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Reallocation of water in agriculture under drought conditions as economic efficiency maximizer

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ABSTRACT

Objective: To analyze the water market scheme for water rights transfer, which could enable the increase of the economic efficiency of water use in the Irrigation District 011 - Alto Río Lerma.
Design/Methodology/Approach: Using linear programming, a first model was developed to determine shadow prices in three water scarcity scenarios (15, 30, and 50% water resources reduction) and to compare them with the irrigation fees currently paid in Irrigation District 011. The second model established a water market scheme, using the same water scarcity scenarios (15, 30, and 50%). This model was developed to compare the net profit of the producers within and outside the water right transfer market.
Results: The average shadow price of water is MN$ 3.9 m^{-3}; this amount is higher than the irrigation fee currently paid (MN$ 0.15 m^{-3}). The water transfer percentages are 25.8, 29.1, and 36.1%, obtaining 7.6, 7.4 and 11.7% net profit, respectively, for each water scarcity scenario (15, 30, and 50%).
Study Limitations/Implications: The research was carried out based on the data from two out of the 11 irrigation modules included in Irrigation District 011. These modules are the most representative, both in extension and crop variety.
Findings/Conclusions: The existence of a water market confirms the advantages of an increase in the net profit of the producers under drought conditions, included within the area of Irrigation District 011.

Keywords: Water scarcity, water market, optimization, productivity.

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INTRODUCTION

For a long time, when water seemed to be abundant, people behaved as if this resource had no value. The fourth principle of the International Conference on Water and the Environment established that "water has an economic value in all its competing uses and should be recognized as an economic good" (ONU, 1992). Theoretical development has proved that water has a series of social, economic, and cultural characteristics. Therefore, water is a special resource; however —like other production resources—, it has an economic value (Hanemann, 2006).

Image by S. Hermann & F. Richter at Pixabay

There are many methods to measure the value of water and its contribution to the different productive processes. Giving an appropriate value to water can become a useful tool to reallocate it to more efficient uses (Young and Loomis, 2014).

In agriculture, increasing the economic efficiency through the reallocation of water to crops with higher value is a way to guarantee that the users can increase their profits. In a mathematical programming model, the economic criteria behind the water reallocation to crops complies with the equivalence between the marginal revenue and the marginal cost (Hazell and Norton, 1986; Beattie and Taylor, 1985). In those cases where the government is involved in the decision-making process regarding the use of water, shadow prices must be estimated, in order to guide the efficient allocation of water (Young and Loomis, 2014).

In its normative and positive forms, mathematical programming shows the importance of its use in the decision-making process about water allocation in agriculture (Filippi *et al.*, 2017; Ren *et al.*, 2017; Ahmad *et al.*, 2018; Li *et al.*, 2018; Zhang and Guo, 2018).

The application of mathematical programming in agriculture allows to reallocate farm and regional resources, taking into account a wide range of situations, such as price variations and availability, new and more profitable production activities, and market or institutional limitations, among others (Hazell and Norton, 1986).

In Irrigation District 011 (ID 011), the agricultural production yield has been impacted by the reduction of the volume in the whole basin. Several studies that tackle the valuation of water within ID 011 have proposed some methodologies to estimate the value of water, mainly in water scarcity scenarios (Florencio-Cruz *et al.*, 2002; Rubiños-Panta *et al.*, 2007; Rodríguez-Flores *et al.*, 2019; Pineda-Espejel, 2019). Overall, these researches focus on the analysis of water optimization aspects between the different crops and the estimation of marginal productivity. Rubiños-Panta *et al.* (2007) and Rodríguez-Flores *et al.* (2019) have analyzed the water right transfer and the water reallocation between the irrigation modules of ID 011.

The existence of water transfer is well known, not only within agricultural activities, but also towards the industry and the services in the area of interest (Sosa-Márquez *et al.*, 2019). Additionally, the agricultural sector is the main water consumer in Mexico and worldwide (FAO-WWC, 2015) and, therefore, looking for short-term alternatives —such as the opportunity to develop a water market within the ID 011— remains an important task. Consequently, the aim of this study was to understand water productivity in two irrigation modules of the ID 011, using them as reference to compare the irrigation fees and to analyze the water market scheme for water right transfer between the producers of the said irrigation modules, which can enable an increase in the economic efficiency of water use.

MATERIALS AND METHODS

The research was carried out in the Irrigation District 011 - Alto Río Lerma, in southern Guanajuato, Mexico. It is located between 19° 55’ and 21° 52’ N and 99° 39’ and 102° 05’ W, at an altitude of 1,722 m. It is part of the Lerma-Chapala drainage basin, where 30% of the industrial production and 12.5% of the agricultural production of the country take place; in addition, 75% of the water of this area is used for agriculture and livestock raising (Fernández-Durán and Lloret, 2016).

Data were gathered from the M02: Salvatierra and M05: Cortázar agricultural production modules. These modules share the same source for the gravity-fed irrigation model and have a higher water demand (29% of the available total); they include representative regional crops. The data used for this study were: yield, average rural price, production costs, sown area, and water volume used. This information was provided by the Head of the Irrigation District 011 - Alto Río Lerma and the Limited Liability Company of the ID 011.

Using this information, a lineal programming model was developed. This model was used to establish both the maximum profit based on the availability of the fixed resources of the farm and crop definition that sets the pattern of the crops that have been sown in ID 011. We used a base model with the real crop pattern for the 2016-2017 agricultural period and the total water volume available that year.

The 2016-2017 information was used because that was a typical year: the water volume remained constant in the dams that supply the ID 011, reaching a historical level. Faced with water scarcity, producers only sow during one cycle (autumn-winter/spring-summer). Several scenarios were developed using different water scarcity levels (15, 30, and 50% water reduction) to carry out agricultural activities.

The mathematical representation of the model can be expressed as follows (Kaiser and Messer, 2011).

Objective function:

Maximize
$$Z = \sum_{j=1}^{n} c_j x_j \tag{1}$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i \text{, for all } i=1,\dots,m \tag{2}$$

$$x_j \leq \beta x_j^{year\ base} \tag{3}$$

$$\text{and } x_j \geq 0 \text{, for all } j=1,\dots,n \tag{4}$$

Where: x_j=is the j-i^{th} activity of the producer, the number of hectares to be sown with a given crop; c_j=is the net profit margin forecast (also known as net prices) of the j-i^{th} unit of the activity (pesos per hectare); a_{ij}=quantity of the i-i^{th} resource (water, land) required to produce a unit of the j-i^{th} activity; m is the number of resources, therefore $i=1, \dots, m$; b_i=is the amount of the i-i^{th} available resource (water, land); β=allowable percentage of the j-i^{th} activity of the producer, dimensionless.

For the development of the empirical model, the crops established in the M02: Salvatierra and M05: Cortázar modules were used —including barley, maize, sorghum, and wheat. They represent 83.1% of the cultivated area and 77.3% of the water delivered to the modules (Table 1).

The net prices were calculated as the difference between the gross income (yield multiplied by the average rural price) and the production cost per sown hectare —not including water costs, which are precisely the value that we are looking for.

Table 1. Crops established in the M02: Salvatierra and M05: Cortázar modules in the 2016-2017 period.

Crop	Area (ha)	Volume of water (dam^3)	Crop	Area (ha)	Volume of water (dam^3)
Garlic (*Allium sativum*)	46.4	275.6	Strawberry (*Fragaria* × *ananassa*)	78.7	508.2
Alfalfa (*Medicago sativa*)	1378.1	17421.2	Beans (*Phaseolus vulgaris*)	1179.5	14996.7
Fodder oats (*Avena sativa*)	81.8	760.0	Bean (*Phaseolus vulgaris*)	30.4	138.9
Broccoli (*Brassica oleracea* var. *italica*)	743.2	5653.7	Chickpea (*Cicer arietinum*)	378.2	1778.6
Peanut (*Arachis hypogaea*)	143.6	721.6	Guava (*Psidium guajava*)	7.5	41.6
Zucchini (*Cucurbita* pepo)	50.9	457.8	Tomato (*Solanum lycopersicum*)	10.1	40.5
Sweet potato (*Ipomoea batatas*)	87.9	833.6	Cabbage (*Lactuca sativa*)	927.1	5546.1
Barley (*Hordeum vulgare*)	8466.9	65900.3	Corn (*Zea mays*)	178.9	2265.5
White onion (*Allium cepa*)	235.7	2868.1	Grain corn (*Zea mays*)	19331.9	102696.6
Chayote squash (*Sechium edule*)	2.8	30.3	Sorghum (*Sorghum bicolor*)	5887.5	21014.7
Coriander (*Coriandrum sativum*)	2.1	51.8	Green tomatoes (*Physalis philadelphica*)	818.7	10242.6
Cauliflower (*Brassica oleracea* var. *botrytis*)	154.7	1113.8	Wheat (*Triticum durum*)	6903.3	71033.4
Asparagus (*Asparagus officinalis*)	484.5	2592.7	Carrot (*Daucus carota*)	734.4	7951.3

Source: Table developed by the authors using information of the Office of the Head of ID 011 and the Limited Liability Company of the ID 011.

Water volume and available area vary according to the agricultural cycle and the irrigation method. Water and land restrictions were considered. The former amounted to 337,007 dam^3 (*i.e.*, the water volume used by M02: Salvatierra and M05: Cortázar modules during the 2016-2017 period). The latter matches the sowing area of each module (Table 2).

Subsequently, a second model was developed. This model enabled —within the same water scarcity scenarios (15, 30, and 50% water reduction)— the existence of a water market scheme between the producers of the two irrigation modules. This model was based on chapter V of the Ley de Aguas Nacionales (DOF, 2020), which allows the transfer of

Table 2. Resources restriction for the lineal programming model.

Type of irrigation	Cycle	M02: Salvatierra		M05: Cortázar	
	Resource	Land (ha)	Water (dam^3)	Land (ha)	Water (dam^3)
Surface	Fall-Winter	12092.3	50955.1	11930.7	73949.4
	Spring-Summer		46282.9		5979.9
	Perennials		10927.6		161.8
	Second crops		18045.8		32159.6
Pumping	Fall-Winter	4075.9	22418.8	7184.0	34658.9
	Spring-Summer		11840.9		346.3
	Perennials		4894.5		4609.9
	Second crops		5915.5		13859.9
	TOTAL	16168.2	171281.3	19114.7	165725.8

Source: Table developed by the authors using information of the Office of the Head of ID 011 and the Limited Liability Company of the ID 011.

concession arrangements for the exploitation or use of national waters between economic agents and sectors.

The lineal programming models were processed using the LINDO 6.1 (Lineal Interactive Discrete Optimization) software. The results were processed with a three-part analysis: the first part covers the shadow prices; the second includes the water volume allocated to the modules; and the third shows the net income of the irrigation modules.

RESULTS AND DISCUSSION

Using the resource optimization model supported by the availability water restriction, the shadow prices of gravity-fed and land were initially obtained (Table 3).

When shadow prices reach a zero value, it does not mean that the resource has ran out completely and, therefore, it is free of charge. This was the overall case of the shadow prices of the land resource. The results showed that the water shadow price of the base model was MN\$3.9 m^{-3}; this price is much higher than the price paid by the users (MN\$0.15 m^{-3}). A similar relation was found by Martínez-Luna *et al.* (2021), who recorded a MN\$1.44 m^{-3} shadow price for the Irrigation District 100, in Alfajayucan, Hidalgo, Mexico. That price is higher than the irrigation fees paid by the producers (MN\$0.02 m^{-3}). Ramírez-Barraza *et al.* (2019) carried out a study in the Comarca Lagunera and recorded a MN\$0.91 shadow price; this price is higher than the price paid by the producers of the study area.

The existence of a water market in ID 011 allows the reallocation of water volume to other modules. Figure 1 shows the water transfer between agricultural cycles in M02 and M05 modules. Additionally, it enables a comparison with the established volumes, when the district lacks a water market.

In view of a potential water market, water was used in the agricultural cycles in which the highest shadow prices are obtained. This behavior shows that —within the irrigation modules of a district—the resource was bought and sold in those places where high profit crops are sown, or water demand is lower. Rodríguez-Flores *et al.* (2019) recorded a different situation in their study. They evaluated a formal water market for all the ID 011, where the four modules with highest overall shadow prices imported the resource.

Table 3. Shadow prices of gravity-fed and land per irrigation module (MN\$ dam^{-3}).

Availability	**100%**		**85%**		**70%**		**50%**	
Resource	**M02**	**M05**	**M02**	**M05**	**M02**	**M05**	**M02**	**M05**
Water								
F-W	1284	1371	1284	1371	3484	1371	4246	1371
S-S	2084	3872	2084	3872	2084	3872	2631	3872
Perennial	1964	12771	1964	12771	1964	12771	1964	12771
Second crops	4222	3640	4222	3640	4222	3640	4222	3640
Land								
June	0	9987	0	0	0	0	0	0
July	0	9953	0	17027	0	12687	0	3507

Source: Table developed by the authors using information of the outputs of the MPL of the LINDO 6.1.

The main aim of this water market projection is to prove the economic effect that it can have on the ID 011 users. In addition, along with an optimal crop pattern, it can increase their net profit. Table 4 shows the results of the M02 and M05 modules net income. A water market can indeed favor the total net income in all scarcity scenarios.

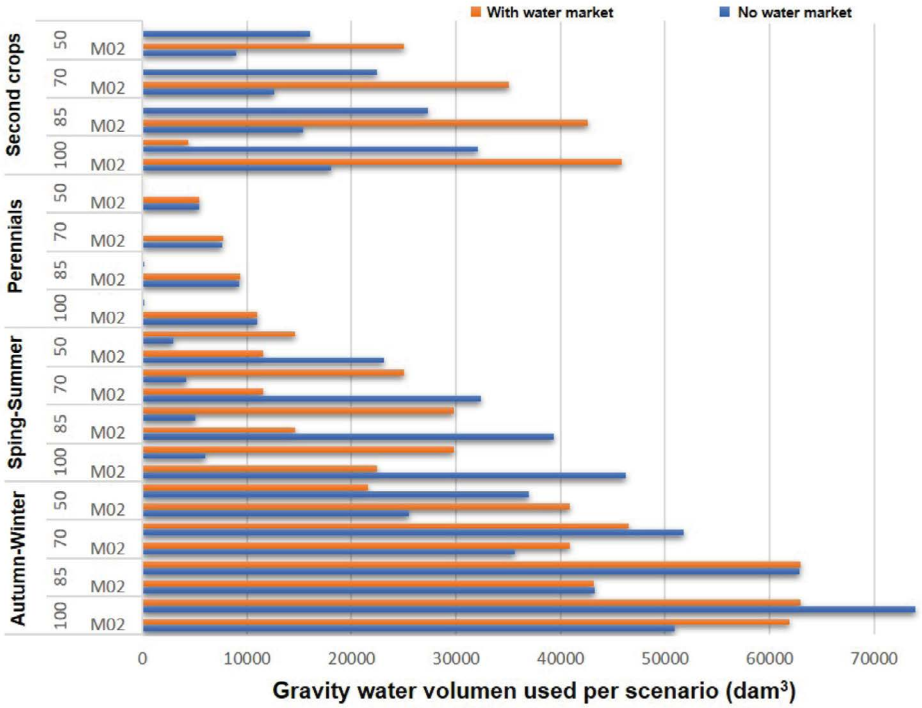

Figure 1. Water volume for gravity-fed irrigation used per module and each availability scenario. Source: Table developed by the authors using information of the outputs of the MPL of the LINDO 6.1.

Table 4. Net income of the M02 and M05 irrigation modules in different availability and water market scenarios (millions MN$).

Water availability	**Net income in millions of Mexican pesos**					
	No water markets			**With water markets**		
	85%	**70%**	**50%**	**85%**	**70%**	**50%**
M02: SALVATIERRA						
Spring-Summer	187.31	171.28	129.05	187.18	184.19	184.19
Fall-Winter	195.91	181.44	159.6	137.07	126.73	126.73
Perennials	17.95	14.73	10.43	18.08	14.81	10.46
Second crops	64.76	53.33	38.09	180.04	148.25	105.86
M05: CORTÁZAR						
Spring-Summer	88.57	73.36	53.09	88.7	66.21	31.97
Fall-Winter	29.14	25.67	21.04	124.99	106.46	66
Perennials	1.76	1.45	1.03	0.88	0.88	0.88
Second crops	99.87	82.32	58.91	0.49	0.49	0.49
Total:	685.27	603.58	471.24	737.43	648.02	526.58

Source: Table developed by the authors using information of the MPL of the LINDO 6.1.

CONCLUSIONS

The irrigation fees paid within ID 011 do not represent the actual value of water. An adjustment in the fee prices could benefit ID 011. Such benefits would include better management or improvements to the current hydro-agricultural infrastructure that would enable a higher irrigation efficiency for the distribution of water to the local users.

Further crop pattern analysis must be carried out in ID 011. Additionally, crops with better characteristics (*i.e.*, profitable, low investment, existing market, etc.) must be taken into account as an option for future agricultural years. Crops such as alfalfa, oats, maize, and sorghum should not be sown because of their low profitability and/or water demand. Water commercialization is an efficient mechanism in the economy of the hydric resources. It should spark an interest in water governance for lost markets. This situation could be the result of legal restrictions related to the commercialization of water rights. It can improve the efficient use of water in agriculture, supplying the forecasted water demands, resulting from population growth. The results of this research lay the foundations for the generation of a market policy for right water transfer in ID 011. This policy should motivate both buyers and sellers to evaluate water use strategies related to scarcity water values. In addition, we must be aware of the costs of the infrastructure involved in the water market development.

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