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Ecological Flow as a Water Stress Control Strategy: San Rodrigo River, Coahuila, Mexico

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Abstract: Ecological flow refers to the minimum amount of water that must be maintained in a body of water to protect and preserve aquatic ecosystems. This article aims to analyze the function of ecological flow to address the reproduction of the natural hydrological regime of the San Rodrigo River, Coahuila, Mexico. A quantitative methodology was used where the ecological flow was determined based on the Mexican Standard NMX-AA-159-SCFI-2012 considering the period from 1962 to 2016. The maximum data allows us to identify runoffs of low magnitude of 6.65–15.60, those with an average trend close to 500 Mm^3, and floods of extraordinary volume (namely, those 844–1260 and 1670 Mm^3) with a frequency of every 35 years. Likewise, the river marks drastic changes in the flow in certain years, ranging from 0.64 to 1260 Mm^3, so that the rate of variation would possibly exceed several orders of magnitude scaled in an annual phase. In conclusion, this calculation indicates that the body of water may have the function of environmental conservation covered throughout the year, with the data suggesting that in the short term the river will recover part of the water that passed through its course and thus avoid its deterioration.

Keywords: environmental; flow; hydrological regime; aquatic ecosystems; runoff

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1. Introduction

The first civilizations emerged near flood-prone plains, and rivers still play an important role in our lives today. We depend on streams and rivers for drinking water, irrigation, and hydropower by controlling water flow in ways that may not be natural. This has led many rivers to have flow patterns that are atypical in terms of how much water flows, how often, for how long, and when [1]. Effective river management requires a deep understanding, and the field of environmental flows addresses this by establishing "flow ecology" relationships—mathematical models that connect ecological attributes and dynamics with the fundamental flow regime [2]. Environmental flow is the minimum amount of water necessary to maintain aquatic ecosystems and plays a crucial role in preserving biodiversity, water quality, and the ecological functions of river systems. The Mexican Standard NMX-AA-159-SCFI-2012 [3] defines environmental flow as a measure to regulate the exploitation, use, and conservation of water to protect related ecosystems [4]. According to Poff et al. [5], the characteristics of a river's flow, such as its duration, frequency, magnitude, predictability, and periodicity, are fundamental to its ecological functioning. Any change in any of these aspects can have direct or indirect impacts on the integrity of the river ecosystem, meaning that any alteration in the way water flows can influence aquatic life, riparian habitats, and other important aspects of the river's ecological integrity.

The San Rodrigo River basin is one of six tributaries covered by the water treaty in force since 1944 between Mexico and the United States, which establishes that river runoff must contribute to the Rio Grande. Located in Coahuila, Mexico, the La Fragua dam was built to increase agricultural production and promote the development of the state. However, since the dam began operations in February 1993, environmental problems have arisen, as it meets irrigation demands without analyzing the downstream effects, resulting in inconsistent flow. According to Villareal et al. [6] numerous species of flora can be found around the San Rodrigo River, such as *platanus glabrata* (poplar) associated with *Carya illinoinensis* (walnut), *Fraxinus berlandieriana* (ash), *Quercusfusiformis* (oak), *Morus celtidifolia* (blackberry), *Juglans microcarpa* (walnut), *Chilopsis linearis* (wicker), and *Prosopis glandulosa* (mesquite). In the case of fauna, there is a record of aquatic animals, birds, mammals, and some reptiles [7]. The prolonged absence of water has threatened the existence of species, such as centenarian Mexican cypresses, walnut trees, blackberries, ash trees, and poplars as well as native animals, such as beavers, otters, deer, river frogs, crayfish, and catfish, leading to fish deaths, the loss of biodiversity and the degradation of riparian habitats and wetlands, which are important, since, according to Papadaki et al. [8], considering local biotic elements in the determination of environmental flow provides us with a more holistic view. Currently, the basin faces two main problems: first, the alteration of the flow in the riverbed, which often becomes insignificant downstream due to the inadequate operation of the dam; second, the extraction of gravel by the mining sector, which alters the ecosystem in the lower part of the river and leads to the extinction of local species, among which are beavers, otters, soft-shelled turtles, river godwits, and eels. The civil association Amigos del Río San Rodrigo [9] mentions that a species that has been declining is the monarch butterfly, which used to rest on the banks of the river and is now very scarce. Therefore, there is a pressing need to establish a vital water regime for the conservation of the ecosystem, since there is no specific regulation on the calculation of the environmental flow. Water use and discharge concessions and permits lack adequate control, leading to most untreated wastewater discharges being made into rivers, streams, canals, land, or ravines. Consequently, water bodies in Mexico suffer from very low quality, since the demand for water in the upper areas of the watersheds does not consider the conservation of runoff to lower regions where there is hydraulic infrastructure [10,11]. Gu et al. [12] and Zhang et al. [13] highlight the importance of studying ecological flow to understand the environmental functions of a body of water, which is crucial for the San Rodrigo River basin. Bower et al. [14] argue that maintaining freshwater biodiversity and ecosystem services are essential to preserving the natural flow regime. In this context, Kim et al. [15] emphasize that the determination of environmental flow requires considering the general state of the basin, including the hydrological cycle, the operation of hydraulic infrastructures, and the ecology of the stream. Yarnell et al. [16] recommend adopting a functional flow-based approach, focusing on the components of the natural flow pattern that underpin fundamental ecological processes, allowing a connection between the understanding of these processes and specific, quantifiable measures of flow regime that encompasses a wide variety of native species and communities. Ilinca and Anghle et al. [17] have established four ecological flow values related to hydrological regimes: flood, high tide, mid tide, and low tide, to consider the natural viability of the flow. On the other hand, the method proposed by Zhang et al. [18] involves determining the relationship between the sum of the minimum monthly volume of runoff for each month and the average multiannual flow, while Stamou et al. [19] establishes that the minimum discharge must comply with ecological requirements based on habitat, environmental criteria, water availability in the area, and current applicable legislation. Despite these approaches, it is important to specify that the correct method to determine the ecological flow depends on each region, as is the case of the present study. The objective of this study is to determine the ecological flow based on meteorological data to provide an operational basis for dams, recognizing the vital importance of water for the preservation of ecosystems. The aim is to establish clear criteria to determine the minimum flow necessary to ensure the sustainability of water resources and the health of the natural environment.

2. Materials and Methods

2.1. Study Area

In the Municipality of Piedras Negras, Coahuila, in the rancheria of El Moral, the basin of the San Rodrigo River is located, a perennial system of order 4, which originates in the mountain range of El Burro, north of the Sierra Madre Oriental. The river runs approximately 150 km in an east–west direction, discharging into the Rio Grande [20] (Figure 1). Coordinates of the San Rodrigo River Birth: Latitude: 28.948889°, Longitude: −101.7275°; Mouth: Latitude: 28.902778°, Longitude: −100.630556°.

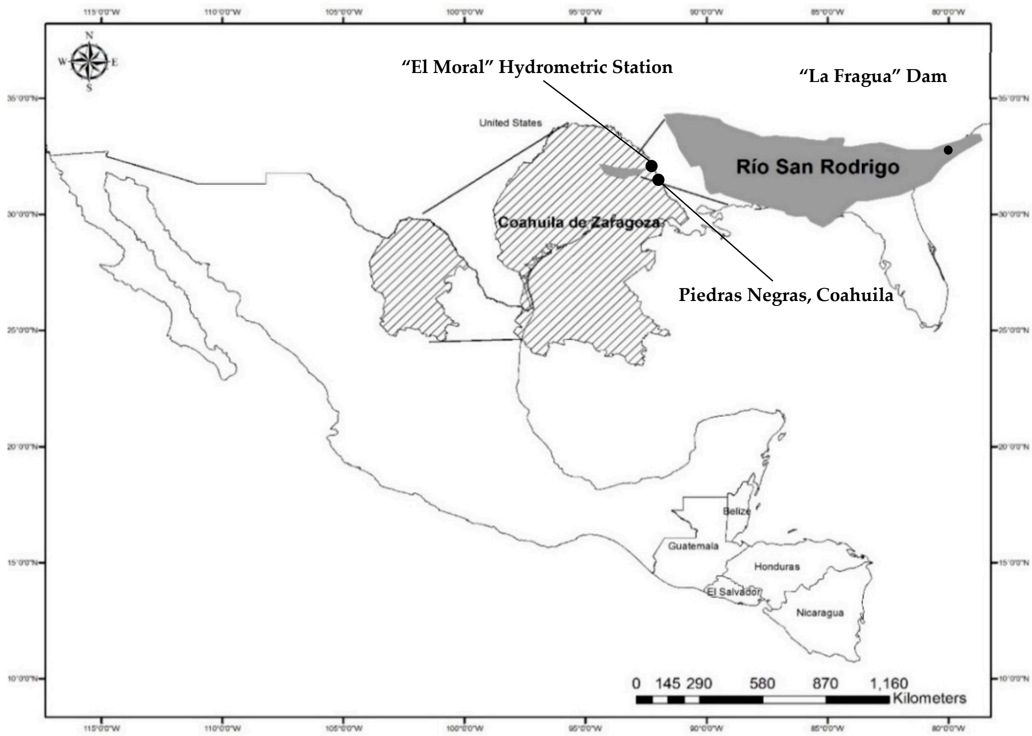

Figure 1. San Rodrigo River Basin belonging to Hydrological Region No. 24 "Bravo-Conchos", Coahuila, Mexico. Source: García-Sánchez [21].

In the basin of the San Rodrigo River, the mainstream is the Río San Rodrigo, of order 4, born in the El Burro Mountain range, north of the Sierra Madre Oriental; it travels approximately 150 km in an east–west direction, discharging into the Rio Grande, in the rancheria of El Moral, Municipality of Piedras Negras. Its coordinates are the following: Birth Latitude: 28.948889°; Longitude: −101.7275°; Mouth: Latitude: 28.902778°; and Longitude: −100.630556°.

Regionally, geology is represented by sedimentary rocks of marine origin and some sandstones with interstratified shales (Figure 2). Stratigraphically, the basal rock is made up of a clayey limestone with a microcrystalline texture with intercalation of greenish-gray shales, which is overlying a medium-grained sandstone of a light gray to greenish color, with intercalations of shales belonging to the Upper Cretaceous [21].

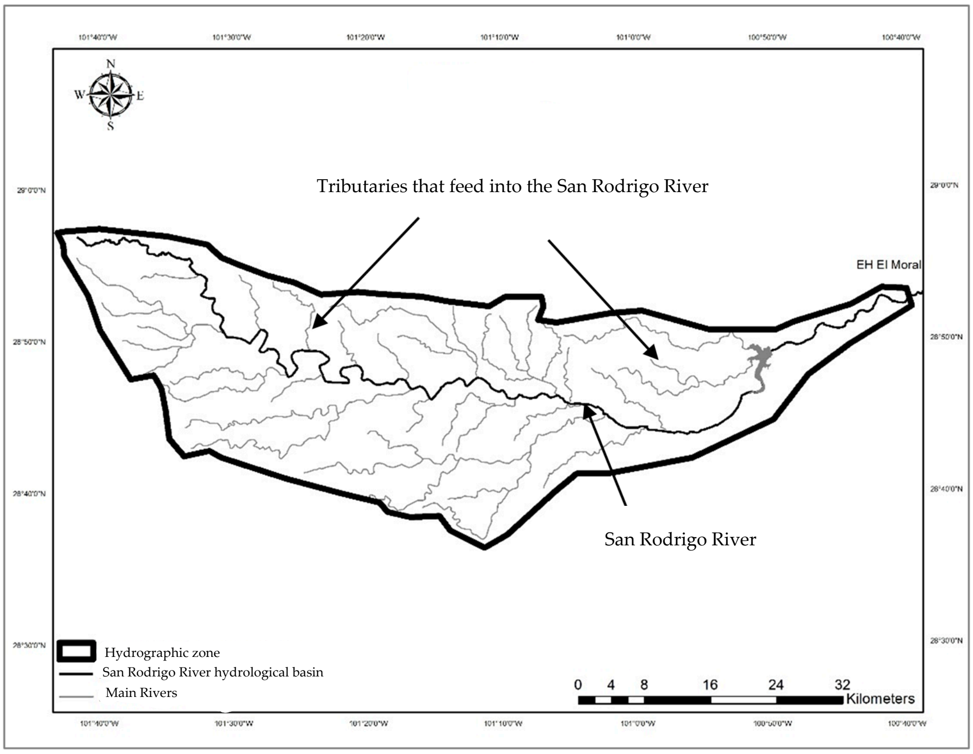

Figure 2. Hydrography of the San Rodrigo River Basin. Source: García-Sánchez [21].

2.2. Legal Framework

In Mexico, CONAGUA, in accordance with the National Water Law (LAN), in its article 29 BIS, Fracc. III, "The Federal Executive, through "the Water Authority", is responsible for protecting the ecological flows, and would have the power to deny the concession, assignment or discharge permit when it affects the minimum ecological flow that is part of the environmental use..." Likewise, in Article 84 of the same law, it is established that CONAGUA will determine the operation of the hydraulic infrastructure. The General Law of Ecological Balance and Environmental Protection (LGEEPA) promotes the conservation of biodiversity and the protection of ecosystems, which includes the regulation of ecological flows. The Mexican standard NMX-AA-159-SCFI-2012 "Establishes the procedure for the determination of ecological flow in hydrological basins". Published in the *Official Gazette of the Federation* in 2012, it establishes the guidelines and methods to identify the ecological flow regime, a concept recognized by the LAN as "the minimum flow or volume required in bodies of water, such as streams or reservoirs, or the minimum natural discharge flow of an aquifer, which must be preserved to safeguard the environmental conditions and the ecological balance of the system".

2.3. Research Data and Methodology

In the present study, the calculation of the ecological flow was carried out using the method proposed by García et al. [22] described in the applicable and current Mexican standard NMX-AA-159-SCFI-2012. A series of data from at least 20 years of continuous hydrometric information must be obtained to determine the monthly and annual ecological flow regime with the definition of dry, medium, and wet years, to finally establish the formulation of the monthly and annual ecological flow regime associated with a clearly pre-established environmental objective (Table 1).

Table 1. Recommendations for the percentage of Average Annual Flow (AAF) and Minimum Flow (Qmi) with related environmental objectives modified by García et al. [22] and proposed by CONAGUA [10].

Objective Environmental	Period			
	Shallow Water		Avenue (Flow Events)	
	% AAF	% Qmi	% AAF	% Qmi
One	30	100	60	50
B	20	80	40	40
C	15	60	30	30
D	5	40	10	20

Source: Authors' elaboration based on CONAGUA [10].

Environmental objective "D" was selected due to its "high" value of ecological importance, since the San Rodrigo River basin is home to important species such as beavers, otters, and bears. It is worth mentioning that the basin is under protection due to the commitments of the 1944 Treaty. The ecological flow will be calculated using the data records from 1962 to 2016 from two hydrometric stations located in the San Rodrigo River basin (Figure 1):

- "El Moral" Hydrometric Station 24275, operated by CONAGUA in Mexico.
- "El Moral" Hydrometric Station, operated by the International Boundary and Water Commission, United States Section.

3. Results and Analysis

Worldwide, the method proposed by García [22] to determine the Ecological Flow regime is one of the most widely used due to the accessibility of its calculations; basically, it is used in streams that have a regulatory structure such as dams, dikes, or other modifications in the channel [10]. The estimation of the flow in a body of water, according to Ziadi et al. [23], is a key parameter for the effective management of water resources and the prevention of flood risk. The calculation begins by estimating the monthly contributions (see Tables 2–4) based on the records from 1962 to 2016 of the hydrometric data at the stations of the San Rodrigo River, Coahuila, Mexico:

According to the hydrometric records analyzed from the stations located in the Moral, the water level is low or non-existent. Table 2 shows values equal to zero in different months and years. In general, the San Rodrigo River lacks pronounced seasonal fluctuations, it could be said that it has a slow flow variability throughout the year, although it may present extraordinary events in deferred years. For the San Rodrigo River, the evaluation of periods of low water and flooding required the determination of dry, medium, and wet years, with this the maximum value for each month is identified from the average monthly flows, being the year 2010, the year with the highest volume of runoff (wet year). In the same way for the dry year, the lowest values of each month were identified from the average monthly flows, determining the year 2006 with minimum runoff (dry year). It must finally be established from the average of each of the months, and based on the average monthly flows of the average year, taking the series of the Natural Hydrological Regime (RHN), the hydrometric data are grouped on a monthly basis, obtaining the monthly contributions (Table 2). In addition, all monthly average flow values that are above the Average Annual flow (AAF) value will be recognized as flood periods. The following determination is for the minimum, maximum, and average flow values, as well as the annual contributions in Mm^3 (Table 3).

Table 2. Average monthly contributions (Mm^3) (1962–2016).

Average (Mm^3)	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**
JAN	2.78	0.00	0.01	2.60	0.23	0.55	3.55	1.29	1.40	5.07	12.31	5.81	5.42	6.95	4.98	14.55	0.69	16.37	1.14
FEB	1.46	0.01	0.00	1.42	0.33	0.45	2.23	1.35	1.03	2.99	8.04	4.46	3.00	4.50	3.52	10.88	0.57	12.25	0.50
MAR	1.10	0.00	0.02	1.35	0.46	0.34	2.68	0.95	1.19	1.95	4.79	4.02	2.92	2.73	2.47	9.63	0.56	8.16	0.33
APRI	5.25	0.50	0.34	1.29	2.79	0.15	1.42	26.76	0.47	1.04	2.78	3.50	1.55	9.43	2.34	7.70	0.37	5.47	0.10
MAY	5.25	1.61	1.40	6.12	5.39	0.02	5.23	7.93	0.18	0.42	1.91	2.30	1.17	5.43	17.30	9.28	0.19	2.87	0.55
JUN	2.12	0.98	0.21	1.00	1.35	0.00	1.16	3.26	0.48	5.80	2.93	0.77	0.28	2.59	4.02	5.13	1.83	15.74	0.04
JUL	0.73	0.00	0.16	0.37	0.32	0.00	35.06	1.65	1.13	15.55	8.06	2.51	0.00	261.00	560.95	3.81	0.69	8.18	0.03
AUG	0.28	0.00	0.00	2.61	0.09	0.03	5.42	14.26	2.33	109.84	34.31	1.47	0.04	26.95	56.39	2.69	1.84	5.29	59.07
SEP	0.00	0.00	0.00	0.00	1.31	49.68	4.47	3.06	35.05	28.00	18.37	1.51	59.30	15.67	31.75	1.87	34.20	4.26	44.45
OCT	0.00	1.46	14.11	0.00	1.03	12.07	6.46	3.57	27.32	59.62	12.67	65.49	21.55	12.62	25.93	2.17	21.49	1.85	28.49
NOV	0.14	0.10	7.58	0.00	0.96	6.63	2.55	3.03	8.13	23.77	9.46	12.69	11.97	9.37	20.88	2.08	103.60	2.27	7.13
DEC	0.00	0.08	5.27	0.00	0.77	4.42	2.16	1.93	7.36	18.58	7.32	8.19	9.41	7.76	17.66	1.73	24.63	1.17	5.93
Average (Mm^3)	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
JAN	3.19	1.96	1.47	2.18	1.07	0.75	14.70	14.79	12.84	0.00	20.07	5.51	3.05	2.83	0.00	0.00	0.00	0.15	0.25
FEB	2.03	1.24	0.93	1.51	1.05	1.85	11.44	11.00	10.68	1.04	2.16	7.47	1.34	2.09	0.00	0.00	0.68	0.06	0.16
MAR	2.12	1.52	1.21	1.26	0.90	1.21	9.64	5.37	9.29	0.04	1.51	5.77	2.19	2.26	0.04	0.00	0.14	0.00	0.25
APRI	35.86	0.89	0.94	1.43	0.44	0.62	6.36	3.65	6.90	46.66	0.44	6.42	0.92	2.11	0.00	0.00	0.00	0.00	0.63
MAY	36.12	0.96	0.55	6.21	1.59	0.47	16.90	3.90	2.61	3.73	0.06	18.84	1.09	3.23	1.93	0.00	0.48	0.00	3.34
JUN	15.00	0.83	0.20	0.52	0.77	23.37	127.17	1.48	0.54	1.06	0.34	23.83	26.53	1.94	0.00	0.02	2.11	0.00	44.73
JUL	8.56	0.67	0.00	0.35	0.59	14.29	113.73	8.01	0.15	39.37	1.16	72.81	10.72	3.12	0.00	0.00	0.00	2.74	31.68
AUG	3.89	0.52	0.00	0.11	0.02	3.86	31.87	25.53	0.64	7.81	0.00	23.43	6.47	0.00	0.00	1.17	0.00	39.37	36.05
SEP	3.97	1.76	6.59	0.04	5.42	51.99	54.65	65.18	0.00	58.79	21.52	14.86	10.60	2.81	2.23	0.62	0.00	0.73	18.94
OCT	4.05	0.92	6.57	21.22	9.87	50.77	25.75	28.37	1.49	80.46	17.28	6.14	5.91	0.00	0.15	0.48	0.00	0.03	7.82
NOV	3.54	0.77	8.56	0.76	6.52	30.77	19.48	19.06	0.00	32.55	8.70	9.78	4.70	0.00	0.42	0.00	0.00	5.48	7.31
DEC	2.69	0.89	3.22	0.85	2.98	22.58	17.67	15.40	0.02	25.99	6.73	8.83	3.64	0.00	0.00	0.00	0.03	0.90	4.25
Average (Mm^3)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016		
JAN	1.26	0.00	0.00	0.78	2.31	4.13	0.09	0.00	0.85	3.84	0.74	2.87	0.00	0.00	1.57	2.30	0.00		
FEB	1.87	0.00	0.00	0.66	1.55	3.48	0.00	0.00	0.43	3.06	1.01	3.63	0.00	0.00	1.10	8.74	0.00		
MAR	6.84	0.00	0.00	0.36	5.51	1.94	0.06	0.00	0.45	2.80	0.39	2.55	0.06	0.36	0.58	1.00	0.00		
APRI	0.84	0.00	0.24	0.19	38.36	0.47	0.09	0.00	0.18	0.94	48.62	1.07	0.00	1.92	0.65	0.06	0.13		
MAY	0.82	0.01	0.00	0.58	12.02	0.31	0.01	0.00	0.81	0.48	8.05	0.40	0.95	0.65	0.17	1.69	0.48		
JUN	0.96	0.03	0.01	2.79	4.06	0.56	0.00	0.05	0.02	0.16	8.05	0.12	0.00	1.72	2.07	0.88	0.19		
JUL	1.17	0.05	2.38	3.78	2.90	0.26	0.00	5.16	0.00	0.19	300.46	0.61	0.00	0.00	1.24	0.00	0.40		
AUG	0.57	0.01	0.03	2.08	4.73	0.29	0.00	5.85	19.39	0.07	16.57	0.46	0.00	0.00	0.05	0.07	1.28		
SEP	0.74	2.99	0.25	2.77	4.82	0.32	1.02	8.24	35.44	0.89	10.76	0.00	1.50	12.78	0.00	0.95	7.35		
OCT	0.06	0.24	31.28	6.10	8.26	31.48	0.00	4.34	7.56	0.04	14.00	0.00	0.00	5.48	0.00	7.90	5.94		
NOV	0.02	0.03	2.05	3.21	7.89	8.27	0.00	0.21	5.49	0.19	6.49	0.00	0.00	3.31	6.45	0.39	6.30		
DEC	0.00	0.00	1.13	2.50	5.33	2.37	0.00	0.84	4.21	0.67	5.06	0.00	0.00	2.65	3.36	0.00	3.82		

Source: García-Sánchez [21].

Table 3. Minimum, maximum, and average flow and inputs (Mm^3) (1962–2016).

Year	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**
MIN (m^3/s)	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.29	0.00	0.08	0.49	0.22	0.00	0.64	0.59	0.58	0.05	0.30	0.00
MAX (m^3/s)	42.20	13.50	13.00	28.20	28.90	175.0	49.60	168.0	124.0	154.0	54.1	235	225	1260	844	18.5	277	17.4	201.0
Flow rate (m^3/s)	0.61	0.15	0.95	0.53	0.48	2.36	2.30	2.19	2.73	8.65	3.90	3.57	3.70	11.57	23.73	2.27	6.05	2.66	4.69
Average (Mm^3)	19.12	4.75	30.08	16.60	15.02	74.35	72.39	69.05	86.08	272.64	122.93	112.72	116.61	365.00	748.20	71.52	190.67	83.88	147.77

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
MIN (m^3/s)	0.21	0.17	0.00	0.00	0.00	0.10	1.93	0.15	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAX (m^3/s)	54.10	6.65	69.70	169.0	36.00	84.70	164.0	165.0	14.10	481.0	35.40	160.0	110.0	26.80	16.00	12.30	18.70	275.00	85.50
Flow rate (m^3/s)	3.84	0.41	0.96	1.16	0.99	6.42	14.25	6.40	1.43	9.43	2.54	6.46	2.45	0.65	0.15	0.07	0.11	1.57	4.93
Average (Mm^3)	121.03	12.93	30.24	36.44	31.21	202.54	449.37	201.73	45.15	297.51	79.98	203.68	77.16	20.41	4.76	2.29	3.44	49.45	155.41

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
MIN (m^3/s)	0.00	0.00	0.00	0.01	1.08	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAX (m^3/s)	10.20	42.70	494.00	59.00	223.00	512.00	15.30	79.60	218.00	15.60	1670.00	8.31	34.00	105.00	28.50	27.60	34.40
Flow rate (m^3/s)	1.26	0.28	3.17	2.16	8.14	4.52	0.11	2.07	6.24	1.10	35.48	0.96	0.21	2.40	1.43	1.96	2.16
Average (Mm^3)	39.86	8.74	99.83	68.14	256.66	142.60	3.32	65.39	196.76	34.70	1118.79	30.31	6.57	75.63	45.13	61.78	68.10

Source: García-Sánchez [21].

Table 4. Periods of low water and flooding within dry, medium and wet years.

Flow (m^3/s)	Flow Rates for Dry, Medium and Wet Conditions			Hydrological Periods		
	Dry Year	Average Year	Wet Year	Dry Year	Average Year	Wet Year
JAN	0.00	1.53	7.49	Low water	Low water	Flow Events
FEB	0.00	1.33	8.74	Low water	Low water	Flow Events
MAR	0.00	1.03	6.84	Low water	Low water	Flow Events
APR	0.00	3.02	48.62	Low water	Low water	Flow Events
MAY	0.00	1.70	13.49	Low water	Low water	Flow Events
JUN	0.00	2.64	49.06	Low water	Low water	Flow Events
JUL	0.00	13.99	300.46	Low water	Flow Events	Flow Events
AUG	0.00	4.35	41.01	Low water	Flow Events	Flow Events
SEP	0.00	6.24	35.44	Low water	Flow Events	Flow Events
OCT	0.00	6.20	31.48	Low water	Flow Events	Flow Events
NOV	0.00	3.66	39.97	Low water	Low water	Flow Events
DEC	0.00	2.22	9.70	Low water	Low water	Flow Events
AAF (m^3/s)				4.0		

Source: García-Sánchez [21].

Table 3 shows low-magnitude runoff ranging from 6.65 to 15.60 Mm^3 (1962–2016), with an average trend close to 500 Mm^3 (1962–2016) and extraordinary volume floods of 844, 1260, and 1670 Mm^3 (in the years 1975, 1976, and 2010). The latter occurred with a frequency of about 35 years, considering that during the study period (54 years) the first extraordinary flood was recorded in 1975 and the last in 2010. In the Acaponeta River, Salinas [24] recorded three extraordinary floods with magnitudes of 1632.4, 2713.5, and 4145.0 Mm^3 between 1946 and 2002 (a period of 56 years), with similar incidence in both cases given their equivalent analysis period. Although these events cause damage, they are also essential for the river, as they help reconfigure its course and are crucial for redistributing nutrients or sediment material. Over time, the San Rodrigo River in Coahuila can exhibit drastic changes in flow during certain years (1975), ranging from a minimum of 0.64 to 1260 Mm^3, which means that the rate of change could exceed four orders of magnitude (Table 3) projected on an annual basis.

Table 4 shows the results of the dry and flood periods within the dry, medium, and wet years. Basu et al. [25] mention that the estimation of the maximum flow is necessary to address the flood risk corresponding to climate change. The calculated value for the San Rodrigo River, Coahuila, of the Average Annual Flow (AAF) was 4.0 m^3/s and it is possible to consider that this is equivalent to the average of the daily flows recorded.

In the San Rodrigo River, Coahuila, the year 2010 was identified as outstanding because it was a particularly wet year, with a maximum flow of 300.46 m^3/s recorded in the month of July. According to the average monthly flow in dry and wet periods (Table 5), the month of July stood out with a flow of 13.99 m^3/s; this makes it the wettest month.

The annual ecological flow regime is determined from the selection of a standard year (dry, medium, or wet). According to the average value determined per month, a comparison is made with respect to the average flow, and if it is higher, then it corresponds to a dry period and if it is less to a wet period (See Table 5). Based on Table 1 (in the Section 2) as an example for an objective A in the determination of the % AAF: if the average monthly flow (Table 6) corresponds to the month of January, and is lower than the annual average, the annual average is multiplied by the % AAF of low water (30%), and if it is higher, the annual average is multiplied by the % AAF of flooding (60%). Therefore, as it is lower, it is multiplied by the 30% that would correspond to the selected environmental objective.

Table 5. Dry and wet periods.

Average Monthly Flow (m^3/s)		
JAN	1.53	Dry
FEB	1.33	Dry
MAR	1.03	Dry
APR	3.02	Dry
MAY	1.70	Dry
JUN	2.64	Dry
JUL	13.99	Wet
AUG	4.35	Wet
SEP	6.24	Wet
OCT	6.20	Wet
NOV	3.66	Dry
DEC	2.22	Dry
Average	4.0	

Source: García-Sánchez [21].

Table 6. Evaluation of % AAF for the San Rodrigo River, Coahuila, according to each environmental objective, considering the average annual flow.

Based on Average Annual Flow (m^3/s).				
Year	A_{AAF}	B_{AAF}	C_{AAF}	D_{AAF}
JAN	1.20	0.80	0.60	0.20
FEB	1.20	0.80	0.60	0.20
MAR	1.20	0.80	0.60	0.20
APR	1.20	0.80	0.60	0.20
MAY	1.20	0.80	0.60	0.20
JUN	1.20	0.80	0.60	0.20
JUL	2.40	1.60	1.20	0.40
AUG	2.40	1.60	1.20	0.40
SEP	2.40	1.60	1.20	0.40
OCT	2.40	1.60	1.20	0.40
NOV	1.20	0.80	0.60	0.20
DEC	1.20	0.80	0.60	0.20

Source: García-Sánchez [21].

In the formulation of the proposals for a monthly and annual ecological flow regime for a typical year, in accordance with Table 1 described in the Section 2 for a selected environmental objective, the monthly flow regime is first defined from the average year with the percentages proposed for the determination of the monthly average flow regime % Qmi for each annual period. Thus, if the environmental objective were "A" the determination of % Qmi would indicate that if the average monthly flow was the month of January, and is lower than the annual average, the average monthly flow is multiplied by the % Qmi of low water (100%), and if it is higher, the average monthly flow is multiplied by the % Qmi of flood (50%). In this case, being lower, it is multiplied by 100% for the month and environmental objective selected. This is summarized for the San Rodrigo River in Table 7.

In addition, the ecological flow is obtained by comparing the average annual runoff flow % AAF (Table 6) against the average monthly flow % Qmi (See Table 7), multiplied by the corresponding percentages according to the selected environmental objective. Considering a base flow of zero, for the selection of the value of the ecological flow with the environmental objective (A, B, C, or D), the lowest value is chosen if it corresponds to the dry month, and the highest value in the case of the wet month. With the base flow as the lower limit, the ecological flow for the San Rodrigo River is proposed in terms of the minimum flow and the average annual flow (%AAF) for each of the environmental objectives (see Tables 6 and 7).

Table 7. Determination of the % of Qmi according to each environmental objective, considering the average monthly flow.

Based on Average Monthly Flow (m^3/s)				
MIDDLE YEAR	HERE	BQmi	CQmi	DQmi
JAN	1.53	1.23	0.92	0.61
FEB	1.33	1.07	0.80	0.53
MAR	1.03	0.82	0.62	0.41
APR	3.02	2.42	1.81	1.21
MAY	1.70	1.36	1.02	0.68
JUN	2.64	2.11	1.58	1.06
JUL	7.00	5.60	4.20	2.80
AUG	2.18	1.74	1.31	0.87
SEP	3.12	2.49	1.87	1.25
OCT	3.10	2.48	1.86	1.24
NOV	3.66	2.92	2.19	1.46
DEC	2.22	1.77	1.33	0.89

Source: García-Sánchez [21].

Regarding Environmental Objective D selected for the San Rodrigo River basin, the minimum ecological flow of 0.20 m^3/s is adequately manifested in the dry months that belong to a period that covers from November to June, and with the maximum value of 2.80 m^3/s (Table 8) typical of July, which, according to the series analyzed 1962–2016, coincides with the rainiest month.

Table 8. Selection of the Ecological Flow based on the Method proposed by García (1999) (m^3/s) (1962–2016) based on the average annual flow.

Ecological Flow Proposal (m^3/s)				
	Environmental Objective			
	To	**B**	**C**	**D**
JAN	1.20	0.80	0.60	0.20
FEB	1.20	0.80	0.60	0.20
MAR	1.03	0.80	0.60	0.20
APR	1.20	0.80	0.60	0.20
MAY	1.20	0.80	0.60	0.20
JUN	1.20	0.80	0.60	0.20
JUL	7.00	5.60	4.20	2.80
AUG	2.40	1.74	1.31	0.87
SEP	3.12	2.49	1.87	1.25
OCT	3.10	2.48	1.86	1.24
NOV	1.20	0.80	0.60	0.20
DEC	1.20	0.80	0.60	0.20

Source: García-Sánchez [21].

In accordance with environmental objective "D", the recommended reference value is proposed to assign a volume of ecological flow; in the case of perennial streams, this value would be in the range of 5–14% AAF, while for temporary flows it would be 5–9% AAF [23]. In this context, the estimated value of 16.33% AAF for the San Rodrigo River is close to the maximum recommended for perennial streams. If it is considered that throughout the year the river permanently maintains a minimum expenditure that, although small, maintains the flow (Figure 1), it would be possible to manage the ecological flow and release these quantities (Table 9) estimated for the proposed environmental objective "D" that would correspond to the San Rodrigo River basin as a dynamic variant of monthly ecological flow, which in turn would be a proposal equivalent to deriving an ecological flow of 20.56 Mm^3 of the annual total (Table 9). This would thus allow for the restoration of the environmental function of the channel without prejudice to the economic activities it supports. But it would be important to verify that the ecosystem will be restored in the future by limiting the water circulating in the river to that flow (Table 9) and avoiding zero flow. This refers to what Ali et al. [26] said when they mentioned that human influence on the river ecosystem has in recent years increased the construction of different water structures to feed the growing demand for water from communities. Based on the records of the CILA "El Moral" hydrometric station and the method proposed by García [22] in accordance with Normative Appendix A [3], the verification of compliance with the flow with respect to Environmental Objective D indicates the data (Table 10).

Table 9. Result of the Ecological Flow based on the Method proposed by García [22] (Mm^3) (1962–2016) based on the average annual flow.

Ecological Flow Proposal (Mm^3)				
	Environmental Objective			
	One	B	C	D
JAN	3.21	2.14	1.60	0.53
FEB	2.90	1.93	1.45	0.48
MAR	2.76	2.14	1.60	0.53
APR	3.10	2.07	1.55	0.52
MAY	3.21	2.14	1.60	0.53
JUN	3.10	2.07	1.55	0.52
JUL	18.74	14.99	11.24	7.50
AUG	6.42	4.66	3.50	2.33
SEP	8.08	6.47	4.85	3.23
OCT	8.31	6.65	4.98	3.32
NOV	3.10	2.07	1.55	0.52
DEC	3.21	2.14	1.60	0.53
TOTAL	66.14	49.47	37.10	20.56
% AAF	52.53	39.28	29.46	16.33

Source: García-Sánchez [21].

Table 10. Compliance with the ecological flow.

Month	CMM (m^3/s)	MMC (Mm^3)	CMM-CE
JAN	0.53	4.11	3.58
FEB	0.48	3.23	2.74
MAR	0.53	2.76	2.22
APR	0.52	7.83	7.31
MAY	0.53	4.55	4.01
JUN	0.52	6.84	6.32
JUL	7.50	37.48	29.99
AUG	2.33	11.66	9.33
SEP	3.23	16.16	12.93
OCT	3.32	16.61	13.29
NOV	0.52	9.47	8.96
DEC	0.53	5.94	5.40

Source: García-Sánchez [21].

The theoretical values calculated show that throughout the year the ecological flow and the monthly average were similar, except in July, when the ecological flow was higher, regardless of the environmental objective observed (Figure 3). This similarity was maintained for a long period of time—54 years (1962 to 2016)—demonstrating that it is feasible to release the estimated ecological flow (Tables 9 and 10) due to its correspondence with the natural behavior of the San Rodrigo River, Coahuila. This calculation (Table 11) is based on a straightforward scientific formulation, not on arbitrary decisions or agreements. It can be interpreted that, for the four environmental objectives, the ecological flow reaches its maximum only in the month of July, an attempt has been made to project a conservation status represented by environmental objective "D" (deficient), the lowest and most restrictive, in order to contribute to the adequate mitigation of water stress. This is achieved by estimating a conservation flow (Table 9) according to the environmental and social aspects of the place, which implies accessing the lowest possible flow (a total of 20.56 Mm^3 per year) compared to other environmental objectives. This calculation is considered sufficient to fulfill the environmental function of conservation, even throughout the year (Table 9), and would behave in a similar way to the natural hydrometric state of the average monthly flow of the San Rodrigo River, Coahuila (Figure 1).

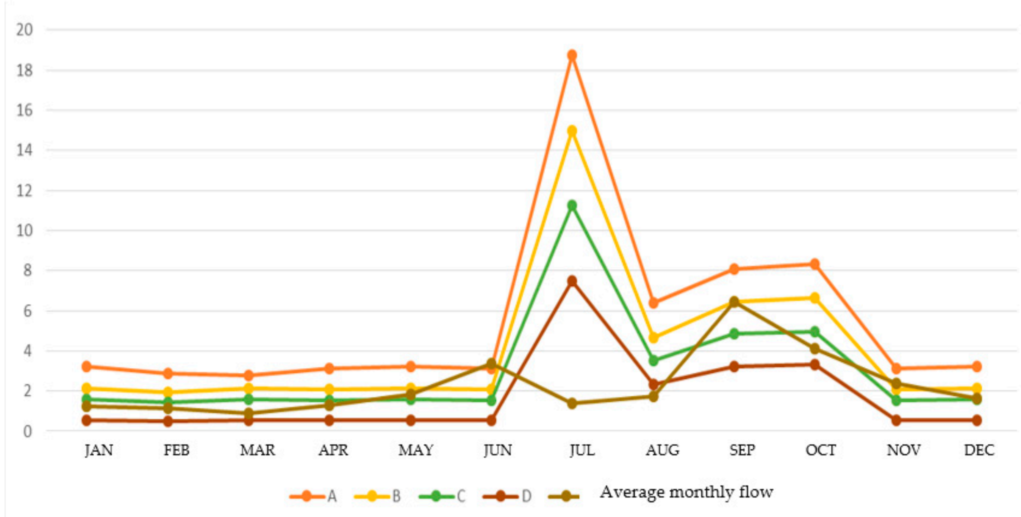

Figure 3. Comparison of the average monthly flow with the result of the Ecological Flow (Table 11) CILA- Method "El Moral" by García (Mm^3) Source: Own elaboration.

Table 11. Proposed ecological flow according to the results obtained.

Proposed Ecological Flow (Mm^3)				
	Environmental Objective			
	One	B	C	D
Total amount	66.14	49.47	37.10	20.56
% AAF	52.53	39.28	29.46	16.33

The objective is to cover one of the functions of ecological flow, which is habitat restoration [27], taking into account the minimum value necessary to recover the habitat without affecting the current irrigation concession. The analysis reveals that the San Rodrigo River is a system characterized by long periods of low water, which according to Rincón Lara [28] leads to an increase in temperature, a reduction in flow and the progressive accumulation of fine materials in the riverbed. This promotes the growth of macrophytes and alters different aspects of the oxygen balance, in addition to reducing the area available to organisms; as a consequence, the system experiences increasing stress as resources decrease and becomes gradually impoverished until it disappears. For Hairan et al. [29], the lack of an environmental flow can affect water supply, agriculture, and fisheries. According to Arthington et al. [30], the use of ecological flow regimes is a promising way to protect and restore rivers, wetlands, and estuarine ecosystems, as well as their critical environmental services and their cultural and social values. The determination of ecological flow represents a vision towards sustainability for ecosystem preservation.

4. Conclusions

It is concluded that the water flow in the San Rodrigo River exhibits a remarkable constancy, with practically zero values in several different months and years, which indicates a low seasonal variability. Although extraordinary events are recorded in specific years, as observed in the extraordinary volume floods in 1975, 1976, and 2010, these are rare, with an approximate occurrence every 35 years throughout the studied period of 54 years.

From the perspective of environmental objective "D", it is observed that the estimated value of % AAF 16.33 for the San Rodrigo River is close to the maximum recommended for perennial streams (5–14%). Even though the minimum annual flow is reduced, the possibility of managing an annual ecological flow of 20.56 (Mm^3) is proposed, releasing estimated monthly amounts ranging between 0.48 and 7.50 Mm^3, which could be feasible and benefit the riparian ecosystem.

With this, it is possible to point out that the operation of the dams must guarantee a minimum flow of 0.53 m^3/s during the periods of greatest water stress. In addition, the delivery quota to the Rio Grande established in the 1994 Treaty must be considered, which is essential for the preservation of the ecosystem. This flow would not only benefit the local population but would also contribute to the conservation of native species, as well as the flora and fauna of the hydrological region. It would also help alleviate water stress and mitigate the effects of water scarcity on the environment.

It is important to note that, although the San Rodrigo River is currently closed, the aforementioned quantitative proposal provides a scientific approach to its management, responding to the demands of the Friends of the San Rodrigo River Civil Association. This proposal could contribute to the recovery of the river's flow in the short term, without compromising the needs of water users. To ensure the success of this proposal, it is essential to carry out an exhaustive verification that considers additional elements, especially those of a biotic nature, such as the fauna and flora characteristics of the habitat of the San Rodrigo River, in Coahuila. The integration of these elements will make it possible to determine whether the environment is conducive to the long-term sustainability of biological communities. An on-site assessment is therefore urged to ensure that the calculation of the ecological flow meets the needs of the riparian landscape and promotes its long-term sustainability.

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