Bhattacharjee(2006)
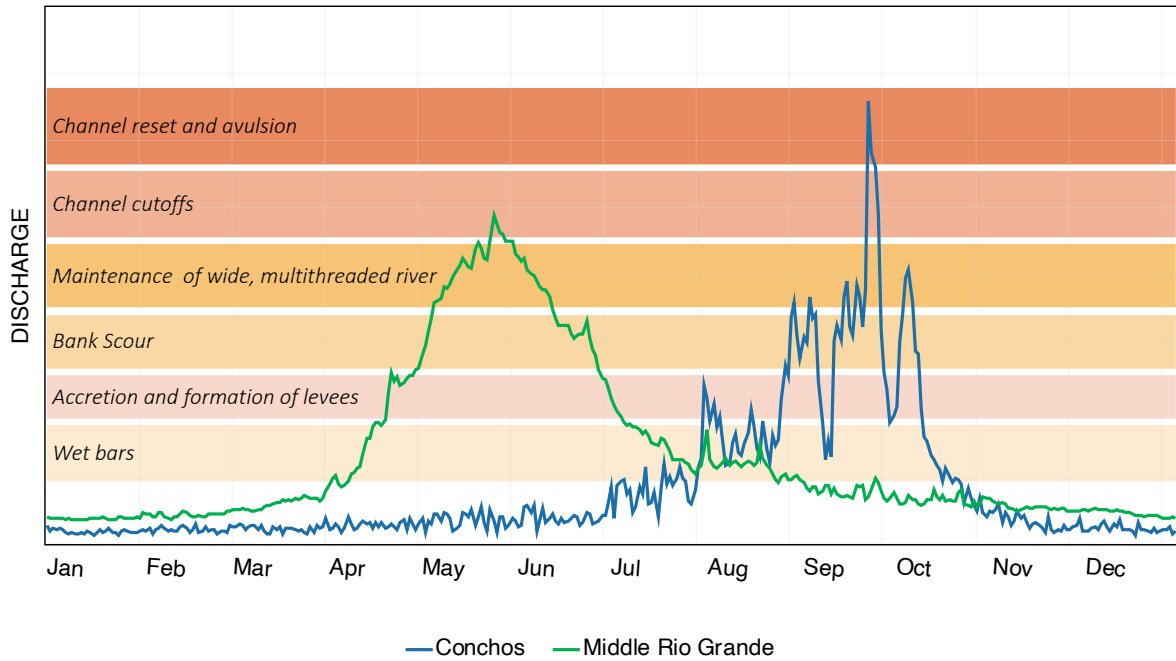
Figure 3. Abiotic responses for the snowmelt flow regime of the Middle Rio Grande and for the hurricane-driven flow regime of the Conchos River.
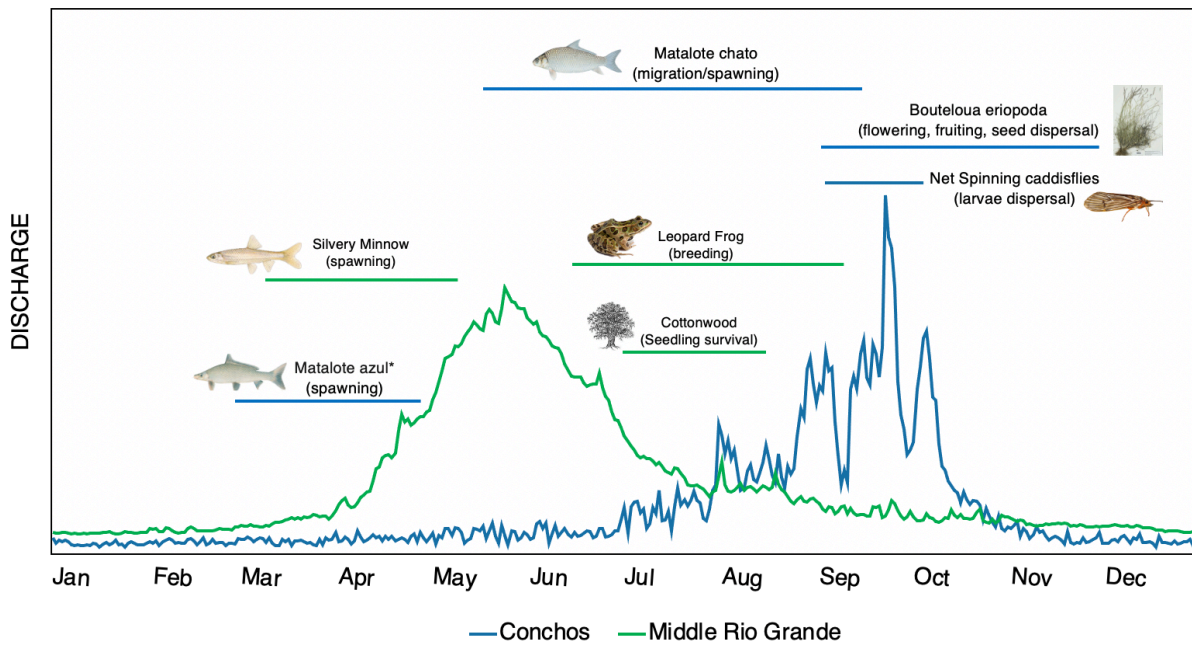

Figure 4. Biotic responses for the snowmelt flow regime of the Middle Rio Grande and for the hurricane-driven flow regime of the Conchos River.

4. Discussion

4.1. The Functional Flow Components of the Rio Grande – Bravo Basin

Building on previous instream flows and environmental flow research studies of Chapter I, and the growing recognition that ecological functions are inherent in the resilient adaptive capacity, functionality, and biodiversity of riverscapes, this study proposes five essential functional flows of the transboundary Rio Grande – Bravo basin that support physical and biotic processes for the snowmelt driven tributaries, the monsoon driven tributaries, and the bimodal driven tributaries.

Dry-season baseflow: *flows sustained by groundwater discharge to rivers.*
Dry-season low flows are of great importance to native and endemic species that rely on dry conditions for their life strategies. The average duration of dry low flows lasts approximately from 4 to seven months, from the beginning of November to the mid-end of May and an average flow magnitude of 2.5 million cubic meters (mcm) for the snowmelt driven tributaries, to 1 mcm for the monsoon driven tributaries and up to 10 mcm for the bimodal portion of the RGB. Low flow periods are characterized by sediment accumulation, low flow velocities, and vegetation establishment. Temporary and seasonal standing waters provide essential habitat and refugia for native and opportunistic species, including zones to hunt, burrow, or nest. In addition, water quality requirements, including elevated water temperatures, are essential for spawning, reproduction, and life-cycle development.

Summer pulse flow: *first major storm event that leads to the start of the monsoon season.*
The transition from dry season to the wet season begins with the North Pacific monsoon's first storms typically initiating from mid-May and July. This first pulse of stormwater has a magnitude of 130 mcm for the bimodal driven tributaries and 5 mcm for the monsoon driven tributaries. This flow introduces high loads of suspended solids and nutrients. The timing and magnitude of flow determined by the pulse are essential for life-cycle cues such as migration and spawning.

Wet-season high flows: *flows sustained by prolonged rains caused by snowmelt or tropical depressions.*
Concentrated high flows occur during the beginning of the snowmelt flows or at the beginning of the summer pulse. These flows are instrumental in altering floodplain and channel morphology and are essential for maintaining wide and multithreaded streams, which will increase the movement and dispersal of riverine species at a more extended scale. Some riverine fishes spawn in specific locations for their eggs and or larvae to disperse downstream and laterally; the same applies for seed dispersal.

Monsoon peak flows: *large magnitude peak flows in the wet-season*
Peak magnitude discharges occur within the natural season of the monsoon. The periods where monsoon peak flows occur typically start at the hurricane season from mid-July to mid-August and end at the end of September. These flows have on average a magnitude of 200 mcm but in extraordinary events peak flows can have discharges of >1000m3/s and occur at a frequency of 10-15 years. Floods of this magnitude can completely reconfigure the geomorphology of the ecosystem by resetting and rewidening the river. During flooding, floodplains enrichment happens by the deposition of organic matter and soil nutrients. The timing of the peak magnitude floods is vital to life-history strategies to survive and provide ecologic cues for migration and spawning of native species.

Snowmelt flow: *flows sustained by snow melting runoff*
Snowmelt flows dominate from rivers emerging from snowpack headwaters. These flows begin in spring during late March or beginning of April and have an average duration of 110 days. These flows can provide the annual total flow in high-elevation basins where the snowmelt pulse typically correspond to the annual peak flow. However, in systems subject to monsoon events, such as tropical storms and hurricanes, the annual peak flow usually corresponds to the extreme monsoon event. These flows can have a discharge volume of 264 m3/s. The timing and rate of change provides distinctive cues for reproduction

and migration and the spring recession which is the gradually receding flows have primary ecologic drivers in population dynamics of native species.

5. Conclusion

The adaptive capacity of a river basin is defined in this study as the property of a river systems to modify ecological resilience to cope with disturbances. Hydrologic variability is a key principle to ecological resilience – the capacity of ecosystems to adapt to shocks and shifts while preserving desired functions and services. Which in river basins is defined by the natural flow regime. The natural flow regime is master variable of rivers as the components of magnitude, frequency, timing, duration, and rate of change determine the hydrologic regimes of a system. In the RGB three types of flow regimes classes were identified: the snowmelt flow, the monsoon flow, and the bimodal snowmelt-monsoon flow. Each of these regimes have distinctive patterns of structures, functions, and processes that define ecosystem functioning namely functional flow components which are quantified using the five metrics of the natural flow regime. To describe the three types of flow regimes in the RGB, five functional flow components were defined: the dry-season baseflows, flows sustained by groundwater discharge to rivers; the wet season, flows sustained by prolonged rains caused by snowmelt or tropical depressions; the summer pulse, first major storm event that leads to the start of the monsoon season; the monsoon peak flows, large magnitude peak flows in the wet-season; and the snowmelt flow, flows sustained by snow melting runoff. The quantification of the functional flows in the RGB is the first study, to the author's knowledge, to provide instream flow requirements, which consider ecological water needs for the RGB as a whole. These instream flows are key for determining environmental flows as they define a set of initial flow targets for flow regimes that balance human and ecosystem water needs. The quantification of the adaptive capacity in the RGB provides a fundamental strategy to manage for ecosystems to prevent regime shifts or to modify basins of attraction to a suitable system for ecological resilience and sustainability.

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CONCLUSIVE REMARKS

River basins are complex social-ecological systems (SES) that are inextricably linked with hydrological, ecological, socioeconomic, and institutional components. These SES are central to the genesis, prosperity, and development of many ecosystems and societies. However, the near-ubiquitous anthropogenic activities in river systems (e.g., reservoirs, agricultural expansion, land-use change, water compacts, and treaties) and the accelerated climate changing conditions (e.g., extreme events such as droughts and floods) pose environmental and socioeconomic hardship, including the unwanted consequences of altering natural systems beyond their resilience capacity. The concept of resilience is now used in a variety of interdisciplinary work concerned with the interactions between people and nature. Given that the property of resilience is the magnitude of disturbance that can be tolerated before a socio-ecological system (SES) moves to a different region of state space controlled by a different set of processes, practitioners such as researchers, environmentalists, water managers, and politicians have repeatedly asked how resilience, and trends in resilience, can be measured for particular SES. The main problem is going from the metaphor to the measurement of ecological resilience. This dissertation addresses this limitation by developing an ecological resilience assessment framework for river basins. The framework quantifies three resilience surrogates; alternative regimes, thresholds, and adaptive capacity, and is assessed in the transboundary river basin of the Rio Grande-Rio Bravo.

Chapter 1 dives into analyzing the transboundary Rio Grande-Rio Bravo basin. This water-scarce basin full of extreme climate conditions, shared between two countries and eight states, was reviewed as an SES and considered a whole-basin perspective under the lens of environmental flows. The Rio Grande/Bravo basin has experienced a long history of human manipulation and ecosystem degradation. It underpins the need for a change in thinking, practice, and implementation of environmental management strategies by switching to a whole-basin thinking perspective to help find common ground solutions to implementing sustainable strategies in the Rio Grande/Bravo basin such as environmental flows.

The overall human central management of the RGB raises awareness of three main management drawbacks: (1) the fragmented view of a shared transboundary basin as "my land, my water". (2) The assumption that river basin responses to human use and management are linear, predictable, optimal, and controllable. (3) The disconnection between the human and natural aspects of this SES, which are treated independently. Ecological resilience theory suggests that natural and social systems behave in nonlinear ways, exhibit marked thresholds in their dynamics, and that social-ecological systems act as strongly

coupled, complex, and evolving integrated systems which are affected by natural and anthropogenic perturbations.

Chapter 2 explores the RGB's hydrologic natural dynamics, where synchronous and asynchronous wet and dry periods occur throughout different locations within the basin. The cyclical hydrologic periods disappear in the modern RGB, and a perennial drought state is the common denominator throughout the basin. The perennial drought can be described as an anthropogenic megadrought, a compound multidimensional and multiscale phenomenon governed by the combination of natural water variability, human decisions, increased water use for human activities, climate change, and altered microclimate conditions due to changes in land and water management. Alternative regimes of the RGB are demonstrated in the form of basins of attraction, where two states were identified: (1) a dry state portrayed as a constricted-deep basin of attraction located in the persistent dry zone; and (2) a wet state located portrayed as a shallow-wide basin located in the persistent wet zone. However, the erosion of ecological resilience has changed the stability landscape of the RGB for a single wide-deep basin of attraction located in the persistent dry zone. The loss of ecological resilience demonstrated in Chapter 2 can lead to vulnerability, uncertainty, and environmental surprise to the SES. Once the stability landscapes are observed, the following steps are identifying resilience thresholds and early warning signals which provide input to assessing the resilience erosion, carrying capacity, and the magnitude of shock the system can absorb. Chapter 3 identifies how much accumulated perturbations for several locations in the basin are needed for a system to cross a resilience threshold. Thresholds and regime shifts allowed us to identify periods where perturbations were absorbed, and the current conditions preserved the natural dynamics. These periods can provide baseline conditions where human and economic development and the natural flow regime coexist. Moreover, identifying mechanisms under which regime shifts occurred, including safeguards and early warning signals for upcoming changes, are essential to incorporate into environmental modeling, monitoring, and assessment of management practices.

And finally, Chapter 4 explored the adaptive capacity by determining the functional flows of the RGB as: dry season baseflows, a wet season, snowmelt flow, summer pulse, and monsoon peak flows described by functional flow metrics. The results provide an ecologically relevant matrix that links ecological, biological, biogeochemical, and geomorphic functions to discrete aspects of the natural flow regime that can be directly linked to key bioindicators and used as instream flows. These results have a two-folded implication 1) it can help to bring the seasonal and interannual variation that allows for recovery of the resilience system dynamics of the river basin. And 2) the functional flow approach adds a set of instream flows throughout the basin, keeping a whole-basin perspective.

This body of knowledge uses resilience theory at its core and defines the methods to bring resilience theory into practice while allowing to define strategies for instream flows, resilient flow regimes, identifying human-induced megadroughts, and early warning signals for regime shifts. As a contribution to the advancement of water management in the RGB this dissertation provides 110 years of daily streamflow data, which is necessary for water budgets, flow regime analysis, water management strategies, estimation of historical water use, revision of historic treaty water availability, and sustainable allocation of water resources.

Overall, water is a cross-cutting issue; managing common-pool resources in a transboundary context requires a coupled understanding of both the natural system's reorganization response and adaptive capacity, including the basin's water governance institutions of learning, cooperating, adapting, and ultimately transforming. Unlike other management approaches, this approach looks at water challenges through a fresh lens; it is simple and flexible enough to assess the resilience of different water basins worldwide on a local, regional, and transboundary scale. Managing water resources for resilience enhances the likelihood of sustaining development in a changing world where surprise is likely. A changing, uncertain world in transformation demands action to build the resilience of the social-ecological systems, and it can be accomplished through resilient and adaptive strategies that harmonize the use of shared natural resources in a transient and dynamic ecosystem.

GLOSSARY

Term	Definition	Reference
Engineering Resilience	Engineering resilience focuses on the return of structural and functional attributes of systems to pre-disturbance conditions following a disturbance. Rapid return times are interpreted as reflecting high engineering resilience	Hashimoto et al., (1982) and Pimm, (1991)
Ecological resilience	The amount of change needed to change an ecosystem from one set of processes and structures to a different set of processes and structures. Resilience is an emergent property of ecosystems and recognizes multiple basins of attraction.	Holling, (1973) and Walker, Holling, Carpenter, & Kinzig, (2004)
General Resilience	In ecological resilience: The capacity of social-ecological systems to adapt or transform in response to unfamiliar, unexpected and extreme shocks of all kinds, including novel and unforeseen ones, without changing state.	Carpenter et al., (2012)
Specified Resilience	In ecological resilience: The resilience of a specific system or component of a system to a particular control variable to one or more identified shocks.	Carpenter et al., (2001)
Ecological resilience for freshwater systems	The capacity of ecosystems to collectively adjust and adapt to shifting and potentially novel environmental conditions while preserving desired functions, species, and services.	Grantham, Matthews, & Bledsoe, (2019)
Alternative state/regime	An attribute in the ecological resilience. A potential alternative configuration in terms of abundance and composition, function and process, of a system.	Angeler & Allen, (2016)
Thresholds	An attribute in the ecological resilience. Thresholds indicate that ecosystems can undergo a shift between alternative states when critical disturbance levels are surpassed. Are equivalent to tipping points and may be detected as discontinuities or bifurcation points in complex systems.	Groffman et al., (2006)
Adaptive Capacity	An attribute in the ecological resilience. The "constant adjustment" of ecosystem properties, including community composition and function to changing environmental conditions	Carpenter, Walker, Anderies, & Abel, (2001)
Scale	An attribute in the ecological resilience; the hierarchical organization of a system wherein structures, functions, and processes are compartmentalized by distinct scales of space and time	Angeler & Allen, (2016)
Regime	A set of states that a system can exist in and still behave in the same way—still have the same identity (basic structure and function). A regime can be thought of as a system's basin of attraction.	Walker & Salt, (2012)
Regime shift	When a system crosses a threshold into an alternate regime of that system.	Walker & Salt, (2012)

| Basin of attraction | All the stable states of the system that tend to change toward the attractor. An attractor is a stable state of a system, an equilibrium state that does not change unless it is disturbed. | Walker & Salt, (2012) |
| Stability Landscape | A hypothetical figure that reflects the various basins of attraction that a system may occupy, and the boundaries that separate them. | Walker, Holling, Carpenter, & Kinzig, (2004) |

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