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Rainfall uncertainty and water availability: elements for planning water allocation to users in irrigation districts of Mexico. Study case Irrigation District 041 Yaqui River

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HIGHLIGHTS

- We studied the impact of the ENSO on water availability in an irrigation district
- The ENSO strongly affect runoff to dams within the watershed
- The SPI and ENSO are correlated, and this defines water availability for agriculture
- The correlation SPI-RUNOFF may serve as criteria for water allocation to farmers
- Less water demanding crops should be part of a mitigation strategy under dry periods

Graphical Abstract

Rio Yaqui watershed with four main reservoirs

Regional ENSO and SPI relationships for the entire Yaqui River Watershed.

Rainfall (p) – runoff (Q) relationships and runoff coefficients (RC) for the three sub-watersheds of the Yaqui River.
Abstract

The aim of the work is to present a protocol for analyzing readily available climatic and hydrological information on watersheds for achieving a rational planning of irrigation water allocation under rainfall uncertainty conditions. We present as a case study the Rio Yaqui watershed and Irrigation District (ID) No. 041 in the state of Sonora in Mexico. The watershed is divided in three sub-watersheds that drain into three reservoirs. Findings indicate the strong dependence of water availability on the reservoirs, depending on El Niño phenomenon. In addition, rainfall-runoff relationships indicate the capability to produce runoff of each sub-watershed and the differentiated impact of El Niño. The three sub-watersheds require about the same amount of antecedent rainfall for initiating runoff (5 mm). A Standardized Precipitation Index (SPI) highlights the dynamics of dry and wet spells and the impact on planted area in the irrigation district. Overall, the functional relationships among El Niño, the SPI, and planted area in the irrigation district may serve for planning purposes under climate uncertainty scenarios.

Keywords. El Niño, irrigation, rainfall, runoff, SPI, watershed

Introduction

Spatial and temporal variations of water availability for agricultural and livestock purposes in irrigation basins have highlighted the vulnerability (i.e. resilience capacity) of these economical activities and enhance decision makers to consider changes within the productive systems aiming to make a more rational use of limited amounts of water. The impact of such variation in water availability and the consequent vulnerability has deeply affected the regional economy of arid lands in northern Mexico. The main irrigation districts in Mexico are located within the arid and semi-arid portions of the country where agriculture is strongly dependent upon runoff to the reservoirs. Water allocation to users for irrigation purposes is performed considering the history of flows to the dams. These flows are subject to rainfall uncertainty
The spatial variation of water availability in Mexico is of considerable magnitude; in this way, population and economic activities are inversely related to water availability. Less than a third of total runoff occurs within the 75% of the territory where most of the country's largest cities, industrial facilities, and irrigated land are located. Consequently, surface runoff and groundwater are becoming insufficient to support the high population growth rates and economic activity, resulting in disputes over surface water usage (Gonzalez and Magaña, 2018). Furthermore, the southwest part of Mexico accounts for two thirds of the renewable water in the country and one fifth of the population, whereas the northern part, where the main irrigation districts are located, accounts only for one third of renewable water and four fifths of the total population (CNA, 2018).

The northwest region of Mexico has been impacted by severe droughts through time (Buechler, 2009) and there is a lack of adaptation strategies to cope with the situation (Eakin et al., 2007). Climate uncertainty has been reported within the irrigation districts of Mexico. For instance, Sánchez-Torres et al. (2011) indicate that climate change scenarios have the most negative impact on water availability in the agricultural sector. The authors argue that water concessions, irrigation districts, and hydraulic infrastructure in the river basin need to be reconsidered and updated to assure water availability to all its users. On the other hand, Sanchez et al. (2018) analyzed the impact of El Niño Southern Oscillation (ENSO) on water availability in an irrigation district of northern Mexico. Their findings suggest a deep impact on water availability for all uses. Martínez, Patiño and Tamayo (2014) analyzed the climatic trends in Irrigation District 041, located in the lower watershed of the Yaqui River, concluding that there is an increasing trend of temperatures, but not in precipitation records. Paredes et al. (2018) also evaluated the impact of water resources availability on crops of the irrigation districts of the Rio Bravo Basin; they concluded that temperatures, rates of evapotranspiration, and crop water demand would increase under the different scenarios evaluated with impact on the irrigation districts’ operation.

This study aims to present a protocol for analyzing readily available climatic and hydrological information for achieving a rational planning of irrigation water allocation to users through optimal irrigation plans considering the impact of climate change on water resources. We present as a case study Irrigation District No. 041 in northern Mexico.
Methods

The algorithm seeks to link climate and hydrologic information to have a rational appraisal of the impact of climate variability on water resources for agricultural purposes. Figure 1 presents the general flux diagram of the protocol for achieving the objectives of the study. The core of the planning is the availability of databases. In Mexico, there exist databases of easy access through official dependences concerning natural resources. For instance, Table I presents some of the databases available from where information may be drawn for analysis purposes.

Fig. 1. Flux diagram of the protocol for data analysis.

<table>
<thead>
<tr>
<th>Table I. Some sources of spatial information on natural resources and geographic data in Mexico.</th>
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In Mexico, there are 85 irrigation districts and 13 administrative regions that annually register more than 3 million irrigated hectares throughout the country. Only the northwest region, predominantly arid, reports 480,000 hectares within seven irrigation districts. In this region, the main irrigation district (ID) is 041 (Rio Yaqui) with an average of 280,000 irrigated hectares planted each year (CNA, 2018). ID No. 041 is located in the lower part of the Yaqui River Watershed. The watershed has an area of 75,452 km². The ID is strongly dependent on the runoff captured in the upper watershed that feed the reservoirs. In this way, the planted area in the ID variates through time. The watershed of the Rio Yaqui encompasses two states: Sonora and Chihuahua in the northern portion of the country (Fig. 2). Even though runoff is gaged for each sub-watershed that drains off to each reservoir, the planning of the irrigation district takes into account the total available volume considering the system of reservoirs. Not all the available water is used for agricultural purposes in the region; specific uses are presented in Table II.

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Fig. 2. Rio Yaqui watershed with four main reservoirs. Lazaro Cardenas (upper), Plutarco Elias Calles (middle) and Alvaro Obregon (bottom). The Abraham Gonzalez dam does not provide water to the system of dams that irrigate the irrigation district in the lower watershed.

Table II. Reservoir use and respective watersheds within the Rio Yaqui River.

Hydrologic data

Local authorities of the National Water Commission provided monthly runoff data (volumes) for each sub-watershed considered within the study; the length of the record was from 1941 through 2018. This data comes from the gauging stations of each sub-watershed (Fig. 2).

Rainfall data

Daily rainfall records were obtained from the climatic stations within the watershed. The criteria for selecting the climatic stations was to have at least 30 years of consecutive information with no more of 10% of missing information and having been operated at least through 2005. Afterwards, a consistency and homogeneity analysis of the climatic information was performed for verifying the usefulness of the data (Esquivel et al., 2019). The length of runoff records was larger than rainfall data.

Standardized Precipitation Index (SPI)

The method for Standardized Precipitation Index (SPI) computation was developed by McKee et al. (1993) and Edwards and McKee (1997) to study relative departures of precipitation from normality. It uses monthly precipitation aggregates at various time scales (1, 3, 6, 12, 18, and 24 months). The SPI is obtained by fitting a gamma or a Pearson Type III distribution to monthly precipitation values. Generally, monthly precipitation is not normally distributed, thus a transformation is performed such that the derived SPI values follow a normal distribution. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. The scale of the SPI is: 2.0+ extremely wet, 1.5 to 1.99 very wet, 1.0 to 1.49 moderately wet, -0.99 to 0.99 near normal, -1.0 to -1.49 moderately dry, -1.5 to -1.99 severely dry, and -2 and less extremely dry (WMO, 2012).
The irrigation district 041 has a system of reservoirs in the upper watershed of the Rio Yaqui that provide water for the irrigation purposes as well as for energy generation and industrial activities. For assessing the water availability to the irrigation district, we computed a SPI for each sub-watershed of the Yaqui River, and then, a regional SPI was obtained after a principal component analysis (PCA) for obtaining those climatic stations that better account for data variability. The PCA is a statistical procedure for filtering data. This procedure synthetizes in a few new variables not correlated the major part of the total variation of a high number of variables highly inter-correlated. This reduction in dimensionality leads to a better understanding and interpretation of the data. The newly non-correlated variables are called Principal Components and they consist in linear combinations of the original variables (Sigdel and Ikeda, 2010). This analysis allowed to determine the percentage of the common variability among climatic stations and to the integration of a regional SPI.

**El Niño Southern Oscillation (ENSO)**

For assessing the impact of general circulation patterns on rainfall regimes within the study region, we correlated El Niño Southern Oscillation (ENSO) data with the SPI for the three sub-watersheds of the Yaqui River. The ENSO cycle is a scientific term that describes the fluctuations in temperature between the ocean and atmosphere in the east-central Equatorial Pacific, approximately between the International Date Line and 120 degrees west (NOAA, 2020).

Indices used to monitor the tropical Pacific are based on sea surface temperatures (SST) anomalies averaged across a given region. Usually, the anomalies are computed relative to a base period of 30 years. The Niño 3.4 index (5°N - 5°S, 120° - 170°W) and the Oceanic Niño Index (ONI) are the most commonly used indices to define El Niño and La Niña events (Trenberth and Stepaniak, 2001). The numbers (3.4 index) correspond with the labels assigned to ship tracks that crossed these regions. The Niño 3.4 anomalies may be thought of as representing the average equatorial SSTs across the Pacific from about the dateline to the South American coast. For an event to be classified as El Niño, the 5-month running mean must exceed +/- 0.4°C for a period of six months or more. The ONI uses three month averages and to be classified as a full-fledged El Niño or La Niña, the anomalies must exceed +0.5°C or -0.5°C for at least five consecutive months (Trenberth, 2020). The El Niño Southern Oscillation Index (commonly used as SOI) is a
standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia. The computation of SOI is shown in equation (1):

\[
SOI = \frac{STD \, T_a - STD \, D_a}{MSD} \tag{1}
\]

Here \(STD \, T_a\) is the standardized sea level pressure for Tahiti; \(STD \, D_a\) is the standardized sea level pressure for Darwin and \(MSD\) is the monthly standard deviation. For computing the standardized sea level pressure either for Tahiti or Darwin the equation (2) is used:

\[
STD \, T_a-D_a = \frac{AT_{a-D_a} \, SLP - M \, T_{a-D_a} \, SLP}{STD_{a-D_a}} \tag{2}
\]

where \(AT_{a-D_a} \, SLP\) is the actual sea level pressure either for Tahiti \((T_a)\) or Darwin \((D_a)\), \(M \, T_{a-D_a} \, SLP\) is the mean sea level pressure for either Tahiti or Darwin and \(STD_{a-D_a}\) is the standard deviation for the sea level pressure for either Tahiti or Darwin. The monthly standard deviation is computed as shown in equation (3):

\[
MSD = \sqrt{\frac{(STD \, T_a - STD \, D_a)^2}{N}} \tag{3}
\]

where \(STD \, T_a\) is the standardized sea level pressure for Tahiti, \(STD \, D_a\) is the standardized sea level pressure for Darwin and “\(N\)” is the number of months.

Data of the El Niño were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2019).

**Rainfall runoff relationships**

For better appreciation or watershed potentiality for producing runoff and as a basis for planning purposes, we computed the rainfall runoff relationships for the three sub-watersheds that drain to the irrigation reservoirs. In this way, rainfall and runoff depths were correlated and the
rainfall-runoff functions obtained. Runoff depth (mm) was obtained dividing the runoff volume by the watershed area. Equation (4) describes this relationship:

\[ Q = a e^{bp} \]

(4)

where “\( a \)” and “\( b \)” are regression parameters that depend on watershed characteristics and “\( p \)” is precipitation (mm).

Results and discussion

Figure 3 shows the relationship of ENSO and the SPI for the three sub-watersheds of the study named according to the reservoir they drain to: Lazaro Cardenas, Plutarco Elias Calles, and Alvaro Obregón. It should be noted how the ENSO modulates the rainfall patterns in the sub-watersheds, therefore, it also influences the volume that runs off the sub-watersheds to the reservoirs. As previously stated, the ENSO phenomenon is a change in the thermal conditions of the ocean; therefore, the main impact is in a substantial modification in rainfall patterns in the continents. According to this, from figure 3, it should be noted that the SPI responds accordingly to the signal of the ENSO; also, periods of dry and wet spells are evident. Runoff generation is differentiated in each sub-watershed depending on physical and surface condition of each area.

The regional SPI was used for runoff generation in the whole watershed. As previously noted, the climatic stations considered for the regional SPI computation were chosen from a PCA. Figure 4 shows the regional SPI for the Yaqui watershed.

Fig. 3. ENSO and SPI relationships for the three sub-watersheds of the Rio Yaqui Watershed.

Fig. 4. Regional ENSO and SPI relationships for the entire Yaqui River Watershed.
Dry spells have had a huge impact on planted area in the irrigation district down below the Rio Yaqui Watershed. Planted area in the irrigation district is a function of the available water for irrigation purposes; in this way, figure 5 shows the variation of the planted area in the irrigation district through time as a function of the SPI and the runoff generated in the upper watershed.

Fig. 5. Runoff volume to the system of dams and planted area in ID No. 041 as a function of SPI.

The volume of runoff is strongly dependent upon the watershed characteristics, soil type, soil cover, slope, and management (Hudson, 1993). From this relationship, a runoff coefficient (RC) can be obtained. The RC is a parameter describing basin response, on either an annual, or an event basis (Blume Zehe and Bronstert, 2007). Rainfall-Runoff curves depict the behavior of these combined variables and serve for having an appreciation of the runoff that may be expected given a rainfall event. Figure 6 shows the rainfall-runoff curves for the three sub-watersheds of the Yaqui River.

Fig. 6. Rainfall (p) – runoff (Q) relationships and runoff coefficients (RC) for the three sub-watersheds of the Yaqui River.

From figures 3, 5, and 6 some useful information may be obtained for decision-making processes:

- In terms of SPI values, the most impacted sub-watershed by the EL NIÑO and its associated SPI is Lazaro Cardenas, followed by Alvaro Obregon and Plutarco Elias Calles sub-watersheds. Data querying and visual appreciation of figure 4 displays that SPI values for the Lazaro Cardenas shows the most persistent negative values for this index, indicating more dry spells within the data series. The SPI also indicates, besides the magnitude of the spell, the duration of the dry or wet period.

- Under a “normal year” (SPI ≈ 0), the allocated volume for irrigation should be close to 3,500 Mm$^3$ (where the regression line crosses the “Y” axis).
- The irrigated area with the above condition would be near to 212,000 hectares.
- The decision criteria for allocating water to users under moderately drought conditions (-1 < SPI ≤ -1.49) with available volumes below 2,000 Mm³, should consider less water-demanding crops and irrigation schemes that increase water use efficiencies.
- Even though the Lazaro Cardenas and Alvaro Obregon sub-watersheds have a greater RC (0.11), under the same amount of rainfall, the Plutarco Elias Calles (RC = 0.10) produces more runoff given its relatively larger area.
- Without losing generality, the three sub-watersheds require about the same amount of antecedent rainfall for initiating runoff (≈ 5 mm) which is an indicator of the generalized surface condition in the three sub-watersheds.
- The rainfall runoff relationships shown are fitted curves to observed data; therefore, applying the regression models do not imply that under cero precipitation a runoff event will occur. The R² of these relationships between rainfall and runoff highlight the need of having more hydrologic data that better represents the watershed behavior. Therefore, the models should be used as a first approach for having a rational assessment of the amount of runoff that a given amount of rainfall will produce.
- The coefficients of determination (R²) shown in figure 5 are of significance at α = 0.05% for one tailed test. The results of a one-tailed test will double the significance compared with the corresponding two-sided test. Our null hypothesis was that increasing the SPI value (representing precipitation) will increase runoff events and therefore planted area; to expect the opposite will be unreal and unphysical.

Conclusions

We delineated a protocol for analyzing readily available climatic and hydrologic information for achieving a rational planning of irrigation water allocation to users. The SPI and the rainfall-runoff relationships linked to El Niño phenomenon, involve the climatic variation of a region that have a huge impact on water availability for irrigation. Within this context, the operation of irrigation districts should consider the availability of water volume in the reservoirs, accounting for the composition of the crop pattern that maximizes net income and water productivity. We agree with the work of Sanchez-Torrez et al. (2011) where they conclude that climate change
scenarios have the most negative impact on water availability in the agricultural sector. Also the Environmental Protection Agency of the United States of North America (EPA, 2017), considers that dealing with drought could become a challenge in areas where rising summer temperatures cause soils to become drier.

The functional relationships obtained between climatic and hydrological information may be useful to anticipate irrigation plans under climate uncertainty scenarios that characterize watersheds in arid and semi-arid regions, as the one used as a model in this study.

Acknowledgments

The authors wish to thank the Foundation Board for Agricultural Research for the State of Sonora (PIAES) and the Ministry of Agriculture for Rural Development (SADER) for their economical support.

References


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<thead>
<tr>
<th>Reservoir</th>
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