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Analysis of meteorological drought in the Rodrigo Gómez Dam basin

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ABSTRACT
Objective: To identify the return periods of meteorological drought in the Rodrigo Gómez "La Boca" Dam basin, located in the state of Nuevo León.
Design/Methodology/Approach: Based on the Streak, Foley, and moving-average methods, a probabilistic approach was applied to annual rainfall data (1973-2015) from five climatological stations located within the Rodrigo Gómez Dam basin to forecast drought recurrence. Years in which at least two methods identified drought conditions were considered drought years for the purpose of calculating return periods.
Results: A meteorological drought is highly probable with a return period of 3 to 5 years.
Study Limitations/Implications: For the drought analysis, climatological stations with at least 30 years of rainfall records were required. The study area was reduced during the data collection, as two stations within the Rodrigo Gómez Dam area were excluded given their insufficient precipitation data.
Findings/Conclusions: This research confirmed the existence and persistence of drought-related problems at the dam. The results indicate a high probability of a meteorological drought with a return period of 3 to 5 years. This recurrence reinforces the need for a Drought Action and Prevention Plan in the state of Nuevo León, aimed at ensuring the sustainable management of water resources and minimizing impacts on the population.

Keywords: water security, water management, meteorological phenomenon, water stress, precipitation forecast.

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INTRODUCTION

Drought is a natural phenomenon characterized by the lack of water (mainly rainfall), in a given period and area, preventing humans from meeting their basic needs. This phenomenon impacts society, the agricultural sector, and the economy. Lobato-Sánchez (2016) defines drought as one of the phenomena with the greatest impact on the main sectors involved in water management, because the long-term precipitation deficit is reflected in hydrological and socioeconomic areas. Drought classification is complicated by its dependency on the approach with which they are analyzed and the magnitude of their impact. Given the lack of a universal definition, drought has not received enough attention and its analysis and research have been scattered. Wilhite and Glantz (1985) suggested differentiating between conceptual and operational definitions of drought. In general terms, conceptual definitions are developed to identify the boundaries of the concept, while operational definitions seek to characterize the drought with specific onset, severity, and duration data. The authors proposed classifying droughts from the point of view of four scientific concepts: meteorological drought, agricultural drought, socio-economic drought, and hydrologic drought.

In Mexico, droughts are classified according to their intensity and impact. Based on their intensity, droughts are divided into abnormally dry, moderate, severe, extreme, and exceptional. Meanwhile, based on their impact, droughts are classified as agricultural, meteorological, and socio-economic droughts.

This study analyzes meteorological droughts, which are characterized by the lack of rainfall. Its main indicator is the climatic data of the study region. This type of drought occurs when the mean annual precipitation is lower than historical records, resulting in a lower storage volume of surface water in hydraulic structures and a decrease in groundwater recharge.

Various authors have provided their own definitions of this type of drought. For example, Palmer (1965) defines it as a meteorological anomaly characterized by a lengthy and abnormal lack of moisture in a given location. Its severity is determined by its duration and magnitude. Marcos (2001) bases his definition of drought on climate data, considering that precipitation deviates from the mean over a given period. This type of drought varies depending on the study region, as it is directly related to the characteristics of the regional climate. All over the world, droughts are a result of climate change and poor water resource management. In 1984, Africa faced one of the worst droughts in history, endangering the lives of 35 million people and causing one million deaths. In response to this phenomenon, drought was first recognized as a global issue in the first report of the World Commission on Environment and Development (1987).

The United Nations Educational, Scientific and Cultural Organization (2020) declared it a serious problem. It poses a risk to the health of the population, because the concentration and proliferation of pathogens are higher during droughts. Given the increased visibility of environmental issues, countries began to act accordingly.

Mexico became a pioneer in water management in 1989 with the creation of the National Water Commission (CONAGUA: Comisión Nacional del Agua), a public agency responsible for managing the country's water resources. In addition, various local operating agencies, such as basin councils, were established. In 1994, Mexico was the first country to sign the United Nations Convention to Combat Desertification. In the same year, Mexico developed its national action plan, which included a comprehensive analysis of the desertification and drought issues in the country (Ruiz and Febles, 2004).

Despite the efforts of the Mexican government to manage climate risks, the country has not been immune to climate crises. In 2011 and 2012, a severe drought affected more than 80% of the country, causing losses exceeding MXN$16 billion in the agricultural sector, as well as water shortages in rural and vulnerable communities (Ortega-Gaucin, 2018). More than half of its territory is classified as arid or semi-arid, making Mexico susceptible to droughts. Its territory has a great climatic diversity, ranging from very warm areas in the south to deserts in the north. These natural conditions make Mexico more vulnerable to droughts.

There are three reasons why Nuevo León is particularly vulnerable to these types of natural phenomena: its location, its prevailing weather conditions, and the natural availability of water. This state lies within the northern belt of the world's great deserts and it is part of an arid zone with a natural water deficit. The diverse climate of Nuevo León is the result of diverse orography within the state; however, the prevailing weather conditions are dry and semi-dry. The combination of all these natural conditions, coupled with the growing impact of climate change, makes Nuevo León a region of interest for the research and implementation of drought mitigation and prevention strategies. The objective of this research was to determine the return period of droughts for each season, with the goal of preventing and mitigating the short- and long-term effects of this phenomenon.

MATERIALS AND METHODS

The Rodrigo Gómez Dam, more commonly known as "La Boca," is a hydraulic structure located in the municipality of Santiago, state of Nuevo León. It was built in 1961 by CONAGUA to supply drinking water to the city of Monterrey. It has a storage capacity of 40 hm^3 and an area of approximately 455 ha. Its tributaries are the following streams: La Chueca, Cavazos, Cristalinas, Dolores, Escamilla, Puerco, and San Antonio (CONAGUA, 2015).

Beyond its hydraulic function, the dam is used for various recreational activities, such as sportfishing, water sports, and ecotourism.

This analysis required climate data from weather stations within the Rodrigo Gómez Dam basin. Since not all-weather stations located within the basin have uninterrupted precipitation records, three off-site stations were included for a more accurate characterization. "La Boca" and "El Cerrito" stations are located within the dam basin, while the "El Pajonal," "Laguna de Sánchez," and "Allende" stations are located outside of it.

The relevant information of each weather station (i.e., identification code, name, coordinates, and altitude) is summarized in Table 1.

This analysis used historical monthly precipitation data in millimeters (mm) from the aforementioned weather stations from 1973 to 2015 (Table 2). Based on these data, the mean annual precipitation for each station was calculated (Table 3), considering years when recorded precipitation was lower than the calculated annual mean as drought years.

Statistical models are increasingly used to identify the occurrence and duration of droughts, as a result of their significant usefulness in planning and managing water resources. Three drought identification methods were used to forecast meteorological droughts in the "La Boca" Dam basin.

Table 1. Specifications of the weather stations.

ID Code	Name	Latitude	Longitude	Altitude (m)
19069	La Boca	25° 25' 46"	−100° 7' 44"	460
19015	El Cerrito	25° 30' 36"	−100° 11' 36"	510
19018	El Pajonal	25° 29' 23"	−100° 23' 20"	2576
19003	Allende	25° 17' 01"	−100° 01' 13"	454

m = meters.
Source: Table developed by the authors, based on information from the SMN (National Meteorological Service of Mexico) (2023).

Table 2. Precipitation (mm) of the weather stations (1973-2015).

Year	La Boca	El Cerrito	El Pajonal	Laguna de Sánchez	Allende
1973	1,839.30	1,561.30	543.00	903.00	1,937.00
1974	719.80	766.50	162.00	601.50	1,030.00
1975	978.90	945.50	318.00	582.00	1,503.10
1976	1,368.40	1,207.50	817.30	878.00	1,395.50
1977	851.90	609.00	592.20	693.00	850.00
1978	1,547.40	1,307.00	722.40	1,172.00	1,570.50
1979	984.70	791.90	587.90	224.50	945.00
1980	867.40	743.60	802.10	616.00	706.50
1981	1,116.70	974.40	888.90	516.50	1,410.80
1982	771.10	205.40	570.30	527.10	756.10
1983	1,157.90	901.20	111.00	276.00	1,224.20
1984	530.80	502.80	70.00	452.10	518.50
1985	749.70	826.20	653.00	482.00	893.50
1986	593.10	1,351.80	599.60	496.00	1,088.00
1987	869.50	936.70	478.00	719.00	1,039.80
1988	1,036.60	1,115.00	815.00	965.70	1,275.50
1989	613.80	833.20	459.50	474.50	835.00
1990	991.30	957.00	619.00	633.60	958.50
1991	854.20	897.00	513.00	484.00	1,036.50
1992	776.90	772.60	448.00	907.70	1,155.50
1993	1,154.90	1,258.00	497.00	525.50	1,176.00
1994	926.40	878.00	394.00	400.10	793.50
1995	1,132.60	853.30	285.00	268.00	105.50
1996	839.70	772.00	307.90	618.50	176.60
1997	966.90	724.30	641.40	648.80	826.30
1998	927.90	1,008.90	692.50	390.50	690.50
1999	789.00	261.50	360.50	722.00	467.50
2000	1,236.90	939.50	148.00	324.00	797.90
2001	1,233.40	939.30	475.00	795.80	1,128.30
2002	1,148.50	937.00	718.00	995.40	945.40
2003	1,565.70	129.50	707.20	803.00	1,302.70
2004	1,210.50	488.20	551.50	828.70	1,254.00
2005	1,396.70	1,010.40	592.60	1,458.90	1,224.50
2006	775.60	762.10	447.90	596.50	774.20
2007	1,039.50	682.60	497.40	851.30	760.90
2008	1,313.70	1,230.30	723.00	779.40	1,496.50
2009	666.70	624.30	551.80	793.20	817.00
2010	2,084.10	1,737.05	1,075.60	1,915.50	1,079.80
2011	637.70	542.10	281.00	416.40	605.70
2012	799.20	818.34	405.00	575.70	796.60
2013	1,393.90	1,366.50	963.00	1,625.40	1,313.00
2014	1,346.90	1,271.40	508.00	1,153.90	1,290.00
2015	991.50	987.10	588.20	707.90	1,029.30

mm = milimeters.
Source: Table developed by the authors, based on information from the SMN (2023).

Table 3. Mean annual precipitation.

Station	Mean Annual Precipitation (mm)
La Boca	1041.8
El Cerrito	539.1
El Pajonal	893.7
Laguna de Sánchez	716.2
Allende	999.6

mm= milimeters.
Source: Table developed by the authors, based on information from the SMN (2023).

1. **Runs or sequences method**. This method originated with the work of Yevjevich (1967), who first developed this model based on geometric distribution. Over time, he continued refining the method to incorporate techniques of series analysis to predict the occurrence and duration of droughts. The principle of this method is the analysis of periods that are below the mean (known as dry periods).
   The equations used in this method are as follows:

$$Sequences = hpi - hp_{media} \quad (1)$$

$$Severity = duration \times magnitude \quad (2)$$

2. **Foley method (Residual Mass Curve)**. This method examines the temporal behavior of dry and wet periods, as well as the monthly precipitation excesses and deficiencies in relation to the historical mean. According to this method, dry periods accumulate negative differences and consequently have a downward slope (Flores and Campos Aranda, 2015).
   The following equation was used for the Foley method:

$$Foley = \left(hpi - hp_{media}\right) + \left(hpi - hp_{media2}\right) \quad (3)$$

3. **Moving-average method**. This technique smooths out irregular, random variations in a series of chronological precipitation events, with the goal of prioritizing the recording of wet and dry cycles. The threshold for this method is the mean of the accumulated rainfall. One of the special features of this analysis is that the variables are evaluated in groups of five. Wet periods are identified by comparing the moving-average line against the mean rainfall line. In rainy periods, the first line is above the second, while dry periods are below the mean (Campos-Aranda, 1988).
   The main equation used in this method is:

$$\left[\left(hp_1\right) + \left(hp_2\right) + \left(hp_3\right) + \left(hp_4\right) + \left(hp_5\right)\right] / 5 \quad (4)$$

Once the drought periods have been identified at each weather station, the severity of the drought will be calculated. The results will indicate the yearly recurrence of this natural phenomenon. Further details about this calculation can be found in Campos Aranda (1988).

The return period calculation forescasts when an event of equal or greater magnitude will occur again. Mélice and Reason (2007) define the return period as the number of years when an extreme weather event is expected to be replicated or exceeded. The return period will be calculated with the following formula:

$$T_R = \left(\sum Recurrence\right) / \left(Periods - 1\right) \quad (5)$$

RESULTS AND DISCUSSION

After the three previously defined methods were used to identify droughts and return periods, the following results were obtained. According to the runs method (Table 4), 12 dry periods were identified at "La Boca," making it the station where the greatest drought was recorded.

The results of the Foley method (Table 5) are more conservative than those of the runs method. Although both methods identify "La Boca" as the station with the greatest number of droughts, the Foley method only identifies seven dry periods.

The third method (moving-average) was the most limited of all, although it showed the highest recurrence rates (Table 6). This method identified two stations ("El Pajonal" and "Allende") with three dry periods each.

More reliable results can be obtained through the classification as drought of those years in which at least two of the three applied methods identify the phenomenon at the same time (1982, 1983, 1984, 1985, 1986, 1991, 1992, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2006, 2007, 2011 and 2012). To increase the accuracy of the values of the return and recurrence periods shown in the previous tables, the return period for each station and method analyzed will be calculated (Table 7), using the weighted mean of the results obtained by the three methods.

The AX.EXE software —a program developed by the Mexican National Center for Disaster Prevention (CENAPRED: Centro Nacional de Prevención de Desastres)— was used to adjust the various probability distribution functions to the annual precipitation data. The expected annual precipitation for the return periods of interest was calculated based on these adjustments (Table 8). The results of this analysis provide projections of the maximum annual precipitation that could occur in the future in the Rodrigo Gómez Dam basin.

Research conducted in the Rodrigo Gómez Dam basin highlights the high vulnerability to drought events faced by the region. A return period of 3 to 5 years is predicted in the study area, highlighting the urgency of implementing preventive measures.

Although Mexico played an important role in the development of integrated water management, it is currently an area with deficiencies and which is rarely updated. Mexico is naturally vulnerable to these types of climate events; however, other factors increase this risk, such as water overexploitation, ecosystem destruction, uncontrolled population growth,

Table 4. Results of the runs method.

Station	Period	Year	Magnitude (mm)	Duration (years)	Severity	Recurrence
La Boca	1	1974	322	1	322	/
	2	1977	189.9	1	189.9	3
	3	1980	174.4	1	174.4	2
	4	1982	270.7	1	270.7	1
	5	1984-1987	356	4	1424.1	1
	6	1989	428	1	428	1
	7	1991-1992	226.25	2	452.5	1
	8	1996	202.1	1	202.1	3
	9	1999	252.8	1	252.8	2
	10	2006	266.2	1	266.2	6
	11	2009	375.1	1	375.1	2
	12	2011-2012	323.4	2	646.7	1
El Pajonal	1	197-1975	299.1	2	598.2	/
	2	1983-1984	448.6	2	897.2	7
	3	1989	79.6	1	79.6	4
	4	1992	91.1	1	91.1	2
	5	1994-1996	210.1	3	630.4	1
	6	1999-2000	284.85	2	569.7	2
	7	2006	91.2	1	91.2	5
	8	2011-2012	196.1	2	392.2	4
El Cerrito	1	1974	127.2	1	127.2	/
	2	1977	284.7	1	284.7	2
	3	1980	150.1	1	150.1	2
	4	1982	688.3	1	688.3	1
	5	1984	390.9	1	390.9	1
	6	1992	121.1	1	121.1	7
	7	1996-1997	145.55	2	291.1	3
	8	1999	632.2	1	632.2	1
	9	2003-2004	584.83	2	1169.66	3
	10	2006-2007	171.37	2	342.75	1
	11	2009	269.4	1	269.4	1
	12	2011	351.6	1	351.6	1
Laguna de Sánchez	1	1974-1975	124.45	2	248.9	/
	2	1979-1986	267.43	8	2139.4	3
	3	1989	241.7	1	241.7	2
	4	1991	232.2	1	232.2	1
	5	1993-1996	263.2	4	1052.7	1
	6	1998	325.7	1	325.7	1
	7	2000	392.2	1	392.2	1
	8	2006	119.7	1	119.7	5
	9	2011-2012	220.15	2	440.3	4

Table 4. Continues...

Station	Period	Year	Magnitude (mm)	Duration (years)	Severity	Recurrence
Allende	1	1977	149.6	1	149.6	/
	2	1980	293.1	1	293.1	2
	3	1982	243.5	1	243.5	1
	4	1984	481.1	1	481.1	1
	5	1989	164.6	1	164.6	4
	6	1994-2000	448.5	6	2690.9	4
	7	2006-2007	232	2	464.1	5
	8	2009	182.6	1	182.6	1
	9	2011-2012	298.5	2	596.9	1

mm = millimeters
Note: The symbol "/" in Recurrence indicates no recurrence data available.

Table 5. Results of the Foley method.

Station	Period	Year	Magnitude (mm)	Duration (years)	Severity	Recurrence
La Boca	1	1973-1975	137.5	3	412.6	/
	2	1978-1980	91.4	3	274.1	2
	3	1983-1988	218.9	7	1532.1	2
	4	1989-1993	163.6	5	817.9	1
	5	1996-1999	160.9	4	643.7	2
	6	2005-2007	28.8	3	86.4	5
	7	2010-2012	131.9	3	395.6	2
El Cerrito	1	1978-1980	916.7	3	2750.1	/
	2	1983-1985	222.23	3	666.7	2
	3	1993-1997	576.54	5	2882.7	7
	4	2002-2004	678.22	3	2034.66	1
	5	2005-2007	1244.7	3	3734.02	1
El Pajonal	1	1973-1975	323.8	3	971.4	/
	2	1982-1984	360.73	2	721.47	6
	3	1990-1996	226.69	7	1586.8	5
	4	1998-2001	774.13	4	3096.5	1
	5	2005-2007	724.21	3	2172.63	3
	6	2010-2012	266.09	3	798.28	3
Laguna de Sánchez	1	1973-1975	65.6	3	196.8	/
	2	1978-1986	581.1	9	5229.7	2
	3	1988-1991	1635.4	4	6541.7	1
	4	1992-1998	2472.8	7	17309.7	1
	5	2010-2012	1143	3	3429	12

Table 5. Continues...

Station	Period	Year	Magnitude (mm)	Duration (years)	Severity	Recurrence
Allende	1	1983-1985	120.9	3	362.6	/
	2	1988-1990	23.4	3	70.2	2
	3	1992-2000	288.9	9	2599.7	1
	4	2005-2007	79.7	3	239.2	4
	5	2010-2012	368.5	3	1105.4	2

mm = millimeters
Note: The symbol "/" in Recurrence indicates no recurrence data available.

Table 6. Results of the moving-average method.

Station	Period	Year	Magnitude (mm)	Duration (years)	Severity	Recurrence
La Boca	1	1983-2001	201.4	19	3826.1	/
	2	2009	375.1	1	375.1	7
El Cerrito	1	1981-1986	752.98	6	4517.9	/
	2	1998-2009	742.51	12	8910.09	11
El Pajonal	1	1977-1978	118.2	2	236.4	/
	2	1984-1988	196.1	5	980.5	5
	3	1993-2004	160.1	12	1921.4	4
Laguna de Sánchez	1	1981-2002	215.9	3	647.8	/
Allende	1	1984-1988	939.15	5	4695.76	/
	2	1995-2003	692.26	9	6230.3	6
	3	2010-2013	954.8	4	3819.2	6

mm = millimeters
Note: The symbol "/" in Recurrence indicates no recurrence data available.

Table 7. Return periods (years).

Station	Runs Drought Periods	Runs Retorn Period	Foley Drought Periods	Foley Return Period	Moving Averages Drought Periods	Moving Averages Return Period	Weighted Average	Rounded
La Boca	12	2.09	7	2.33	2	5.69	3.37	3
El Cerrito	12	2.09	5	2.75	2	9.14	4.66	5
El Pajonal	8	3.57	6	3.6	3	7.05	4.74	5
Laguna de Sánchez	9	2.25	5	4	1	2.57	2.94	3
Allende	9	2.38	5	2.25	3	5.36	3.33	3

Source: Table developed by the authors, based on information from the SMN (2023).

Table 8. Projection of precipitation (mm) for the calculated return periods.

Station	Return Period	Mean Annual Precipitation (mm)	Expected Annual Precipitation AX.EXE (mm)
La Boca	3	1,041.8	190.9
El Cerrito	5	539.1	1,171.0
El Pajonal	5	893.7	724.4
Laguna de Sánchez	3	716.2	650.1
Allende	3	999.6	1,099.7

mm = millimeters.
Source: Table developed by the authors, based on information from CENAPRED (2023).

industrialization, a deficient regulatory framework, and institutional opacity, to name a few. Unfortunately, Mexico lacks a public policy on drought prevention and mitigation. Its implementation would be key to develop a more efficient water and environmental management, as well as to reduce the vulnerability of Mexico to the growing effects of climate change. Arreguín-Cortés *et al.* (2016) suggest that, in order to ensure continuity, public policy needs to establish a new paradigm to address drought, shifting from a reactive to a preventive approach that transcends six-year administrations.

The lack of water literacy in Mexico makes people mistakenly believe that these types of problems are solely the responsibility of the authorities or that solutions are beyond the reach of common citizens. Droughts directly affect living beings, who depend on water for survival, and they also have a negative impact on the economy and health.

Esparza (2014) emphasizes that the large hydraulic structures built in the 20th century created a false sense of water abundance in Mexico. This perception has now been replaced by water waste and pollution, as well as by the concentration of the population in areas where there is not enough water to meet the basic needs. Drought prevention and planning not only reduces the negative impact on the environment and the economy, but also protects the well-being of communities. Barcia *et al.* (2014) emphasize that economic, social, and environmental consequences are more severe for populations that are not prepared to cope with them.

Droughts have economic, environmental, and social impact. The economic impact includes the loss of agricultural, livestock, forestry, and fishery production. The environmental impact directly affects ecosystems, altering their cycles, increasing erosion, and deteriorating water and air quality. Finally, the social impact can lead to food shortages, health problems, and conflicts between users and institutions responsible for water management; in addition this type of impact reduces the quality of life and increases poverty (Velasco *et al.*, 2005).

From an environmental point of view, the most damaging effects of droughts can be perceived in ecosystems, natural resources, flora, and fauna. These problems must be addressed: once an ecosystem has deteriorated, it is unlikely to survive the consequences of a drought (Vázquez *et al.*, 2007).

The drought in the Rodrigo Gómez basin not only impacts the population that depends on this source of drinking water, but also has a significant impact on the agricultural and recreational activities connected with the dam. Furthermore, droughts harm aquatic habitats and the species that live in this body of water.

The results of this study provide a solid basis for informed decision-making regarding water management and drought prevention in Nuevo León. Droughts have diverse consequences that impact key sectors —including agriculture, one of the pillars of the regional economy—, jeopardizing both food security and the income of rural families. Furthermore, water scarcity impacts the supply of drinking water in the metropolitan area of Monterrey and has a negative impact on local flora and fauna.

CONCLUSIONS

Drought is a complex phenomenon that requires a multidisciplinary solution. Such a solution must implement sustainable measures that promote a balance between society and the environment. For this purpose, the institutions responsible for managing these extreme events must be supported. The results of this research can provide the authorities of the state of Nuevo León with a key tool to strengthen action plans and establish the necessary measures that ensure the well-being of the population impacted by these types of climatic events. Furthermore, these findings provide a basis for the implementation of public policies that not only address drought prevention and mitigation, but also foster community resilience, improve natural resource management, and promote more sustainable practices. Incorporating these results into governmental strategies will enable a more effective response to future climate challenges, guaranteeing the safety, health, and quality of life of the inhabitants of Nuevo León.

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