Article **Journal of Natural and Agricultural Sciences**
June 2022, Vol.9 No.24 28-35

Optimization of water for agriculture from the Calera Zacatecas Aquifer

Optimización de agua para la agricultura del Acuífero de Calera Zacatecas

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DOI: 10.35429/JNAS.2022.24.9.28.35 Received January 30, 2022; Accepted June 30, 2022

Abstract

The objective of this work was to determine the optimal pattern of 11 crops in the Calera aquifer, using different scenarios of water availability, irrigation technologies and alternative crops. The planting area (SS) of each crop was determined to maximize the net benefit (BN) and increase water productivity (PA). It was observed that alfalfa and oat crops are less profitable and tomato and potato are the most profitable. The minimum SS of 9.7 thousand ha, They was obtained with 150.7 hm3, where a BN of $0.6 million was estimated and the PA of $4.45 m-3, that is, to adjust production to the volume granted with current traditional agriculture, future production is not guaranteed. The maximum SS of 28 thousand ha, was obtained with a volume of 125.8 hm3 using alternative crops (lettuce, squash and nopalitos), where a BN of more than $2 million and PA of $18.18 m-3 were obtained using the recharge volume. In conclusion, it is possible to have a balance in the recharge - extraction of the Calera aquifer, obtain a greater benefit, and increase the productivity of the water by making a controlled productive reconversion.

Water Pproductivity, Maximizealternative crops, Production agricultural planning

Resumen

El objetivo de este trabajo fue determinar el patrón óptimo de 11 cultivos en el acuífero de Calera, usando diferentes escenarios de disponibilidad de agua, tecnologías de riego y cultivos alternativos. Se determinó la superficie de siembra (SS) de cada cultivo para maximizar el beneficio neto (BN) e incrementar la productividad del agua (PA). Se observó que los cultivos de alfalfa y avena son menos rentables, tomate y papa son los de mayor rentabilidad. La SS mínima de 9.7 mil ha, se obtuvo con 150.7 hm3, donde, se estimó un BN de $ 0.6 millones y la PA de $ 4.45 m-3, es decir, ajustar la producción al volumen concesionado con la agricultura tradicional actual, no se garantiza la producción a futuro. La SS máxima de 28 mil ha, se obtuvo con un volumen de 125.8 hm3 utilizado cultivos alternativos (lechuga, calabaza y nopalitos), donde, se obtuvo un BN de más de $ 2 millones y la PA de $ 18.18 m-3 usando el volumen de recarga. En conclusión, es posible tener un equilibrio en la recarga - extracción del acuífero de Calera y obtener un mayor beneficio e incrementar la productividad del agua haciendo una reconversión productiva controlada.

Productividad del agua, Maximización, Produccicultivos alternativos, planeación agrícolóna

Citation: SERVIN-PALESTINA, Miguel, MARTINEZ-RUIZ, Antonio and, ECHAVARRIA-CHAIREZ, Francisco Guadalupe. Optimization of water for agriculture from the Calera Zacatecas Aquifer. Journal of Natural and Agricultural Sciences. 2022. 9-24:28-35.

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Introduction

A large part of Mexico's agricultural land is located in an area with a high evapotranspiration deficit, poor rainfall distribution and unfavorable climatic conditions make food production highly dependent on irrigation. In particular, the state of Zacatecas. For example, Zacatecas has 23, 814 irrigated agricultural production units representing 198, 470 ha and contributing 67% of the GDP of primary activities (INEGI 2012). Despite the enormous efforts of the three levels of government in irrigation technification, wastewater treatment and construction of catchment works, this resource continues to be increasingly scarce and costly due to the alarming waste in traditional agriculture. This is due, among other factors, to the fact that producers are unaware of the water requirements of crops, the interaction that plants have with the environment where they develop and their effect on irrigation management (Servin et al., 2017), on the other hand, there is no adequate planning of the crop pattern to be established according to the amount of water available, to avoid overexploitation of groundwater. Such is the case of the Calera aquifer located in the central part of the state of Zacatecas which represents 15.2% of the irrigated agricultural area of the state, but has a deficit in its extraction levels, as it presents an annual rate of depletion of 1.5 to 2.5 m. (CONAGUA, 2018), in this region irrigated agriculture is the most important economic activity and the one that consumes 82% of the total water extracted.

The low rainfall combined with an evaporation greater than 2 thousand millimetres results in a negative hydro-climatological balance with a total annual demand of 190.4 hm^3 and a recharge of 125.8 hm^3, i.e., the demand exceeds the natural recharge by 34 %. Based on the distribution of concessioned volumes reported on 31 March 2009 in the Public Registry of Water Rights (REPDA), where the total water concessioned was 150.713 hm^3 (IGH, 2010), which represents an average agricultural surface area of 20,183.2 ha (2004-2017) within the aquifer. It is of interest to make efficient use of available resources such as water and agricultural area.

Linear programming (LP) is a tool used for planning activities in agricultural production units (Ortega et al., 2008) and has been developed to search for more efficient production alternatives. Linear programming models have been used to obtain the economic value of water in Irrigation District 100, Alfajayucan, Hidalgo (Martínez-Luna et al., 2021), land management in urban areas (Liu et al. 2007), value of irrigation water (Jabeen et al. 2006) and water productivity in Irrigation District 011, Alto Río Lerma (Florencio-Cruz et al. 2002). Bueno, (1988) mentions that it can be used to determine optimal cropping patterns according to available resources, with different water sources, considering hydrological and management constraints, in an irrigation district in China (Yu et al., 2021) Pakistan (Haq et al., 2020) in India (Khare et al., 2007), in a 100 ha farm in Iran (Zare & Koch, 2014), determines the optimal sowing area (Sofi et al., 2015).

PL is an alternative to determine the area to be planted and the cropping pattern that maximizes the net income of producers, the simplex method is the most widely used for these tasks, it has been successfully used to solve complex and large-scale problems (Exebio-García et al., 2021; Alvarado, 2010) and help decision making in broad applications in agriculture (Alotaibi, & Nadeem, 2021). Therefore, the objective of this work was to define the optimal crop pattern in the Calera Zacatecas aquifer and to estimate the irrigation water productivity in weight per cubic meter according to the statistics of the last 14 years and for different scenarios of irrigation water availability, using more efficient irrigation technologies for production and making a change in the crop pattern (productive reconversion), to maintain a balance in the balance of recharge and extraction, in order to make more efficient use of soil and water resources to ensure sustainability for future generations.

ISSN: 2410-356X

Materials and method

Description of the study area

The Calera aquifer is located in the centre of the state of Zacatecas, Mexico between the geographical coordinates 22 ° 38 ′ to 23 ° 15 ′ LN and 102 ° 35 ′ to 103 ° 00 ′ LO. The watershed covers an area of approximately 2,087.6 km², which represents 2.8% of the state area. It is a flat terrain that extends from south to north without any obstructions, bordered to the east by the Zacatecas Mountains, to the west by the Fresnillo and Los Cardos mountain ranges, to the north by the "Cerro del Algodón" and to the south, by the Cerro de la Mesa (Ávila-Carrasco et al 2012). The climatic characteristics of the area are: average annual precipitation of 425 mm, average annual temperature of 16 °C and average potential evapotranspiration of 1 990 mm per year (SAGARPA, 2010), in addition, an average extraction volume of 189.6 hm3 is estimated with an annual rate of depletion of 1.5 and 2.5 m.

Problem statement

The selection of crops was based on the study carried out by the consultancy firm Ingeniería y Gestión Hídrica (IGH 2010) where it mentions that, for the case of the Calera aquifer, it is estimated that an annual average of 21,720 ha. with the crops: Garlic, Alfalfa, Forage Oats, Onion, Chile, Beans, Corn, Potato, Tomato, Grape and Carrot, equivalent to 15.2% of the surface area in the state, based on 2004-2006 data provided by SAGARPA-Delegación Zacatecas and Agricultural Statistics of the Irrigation Units. Subsequently, information was obtained from the Statistical Yearbook of Agricultural Production (SIAP 2017) for agricultural production variables by crop such as area sown (S; ha), yield (R; t ha^{-1}) and rural price (PMR; \$ ha^{-1}) from 2000-2017 for the state of Zacatecas.

In the case of alfalfa and fodder oats, the area sown was summed for the three presentations (dry, green and limed). To obtain the annual area for each crop and adjust it to the aquifer level, the state unit area per crop and for each year was multiplied by 0.1919 so that the average of the sum of the 12 crops from 2004-2006 coincides with the area obtained by the consultancy (21,720 ha).

With the data obtained for each crop from 2000 to 2017, the maximum and minimum area sown was obtained for each of the 12 crops (Table 1), removing the data from 2003 because they overestimate the area, i.e., we worked with 17 years of data. Except for alfalfa and grapes, which only have 10 years of data from 2007-2017. It is worth mentioning that the minimum sown area was adjusted by half for the simulation (SMS).

Cultivation	Area sown			
	Mean (ha)	Maximum (Ls; ha)	Minimum (ha)	MSS* (LI; HA)
Garlic	379.6	636.9	267.8	133.9
Alfalfa	2284.2	2846.4	1800.5	900.3
Fodder Oats	1788.6	4688.1	892.9	446.5
Onion	695.6	884.4	449.0	224.5
Chilli	3196.6	7584.7	721.8	360.9
Beans	5407.0	7719.8	4302.5	2151.3
Corn	6034.4	7620.2	4796.9	2398.4
Potato	150.1	329.8	70.0	35.0
Tomato	499.3	672.1	275.3	137.7
Grape	712.3	810.4	674.8	337.4
Carrot	470.7	609.5	307.6	153.8
Total	20560.8	24198.7	18253.2	7279.6

*Minimum area used for simulation.

Table 1 Area planted in the calera aquifer 2000- 2017 for each proposed crop

With regard to yield (R) and rural price (PMR), data from the year 2017 was used, for alfalfa and oats the data in its green presentation was used, for the chili crop the data of dry chili was used. The volume of water required and production costs for each crop were estimated based on experimental data and consultations with users and technicians.

Cultivation	R ($t\ ha^{-1}$)	P Miles (\$ t^{-1})	*a* ($m^3\ ha^{-1}$)	C Miles (\$ ha^{-1})
Garlic	14.82	\$ 15.19	6,450	\$ 120.00
Alfalfa	87.91	\$ 0.54	120,000	\$ 15.00
Fodder Oats	20.66	\$ 0.51	2,500	\$ 4.50
Onion	44.37	\$ 3.65	5,800	\$ 110.00
Chilli	3.66	\$ 52.76	5,500	\$ 135.00
Beans	1.98	\$ 13.83	3,100	\$ 6.00
Corn	5.89	\$ 4.86	4,800	\$ 18.00
Potato	43.52	\$ 7.09	6,300	\$ 220.00
Tomato	83.43	\$ 9.42	7,500	\$ 250.00
Grape	7.95	\$ 12.49	6,000	\$ 80.00
Carrot	33.04	\$ 3.24	5,500	\$ 55.00

R - yield, P - rural price, a - volume of water required and C - production costs

Table 2 Yield and price of the rural environment for the year 2017, required volume and production costs for the main crops established in the aquifer of Calera Zacatecas.

ISSN: 2410-356X

For this work, 4 optimisation scenarios were proposed with different volumes of water available, technologies to increase water use efficiency and crops with low water requirements (Table 3), and water productivity (PA; $ m^{-3}) was calculated by relating the total net benefit (BN; $) and the volume of water used (V; m^3) in each scenario.

Scenario	Management condition	Volume available (hm^3)
Current Extraction	Conventional Agriculture	189.6**
Concessioned Volume	Conventional Agriculture	159.2*
Recharge Volume	a) Use of Technologies	125.8 *
Recharge Volume	b) Alternative Crops	125.8 *

Table 3 Proposed scenarios, management condition and available volume
*Source: ** IGH 2010; *CONAGUA 2018*

Restrictions on available planting area in the aquifer were also used, considering that the sum should not exceed 24,198.72 ha, the average area sown during the last 17 years of the 11 proposed crops (Table 2).

The objective function to find the optimal crop pattern that maximises profits can be formulated as follows:

Model

$$^{max}BN = \sum_{i=1}^{n}\left[R_i\, P_i - C_i\right]x_i \quad (1)$$

where BN = net profit ($), Ri = yield of the i-th crop (t ha-1), Pi = farm-gate price of the i-th crop, Ci = production costs of the i-th crop (thousands of $ t-1) and Xi = area sown to the j-th crop (ha).

Subject to:

Area restrictions:

$$L_I \leq x_i \leq L_S \quad (2)$$

$$\sum_{i=1}^{n} Xi \leq 24{,}198.72 \quad (3)$$

Where x_1 to x_{11} are the crops: Garlic, Alfalfa, Fodder Oats, Onion, Chilli, Beans, Maize, Potato, Tomato, Grape, Carrot respectively, and the total agricultural area must be less than the available area.

Water use restrictions:

$$\sum a_i x_i \leq W \quad (4)$$

Where: a_i = gross volume required by crop $_i$ per m^3 ha^{-1}, xi = area occupied by crop i with respect to the total agricultural area and W = total available water volume (m^3).

To solve the net profit maximisation problem, the Matlab (Grace 1992) optimisation toolbox will be used, specifically linprog.m which allows solving linear programming problems using the modified simplex method.

Results and discussion

Objective functions and constraints

For scenario 1 and 2, the cost coefficient $K = \left[R_i\, P_i - C_i\right]$ was obtained for each crop (Table 2) and the following objective function was derived:

$$^{max}BN = [104.99]x_1 + [32.48]x_2 + [6.08]x_3 + [52.10]x_4 + [58.10]x_5 + [21.39]x_6 + [10.63]x_7 + [88.40]x_8 + [536.16]x_9 + [19.26]x_{10} + [52.21]x_{11} \quad (5)$$

With restrictions (W) of current and concessioner extraction volume of 189.6 hm³ = 1.896 x 10^{-8} m^3 and 159.2 hm³ = 1.507 x 10^{-8} m^3 for scenario 1 and 2 respectively.

$$[6450]x_1 + [120000]x_2 + [2500]x_3 + [5800]x_4 + [5500]x_5 + [3100]x_6 + [4800]x_7 + [6300]x_8 + [7500]x_9 + [6000]x_{10} + [5500]x_{11} \leq W \quad (6)$$

For scenario 3, technologies described on the INIFAP Zacatecas website were used. http://www.zacatecas.inifap.gob.mx/index.php, (Medina et al., 2003, Medina et al., 2016). The technologies used on the one hand increase production costs (C), but also in yield (R) and in some cases there is a decrease in the volume required by the crop (a) Table 5.

ISSN: 2410-356X

Cultivation	R (t ha^{-1})	a (m^3 ha^{-1})	C Miles ($ ha^{-1})
Garlic	20.00	6200	$ 150.00
Alfalfa	105.00	10000	$ 18.75
Fodder Oats	20.00	2400	$ 5.63
Onion	50.00	5600	$ 137.50
Chilli	4.50	5500	$ 168.75
Beans	2.80	2800	$ 7.50
Corn	8.50	4500	$ 22.50
Potato	60.00	6000	$ 275.00
Tomato	100.00	7300	$ 312.50
Grape	13.00	5500	$ 100.00
Carrot	70.00	5500	$ 55.00
R- yield, a- volume of water required and C - production costs.			

Table 4 Yield, volume required and production costs using technologies developed by INIFAP

With the data in table 4, the following objective function was developed:

$$^{max}BN = ([153.74]x_1) + ([37.96]x_2) + ([4.61]x_3) + ([45.19]x_4) + ([68.67]x_5) + ([31.21]x_6) + ([18.85]x_7) + ([150.19]x_8) + ([629.86]x_9) + ([62.32]x_{10}) + ([132.13]x_{11}) \quad (7)$$

For this scenario a recharge-extraction balance is expected to be reached and a volume of 125.8 hm³ =1.258 x 10^{-8} m^3 was considered. That is, subject to the following restriction:

$$[6200]x_1 + [10000]x_2 + [2400]x_3 + [5600]x_4 + [5500]x_5 + [2800]x_6 + [4500]x_7 + [6000]x_8 + [7300]x_9 + [5500]x_{10} + [5500]x_{11} \leq 1.258E + 08 \quad (8)$$

For scenario 4, alternative crops with low water requirements that are gaining importance in the region due to their higher cost-benefit ratio were used. Alfalfa was replaced by sunflower (x^2), beans by lettuce (x^6), oats by pumpkin (x^3) and grapes by nopalitos (x^{10}). The cost coefficients were estimated with the data in table 5.

Crop	R (t ha^{-1})	a (m^3 ha^{-1})	C Miles ($ ha^{-1})	P Miles ($)
Sunflower	2.10	3,500	$ 6.20	$ 5.87
Lettuce	50.00	2,500	$ 32.00	$ 2.76
Pumpkin	20.39	2,000	$ 6.50	$ 2.22
Cactus	25.65	2,300	$ 21.00	$ 3.03
R - yield, P - rural price, a - volume of water required and C - production costs. water required and C - production costs.				

Table 5 Yield, required volume, production costs and price of alternative crops

The objective function proposed for scenario 4 was as follows:

$$^{max}BN = [104.99]x_1 + [6.12]x_2 + [38.72]x_3 + [52.10]x_4 + [58.10]x_5 + [134.54]x_6 + [10.63]x_7 + [88.40]x_8 + [629.86]x_9 + [56.74]x_{10} + [52.21]x_{11} \quad (9)$$

Restricted to recharge volume 125.8 hm³ =1.258 x 10^{-8} m^3.

$$[6450]\ x\_1 + [3500]\ x\_2 + [2000]\ x\_3 + [5800]\ x\_4 + [5500]\ x\_5 + [2500]\ x\_6 + [4800]\ x\_7 + [6300]\ x\_8 + [7500]\ x\_9 + [2300]\ x\_10 + [5500]\ x\_11 \leq 1.258E + 08 \quad (10)$$

For all scenarios the maximum and minimum area restrictions (Table 1) were used using equation 2 and 3.

Area planted per crop

For the four scenarios with the different volumes of water availability and water use efficiency with the different technology packages and alternative crops, the following was used obtained the optimal pattern of the sown area of each crop that maximises the net income of the producers located in the Calera Zacatecas aquifer for each scenario. For scenario 1 the crops: Alfalfa, Oats, Beans, Corn and Grapes went to the lower limit which is deduced that they are the least profitable crops, by decreasing the volume of current extraction to the concessioned volume Carrot was added to the least profitable crops and decreased the area of Chile and Onion, in scenario 3 by improving the efficiency of water use and increase in yield most crops went to the upper limit of established area except for alfalfa and oats that are at the lower limit, For this reason, in scenario 4 they were replaced by alternative crops, sunflower and pumpkin respectively, as well as grapes and beans, which remained at the lower limit in the first two scenarios, while maize remained as a wildcard crop, adapting to water availability. In this same scenario, the crop selected as an alternative did not provide much benefit, as it remained at the lower limit of the established area. The results coincide with those observed by Florencio-Cruz et al. (2002) and Zetina-Espinosa et al., (2013), both of which mention that crops with low profitability and water consumption will reduce their area.

Cultivation	Scenario / Surface (ha)			
	1	2	3	4
Garlic	636.90	636.90	636.90	636.90
Alfalfa/sunflower*	900.30	900.30	900.30	900.30
Oats/Squash* Oats/Squash* Onion	446.50	446.50	446.50	4688.10
Onion	681.10	224.50	884.40	884.40
Chilli	7584.70	1449.30	7584.70	7584.70
Beans/Lettuce* Corn	2151.30	2151.30	7719.80	7719.80
Corn	2398.40	2398.40	6399.60	6392.70
Potato	329.80	329.80	329.80	329.80
Tomato	672.10	672.10	672.10	672.10
Grape/Cactus* Grape/Cactus	337.40	337.40	810.40	810.40
Carrot	609.50	153.80	609.50	609.50
Alternative crops for scenario 4				

Table 6 Simulated surface area for each of the scenarios proposed for 2017 and for each crop in the Calera Zacatecas aquifer

Net benefit and water productivity

The results of the optimisation where the 4 scenarios were simulated (Table 6) show that the least profitable scenario is the one that adjusts to the concessioned volume with a volume of 150.71 hm^3 and generates a net benefit of 670 million pesos and achieves a productivity of 4.45 pesos per cubic metre of water used, while applying technologies that improve crop production and in some cases save water achieves a higher productivity with a value of 13. 20 pesos per square metre, while changing the traditional crops for more profitable alternative crops, but above all, more efficient in the use of water, the net income is more than 2 million pesos, establishing 28,456.50 ha and using only 125.8 hm^3 equal to the recharge, maintaining the aquifer in equilibrium and reaching a productivity of 18.18 pesos per square metre. The results are contradictory to those reported by Ortega et al (2009) who mention that when more water is used, the net benefit obtained per unit volume decreases in works carried out in irrigation districts, which is the opposite case of scenario one and two of this work.

Scenario	Area (ha)	Net profit (miles $)	PA ($/m^3)
1) Current Extraction	16,748.00	$1,074,300.00	$ 5.67
2) Concessioned	9,700.30	$670,270.00	$ 4.45
3) Technologies	26,994.00	$1,660,400.00	$13.20
4) Alternatives	28,456.50	$2,287,542.46	$18.18

Table 7 Net benefit and water productivity of the simulated planting area for each of the proposed scenarios in the Calera Zacatecas aquifer

Conclusions

As can be seen, alternative crops (Pumpkin, Lettuce and Nopalitos) are a good option to increase water productivity and maintain a balance in the aquifer without putting at risk the economy of the producers, on the other hand, the most profitable crops are: Tomato, Garlic and Potato. However, the scope of this work was limited to 11 crops, so it is recommended a wider pattern and modify the maximum areas established according to the commercial demand of the final product of each crop considering the law of supply and demand in order not to saturate the market, which has a direct impact on the selling price. Similarly, these tools are very useful to develop planning or reorganisation programmes at regional level in order to make resources more efficient and implement a strategy of a single planting permit, which ensures maximum benefit from the resources.

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Journal of Natural and Agricultural Sciences
June 2022, Vol.9 No.24 28-35

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