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Economic Effects of Drought in Irrigation District 023 San Juan del Río, Querétaro

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ABSTRACT

Objective: To analyze the impact of various levels of drought and increase in groundwater use on agricultural income in Irrigation District 023 of San Juan del Río, Queretaro, and to determine water productivity as drought intensifies.

Design/methodology/approach: Linear programming was used; Four scenarios were built: a typical year with surface and groundwater, two with moderate drought levels and one, only with groundwater for irrigation. Additionally, four other scenarios with the same characteristics were considered, incorporating the cultivation of 60% of alfalfa to serve the dairy sector due to its importance

Results: Reductions in agricultural income range from 8.6% to 19.1% in the first set of models and from 9.7% to 23.1% when alfalfa planting is enforced. The most water-demanding crops cause a significant reduction in agricultural income. Shadow water prices range from \$800 per thousand m^3 to \$5,819 per thousand m^3 for the W-I cycle as drought intensifies.

Limitations on study/implications: The research included the most representative crops in the district and limited the area of crops with high profitability due to market aspects.

Findings/conclusions: It is concluded that droughts significantly affect agricultural income and that the shadow price of water increases significantly as the drought increases, so groundwater should be allocated to the most productive and less water-demanding agricultural activities.

Keywords: Water scarcity, shadow price, water productivity

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INTRODUCTION

Productive activities in agricultural production units are diverse. Various crops can be grown using a range of technologies and production techniques. The seasonality of agriculture leads to certain resources having a well-defined temporary use. These units have a specific amount of resources available to implement their production plans, such as land, labor, and, in particular, water.

In the literature, irrigation water has been recognized as the input that most significantly influences crop yields (FAO, 2004). Climate change has made rainfall patterns more erratic, and droughts are becoming increasingly frequent. This, combined with the development of well-drilling and pumping technologies, has led to the excessive use of groundwater

worldwide, a phenomenon referred to as "the silent revolution of intensive groundwater use" (Llamas M. & Martínez-Santos, 2006).

It is important to make the best use of water resources. A useful tool in this task is linear programming (LP), which aids decision-making in agricultural production, incorporating theoretical advances that allow for solving systems of equations with inequality constraints based on the application of the Kuhn-Tucker conditions, duality theory, and, as a result, the demonstration of the symmetry between primal and dual problems. This approach highlights the usefulness of shadow prices for the resources used in the primal problem, which are derived through the dual problem without formulating and solving the dual problem itself, marking a significant advance (Hazell and Norton, 1986).

Linear programming (LP) is used to solve a wide range of optimization problems (Kaiser and Messer, 2011). Estimating water productivity is important to understand the contribution of non-priced productive inputs to total output. Young and Loomis (2014) note that LP models are an appropriate tool for assessing the productivity of inputs such as water. This method has been used to evaluate water productivity in an irrigation district in Mexico (Florencio *et al.*, 2002; Botello *et al.*, 2022). The Technical Committee on Groundwater (COTAS, 2024), in relation to the San Juan del Río Valley aquifer, reports a deficit in groundwater availability of nearly 57 million m^3.

The objective of the research was to analyze the impact of various levels of drought and groundwater use on agricultural income in ID 023 in San Juan del Río, Querétaro, and to determine water productivity. The hypothesis is that during drought conditions, when surface water is unavailable and only the concessioned groundwater is used, the crops that require the most water will experience a reduction in the area cultivated, leading to significant decreases in agricultural income.

MATERIALS AND METHODS

This research was conducted in the San Juan del Río Valley, Querétaro, with coordinates: Latitude 20° 29"12.2" and Longitude 99° 44' 49.7", specifically in ID 023 San Juan del Río. The main user of groundwater in the San Juan del Río aquifer is the agricultural sector, which includes the central region of ID 023 San Juan del Río, as shown in Figure 1 (CONAGUA, 2023). The static water level evolution for the period 2014-2023 recorded declining values across most of the exploited area, ranging from 1 to 10 meters, with some areas showing declines of up to 15 meters, representing annual reductions of 0.1 to 1.7 meters. The greatest declines, ranging from 1.1 to 1.7 meters annually, occur in the northern and northwestern areas of the agricultural zone.

Models were constructed using LP to estimate the effects of a range of droughts, from moderate to severe, on economic income in the region, cropping patterns, and water productivity. An LP model consists of an objective function and a set of constraints. The objective function (1) is made up of the dot product of the decision variables (activities) of the model multiplied by their corresponding net utilities. The set of constraints consists of restrictions expressed in a coefficient matrix, with technical coefficients, and on the right-hand side of the equation (RHS), the fixed available resources (2). In addition to the non-negativity conditions (3) for the activities (decision variables) considered.

Figure 1. Location of the Aquifer.
Source: CONAGUA.

The mathematical representation of the theoretical linear programming model can be expressed as follows (Hazell and Norton, 1986).

Objective Function:

$$\text{Maximize} \qquad Z = \sum_{j=1}^{n} C_j X_j \qquad 1$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i, \quad \text{for } i=1 \text{ to } m \qquad 2$$

and

$$X_j \geq 0, \quad \text{for } j=1 \text{ to } n \qquad 3$$

Where: X_j=It is the level of the *j*-th activity of the producer, the number of hectares to be planted with a specific crop *j*. *Cj*=It is the net profit margin (also called net prices) of the *j*-th activity unit (pesos per hectare). A_{ij}=It is the amount of resource (water, land) required to produce one unit of the *j*-th activity. Denoted by m as the number of resources, so i=1 to m. b_i=It is the amount of the *i*-th available resource (*e.g.*, hectares, labor days, etc.).

For the construction of the empirical model, the cropping pattern was broken down by agricultural cycle and by module. The following crops were considered: forage oats, barley, maize, alfalfa, roses, grapevines, and second crops such as maize. In total, there were 21 activities. Net prices were calculated using information on rural average prices (RAV), yields, and production costs provided by the ID.

The labels for the variables considered for Module 1 are: forage oats A-W (FOI1), barley A-W (COI1), maize S-S (MPV1), alfalfa (AP1), grapevines (VP1), roses (RP1), and second-crop maize (MSC1). For Module 2: forage oats A-W (AFOI2), barley S-S (COI2), maize S-S (MPV2), alfalfa (AP2), roses (RP2), grapevines (VP2), and second-crop maize (MSC2). For Module 3: forage oats A-W (AFOI3), barley A-W (COI3), carrots A-W (ZOI3), maize S-S (MPV3), alfalfa (AP3), and second-crop maize (MSC3).

The modeling regarding land use in each module was seasonal. Water constraints were organized by production cycle and by module, resulting in a total of 6 water constraints. Water use per crop and cycle was taken from the irrigation schedule of the ID for the 2021-22 agricultural year.

Eight scenarios were constructed. The first considers the available water for the irrigation schedule of the mentioned agricultural year, including both surface water and groundwater. The first model is based on the 2021-22 agricultural year, considered as typical. The second scenario includes a 15% reduction in available water due to moderate drought. The third considers a greater drought with a 25% reduction in water compared to the typical year. The fourth scenario considers a severe drought with no surface water and a 30% reduction in water.

Given the importance of livestock in the region and its connection to agriculture through forage supply, the other four models consider the cultivation of alfalfa at 60% of the amount sown in 2021-22.

Regarding the number of cattle, it is reported that San Juan del Río and neighboring municipalities account for 38% of the total statewide and 13% of the dairy cows (INEGI, 2023).

RESULTS AND DISCUSSION

The results obtained from the different models constructed are presented below. The analysis begins with the effects of the reduction in water availability in the district on the value of the objective function; then, the effects of this availability on the crop pattern are examined. Next, the magnitude of the shadow price of water is analyzed, assuming it is the most scarce input. Finally, results are presented when the model is restricted to consider the planting of alfalfa at 60% of the planned amount for the base year due to the presence of dairy farming in the region.

Table 1 shows the effects of water scarcity on agricultural income in ID 023. The estimation of the effects of a 15% reduction in water availability in the district indicates that it would lead to an 8.6% reduction in agricultural income in ID 023. This is undoubtedly a significant reduction, considering the importance of agricultural activities in the region.

A 25% reduction in water availability would lead to an almost 15% decrease in the income of the population dependent on agriculture in ID 023, while a 30% reduction would result in a 19.1% income loss. Florencio-Cruz *et al.* (2002), Botello-Aguillón *et al.* (2022), and Ramírez Barraza *et al.* (2019) found similar effects on the agricultural income of the district they analyzed. However, the reduction was smaller, as the percentage decrease in water availability was also lower.

These estimates only consider the direct effects on income resulting from the reduction in agricultural activity within the irrigation district. They do not account for the impact on businesses supplying agricultural inputs, nor on related services such as credit and insurance. Additionally, the reduction in labor demand and the wages earned from agricultural work are not included.

It should also be noted that there would be an uncalculated effect on livestock activities in the region, as a significant portion of the irrigation district's land is used for forage crops. A reduction in forage crop production could decrease the net profits of the livestock sector due to the potential scarcity of inputs.

In the four models that consider alfalfa cultivation at 60% of the area sown in each module during the baseline agricultural year, income reductions increase as water scarcity intensifies. Ramírez Barraza *et al.* (2029) found that in the optimal cropping pattern, alfalfa did not appear, despite being present in the district's historical patterns. Forcing its inclusion through a minimum constraint reduced the objective function value. Similarly, Rodríguez *et al.* (2019) demonstrated that with decreasing water availability, alfalfa is the first crop to be removed from the optimal pattern.

The comparison between models with the same water availability, but without and with alfalfa, shows a 4.6% income reduction in the first case. When water availability decreases by 15%, the income reduction reaches 5.7%. With a 25% reduction in water, income decreases by 8.3%, and under severe water scarcity, the reduction is 10.8%. These results are similar to those found by Rodríguez *et al.* (2019).

The most severe drought scenario closely resembles the crops planted in the 2023-24 agricultural year, allowing for an estimation of the economic impact of severe drought on the income of ID 023 users.

Table 2 shows the optimal activities in each model constructed under drought conditions. The activities selected in each model meet the economic optimization criterion, which states that a crop will be included until its marginal income equals its marginal cost. The crops in which the resource is more productive are the ones that will be in the optimal pattern and contribute most to the value of the objective function. In this case, maize SS, second-crop maize, and forage oats. In other cases, crops like strawberries have been favored, as reported by Flores Lázaro *et al.*, (2017).

The activities that were not selected in the optimal solution do not meet this optimization criterion; in other words, in these cases, the marginal cost is higher than

Table 1. Income in the Agricultural Year of ID 023 with Water Scarcity.

Model Water reduction	Value (Millon pesos)	Reduction (%)	Value (Millon pesos) with alfalfa	Reduction (%)
Base	292.76	N/A	279.22	
15% Less	267.71	8.6	252.18	9.7
25% Less	250.43	14.5	229.60	17.8
30% Less	240.86	19.1	214.83	23.1

Note: The models with alfalfa contain 60% of this crop from the area planted in the 2021-2022 agricultural year, under all drought conditions. Source: Prepared by the authors with information from the constructed models.

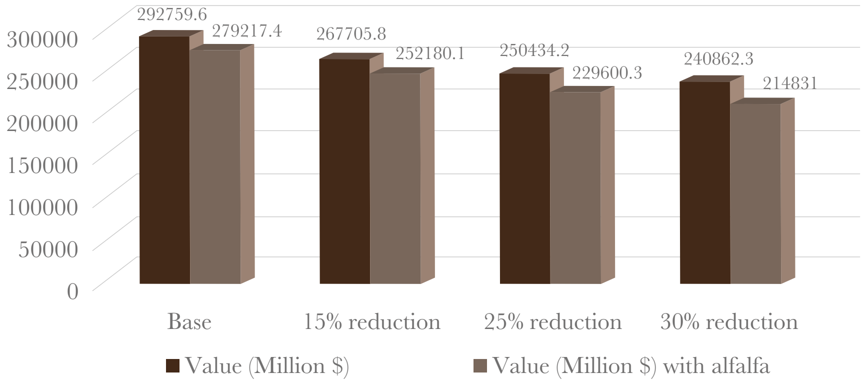

Figure 2. Variations in Agricultural Income of ID 023 in the Agricultural Year Due to Water Scarcity. Source: Prepared by the authors with information from the constructed models.

Table 2. Crops in the optimal solution in the constructed models.

Crop	Base model (ha)	15% Less water (ha)	25% Less water (ha)	30% Less water (ha)
AFOI1	1125	546	160	0
MPV1	2085	1454	1033	849
VP1	17	17	17	17
RP1	6	6	6	6
MSC1	1425	2056	2476	2619
AFOI2	2172	1685	1360	1204
MPV2	1330	656	206	0
RP2	100	100	100	100
VP2	4	4	4	
MSC2	2956	3443	3768	3893
AFOI3	100	0	0	0
ZOI3	50	50	50	50
MPV3	385	314	279	261
MSC3	380	416	354	324

Source: Prepared by the authors with information from the constructed models.

the marginal income. Duality theory states that associated with a primal model whose objective is to maximize a function, provided this function has a solution and is optimal, there is a dual model whose optimization will be minimization. The primal maximizes profits, and the dual minimizes costs (Hazell and Norton, 1986). In this case, the net price of each activity is equivalent to the marginal income, and the concept of "reduced cost" is the marginal cost obtained from the valuation the model imputes for the resources used in its production.

When resources are abundant in the model, there will be surpluses, and they will have a shadow price of zero. In contrast, the scarce resources, the ones that are exhausted, will have a positive value. The crops that use a greater amount of scarce resources in their production will have a higher marginal cost, and consequently, they will not be selected.

For example, in the base model, the activity of barley in the A-W cycle (COI1) has a marginal cost that exceeds the marginal income by $10,520. In this case, if barley production is insisted upon under the conditions set in the model, the income of the ID will decrease by $10,520 for each hectare of this crop produced. In the base model, the crop with the highest excess of marginal cost over marginal income is alfalfa AP1 ($23,280) and AP3 ($22,570).

When water is scarcer (and thus more expensive), crops that use more of this resource for production will have a higher marginal cost. In the scenario with the greatest water scarcity, the alfalfas in the three modules (AP1, AP2, and AP3) have the highest amounts where the marginal costs exceed the marginal incomes by the following amounts: $42,038, $40,195, and $33,917 per hectare, respectively.

The LP model obtains the marginal productivity of water by extracting the values of the Lagrangian variables from the dual problem solution, and these are known as the shadow prices of water (Hazell and Norton, 1986). This type of model is most suitable for determining the value of water when the resource does not have a market price (Young and Loomis, 2015).

In Table 3, the magnitudes of the marginal productivity of water by cycle are presented. All models record shadow prices with values greater than zero in both production cycles. In the base model, the highest values are recorded in the autumn-winter cycle in the three modules. For module 3, the highest value is recorded at $3,922 per thousand cubic meters. This means that for each additional thousand cubic meters in module 3 in the autumn-winter cycle, the ID income would increase by $3,922. This is the interpretation for the rest of the values.

In the models with moderate droughts (15% and 25% less water), the water productivity remains the same as in the base model, except in module 3, autumn-winter cycle, where it increases significantly ($5,597/mm^{3}).

When the drought is severe (with a 30% reduction in water and only underground water is used), in all models, the magnitude of the shadow price increases significantly, with values ranging from $3,467 to $7,144 per thousand cubic meters. These results align with those reported by Rubiños-Panta *et al*., (2007). Furthermore, the values are higher when only underground water is used, which is consistent with findings by Florencio-Cruz *et al*., (2002).

Table 3. Shadow price of water under different drought conditions in the ID023.

Module and cycle	**Base model ($/mm^{3})**	**15% Less ($/mm^{3})**	**25% Less ($/mm^{3})**	**30% Less ($/mm^{3})**
1 A-W	3448	3448	3448	5819
1 S-S	2054	2054	2054	3467
2 A-W	894	894.4	894	3922
2 S-S	3077	3077	3077	7145
3 A-W	3922	5597	5597	5597
3 S-s	2530	3611	3611	3611

Source: Prepared by the authors with information from the constructed models.

Shadow price values for water have been calculated for various locations at different times, with the aim of making a comparison with those found in this research. These shadow prices per thousand cubic meters were converted into dollars per thousand cubic meters using the exchange rate at the time of each study (BANXICO, 2024). Florencio *et al.* (2002) reported a price of $106.32 per cubic meter for the ID 011. Although they registered lower values for some crops, they also accounted for values higher than those used here, specifically for high-value crops. Martínez *et al.* (2021) found a price of $81 per thousand cubic meters for the ID 100 in Alfajayucan in a 2016 study. Ramírez *et al.* (2019) found a shadow price of $50.63 per thousand cubic meters for the Lagunera region in Mexico. Botello *et al.* (2022) found shadow price values for some irrigation modules of the ID 011 in Celaya, with prices of $195.39 per thousand cubic meters. In all cases, the shadow price is significantly higher than the irrigation fee paid by users.

In the research presented here, as of the exchange rate on April 17, 2024, different shadow price values were found, ranging from the lowest value of $52.62 per thousand cubic meters in the base model for the A-W cycle of module 2, to $420.54 per thousand cubic meters in the extreme drought model for the S-S cycle of module 2.

Given the connection between agriculture in the ID 023 and livestock in the municipality and region, both for beef and dairy cattle, as previously mentioned, versions of comparable models were constructed with the initial ones. The difference is that all of them include 60% of the alfalfa area sown in the year used as a reference.

Figure 3 compares the optimal solution when only groundwater is used for irrigation, with and without sowing 60% of alfalfa. It is observed that the presence of alfalfa causes a significant reduction in the cultivation of forage oats (AW) and maize (SS), as well as in second crops.

In the other models tested with drought conditions, when alfalfa is included, it causes a drastic reduction in the other crops, with a slight gain in the second-crop maize. Similar results were reported by Ramírez Barraza *et al.* (2019).

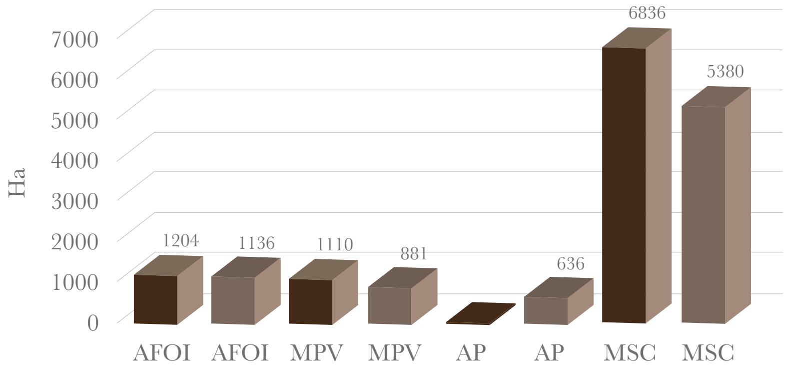

Figure 3. Crops with groundwater irrigation only. Without and with 60% alfalfa.
Source: Prepared by the authors with information from the constructed models.

CONCLUSIONS

It is concluded that the inclusion of high water-consuming crops, such as alfalfa, under drought conditions would only be justified when dairy farming is important in the area. The increase in the shadow prices of water as this resource becomes scarce serves as a signal indicating to which activities the resource should be allocated.

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