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Posted Date: 28 January 2025

doi: 10.20944/preprints202501.2100.v1

Keywords: Efficiency; DEA; Tobit; Determinant; Water management



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Article

Factors Impacting Technical Efficiency in Mexican WUOs: A DEA with a Spatial Component

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Abstract: Urbanization is creating an increasing number of challenges for efficient water management in cities with climate change. The present study investigates the technical efficiency of 49 Water Utility Organizations (WUOs) through a combined Data Envelopment Analysis (DEA) and Tobit Model approach. The DEA assesses the relative efficiency of each WUO based on resource use and cost inputs for volume and population outcomes of drinking water production and distribution. Ultimately, the Tobit Model analyses the effect of location on efficiency. The results show an average efficiency of 0.73 under CRS and 0.82 under VRS, indicating that several WUOs could significantly reduce resource use while maintaining output. While the Tobit analysis does not identify a statistically significant effect of geography on efficiency, regional influences such as population density and resource availability may still impact WUO performance. The contribution of this study will be towards understanding the efficiency of water management in Mexico, identifying areas for improvement and paving the way for future research on the determinants of efficiency in the sector.

Keywords: efficiency; DEA; tobit; determinant; water management

1. Introduction

Urbanization poses challenges in drinking water supply and sewerage management due to higher demand and greater wastewater generation, necessitating an integrated approach to infrastructure and resource optimization. Increasing urban development increases the demand for drinking water, which may go beyond the capacity of existing infrastructure [1]. Furthermore, the concentration of people intensifies the generation of domestic wastewater [2]. This requires much more efficient sewerage systems [3,4]. Efficiency in management becomes crucial to have an adequate and continuous supply [5,6]. Urbanization, on the other hand, has negative implications in terms of aggravating the impact of climate change [7], requiring adaptations [8]. Water management in this scenario will be transversal to include efficiency, sustainability and adaptation to climate change. Therefore, it is necessary to examine how WUOs have decided to use resources for this purpose and whether geography influences their performance.

Efficiency in the water sector is critical to ensuring universal access to drinking water, sustainability of water resources, and user satisfaction; several studies have shown that inefficiency in water management can have adverse effects in terms of economic losses, waste of resources, and deterioration in service quality [9,10]. In this context, DEA has emerged as an important tool to examine the efficiency of water utilities, their ability to identify best practices, and guide performance improvement decisions [11].

DEA faces problems related to data comparability and underlying assumptions regarding production frontiers. Different data quality [12], information availability [13,14] and data collection methods [5] (Molinós-Senante et al., 2010) do not allow for comparisons across firms. Ferro et al. [16] indicate that data comparability is important. The definition of production frontier [17] is also likely

to be affected by external factors [18] and assumptions related to technology [19]. When comparing companies from different geographical locations [20] or companies with different structures [21], the idiosyncrasies of each scenario are paramount. Camanho et al. [22] indicated that the selection of variables is important in performance evaluation. It can even distort the analysis and require some specific models [23] since there could be results that are not useful, such as unaccounted for water [24]. These are key obstacles that need to be addressed to ensure that efficiency analyses remain valid in the water industry.

There is a spatial component included in the DEA, which speaks of all those regional influences on the efficiency of the WUOs. Previous work has shown that population density, water resource availability, socioeconomic conditions and management policies can significantly affect water utilities [25–27]. Spatial analysis allows to model spatial dependence and capture the interactions of WUOs with their geographic environment, thus allowing a more comprehensive view of the factors that cause their efficiency.

This work was carried out with data from 2020 and deals with the efficiency of water management in 49 WUO in Mexico, by applying a methodology through the DEA model with Tobit. DEA evaluates the relative efficiency of these WUOs in obtaining resources (total employment, total costs) for the production and distribution of drinking water (volume produced, population served). The premise is that the geographic location of WUOs in Mexico significantly affects their performance due to differences in socioeconomic conditions, population density, geographic conditions, and access to resources. To demonstrate this, a Tobit model is deployed that analyzes the influence of geographic location on the efficiency estimated by DEA.

The paper is organized in several stages: first, the literature on water sector efficiency, governance, and the use of DEA and Tobit models in this context is reviewed. The methodology employed is described, which combines DEA to assess the technical efficiency of WUOs and a Tobit model to analyze the effect of geographic location. Next, the PIGOO-CONAGUA data and the selected variables (employment, costs, production volume, and population served) are presented. The results of the DEA are shown, accompanied by estimates of average efficiency for WUOs under CRS and VRS, as well as the least and most efficient WUOs identified. Finally, a Tobit analysis is performed to test whether geographic location is a factor in efficiency, after which the discussion of the results is presented, a comparison with previous literature, the limitations of the study, and lines for future research are outlined.

2. Literature Review.

Governance in the water sector is essential for efficiency and public trust. Transparent, accountable, and participatory governance [28,29] is often linked to more efficient resource management, though its impact may vary based on local implementation and political dynamics [30,31], process optimization [32] and continuous service improvement [33]. Control has incorporated transparency into trust generation [1], while public participation [34] legitimizes actions and facilitates adaptive solutions. Pinto et al. [35] and Molinos-Senante et al. [36] have confirmed the importance of governance for efficiency and optimization of services. Public participation enhances public trust, as noted by Walker et al. [37]. Strong governance ensures the efficiency, sustainability and legitimacy of water companies.

Since the 1983 reform, the institutional framework for water in Mexico aimed to decentralize management and grant greater autonomy to WUOs, adopting a client-oriented approach. However, challenges remain in separating service provision from political influence. However, this model failed to sever the ties between the service and politics, maintaining subordination to mayors and governors. Although private participation was encouraged, it prospered mainly in the construction of treatment plants, not in the operation of services, which are mostly maintained in the public sphere with a "low-level equilibrium" [38].

The evaluation of water companies' performance takes into account parameters other than technical and economic efficiency. Service quality, which includes aspects such as continuity of

supply [39], water quality [40] and customer service [41], has a considerable impact on customer satisfaction.

Environmental sustainability also acquires much greater importance and studies that analyse eco-efficiency [25,42], greenhouse gas emissions [43] and water loss management [10,44] have identified it as one of the main indicators.

Several factors influence firm performance, including efficiency, service quality, and financial sustainability. These factors are regulations [12,45], incentives [46,47], ownership structure [48–50], responsiveness [35,51], and governance structure [52,53]. Finally, asset management, including investment planning and infrastructure maintenance, is crucial for future service continuity and quality [54,55].

Performance evaluation and benchmarking are crucial for water utilities to optimize their efficiency and improve customer service. Techniques such as DEA [21,46,56,57] and the Malmquist index [8,24], among others, allow identifying best practices and inefficiencies [57,58]. This process of learning and sharing successful strategies [59,60], which is facilitated by benchmarking and comparison between companies [32,61] or operational units [62], promotes efficiency in the use of resources [63], encourages innovations [15,47] and drives improvements in service quality [46,64]. Studies such as Marques et al. [65], Marques & De Witte [66] and Molinos-Senante et al. [67] attest to these tools for service optimization and improvement. Combined, they result in efficient, transparent and customer-oriented management.

The decision to combine the DEA with a Tobit model in efficiency studies arises from the need to have a broader and more precise view of the subject. The DEA allows the relative efficiency of a set of decision units to be assessed without restrictions on the functional form of the production frontier [68] as it is a non-parametric technique. However, on its own, the DEA does not allow the identification of those factors that explain the differences in efficiency between decision units. This is where the Tobit model complements the analysis. It is a regression model for limited or censored dependent variables, so Tobit allows the impact of various explanatory variables on the efficiency scores obtained in the DEA to be analysed [69]. In the specific case of water efficiency, this means that factors such as regulation, investment in infrastructure, socioeconomic characteristics and climatic conditions that influence the performance of water companies can be identified [70]. DEA-Tobit therefore presents a robust methodology through which efficiency and its determinants can be analysed, thereby leading to a more complete understanding of the phenomenon and more precise recommendations for improving it. This study aims to provide an understanding of the very complex interactions underpinning efficiency and to equip decision-making with such knowledge. It is therefore particularly designed to analyse whether geographical location has a significant influence on the efficiency of WUOs.

There is a debate about the role of geography in the efficiency of water industries. Some studies indicate that companies located in rural areas tend to be inefficient due to population dispersion and extensive distribution networks [23,61], while others argue that rurality alone is not a determining factor, but interacts with variables such as customer density and available infrastructure [46,59]. Ferro et al. [51], Zschille and Walter [71] emphasize that regional factors, including resource availability, socioeconomics and ownership structure, affect efficiency. However, there is no clear link between region and efficiency, according to Peda et al. [72]. This interrelation is complex and requires a multifactorial analysis, according to the particularities of each context [19,73].

Most research on water efficiency in industry has opened some gaps in terms of research on how the interaction between region and demand side management influences performance. Although there have been studies on the effect of population density [46,47,59,61,63] and water availability [61], only few have explored how demand side management strategies such as tariffs [74], public education [34] and saving technologies [6] interact with regional specificities. With this in mind, a study is proposed that combines DEA with a quantitative approach and examines the impact of DEA on various microregions to analyse their strategies. Studies such as Suárez-Varela et al. [75],

Molinos-Senante and Sala-Garrido [76], Ferro et al. [51] and Zschille and Walter [71] have highlighted the need to analyse this interaction between regional factors and demand management.

Studies combining DEA and Tobit models provide a more comprehensive analysis of water use efficiency. While DEA identifies efficient and inefficient units [21,46,56,57], Tobit models analyze which factors lead to inefficiency [21,60]. This combination also allows for the study of relationships such as regulation, ownership, and management. Simar and Wilson [21] applied this approach to the study of efficiency in water services and found ownership and organizational structure to be key. Renzetti and Dupont [60] applied it to the analysis of municipal water agencies and included environmental factors. Together, it is a powerful combination that provides analysis to measure inefficiency and directs the identification of its determinants.

The Tobit model: It is useful for investigating censored or limited dependent variables. It has been used quite successfully along with DEA to identify the different factors affecting water use efficiency. Integration of both techniques can facilitate the measurement of efficiency and an investigation into how regulation, ownership and management influence the level of efficiency across firms. Chakraborty et al., [77] in education and Rangan et al., [78] in the banking sector reveal its usefulness. The Tobit model along with DEA provides a very strong argument for efficiency analysis in the water sector.

3. Methodology

To analyse water efficiency, a two-phase methodological scheme is suggested, first using DEA to obtain efficiency scores for each company [21,56,57], comparing it with best practices [57,58], then detecting potential input reductions [58,60]. The approach is supported by studies such as those by Charnes et al. [56] and Ferreira da Cruz et al. [79]. Second, a Tobit model is used to study the impact of uncontrollable factors on inefficiencies [21,60], such as regulations, population density and water availability. Maddala [80] describes the combination of DEA and Tobit, which provides a deeper understanding of the determinants of efficiency and helps identify gaps in this area and formulate more effective policies.

This is a DEA model in which inputs seek to minimize resources, even to produce a specific quantity of products [17]. In the study of water, this will be the evaluation of how resource inputs such as water, energy and capital can be reduced in companies while maintaining the level of services [63,81]. The efficient frontier is the one that represents those companies that cause production maximization from the lowest input [21,56,57] that also function as a 'reference point'. Inefficient companies will be projected on this frontier to identify possible reductions [58,60] and show how much reduction of resources they would have if they had produced at the same level of efficiency as the best. Studies such as Ferreira da Cruz et al. [79] and Charnes et al. [56] have validated this approach. Therefore, the input-oriented treatment of DEA theory studies would guide water utilities towards optimization, cost reduction and improved sustainability of their operations [64,82].

The choice of an input-oriented DEA model is concerned with assessing the efficiency of public utilities, especially when cost reductions and optimal use of resources must be achieved without affecting the quality of services provided. This model can identify best practices in the management of inputs [17], such as water, energy and capital [63,81], to achieve a certain level of service. Faraia et al. [83] advocate for the same model. In water utilities, efficiency, sustainability [82], cost reduction [63,84] and supply optimization [2](Cetrulo et al., 2019) are crucial. The input-oriented DEA model identifies opportunities for improvement [58,60] with service levels being maintained [85]. Furthermore, by comparing companies [19,32], it encourages learning and the adoption of more efficient strategies [59,60]. Therefore, this model is promising with respect to improving efficiency and sustainability, ensuring optimal use of resources without compromising service.

The DEA of this study to determine efficiency among water companies has considered as inputs EmplTotal (number of employees) [86,87] and CostoTotal (total costs) [28,63], reflecting human and financial resources (See Table 1). As outputs, there are VolProd (production volume) [28,84] and PoblAtend (population served) [31]. It is assumed that a greater number of employees and costs are

related to greater production and attention. However, efficiency is maximizing production with minimum resources [21,56,57]. At this stage, the DEA would only be responsible for identifying efficient and inefficient companies for decision making.

Table 1. A list of input and output variables of the DEA study.

Variable	Definition
Total employees (EmplTotal).	Represents the number of human resources assigned to the production and distribution of drinking water [89]. EmplTotal is used as input.
Total Cost (TotalCost).	The variable TotalCost, which includes all operational costs of a water utility (energy, chemicals, maintenance, administration), is used as an input in the DEA to assess efficiency. The objective is to minimize these costs to achieve a given level of production and service [90].
Total volume of drinking water (VolProd).	It represents the total volume of potable water produced by a company, entering the output in the DEA efficiency assessment. This is further justified because production is maximized with the available resources, meaning that higher production with similar inputs highlights greater efficiency [91].
Population served (PoblAtend)	It represents the total number of people who receive drinking water service, it is an outcome used in the DEA to evaluate the efficiency of the result. It is necessary to maximize the coverage capacity in relation to the available resources: a greater number of people served with the same contribution indicates greater efficiency [92]. Several studies, including PoblAtend, have applied it as an indicator of canned service, social impact and overall capacity of the company on demand.

Source: Prepared by the authors.

In an environment that demands efficiency and transparency in public services, tools such as DEA are essential to assess performance and improve management functions. DEA offers a comparison between several units in terms of their relative efficiency [56,57], presents an objective picture of the company's performance [19,32] and identifies best practices [59,60]. By including multiple inputs and outputs, DEA offers a more comprehensive assessment than traditional methods [58]. Charnes et al. [56] and Carvalho and Marques [5] prove the effectiveness of DEA in assessing efficiency. Furthermore, by considering the particularities of each company [21,60], the DEA promotes equity in comparisons, thus avoiding bias [19,20]. Through the DEA, efficient and transparent management of public services is achieved, promoting continuous improvement.

CRS and VRS models are used in DEA for efficiency evaluation. CRS (Constant Returns to Scale) stands for constant return to scale [56]. VRS (Variable Returns to Scale) indicates that the returns are variable [57]. The selection of requirements is made based on whether the increase in inputs leads to an equivalent increase in outputs or not.

According to Charnes et al. [56], the input-oriented CRS model within data envelopment analysis is recognized as a robust framework for assessing the efficiency of data measurement units. The model minimizes the inputs required to produce a predetermined level of output, which lends itself particularly well to measuring efficiency based on given quantities of resources generated in the outputs. Input reduction especially benefits organizations that focus on optimizing resources and improving their performance in terms of productivity.

Mathematical Model

In this context, we consider n Decision-Making Unit(s) (DMUs), each with m inputs and s outputs. We define:

- x_{ij} : quantity of input i used by DMU j (where i varies from 1 to m and j to 1 to n).
- y_{rj} : quantity of product r produced by DMU j (where r varies from 1 to 1).

The objective is to evaluate the efficiency of a specific DMU, say DMU k . Efficiency is measured by minimizing the total amount of inputs used, given a desired level of output.

The input-oriented CRS model can be expressed as a linear programming problem that seeks to minimize the amount of inputs used by the DMU k , subject to the constraint that at least the output levels of the outputs must be achieved. This is formulated as follows :

$$\begin{aligned} & \text{Minimize } \theta_k = \sum_{i=1}^m v_i x_{ik} \\ & \text{subject to:} \\ & \sum_{i=1}^m v_i x_{ik} \leq \sum_{r=1}^s v_r y_{rj} \quad \forall j = 1, 2, \dots, n \\ & y_{rj} \geq 0 \quad \forall r, j \\ & v_i \geq 0 \quad \forall i \end{aligned}$$

Using the CRS input-DEA model, the efficiency of a DMU is analyzed using the θ_k criterion. The value of θ_k is set equal to 1 so that it is considered efficient by the DMU, that is, with the minimum amount of inputs to produce it. If θ_k were greater than 1, the DMU would be inefficient and could reduce the use of inputs. Additionally, in the model, the relative importance of each input (v_i) is determined to minimize its use in production.

On the other hand, the VRS Model in DEA, according to Banker [57], evaluates efficiency on the basis that the relationship between inputs and products, according to the size of each DMU, varies with the scale of operation. This allows us to observe how the quantity of inputs and their volume influences efficiency itself. The input-oriented VRS model specifies the minimization of inputs given the products obtained, and thus performs a more precise evaluation in reference to DMUs of different scales. The objective function is expressed as:

$$\min \theta = \frac{\sum_{i=1}^m v_i x_{ij}}{\sum_{r=1}^s u_r y_{rj}}$$

where x_{ij} represents the inputs used by DMU j , y_{rj} are the products obtained, v_i are the weights assigned to the inputs and u_r are the weights assigned to the products.

To ensure the validity of the evaluation, constraints are imposed to ensure that the level of inputs used by DMU j is not lower than that of the other DMUs in the set. This can be expressed as follows:

$$\frac{\sum_{i=1}^m v_i x_{ij}}{\sum_{r=1}^s u_r y_{rj}} \geq 1 \quad \forall j \in J$$

where J is the set of all DMUs.

To incorporate the concept of variable returns to scale, an additional restriction is imposed that allows the sum of the weights to be less than or equal to one:

$$\sum_{i=1}^m v_i$$

This restriction allows the efficiency frontier to be properly adjusted to the operating scale of each DMU, given that not all DMUs operate under fully optimized conditions with respect to the their inputs.

After the DEA, the Tobit model in the second stage will include the variable "region" [70] in order to analyze whether the geographic location (microregions¹) has an effect on the efficiency scores of the WUOs, thus completing the DEA and allowing a greater understanding of whether there are regional disparities in performance. Smithson and Merkle [93] explain that the Tobit model is used to analyze censored variables, assuming that the dependent variable follows a normal distribution. It is expressed as:

$$y_i^* = x_i \beta + \varepsilon_i$$

where y_i^* is the latent variable and ε_i is the normally distributed error. Censoring is defined as:

$$y_i = \begin{cases} 0 & \text{Si } y_i^* \leq 0 \\ y_i^* & \text{Si } y_i^* > 0 \end{cases}$$

¹ In Mexico, there are nine regions: Northwest, Northeast, West, East, North Central, South Central, Southwest, Southeast, and Center. However, the selected OOAs, which will be part of the analysis, belong to the Central, West, Northeast, Northwest, and South-Southeast regions. They will focus solely on analyzing those five regions.

The model allows inferences about relationships between variables, estimating parameters using maximum likelihood, being useful for limited data.

Finally, this study was developed with information from the Program of Management Indicators of Operating Agencies (PIGOO) available on the official portal of the Mexican Institute of Water Technology (<http://www.pigoo.gob.mx/>) which depends on the National Water Commission (CONAGUA) for the year 2020. The technical efficiency analysis was carried out using the DEA methodology with the DEAP software version 2.1. In addition, the Tobit model analysis was carried out with RStudio, thus guaranteeing a robust and adequate statistical treatment of the analyzed data.

4. Results

Table 2 shows the results of the descriptive statistics for the WUOs, which reflect a fairly high variability between the variables considered, so the differences in operation and capacities are significant. The variable EmplTotal registers a maximum of 4,684 and a minimum of 127, obtaining a standard deviation of 787.06, indicating a medium dispersion between the numbers of workers among the agencies. The coefficient of variation (CV) of 1.12 (112%) reflects a marked heterogeneity in the labor structure of the agencies, which could be due to differences in size and scope in their operations. On the other hand, the variable Vprod presents an extremely wide range - from a maximum of 8,501,117,672.79 to a minimum of 52,474,136.00 with a standard deviation of 1,306,895,758.27 and a CV of 1.70 (170%). This highlights significant differences in productivity and revenue-generating capacity between agencies.

Table 2. Results of Descriptive Statistics of Input and Output Variables.

	Max	Min	Standard Deviation (SD)	Coefficient of variation (CV)
TotalEmployees (total employees)	4,684.00	127.00	787.06	1.12
CostTotal (total cost)	\$478,689,022.10	\$935,663.00	85,065,234.75	1.28
Vprod (Volume of drinking water production)	8,501,117,672.79	52,474,136.00	1,306,895,758.27	1.70
PobAtend (population served)	4,957,280.00	105,201.00	931,248.79	1.36

Source: Prepared by the authors using data from PIGOO-CONAGUA.

For the variable TotalCost, values range from a maximum of \$478,689,022.10 to a minimum of \$935,663.00, with a standard deviation of \$85,065,234.75 and a CV of 1.28 (128%). This reflects a large dispersion between operating costs, which probably originates from variations in the scale of operation, efficiency, and characteristics of the areas served. Finally, the variable PobAtend has a maximum of 4,957,280 people and a minimum value of 105,201, with an associated standard deviation of 931,248.79 and a CV of 1.36 (136%), showing differences within the population served by each agency, probably due to density and territory factors that influence the amount of population served.

In Table 3, the correlation matrix comprises the correlation coefficients of variables, which analyze the linear relationships between them. First, total employment versus total costs is correlated at a level of 0.95, which represents a highly positive linear relationship. This means that, in general, the increase in the total number of employees is related to higher expenditures incurred on operating costs.

EmplTotal correlates with Vprod at a coefficient of 0.93, again suggesting a strong positive linear correlation. From the above correlations, it can be seen that higher staff strength tends to be associated with higher outputs measured as value, reflecting the value placed on human resources to achieve production capability.

Table 3. Analysis of correlation coefficients of variables.

	EmplTotal	TotalCost	Vprod	PopAtend
EmplTotal	1			
TotalCost	0.95389497	1		
Vprod	0.93444161	0.92170399	1	
PopAtend	0.94560348	0.91203689	0.95531224	1

Source: Prepared by the authors using data from PIGOO-CONAGUA.

On the other hand, EmplTotal and PobAtend represent a correlation of 0.95, so this indicates a very substantial and strong positive linear correlation. This indicates that cities or entities with a larger number of employees tend to serve larger populations, which is indicative of a possible larger operational scale as well.

For example, the correlation between CostTotal and Vprod is 0.92, indicating a strong association. However, this does not establish causality between the variables. This would mean that if total costs were to increase, the value of output would follow suit, probably due to the cost factor of the inputs and materials that the stakeholders have to produce.

CostTotal and PobAtend have a correlation of 0.91, indicating a strong positive linear relationship, but not as strong as some other combinations. This suggests that costs have generally increased with a population being served, but the relationship is not as close as in other cases. Between Vprod and PobAtend, the correlation is 0.96, the highest.

In Figure 1, the DEA shows an average efficiency of 0.73 under CRS and 0.82 under VRS. This means that, on average, cities could reduce their inputs by 27% (under CRS) or 18% (under VRS) without affecting their level of output.

The cities with the lowest efficiencies (Huixquilucan, Zihuatanejo, Naucalpan, Zacatecas and Matamoros) exhibit substantial potential for improvement. Conversely, 7 cities are efficient under CRS and 18 under VRS, making them exemplary cases.

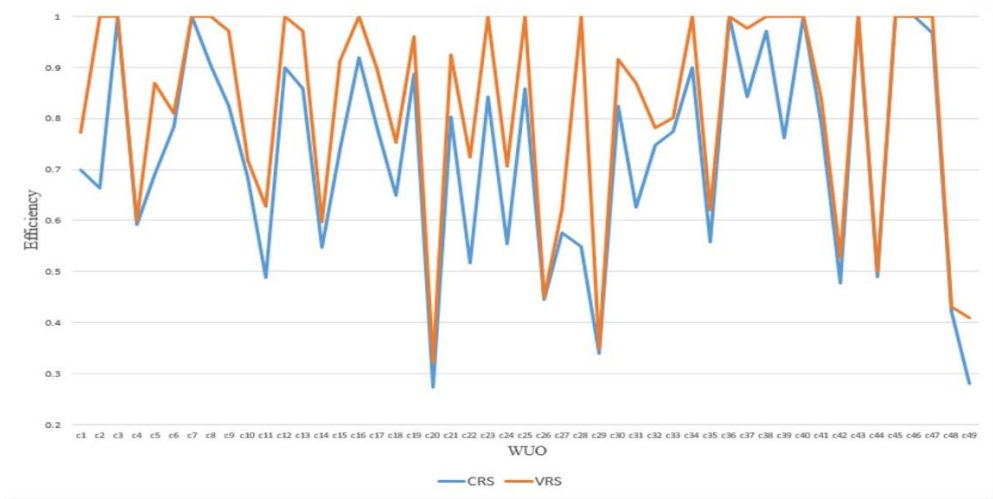


Figure 1. Relative efficiency by DEA of the WUO in 2020. Source: Prepared by the authors using data from PIGOO-CONAGUA.

Optimizing resource management primarily requires cities, especially those lagging behind in efficiency, to measure inefficiency in various areas, learn from and adopt best practices, optimize their resource allocations, reduce waste, improve technology and staff training.

In order to better understand the differences in terms of efficiency, it would be possible to complement the DEA with a Tobit model, because the DEA alone does not consider external factors that may influence the efficiency of the WUOs, adding the geographical location as an independent variable. This will then allow taking into account the external factors that determine efficiency and also understanding regional differences, thus improving the accuracy of the analysis and, consequently, the decisions that are taken.

A first Tobit analysis was performed on the efficiency data from the DEA-CRS analysis in 49 WUOs and “microregions” was used to denote geography. The results suggest that this variable has no statistically significant effect on efficiency (p-value = .814). This means that geography, as interpreted here, does not account for the differences in efficiency. The constant coefficients of the model, 0.731 and -1.466, are statistically significant (p-value < 2e-16), and no reliability problems in the estimates, such as the Hauck-Donner effect, were detected.

Despite these observations, the model has very low explanatory power with an R² of only 0.003 and a correlation of 0.055 between the fitted and observed values. "Microregions" are not a significant factor in explaining service delivery efficiency in the cities studied; greater explanatory power could come from the inclusion of additional variables.

A second Tobit analysis was performed with the efficiency data from the DEA-VRS analysis in 49 WUOs and the variable microregions was used to denote geography. This analysis reveals that this variable has no statistically significant influence on efficiency (p-value = 0.794). In other words, according to the requested representation, the region does not explain the differences in efficiency between the cities considered.

Among the key results of the model, the coefficients for the constant “(Intercept):1” are at 0.871 and for “(Intercept):2” -1.215; both are highly significant with a p-value < 2e-16. The log-likelihood of the model is -21.2935 with 95 degrees of freedom and no Hauck-Donner effect was found, supporting the reliability of the estimates. The explanatory capacity of the model, however, is small, as evidenced by the low coefficient of determination (R²=0.002) and only a correlation of 0.045 between the fitted and observed values under the Variable Return on Scale (VRS) model. In other words, the analysis suggests that “Microregions” are not a significant factor in terms of efficiency in public service provision in the cities focused on.

Comparison of the Tobit model results using DEA-CRS and DEA-VRS efficiencies shows that in both cases microregions were found to have no statistically significant effect on efficiency. However,

the correlation between modeled and observed values is slightly higher in the case of CRS (0.055) than in the case of VRS (0.045), while the R^2 of the model remains very low in both approaches (0.003 for CRS and 0.002 for VRS). These measurements reinforce the idea: regardless of the returns to scale assumption, the Tobit model has limited explanatory power and geographic location, represented by the microregions variable, does not seem to be a critical determinant of WUO efficiency.

5. Discussion

This DEA-Tobit analysis assessed the water management efficiency of 49 Mexican water utilities, analyzing employment, costs, production volume, and population served at the water utility level. The DEA results indicated average efficiencies of 0.73 (CRS) and 0.82 (VRS), which were consistent with previous studies but still show potential for improvement. Aguascalientes, Celaya, and Saltillo were identified as efficient water utilities, while Huixquilucan, Zihuatanejo, and Naucalpan were identified as having potential optimization possibilities, among others.

According to Tobit analysis, geographic location does not affect efficiency. We take this opportunity to acknowledge the relevance of applying regional factors such as resource availability, socioeconomics and climatic conditions; these factors could have an effect on the efficiency of WUOs.

Some limitations of the study, such as the selection of variables and the possible omission of other important factors such as water quality, customer satisfaction and demand management, deserve to be pointed out. Although digitalisation and new technologies are changing the way water is managed, the existing literature largely fails to address their effect on the efficiency of water utilities. This calls for research into how the adoption of information and communication technologies (ICT), remote sensing, data analytics and other technologies can lead to more efficient management of water resources, with cost reduction and improved service delivery.

The literature on water efficiency has mainly focused on factors such as regulation, ownership, operations management, and environmental variables. However, climate change and increasing uncertainty about the availability of water resources pose new challenges in water management [94]. There is a need to investigate how uncertainty and climate change affect the efficiency of WSOs and the means by which water utilities can adapt to these challenges to ensure sustainability.

While the result is valid, it would be worth investigating the possible reasons for this lack of significance. The lack of significance of "microregions" in the Tobit model, which indicates that geographic location does not affect the efficiency of WUOs, may be the result of several factors. First, efficiency may be more closely related to management, investment, water quality, and consumer satisfaction than to region [39,95]. Second, The variable 'microregions' used in this analysis represents broad geographic categories. Its lack of granularity may obscure finer regional differences such as socioeconomic conditions or infrastructure levels [26,95]. Third, heterogeneity between micromicroregions can blur the regional effect [9,27].

The article therefore contributes to understanding the efficiency of water management in Mexico, showing the need to optimize resources and take into account contextual factors. Future research should examine the determinants of efficiency in the sector to contribute to improving the management of this vital resource.

6. Conclusions

The DEA assessed the water management efficiency of 49 water utility organizations in Mexico, showing significant potential for improvement. Cities such as Aguascalientes, Celaya and Saltillo were identified as performing efficiently, but could be examples of best practices for those with greater room for improvement, such as Huixquilucan, Zihuatanejo and Naucalpan.

The Tobit model did not show a significant effect of geographic location on efficiency; however, this research provided an avenue for further studies that delved deeper into regional-specific factors such as water availability, population density, and climatic conditions on WUO performance.

It is very important to highlight the importance of this type of studies in decision-making in the water sector in Mexico. A clear identification of the areas where there are inefficiencies and the factors that affect performance could help WUO to optimize resource management, improve service quality and contribute to environmental sustainability.

Future studies should include additional variables such as water quality, customer satisfaction, and demand management to gain a more complete understanding of water management efficiency; further exploration of the application of complementary techniques such as stochastic frontier analysis for more robust analysis is also recommended.

In fact, this study advances the understanding of the efficiency of the water sector in Mexico and contributes to laying the foundations for future research aimed at improving this key service.

Author Contributions: G.N.L.: Writing—original draft, Methodology; Conceptualization, Administration; J.A.S.R.: Writing—review and editing; R.C.L.B.: Writing—original draft, Methodology; L.A.C.R.: Conceptualization and Methodology. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare that they do not have any conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WUOs	Water Utility Organizations
DEA	Data Envelopment Analysis
CRS	Constant Returns to Scale
VRS	Variable Returns to Scale
DMUs	Decision-Making Unit(s)
CV	Coefficient of variation
SD	Standard Deviation
PoblAtend	Population served
EmplTotal	Number of employees
CostoTotal	Total costs
VolProd	Total volume of drinking water
PIGOO	Program of Management Indicators of Operating Agencies
CONAGUA	National Water Commission

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