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Resilience Changes in a River Basin: Identifying Hydrologic Regime Shifts Using Long-term Streamflow Data

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Abstract

River basins are unique dynamic systems shaped by hydrologic variation patterns that can adapt and thrive to changes in hydrologic patterns over time. River basins are resilient systems that can adapt and thrive to changes in hydrologic patterns over time and absorb disturbances. Persistent forcing, either natural or anthropogenic, can bring the system to a critical threshold or limit, causing undesirable regime shifts or ecosystem switching to an alternative state. How ecosystems react to perturbations is a central question in ecology today because these can cause catastrophic, undesirable, and even irreversible changes in natural systems. This study addresses how much forcing a river basin can take until the system undergoes a regime shift and into an alternative state? As a representative case, the Rio Conchos is selected. Resilient indicators for quantitatively assessing resilience require long-term records sampled as temporal and spatial scales. This study analyzes years of daily natural flows from 9 to 2010. First, the hydrologic variability of a river basin is analyzed to describe the hydrologic states or basins of attraction of the naturalized system compared to a regulated system using the Streamflow Drought Index (SDI). Second, the detection of regime shifts is captured by the quantitative indicator Fisher information, followed by quantifying anthropogenic pressures that have caused the shift. Preliminary results indicate that a resilience threshold was surpassed, and a regime shift occurred in the control point of the Rio Conchos subbasin after three substantial anthropogenic perturbations occurred by 9 8.

Keywords: river basin, regime shifts, thresholds, alternative regime, resilience

1. INTRODUCTION

River basins are unique dynamic systems shaped by hydrologic variation patterns that can adapt and thrive to changes in hydrologic patterns over time. As resilient systems, river basins are self-organizing systems able to absorb disturbances, reorganize, and continue to perform their function in response to changes. Moreover, river basins are considered unique social-ecological systems consisting of hydrological, ecological, socioeconomic, and institutional components that are inextricably linked as the pillars of human development and environment interaction. Given its complexity and the various ecosystem services provided by large river basins, widespread development and modifications of river basins have resulted in highly stressed water ecosystems and societal dependence on engineered services (Cosens and Fremier, 2014). In addition, to the escalating pressures of climate change that have affected river basins resulting in prolonged droughts and floods which affect water availability and water security. From both analytical and management perspectives, it is important to understand the ecological capacity of a river basin and identify how much anthropogenic pressure a river basin can absorb before undesirable regime changes occurs.

This idea traces back to the theory of resilience, a term that describes the property of a system to organize into discrete stable states or regimes, in which perturbations may result in pushing a system from a regime shift into an alternative state (Holling, 1973). Persistent forcing, either natural (e.g., extreme hydrologic events, climate change) or anthropogenic (e.g., impoundments, land-use change, increasing water demand), can bring the system to a critical threshold or limit, causing undesirable regime shifts or ecosystem switching to an alternative state. Meaning that the system exists in a new state but still has the same identity. For instance, it's important to put emphasis on thresholds of systems because crossing them can cause catastrophic, undesirable, and even irreversible changes in natural systems (Sutherland et al., 2013).

Perturbations may produce a displacement and an underlying change to the stability landscape of the hydrologic system, a hypothetical state of the system with the boundaries that separate state regions (basins of attraction) in which the system tends to remain (Walker et al., 2004). Although the work on resilience has been influential, the literature has long remained mostly conceptual; thus, there is a need to use quantitative methods for estimating resilience is needed to understand the effects of rapid global change on complex natural systems (Scheffer et al., 2012). To bridge ecological theory with water resources management, the objective of this study is to determine when does a river basin reaches a resilience threshold and suffers a regime shift and calculate how many anthropogenic disturbances the river basin absorbs before changing to a new regime.

2. CASE STUDY

As a representative case, the Rio Conchos basin is selected given that it is subject to a wide range of environmental, socioeconomic, and climatic challenges under a complex political climate. From a combination of highly variable climatic conditions and increased anthropogenic pressure, The Rio Conchos Basin is one of the most important hydrologic regions in northern Mexico and one of the most important tributaries of the transboundary basin of the Rio Grande-Bravo, it bring the RGB back to life because it supplies more than 70 percent of the RGB flow at Ojinaga. This basin originates in the arid Tarahumara range in the Sierra Madre Occidental. It has a drainage area of 71,964 km2, a mean altitude of 2,300m, and annual precipitation ranging from 700 to 200 mm with a strong influence of the North American monsoon. The historical basin runoff is 2,442.6 million m3, of which 44% of this volume is produced in the upper basin (CONAGUA, 2016). Like other river basins worldwide, water availability in the basin is highly impacted by the increased demand for food production, urbanization, degradation of water bodies, aquifer overexploitation, and climate change.

The Rio Conchos and its three main tributaries (Chuviscar, Florido, and San Pedro) are regulated by seven main reservoirs with a total capacity of 3,654 million m3. La Boquilla, Francisco I. Madero, and Luis L. Leon are the three main reservoirs that allocate water to five irrigation districts, industrial and domestic users, and binational water treaty delivery obligations. Besides, important Mexican cities such as Chihuahua, Hidalgo de Parral, and Delicias are overgrowing due to increasing industrialization. Increased water use regulation results in consistent perturbations in flow, reduction of hydrologic variability, and alteration of hydrological regimes with high risks on riverine ecosystems. Also, extreme hydrologic variability characterizes the basin, where long term dry periods can last on average 12 years. These concurrent dry periods are a component of the natural hydroclimatic variability of the basin, however, these are likely to increase as future projections show a 15 to 20% decrease in precipitation (Martínez-Montero, and Hernández-Ibáñez., 2017).

3. METHODS

To describe regime shifts in a highly regulated river basin, long-term natural, historical conditions are needed to contrast them to the regulated system. Therefore, streamflow naturalization is used in this analysis to convert gaged flows to natural flows that would have occurred in the absence of anthropogenic impacts such as reservoir development, water supply diversions, return flows, stream losses, and other factors (Wurbs, 2006). In this study, estimating daily natural flow at a selected gaging station consists of using the water budget to convert gaged flows to naturalized flows. Resilient indicators for quantitatively assessing resilience requires long-term records sampled as temporal and spatial scales of systems.

For instance, this study analyzes 110 years of daily natural flows in seven control points from 1900 to 2010. The gauge stations used are Jimenez, Colina, Villalba, Conchos, Las Burras, Chuviscar and Ojinaga. Once the naturalized and regulated streamflow time-series are available; the Streamflow Drought Index (SDI), a standard index that characterizes the severity of hydrological droughts (Nalbantis and Tsakiris., 2009), is used to evaluate and illustrate the hydrologic extremes of a basin. To calculate the SDI of the naturalized time-series, each gauge is aggregated into the desired time window e.g., 6-, 12-, 120-month periods. The hydrologic states will be described as extremely dry, dry, normal, wet, and extremely wet. Then, to calculate the regulated SDI, each gauge is correlated with the closest aggregated naturalized volume, and its corresponding SDI value is assigned. The SDI values for both natural and regulated systems are then used to evaluate regime shifts.

Detection of regime shifts is captured by the quantitative indicator Fisher Information (FI), a method used to collapse the behavior of one or multiple variables of a complex system into an index, showing the overall system dynamics, regimes, and regime shifts (Fath et al., 2003).To assess FI of the naturalized and the regulated systems, the natural and regulated SDI values are evaluated using the python package csunlab/fisher-information (Ahmad, et al., 2016).The model runs through a window of 12-month, a window increment of 1-month, and the default size of state. At last, the probability density of the SDI hydrologic states is additionally used to compute a hypothetical stability landscape representation of resilience along with its approximate shapes of basins of attractions. These representations will allow visualizing changes in a system's regime.

4. RESULTS AND DISCUSSION

Results focus on the outlet of the Rio Conchos Basin at the Ojinaga station. This gauge was selected to portray the accumulated representation of upstream dynamics and disturbances suffered by upstream sub-catchments. A regime shift analysis for the natural and regulated system using FI is shown in (Figure 1). The FI results for the natural streamflow system vary from 1 to 5. The boundaries to detect regime shifts are 1 and 4, given the two standard deviations from the mean threshold, these limits are also used to detect regime shifts for the regulated system. FI values for the natural system are relatively stable from 1910 to 1988. During this period, the system remains in between the two standard deviations limit from the mean. However, there is a shallow decrease from 1948 to 1969, after which the system appears to rebound. Four years (1921, 1947, 1974, 1986) surpasses the two standard deviations limit, with consecutive rebounds to their earlier states. After 1986, a steady decrease starts with smaller rebounds reaching in 2010, the lower limit of the two standard deviations with an FI of 1. The decrease in the FI trajectory after 1988 corresponds with periods of extreme hydrologic variability with consecutive and alternate trends of extremely wet to extremely dry periods. A Mann-Kendall non-parametric test for the entire period yielded a decreasing trend. These decreasing patterns may indicate a warning for an upcoming regime shift given that the system's instability is increasing.

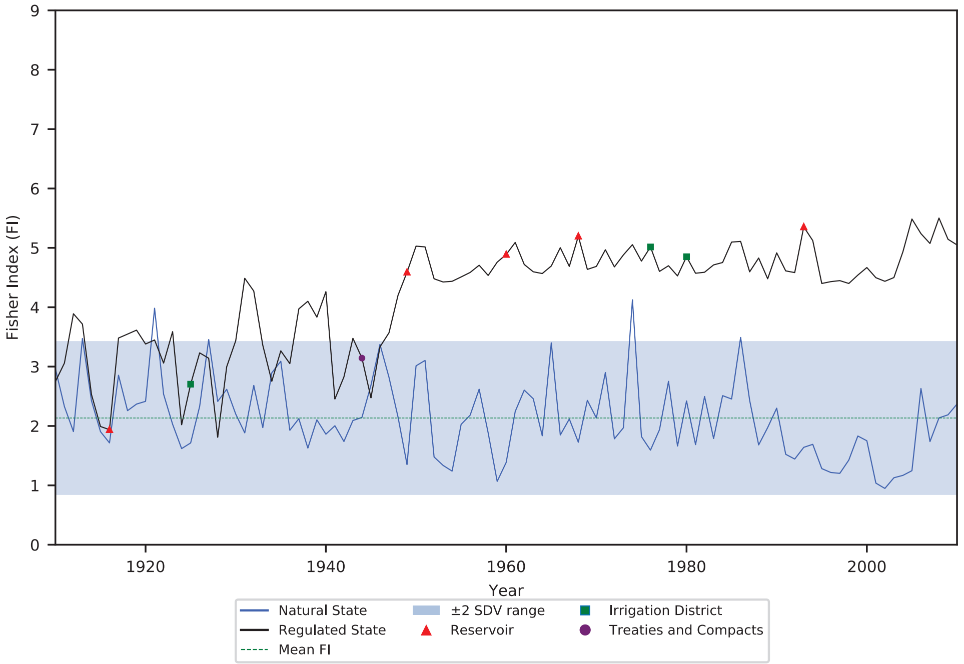

Figure 1. Fisher information results for the Rio Conchos comparing the natural state (blue line) and the regulated state (black line) and the upper and lower boundaries of the two standard deviation range (±2SDV range) from the mean FI (dashed green line). Perturbations along the regulated system appear as reservoirs, irrigation districts, and treaties or compacts.

As for the regulated streamflow system, results show volatile FI values ranging from 1 to 8. In which the system crosses the two standard deviation thresholds from the mean. Therefore, the system undergoes a regime shift after 1948. Four peaks appear outside the thresholds before 1948, but none moved the whole system outside of the thresholds. However, the last two peaks before 1948 indicate a strong perturbation, as they cross the upper limit by three units. The system appears to contain the perturbation as it bounces back inside the thresholds. The observation of these two large peaks suggests instability of the system to remain in the same state, and it is not until 1948 where the regime shift occurs, moving the system into a static and stable state. An increase in the system is related to dynamic order. However, it is not an indication that the system is moving toward a more humanly preferable state (González-Mejía et al., 2012). In this study, a sharp increase that reaches the upper or lower range of the FI without rebounds means a regime shift—in particular, shifting from an orderly dynamic regime to a steady static regime. Three perturbations are identified as the causes of a regime shift. First, the construction of La Boquilla dam in 1916, built to deliver water for irrigation District 005 Delicias and the international treaty. This event marks a sharp decline of the FI to -4. Second, the expansion of irrigation districts from 1934 to 1938 went from approximately 8000 hectares to 22,000 hectares in 1934, reaching a maximum of 40,000 hectares by 1938 (ID. Delicias, source). This agriculture expansion period aligns with sharp increases and decreases, with peaks of +4 and a 50% rebound. At this point, the system becomes highly variable and more sensitive to perturbations. Thrd, the construction of the Francisco. I. Madero dam was built in 1948 to deliver water to the expanded irrigation district. This third event is most likely the perturbation that transitioned the system to a new regime, going from an FI of 2 to a persistent 8. Several other anthropogenic perturbations maintained the system in this new regime as the construction of three more reservoirs: Luis L. Leon, Pico del Aguila and Chihuahua; in addition, to the development of two irrigation districts DR-103 Rio Florido, and DR-090 Bajo Rio Conchos.

The system's behavior exposed to strong perturbation regimes hints at underlying stability landscape features (Scheffer et al., 2012). The probability density distribution of a system can be used to reflect the stability landscape properties and how they change over time (Hirota et al., 2011). Hypothetical three-dimensional stability landscapes for the Rio Conchos basin were computed under a natural and regulated streamflow regime (**Figure 2**). Disturbances can shift the system from one basin of attraction to another, for clarity, the contours in the quadrant plate reflects the depth of the basins of attraction of the system. In the natural system (**Figure 2A**), two basins are identified: (1) a persistent dry zone, characterized by a constricted and deeper basin of attraction, and (2) a persistent wet zone is portrayed as a shallow and wider basin. In contrast, the regulated system (**Figure 2B**) only shows a persistent dry zone and only one wider and deeper basin of attraction. The stability landscape is depicted to demonstrate itself as dynamic and non-stationary, and basins of attraction.

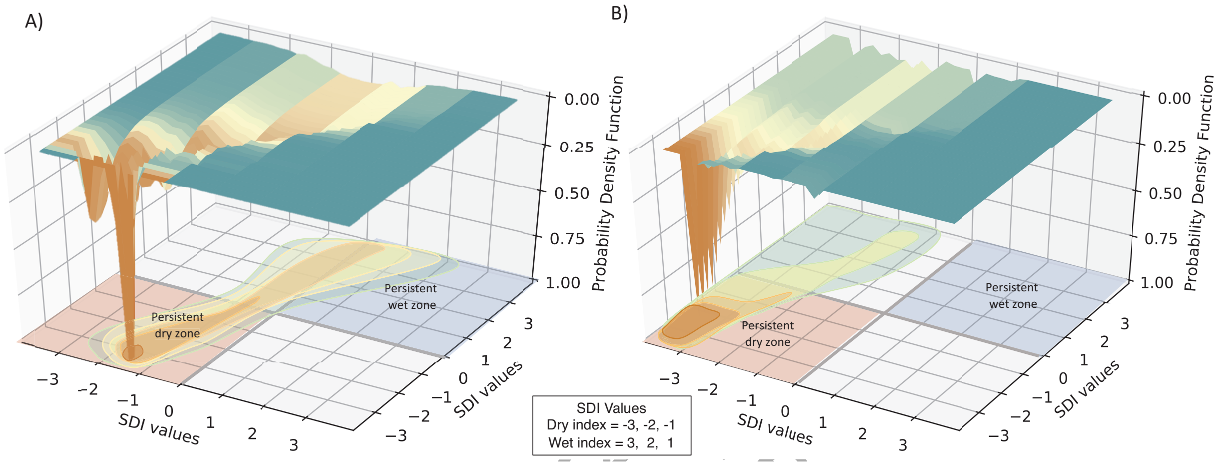

Figure 2. Hypothetical stability landscape of the natural (A) and regulated (B) streamflow system. The natural system's stability landscape shadow reflects two basins of attraction a persistent dry and a persistent wet zone. In contrast, the regulated system's stability landscape shows only a dry zone basin of attraction.

5. CONCLUSION

With the goal of identifying behavior indicative of regime changes in a single basin, this study reveals that a regime shift occurred in the Conchos River Basin after three substantial anthropogenic perturbations by 1948. Additionally, the analysis of the naturalized streamflow data exhibits a warning for an upcoming regime shift, given that the instability of the system is increasing. River basins are exposed to natural changes in precipitation, temperature, climate, or extreme weather. In nature, conditions are never constant. Nevertheless, as resilient systems, rivers can cope with perturbations and gradually respond to changes in a smooth, continuous way. Diverse events, either natural or anthropogenic, can trigger abrupt shifts that can cause large ecological and economic losses. Hence, assessing these shifts is essential in two ways: first, to broaden our understanding of the overall dynamics and resilience of the system, and second, to provide insights into new opportunities for ecosystem improvement and management adjustments.

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