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WATER USE AND SUPPLY IN THE NORTHERN REGION OF BAJA CALIFORNIA, MEXICO

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ABSTRACT

The demographic and economic growth in the northern region of the Mexican state of Baja California has led to increased water use and competition for this resource among diverse consumer sectors. The regional dynamism has made it increasingly difficult to meet the demand for water provision. The aim of this investigation was to allocate the water withdrawn from the Mexicali Valley and San Luis Río Colorado (SLRC) aquifers in a scenario of water scarcity among the various consumer sectors by municipality of the states of Baja California and Sonora, as well as to determine the price that would allow for a reduction in the amount of water taken from the aquifers. A spatial equilibrium model was formulated and validated, considering fixed supply and functions of demand. The 2019 results show that the total demand for water from municipalities in residential, commercial, industrial, agricultural and livestock sectors were 197.2, 21.7, 16.7, 758 and 5.7 hm^3, with Tijuana standing out in the first three sectors, whereas Mexicali and SLRC were highlighted in the farming sector. Regarding the water price, the Tijuana, Tecate, and Ensenada municipalities pay a high tariff for its use, whereas Mexicali and SLRC pay the lowest tariffs. A 10 % reduction in water availability would be achieved if the price in the agricultural sector in Mexicali and SLRC increased by 20 and 22 %, respectively, over the base price. As the price rises, the demand in this sector for both municipalities would decrease by 2.6 %.

Keywords: residence, commerce, industry, agriculture, livestock, spatial equilibrium model.

INTRODUCTION

Worldwide, the average annual availability of water is estimated in 1386 trillion hm^3, 97.5 % of which is saltwater (1351 trillion hm^3) and 2.5 % is freshwater (35 trillion hm^3). Approximately 70 % (24.4 trillion hm^3) of the freshwater is not usable for drinking by people, since it is found in glaciers, snow and ice; 30 % (10.5 trillion hm^3) is underground water and 0.4 % (0.14 trillion hm^3) is found in lakes, rivers and wetlands. According to the National Water Commission (CONAGUA), one of the factors limiting human access to 0.77 % of the world's freshwater is the distance between water sources and population centers. Mexico gets a yearly average of 1.4 million hm^3 in the form of rainfall, out of which 72.1 % goes to evapotranspiration, 21.4 % runs off by rivers and 6.4 % reloads the aquifers by infiltration. Taking into account water imports and exports to nearby countries, Mexico has an annual positive surplus of 451 585 hm^3 of renewable water. (CONAGUA, 2018).

The overexploitation of underground water has several negative effects, including a significant and continuous decline of the phreatic level which directly reduces the flow volume, the increase in operation costs and the drilling of new wells, the emergence of cracks and sinkholes in the ground caused by gaps generated in upper strata, and increased competition and disputes between water users (Mayta and Durán, 2015).

Water-consuming sectors (farming, industrial, commercial and residential) contribute to the water overexploitation problem since its expansion exerts pressure on natural resources (water, soil, subsoil). The depletion of drinkable water and other natural resources would be catastrophic for humanity, which is why it is essential to create plans and monitor water usage efficiency (Palacios-Vélez and Escobar-Villagrán, 2016).

The Baja California Peninsula ranks fourth out of 13 water administration regions in the country with the most overexploited aquifers, only behind the Lerma Santiago Pacífico, Cuenca Central del Norte and Río Grande regions. In 2011, 13 overexploited aquifers and 10 with seawater intrusion were reported. As of 2019, there were 18 overexploited aquifers and 11 with seawater intrusion. In this hydrological region, the municipalities of Mexicali (Baja California) and San Luis Río Colorado (SLRC, in Sonora) are known for consuming large amounts of water, particularly in the agricultural sector which belongs to irrigation istrict 014 (CONAGUA, 2019). In 2019, out of the 602 hm^3 of the overexploited Valle de Mexicali aquifer, the agricultural sector at Mexicali consumed 588 hm^3 of water. From the 263.5 hm^3 of the Valle de SLRC aquifer, which is close to overexploitation, the agricultural sector in SLRC consumed 170 hm^3 (CONAGUA, 2020).

Tijuana is notable for its demographic, commercial and industrial dynamism. In 2019, Baja California had an estimated population of 3.6 million people, out of which 49 % (1.8 million people) were concentrated in Tijuana and 30 % in Mexicali. According to information provided by the National Population Council (CONAPO), population in Tijuana is projected to grow 19.5 % between 2019 and 2030 (CONAPO, 2018). The National Statistics and Geography Institute (INEGI) showed the dynamism in the commercial and industrial sectors in Tijuana, since 97.2 % of the Economically Active Population (EAP) were working in the second quarter of 2019. Among them, 59.4 % were working in the tertiary sector (which includes businesses, restaurants and housing services, among others), while 34.3 % were employed in the secondary sector (extractive, electric and manufacturing industries, among others). 6.2 % of workers did not specify the economic activity they were working in (INEGI, 2021a).

The Baja California State Water Commission (CEABC) stated that Tijuana (including Playas de Rosarito), Tecate and a part of Ensenada are granted concessions from the aquifers mentioned above in order to meet their water needs. The water is transported by the Río Colorado-Tijuana Aqueduct (ARCT) until it reaches the Carrizo and Las Auras dams (CEABC, 2018). As already indicated, the expansion of the population and the economy implies a higher demand of water and an increase in the overexploitation of aquifers. In the light of this situation, possible solutions come into view. On the one hand, increasing the water supply to satisfy the growing demand for water. On the other, administrating and decreasing demand to reduce the pressure on the regional water resources.

Palacios-Vélez and Escobar-Villagrán (2016) proposed the following measures to prevent overexploitation of the aquifers: updating the census of pumping wells, estimating the water volume that is illegally extracted, implementing studies on the components of the hydrological balance, promoting the formation of an expert committee on underground water management, promoting a payment culture for water services in both cities and irrigation areas, a reduction in subsidies to irrigation water and urban water supply services, among others.

Studies have determined that the price of water (fees) can be used as a mechanism to reduce demand and make a more efficient use of water in different consumer sectors (Gómez-Ugalde *et al.*, 2012; Torres-Sombra *et al.*, 2013; Cota-Verdugo *et al.*, 2013; Romano *et al.*, 2016). Other studies have focused on assigning water spatially and inter-temporarily among consumer sectors in the light of a situation of scarcity and competition for the resource (Miranda-Trejo *et al.*, 2015; Castro *et al.*, 2017).

Some industries may need to reduce their consumption as a result of a decrease in water supply, and their costs will rise. Although water is necessary for all consumer sectors, this reduction would be observed in sectors in which water has the lowest use value. In economics terms, the highest water value shall be observed in sectors with the most inelastic demand, such as residential sector, in which the final consumer is a living being and there is no possibility of reducing consumption per capita. Water demand in the residential sector will be more inelastic in low-income neighborhoods, where the use of water is minimal, ensuring that demand remains high despite a significant price increase. A similar situation shall be observed in livestock production, where the final consumer is also a moving living being.

The lowest value will be observed in sectors in which demand is less inelastic, such as the agricultural sector, in which it is technically possible to reduce water use with more efficient irrigation methods. In this sector, an increase in the price of water may lead the farmer to make a more efficient use of water resources. The increase in price may also motivate the adoption of technified irrigation systems that help save water for every surface unit. The productivity of irrigation agriculture may even increase. The cost of the water may give the producer information about the value and scarcity of the resource and may prompt farmers to change their farming methods. Plants are living beings that can effectively be conducted to efficient water use. A similar situation occurs in the industrial sector, where a rise in price may encourage business owners to implement water recycling systems, resulting in significant water savings and decreased consumption.

The reallocation of water shall seek to increase the Net Social Payoff (NSP). Spatial optimization techniques at basin scales to evaluate the benefits and relative costs of water allocation are usually applied on a region. Maximizing the net social value obtained from the use of water in all sectors under the adequate restrictions would result in optimum water use levels for all sectors, along with economic benefits of water use and opportunity costs of water allocation throughout and within the productive sectors in the region (Ghosh *et al.*, 2017).

The aims of this study were to assign the water extracted from the Mexicali Valley and SLRC aquifers within a water scarcity scenario, among the different consuming sectors per municipality of the states of Baja California and Sonora, Mexico, as well as to determine the price that would make it possible to reduce the amount of water taken from the aquifers. The hypothesis established that within a scarcity scenario, the use of water would be reduced in those sectors with a lower value of use.

MATERIALS AND METHODS

The quadratic programming model maximizes the NSP, which equals to the sum of the areas below the demand curve minus the cost of underground water extraction, the value of the amount of water available in the dam for deriving and distribution costs.

If we assume r water-consuming regions of residential sector (r = 1... R = 5), c water-consuming regions of the commercial sector (c = 1... C = 4), i water-consuming regions of the industrial sector (i = 1... I = 4), f water-consuming regions of the agricultural sector (f = 1... F = 2), g water-consuming regions of the livestock farming sector (g = 1... G = 2), s underground water sources (s = 1... S = 2) and p dams (p = 1... P = 2), the proposed model is the following:

$$MAXN\ SP = \sum_{r=1}^{R}\left[\lambda_r y_r + \tfrac{1}{2} w_r y_r^2\right] + \sum_{c=1}^{C}\left[\lambda_c y_c + \tfrac{1}{2} w_c y_c^2\right] + \sum_{i=1}^{I}\left[\lambda_i y_i + \tfrac{1}{2} w_i y_i^2\right] + \sum_{f=1}^{F}\left[\lambda_f y_f + \tfrac{1}{2} w_f y_f^2\right] + \sum_{g=1}^{G}\left[\lambda_g y_g + \tfrac{1}{2} w_g y_g^2\right] + \sum_{p=1}^{P}\left[PAPy_p\right]$$

$$-\sum_{s=1}^{S}\left[PASX_s\right] - \sum_{p=1}^{P}\left[PAPX_p\right] - \sum_{s=1}^{S}\sum_{r=1}^{R}\left[D_{sr}X_{sr}\right] - \sum_{s=1}^{S}\sum_{c=1}^{C}\left[D_{SC}X_{SC}\right] - \sum_{s=1}^{S}\sum_{i=1}^{I}\left[D_{si}X_{si}\right]$$

$$-\sum_{p=1}^{P}\sum_{r=1}^{R}\left[D_{pr}X_{pr}\right] - \sum_{p=1}^{P}\sum_{c=1}^{C}\left[D_{pc}X_{pc}\right] - \sum_{p=1}^{P}\sum_{i=1}^{I}\left[D_{pi}X_{pi}\right] \quad (1)$$

Subject to:

$$X_s \geq \sum_{r=1}^{R} X_{sr} + \sum_{c=1}^{C} X_{sc} + \sum_{i=1}^{I} X_{si} + \sum_{f=1}^{F} X_{sf} + \sum_{g=1}^{G} X_{sg} + \sum_{p=1}^{P} X_{sp} \quad (2)$$

$$X_p \geq \sum_{r=1}^{R} X_{pr} + \sum_{c=1}^{C} X_{pc} + \sum_{i=1}^{I} X_{pi} \quad (3)$$

$$\sum_{s=1}^{S} X_{sr} + \sum_{p=1}^{P} X_{pr} \geq y_r \quad (4)$$

$$\sum_{s=1}^{S} X_{sc} + \sum_{p=1}^{P} X_{pc} \geq y_c \quad (5)$$

$$\sum_{s=1}^{S} X_{si} + \sum_{p=1}^{P} X_{pi} \geq y_i \quad (6)$$

$$\sum_{s=1}^{S} X_{sf} \geq y_f \quad (7)$$

$$\sum_{s=1}^{S} X_{sg} \geq y_g \quad (8)$$

$$\sum_{s=1}^{S} X_{sp} \geq y_p \quad (9)$$

$$y_r, y_c, y_i \ldots X_{sr}, X_{sc}, X_{si}, \ldots X_{sg}, X_s, X_p, \geq 0 \quad (10)$$

where $\lambda_r, \lambda_c, \lambda_i, \lambda_f, \lambda_g,$ are the intercepts of the reverse functions of the demand in the regions *r, c, i, f, g*; y_r, y_c, y_i, y_f, y_g are the amounts of water consumed in sectors *r, c, i, f, g*; $\omega_r, \omega_c, \omega_i, \omega_f, \omega_g$ are the slopes of the reverse functions of the demand for water in the regions *r, c, i, f, g*; y_p is the total amount of water available in dam *p*; *PAS* is the cost of extracting underground water in the region *s*; *PAP* is the price of water at the exit of the dam *p*; X_s is the amount of water extracted in the region *s*; X_p is the amount of water available in the dam *p* for deriving; $D_{sr}, D_{sc}, D_{si}, D_{sf}, D_{sg}, D_{sp}$ are the costs of distributing the water from *s* to *r, c, i, f, g, p*; D_{pr}, D_{pc}, D_{pi} are the costs of distributing the water from *p* to *r, c, p*; $X_{sr}, X_{sc}, X_{si}, X_{sf}, X_{sg}, X_{sp}$ are the amounts of underground water sent from *s* to *r, c, i, f, g, p*; X_{pr}, X_{pc}, X_{pi} are the amounts of water sent from *p* to *r, c, i*.

The target function (Equation 1) is subjected to restrictions of water supply budget and water demand (Equations 2 to 9). The condition of non-negativity of the variables is represented in Equation 10.

The solution of the model was obtained using demand functions for each sector of water consumers: residential, commercial, industrial, agricultural and livestock farming. With the price elasticity of the demand, the fees and the amounts in demand, a total of 17 demand functions were estimated for the five municipalities (Tijuana, Tecate, Ensenada, Mexicali and SLRC) and the five consumer sectors (residential, commercial, industrial, agricultural and livestock farming) (Kawaguchi *et al.*, 1997). The elasticities were estimated via multiple linear regression for the municipality of Tijuana, as representative for Baja California. Water consumption per capita was considered the endogenous variable; whereas the water and energy prices, income, rainfall and temperature were considered exogenous variables. The data of the variables used in the regression covered the period 2006-2019. The estimated elasticity coefficients were -0.23 for the residential sector, -0.04 for the commercial sector, -0.07 for the industrial sector and from Torres-Sombra y García-Salazar (2015) were obtained elasticities of -0.125 for the agricultural sector and -0.065 for the livestock farming sector.

Water use for residential, commercial and industrial sectors for the municipality of Tijuana were taken from the CEABC (2021). For the municipalities of Tecate, Ensenada, Mexicali and SLRC, residential use was estimated as follows: number of households times the average consumption per capita of water; this information came from the CEABC (2017) and INEGI (2021b). The use of commercial and industrial water for Tecate, SLRC and Mexicali was obtained as a result of multiplying the number of shops and industries (in Tecate and SLRC), as well as the number of taps of commercial and industrial use (in Mexicali) times the average consumption per capita of commercial and industrial water, respectively; the information was taken from CEABC (2017) and INEGI (2021c).

Agricultural water consumption in the municipalities of Mexicali and SLRC came from CONAGUA (2020). In 2019, water consumption for livestock farming in the municipalities of Mexicali and SLRC was obtained by multiplying the number of livestock heads per species by the average consumption of water per capita per species; this information was taken from the Food and Agriculture Organization (FAO, 2013) and from the Agrifood Information System for Consultation-Agricultural and Fisheries Information System (SIACON-SIAP, 2020). It is important to highlight that in the municipalities of Tijuana, Tecate and a part of Ensenada, water consumption for the farming sector was not taken into consideration because the amounts of water that reach these municipalities from the dams (El Carrizo and Las Auras), which in turn obtain water from underground sources (the aquifers Valle de Mexicali and SLRC), are used exclusively for residential, commercial and industrial sectors.

For the sectors directly supplied from underground sources (Mexicali and SLRC), the distribution costs were calculated with a differences in prices (the fee paid by the end users minus the extraction costs); this difference represents all the costs involved in water supply. Similarly, for the sectors that are supplied with the water available in the dams (Tijuana, Tecate and a part of Ensenada), the difference in prices was calculated with the fees paid by the end consumer and the costs of water derived from the dam (including the costs of extracting water, electricity, maintenance and operation to be able to transport the water from the points of extraction to the dams); the information was taken from the CEABC (2018) and CONAGUA (2021).

The data on the electricity fees were obtained from INEGI (2021d), the income (general minimum wage) was obtained from the National Minimum Wage Commission (CONASAMI, 2021), the Gross Domestic Product (GDP) of the secondary activities of the state of Baja California was obtained from INEGI (2021e) and the national average rainfall and temperature were provided by the National Weather Service (SMN, 2021).

RESULTS AND DISCUSSION

The validation of the model of both water use and price in the municipalities of Baja California and Sonora (SLRC), as well as for the different water-using residential, commercial, industrial and livestock farming sectors (R, C, I, F, G) are shown in Table 1. The base model either overestimates or underestimates the observed values, as

Table 1. Water model validation for the municipalities of Baja California and Sonora, 2019.

Municipality	R[†]	C[¶]	I[§]	F[þ]	G[¤]	R[†]	C[¶]	I[§]	F[þ]	G[¤]
	Millions of m^3					MXN $ m^{-3}				
	Use observed					Price observed				
Tijuana	98.5	15.4	10.0			19.53	80.05	83.78		
Tecate	1.8	0.2	1.4			13.91	66.86	64.51		
Ensenada	9.0					14.15				
Mexicali	63.4	4.2	4.7	588.0	5.7	7.15	51.16	59.82	0.19	0.19
SLRC	24.6	2.0	0.7	170.0	0.0	8.28	6.68	9.70	0.19	0.19
Total	197.2	21.7	16.7	758.0	5.7					
	Base model use					Base model price				
Tijuana	98.5	15.4	10.0			19.53	80.05	83.78		
Tecate	1.8	0.2	1.4			13.91	66.84	64.51		
Ensenada	9.0					14.15				
Mexicali	63.4	4.2	4.7	584.6	5.7	7.15	51.16	59.82	0.20	0.19
SLRC	24.6	2.0	0.7	170.8	0.0	8.28	6.68	9.71	0.18	0.19
Total	197.3	21.7	16.7	755.4	5.7					
	Difference to the observed									
Tijuana	0	0	0			0	0	0		
Tecate	0	0	0			0	-0.02	0		
Ensenada	0					0				
Mexicali	0	0	0	-3.4	0	0	0	0	0.01	0
SLRC	0	0	0	0.8	0	0	0	0.01	-0.01	0
Total	0	0	0	-2.6	0					
	Difference to the observed (%)									
Tijuana	0.0	0.0	0.0			0.0	0.0	0.0		
Tecate	0.0	0.0	0.0			0.0	0.0	0.0		
Ensenada	0.0					0.0				
Mexicali	0.0	0.0	0.0	-0.6	0.0	0.0	0.0	0.0	4.6	0.1
SLRC	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.1	-3.7	-0.1
Total	0.0	0.0	0.0	-0.1	0.0					

R[†]: residential sector; C[¶]: commercial sector; I[§]: industrial sector; F[þ]: agricultural sector; G[¤]: livestock sector. MXN $: Mexican pesos.

indicated by the positive and negative signs in the percentage differences. Even yet, the difference is minimal, which allows to preduct some scenarios.

In 2019, the total water use in the residential sector was 197.2 hm^3, out of which Tijuana and Mexicali used 98.5 and 63.4 hm^3. The total use in the commercial sector was 21.7 hm^3, out of which Tijuana and Mexicali demanded 15.4 and 4.2 hm^3, respectively. Likewise, the total use in the industrial sector was 16.7 hm^3, out of which Tijuana and Mexicali demanded 10 and 4.7 hm^3, respectively. The agricultural sector demanded a total of 758 hm^3 of water, of which Mexicali is by far the greatest consumer with 588 hm^3 of water, and the remainder is used by SLRC. Additionally, the total use of water in the livestock sector was slightly higher than 5.7 hm^3, out of which Mexicali used the majority, and the remainder was used by SLRC (Table 1).

Regarding water prices, the municipalities of Tijuana, Tecate and a part of Ensenada were found to pay the highest prices in the residential, commercial and industrial sectors in the state of Baja California. For example, the prices paid by Tijuana in these sectors were 19.5, 80.0 and 83.8 MXN \$ m^{-3}, respectively, whereas Mexicali and SLRC paid the lowest prices for water; Mexicali pays 7.2, 51.2 and 59.8 MXN \$ m^{-3} for residential, commercial and industrial use, while SLRC pays 8.3, 6.7, 9.7 MXN \$ m^{-3} for the same sectors. It is evident that SLRC, belonging to the state of Sonora, pays the least for the use of water (Table 1).

Low costs for water consumption encourage waste and imply greater water use from overexploited aquifers, which increases the danger of a short-, middle-, and long-term water crises. To avoid this situation, it is important to pay a price for water, since this would allow for a more efficient water use, and exert less pressure on overexploited aquifers. The high prices found specifically in the municipalities of Baja California are widely related with two issues. The first is the distance between water sources and consumption areas, where the price of water is more expensive due to transportation and infrastructure maintenance costs. The second is a high reliance on external water sources to supply internal demand as local water supplies are scarce.

The effects on the use and water price when reducing water availability by 10 % in the aquifers Valle de Mexicali and SLRC were calculated (Cuadro 2). The use by all the sectors of all municipalities, including the water available in the dams is equal to the water extracted from both aquifers (losses by piping or evaporation were not considered); thus, the base model estimated an extraction rate of 996.8 hm^3. As water supply contracts as indicated, it would become 897.2 hm^3. This measure would result in a decrease in the demand for water and an increase in the price of water.

In this scenario, the use of water in residential, commercial and industrial sectors of all municipalities did not undergo significant changes. On the contrary, regarding the use in the agricultural sector notorious changes did occur. In Mexicali, water use fell from 584.6 to 569.2 hm^3 (2.6 % compared to the base model), and in SLRC it dropped from 170.8 to 166.3 hm^3 (2.6 % in regard to the base model). The livestock farming sector of Mexicali and SLRC experienced a reduction in the use, considering the base model of 1.4 %, respectivaely (Table 2).

The effects obtained are a consequence of the magnitude of price elasticity of demand observed in every consumer sector. Although demand is inelastic across all sectors, there are variations in the size of their coefficient of elasticity.

The findings of this study supported those of Ghosh *et al*. (2017), who claimed that in face of a reduction in water supply, the farming sector would be the most impacted, in contrast to the other water consumer sectors such as residential, commercial or industrial, since farming has the lowest value in water use. Guzmán-Soria *et al.* (2009) reported price elasticity coefficients for the urban, livestock, irrigation agriculture and industrial in Guanajuato. The coefficients were -0.0150, -0.0038, -0.052 and -0.126,

Table 2. Water allocation among users and the increase in the price within a water scarcity scenario.

Municipality	R†	C¶	I§	Fþ	G¤	R†	C¶	I§	Fþ	G¤
	Millions of m³					MXN $ m⁻³				
	Base model use					Base model price				
Tijuana	98.5	15.4	10.0			19.53	80.05	83.78		
Tecate	1.8	0.2	1.4			13.91	66.84	64.51		
Ensenada	9.0					14.15				
Mexicali	63.4	4.2	4.7	584.6	5.7	7.15	51.16	59.82	0.20	0.19
SLRC	24.6	2.0	0.7	170.8	0.0	8.28	6.68	9.71	0.18	0.19
Total	197.3	21.7	16.7	755.4	5.7					
	Availability reduced by 10 %									
Tijuana	98.5	15.4	10.0			19.57	80.09	83.82		
Tecate	1.8	0.2	1.4			13.95	66.94	64.55		
Ensenada	9.0					14.19				
Mexicali	63.3	4.2	4.7	569.2	5.6	7.19	51.20	59.86	0.24	0.23
SLRC	24.5	2.0	0.7	166.3	0.0	8.32	6.72	9.75	0.22	0.23
Total	197.1	21.7	16.7	735.5	5.6					
	Difference to the base scenario									
Tijuana	0	0	0			0.04	0.04	0.04		
Tecate	0	0	0			0.04	0.10	0.04		
Ensenada	0					0.04				
Mexicali	-0.1	0	0	-15.4	-0.1	0.04	0.04	0.04	0.04	0.04
SLRC	0	0	0	-4.5	0	0.04	0.04	0.04	0.04	0.04
Total	-0.2	0	0	-19.9	-0.1					
	Difference to the base scenario (%)									
Tijuana	0.0	0.0	0.0			0.2	0.0	0.0		
Tecate	-0.1	0.0	0.0			0.3	0.1	0.1		
Ensenada	-0.1					0.3				
Mexicali	-0.1	0.0	0.0	-2.6	-1.4	0.6	0.1	0.1	20.0	21.0
SLRC	-0.1	0.0	0.0	-2.6	-1.4	0.5	0.6	0.4	22.0	21.1
Total	-0.1	0.0	0.0	-2.6	-1.4					

R†: residential sector; C¶: commercial sector; I§: industrial sector; Fþ: agricultural sector; G¤: livestock sector. MXN $: Mexican pesos.

respectively. These showed that the agricultural sector would reduce their demand for water in greater magnitude in response to a price increase. The same takes place in the Comarca Lagunera (Mexico's most noticeable milk production region), according to the price elasticities of demand found by Guzmán-Soria *et al.* (2006). The elasticities were -0.108 for pump irrigation agriculture, -0.023 for gravity irrigation, -0.003 for urban zone, -0.002 for livestock farming and -0.178 for the industry. These indicate that irrigation agriculture has one of the highest elasticities, which means that should prices increase, the amount of water needed for agriculture would be reduced in a greater percentage than in the majority of the other sectors examined. It is worth mentioning that the effects reported by other authors were different in magnitude compared to those found in this research, which is probably due to spatial and temporal conditions in each study.

The decline in water consumption by consumer sector and by municipality basically responds to an increase in the price of water. For example, for the residential sector it fluctuated between 0.2 and 0.6 %; within the commercial sector, from 0 to 0.6 %; and in the industrial sector, from 0 to 0.4 %. This is why, despite a 10 % decrease in water supply, water use in those industries remained essentially constant. Meanwhile, in the agricultural sector of the municipality of Mexicali, the price increased from 0.20 to 0.24 MXN \$ m^{-3} (20 % compared to the base model) and in SLRC, the rise was from 0.18 to 0.22 MXN \$ m^{-3} (22 % in regard to the base model). Similarly, for the livestock farming sector in Mexicali and SLRC, the price increased from 0.19 to 0.23 MXN \$ m^{-3}, a 21 % increase in regard to the base model (Table 2). The findings showed that the agricultural and livestock farming sectors would be most impacted by a decrease in water supply, both in terms of use and price, since water use declines in a greater proportion than in the other sectors evaluated due to an increase in water price.

The GDP of the state of Baja California in 2019 was 575.8 billion MXN $, a value relatively constant since 2013, out of which the primary, secondary and tertiary activities contributed 15.5, 221.2 and 339.1 billion MXN $, respectively (INEGI, 2021d). Regarding water use, the primary sector is the one which uses the greatest amount of water, yet it contributes the least to the GDP of the state. The other non-agricultural sectors use less water but their contribution to the GDP is higher; consequently, facing water scarcity or reduction in the amount of water in the aquifers, the extracted water would be allocated to the sectors with the highest water use value (Ghosh *et al.*, 2017). In the case of the municipalities of Baja California, it would be possible to transfer water from the municipality of Mexicali with agricultural purposes to Tijuana due to the dynamism of activities in the residential, commercial and industrial sectors. This is consistent with the statement made by Scott *et al.* (2012), that a lack of additional water sources in areas with a growing demand for water can lead to a reallocation from agriculture towards other consumer sectors. The reallocation of water between sectors can benefit some and harm others (Elbakidze *et al.*, 2018). In the municipalities analyzed, Tijuana could be benefitted while Mexicali and SLRC could be harmed. To avoid this situation, it would be adviced to take regulations and restrictions into account when transfering water from one sector to another, as well as carrying out research to determine the optimal water consumption in Mexicali's agricultural sector to define the transfer limits towards residential, commercial and industrial sectors of Tijuana. It is then evident that more research on the subject is required.

The reduction of the overexploitation of aquifers and underground water is desirable, in order to avoid problems like those aforementioned and to prevent jeopardizing the expansion of the economic sectors that support a state or a country. Based on the model, the reduction in the sectors with the highest demand for water such as agriculture and livestock farming in the municipalities of Mexicali and SLRC is a feasible path, since they use the greatest amount of water and less contribute to the GDP. Additionally, both industries pay very little for water, thus it makes sense to raise prices by 20 and 22%, respectively, even if the increase is greater than this percentage. For example, if the price increased by 100 %, the demand for water in the agricultural sector would be reduced more than 10 %, which is desirble considering the overexploitation of aquifers.

The results of this study are similar to those found by other authors in Mexico. García-Salazar *et al.* (2006) indicated that a 98.6 % increase in the price of water is required in the agricultural sector in order to reduce 10 % water extractions in the Comarca Lagunera. They stated that such a rise in the price could be achieved by eliminating or reducing the subsidies in this sector, for example, increasing the price of electricity, which is the primary input for water pumping. The increase in price would encourage farmers to save water by introducing technology into their crops and irrigation systems, such subsuperficial drip irrigation. Therefore it is possible to increase the price in order to reduce the demand for water in the agricultural sector in the studied region.

Ramírez *et al.* (2019) indicated that in many of the irrigation districts of Mexico, water is not charged by volume, but by hectare. They stated that farmers pay a fee that does not reflect the real price of water; consequently, an inefficient use of water is made. They concluded that to encourage effective water use, a higher tariff must be established than the one already in place. García-Salazar *et al.* (2006), Ramírez *et al.* (2019) and the findings of this study all agreed that the price of water should be raised in the agricultural sector to significantly reduce water extractions from aquifers.

Such a recommendation must consider the inelasticity that characterizes the water demand in response to price changes. The demand for water in all sectors is inelastic, since there are no substitute goods, and the value of the price elasticity of the demand in the different sectors depends on reducing water use when the price changes. Results in this study indicate that if water availability was to decrease, water use should also decrease in agriculture, the sector in which water price is the lowest. As indicated before, it is technically possible to reduce the demand for water in this sector. A reduction in water demand shall have positive effects on the region. The lower water use shall reduce the pressure on water resources of the region, it shall not be an obstacle for its economic development.

On the contrary, keeping water prices low in the agricultural sector of the municipalities of Mexicali and SLRC encourages an irrational and inefficient use of water; it may hinder the development of other sectors such as water for residential, commercial and industrial uses in the other municipalities of the state of Baja California. Particularly the municipality of Tijuana, where those sectors are relevant. Price becomes an important instrument in regions with water scarcity, like some cities in the north of Baja California that lack local sources for water supply. Low water prices can be related to a high level of consumption which exert pressure on the water resources, and they usually create critical events regarding water supply in times of scarcity.

In addition to rely on water prices as a measure to use water efficiently, other additional measures can be applied in some sectors. For example, in the farming sector in Mexicali and SLRC, along with the introduction of new technologies in crop irrigation, treated water from other municipalities could be used. The commercial and industrial sectors would reuse volumes by implementing water treatment. In the residential sector water use may be reduced with water-saving technology in showers, toilets and sinks, as well as changing water use habits such as quick showers or reusing water from washing machines, among others.

CONCLUSIONS

The analysis of a reduction in the supply of water indicated that if the consumption and the price increases by consumer sectors, the agricultural and livestock farming sectors of the municipalities of Mexicali and San Luis Río Colorado can be the most affected, due to farming sector which has the lowest price value in the use of water.

Based on overexploitation of the aquifers in the region and the low prices paid by different water users in Mexicali and San Luis Río Colorado, the recommendation would be to use water price as a mechanism to reduce the demand for water use, in order to reduce water extracted.

If water reallocation and water use value are considered within the consumer sectors, a reduction in water supply would benefit residential, commercial and industrial sectors of Tijuana; although it may harm the farming sector of both Mexicali and San Luis Río Colorado. Therefore, it is recommendable for water-related decision-makers to consider regulations or restrictions, mainly to avoid harms on the agricultural sector.

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REFERENCES

Atucha AJ, Gualdoni P. 2018. El funcionamiento de los mercados. Universidad Nacional de Mar del Plata, Facultad de Ciencias Económicas y Sociales. http://nulan.mdp.edu.ar/2879/1/atucha-etal-2018.pdf (Retrieved: June 2022).

Castro R JC, Cruz G FV, Magaña Z JD, Martínez A G, Reyes M A, Sainz Z RO. 2017. La demanda del agua y su asignación eficiente en la agricultura: un caso en Guanajuato, México. Economía Coyuntural 2 (2): 145–180. http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S2415-06222017000200005&lng=es&tlng=es (Retrieved: May 2021).

CEABC (Comisión Estatal del Agua de Baja California). 2017. Informe mensual diciembre 2017. http://www.cea.gob.mx/documents/indicadores/CIERRE %20DE %20INDICADORES %202017.pdf (Retrieved: June 2021).

CEABC (Comisión Estatal del Agua de Baja California). 2018. Programa hídrico del Estado de Baja California. http://www.cea.gob.mx/phebc/resejec/RESUMEN %20EJECUTIVO %20PHEBC.pdf (Retrieved: March 2021).

CEABC (Comisión Estatal del Agua de Baja California). 2021. Indicadores OOA. http://www.cea.gob.mx/indicadores.html (Retrieved: May 2022).

CONAGUA (Comisión Nacional del Agua). 2018. Estadísticas del agua en México. Edición 2018. http://sina.conagua.gob.mx/publicaciones/EAM_2018.pdf (Retrieved: January 2021).

CONAGUA (Comisión Nacional del Agua). 2019. Acuíferos por región hidrológico-administrativa. http://sina.conagua.gob.mx/sina/tema.php?tema=acuiferos&ver=reporte (Retrieved: January 2021).

CONAGUA (Comisión Nacional del Agua). 2020. Disponibilidad por acuíferos. https://sigagis.conagua.gob.mx/gas1/sections/Disponibilidad_Acuiferos.html (Retrieved: February 2021).

CONAGUA (Comisión Nacional del Agua). 2021. Recaudación de la CONAGUA. http://sina.conagua.gob.mx/sina/tema.php?tema=recaudacion&ver=mapa&o=0&n=nacional (Retrieved: August 2021).

CONAPO (Consejo Nacional de Población). 2018. Proyecciones de la Población de México y de las Entidades Federativas 2016–2050. https://datos.gob.mx/busca/dataset/proyecciones-de-la-poblacion-de-mexico-y-de-las-entidades-federativas-2016-2050 (Retrieved: February 2021).

CONASAMI (Comisión Nacional de los Salarios Mínimos). 2021. Tabla de Salarios Mínimos Generales y Profesionales por Áreas Geográficas. https://www.gob.mx/conasami/documentos/tabla-de-salarios-minimos-generales-y-profesionales-por-areas-geograficas?idiom=es (Retrieved: March 2021).

Cota-Verdugo LF, Beltrán-Morales A, Troyo-Diéguez E, García-Hernández JL, Beltrán-Morales LF, Hernández-Trejo VA, Ortega-Rubio A, Navarro BA. 2013. Mercado de derechos de agua para uso agrícola en el noroeste de México. Revista Mexicana de Ciencias Agrícolas 4 (1): 63–75. https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-09342013000100005 (Retrieved: March 2021).

Elbakidze L, Vinson H, Cobourn K, Taylor RG. 2018. Efficient groundwater allocation and binding hydrologic externalities. Resource and Energy Economics 53: 147–161. https://doi.org/10.1016/j.reseneeco.2018.05.002

FAO (Organización de las Naciones Unidas para la Alimentación y la Agricultura). 2013. Captación y almacenamiento de agua de lluvia: opciones técnicas para la agricultura familiar en América Latina y el Caribe. Oficina regional de la FAO para América Latina y el Caribe. Santiago, Chile. http://www.fao.org/fileadmin/user_upload/AGRO_Noticias/docs/captacion_agua_de_lluvia.pdf (Retrieved: July 2021).

García-Salazar JA, Guzmán-Soria E, Fortis-Hernández M. 2006. Demanda y distribución del agua en la Comarca Lagunera, México. Agrociencia 40 (2): 269–276. https://agrociencia-colpos.org/index.php/agrociencia/article/view/461 (Retrieved: September 2021).

Ghosh S, Ibarrarán ME, Willett KD, Sanchez T EG. 2017. Water allocation and management along the Santa Cruz border region. Water Resources and Economics 19: 1–17. https://doi.org/10.1016/j.wre.2017.09.004

Gómez-Ugalde SG, Mora-Flores JS, García-Salazar JA, Valdivia-Alcalá R. 2012. Demanda de agua para uso residencial y comercial. Terra Latinoamericana 30 (4): 337–342. https://www.terralatinoamericana.org.mx/index.php/terra/article/view/1089/1335 (Retrieved: March 2021).

Guzmán-Soria E, García-Salazar JA, Mora-Flores JS, Fortis-Hernández M, Valdivia-Alcalá R, Portillo-Vázquez M. 2006. La demanda de agua en la Comarca Lagunera, México. Agrociencia 40 (6): 793–804. https://agrociencia-colpos.org/index.php/agrociencia/article/view/510 (Retrieved: September 2021).

Guzmán-Soria E, Hernández-Martínez J, García-Salazar JA, Rebollar-Rebollar S, de la Garza-Carranza MT, Hernández-Soto D. 2009. Consumo de agua subterránea en Guanajuato, México. Agrociencia 43 (7): 749–761. https://agrociencia-colpos.org/index.php/agrociencia/article/view/759 (Retrieved: October 2021).

INEGI (Instituto Nacional de Estadística y Geografía). 2021a. Encuesta Nacional de Ocupación y Empleo (ENOE), Población de 15 y más años de edad. https://www.inegi.org.mx/programas/enoe/15ymas/default.html#Tabulados (Retrieved: February 2021).

INEGI (Instituto Nacional de Estadística y Geografía). 2021b. México en cifras. https://www.inegi.org.mx/app/areasgeograficas/?ag=02 (Retrieved: June 2021).

INEGI (Instituto Nacional de Estadística y Geografía). 2021c. Censos económicos 2019. https://www.inegi.org.mx/programas/ce/2019/#Datos_abiertos (Retrieved: June 2021).

INEGI (Instituto Nacional de Estadística y Geografía). 2021d. Publicaciones. https://www.inegi.org.mx/app/publicaciones/ (Retrieved: August 2021).

INEGI (Instituto Nacional de Estadística y Geografía). 2021e. Banco de Información Económica (BIE). https://www.inegi.org.mx/app/indicadores/?tm=0#divFV472180 (Retrieved: August 2021).

Kawaguchi T, Suzuki N, Kaisier HM. 1997. A Spatial Equilibrium Model for Imperfectly Competitive Milk Markets. American Journal of Agricultural Economics 79: 851–859. https://doi.org/10.2307/1244426

Mayta A, Durán A. 2015. Sobre-explotación de aguas subterráneas en Punata: causas y efectos. Reporte de investigación. https://docplayer.es/57974867-Sobre-explotacion-de-aguas-subterraneas-en-punata-causas-y-efectos.html (Retrieved: January 2021).

Miranda-Trejo M, Ocampo-Fletes I, Escobedo-Castillo JF, Hernández-Rodríguez ML. 2015. La distribución del agua potable en Tepexi de Rodríguez, Puebla. Agricultura, Sociedad y Desarrollo 12 (3): 261–277. https://www.scielo.org.mx/scielo.php?pid=S1870-54722015000300001&script=sci_abstract (Retrieved: May 2021).

Palacios-Vélez OL, Escobar-Villagrán BS. 2016. La sustentabilidad de la agricultura de riego ante la sobreexplotación de acuíferos. Tecnología y Ciencias del Agua 7 (2): 5–16. https://www.redalyc.org/articulo.oa?id=353545556001 (Retrieved: February 2021).

Ramírez B BA, González E A, Valdivia A R, Salas G JM, García S JA. 2019. Tarifas eficientes para el agua de uso agrícola en la Comarca Lagunera. Revista Mexicana de Ciencias Agrícolas 10: 539–550. https://doi.org/10.29312/remexca.v10i3.1295

Romano G, Salvati N, Guerrini A. 2016. An empirical analysis of the determinants of water demand in Italy. Journal of Cleaner Production 130: 74–81. https://doi.org/10.1016/j.jclepro.2015.09.141

Scott CA, Megdal S, Oroz LA, Callegary J, Vandervoet P. 2012. Effects of climate change and population growth on the transboundary Santa Cruz aquifer. Climate Research 51: 151–170. https://doi.org/10.3354/cr01061

SIACON-SIAP (Sistema de Información Agroalimentaria de Consulta–Sistema de Información Agropecuaria y Pesquera). 2020. Anuario Estadístico de la Producción Agrícola. https://www.gob.mx/siap/documentos/siacon-ng-161430 (Retrieved: July 2021).

SMN (Servicio Meteorológico Nacional). 2021. Resúmenes Mensuales de Temperaturas y Lluvia. https://smn.conagua.gob.mx/es/climatologia/temperaturas-y-lluvias/resumenes-mensuales-de-temperaturas-y-lluvias (Retrieved: August 2021).Torres-Sombra J, García-Salazar JA, García-Mata R, Matus-Gardea J, González-Estrada E, Pérez-Zamorano A. 2013. Respuesta de la demanda de agua a cambios en el precio: un estudio por tipo de consumidor en el norte de Sinaloa, México. Agrociencia 47 (3): 293–307. https://agrociencia-colpos.org/index.php/agrociencia/article/view/1020 (Retrieved: March 2021).

Torres-Sombra J, García-Salazar JA. 2015. Uso del agua en el norte de Sinaloa: ¿a cuál consumidor asignar el recurso? Tecnología y Ciencias del Agua 6 (1): 167–173. https://www.redalyc.org/articulo.oa?id=353539900010 (Retrieved: June 2021).

Annex I

Based on the economic theory (Atuch and Gualdoni, 2018) and on empirical evidence (Gómez-Ugalde *et al*., 2012; Torres-Sombra *et al*., 2013; Romano *et al*., 2016), the following multiple linear regression models were formulated to estimate the price elasticities of the demand in residential, commercial and industrial sectors in the municipality of Tijuana:

For residential:

$$CPAR_t = f\,(PAR_t, PEER_t, INGR_t, CPAR_{t\text{-}1}, TEM_t, PP_t) \tag{11}$$

where $CPAR_t$ is the consumption per capita of water for residential; PAR_t is the real price of water for residential; $PEER_t$ is the real price of eletricity for residential; $INGR_t$ is the real income (the general minimum wage was used as an approximate variable to the income); $CPAR_{t\text{-}1}$ is the consumption per capita of water for residential with a delay period; TEM_t is the average temperature; PP_t is the average rainfall.

For the commercial sector:

$$CPAC_t = f\,(PAC_t, CPAR_{t\text{-}1}) \tag{12}$$

where $CPAC_t$ is the consumption per capita of water for commercial use; PAC_t is the real price of water for commercial use; $CPAC_{t\text{-}1}$ is the consumption per capita of water for commercial use with a delay period.

For the industrial sector:

$$CPAI_t = f\,(PAI_t, PEEI_t, PIBAS_t) \tag{13}$$

where $CPAI_t$ is the consumption per capita of water for industrial use; PAI_t is the real price of water of industrial use; $PEEI_t$ is the real fee of electricity of industrial use; $PIBAS_t$ is the gross domestic product of secondary activities of the state of Baja California.

These regressions considered explanatory variables that turned out to be more ($p \leq 0.05$) significant. The price elasticity of the water demand for residential, commercial and industrial sectors in the municipality of Tijuana were taken from the estimated parameters and the mean price value of water per type of use. The demand functions used in the programming model at a municipality level were obtained using the price elasticities of the demand, along with demand prices and amounts. Based on Kawaguchi *et al*. (1997), the slope and the intercept were obtained as follows:

$$Y_{ij} = \alpha_{ij} + \beta_{ij} P_{ij} \quad (14)$$

Equation 14 is the function of demand by water consumer sector (*i*) and municipality (*j*).

$$\beta_{ij} = \varepsilon_{ij}^{pd} \frac{Y_{ij}}{P_{ij}} \quad (15)$$

Equation 15 was used to estimate the slope of the function of the demand, where β_{ij} is the slope of the demand by consumer sector *i* (residential, commercial, industrial, agricultural and livestock) and municipality *j* (Tijuana, Tecate, Ensenada, Mexicali and SLRC); ε_{ij}^{pd} is the price elasticity per consumer sector and per municipality; Y_{ij} is the amount of water consumed by consumer sector and by municipality; P_{ij} is the price or fee of water per consumer sector and per municipality.

$$\alpha_{ij} = Y_{ij} - \beta_{ij} P_{ij} \quad (16)$$

Equation 16 was used to estimate the intercept of the function of the demand, and it was obtained through the values of the slope, the amount of demand and the price for the consumer.

$$P_{ij} = \frac{-\alpha_{ij}}{\beta_{ij}} + \frac{1}{\beta_{ij}} Y_{ij} = \lambda_{ij} + w_{ij} y_{ij} \quad (17)$$

Equation 17 represents the reverse function of the demand function, and it was obtained by solving the price in Equation 14.

$$AUDC = \lambda_{ij} y_{ij} + \frac{1}{2} w_{ij} y_{ij}^2 \quad (18)$$

Equation 18 was used to estimate the area under the demand curve (AUDC), which appears in the target function of the model; it was obtained by the integral of Equation 14.