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PRELIMINARY STUDY FOR CHANGING THE ENERGY QUOTA FORMULA IN MEXICO

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ABSTRACT

The impact of the agricultural electric tariff, known as the "energy quota", on groundwater extraction was studied in the municipalities of Linares and Hualahuises, located in Nuevo León, Mexico. The objective of the study was to evaluate water use associated with the energy quota in cases of extreme energy consumption, to compare the electricity provided under the quota with the energy requirements of producers in the study area, and to propose a methodology for establishing a limit based on the authorized water volumes. The energy consumption of 195 services that benefited from the stimulus tariff in the region was recorded and compared, through a non-parametric test, with the maximum energy limit established for the energy quota. Three orchards under the energy quota scheme were selected based on their high annual energy consumption and ease of access. In these orchards, volumetric gauges were inspected, and annual water consumption was recorded. An excess of 13.047 hm^3 (cubic hectometers) was recorded, equivalent to 1,123% of the granted volume and 17.4% of the aquifer's annual recharge in the southern citrus region. It was observed that the energy quota allows significantly higher energy use than the currently required, indicating that excessive water extraction is not being efficiently limited. An exploratory analysis was conducted to establish a limit in the current formula, based on granted water volumes, extracted volumes, and observed energy consumption.

Keywords: energy, extraction, irrigation, limit, tariff.

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INTRODUCTION

The Special Energy Program for the Countryside in the Area of Electric Energy for Agricultural Use (*Programa Especial de Energía para el Campo en Materia de Energía Eléctrica de Uso Agrícola*, PEUA), aims to promoting productivity and the development of agriculture and livestock activities in an environmentally sustainable manner, in order to help make them more profitable by providing agricultural producers with access to electric energy (DOF, 2005). In this context, the Program focused on supporting water pumping and repumping activities through a subsidized rate called energy quota.

Achieving a balance between the assigned energy quota and the authorized water extraction volume for each producer is challenging due to the influence of various factors on the final energy required for extraction. These factors include the power factor, the efficiency of the pumping equipment, and dynamic loads, which are determined by the depth and diameter of the well, the irrigation system used, the irrigated area, and its distribution, among other aspects.

Initially, the energy quota was calculated based on the Annual Energy Limit (AEL), which took into account the granted water volume, the depth of the well, and a minimum electromechanical efficiency of the pumping equipment. However, applying the AEL as energy quota proved insufficient to meet the demands of producers, as it did not reflect the real operating conditions of the pumping systems. This led to increased production costs and negatively affected users' competitiveness. In response to this issue, a modification agreement was published in 2005, establishing a new formula, still in effect, which focuses exclusively on the power capacity of the pumping equipment. The granted water volume was removed as a variable from the calculation, and the responsibility for measuring the extracted water volume was assigned to the water right holders, in accordance with the National Waters Law and its regulations (DOF, 2005).

One of the problems with the current energy quota formula is that the subsidy encourages excessive water extraction and waste of the resource, the use of inefficient equipment, and the cultivation of unprofitable crops (Olavarrieta *et al*., 2010). To contextualize this issue, it is relevant to mention some data on national and regional water consumption in Mexico. According to CONAGUA (2022), agricultural use accounted for 76.29% of the national total, with 68,515.7 hm^3 allocated for crop irrigation. In this same year, a total of 1,914 hm^3 was used in Nuevo León. This volume was distributed as follows: 65.99% for agricultural use (605 hm^3 from surface water sources and 658 hm^3 from groundwater sources), 29.36% for drinking water consumption (406 hm^3 from surface water sources and 156 hm^3 from groundwater sources), and 4.5% for industrial use (87.6 hm^3 from groundwater sources).

Although agriculture is the sector with the largest water allocation, there is a significant lack of knowledge about water use in this sector (González-Sánchez *et al*., 2017). This is mainly due to the absence of water use measurements by users, the lack of instruments to measure volumetric consumption, insufficient staff to take measurements, and the failure of CONAGUA to enforce the regulatory framework. Crespo and Ramírez (2018) state that there is no precise information on how much water is actually used for its intended purposes, and in general, the available data consists of the concessions granted by the water authority, which are recorded in the Public Registry of Water Rights (*Registro Público de Derechos de Agua*, REPDA).

The objective of this study is to evaluate water use associated with the energy quota in extreme cases of energy consumption, to verify the volume of these extractions, to compare the electricity provided under the energy quota with the energy requirements of producers in the study area, and to propose a methodology for establishing a limit based on the granted water volumes. The methodology suggested has the aim of guaranteeing the energy demands of the different agricultural productive systems, avoiding subsidizing consumption that would potentially exceed the extraction allowed by CONAGUA. Its implementation is analyzed in a preliminary way, due to the limited availability of data on volumetric measurements of the region's extractions.

THEORETICAL FRAMEWORK

Groundwater is essential for agricultural production (Richter and Ho, 2022) and the ecosystems that depend on it are vital for maintaining stream and rivers flows, providing habitats, supporting biodiversity, and protecting aquifers from contamination (Eamus *et al.*, 2015; Poeter *et al.* 2020). In addition to its socioeconomic value through productive extraction, groundwater provides important environmental services such as drought mitigation, protection against saltwater intrusion, mainly in coastal aquifers, and prevention of land subsidence (Grundmann *et al.*, 2016; Alcalá *et al.*, 2023).

Irrigated agriculture plays a fundamental role in global food production, contributing to more than 40% of it (Hamidov and Helming, 2020). However, water scarcity, exacerbated by the depletion of watersheds and urban and industrial contamination, has deteriorated lands designated for irrigation. Issues such as waterlogging, salinization and erosion are common due to poor irrigation water management practices (Magdoff and Van Es, 2021). In addition, the high costs of modernization, maintenance, and repair of irrigation and drainage systems, combined with limited financial resources among farmers, pose a significant challenge for governments, which must decide how to allocate resources to address these problems without fully passing the costs on to end users (Zúniga and Mendoza, 2021).

Agricultural policy is an important factor to consider in groundwater management. In particular, energy subsidies for agricultural irrigation costs can encourage excessive water extraction due to inefficient use, such as the cultivation of low-productivity crops or the adoption of inefficient irrigation systems. These practices allow users to benefit while bearing only a fraction of the real costs, with the remainder being absorbed by society (Srivastava *et al.*, 2017), without accounting for the broader socioeconomic impacts resulting from aquifer depletion and contamination.

On the other hand, the imposition of electric rates can serve as a tool to encourage farmers to use energy more efficiently by improving irrigation practices, which can lead to higher production per energy unit, while also influencing groundwater extraction and use. However, it is important to consider that, if the marginal productivity of the energy used in pumping remains higher than the total cost, increasing the rate may not be as effective in controlling energy consumption, and therefore, the extraction of groundwater. In addition, if this strategy becomes unprofitable for producers, they might opt for alternative energy sources such as solar or diesel pumps (Saleth, 1997). Likewise, it is necessary to address agricultural pollution and to promote more sustainable agricultural practices to protect this resource in the long term, reconsidering subsidies for fertilizers and pesticides that can damage groundwater quality if used indiscriminately (UICN, 2016).

Total crop productivity must be integrated into agricultural planning and the long-term sustainable management of water resources, since a productivity-based approach can optimize the water use and promote savings in high-consumption systems (Villa-Camacho *et al.,* 2021). To achieve this, crop water requirements must be identified and irrigation system efficiency optimized, especially in arid and semi-arid zones (Ávila-Dávila *et al.,* 2021). In some cases, productivity can be improved through techniques such as soil mulching (Escobosa-García *et al.,* 2022) and the selection of drought-resistant varieties combined with different fertilization treatments and planting densities (Alonso-Sánchez *et al.,* 2023). El-Beltagi *et al.* (2022) report that plastic mulch increases the efficiency of water use by 31% and improves wheat yield by up to 50%, while straw mulch reduces evaporation by 35%. In addition, combining mulching with drip irrigation enhances water use efficiency and reduces water consumption by up to 40-50% (Bwire *et al.*, 2024).

With the aim of creating effective policies that promote the sustainability of water use and productivity in the agricultural sector, it is necessary to accurately understand the extraction levels. However, in many regions, these estimates are difficult to obtain due to physical, regulatory and social barriers (Brookfield *et al.*, 2023).

An important aspect to take into consideration when estimating water volume extraction is consumptive use. Hanson *et al*. (2014) point out that the consumptive use of water in crops is divided into six specific components. These elements include transpiration resulting from groundwater uptake through roots, transpiration from precipitation, transpiration of irrigation-applied water, evaporation of irrigation water, evaporation caused by precipitation, and evaporation of groundwater. The sum of these components represents the final consumptive use (CU) of the crops, while the remaining water is either converted into surface runoff or percolates through the root zone as deep percolation, eventually reaching the groundwater. In general, it is estimated that more than 60% of all water extraction returns to local hydrological systems, either through return flows to rivers or to groundwater, while the remaining portion is considered consumptive use due to evaporation and plant transpiration (FAO, 2011).

Energy consumption in agriculture could be used as an indicator of the amount of water extracted for irrigation. According to Espino *et al.* (2011), this consumption is influenced by several key factors, among which are included the depth of the well, the transport of water through pipes, and the irrigation method used (such as flood, sprinkler, or drip irrigation). The stages of a typical irrigation system range from water extraction and conditioning, to conveyance, distribution, and finally, the irrigation itself. Each stage of the irrigation process has significant energy consumption: from the water extraction from the well (which can consume between 40% and 80% of the energy), to conveyance and distribution (0%-50%), and proper irrigation (10%-30%). The optimization of water distribution schemes is not always aligned with the optimization of energy use. In general, greater technification of irrigation systems leads to higher energy consumption and lower water use to achieve the same crop yield, since the modern irrigation systems, commonly based on pipeline conveyance, face additional challenges such as electricity quality, motors and pumps efficiency, and losses caused by aging infrastructure and the design of distribution lines (Espino *et al.*, 2011).

Martindill *et al.* (2021) point out that the volume of groundwater pumped is directly related with the power required to extract the water. In their study, they used the Efficiency Lift Method (ELM), which takes advantage of this relationship to estimate the water volume pumped, based on three main data: energy consumption of the pump (kWh), electromechanical efficiency of the pumping equipment (relationship between the mechanical output power of the pump and the electrical input power, expressed as a percentage), and Total Dynamic Head (TDH), which corresponds to the total equivalent vertical distance that the pump moves the water, expressed in meters. To obtain the data, the authors indicate that the using pump efficiency test reports was the most effective approach to minimizing calculation errors, achieving an error rate of 13.5%. This rate could be reduced to 5% when accounting for efficiency variations throughout the year. In contrast, using regional average data increased the error rate to 19.9%.

González-Sánchez *et al.* (2017) proposed using an energy index to estimate the volume of water extracted based on electric energy consumption in irrigation units in Zacatecas. In their study, they calculated the index at specific points in time, using the instantaneous flow and active power obtained from electromechanical efficiency tests of the pumping equipment. They note that the pumping equipment can experience deterioration in some components in a short period, which can alter the flow and result in differences in the energy indices from year to year. The results show that the energy indices, calculated in kWh/m^3, generally decrease as both the water consumption and electromechanical efficiency increase. However, when the energy index is calculated based on the water flow per second and active power at specific points in time, the initial energy required to start the pumping and irrigation system, as well as the pressure changes in the conveyance system caused by increase flow, are not considered. This could affect the value of energy index and the final calculation of the extracted volume.

Monteagudo-Yanes and Gaitan (2005) and Ibarguen-Valverde *et al.* (2017) used a formula to determine the function of an energy consumption index. This formula is based on calculating the slope of the linear regression between energy consumption and production, which represents the energy associated with production, and in the value of the intercept, which indicates the energy not associated with production. This indicator is affected by changes in production volume. For example, in the context of volumetric water extraction, as water extraction decreases, it is likely that an increase in the value of the index will be observed. This is because of the need for initial energy not associated with water extraction, which results in an increase in the relative weight of this energy in the total energy consumed. Conversely, when the extraction volume increases, the value of the index is likely to decrease.

METHODOLOGY

The study area is found within the administrative hydrological region VI "Río Bravo", specifically in the Citrícola Sur 1914 aquifer, situated in the southern portion of the state of Nuevo León, on the border with the state of Tamaulipas, between parallels 24° 32′ and 24° 55′ north latitude, and meridians 99° 04′ and 100° 14′ west longitude (Figure 1). According to the information published in the DOF (2013), this aquifer has been under a water extraction ban since April 2013. The Citrícola Sur aquifer has an average annual recharge of 75.1 hm^3, which corresponds to the total volume of water entering the aquifer each year (CONAGUA, 2024).

Data from 195 active services registered in the Energy Program for the Countryside were used, all located within the study area covering the municipalities of Linares and Hualahuises, Nuevo León. The Annual energy consumption data were obtained from electricity bills issued by the Federal Electricity Commission (*Comisión Federal de Electricidad*, CFE), which were provided by program beneficiaries in November 2023.

Two water consumption variables were also considered: the granted water volume, calculated from the sum of the granted volumes to each service point,

Source: CONAGUA (2024).
Figure 1. Location of the study area.

and the annual volumetric water consumption, which was estimated in only three citrus orchards that use surface irrigation systems. This estimation was based on flow meter readings taken during three field inspections conducted in November 2022. These three service points were selected based on two criteria: the high annual energy consumption and the ease in access and measurement. The Kolmogorov-Smirnov (KS) test was used to assess the normality of the annual energy consumption and energy quota data. Subsequently, the Mann-Whitney U test was applied to compare these data. The objective was to determine whether the energy quota subsidizes energy consumptions levels that may be higher than current usage.

Two indicators are proposed to provide an initial estimate on the amount of energy required for irrigation in the study area. The first indicator, Extraction Potential (EP), represents the energy required to extract and distribute one cubic meter of water within a productive system.

$$EP = \frac{C}{V}$$

where *EP*: Extraction Potential (kWh/m^3); *C*: Energy consumption in kilowatt-hour (kWh); *V*: Annual volume of water used in cubic meters (m^3).

The second indicator is the hypothetical Extraction Potential (hEP) and refers to the amount of energy required to extract and distribute one cubic meter of water in the hypothetical scenario where the producer consumes the entire granted water allocation for the year. The formula is as follows.

$$hEP = \frac{C}{Gv}$$

where *hEP*: Hypothetical Extraction Potential (kWh/m^3); *C*: Annual energy consumption in kilowatt-hour (kWh); *Gv*: Annual granted water volume in cubic meters (m^3).

The relationships between the variables hEP, energy consumption and granted volume were evaluated using Spearman's correlation coefficient, to understand the behavior of the indicators proposed in this study and to ensure its effective use in a proposal to calculate the energy quota.
In addition, the function of the energy consumption index proposed by Monteagudo-Yanes and Gaitan (2005) was evaluated using the following equation:

$$f\left(EP\right) = \frac{b}{V} + m$$

where *Ep*: Extraction potential kWh/m^3; *m*: Slope of the linear regression between energy consumption and extracted volume; *b*: Intercept of the linear regression between energy consumption and extracted volume; *V*: Extracted volume in cubic meters (m^3).

Given that there are only three pairs of data, the Theil-Sen regression was used to estimate the slope and the intercept point in the linear relationship between energy consumption and extracted volume. Because of the limitations of extrapolating this linear relationship to the 195 services evaluated with such a small data set, 95% confidence intervals were calculated for the slope and the intercept point.
Using these values, the functions to predict the extraction potential were calculated, considering the limits of the confidence interval. These calculations involved the combinations of the minimum and maximum slope and intercept values.

It is suggested to modify the extraction potential function to a potential-type function that approximates the EP values for each service. This function, called extraction limit function *f*(*El*), should vary across different regions and productive systems in the country, and it will be adjusted after conducting field verifications, then serving for the calculation of the energy quota.The *f*(*El*) can be defined as the curve based on a power regression of the verified EP values, which is then adjusted according to the highest and most distant energy requirement. This function allows the calculation of the maximum EP value for different volumes of water extracted and is expressed by the following formula:

$$f\left(El\right)=c\times V^{a}$$

where *El*: Extraction limit (kWh/m^3); *V*: Extracted volume; *a*: Exponent of the function; *c*: Constant of the function.

Assuming the producer extracts the entirety of their granted volume, this volume can be substituted into the formula to calculate the maximum value of EP that the producer can generate. Subsequently, the EP value can be used to establish a clear limit of the amount of energy the producer may consume.
To calculate the coefficient *a*, representing the exponent of the extraction limit function, and the coefficient *c*, the constant, a regression must be performed on the variables: Extraction Potential and extracted volume. First, the natural logarithms of both the independent variable, extracted volume (*x*), and the dependent variable, Extraction Potential (*y*), are calculated. Then, a linear regression is applied to the transformed data [ln(*x*), ln(*y*)], resulting in the equation of the line that best fits the data.
To transform this line into a power regression curve, the coefficient *a* is determined as the slope of the linear regression line of the transformed data, while the coefficient *c* is calculated as $c = e^b$, where b, is the y-intercept on the regression line, which is calculated using the following formula:

$$b=\overline{y}-m\overline{x}$$

where *b*: Intercept point; $\overline{y}$: Mean of the data transformed to natural logarithm of the extracted volume; $\overline{x}$: Mean of the data transformed to natural logarithm of energy consumption; *m*: Slope of the regression line of the transformed data.

To adjust the curve so that all the verified values fall below it and it can serve as an upper limit, the coefficient *c* can be calculated from *b′* defined as:

$$b'=\max_{i=1}^{n}\left(y_i-mx_i\right)$$

where b': Adjusted intercept point; y_i: Data transformed to natural logarithm of extracted volume; x_i: Data transformed to natural logarithm of energy consumption; m: Slope of the regression line of the transformed data; n: Number of transformed data.

Therefore, the calculation of the constant c in the extraction limit function would be defined by $c=e^{b'}$.
With the aim of arriving at a solution that helps to limit the energy subsidized, based on granted volumes, the starting point can be the current formula of the energy quota, which is simplified in the following manner:

$$Energy\ Quota=(HP\times0.746\times365\times24)\times0.75+438$$
$$Energy\ Quota=438+HP\times4901.22$$

where HP: Power of the pumping equipment expressed in horsepower; 0.746: Constant to convert the HP into KW; 365: Maximum time in days of the year that the equipment could operate; 24: Maximum time in hours of the day that the equipment could work; 0.75: Proportion of time estimated from the equipment operation; 438: Constant that represents the annual average consumption of local lighting; 4901.22: Constant to convert the power into Kwh during 75% of the year.

Since the extraction potential is a measure of the relation between the energy consumption and the volume, once the EP value is known, it is possible to use it to calculate the necessary energy to extract a specific volume of granted water, through the following equation:

$$E = EP \times V$$

where E: Energy required in kWh; EP: Extraction Potential in kWh/m^3; V: Volume of water in m^3.

By replacing EP with the extraction limit function, which calculates the maximum values of EP in different points depending on the extracted volume, the resulting formula is as follows:

$$E = c \times V^a \times V$$

This can be simplified into:

$$E = c \times V^{a+1}$$

The proposed new formula would not completely replace the current calculation, but would instead establish a limit based on the extraction potential observed in the field. If the energy quota does not exceed this limit, it can be calculated using the current method. Therefore, the new formula is defined as the minimum of the current formula and the limit allowed for a specific region and productive system:

$$Energy\ Quota = 438 + \min(HP \times 4901.22c \times V^{a+1})$$

where *HP*: Power of the pumping equipment expressed in horsepower; 4901.22: Constant to convert the power into Kwh during 75% of one year; 438: Constant that represents the annual average consumption of local lighting; *V*: Granted volume in m^3; *c*: Constant of the limit function; *a*: Exponent of the limit function

RESULTS

The three service points evaluated in the field correspond to citrus crops with surface irrigation systems in the zone of Linares-Hualahuises, Nuevo León. In all cases, the volume of water consumed exceeded the granted volume. In the first service point, water consumption was 36 times higher than the granted volume, while in service points 2 and 3, the excess was 11 times greater (Table 1). Annual energy consumption did not exceed the allocated quota at service points 1 and 2, whereas at service point 3, it surpassed the quota by 14%. It can also be seen that the service point with the highest water overuse corresponds to the lowest EP value (0.0619 kWh/m^3).

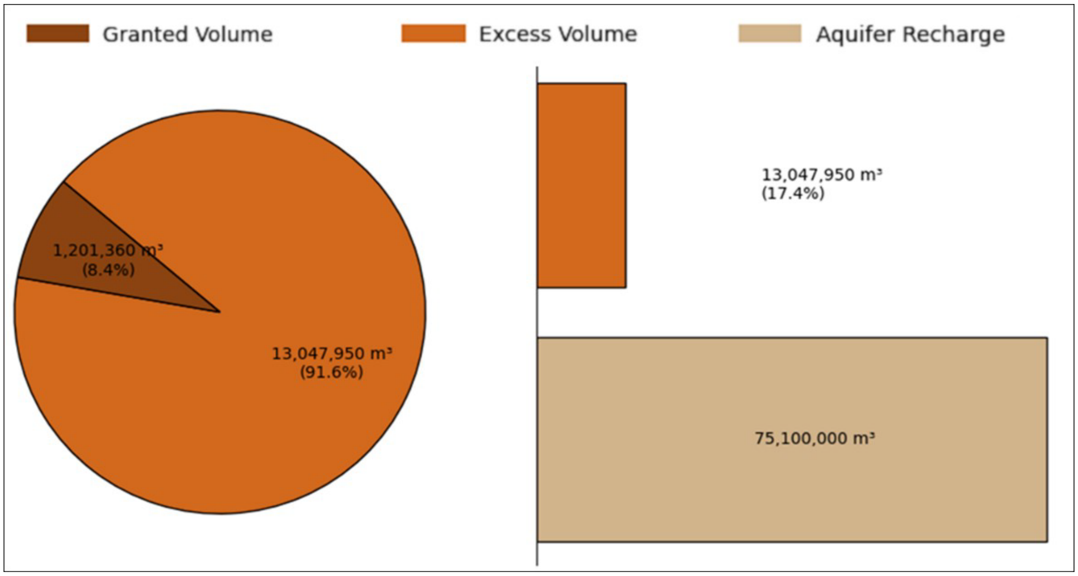
From the total extracted volume in the orchards verified, only 8.4% corresponds to the granted volume; the rest is the excess volume. It is significant to compare this excess visually, with a reference volume such as the mean annual recharge of the Citrícola Sur aquifer estimated by CONAGUA (Figure 2).

It was observed that both the annual energy consumption values (D=0.28817, p=1.721e-14) and energy quota values (D=0.18651, p=2.565e-06) do not follow

Table 1. Consumption data of the 3 services verified in November 2022.

#	Energy Quota (kWh)	Annual consumption (kWh)	Granted Volume (m^3/year)	Extracted volume (m^3/year)	Excess volume (m^3/year)	EP (kWh/m^3)	hEP (kWh/m^3)
1	637,596	189,600	39,840	1,464,980	1,425,140	0.1294	4.7590
2	355,776	209,310	117,000	1,304,608	1,187,608	0.1604	1.7890
3	622,892	711,069	1,044,520	11,479,722	10,435,202	0.0619	0.6807

Source: prepared by the authors.



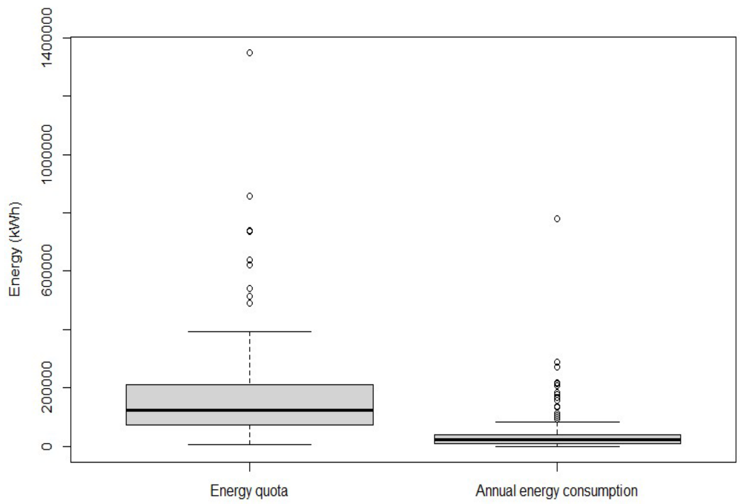
Source: prepared by the authors.
Figure 2. Relationship between granted volume, excess volume in the 3 verified services, and recharge of the Citrícola Sur aquifer.

a normal distribution. In addition, the annual energy consumption values were significantly lower (W=33193, p<2.2e-16) compared to the current energy quota values, indicating that the energy subsidized by the current energy quota significantly exceeds the actual energy requirements of the producers in the study area (Figure 3).

From the coefficients obtained through the Theil-Sen regression between the energy consumption and the volume extracted from the three services verified in the field, a slope of 0.0493 was estimated, with a 95% confidence interval of [-0.1229, 0.0520] and an intercept point of 137,068, with a confidence interval of [133028, 389358].

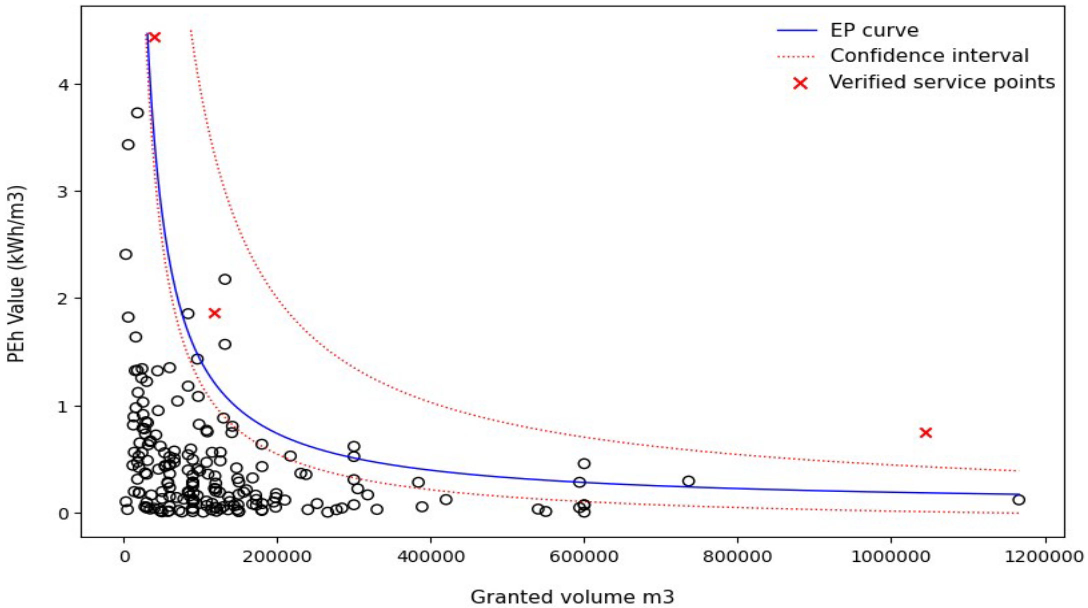
With these values, the function to predict extraction potential and its confidence interval were calculated and compared with the dispersion data of the granted volume and the hEP value from the 195 services evaluated, with the aim of analyzing their behavior. It can be observed that the values of the selected services do not align with most of the services evaluated, which could be explained by their selection due to high annual energy consumption (Figure 4).

A significant positive correlation was identified between the annual energy consumption and granted volume (R=0.3061, p=1.35e-05, n=195). However, the coefficient of determination (R^2=0.0937) indicates that granted volume has



Source: prepared by the authors.
Figure 3. Comparison of the assigned energy quotas versus the annual energy consumption in the study area.

a limited influence on user's final energy consumption. Likewise, a significant negative correlation was identified between the granted volume and hEP



Source: prepared by the authors.
Figure 4. Dispersion of granted volume and hEP values, EP curve=(137068/V)+0.0493, EP_{min}=(133028/V)-0.1229, EP_{max}=(389358/V)+0.0520.

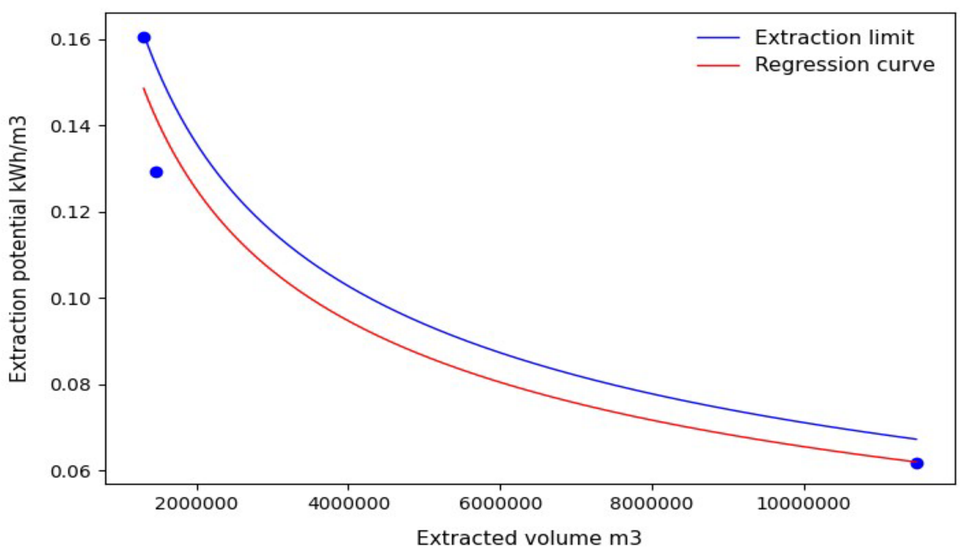
values (R=-0.4019, p=5.75e-09, R^2=0.1615), indicating that higher volumes of granted water are associated with lower hEP values.

When the proposed methodology for calculating the extraction limit is applied, the power regression curve generated from the energy consumption and extracted volume data of the three verified service points shows a similar pattern to the modified extraction limit curve (Figure 5). However, given the small sample size, the results may not accurately reflect the true relationship between the variables in the population. Nevertheless, they provide a good starting point for further verification and adjustment of the curves.

When analyzing the scatter plot of the hEP values against the granted volume values and plotting the extraction limit curve based on field verified data, it is observed that all the service points with hEP values above the curve may be consuming more water than they have authorized. This serves as an indicator that could be used to prioritize field inspections for service points whose hEP value exceeds the extraction limit (Figure 6).

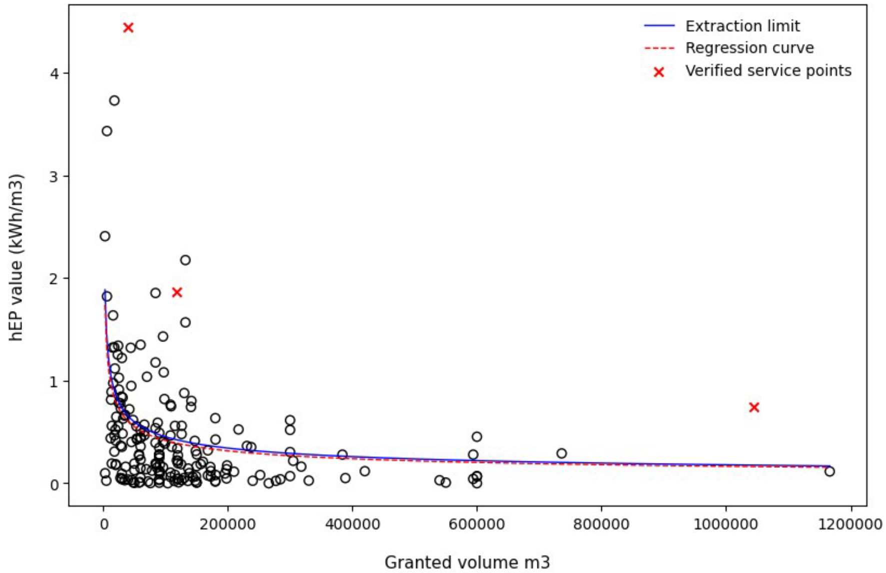
DISCUSSION

One of the reasons for reducing water use in agriculture is the growing demand driven by the global population growth (El-Beltagi *et al.*, 2022). According to data from CONAGUA (2024), the average annual groundwater availability in the Citrícola Sur aquifer shows a deficit of -88.86 hm^3/year, as the sum of



Source: prepared by the authors.

Figure 5. Power regression and extraction limit calculated from the three data pairs verified in the field. The regression equation is $42.689x^{-0.402}$, the extraction limit equation is $46.325x^{-0.402}$.



Source: prepared by the authors.
Figure 6. Estimated extraction limit for the surface irrigation system.

natural discharges and the total volume of extracted groundwater (calculated from concessions, ongoing records, and water scheduling up to December 2022) exceeds the natural recharge of the aquifer.

The deficit estimated by CONAGUA could be even higher, as in the three verified orchards, the total extraction volume was 14.25 hm^3/year, of which only 1.2 hm^3/year corresponded to the granted volume. This increases pressure on water availability, which could lead to a decrease in agricultural yields and significant crop losses in the future, necessitating the adoption of more efficient and sustainable food production methods (Dinar *et al.*, 2019).

In establishing subsidized energy for agriculture, it is essential to consider various aspects, including the availability of accurate data, particularities of agricultural systems, the sector's competitiveness needs, and the sustainability of resource use. A key aspect is the priority assigned to the competitiveness of users. In recent decades, the agricultural policy has focused on the sector's economic profitability, which led to the removal of the annual energy limit in the original equation.

Another relevant factor is the accuracy of the data used in the calculations. The original equation for the energy quota is based on the efficiency improvement method, which allowed for defining the energy limit. According to Martindill *et al.* (2021), the errors associated with this method can be significantly reduced if detailed information is available on the efficiency of the pumping equipment and its variations throughout the year, as well as accurate data on the total dynamic head. However, obtaining this information represents a considerable challenge due to the heterogeneity of the production systems in Mexican agriculture, which makes it difficult to collect and standardize the required data.

The use of indices allows for taking advantage of the available accurate data and facilitates estimating water extraction. However, it is important to note that it is incorrect to restrict the energy quota to a single value of Extraction Potential (EP) for all the services, since EP values are likely to change significantly as the extraction volume increases or decreases. In other words, a service that uses less water may require more energy per cubic meter extracted than when it extracts greater volumes. Likewise, a service with high volume of extracted water could have relatively low EP values. This can be attributed to energy not related to water extraction, which manifests as a fixed energy cost.

When trying to establish a function that predicts the value of EP using the formula proposed in the study by Monteagudo-Yanes and Gaitan (2005), a significant issue was observed for this specific case. In this formula, the energy unrelated to extraction remains constant for both large and small services, which can, in some cases, lead to an overestimation of the EP value. According to the results obtained, it is observed that the value of b, or intercept point obtained from the regression of energy consumption and total volume extracted in the services evaluated in the field, represents 137,068 kWh of energy unrelated to water extraction. This value, which is considerably high, would significantly influence the calculation of EP in small services (or with lower extraction volume).

In the context of the energy used for agricultural irrigation, it is reasonable to expect that the energy unrelated to water extraction is lower in the smaller services, which have a reduced volumetric extraction compared with the larger services. This is because less complex irrigation systems are typically used. For example, when comparing the necessary energy to start the pumping equipment and the initial distribution of water in a 2-hectare orchard with that in a 100-hectare orchard, it is very likely that the startup energy and initial distribution will be higher in the second case.

The proposal to establish a limit in the formula for the energy quota is supported by two main assumptions. In the first place, it is considered that the current energy quota allows significantly higher energy consumption than what is needed by producers. In the second place, it is assumed that the EP values have a decreasing behavior as the volume extracted increases.

The curve obtained through this methodology could solely represent the energy requirements of the study area and the evaluated irrigation system, which in this case was surface irrigation with repumping. For this reason, calculating different curves for the extraction limit ought to be considered, according to the region and the irrigation system, enabling the management of different f(El) functions for each zone.

Once the maximum limit of the energy quota is established, significant pressure will be placed on producers with higher energy consumption to reduce their usage levels. Ávila *et al.* (2005) argue that the increases in the electricity tariffs act as a gradual incentive for the adopting more efficient irrigation technologies. This not only results in direct benefits by reducing electricity consumption but also promotes the modernization and optimization of the irrigation systems, thereby contributing to more sustainable management of the water and energy resources.

The new energy quota proposed in this study is a tool that could complement existing policies for regulating the use of water and energy in agriculture. It is essential to continue enforcing the Energy Law for the Countryside (*Ley de Energía para el Campo*) (DOF, 2002) and the National Waters Law (*Ley de Aguas Nacionales*) (DOF, 1992), to ensure the proper and rational use of water for agricultural purposes, as well as compliance with water extraction permits and authorized volumes. Even if the energy quota is not modified, results of this study offer guidance on which services may be extracting water in volumes exceeding those authorized.

The sample evaluated in this study represents only a small fraction of the services with energy quotas in the state of Nuevo León and nationwide. Therefore, it is necessary to investigate the distribution of Extraction Potential values across different regions of the country. Additionally, different methodologies should continue to be explored to address the problem of excessive water consumption. It is also important for the authorities responsible for overseeing the program to maintain records on energy consumption, granted water extraction volumes, and the irrigation systems used by the benefiting producers, as part of the preparation for the potential application of future estimates.

CONCLUSIONS

Based on the results obtained, it is observed that the quotas calculated with the current formula are significantly higher than the energy requirements of the producers. In addition, evidence was found of a considerable excess in water extraction, derived from the high energy consumption subsidized by the current agricultural tariff, in the three verified orchards.

REFERENCES

Alcalá FJ, Senent AJ, Martínez PP. 2023. Coastal aquifer management: Hydrological, environmental, economic and social challenges in the context of global change. Water. 15(20). 3561.

https://doi.org/10.3390/w15203561.
Alonso-Sánchez H, Tadeo-Robledo M, Espinosa-Calderón A, Zaragoza-Esparza J, López-López C, Zamudio-González B, Monter-Santillán A, Turrent-Fernández A, Arteaga-Escamilla I, Mora-García K. 2023. Efecto de la densidad de población y la fertilización sobre la productividad del agua y rendimientos de híbridos de maíz en el Valle de México. Terra Latinoamericana, 41. 1-15. https://doi.org/10.28940/terra.v41i0.1577.
Ávila-Dávila L, Molina-Martínez JM, Bautista-Capetillo C, Soler-Méndez M, Robles-Rovelo CO, Júnez-Ferreira HE, González-Trinidad J. 2021. Estimation of the Evapotranspiration and Crop Coefficients of Bell Pepper Using a Removable Weighing Lysimeter: A Case Study in the Southeast of Spain. Sustainability. 13. 747. https://doi.org/10.3390/su13020747.
Ávila S, Muñoz C, Jaramillo L, Martínez A. 2005. Un análisis del subsidio a la tarifa 09. Gaceta Ecológica, 75. 65-76.
Bwire D, Watanabe F, Suzuki S, Suzuki K. 2024. Improving irrigation water use efficiency and maximizing vegetable yields with drip irrigation and poly-mulching: A climate-smart approach. Water. 16(23). 3458. https://doi.org/10.3390/w16233458.
Brookfield AE, Zipper S, Kendall AD, Ajami H, Deines JM. 2023. Estimating groundwater pumping for irrigation: A method comparison. Groundwater. 62(1). 15–33. https://doi.org/10.1111/gwat.13336.
CONAGUA (Comisión Nacional del Agua). 2022. Sistema Nacional de Información del Agua. Disponible *In*: https://sinav30.conagua.gob.mx:8080/SINA/?opcion=avirtual (Consultado: el 12 de febrero de 2024).
CONAGUA (Comisión Nacional del Agua). 2024. Actualización de la Disponibilidad Media Anual de Agua en el Acuífero Citrícola Sur (1914), Estado de Nuevo León. https://sigagis.conagua.gob.mx/gas1/Edos_Acuiferos_18/nleon/DR_1914.pdf.
Crespo-Elizondo R, Ramírez-Orozco A. 2018. Plan Hídrico Nuevo León 2050. Fondo de Agua Metropolitano de Monterrey. Recuperado de https://famm.mx/wp-content/uploads/2018/10/Plan-H%C3%ADdrico-NL-2050.pdf.
Dinar A, Tieu A, Huynh H. 2019. Water scarcity impacts on global food production. Global Food Security. 23. 212–226. https://doi.org/10.1016/j.gfs.2019.07.007.
DOF (Diario Oficial de la Federación). 1992. Ley de Aguas Nacionales. https://www.diputados.gob.mx/LeyesBiblio/pdf/LAN.pdf Última reforma publicada DOF 08-05-2023.
DOF (Diario Oficial de la Federación). 2002. Ley de Energía para el Campo. https://www.diputados.gob.mx/LeyesBiblio/pdf/246.pdf Última reforma publicada DOF 28-12-2012.
DOF (Diario Oficial de la Federación). 2005. Acuerdo que modifica los lineamientos por los que se regula el programa especial de energía para el campo en materia de energía eléctrica de uso agrícola, publicados el 4 de abril de 2005. https://dof.gob.mx/nota_detalle.php?codigo=2088492&fecha=03/08/2005#gsc.tab=0 Última reforma publicada DOF: 03/08/2005.
DOF (Diario Oficial de la Federación). 2013. Acuerdo General por el que se suspende provisionalmente el libre alumbramiento en las porciones no vedadas, no reglamentadas o no sujetas a reserva de los 18 acuíferos que se indican. https://www.dof.gob.mx/nota_detalle.php?codigo=5294659&fecha=05/04/2013 Última reforma publicada DOF: 05/04/2013.
Eamus D, Zolfaghar S, Villalobos-Vega R., Cleverly J, Huete A. 2015. Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. Hydrology and Earth System Sciences. 19. 4229–4256. https://doi.org/10.5194/hess-19-4229-2015.
El-Beltagi HS, Basit A, Mohamed HI, Ali I, Ullah S, Kamel EAR, Shalaby TA, Ramadan KMA, Alkhateeb AA, Ghazzawy HS, 2022. Mulching as a sustainable water and soil saving practice in agriculture: A review. Agronomy. 12(8). 1881. https://doi.org/10.3390/agronomy12081881.
Escobosa-García I, Vázquez-Medina MM, Samaniego-Gámez BY, Valle-Gough RE, Vázquez-Angulo JC, Núñez-Ramírez F. 2022. Efecto del acolchado en repollo cultivado en el Valle de Mexicali. Revista Mexicana de Ciencias Agrícolas. 28. 197-206. https://doi.org/10.29312/remexca.v13i28.3275.
Espino del Pozo JF, Martínez JA, Hernández-Yáñez C. 2011. Diagnóstico de los sistemas de bombeo para riego agrícola. *In:* Estudio de sistemas de bombeo agropecuarios en México; Ruiz, A., Feilbogen, E., Nieto-Vázquez, MA., Sierra, ME, Gómez-Ortega, BI., Velazquez-Martínez, AA. Eds.; Comisión Nacional para el Uso Eficiente de la Energía (CONUEE), Deutsche Ge-

sellschaft für Internationale Zusammenarbeit (GIZ), Secretaría de Energía (SENER). México D.F. 2011; pp: 3-26.

FAO (Organización de las Naciones Unidas para la Alimentación y la Agricultura). 2011. Estado y tendencias de los recursos de tierras y aguas. *In:* El estado de los recursos de tierras y aguas del mundo para la alimentación y la agricultura. La gestión de los sistemas en situación de riesgo. Organización de las Naciones Unidas para la Alimentación y la Agricultura, Roma y Ediciones Mundi-Prensa, Madrid, España. pp: 21-65.

González-Sánchez A, González-Casillas A, Guillén-González JÁ. 2017. Uso del índice energético para la estimación de extracciones volumétricas en unidades de riego de Zacatecas. Actas del III Congreso Nacional de Riego y Drenaje, Puebla, Puebla, México, del 28 al 30 de noviembre de 2017, Coordinación de Riego y Drenaje. Instituto Mexicano de Tecnología del Agua. Articulo COMEII-17045.

Grundmann J, Al-Khatri A, Schütze N. 2016. Managing saltwater intrusion in coastal arid regions and its societal implications for agriculture. PIAHS. 373. 31–35. https://doi.org/10.5194/piahs-373-31-2016.

Hamidov A, Helming K. 2020. Sustainability considerations in water–energy–food nexus research in irrigated agriculture. Sustainability. 12(15). 6274. https://doi.org/10.3390/su12156274.

Hanson RT, Boyce SE, Schmid W, Hughes JD, Mehl SW, Leake, S. A., Maddock T, III, Niswonger RG. 2014. Consumptive Use and Evapotranspiration in the Farm Process *In:* One-water hydrologic flow model (MODFLOW-OWHM). U.S. Geological Survey. Reston VA. https://doi.org/10.3133/tm6A51. 120 p.

Ibarguen-Valverde JL, Angulo-Lopez, JE, Rodríguez-Salcedo J, Prías-Caicedo O. 2017. Indicadores de desempeño energético: Una ruta hacia la sustentabilidad. Caso de estudio una industria torrefactora de café. DYNA, 84(203). 184-191. https://doi.org/10.15446/dyna.v84n203.65336.

Magdoff F, Van Es H. 2021. Building soils for better crops: Ecological management for healthy soils (4ª ed.). Sustainable Agriculture Research & Education: University of Maryland Printing Services, https://lccn.loc.gov/2021018006. 410 p.

Martindill JR, Good RT, Loge FJ. 2021. Estimating agricultural groundwater withdrawals with energy data. Journal of Water Resources Planning and Management. 147(5). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001348.

Monteagudo-Yanes JP, Gaitan RO. 2005. Herramientas para la gestión energética empresarial. Scientia Et Technica. 11(29). 169-174.

Naciones Unidas. 2022. Aguas Subterráneas y Agricultura. *In:* Informe Mundial de las Naciones Unidas sobre el Desarrollo de los Recursos Hídricos 2022: Aguas subterráneas, Hacer visible el recurso invisible. UNESCO. París, Francia 2022; pp: 49-61.

Olavarrieta-Carmona MV, Watts-Thorp CJ, Saiz-Hernández JA. 2010. Beneficios de la cuota energética. Estudio de caso de la Costa de Hermosillo, Sonora, México, 2006-2007. Región y sociedad. 22(47). 145-164.

Poeter E, Fan Y, Cherry J, Wood W, Mackay D. 2020. Groundwater in our water cycle – getting to know Earth's most important fresh water source. The Groundwater Project. Guelph. Ontario, Canada 2020; pp: 136. https://doi.org/10.21083/978-1-7770541-1-3.

Richter B, Ho MD. 2022. Sustainable groundwater management for agriculture. WWF World Wide Fund for Nature. 51 p.

Saleth RM. 2015. Power tariff policy for groundwater regulation: Efficiency, equity and sustainability. Artha Vijnana: Journal of The Gokhale Institute of Politics and Economics. 39(3). 312–322. https://doi.org/10.21648/arthavij/1997/v39/i3/115944.

Srivastava SK, Chand R, Singh J, Kaur AP, Jain R, Kingsly I, Raju SS. 2017. Revisiting groundwater depletion and its implications on farm economics in Punjab, India. Current Science. 113(3). 422. http://dx.doi.org/10.18520/cs/v113/i03/422-429.

UICN (Unión Internacional para la Conservación de la Naturaleza y de los Recursos Naturales). 2016. Instrumentos y principios económicos para la gestión sostenible de las aguas subterráneas. *In:* Acuíferos: Gestión sostenible de las aguas subterráneas; Smith, M., Cross, K., Paden, M., Lavan, P. Eds.; San José, Costa Rica; https://doi.org/10.2305/IUCN.CH.2016.

WANI.8.es. pp: 69-88.

Villa-Camacho AO, Ontiveros-Capurata RE, González-Sánchez A, Ordoñez-Hernández LM. 2021. Análisis de la productividad del agua de riego en el estado de Chihuahua. Actas del VI Congreso Nacional de Riego, Drenaje y Biosistemas, Hermosillo, Sonora, México, del 9 al 11 de junio de 2021. Facultad de Ingeniería Agrohidráulica, Benemérita Universidad Autónoma de Puebla; Instituto Mexicano de Tecnología del Agua. Artículo COMEII-21021.

Zúniga D, Mendoza R. 2021. Importancia estratégica del agua *In:* Gestión y manejo del agua en la agricultura. Instituto Interamericano de Cooperación para la Agricultura (IICA). San José, Costa Rica 2021; pp: 6-10.