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Improving the Water-Use Efficiency and the Agricultural Productivity: An Application Case in a Modernized Semiarid Region in North-Central Mexico

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Abstract: The increasing population demands a greater quantity of food. In order to satisfy the world's demand, one of the main challenges worldwide consists of modernizing the current irrigation systems. This research shows an experience carried out in a modernized irrigation module in Central-North Mexico following these objectives: to evaluate the impact of the modernization of the irrigation module, to analyze the agricultural productivity, and to assess a group of parameters related with the agricultural production (system conduction and distribution efficiencies, water productivity, among others) and the water volumes after and before the modernization. After a drought period, a methodology was performed in commercial parcels in 2013 to increase the yield of different crops. Some of the activities were: soil leveling, estimation of the soil properties (field capacity, wilting point, bulk density, pH, and organic matter), optimum fertilization applications, use of a model to scheduling irrigation, measure volumes extracted at the parcel level. With the modernization and the method used, around 1800 and 2000 $m^3\ ha^{-1}$ were saved with respect to the initial granted volume by the Comisión Nacional del Agua and increase in the global efficiency was also achieved (from 55% to 85%). All crop yields increased, i.e., for corn from 2.5 kg/m^3 to 3.8 kg/m^3. The impact of modernization accompanied with an effective operation allowed a significant increase of the crop yield and water productivity. Despite a controlled distribution of water being carried out, future research should contemplate free water demand scenarios and automation irrigation for improving the module operation.

Keywords: Increased water productivity; modernized irrigation module; semiarid area

1. Introduction

Water is a fundamental resource for human and biota development, thus, the generation of knowledge around water and its optimal management contributes to the improvement of life quality [1]. The competence for water resource between the urban, industrial, agricultural, and environmental areas will quickly increase in the near future with the world population [2,3]. The global population will increase to 10 billion by 2050 from a current population of 7.7 billion people [4]; therefore, it will be essential to increase the food production [3,5]. A major challenge to be faced is climate change, associated with longer drought periods and water scarcity worldwide [6]. From the uses of freshwater for human consumption, agriculture represents 70% of the total water, with 86% for consumption. One of the actions to increase the food production is related to increasing the irrigated land, i.e., through the modernization from traditional to pressurized systems. The modernization of irrigation pretends to improve the use of resources and services to the users through the transformation of irrigation infrastructure and the improvement of irrigation water management. According to Tarjuelo et al. [7], an analysis of the irrigation modernization process for each case should be centered on issues regarding the causes that led to modernization of an irrigation system, the actions for the modernization, the impacts of these actions, and the lessons derived or learned.

In Spain, for example, since 1990, an important part of the investment in modernization has been destined to change the open channels networks used with surface irrigation by collective distribution networks of pressurized irrigation, mainly with drip and sprinkler irrigation [8,9]. This modernization plans join the private initiative with European and national public budgets, and they are responsible for the change in the infrastructure from around 2 million of the 3.7 million hectares irrigated in Spain. Nowadays, 50% of the irrigated surface is with drip irrigation, 25% with surface irrigation, sprinkler irrigation with 16% and 9% with self-propelled systems [10]. The transition from a system to another depends on the local conditions and especially on the crop of interest.

The modernization of Chinese agriculture goes further from the infrastructure to the production. Their agricultural infrastructure includes larges plantations and greenhouses; with time, the large-scale farming has increased, which concerns small farmers. The success of the major farmers is due to technical efficiencies, quality control systems, good regulations of pets and weeds, and environmental issues [11–13]. Scott, Marlinde, and Adja [11–13] mentioned that the modernization of the agricultural sector guarantees the food supply; nevertheless, it brings some negative effects on the environment and in small farming (i.e., desert lands in the rural sector), and it is necessary to address the modernization plans following common practices worldwide from policy, economic, social, and environment points of view.

Mexico has a territorial extension of almost 2 million of km^2 and it is classified as an arid and semiarid country. The agricultural sector plays an important role in the economic development of the country and represents 3.5% of the gross domestic product and employed the 13% of the population in the year 2019 [14,15]. The irrigated agriculture represented 21% by 2017 [16] of the total irrigated land. Around 43% of the Mexican agricultural production by 2017 was exported to more than 40 countries [17], so Mexico is within the classification of the 10 larger export economies of agricultural and agribusiness products [18]. The country has 6.5 million hectares of land under irrigation, from which 3.3 million are integrated in 86 irrigation districts, while the other 3.2 million are more than 40 thousand irrigation units [19]. About 69% of the total irrigated area is located in Asia, 17% in America, 9% in Europe, 4% in Africa, and 1% in Oceania. Mexico is globally positioned as the sixth country with infrastructure for irrigation after India, China, United States of American, Pakistan, and Iran [20,21].

In the state of Zacatecas Mexico, around 1,350,047 ha are destined to the agricultural sector; approximately 14% and 86% are irrigated and non-irrigated land, respectively. The rain used to be insufficient to cover the crop water requirements (250–500 mm), particularly in mid-summer, with temperatures from 15 °C to 29 °C. Around 95% of the crops are sown in spring-summer and just 5% in autumn-winter. The main crops not irrigated, depending only on the seasonal rain are: bean, corn, wheat, grain oat, barley, and oat bran; while the irrigated crops are: bean, corn, wheat, chili, vine, guava, and peach, among others [22]. In another sense, the meteorological conditions in the area do not favor the dam storages to satisfy the crop water requirements for the next season (cultivation plan of a season commonly performed on October 1st of the previous season).

This research shows an experience carried out in the irrigated land from the second-most important dam in Zacatecas, Mexico (Leobardo Reynoso, maximum capacity of 95.7 million of m^3). The irrigated land is ~4500 hectares and the non-irrigated land is ~26,000 hectares. A modernization was performed in 2003 to the main conduction system, considered a priority because the irrigated agriculture is the main economic activity in the region and contributes 50% of the total production.

After the modernization, some actions were taken into consideration for the irrigated area, such as the improvement of the surface irrigation and the incorporation of drip irrigation, as well as the use of a model to compute the crop water requirements instead of the conventional practices. Through the experiences of this research, the farmers are advised in order to improve the agricultural water management, increasing their crop yields and optimizing the storage volumes, particularly for dry years. The objectives of this study are: 1) to evaluate the impact of the modernization of the irrigation module over time, 2) to analyze the water productivity after and before the modernization, and 3) to assess a group of parameters related to the agricultural production and irrigation volume after and before the modernization.

2. Materials and Methods

2.1. Location of the Irrigation Module

The Leobardo Reynoso dam is located in the central north of Zacatecas state in Mexico (Figure 1) between the geographic coordinates 23°00′ to 23°15′ N latitude and 103°00′ to 103°20′ W longitude with respect to the Greenwich meridian. Physiographically, the inside of the Mesa Central is characterized by low wavy hills with NW-SW orientation, a highest elevation of 2750 m.a.s.l. (meters above the soil level) and a lowest of 2050 m.a.s.l. [23,24].

Regarding the hydrological aspect, the irrigation module is located inside the Nazas-Aguanaval region. The Aguanaval river flows thought the irrigation module together with other secondary and less important rivers. The water storage of the Leobardo Reynoso dam is provided by the Trujillo dam upstream. In the geological aspect, the igneous rocks such as basalts and rhyolites of the middle volcanic Cenozoic period are predominant in the region and the predominant soil textures are sandy-clay-loam and clay with different permeability and apparent density.

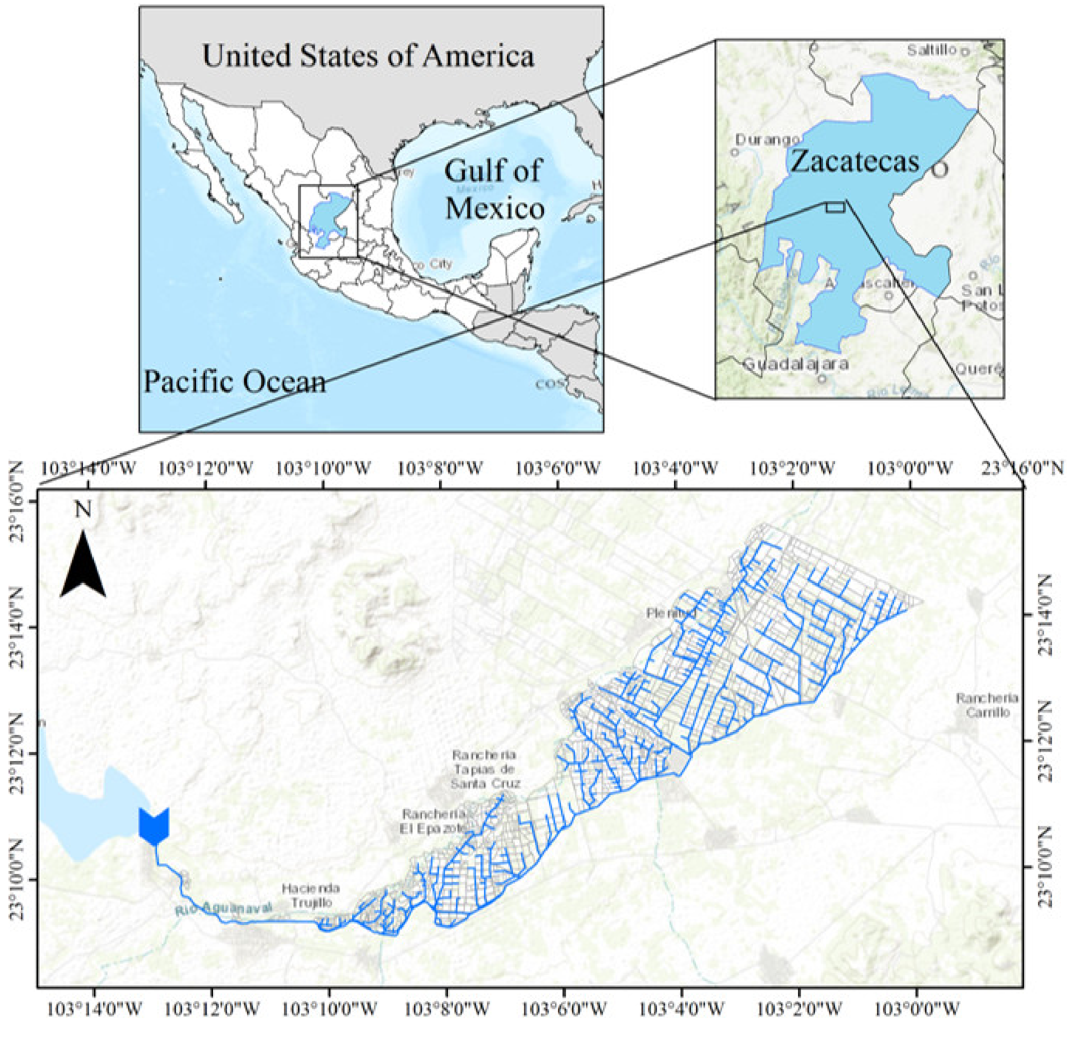

Figure 1. Geographical Location of the Leobardo Reynoso Irrigation Module.

2.2. Agroclimatic Features

In 90% of the Leobardo Reynoso territory the predominant weather is moderate and semi-dry, and the rest correspond with sub-humid with summer rains. There are two weather stations with different periods of data recorded each, one is operated by the Comisión Nacional del Agua (CONAGUA) and the other by the Instituto Nacional de Investigación Agricola, Forestal y Pecuario (INIFAP). The CONAGUA station indicates an average annual rain of 417 mm from June to October. According to CONAGUA and with the hydrologic perspective, 42% of the years were wetted.

Figure 2a shows the average rain for 65 years in the dam—it was observed that in every 12-year period the average rain was over the mean only in three years. From 2010 to 2012 it can be noticed that the rain was lower than the mean, which caused changes in the crop pattern of those years. The maximum and minimum temperatures varied between 20.8 °C and 10.9 °C, respectively, with a mean of 16.1 °C. The average monthly evaporation was 167 mm, with maximum values between March and July (Figure 2b). Table 1 shows the historical average (2002–2019) of the agroclimatic parameters measured by an automatic station located in Leobardo Reynoso dam.

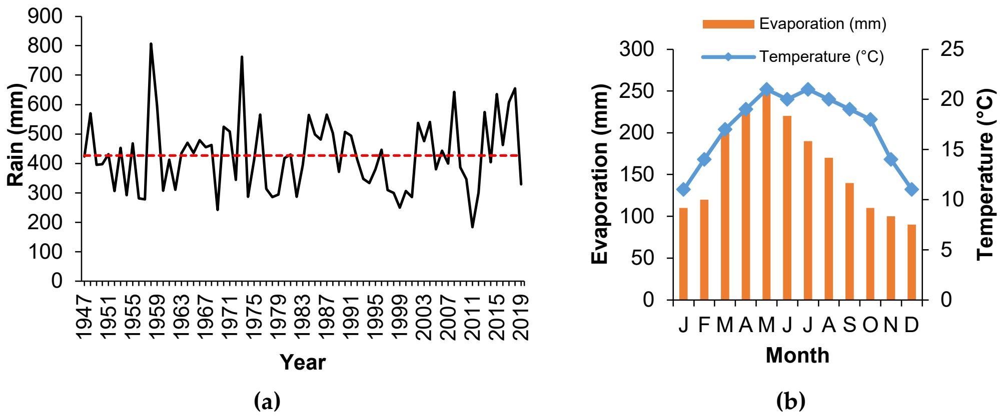

Figure 2. Climatic Parameters of the Leobardo Reynoso Irrigation Module. (**a**) Rain Series for 65 Years, (**b**) Evaporation and Temperature Annual Averages in the Region.

Table 1. Agroclimatic Parameters of an Automatic Station in the Leobardo Reynoso Dam.

Month	Average Temperature (°C)	Average Precipitation (mm)	Air Humidity (%)	Wind Velocity (m/s)	Sunstroke (hours)	ETo (mm/day)	Effective Rain * (mm)
January	10.7	13.1	50	2.8	7.7	2.9	0.0
February	12.5	8.4	44	3.5	7.0	3.7	0.0
March	15.1	3.5	33	3.5	8.4	5.0	0.0
April	18.2	4.7	32	3.2	8.6	5.7	0.0
May	20.2	13.0	40	2.6	9.2	5.6	0.0
June	20.4	61.1	56	2.2	9.1	5.0	26.7
July	18.8	92.3	70	1.9	9.3	4.5	49.8
August	18.5	93.5	72	1.5	9.0	4.2	50.8
September	17.4	72.8	77	1.2	8.3	3.7	34.2
October	15.7	34.0	69	1.4	8.1	3.2	10.4
November	12.4	9.4	56	1.9	7.5	2.8	0.0
December	10.7	11.8	50	2.5	7.6	2.8	0.0
Average	15.9		54	2.4	8.3	4.1	
Seasonal		417.6					171.9 *

* obtained according to Doorenbos and Pruitt [25].

2.3. Hydraulic Infrastructure

From the total irrigated surface that integrates the Leobardo Reynoso module no. 5 (25 ha), 14.6% is distributed to 14 users, 53.1% belongs to 165 farmers, and the remaining 32.3% is owned by 434 "ejidatarios" ("owns several parcels") (Figure 3).

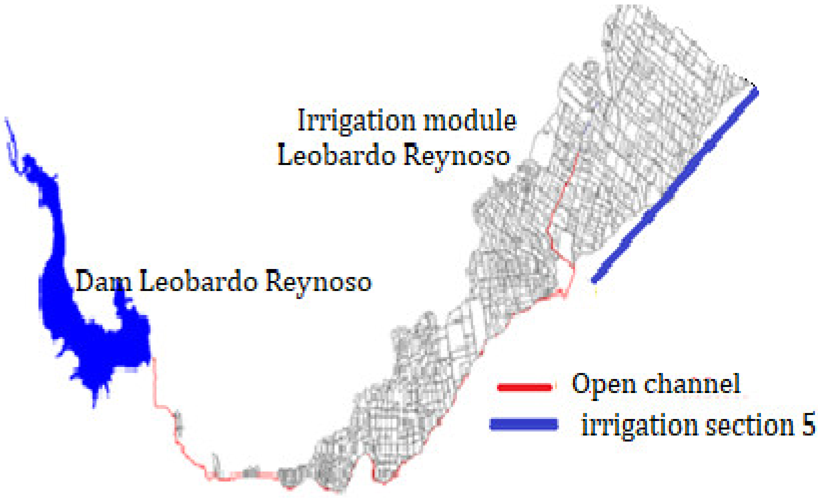

Figure 3. Locations of the Leobardo Reynoso Irrigation Module, Open Channel and Irrigation Sector No. 5.

Considering the maximum volume in a rainy year, the dam has a storage capacity of 120 million of m^3 and 23.9 million of m^3 are destined to the users. Nevertheless, during the dry years the water storage is not enough to satisfy the crop water requirements affecting the cultivation plan, which is related to non-irrigated land, i.e., the 2010–2012 period.

Initially, the dam had a 23 km main open dirt channel of sandy soil with a ~35% conduction efficiency, but after a modernization between the years 1990 and 1998, which consisted of the same 23 concrete-lined open channels, the conduction efficiency increased up to 60%. The channel is connected downstream of the dam where the water is gauged to the users and it is manually delivered, controlled by sliding gates. Regarding the distribution network, it is made up of lateral and sub-lateral channels, branch and sub-branch, and on-farm inlets, all of these made up of the clay soil of the region. The global efficiency of the whole irrigation module was 23%, consisting of 55% of the conduction efficiency and 42% of the application efficiency for that period (1990–1998).

During a second period (2001–2003), a new modernization was performed to the channel from 23 km to the 43 km, consisting of intubating the main network (Figure 3), besides installing the secondary lines and intra-parcel network (120 km in total) to leave the hydrant at each agricultural parcel. One of the benefits of this modernization was for the sector number 5 (Figure 3), where previously to 2001, a number of parcels were not irrigated and those irrigated had the lowest efficiencies values; moreover the irrigated surface of sector 5 (1859 hectares) increased and those already irrigated were much more efficient. With the new modernization after 2003, the conduction and distribution efficiencies increased up to 42% and 90%, respectively; nevertheless, there was not an improvement to the application efficiency because the surface irrigation still prevailed with the same practices as 30 years ago.

During the season of 2013, the dam capacity barely reached 48 million m^3, from which 6.6 million m^3 was delivered to the farmers, irrigating just 1554 hectares, so that some fundamental actions were performed in the irrigation management, such as measuring the flow delivered to each user using an electronic flowmeter (the users were present to let them know the flow delivered. which was between 20 lps and 80 lps), obtaining the soil hydrodynamics features such as field capacity and wilting point, determining the acceptable crops to be sowed in that dry season, and obtaining the reference evapotranspiration (ETo) from the automatic station.

Further, two demonstrative parcels were managed during the 2013 season, with corn and chili irrigated with surface and drip irrigation, respectively. The results and activities were followed by the growers during the whole season. The conduction and application efficiencies were assessed in situ. For the parcel with surface irrigation, the topographic survey of the plot was carried out in detail, so the plot was leveled considering a slope of 0.3% in the furrow direction, the soil hydrodynamic features were obtained (granulometry, θ_0, θcc, bulk density), the soil chemical analysis was performed (pH, organic matter), different amounts and fertilization types were applied during the season, and finally, the irrigation was simulated with the models RIGRAV [26] and WinSrfr [27] in order to obtain the irrigation and the schedule. Regarding the parcel under drip irrigation, the plot was 2 hectares of land with irrigation lines of 110 meters each. The crops established in the parcel demonstration were corn, chili, and beans.

2.4. Crops

The established crops in the region are: alfalfa, oat, corn, vine, onion, chili, bean, red tomato, and others in minor portions, like garlic, apple, peach and walnut. It is necessary to properly quantify the water requirements for all different crops in order to verify if these are suitable, particularly for a dry season, so the cultivation plan could change with the year, as is shown in Table 2 for the main crops. In order to calculate the crop water requirements, the software Cropwat version 8.0 was used [28]. This software uses the Penman Monteith equation to estimate the reference evapotranspiration.

Table 2. Crop patterns of the Irrigated Land in Regular and Dry Years.

Crop	Irrigated Land in a Regular Year (ha)	Irrigated Surface in a Dry Year (ha)
Corn	2310	934
Oat	830	
Bean	100	150
Chili	70	25
Onion	120	
Red Tomato	460	143
Green Tomato	460	107
Alfalfa	200	
Vine	110	110
Total	4660	1554

2.5. Parameters to Evaluate the Water Productivity

The water productivity can be defined as the food production per each volume unit of consumed water, and it can be expressed in terms of the crop yield (Kg/ha), or it can be transformed in monetary units depending the cost of the crop (USD/ha)—both concepts were assessed in this research work. The assessment was performed based on the economic analysis, to quantify the net income due to modernization of the module. This research applied the methodology proposed by Playán and Mateos [8] to relate the crop yield and prices with the economic benefits and the water consumption (USD/m^3); it also considered the efficiencies and the rainwater input. Moreover, some other indicators used by Corcoles et al. [29] and Soto et al. [30] were evaluated and can be shown in Table 3. The procedure for computing each parameter is also shown.

The efficiency of the Leobardo Reynoso irrigation system was assessed in terms of conduction and distribution efficiency, obtained as the ratio of the total volume available to the users and the volume delivered to them (first parameter in Table 3).

Table 3. Parameters to Analyze the Agricultural Productivity in Leobardo Reynoso Irrigation Module

Parameter	Unit	Classification	Description and Estimation
Conduction and distribution efficiency system Vt/Vs	%	Operation of the system	Vt/Vs (percentage), where Vt is the volume gauged at the intake site and Vs is the volume served at the parcel
Seasonal irrigation water supplied to the users by unit of irrigated land	m^3/ha	Operation of the system	Vs/Sr, where Vs is the irrigation volume supplied to the users and Sr is the total irrigated area of the crops
Relative annual irrigation supply (ARIS)	-	Operation of the system	VS/(ETc − Pef), where VS is the annual volume of irrigation supplied to users, Pef represents the annual effective rainfall, and ETc is the annual evapotranspiration demand.
Total MOM cost per unit volume supplied to users (MOMVS)	US$/$m^3$	Financial	MOM/VS, where MOM is the annual management, operation, and maintenance cost of providing the irrigation service, and VS is the annual volume of irrigation supplied to users.
Output per unit irrigation supplied to users (VPVS)	US$/$m^3$	Production	VP/VS, where VP is the total annual value of agricultural production and VS is the annual volume of irrigation supplied to users.
Gross Margin per unit volume supplied to users (GMVS)	US$/$m^3$	Production	GM/VS, where GM is the total annual gross margin of agricultural production and VS is the annual volume of irrigation supplied to users.
Gross Margin per unit irrigated area (GMSr)	US$/ha[1]	Production	GM/Sr, where GM is the total annual gross margin of agricultural production, and Sr is the total annual irrigated crop area.

3. Results and Discussion

3.1. Cropping Patterns

The irrigated surface of the irrigation module, as well as the net and gross delivered volume of water during the period 2000–2019, is presented in Figure 4. Before the modernization in 2012, CONAGUA granted to the users a net volume of 6000 m^3/ha, considering a global efficiency of 60% in the whole irrigation system due the infrastructure, i.e., from 2003 to 2010, the total irrigated area per year was 5025 hectares so the volume of water applied per year was 30.15 million of m^3.

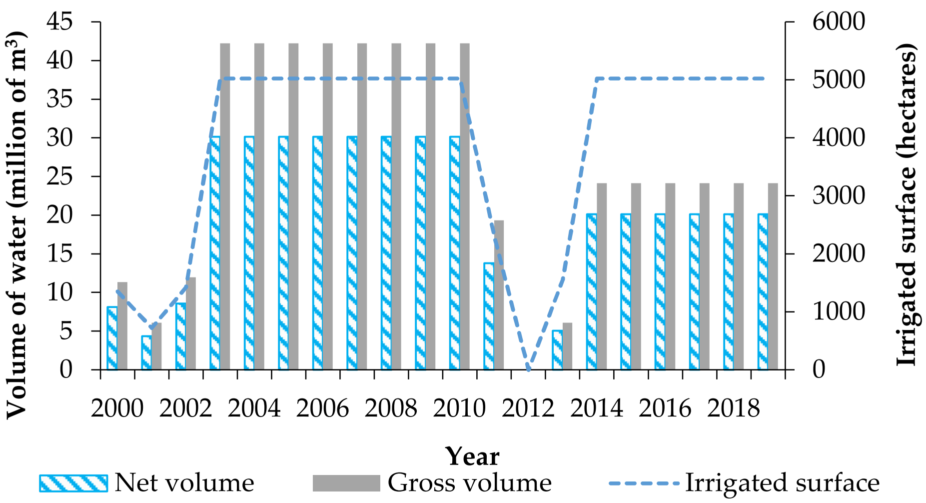

Figure 4. Evolution of the Gross and Net Volume of Water Available for the Users and the Total Irrigated Surface in the Leobardo Reynoso Irrigation Module From 2000 to 2019.

The irrigation module suffered three dry agricultural seasons (1999–2002), decreasing around 72% of the total irrigated area in this period. Subsequently, the meteorological conditions allowed the recovery of the dam's volume storage progressively from 2002 to 2003, maintaining eight regular agricultural seasons from 2003 to 2010. However, from 2011 to 2013 there was a decline in the irrigation surface due to the extreme drought that occurred in this period, therefore the whole irrigation module was not irrigated during the season 2012. The rainy season of 2013–2014 allowed a quick recovery of the dam storage from 2014 onwards, and much as the irrigation surface. Apparently, it seems that the Leobardo Reynoso irrigation module suffers dry periods every 8 to 10 years; nevertheless, a longer period should be analyzed to conclude this assumption.

From 2003–2010 CONAGUA granted a gross volume of 42.21 million m^3 to the users based on a conduction efficiency of 60% for the whole irrigation system, but after the dry season in 2012 and due the modernization, the gross volume granted decreased to 23.12 million m^3, because a conduction efficiency of 85% was achieved without decreasing the irrigated land (5025 hectares) (Figure 4). From 2003 to 2010 the dam volume storage varied between a minimum of 49.6 million m^3 in 2010 and a maximum of 103.6 million m^3 in 2004 (Figure 5), allowing the granted gross volume of 42.21 million m^3 to the users; nevertheless, due to the dry season in 2012 the dam volume of 9.5 million m^3 (lower than 8% of the total capacity of 120 million m^3 was not enough to irrigate any hectares. The rainy 2013 season presented a total precipitation of 574.5 mm (Figure 2a), recovering the dam volume up to 48.6 million m^3 and from 2014 to 2019 the volume storage was higher than 70 million m^3 (Figure 5), ensuring the granted gross volume of 23.12 million m^3.

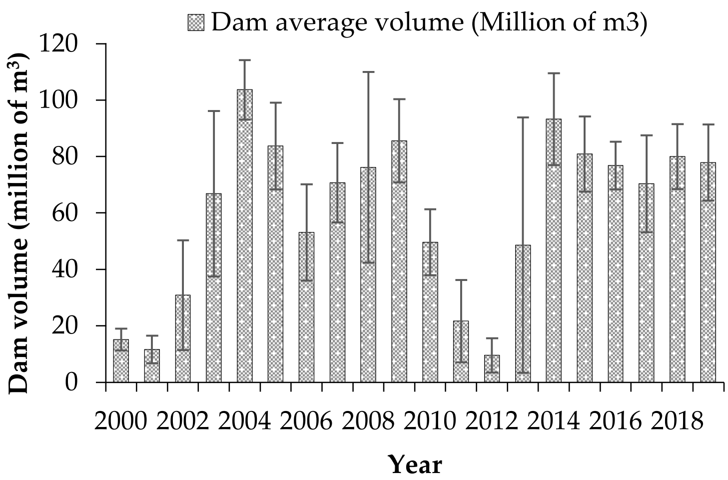

Figure 5. Average Volumes of the Leobardo Reynoso Dam from 2000 to 2019, Volume's Standard Deviation is Shown for Each Year.

On the other hand, all crops, during the study period, maintained their relative importance, especially the vegetable crops that are much more profitable crops compared with grains, however, these are subjected to a subsidy support to the growers by the government, allowing that the agricultural activity in the region has been established and strengthened. As in other regions of the world, the modernization process did not generate an important change in the cultivation plans of the farmers towards more profitable ones, probably due to the lack of interest and technical knowledge [8,30,31].

3.2. Irrigation Module Operation System

The operation of the hydraulic network for the conduction and distribution of irrigation water begins with the capacity of the volume of water delivered to users in the intake work of the Leobardo Reynoso dam, which generally remains for a constant week (for example starts with 1.4 m^3/s and can change to 1.9 m^3/s), depending on the demand of the crop pattern, the maximum capacity of the main network is 3.5 m^3/s, so the annual net and gross volumes are registered.

Comparing the volumes served and the total volume extracted from the supply source, there is a linear behavior due to the factors of provision and conduction that remain constant. To evaluate the impact of modernization, in addition to raising awareness among farmers of the importance of having hydraulic infrastructure that allows improvement of the response times of delivery and application of water at the level of the plot intake, the methodology applied between 2012 and 2013 to monitor the behavior of the expenses in the network of conduction, distribution, and parcel delivery was by using the concept of modular flow. The total volume assigned in 2013 by CONAGUA to the whole module was 6.6 million m^3, considering an endowment of 5500 m^3/ha, the main crop established was corn, with an area of 934 hectares, representing 60% of the total irrigated area (1554 ha). Moreover, the irrigation was scheduled according to the soil hydrodynamic features (moisture content at field capacity (θcc) and initial moisture content (θ_0), and Et_0) [32,33]. The average irrigation applied during the 2013 season was 40 cm, corresponding with a volume of 4000 m^3/ha; if this value is compared with the theoretical (5500 m^3/ha), there was a saving of 1500 m^3/ha that can be attributed to the efficient water management at the plot level and the conduction network because of the modernization.

The Table 4 shows the evolution of the volumes served (Vs) and the total volume (Vt) to evaluate the driving efficiency under the volumetric delivery control for the 2013 season for each irrigation event.

Table 4. Total Available and Delivery Volumes and Conduction Efficiencies During the 2013 Season in Leobardo Reynoso Irrigation Module.

Irrigation Date	Total Volume Available—Vt (m^3)	Delivered Volume—Vs (m^3)	System Conduction and Distribution Efficiency (%)
11–20 April	115,680	76,773	66
20–30 April	329,150	289,793	88
30 April–10 May	756,220	544,340	72
10–20 May	725,220	600,679	83
20–31 May	418,670	411,007	98
31 May–10 June	381,270	290,253	76
10–20 June	297,970	284,951	95
20–30 June	335,070	308,177	92
01–10 July	151,170	145,420	96
10–20 July	- *	-	-
20–30 July	10,620	9500	84
31 July–10 August	934,740	788,029	75
10–20 August	1,089,760	816,683	95
20–31 August	437,900	415,071	95
31 August–10 September	- α	-	-
10–21 September	82,910	78,060	94

*, α Not irrigated events with significant rain. *114.4 mm and α83.2 mm of effective rain obtained according to Doorenbos and Pruitt [25].

The evolution of the water conduction efficiency of the main system (Vs/Vt) under the concept of modular flow in the 2013 season presented high values between 66% and 95%. The 66% conduction efficiency of the irrigation event on 11 April 11 2020 was due to the channels and pipes filling. Figure 6 shows a highly significant correlation between the total volume available and the delivered volume ($R^2 = 0.98$, $p < 0.001$). Taking into account the total volume extracted (6067.13 m^3/ha) and the volume delivered (5058.74 m^3/ha), the global efficiency was 83%, highlighting that 2013 was not a regular year. If we compare this 83% with the estimated by the theoretical volume before the modernization (global efficiency of 60%), there was an increase of 23% in the system general efficiency. This value represents an excellent performance of the system in accordance with different countries, such as Spain, China, USA, and Italy, among others, where the conduction and distribution network has been modernized, reporting significant increases in the performance efficiencies of the hydro-agricultural system [30,34] similar to those found in this research.

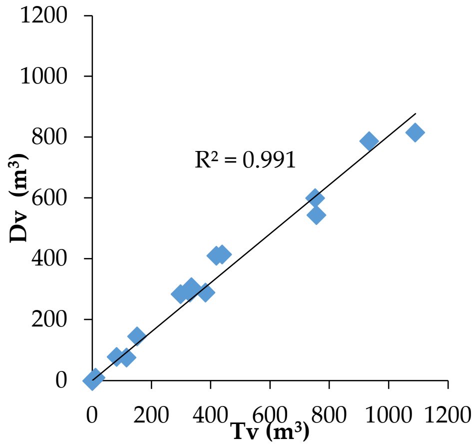

Figure 6. Linear Regression Main System Water Delivery Efficiency (Dv/Tv).

3.3. Water Productivity

A fundamental part of the irrigation system to increase the overall efficiency of irrigation water is the management, in which three aspects must be considered: when, how much, and how to apply. The last of those is explained with the way of applying the water, in this case considering surface irrigation with an estimated efficiency between 50% and 70%; however, if other practices are considered, such as leveling of the soil, improving the application to the furrow or melga, it is possible to achieve efficiencies greater than 80% and even to be compared with pressurized irrigation (by sprinklers or drip) that are high-frequency irrigation and could achieve application efficiencies greater than 85% [34].

In the irrigation module before the modernization, the land was irrigated by surface irrigation (commonly by furrows and melgas), where the producers applied the water directly through the ditch without using any accessory and with low efficiency (lower than 40%); this practice was improving and some began to use siphons and lined the ditch with plastic, thereby allowing better water management and increasing efficiency between 50% and 60%. The modernization of the hydro-agricultural infrastructure (main and parcel networks) allowed a significant improvement in the use of water, based on the fact that the pipe network increased the efficiency of conduction and by having a hydrant intake at the parcel level, the irrigation could be used by a gravity gate or pressurized, where there is enough hydraulic head to install a sprinkler or drip irrigation.

The characteristics of the experimental parcel under surface irrigation managed during the 2013 season were: 4 ha land, irrigation slope of 0.3%, sandy loam soil, organic matter of 2.2%, θ_0 = 0.40 cm^3/cm^3, θcc = 0.20 cm^3/cm^3, and θpmp = 0.10 cm^3/cm^3, 6 cm pre-sowing irrigation and 5 cm as auxiliary irrigation, an irrigation length of 181 m, unit irrigation flow 1.5 lps, irrigation time of 45 min, the spacing between rows was 75 cm, the modular flow in the plot was 40 lps, for which the irrigation lines were according to the simulations. The first irrigation was applied with these values and 7 cm of irrigation was simulated, generating an application efficiency of 86%, in accordance with the literature, where the surface irrigation achieves application efficiencies of the order of 70% to 80% [35–37].

In order to obtain the amount of water applied and the irrigation schedule some other variables were obtained for each crop, such as the residual humidity of the soil, depth of roots, and the relationship between the saturation content, evapotranspiration, and effective rainfall. The estimation of the evapotranspiration was performed through the Blanney-Criddle methodology, using the Pirez software [38] and Penman-Monteith Equation.

The production cost, the irrigated surface, the volume of water applied per hectare, the crop yield, the irrigation method, and the parameters of the water productivity, such as annual relative irrigation supply (ARIS), total maintenance, operation and management cost per unit volume supplied to users (MOMVS), the output per unit irrigation supplied to users (VPVS), and the gross margin per unit irrigated area (GMSr), are reported for each crop in Table 5 for the 2013 season.

The production costs per crops shown in Table 5 were estimated considering the establishment cost per crop, including the soil preparation for sowing, the seed, herbicide, and fertilization applications along the season, the typical soil labors of the area along the season, weed and pest control, water cost, and mechanical harvest. The prices are according to each irrigation area and the agricultural prices handled by the Fideicomiso Instituidos en Relación con la Agricultura (FIRA) [39]. The annual management, operation, and maintenance cost (MOM) for providing the irrigation service was 104.76 dollars per hectare for each grower for the 2013 season, from which 2.54 dollars was the cost for every 1000 m^3 of irrigation water consumed by the users and it was paid to CONAGUA for the dam maintenance.

Table 5. Production Cost, Irrigation Applied, and Yield for Each Crop in the 2013 Season.

Crop	Production Cost (USD/ha)	Irrigated Surface (ha)	Volume of Water Applied (m^3/ha)—Vs/Sr-	Crop yield (kg/ha)	Irrigation method	ARIS (–)	MOMVS (USD/m^3)	VPVS (USD/m^3)	GMSr (USD/ha)
Dry Chili	2619	25	4500	3000	Drip	0.63	0.02328	0.79365	38.0971
Corn	858	934	4000	15,000	Furrow and drip irrigation	0.78	0.02619	0.71428	2.14040
Bean	714	150	3500	3500	Furrow irrigation	0.62	0.02993	0.45238	5.79555
Red Tomato	9635	143	3000	88,000	Drip	0.66	0.03492	4.88888	35.18648
Vine	1300	110	8000	22,000	Furrow and drip irrigation	0.53	0.01309	0.48452	23.41991
Green Tomato	2026	107	3000	27,128	Drip	0.66	0.03492	1.92479	35.03159
Peach	667	15	6000	3200	Furrow and drip irrigation	0.68	0.01746	0.30952	79.34285
Alfalfa	810	30	10,000	30,000	Furrow and drip irrigation	0.55	0.01047	0.32857	82.52380
Apple	548	10	7000	8000	Furrow and drip irrigation	0.77	0.01496	0.65306	402.34286
Onion	857	30	4000	70,000	Drip	0.66	0.02619	1.33333	149.21111

The most expensive crop production (MOMVS) was for red tomato, but this was also the most profitable crop (VPVS) with the highest yield (88 t/ha) and the third-most planted crop in the area (143 ha). The apple was produced with the lowest irrigated area (10 ha) but with the highest gross margin per hectare (GMSr). The largest irrigated area was corn, with 934 ha.

The 2013 water productivity was 0.7 kg/m^3, 3.8 kg/m^3, 1 kg/m^3, 29.3 kg/m^3, 2.8 kg/m^3, 9 kg/m^3, 0.5 kg/m^3, 3 kg/m^3, 1.1 kg/m^3, and 17.5 kg/m^3 for dry chili, corn, bean, tomato, vine, tomatillo, peach, alfalfa, apple, and onion, respectively. In contrast, considering the theoretical volume granted by CONAGUA before the modernization, which was 6000 m^3/ha, and considering the crop yield for each crop, the ratios were 0.5 kg/m^3, 2.5 kg/m^3, 0.6 kg/m^3, 14.7 kg/m^3, 3.7 kg/m^3, 4.5 kg/m^3, 0.5 kg/m^3, 5 kg/m^3, 1.3 kg/m^3, and 11.7 kg/m^3 for dry chili, corn, bean, tomato, vine, tomatillo, peach, alfalfa, apple, and onion, respectively. The previous productivity shows that the modernization increased the water use efficiency (WUE) between 25% and 50% for all the crops. This increase was also noticeable in alfalfa—with the granted theoretical volume, a yield between 7000 kg/ha and 9000 kg/ha was obtained, so a maximum water productivity of 1.5 kg/m^3 could be achieved, and if this is compared with the yield per water used in 2012 (3 kg/m^3) there was a 50% increase in the water productivity.

The same situation is presented with the vine and apple crops. The water saving considering the increase in the WUE (between 25% and 50%) must be interpreted as an increase for the dam storage and should be an important practice, for example, to satisfy the crop water requirements during the next dry seasons.

The cost–benefit analysis varied from 4.64 USD/m^3 for tomato, 1.05 USD/m^3 for tomatillo, 1.04 USD/m^3 for onion, to 0.25 USD/m^3 for alfalfa (obtained for the most profitable crops). In general, it has been reported that the cultivation patterns of vegetables crops and their water use are much more profitable, however, these are subject to the market prices, which are so variable that sometimes the production is not profitable, since they generate important economic losses and important establishment costs.

The profitability analysis of crops and its relationship with the water consumption, taking as reference a guarantee price of the current crop market, showed that prices before the modernization were: 0.4 USD/m^3 for dry chili, 0.04 USD/m^3 for beans, and 0.02 USD/m^3 for corn, which were consistent values according with the data presented by Escobedo et al. [40]. However, the prices (GMVS) after the modernization were: 1.0 USD/m^3 for dry chili, 0.30 USD/m^3 for beans, and 0.30 USD/m^3 for corn—this represent an important impact in the irrigation module because of the modernization in the hydraulic networks and the other factors described above.

3.4. Integrating Actions for the Mexican Water User Associations (Wua)

Net economic profits are the key for accepting any change in the current irrigation systems. In this research we have shown an application case of the irrigation management after a modernization process in a Mexican irrigation module following a number of actions. It is widely known in developed countries that a good irrigation management could improve the farmers' benefits, even when a traditional system is used, i.e., using automatic or semiautomatic irrigation systems, monitoring irrigation and meteorological variables in real-time, irrigating following the evapotranspiration, the plant status, the soil properties, or a combination of them, among other factors.

In the Mexican agricultural sector, there is a bilateral relationship between the governmental organism (through CONAGUA) and the farmers for different aspects, such as: establishing the granted volume based in the dam storage, cultivation plans, the dam operation during the season, among others. It is essential that the interaction of an extension area is linked to the academia, i.e., government↔academia↔users, in order to improve the agricultural water management of irrigated areas attending issues related with the irrigation systems, the plant, the soil, the water, and the environmental conditions. An important effort of the academia, the private sector, and the government institutions needs to be done hand in hand with the farmers to show them any research results in order to overcome the WUA's customs and traditions.

The progressive change of the traditional crop pattern for more profitable crops is one of the main challenges for the water user associations in North-Central Mexico. The product of the modernization of the hydro-agricultural infrastructure is accompanied by the paradigm of changing the irrigation method for a more efficient one; however, although there is a will in the growers, it is limited, because it requires greater investments for its establishment. In this research, this was demonstrated to the farmers through the establishment of demonstration plots, under two approaches, for basic grain crops (such as the corn) and one of the most important crops in the area (such as the chili). For the first, it was possible to increase grain production by 50%, coupled with 33% savings in irrigation water, generating an economic benefit higher than the traditional one of 0.30 USD/m^3. Regarding the price for chili of 1.0 USD/m^3, it was necessary to carry out an evaluation with greater periodicity, because the variability of market prices is discouragement for farmers.

The main problem to achieve the benefits shown in this research is the initial economic investment, which is highly considerable so the farmer generally cannot afford it, however, there is an important support of governmental programs to the growers. The cost of modernization of the Leobardo Reynoso dam was tripartite: Federal Government of Mexico through the National Water Commission CONAGUA (50%), the Government of the Zacatecas state (25%), and the Water Users Association (25%). Following the technical recommendations to evaluate the benefits of the modernization, the users could recover their investments in two regular years. However, if they contributed with the whole modernization cost, it would probably take them from 10 years to 15 years to recover the invested capital as long as the following years are regular.

Further research is needed on the modernization process of Mexican irrigated areas, aimed at automation techniques (remote control), installation of automatic stations, and use of geographical information systems (GIS) in order to improve the management and operation of the irrigation module. In addition, technical support in the area is necessary, since this will allow an increase in their economic incomes, this permanent advice will give greater profitability of the irrigation water.

4. Conclusions

In this research, the behavior of the restrictions on the provision of volumes of water to users was presented, with the modernization of the hydro-agricultural infrastructure due to the recurrent cyclical events of drought that occur in the irrigation zone. The modernization process was analyzed, paying attention to important changes in the indicators of the operation of the irrigation module of the Leobardo Reynoso Dam. The behavior of the indicators evaluated in the water productivity are influenced by sociocultural factors of the users, adaptation of the technology by the producers, and, perhaps the most important, by the economic variation of the marketing of the crop harvests established.

To evaluate the effect of modernization, it is necessary to know in detail the operation of the system, during a time series where there are years with water shortages and years that exceed the average rainfall; on the other hand, further work is necessary to develop a system of geographic information (GIS) generating a conceptual model which contemplates the spatio-temporal variation of the irrigation module.

The results highlight that compared with recurrent drought periods and the different modernization processes (lining and piping of the main, secondary and parcel network), there was a water losses reduction due to the improvement in driving efficiency from 55% (not modernized) to 85% (modernized). Although the increase is significant, it is necessary to continue with the improvement of the distribution and regulation methods of the channels and pipes. The 35% increase is because of the volumetric granted and the practice of measuring the irrigation water generates transparency in the delivery of irrigation water and irrigation management.

From what was learned in this research work, the following basic recommendations are given for Mexican semi-arid modernized irrigation lands:

- To reconsider adjusting the granted volume through an exhaustive analysis depending on the irrigated area;
- Is essential that the Water User Associations consider having an exclusive office with the suitable personnel, mainly technicians (with knowledge on irrigation, agricultural water management, or agronomy), non-technicians, and administration, in order to operate the irrigated area;
- Within the agricultural technician/manager´s activities, the following most be considered: obtaining the irrigation schedule following the Et_0, the plant status, the soil properties (essential to know them), or a combination among them, to control and record the extracted volumes at each farm continuously, to continue with the maintenance labors of the main and secondary channels/pipes to ensure a good efficiency of the whole irrigation system;
- To consider the crop rotation;
- To consider the modernization at the plot level.

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References

1. Horst, M.G.; Shamutalov, S.S.; Goncalves, J.M.; Pereira, L.S. Assessing impact of Surface flow irrigation on water saving and productivity of cotton. *Agric. Water Manag.* **2007**, *87*, 115–127.
2. Baltazar, M.B. *Diversidad Genética del cultivo del Chile (Capsicum spp.) Determinada por Isoencimas y RFLP'S Tipos: Serrano, Jalapeño, Manzano y Silvestre en su Área de Distribución*; Informe de investigación: Texcoco, Edo. México, México, 1997.
3. Ayars, J.E.; Christen, E.W.; Soppe, R.W.; Meyer, W.S. The resource potential of in situ shallow ground water use in irrigated agriculture. *Irrig. Sci.* **2006**, *24*, 147–160.
4. ONU. Población. Available online: https://www.un.org/es/sections/issues-depth/population/index.html (accessed on 20 March 2020).
5. Anthony, D. On farm water productivity, current and potential: Options, outcomes, costs, irrigation. *Australia* **1995**, *10*, 20–23.
6. Borrego-Marín, M.M.; Berbel, J. Cost-benefit analysis of irrigation modernization in Guadalquivir River Basin. *Agric. Water Manag.* **2019**, *212*, 416–423, doi:10.1016/j.agwat.2018.08.032.
7. Tarjuelo, J.M.; Rodriguez-Diaz, J.A.; Abadía, R.; Camacho, E.; Rocamora, C.; Moreno, M.A. Efficient water and energy use in irrigation modernization: Lessons from Spanish case studies. *Agric. Water Manag.* **2015**, *162,* 67–77, doi:10.1016/j.agwat.2015.08.009.
8. Playán, E.; Mateos, L. Modernization and optimization of irrigation systems to increase water productivity. *Agric. Water Manag.* **2006**, *80*, 100–116.
9. Fernández García, J.A.; Rodríguez Díaz, E.; Camacho, P.; Montesinos, P.; Berbel, J. Effects of modernization and medium term perspectives on water and energy use in irrigation districts. *Agric. Syst.* **2014**, *131*, 56–63, doi:10.1016/j.agsy.2014.08.002.
10. ESYRCE. *Encuesta de superficies y rendimientos de cultivos en España;* Ministerio de Agricultura y Pesca Alimentación y Medio Ambiente—MAPAMA: Madrid, España, 2017; p. 101.
11. Waldron, S.; Brown, C.; Longworth, J. A critique of high-value supply chains as a means of modernizing agriculture in China: The case of the beef industry. *Food Policy* **2010**, *35*, 479–487, doi:10.1016/j.foodpol.2010.05.005.
12. Koopmans, M.E.; Rogge, E.; Mettepenningen, E.; Knickel, K.; Sumane, S. The role of multi-actor governance in aligning farm modernization and sustainable rural development. *J. Rural Stud.* **2018**, *59*, 252–262, doi:10.1016/j.jrurstud.2017.03.012.
13. Adalja, A.; Lichtenberg, E. Implementation challenges of the food safety modernization act: Evidence from a national survey of produce growers. *Food Control.* **2018**, *89*, 62–71, doi:10.1016/j.foodcont.2018.01.024.
14. World Bank. Agricultura, valor agregado. Available online: https://datos.bancomundial.org/indicador/NV.AGR.TOTL.ZS (accessed on 2 August 2020).
15. World Bank. Empleo en agricultura. Available online: https://datos.bancomundial.org/indicator/SL.AGR.Empl.Zs (accessed on 2 August 2020).
16. INEGI. Available online: https://www.inegi.org.mx/temas/agricultura/ (accessed on 2 August 2020).
17. SIAP. Available online: https://nube.siap.gob.mx/gobmx_publicaciones_siap/pag/2018/Atlas-Agroalimentario-2018 (accessed on 2 August 2020).
18. El economista newspaper. Available online: https://www.eleconomista.com.mx/empresas/Mexico-ingresa-al-top-10-de-exportadores-agroalimentarios-20190805-0122.html (accessed on 2 August 2020).
19. CONAGUA. Available online: https://www.gob.mx/conagua/acciones-y-programas/infraestructura-hidroagricola. Capítulo 4: Infraestructura hidráulica. (accessed on 2 August 2020).
20. AQUASAT. Area equipped for full control irrigation. Available online: http://www.fao.org/nr/water/aquastat/data/query/results.html (accessed on 16 September 2020).
21. FAO. Update of the Digital Global Map of Irrigation Areas (GMIA) to Version 5. Institute of Crop Science and Resource Conservation Rheinische Friedrich-Wilhelms-Universität Bonn, Germany. Available online: http://www.fao.org/3/I9261EN/i9261en.pdf. (accessed on August 2020)
22. Galindo, G.; Alexander, F.J.; De León, M.B. *Organización de Usuarios y Planes Directores en Unidad de Riego*; Congreso Nacional de Irrigación: Acapulco, Guerrero, México, 2006.
23. Chávez, C.D. Organización de la operación de la sección 04 del módulo de riego Presa Leobardo Reynoso, Fresnillo, Zacatecas. Master's Thesis, Universidad Autónoma de Zacatecas, Zacatecas, México, 2001.

24. González, T.J.; Júnez, F.H.E.; Pacheco, G.A.I.; Bautista, C.C.F.; Chávez, C.D. *Proyecto De Modernización De La Red De Conducción Y Distribución Parcelaria Del Módulo De Riego Presa Leobardo Reynoso, Fresnillo, Zacatecas. Informe Técnico Para La Asociación De Usuarios (AUPLR, S.A)*; Universidad Autónoma de Zacatecas: Zacatecas, México, 2013.
25. Doorenbos, S.; Pruitt, W.O. Crop water requirements. *Irrig. and Drain.* **1977**, *24*, 144.
26. Instituto Mexicano de Tecnología del Agua (IMTA). Riego por Gravedad. Jiutepec, Morelos, México. Available online: www.imta.gob.mx (accessed on 2 April 2013)
27. Arid Land Agricultural Research center. *WinSrf User Manual DRAFT. © USDA/ARS/Arid-Land;* Agricultural Research Center: Giza, Egypt, 2006.
28. Smith, M. CROPWAT: A computer program for irrigation Turner, N.C. 1986 Crop water deficits: A decade of progress. Adv. planning and management. *FAO Irrig. and Drain. Agron.* ***1992***, *39*, 1–51.
29. Córcoles, J.I.; de Juan, J.A.; Ortega, J.F.; Tarjuelo, J.M.; Moreno, M.A. Management evaluation of Water Users Associations using benchmarking Techniques. *Agric. Water Manag.* **2010,** *98,* 1–11, doi:10.1016/j.agwat.2010.07.018.
30. Soto-García, M.; Martínez-Alvarez, V.; García-Bastida, P.A.; Alcon, F.; Martin-Gorriz, B. Effect of water scarcity and modernization on the performance of irrigation districts in south-eastern Spain. *Agric. Water Manag.* **2013**, *124*, 11–19, doi:10.1016/j.agwat.2013.03.019.
31. Huttunen, S. Revisiting agricultural modernisation: Interconnected farming practices driving rural development at the farm level. *J. Rural Stud.* **2019**, *71*, 36–45, doi:10.1016/j.jrurstud.2019.09.004.
32. Velde, P.; Barré, P. *Soils, Plants and Clay Minerals– Mineral and Biologic Interactions*; Springer-Verlag: Berlin/ Heidelberg, Germany, 2010; doi: 10.1007/978-3-642-03499-2.
33. Gillies, M.H.; Smith, R.J. Infiltration parameters from Surface irrigation advance and runoff data. *Irrig. Sci.* **2005**, *24*, 25–35.
34. Palacios-Velez, E.; Palacios-Sanchez, L.A.; Espinosa-Espinosa, J.L. Evaluation of water use efficiency in irrigated agriculture supported by satellite images. *Water Technol. Sci.* **2018**, *9*, 31–38, doi:10.24850/j-tyca-2018-01-02. (In Spanish)
35. Playán, E.; Slatni, A.; Castillo, R.; y Faci, M. A case study for irrigation modernization: II Scenario analysis, *Agric. Water Manag.* **2000**, *42*, 335–354.
36. Bautista, E.; Warrick, A.W.; Schlegel, J.L.; Thorp, K.R.; Hunsaker, D.J. Approximate furrow infiltration model for time-variable ponding depth. *J. Irrig. Drain. Eng.* **2016**, *142*, 04016045, doi:10.1061/(ASCE)IR.1943-4774.0001057.
37. Hossain, A. *Fundamentals of Irrigation and On-farm Water Management: Volume 1;* Springer-Verlag New York, 2010; doi: 10.1007/978-1-4419-6335-2.
38. Mojarro, D.F.; González, T.J.; Gutiérrez, N.J.; Toledo, B.A.; y Araiza, E.J.A. *Software PIREZ;* Proyecto Integral de Riego para el Estado de Zacatecas: Zacatecas, México, 2004.
39. FIRA. *Fideicomiso Instituidos en Relación con la Agricultura*; Agrocostos: Mexico City, México. 2016. Available online: www.fira.gob.mx (accessed on 20 August 2020)
40. Escobedo, G.F. Evaluación De La Productividad Del Chile Regado a Través De Métodos De Riego Por Gravedad. Master's Thesis, Unidad Académica de Ingeniería, Universidad Autónoma de Zacatecas, Zacatecas, México, 2009.