The impact of climatic patterns on runoff and irrigation water allocation in an arid watershed of northern Mexico

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Abstract. The uncertainty of water availability is the main problem in planning for water resources in watersheds of agricultural drylands. Water availability for different uses depends on the runoff that is generated in the upper portion of the watersheds, where there are higher elevations and lower temperatures. Proximity to the ocean is a main factor that defines rainfall amounts. In this research we linked the effects of El Niño to a regional Standardized Precipitation Index (*SPI*) and the subsequent impact on runoff production and irrigation water allocation. Findings indicate the cascading impacts of the El Niño on the *SPI*, the *SPI* on the runoff discharge to the irrigation reservoir, and the final impact on the planted area within the irrigation district. An optimization procedure was applied to maximizing net income in agriculture under different water availability scenarios. The restrictions to the optimization model were: total available water, crop water demand, and available land. Local criteria for defining the maximum allowable planted area by crop also were taken into account. The analysis with various water availability scenarios demonstrated that with limited amounts of water for irrigation, forage area would be limited, thereby increasing the area of crops with lower water demands. In both scenarios the area of forage maize was reduced from 11 300 to 1 764 ha. Increasing irrigation water use efficiency may save water for expanding the irrigated area, or for other uses.

Keywords: *ENSO*, *SPI*, watershed, cropped area, irrigation

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1. Introduction

Climate variability, water scarcity, and water quality have been important issues for many countries. Thus, there is a need for planning preventive measures for avoiding huge impacts on human populations; water resources are essential to health as well as social and economic development. According to The Water Project (2018) water status within various nations may take distinctive forms: physical water scarcity or low quantity of water, and economic water scarcity or low quality of water. The agricultural sector is more concerned about the availability of sufficient water for irrigation than in its quality; nevertheless, agricultural water management has been shown to have impacts on the sustainability of the agricultural sector; see, for example, Ayers and Westcot (1994).

In many parts of the world water availability for the different users depends on the runoff that it is generated in the upper portions of the watersheds where there are higher elevations and lower temperatures. In watersheds of northern Mexico rainfall and runoff amounts are tied to climatic oscillations of the Pacific Ocean, affecting agriculture in the lower areas of watersheds.

In Mexico about 25 million ha are cultivated yearly (nearly 30% of the total area of the country). Of that amount, 6.5 million ha are within irrigation districts and irrigation units, which use almost 77% of the total water available (Sánchez et al. 2002). The remainder of the area is rain-fed agriculture. Agricultural and livestock production accounts for 65.5 km^3 of yearly water use; urban use accounts for 12.5 km^3. The yearly average availability of water per person is 3 736 m^3. This average is biased, because there is a huge imbalance in water availability and rainfall distribution throughout the country. In this way, the southern portion of the country, with 23% of the total population, accounts for 67% of total water availability and contributes only 20.2 % of the GDP. On the other hand, the northern part of the country, with 77% of the population, accounts for 33% of total water availability and contributes 79.8% of the GDP (CNA 2015). It is this portion of the country where the main irrigation districts are located.

Irrigated agriculture in the northern part of the country is heavily dependent upon water storage in the reservoirs, which in turn depends on rainfall and runoff events. As previously outlined, these events are tied to global climatic patterns such as El Niño Southern Oscillation (*ENSO*) (Li et al. 2013). Thus, planning for any agricultural year in the irrigation districts of Mexico takes into account the water storage in the reservoirs at the end of the month October of the previous year. After the balance of the basin is determined, producers meet with water authorities to discuss the crop pattern in the irrigation district that should be authorized according to the yearly storage in the reservoir and the producer's water rights.

In this paper we aim to link the *ENSO* events to the regional Standardized Precipitation Index (*SPI*) and consequent water availability in the middle part of a watershed in northern Mexico. The water availability, in turn, rules the decision-making process for delivering water to irrigation users.

We also seek to propose crop patterns in the irrigation district that maximize net return and water productivity under various water availability scenarios.

2. Materials and methods

2.1. Study area description

The analysis performed in this paper was applied to the Nazas watershed in the northern portion of Mexico. This watershed is located within Hydrological Region No. 36 of the Nazas and Aguanaval Rivers; it has a surface area of 18 321.64 km^2 and a perimeter of 1 162.12 km. (INEGI 2018; Fig. 1). The watershed encompasses the Ramos River (including the rivers Tepehuanes and Santiago) and the del Oro or Sextin River from which surface runoff is stored in the Lazaro Cardenas Reservoir. The highest elevation of the watershed is 3 300 m ASL and the lowest 1 400 m ASL. The study region represents the condition of most watersheds in the arid portion of northern Mexico. For assessing the impact of the *ENSO* within the region, we used daily rainfall data from 17 climate stations located upstream in the Nazas River basin. The climatic stations are operated by the National Meteorological Service of the National Water Commission. The criteria for selecting the stations were (1) to have at least 30 years of consecutive information with no more than 10% of missing information and (2) 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. 2018; Table 1).

2.2. Irrigation district description

Irrigation District 017 encompasses the municipalities of Gomez Palacio, Lerdo, Tlahualilo, Nazas, Rodeo, Mapimi, San Juan de Guadalupe, and Simon Bolivar within the state of Durango, and the municipalities of Torreon, Matamoros, San Pedro de las Colonias, Francisco I. Madero and Viesca within the state of Coahuila. The irrigation district includes 20 irrigation modules, of which 17 correspond to the Nazas River and 3 to the Aguanaval River. The district has a surface area of 223 822 ha with an average annual franchised volume of

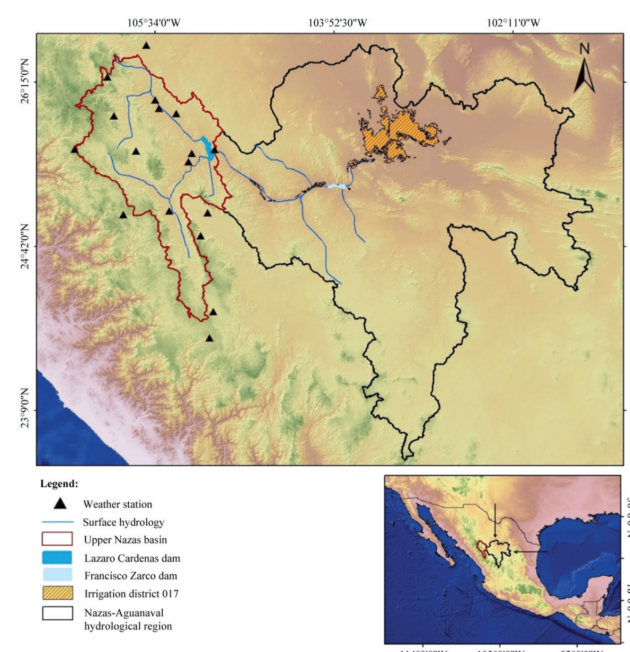

Fig. 1. Location of the study area in Hydrologic Region No. 36, Nazas River in Northern Mexico

Table 1. Climate stations included in the analysis of the watershed

No.	Station	Height (MASL)	Yearly average precipitation [mm]	Latitude	Longitude	Availability of information
1	Santiago Papasquiaro	1822	553	25°03´00´´	105°24´55´´	1922-2016
2	Guanaceví	2181	629	25°55´59´´	105°57´06´´	1922-2016
3	El Palmito	1545	370	25°36´52´´	105°00´13´´	1941-2016
4	Cendrandillas	2423	617	26°16´58´´	106°00´38´´	1961-2014
5	Chinacates	2105	427	25°00´ 36´´	105°12´42´´	1963-2014
6	Otinapa	2369	669	25°03´13´´	105°00´31´´	1963-2013
7	Rosario	1858	457	25°30´22´´	105°38´39´´	1963-2008
8	El Tarahumar	2610	926	25°37´01´´	106°19´28´´	1964-2009
9	Navíos viejos	2587	786	25°50´04´´	105°02´30´´	1964-2014
10	Cienega de Escobar	2218	559	25°36´03´´	105°44´47´´	1965-2008
11	Santa María del Oro	1746	564	25°57´12´´	105°22´00´´	1967-2016
12	Tejamen	2143	691	24°48´30´´	105°08´02´´	1969-2014
13	Sardinas	1722	503	26°05´03´´	105°33´57´´	1970-2016
14	Los altares	2549	827	24°59´20´´	105°53´30´´	1973-2016
15	Tejamen	1663	575	26°00´16´´	105°31´36´´	1976-2008
16	General Escobedo	1643	575	25°30´00´´	105°15´ 00´´	1979-2016
17	Inde	1642	357	25°34´32´´	105°13´11´´	1979-2009

1.024 million m^3, which irrigates 93 409 ha and benefits 37 956 water users (Macías Rodríguez et al. 2007).

The irrigated surface varies depending upon the volume of water in the reservoirs, which in turn depends on rainfall and runoff patterns in the upper watershed.

2.3. Data analysis

Sea surface temperature is the basis for the *ENSO* index among the international scientific community. Internationally, the El Niño regions have been divided into four sub-regions: Niño 1+2, Niño 3, Niño 3.4 and Niño. The regions and numbers are tied to the marine routes within these regions (Trenberth, Stepaniak 2001; NCAR 2017). For this study sub-region Niño 3.4 has been used for projecting the impact of El Niño on the water resources in the study watershed. Therefore, we correlated the *ENSO* 3.4 data with the SPI for the watershed, according the study of Li et al. (2013).

2.4. Precipitation data

The Standardized Precipitation Index (*SPI*) quantifies not only precipitation deficit but also precipitation excess for different time scales; the procedure involves the adjustment of the two-parameter gamma probabilistic model, which is transformed to a normal distribution of the variable *SPI* (McKee et al. 1993). A positive value of the *SPI* represents a wet period whereas a negative value represents a dry spell. *SPI* values range from +2 (extremely wet) through –2 (extremely dry).

The *SPI* was obtained for the region after computing the index for each of the 17 climatic stations included in the project. For obtaining the regional *SPI*, internal variations of this index were checked using principal components analysis.

2.5. Runoff data

Runoff data for the region were obtained from the National Water Commission of Mexico through the National Depository of Data of Surface Water (CNA 2018). This data base contains the daily flow of the main rivers of Mexico [m^3 sec^{-1}] as well as the volume that the reservoirs capture after each runoff event [m^3].

3. Results

Figure 2 shows the relationship between the *ENSO* and the *SPI* for the study region. The analysis extends through 2005, covering the available record (Li et al. 2013). From this figure it can be seen that the trend of the *SPI* resembles that of the *ENSO*, indicating the influence of the latter on the former, with some variations. The presence of wet and dry years is characterized by the highs and lows of the series, respectively.

There is information through 2016 about runoff generated in the watershed, permitting the expansion of the

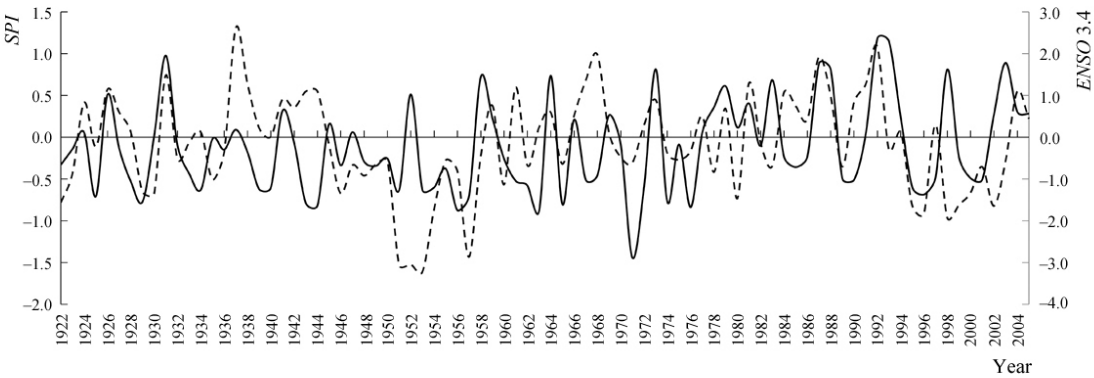

Fig. 2. Relationship between the *ENSO* (solid line) and the *SPI* (dotted line) for the study region

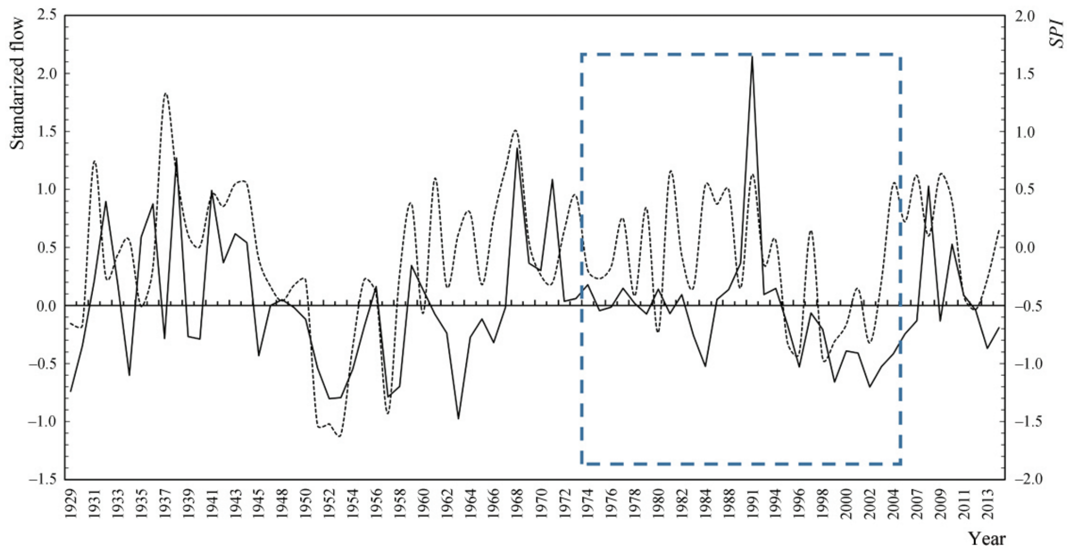

Fig. 3. Relationship between the *SPI* (dotted line) and the flows to the reservoir (solid line) for the study region. The inset frame encompasses the data availability for *ENSO* episodes

trend of Fig. 2 to show that these variations have had an impact on runoff to the storage reservoir that feeds the irrigation district lower in the watershed. In Figure 3 the relationship between the *SPI* and the runoff is shown. The flows have been standardized following the work of Zhai et al. (2010) as:

$$Qs = \frac{Qi - \hat{Q}}{\hat{Q}} \tag{1}$$

where Qs is the standardized flow, Qi is the i^{th} observed flow and is the average flow.

The variability of the *SPI* in the watershed has affected the runoff to the Lazaro Cardenas reservoir and hence has had an impact on the planted area within the irrigation district, as shown in Fig. 4.

The correlation coefficients for the dependent variables *SPI* and Planted Area are of significance at 95% confidence, with p values of 0.04 and 0.0005, respectively (one-tailed test), below the threshold for significance ($\alpha = 0.05$). The corresponding t values support the evidence against the null hypothesis that there is no significant difference between the population mean and a hypothesized value. For the dependent variable Q, the correlation coefficient is significant at $\alpha = 0.10$.

According to the results, for a wet *SPI* (≈ 1), the flow to the reservoir will increase about 7.87 $m^3 \cdot sec^{-1}$, leading to an increase in planted area of 23 849 ha. On the other hand,

Table 2. Statistical parameters for the linear regression analysis

Predicted variable	Constant	Coefficient		*t*	*p*	Standard coefficient
		SPI	*ENSO*			
Q	33.08	7.874		1.331	0.09	0.248
SPI	–0.073		0.164	1.713	0.04	0.361
AREA	50 670.235	23 849.579		4.244	0.0005	0.717

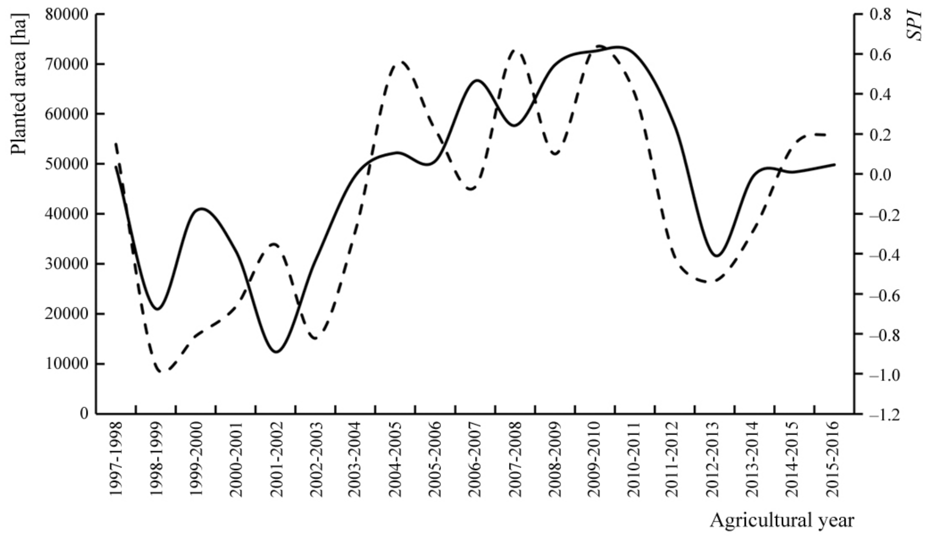

Fig. 4. Time variation of planted area (irrigated) for a given year (solid line) in the irrigation district as a function of the *SPI* (dotted line); for a wet *SPI* (> 0) planted area tends to increase and for a dry *SPI* (< 0) the planted area decreases; the correlations and statistical significance of the trends of Fig. 2, 3 and 4 above are shown on Table 2

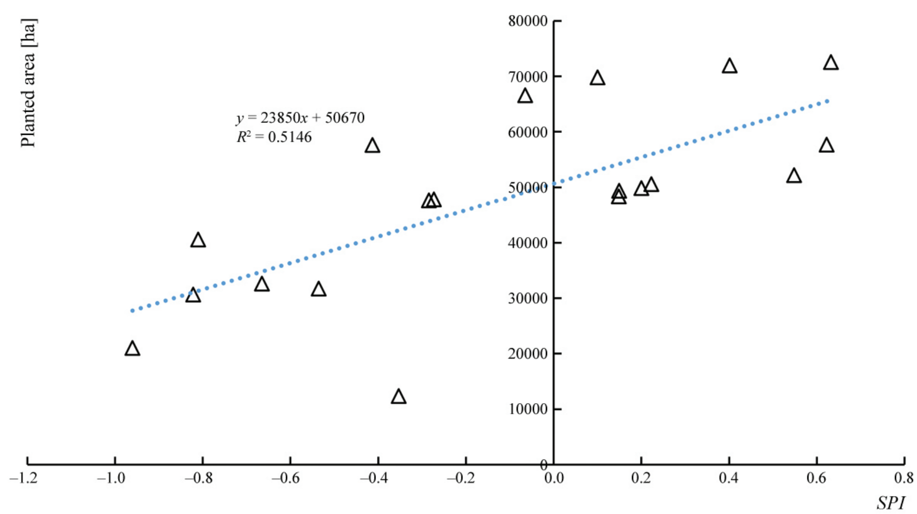

Fig. 5. Statistical correlation between *SPI* and planted (irrigated) area; as the *SPI* increases, so does the planted area, since *SPI* > 0 indicates a wet year

for a moderate *ENSO* 3.4 index (≈ 1), the *SPI* will increase about 0.164 units with impacts on the flow to the reservoir.

Nevertheless, the volume delivered to the irrigation water users in any given year depends on the storage volume in the reservoir during October of the previous year.

Of special interest is to expand the correlation between the *SPI* and planted area shown in Fig. 4; in this way, Fig. 5 shows the statistical correlation between these two variables.

Water allocation criteria

According to the irrigation district regulations, the irrigation district managers allocate the irrigation water according to the water balance in the reservoir up to the end of October. The historical crop pattern from the agricultural year 1997-1998 through 2015-2016 is shown in Table 3. In the last two columns the presence of the El Niño or La Niña is marked to show the lagged impact of these phenomena through time.

The predominant crops within the irrigation district have been forage, since this part of the country is the main milk producer of Latin America. It accounts for more than 230 000 head of cattle that produce about 6 million L of milk daily (Sánchez Cohen et al. 2016).

An optimization procedure was undertaken to assess the economic feasibility of the traditional crop pattern under limited amounts of water for irrigation. In this way, an objective function was proposed for maximizing net income, having as constraints: (1) the number of ha to be planted according the historical record of allowable cropped area; (2) the total water volume needed to fulfil the evapotranspiration needs of each crop; and (3) the availability of water in the reservoir. Two scenarios were considered: below average availability of water (year 1998-

Table 3. Historical crop patterns and areas [ha] for Irrigation District 017 from 1977 through 2016

Year	Crop											Climate	
	Cotton	Peanuts	Chile peeper	Beans	Tomato	Corn (forage)	Corn (grain)	Cantaloupe	Water melon	Shorghum (industrial)	Shorghum (forage)	El Niño	La Niña
1997-1998	16 100	251	753	4 861	780	6 738	2 919	861	779	2 601	3 889	Very strong	
1998-1999	5 413	10	221	725	57	2 203	343	790	540		2 951		strong
1999-2000	7 048		1 318	1 055	207	8 737	1 956	689	993		5 465		Strong
2000-2001	7 692	50	538	478	577	6 717	1 361	654	671		2 535		Weak
2001-2002	1 120		190	356	64	2 652	21	360	85	721	2 019		
2002-2003	4 497	95	628	1 060	276	10 077	308	1 013	1 307	2 047	2 871	Moderate	
2003-2004	13 590		1 240	272	556	15 691	445	924	495	1 836	3 607		
2004-2005	17 284	257	1 950	178	604	12 031	3 974	796	890	2 415	3 246	Weak	
2005-2006	15 866	260	1 849	177	612	11 982	3 970	792	855	2 365	3 242		Weak
2006-2007	18 066	129	518	69	145	21 227	28	1 624	1 298	603	12 833	Weak	
2007-2008	14 324	137	477	15	10	15 297	881	1 090	1 327	1 084	13 710		Strong
2008-2009	16 522	85	1 151	89	361	16 888	905	1 003	489	1 277	19 164		Weak
2009-2010	23 299	100	644	80	389	14 842	517	1 400	1 034	1 678	15 183		
2010-2011	23 197	100	572	64	480	14 224	605	1 024	369	1 736	16 960		Strong
2011-2012	16 610	90	270	30	310	11 506	470	554	244	218	15 520		Moderate
2012-2013	5 788	10	209	4	50	4 352	384	464	140	84	10 948		
2013-2014	12 654	200	497	7	123	7 571	487	443	345	249	13 816		
2014-2015	11 674	200	590	9	225	9 461	447	495	586	42	13 075	Weak	
2015-2016	10 284	200	630	2	296	22 295	62	945	438	142	3 853	Very strong	

1999) under the influence of the strong La Niña event, and a scenario with a moderate El Niño event (2002-2003), see Table 3. No further scenarios with sufficient water in the reservoir were analyzed since under this condition the available land (within the limits of the irrigation district) and water for irrigation will be unlimited. The objective function and their restrictions have the form of:

A. For the objective function:

$$\max(NI)\sum_{c=1}^{N} Mp \cdot F \text{ [ha]} \tag{2}$$

where *NI* is the net income to be maximized, *c* is a particular crop, *N* is the total number of crops, *Mp* is the market price and *F* is the number of ha to be planted.

B. For the restriction on availability of land:

$$\sum_{c=1}^{N} \leq \text{Available land} \tag{3}$$

The available land refers to the total irrigable land and the total area to be planted should not exceed this amount.

C. For the restriction of available water volume:

$$\sum_{c=1}^{N} F \cdot E\text{t} \leq \text{Available volume} \tag{4}$$

where *Et* is the evapotranspiration or crop water needs. The available volume is that in the runoff collecting reservoir and the amount to be used (equation 4) is a function of the water user's association criteria considering the National Water Commission regulations.

An additional restriction to the model was the maximum allowable limit to plant for each crop to be considered in the crop pattern. This value considers economic and social inputs. For instance, if the water user's association decides to plant the whole area of the irrigation district with the crop that generates the most revenues, then the market price will be affected with a serious impact on the regional economy. On the other hand, if the selected crops are those with the higher water demands, then the crop pattern resulting from the optimization procedure will be affected, reducing the number of ha to be planted according to the availability of water in the reservoir. So, for this study the average crop area planted historically was considered within the optimization procedure.

For the objective function, in each scenario analyzed the market prices were set to those prevailing within the respective year according the National System of Agricultural Information (SIAP 2018). In both scenarios the objective function maximized net income by restricting the planted area of forage crops, given their comparatively low earnings per ton and the relatively higher water use. Forage maize was restricted from a proposed 11 300 ha down to 1 764 ha. Under the limited water availability scenario, the crops with higher market prices and lower evapotranspiration comprise the solution of the objective function. Crops entering the solution were: cotton, peanuts, chili, tomato, forage maize, grain maize, beans, industrial sorghum, forage sorghum, cantaloupe, and watermelon. An increase in irrigation water use efficiency may increase the planted area by saving water for other less water demanding crops.

The scheme for the analysis of the impact of global climate patterns presented in this paper may help decision-makers in the irrigation districts to plan in advance the area that should be planted given the behavior of the *ENSO* and *SPI* indexes. The *SPI* is readily computed and, since its value is influenced by the *ENSO*, planners may use the *SPI* index for an objective computation of possible available volumes of water for irrigation.

4. Conclusions

The impact of *ENSO* on the northern part of Mexico has been assessed indicating the cascading effect this climatic pattern has on the agriculture of the watersheds of this part of the country. The nested algorithms used are useful for planning water assets for agriculture under different climate scenarios. Even though the study was directed only to a watershed located in the northern part of Mexico, the analytical process may serve for data from any watershed that may be influenced by this climatic phenomenon. The *SPI* is an efficient yet easy tool for measuring this impact with readily available information. If there is available information on runoff within the watershed of interest, then an economic analysis may be performed to synthesize information for planning irrigated agriculture in the lower watershed. The optimization of net income is of crucial importance in maximizing water productivity as a decision variable under different water availability scenarios. For this study, results have indicated the need for shifting to less water-demanding crops, reducing the planted area of forage crops even though they sustain a very important industry (milk) that in turn stimulates the local economy. Nevertheless, the ecological implications of an economic benefit analysis should prevail within the decision-making regime when allocating limited amounts of water within the region. Increasing water use efficiency in the irrigated agriculture sector should play an important role, since competition among water users (agricultural, households, industry, etc.) is increasing and the agricultural sector remains as the main user of the water resources of the country (77%). The analytical processes used in this paper serve to downscale a global phenomenon *ENSO* to local impacts.

Bibliography

Ayers R.S, Westcot D.W., 1994, Water quality for agriculture, FAO Irrigation and Drainage Paper, 29, available at http://www.fao.org/docrep/003/t0234e/t0234e00.HTM (data access 11.05.2018)

CNA, 2015, Atlas del agua en Mexico, Comisión Nacional el Agua, available at http://www.conagua.gob.mx/CONAGUA07/Publicaciones/Publicaciones/ATLAS2015.pdf (data access 11.05.2018)

CNA, 2018, Comisión Nacional el Agua, available at ftp://ftp.conagua.gob.mx/Bandas/Bases_Datos_Bandas (data access 11.05.2018)

Esquivel A.G., Cerano Paredes J., Sánchez Cohen I., Velasquez Valle M.A., Flores Lopez F., Bueno Hurtado P., 2018, Influencia de ENSO en la variabilidad de la precipitación en la cuenca alta del Nazas, México, Journal Tecnología y Ciencias del Agua, (in press)

INEGI, 2018, Instituto Nacional de Estadística y Geografía, available at http://antares.inegi.org.mx/analisis/red_hidro/siatl/# (data access 11.05.2018)

Li J., Xie S.-P., Cook E.R., Morales M.S., Christie D.A., Johnson N.C., Chen F., D'Arrigo R., Fowler A.M., Gou X., Fang K., 2013, El Niño modulations over the past seven centuriesm Nature Climate Change, 3, 822-826, DOI: 10.1038/nclimate1936

Macías Rodríguez H., Sánchez Cohen I., Catalán Valencia E.A., 2007, A decision support system for integrated water management in the irrigation district no. 017, Coahuila and Durango, Mexico, Revista Chapingo Serie Zonas Aridas, 6, 77-89

McKee T.B., Doesken N.J., Kleist J., 1993, The relationship of drought frequency and duration to time scale, [in:] Proceedings of the Eighth Conference on Applied Climatology, 17-22 January 1993, Anaheim, California, American Meteorological Society, Boston, 179-184

NCAR, 2017, Climate Data Guide: Nino SST indices (Nino 1+2, 3, 3.4, 4; ONI and TNI), National Center for Atmospheric Research Staff, available at https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni (data access 11.05.2018)

Sánchez Cohen I., Estrada Avalos J., Gonzales Cervantes G., 2002, Irrigation technology in the irrigation districts of

Mexico, Water International, 27 (4), 578-584, DOI: 10.1080/02508060208687045

Sánchez Cohen I., Delgado Ramírez D., Esquivel Arriaga G., Bueno Hurtado P., Román López A., 2016, Forage water footprint in the Comarca Lagunera, [in:] Water, food and welfare. Water footprint as a complementary approach to water management in Mexico, R. Pérez-Espejo, R.M. Constantino-Toto, H.R. Dávila-Ibáñez (eds.), Springer Briefs in Environment, Security, Development and Peace series, 23, Springer, 199-214

SIAP, 2018, available at http://infosiap.siap.gob.mx:8080/agricola_siap_gobmx/ResumenProducto.do (data access 11.05.2018)

The Water Project, 2018, available at https://thewaterproject.org/ (data access 11.05.2018)

Trenberth K.E., Stepaniak D.P., 2001, Indices of El Niño evolution, Journal of Climate, 14 (8), 1697-1701, DOI: 10.1175/1520-0442(2001)014<1697:LIOENO>2.0.CO;2

Zhai J., Buda S., Krysanova V., Vetter T., Gao C., Jiang T., 2010, Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China, Journal of Climate, 23 (3), 649-663, DOI: 10.1175/2009JCLI2968