Article

Efficient rates for water for agricultural use in the Comarca Lagunera

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Abstract

Water is an increasingly scarce resource and therefore has an increasing importance for society, which is why it is pertinent and necessary to determine its economic price. The objectives of this research were to determine the shadow price of agricultural water supplied by gravity irrigation and pumping in the Lagunera Region (Coahuila and Durango), in order to calculate the efficient rates, which induce an optimal economic use of the resource. A linear programming model with restrictions on availability of labor, land and water was used. Different scenarios of decreasing water availability were analyzed in order to study the behavior of its shadow price in the face of changes in the amount available. The results indicate that the water shadow price is \$1.56 m^{-3} MN for pumping and \$0.91 m^{-3} MN for gravity. It was concluded that the fees paid for irrigation water in the region are considerably lower than the opportunity cost or shadow price of water. It was also concluded that the current allocation of water for agricultural use generates an inefficient crop pattern, as it is used to produce alfalfa and other forages, which do not appear in the optimal crop pattern calculated with the linear programming model built for the region. It is recommended that the rates be defined taking as reference the shadow price of water, which should be adjusted according to the periodic changes in the water scarcity level.

Keywords: efficient rates, optimal crop pattern, water shadow price.

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Introduction

Water is a fundamental element of subsistence; on average more than 70% of the water consumed worldwide is destined for agricultural use. The quantities of water required in the systems of agricultural production (cultivation, livestock, and aquaculture) are many times greater than the 20 liters that a human being requires. It is estimated that between 70 and 90% of freshwater supplies in developing countries are used to produce food. The 75% of the world's 1.2 billion poor people depend on agriculture as the main source of income (Villholth, 2009).

However, the amount of water available is directly affected by the increase in the population. In the twentieth century the world population tripled increasing the pressure on the water resource, so the water extractions were sixfold, which is aggravated in regions with severe water scarcity, since there is about 35% of the world population. In addition, approximately 65% of the world's rivers and aquatic ecosystems exhibit medium or high degradation (sixfold). Among the main countries with the greatest water extraction are India, China and the United States of America with a total extraction of 761, 554.1 and 478.4 billion m^3 $year^{-1}$ respectively (CONAGUA, 2014).

Mexico is in the ninth place with 81.65 billion m^3 $year^{-1}$ and has regions where the concentration of population and economic activity have generated high scarcity areas, because the urban space exceeds the natural water system in which is supported (Morales and Rodríguez, 2007). The main water demand zones are located in the North and Center of the country, an area that concentrates 77% of the population and 84% of the Gross Domestic Product (Garduño, 2003).

A determining factor in the availability of water is the size of the population and its tendency to concentrate in urban areas; it is estimated that by 2030 the population of Mexico will be 137.5 million. From 2015 to 2030, the CONAGUA predicts a decrease of 3 692 to 3 250 m^3 per inhabitant per year and in some regions, it will reach scarcity levels close to or even below 1 000 cubic meters per inhabitant per year (FCEA, 2017). The level of scarcity of water is a trigger factor of conflict between the demanding sectors (agricultural, livestock, industrial and urban) of the resource.

The Comarca Lagunera, located in the North of Mexico, presents acute problems of water scarcity and overexploitation of aquifers. The deficient control of extractions, the lack of additional sources to supply cities, the recurrent presence of droughts and the competition between alternative uses of water, are increasingly acute problems (CONAGUA, 2012). The annual demand for drinking water for human settlements in the municipalities of Coahuila (Torreón, Matamoros, San Pedro de las Colonias, Francisco I. Madero and Viesca) and Durango (Gómez Palacio, Lerdo, Tlahualilo, Nazas, Rodeo, Mapimi, San Juan de Guadalupe, San Pedro del Gallo, Cuencame, San Luis del Cordero and Simon Bolivar,) that make up the Lagunera Region is 127 million cubic meters, which are obtained for the most part from the subsoil.

Currently, the situation is critical, because they have to drill 300 m or more to obtain 30 liters of water, and many times it is contaminated with arsenic, when before they drilled 30 meters to obtain 300 liters of water (El Siglo de Torreón, 2010).

The economic importance of this region is that it occupies the first place in the production of melon, forage sorghum, broom sorghum, bovine milk and poultry meat, the second place in fodder maize production, third place in cotton and egg production, fourth place in walnut and alfalfa and is the fifth place in goat meat production. Of every 10 liters that are produced from milk in Mexico, two correspond to La Laguna, reason why it is considered as the main dairy basin. It also stands out for its export potential of cotton, poultry meat, beef, tomato, melon, fig, watermelon and walnut, agricultural products that some of them already venture into the international market.

The Comarca Lagunera plays a preponderant role in the agricultural sector, given its geographical location, the agricultural and social vocation that the region has tended. There are 44 000 agricultural producers who are assisted by SAGARPA through three sub-delegations, two Rural Development districts and 16 Support Centers for Rural Development (González, 2016). In the case of Irrigation District 017 Comarca Lagunera, an irrigation fee of 1 600 pesos MN ha^{-1} is charged without considering the type of crop. This quota covers partially the operating costs but does not include the maintenance costs of the channels or the main works, as well as the loss of water in the driving and distribution process.

This official price or market price in the irrigation district is much lower than its shadow or opportunity price, so if this price were used when analyzing the production system, an economic optimum would never be reached. To achieve this objective, the shadow price is usually used (Palacios and Excebio, 1989), to make a better allocation of water to the activities that produce the greatest economic and social benefit (Ward and Michelsen, 2002). The definition of the efficient price of water is crucial to improve its allocation, promote its conservation and improve the efficiency of its use, both at an individual and social level (Dinar and Subramanian, 1997). In addition, the shadow price helps improve demand management and increase cost recovery.

It is possible to get an idea about the viability of the cost of recovery by comparing the price paid by irrigation users with the costs of providing irrigation water. It is important to know who gets the benefit from irrigation. Consumers, for example, benefit from irrigation water by having lower food prices. Irrigated agriculture can also support economic development in rural areas, through the creation of jobs and support for agri-food industries in those areas that would otherwise become uninhabited. This explains why the government often covers part of the costs of irrigation (Hellegers, 2007).

The valuation of the water in function of the costs that induces its availability should be, at least, a starting point. The opportunity cost of a good's water does not only depend on the costs demanded by its availability, but also on its usefulness and scarcity. In the case of water, it is increasingly necessary to consider its quality, since productivity in its various uses (agricultural, industrial, domestic and sanitary), depend to a large extent on its physico-chemical characteristics (Arrojo, 1999).

In the case of the Lagunera Region, there is water shortage due to the fact that the supply of the resource does not cover the demand, this represents a conflict of allocation between the different users of the service. Water distribution is made according to the importance of the resource in the different sectors and its allocation is a social issue and is not left to the forces of supply and demand, so the price does not behave in the same way it is explained by economic theory and is affected by government subsidies. The water must have a price in order to achieve two objectives namely, recover the cost of providing the water service in particular and give a clear signal to users that water is in fact a scarce resource that must be used with economic rationality.

The water market is not homogeneous since the different sub-sectors (agriculture, industry, energy, transport, flood protection) have different characteristics. Since water is a vital resource for life for which there is no substitute, the only choice that needs to be made is how to allocate the resource and find the most efficient way to use it. Water availability depends on climate variability, but also on land use and human interference. Demand also varies over time, both in the short and long term due to the structure of the economy and population changes (Van der Zaag and Savenije, 2006).

Because the availability of water and its uses are directly determined by economic and social development, it is of vital importance to adopt measures for the adequate and efficient use of water resources and induce an integral and sustainable management. The identification of priorities and exchanges related to the distribution of water requires careful and timely attention in order to face a growing range of complications such as: sustainability of water resources, justice, pollution, environment, basic services, development, competition and globalization. National policies focused on the water sector should consider these issues, since, otherwise, the tendency to undervalue and overexploit water resources will cause a growing and negative impact on the global economy and society (Asad and Dinar, 2006).

Although the agricultural sector is the main water consumer, there are few studies that estimate the demand function for water for agricultural use, its response to variations in prices and the rates that must be charged to induce an efficient use of water. Consequently, the objectives of this research were: a) to determine the shadow price of irrigation water in the Lagunera Region; and b) calculate the rates that lead to optimal and efficient use.

Materials and methods

Optimization models provide mathematical solutions to problems involving the maximization or minimization of an objective function with a system of well-specified constraint equations. There are two types of optimization model: mathematical programming models and dynamic optimization models. In the mathematical programming model used in this research, the objective function and the inequality constraints are linear. The objective function consists in the maximization of the sum of net gains obtained in the production process of the crops.

The model is subject to various resource availability constraints: water, land, labor force and crop area. The model was solved in the LINDO computer program (Linear Interactive Discrete Optimization). The model considered: a) 24 variables, 12 superficial irrigation crops and 12 irrigation crops with well water; and b) 30 restrictions, 24 maximum and minimum restrictions and 6 restrictions corresponding to the availability of labor, land and water. Finally, scenarios were made to reduce the water available for irrigation to analyze the behavior of prices. The primal model of linear programming is:

$$\text{Max} \sum_{j=1}^{n=24} c_j x_j$$

$$\text{sa:} \sum_{i=1}^{m=30} a_{ij} x_j \leq b_i, \quad x_j \geq 0,\ i=1, 2, \ldots, 30,\ j=1, 2, \ldots, 24$$

Where: x_j represents the jth crop of the producer, the first 12 are irrigation crops and the remaining 12 are irrigated by gravity; c_j represents the net price of the jth crop; a_{ij} represents the quantity of the ith resource needed to produce a unit of the jth crop and b_i represents the available amount of the ith resource.

The corresponding dual problem is:

$$\text{Min} \sum_{i=1}^{m} \lambda_i b_i$$

$$\text{sa:} \sum_{i=1}^{m=30} \lambda_i a_{ij} \geq c_j, \quad \lambda_i \geq 0,\ i=1, 2, \ldots, 30,\ j=1, 2, \ldots, 24$$

The Lagrangian of the primal problem is:

$$L = \sum_{j=1}^{n=24} c_j x_j + \sum_{i=1}^{m=30} \lambda_i \left(b_i - a_{ij} x_j\right), \quad x_j \geq 0,\ \lambda_i \geq 0$$

According to the Khun-Tucker Theorem (Intriligator, 1991), the necessary conditions for the existence of an optimal solution are:

$$(c_j - \lambda_i a_{ij}) \leq 0,\ j=1, 2, \cdots, 24,\ i=1, 2, \cdots, 30 \quad 1)$$

$$\left(c_j - \lambda_i a_{ij}\right) x_j \leq 0,\ j=1, 2, \cdots, 24,\ i=1, 2, \cdots, 30 \quad 2)$$

$$\left(b_i - a_{ij} x_j\right) \geq 0,\ j=1, 2, \cdots, 24,\ i=1, 2, \cdots, 30 \quad 3)$$

$$\left(b_i - a_{ij} x_j\right) \lambda_i \geq 0,\ j=1, 2, \cdots, 24,\ i=1, 2, \cdots, 30 \quad 4)$$

$$x_j \geq 0,\ \lambda_i \geq 0,\ j=1, 2, \cdots, 24,\ i=1, 2, \cdots, 30 \quad 5)$$

According to Intriligator (1991), since the feasibility sets of the primal and dual problems are not empty in the case of the present investigation, and that the objective function is almost concave and the constraints are convex, because they are linear, then the above conditions are necessary and sufficient for the existence of an optimal solution. The so-called complementary condition of slack requires that conditions (2) and (3) be met.

According to the above, if any restriction is met as a strict inequality, then the corresponding dual variable is zero in the solution. If the variable is a positive number in the solution, then the corresponding restriction is satisfied as a strict equality. On the other hand:

$$\frac{\partial L}{\partial \lambda_i} = \left(b_i - a_{ij} x_j\right) \cdot \lambda_i \geq 0 \ \ (= 0, \ \text{si } \lambda_i > 0)$$

Consequently, the Lagrange multipliers: λ_i, i= 1, 2, ..., 30, represent the shadow prices of the resources whose availabilities restrict the model. The lambda corresponding to the restriction of the availability of pumping water and of gravity are the shadow prices of water λ_{29} and $\lambda_{30}$and express how much the optimum value of the objective function increases if the availability of water increases by one unit. An analogous interpretation has the other Lagrange multipliers. The marginal price of water, shadow price or opportunity cost, is related to a change in the total value of a product, associated with several levels of water application; that is, the marginal price of water is an economic price of an extra unit of water at the optimum point (Tang, 2004; Samarawickrema and Kulshreshtha, 2009).

Mathematical programming models are often used to determine the economic price of irrigation water and groundwater. The previous model is designed to serve as a tool for decision-making that is the responsibility of agricultural production planners at the irrigation district level. The solution to the model is a set of activities or crops that maximize the sum of the gains of agricultural production (Amir and Fisher, 1999). This combination of crops represents the optimal allocation of water and other resources of production, using as an objective function the maximization of total or aggregate gains, subject to resource availability restrictions and institutional constraints (Pérez, 2003).

The validity of the model requires producers that maximize income and use productive inputs to the point where the marginal product is equal to the opportunity cost (FAO, 2004). The crops analyzed were: alfalfa (*Medicago sativa* L.), forage oats (*Avena sativa* L.), cotton (*Gossypium hirstium* L.), forage sorghum (*Sorghum vulgare*), forage maize (*Zea mays* L.), melon (*Cucumis melo*), watermelon (*Citrullus lanatus*), tomato (*Solanum lycopersicum*), pepper (*Capsicum annuum* L.), corn grain (*Zea mays* L.), sorghum broom (*Sorghum vulgare*) and walnut (*Juglans regia*), which represent the main crops of the study region.

The data used in the model includes the agricultural year 2015-2016. The information was obtained from SAGARPA-DRL (2016); Soto *et al*. (2016); DOF (2016); CONAGUA and IMTA (2016); SAGARPA (2015) and CONAGUA (2017). The net price was obtained from income per hectare minus production costs without including wages for the use of labor force, land rent and water price (Table 1). All monetary values are expressed in MN of Mexico.

Table 1. Net prices used in the model.

Crop	Variable	Net price thousands of $ MN	Variable	Crop	Net price thousands of $ MN
		Gravity			Pumping
Alfalfa	X_1	74 430.17	X_{13}	Alfalfa	588 042.38
Forage oats	X_2	1 278.31	X_{14}	Forage oats	91 277.87
Cotton	X_3	381 115.42	X_{15}	Cotton	27 299.32
Sorghum forage	X_4	17 005.67	X_{16}	Sorghum forage	32 933.64
Fodder corn	X_5	179 317.68	X_{17}	Fodder corn	392 272.76
Melon	X_6	29 575.9	X_{18}	Melon	187 197.52
Watermelon	X_7	11 371.81	X_{19}	Watermelon	7 039.5
Tomato	X_8	325.45	X_{20}	Tomato	58 275.37
Pepper	X_9	13 265.62	X_{21}	Pepper	11 902.77
Corn grain	X_{10}	9 066.66	X_{22}	Corn grain	1 073.36
Sorghum escobero	X_{11}	2 568.81	X_{23}	Sorghum escobero	505.16
Nut	X_{12}	20 4005.61	X_{24}	Nut	174 499.47

Elaborated from the data of SAGARPA-DRL (2016).

The restrictive resources of the agricultural year were: a) land: includes the largest area planted in the last six years and is 103 793.53 ha irrigated by gravity and 71 570.45 ha irrigated with pumping water. The maximum restriction was applied to alfalfa, forage oats, forage maize, forage sorghum, broom sorghum, cotton and walnut corresponding to the maximum planted area of the period 2011-2016, while the minimum restriction includes minimum area sown in the last five years of the remaining crops (Table 2).

Table 2. Restrictions of maximum and minimum of the crops of the model.

Variable	Cultivation (irrigation with well water)	Hectare	Variable	Cultivation (irrigation with surface water)	Hectare
X_1	Alfalfa	34 363.2	X_{13}	Alfalfa	5 901.15
X_2	Forage oats	17 551.2	X_{14}	Forage oats	838
X_3	Cotton	1 446.08	X_{15}	Cotton	24 835.47
X_4	Sorghum forage	14 422.4	X_{16}	Sorghum forage	17 335.78
X_5	Fodder corn	32 679.16	X_{17}	Fodder corn	17 027.56
X_6	Melon	3 771	X_{18}	Melon	765.3
X_7	Watermelon	244	X_{19}	Watermelon	333.65
X_8	Tomato	656	X_{20}	Tomato	7
X_9	Pepper	221	X_{21}	Pepper	169.4
X_{10}	Corn grain	168	X_{22}	Corn grain	724.5
X_{11}	Sorghum escobero	604	X_{23}	Sorghum escobero	2 142.7
X_{12}	Nut	4 301.75	X_{24}	Nut	4 899.65

Elaborated from the data of SAGARPA-DRL (2016).

b) Labor force: includes the sum of the total number of workers obtained by crop and modality, 2 803 287 wages for irrigation by pumping and 1 385 330 wages for irrigation by gravity. c) Water: the restriction of irrigation water availability comprises 398.51 million m^3 of groundwater (Soto *et al*., 2016) which corresponds to the volume of extraction for agricultural use of the 2015-2016 cycle and 799.62 million m^3 of surface water obtained from the water distribution report of CONAGUA (2016) and represents the volume distributed for irrigation of the 2015-2016 cycle. The volumes of irrigation water by crop included in the model were obtained from the irrigation sheets applied in the Irrigation District 017 (CONAGUA, 2017).

Results and discussion

The results of the linear programming base 1 model indicate that: a) the optimal crop pattern is 51 831.08 ha, of which 31.8% are irrigation by pumping and 68.3% are serious; b) null production for the crops of alfalfa, forage oats, forage sorghum, forage maize and sorghum broom, because these crops are large consumers of water since their income-cost ratio is lower compared to other crops (Table 3); c) an increase in the area sown with cotton is indicated, since it generates higher profits; and d) another crop that generates considerable profits are walnut plantations, which were considered as a maximum restriction. If they had considered at least most of the surface would have been allocated to this crop.

Table 3. Optimal crop pattern.

Crop	Gravity (ha)	(%)	Pumping (ha)	(%)
Alfalfa	0	0	0	0
Forage oats	0	0	0	0
Cotton	24 835.47	47.9	1 446.08	2.8
Sorghum forage	0	0	0	0
Fodder corn	0	0	0	0
Melon	765.3	1.5	3 771	7.3
Watermelon	333.65	0.6	244	0.5
Tomato	3 633.02	7.0	6 318.26	12.2
Pepper	169.4	0.3	221	0.4
Corn grain	724.5	1.4	168	0.3
Sorghum escobero	0	0	0	0
Nut	4 899.65	9.5	4 301.75	8.3
Total	35 360.99	68.2	16 470.09	31.8

Source: elaborated with the data obtained from the estimation of the model.

The value of the objective function that maximizes the total profits in the base 1 model is 1 743 million pesos. The results show that the shadow price of the water for irrigation by pumping is \$1.56 m^{-3} MN and that of irrigation by gravity is \$0.91 m^{-3} MN, which indicates that, faced with an increase of one cubic meter in the available amount of water, the objective function increases by \$1.56 and \$0.91 MN respectively. The Lagrange multiplier (shadow price) corresponding to the pumping water is greater, since the crops with irrigation by pumping have a higher productivity; that is, they require less water per unit of production and have a lower rate of water loss than crops with gravity irrigation (Table 4).

Table 4. Water shadow price.

Decrease in water availability (%)	Value of the objective function (millions of pesos MN)	Shadow price ($ m^{-3}) MN	
		Pumping	Gravity
0	1743	1.56	0.91
1	1729	1.56	0.91
2	1716	1.56	0.91
12	1581	1.56	0.91
14	1554	1.56	0.91
16	1527	1.56	1.23
20	1463	1.56	1.23

Prepared from the results of the model.

In scenario 2, a decrease in water availability was analyzed in 1%, in order to see its behavior in relation to the baseline scenario 1. The results indicate that, by decreasing the availability of water, the value of the function objective obtained is 1 729 million pesos MN; that is, it decreases by 0.8% in relation to the baseline scenario 1. In relation to the cultivated area, it had a decrease of 0.7%. The shadow price remained constant.

In the scenarios where the available water decreases of 1, 2, 4, 6, 8, 10, 12 and 14% the shadow price remains constant at $1.56 m^{-3} MN for pumping and at $0.91 m^{-3} MN for gravity. In the scenario where the available amount decreases 16%, the shadow price of the irrigation water by gravity that is obtained is $1.23 m^{-3} MN while the pump price is still of $1.56 m^{-3} MN. The value of the objective function is 1 527 million pesos; that is, 12.39% lower in relation to baseline scenario 1.

In order to compare the shadow price obtained with the current tariff it was necessary to estimate the magnitude of that tariff, because, as in many irrigation districts in Mexico, water is not charged by volume, but by hectare. The average rate paid was obtained by dividing the cost (quota) ha^{-1} by the average volume ha^{-1}. Since the irrigation fee paid in the Lagunera Region is $1 600.00 ha^{-1} MN and taking into account the average irrigation volume (m^{-3} ha^{-1}) of the main crops, then the average cost would be $0.09 m^{-3} MN for gravity irrigation (Table 5) in the main agricultural products of the region.

The above results allow a comparison between the average rate paid ($0.09 m^{-3} MN) and the estimated rate with the model ($0.91 m^{-3} MN), which shows that the rate paid per unit of irrigation water is 9.06 times lower than the shadow price obtained with the model. This indicates that the fees paid in the Lagunera Region do not correspond with the shadow price of the water obtained here, so it is concluded that an inefficient use of water is being made.

Table 5. Cost of crop water considering a water quota of $1 600.00 ha^{-1} MN.

Cultivo	Precio (\$ m^{-3}) MN
Alfalfa	0.14
Forage oats	0.1
Cotton	0.1
Sorghum forage	0.09
Fodder corn	0.1
Melon	0.07
Watermelon	0.07
Tomato	0.06
Pepper	0.1
Corn grain	0.14
Sorghum escobero	0.06
Nut	0.11

Prepared from the volume of irrigation and the irrigation quota.

Although Godínez *et al*. (2007) also exclude the production of forage crops from the optimum pattern and show that the rate paid is considerably lower than the estimated rate, the shadow prices they estimated were \$0.65 m^{-3} MN of pumping water and \$0.58 m^{-3} MN of gravity water, which are considerably lower than those obtained here. In addition, they did not consider the same crops in the two irrigation modalities. Zetina *et al*. (2013); Escobar and Gómez (2007) agree that the fees paid or that are willing to pay producers for irrigation are less than the shadow price of this resource.

Because irrigation water is usually supplied by public agencies that give it a price based on its average cost of delivery or maintenance, in most cases that cost does not represent its economic price (Young and Loomis, 2014). For this reason, shadow prices should be used as indicators to establish rates that promote the rational use of water.

Conclusions

The crop pattern of the Comarca Lagunera is inefficient and lacks economic rationality. The optimal pattern of crops obtained with the model clearly indicates that forage crops should not be planted in the region, such as alfalfa, sorghum and corn, since they are of low price and economic density and, nevertheless, require a lot of water for their production. After comparing the shadow prices of water with the average price charged for irrigation water by gravity, it is concluded that the irrigation fees paid in the region are considerably lower than the social opportunity cost or water shadow price.

The price so low that they pay in the region for irrigation water, is actually an unjustified transfer of society, through the government. Water is a very scarce input and vitally important for the economic development of the region and for its main economic activities: agriculture and livestock and should be used more rationally and efficiently. It is recommended that the shadow or efficiency price obtained with the model can be used as an indicator to establish rates for efficient water consumption in the agricultural sector of the Lagunera Region.

It is also recommended that other research such as this one be carried out in which all the productive activities of the region are incorporated (livestock, aquaculture, among others), in order to see the stability of the indicators of efficiency in the use of water. Tariffs should be defined based on the shadow price of water and should be adjusted according to changes in the level of water scarcity, since the amount of water available affects all the demanding sectors: industrial, urban and the agricultural.

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