Assessing Public Water Management Efficiency in North-western Mexico with a Two-stage Bootstrap Data Envelopment Analysis Model

DOI: 10.12776/qip.v28i2.2037

Martin Flegl, David Güemes-Castorena, Marien Morán-Valencia,
Aldo I. Ramírez

Received: 2024-06-03 Accepted: 2024-07-17 Published: 2024-07-31

ABSTRACT

Purpose: Mexico faces severe water availability problems, resulting in higher stress on its distribution in many states. To resolve the increasing water demand, it is essential to evaluate public water management to ensure the success of any decision-making policies to decrease the water pressure in the country.

Methodology/Approach: For water management systems, benchmarking their performance relative to others can be an appropriate way to identify possible improvements. Using data from the National Census for drinking water and sanitation in 109 municipalities in the northwest region of Mexico, this analysis aims to evaluate the water management efficiency based on a two-stage Bootstrap Data Envelopment Analysis model with intermediate variables.

Findings: The study found average efficiency in water system management but very low efficiency in system improvements. Additionally, no relationship was identified between the two stages or population size and density.

Research Limitation/Implication: The study highlights the need for transparent water policies to address the country's shortage. It is important to adjust municipal public water system management operations and design future strategic planning.

Originality/Value of paper: The presented analysis investigates a relationship between water management and water system improvements.

Category: Research paper

Keywords: bootstrap; data envelopment analysis; drought; water stress; water system improvement

Research Areas: Strategic Quality Management

1 INTRODUCTION

Effective governance for sustainable and integrated management of water resources is necessary to overcome water supply problems. As Tourinho et al. (2022) point out, regulatory authorities play a crucial role in the governance of water resources by supervising providers and ensuring services' sustainability to enhance sectors' efficiency. Efficiency in water resource management aims to increase water availability by reducing misuse and wastage. Efficient water resource management requires an integrated approach, adjusting both demand and supply (GWP, 2017). However, as Lopez Porras, Stringer and Quinn (2019) pointed out, water governance in Mexico is inefficient due to the lack of transparency in water policies, such as the granting of permits, the lack of registration of water rights and the informal water market, among others. This problem has a foundation in limited regulatory capacities, limited fiscal efficiency, and high resistance to change in resource allocation (WWAP, 2017).

1.1 Mexico's Hydrological Characteristics

From the hydrological perspective, Mexico has three large regions: one moderately dry to very dry located in the North, where mean annual precipitation ranges between 159 to 851 millimetres with an average of 495 mm; a second region in the south-southeast, with much higher precipitation with an average of 2,001 mm. The third region, mainly in central Mexico, lies in the middle of those precipitation values. These regions' disproportions and the different climates cause different demands on water resource management.

The country's water management institution is the National Water Commission (CONAGUA for its Spanish acronym); CONAGUA executes its operations through 13 Hydrological-administrative regions (HARs), which are groups of basins for the management of water resources across the country. At the national level, Mexico experiences a stress level of 19.7% (Conagua, 2022a), which is considered low[1]. However, the country's central, northern, and north-western areas experience high stress. For example, the state of Sonora, in the northwest region, was the most affected by Mexico as it experienced extreme droughts from November 2020 to July 2021 (Conagua, 2022b). In July 2022, the state of Nuevo Leon declared a water shortage in the northern part due to the extreme drought for several months. Moreover, the federal government called for modifying or reducing the existing federal water concessions to private companies in favour of public use (Reuters, 2022).

Considering the high-water stress in the North of Mexico, this study focuses on the Northwest region of Mexico (Figure 2) that consists of the Baja California

---

[1] The water stress index (or pressure grade) is given as a percentage of the water volume already assigned for all consumptive uses compared to the mean renewable water volume. If such a percentage is higher than 40, water stress is classified as high and is considered low if the index is below 20%.

peninsula with Baja California and Baja California Sur states (HAR I), Sonora in the Gulf of California (HAR II), and part of the Pacific coast with Nayarit and Sinaloa (HAR III). Although there are certain water resources in the region (surface basins and more than 170 aquifers), all three hydrological-administrative regions report a high grade of pressure (HAR I 89.9%, HAR II 85.0%, and HAR III 40.5%). More in detail, 19% of the aquifers in the region registered high pressure, with an average recharge of 2,686.3 hm^3. Among the volumes granted for consumptive uses, the state with the highest amount was Sinaloa, with 9,570.1 hm^3, and the one with the least was Baja California Sur, with 425.9 hm^3 (Conagua, 2019). Furthermore, as Figure 1 shows, the region suffers severe and extreme droughts during summer. That is why expanding and strengthening the capacities to establish clear and effective water management policies is crucial.

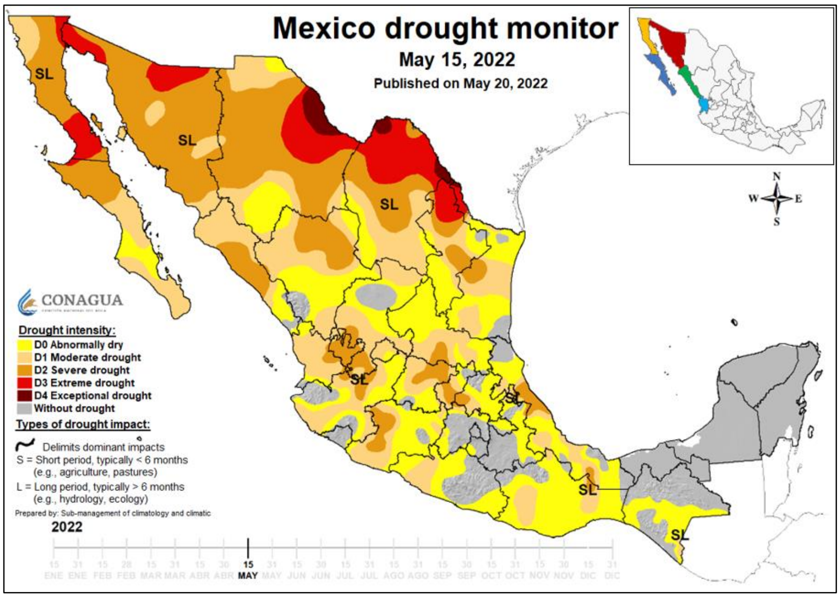


Figure 1 – Drought conditions in Mexico, May 2022 (SMN, 2022)

1.2 Water system management analysis

Data Envelopment Analysis (DEA) is a non-parametric approach widely used for investigating the efficiency and productivity of operational processes. The DEA approach has successfully been applied to various sectors, such as environmental performance (Avilés-Sacoto et al., 2021), education (Hančlová and Chytilová, 2023), assessment of innovation districts (Alarcón-Martínez, Güemes-Castorena and Flegl, 2023), health (Dénes et al., 2017), urban public transportation (Fitzová and Matulová, 2020), among others.

DEA has also been widely used to investigate water management efficiency with diverse objectives. For example, Barbosa, de Lima and Brusca (2016) investigated the relationship between governance structure and water efficiency of 41 Brazilian utilities between 2005 and 2013; Pan et al. (2020) used a super-efficiency Malmquist productivity index to analyse water use efficiency of 17 cities in Shandong province in China; Tourinho et al. (2022) performed a DEA model to investigate water supply and sanitation services performance of 448 Brazilian municipalities and measured the impact of different government models on the water management efficiency, and Yang et al. (2021) applied a DEA model to analyse efficiency of regional industrial water systems in China.

Considering a Mexican context, Ablanedo-Rosas et al. (2020) investigated the operational efficiency of 36 major organisations responsible for supplying potable water in the country. The authors stressed the necessity of increasing wastewater treatment in the country, as only 50% of analysed water organisations perform some type of wastewater treatment. Salazar-Adams (2021) studied a link between the degree of drought hazard (as an indicator of water availability in a region) and the water management efficiency of 359 Mexican water utilities to value the effect of management and reform policies. Morán-Valencia, Flegl and Güemes-Castorena (2023) investigated public water system management performance in 32 Mexican states to design plans for better water usage.

The Bootstrap-DEA approach can be used to check the robustness of the efficiency assessments. DEA estimates the efficiency scores based on a finite sample of observations, which cannot provide any information about the possible uncertainty of these estimated scores. However, the Bootstrap-DEA approach helps to measure the sensitivity of efficiency scores in the DEA models to correct the bias in the estimated scores (Lombardi et al., 2019). In this case, the bootstrap can improve the accuracy of the analysis (i.e., validate the obtained results) by many simulated samples, constructing confidence intervals (Ngo and Hong Tsui, 2021). Considering the benefits of the bootstrapping technique, this approach has been widely used to investigate water management efficiencies: Güngör-Demirci, Lee and Keck (2017) used double Bootstrap method to measure water utility performance in 22 California water districts in the United States; Pan, Hong and Kong (2020) used the Bootstrap-DEA to evaluate the urban wastewater treatment efficiency of 113 cities in China; Walker et al. (2019) applied a double-bootstrap Data Envelopment Analysis method to compare economic and environmental efficiencies for a sample of 13 water and sewage companies. Considering the alarming water situation in Mexico, especially in the northern states, and the necessity of water system improvements, the presented analysis aims to investigate public water system management efficiency in the Northwest region of Mexico. The analysis seeks answers to the following research questions:

R1: What is the level of water system management efficiency in the region?

R2: What is the level of water system improvement efficiency in the region?

R3: Can a relationship between water management and system improvement efficiencies be identified?

2 MATERIALS AND METHODS

2.1 Data Envelopment Analysis

Data Envelopment Analysis is a non-parametric data-oriented approach for evaluating the efficiency and/or performance of a set of homogeneous decision-making units (DMUs) according to their capability to transform different inputs to different outputs (Cooper, Seiford and Zhu, 2011). The basic DEA models consider a single-stage process. However, if a more complex production process is required, multi-stage models are used. Considering the description of the two-stage process proposed by Kao and Hwang (2008), each $DMU_j, (j = 1,2, \dots, n)$ has m inputs $x_{ij}, (i = 1,2, \dots, m)$ used in Stage 1 of the analysed process, and D outputs $z_{dj} (d = 1,2, \dots, D)$ from that stage. These D outputs are used as the inputs in Stage 2 and are commonly reported as intermediate measures. The outputs from Stage 2 are $y_{rj}, (r = 1,2, \dots, s)$. This process considers that the intermediates measures are the unique inputs in Stage 2.

2.2 Bootstrap-DEA method

Simar and Wilson introduced the Bootstrap-DEA (B-DEA) approach (1998). The B-DEA allows analysis of the sensitivity of obtained efficiency scores, which results from the distribution of (in)efficiency in the evaluated sample. As Assaf and Matawiee (2010) mentioned, bootstrap uses a random selection of thousands of pseudo samples from the observed sample data. This procedure creates multiple estimates, which can then be used for statistical purposes (Ngo and Hong Tsui, 2021).

The Bootstrap procedure can be summarised as follows (Tziogkidis, 2012):

a) Calculate the initial efficiency scores for all DMUs using the traditional Data Envelopment Analysis.
b) Draw with replacement from the empirical distribution of the obtained efficiency scores.
c) Divide the original efficient input levels by the pseudo-efficiency scores drawn from the empirical distribution to obtain a bootstrap set of pseudo-inputs.
d) Apply Data Envelopment Analysis using the new set of pseudo-inputs and the same set of outputs and calculate the bootstrapped efficiency scores.
e) Steps a) – d) are repeated B times to obtain a group of efficiency scores for statistical inference.

In this analysis, the B value was set to 2,000 to secure the accuracy of the sampling (Hall, 1986). Further details about the Bootstrap-DEA can be found in Cooper, Seiford and Zhu (2011).

2.3 Data and model structure

The analysis covers 109 municipalities from the Baja California peninsula and the Pacific coast in the Northwest region of Mexico, representing 90.83% of all municipalities. Due to missing data, 11 municipalities were eliminated from the analysis. The analysis includes five municipalities from Baja California (in yellow), five municipalities from Baja California Sur (in blue), 20 municipalities in Nayarit (in cyan), 18 municipalities in Sinaloa (in green), and 61 municipalities from Sonora (in red), illustrated in Figure 2. The region represents 10.47% of the national GDP (INEGI, 2021) and 11,774,706 people (9.34% of Mexico). The municipalities are considered homogeneous since they all have specific offices devoted to installing, maintaining, and operating infrastructure to provide water services under the same standards, they use the same technology, they work under the same governmental structure, and the clime conditions in which they offer the service is highly comparable. So, the basic assumptions for homogeneity are well satisfied (Dyson et al., 2001).

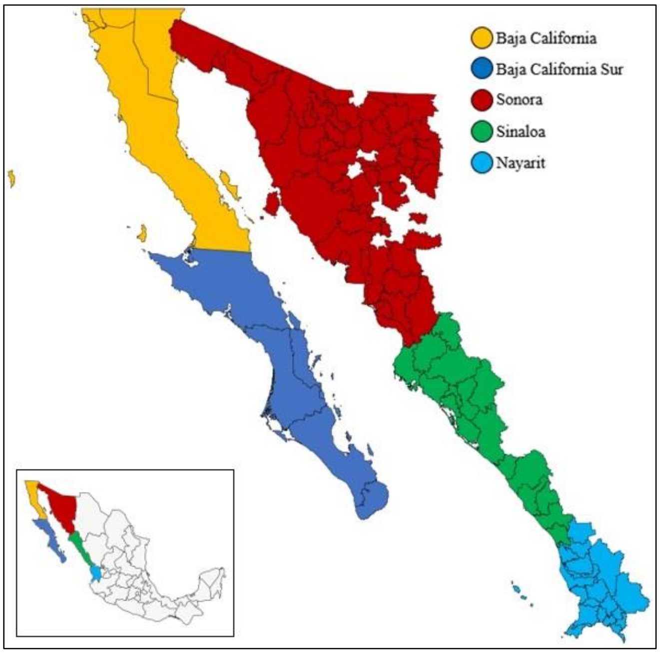


Figure 2 – Baja California peninsula and Pacific coast municipalities

The analysis uses data related to the public administration of each municipality concerning drinking water and sanitation functions for the years 2017, 2018, and 2019 (INEGI, 2020). The evaluation process is divided into two stages:

Stage 1: evaluates each DMU's water system management efficiency, whereas

Stage 2: investigates their water system improvement efficiency (Figure 3).

In Stage 1, the inputs are Total expenditures (TE) of the services consumed in the provision of drinking water and sanitation service and Total personnel (TP) employed by the public network water service. The outputs of Stage 1 refer to Water supplied volume (WSV), which represents the water supplied volume in m^3

of household, industrial, commercial, public, and mixed water intakes, and Total revenues (TR), which consists of the income from the supply of drinking water and sanitation services. Both outputs serve as the intermediates in the model.

Three outputs were considered in Stage 2 of the DEA model to evaluate the efficiency of the water system improvements. The first input describes water distribution network's extension and rehabilitation (in kilometres) (WNE); the second output captures the extension and rehabilitation of the pluvial drainage network (in kilometres) (PDNE); and the last output describes the newly installed water treatment capacity in drinking water plants in each municipality (IEC).

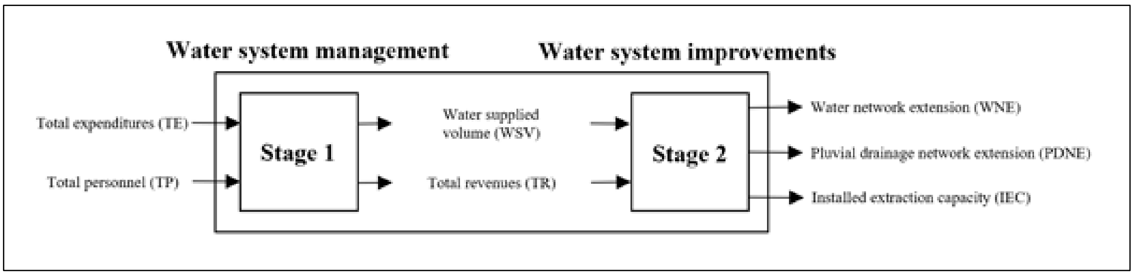


Figure 3 – Input and output structure of the two-stage DEA model

The water system's size regarding access to safe drinking water and sanitisation plays an essential role in efficiency evaluations (Molinos-Senante, Porcher and Maziotis, 2018; Tourinho et al., 2022; Walker et al., 2019). Moreover, population density positively correlates with water system efficiency (Güngör-Demirci, Lee and Keck, 2017). Therefore, data in the model were recalculated regarding the population density in each municipality. Table 2 shows the descriptive statistics of the used variables. For all the calculations, the MaxDEA 7 Ultra software was used. The model uses the output-oriented constant returns to scale model.

Table 2 – Descriptive statistics of the inputs and outputs

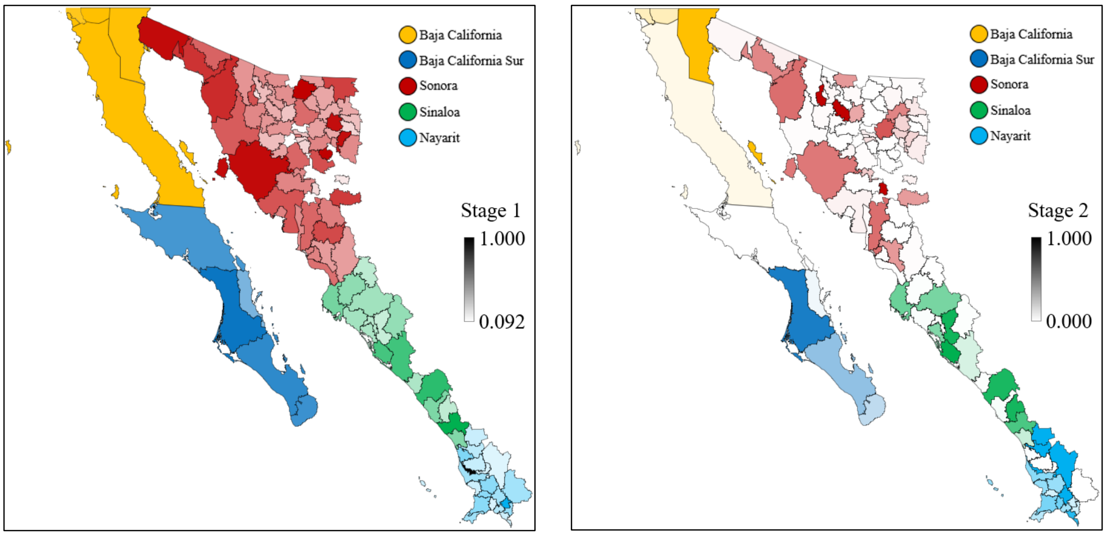
		Units	**Max**	**Min**	**Mean**	**Standard deviation**
Water system management stage						
Input (*x*)	Total expenditures	Mexican pesos	69,369,639.99	3,605.76	3,047,899.29	8,108,567.94
	Total personnel	Persons	88.64	0.31	6.18	12.14
Intermediates (*z*)	Water supplied volume	m^3	48,272,644.87	0.00	1,354,039.26	6,370,301.46
	Total revenues	Mexican pesos	74,621,609.05	9,055.90	2,759,625.02	8,059,477.82

Water system improvement stage		Units	Max	Min	Mean	Standard deviation
Output (y)	Water network extension	km	1,467.36	0.00	24.42	141.19
	Pluvial drainage network extension	km	14.55	0.00	0.38	1.87
	Installed extraction capacity	Liters per second	122.89	0.00	8.14	19.76

3 RESULTS

3.1 Water system management efficiency

The average efficiency of the water system management in the region was 0.500, with a standard deviation (SD) of 0.259 (R1). Out of the total, eight municipalities (representing 7.34% of the region) reached an efficiency of 1.000. Significant differences between the states in the region can be observed (Figure 4a). More in detail, very high efficiency was reported in the Baja California peninsula, where Baja California reported an average efficiency of 0.974 (SD 0.048) and Baja California Sur had an average efficiency of 0.756 (SD 0.159). The efficiency scores of both states are significantly higher ($p < 0.001$) compared to the rest of the analysed region. On the Pacific coast, Sinaloa obtained an average efficiency of 0.487 (SD 0.225) and Sonora 0.491 (SD 0.232). In contrast, the region's worst efficiency in water system management was in Nayarit at 0.357 (SD 0.248). However, considering the confidence intervals for the efficiency (Figure 5a), we can see overlap to some degree in the case of Sinaloa, Sonora, and Nayarit. Thus, their water system management operation is not statistically significant ($p < 0.001$) in terms of technical efficiency.

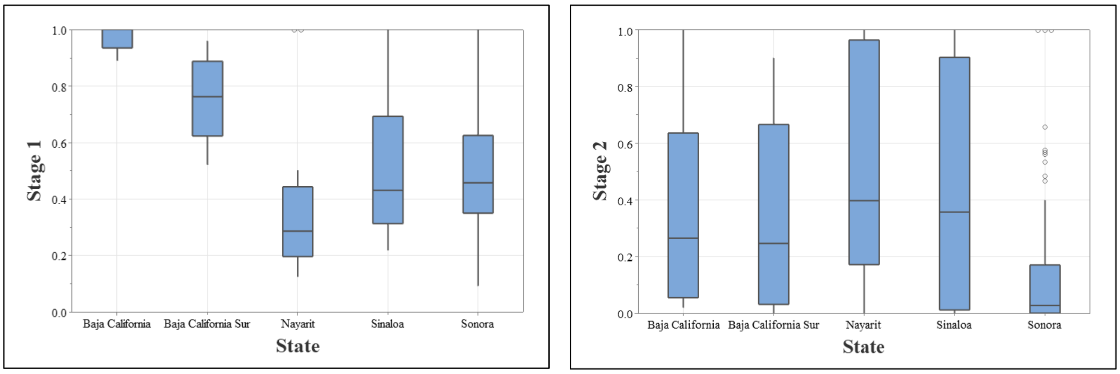


a) b)

Figure 4 – Stage 1 and Stage 2 efficiencies (the darker the colour, the closer to 1; the lighter the colour, the closer to 0).

3.2 Water system improvement efficiency

In Stage 2, the region's water system improvements' average efficiency was 0.276 with an SD of 0.346 (R2). So, a significant drop in the overall efficiency compared to Stage 1 can be identified, indicating a lower orientation to the water system improvements in the region. In this case, as shown in Figure 4b, many municipalities achieved zero or were very close to zero efficiencies. The highest efficiency is reported in Nayarit (0.468, SD 0.381) and Sinaloa (0.419, SD 0.407), both states with statistically higher efficiency compared to Sonora ($p < 0.001$ and $p = 0.004$, respectively). In both cases, the confidence interval is considerably wide (see Figure 5b). In the Baja California Peninsula, the efficiency in both states is nearly the same, as Baja California reached an efficiency of 0.329 (SD 0.390) and Baja California Sur 0.328 (SD 0.362). The lowest efficiency is observed in Sonora (0.162, SD 0.267). Finally, 11 municipalities (10.09%) obtained 1.000 efficiencies of the water system improvements in the whole region.



a) b)

Figure 5 – Boxplot distribution of a) Stage 1 efficiency and b) Stage 2 efficiency by state.

3.3 Analysis of the results

Figure 6 presents the relationship between the municipalities' Stage 1 and Stage 2 efficiencies. The analysis revealed no relationship between the water system management efficiency and the efficiency in the water system improvements (R3), as the correlation is only 0.04 and not statistically significant ($p = 0.677$). Further, to verify whether a low efficiency of the water system management leads to a higher improvement of the water system network, the relationship between Stage 1 and Stage 2 can be classified into four quadrants (Q), as shown in Figure 6.

In this case, Q1 symbolises the best-performing municipalities in water system management operations. Out of the 109 municipalities included in the analysis, only 12 municipalities (11.01%) are in this quadrant. The best-performed municipalities are Tuxpan in Nayarit, with 1.000 efficiencies in both stages, Mexicali in Baja California (0.979 efficiencies in Stage 1 and 1.000 in Stage 2), and Comodú in Baja California Sur (0.960 and 0.901 respectively). The Q2 includes municipalities with low efficiency in water system management but a high orientation to water system improvements. Out of 14 municipalities (12.84%) belonging to this quadrant, five reached 1.000 efficiencies in the 2nd stage: Acaponeta, Huajcori, Del Nayar, and Santa María del Oro in Nayarit, San Javier, and Santa Ana in Sonora.

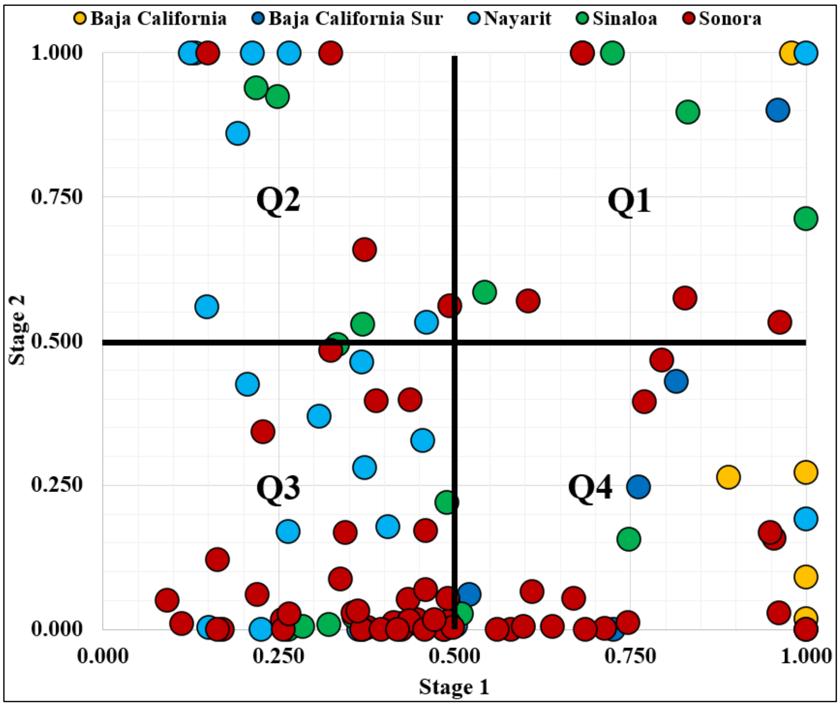


Figure 6 – Relationship between Stage 1 and Stage 2 municipality's efficiencies.

The Q3 represents municipalities with low efficiency in both stages of the analysis. Fifty-five municipalities (50.46% of the region) are in this quadrant, explaining the low overall average efficiencies in Stages 1 and 2. Moreover, 70.91% of the municipalities in Q3 reported that the efficiency of the water system improvement was below 15%, and out of 55 municipalities, 54.55% of the municipalities were in Sonora. The worst-evaluated municipalities are Arivechi in Sonora (0.092 and 0.052), Atil in Sonora (0.112, 0.011), and Ruíz in Nayarit (0.150 and 0.004). Finally, Q4 constitutes municipalities with high efficiency in the water system management (Stage 1), but low efficiency in the improvements of the water system management (Stage 2). Twenty-eight municipalities (25.69% of the total) are in this quadrant, and 57.14% of the municipalities are in Sonora.

4 DISCUSSION

The presented analysis was designed to evaluate the Mexican water system's efficiency and identify whether a relationship exists between water management efficiency and water network improvements. The two-stage Bootstrap DEA model found significant differences between the states of the northwest region. In general, the average efficiency of the water system management operations is 0.500, and 0.276, regarding the efficiency of the water system improvements. The obtained results correspond with the recommendations presented by Ablanedo-Rosas et al. (2020), who urged for water distribution network improvements. The results revealed that most of the municipalities do not target their effort to the network improvements, as 52.29% of the municipalities recorded water system improvements efficiency lower than 10%, and 62.39% of the municipalities with an efficiency lower than 25%.

Providing safe drinking water is one of the most pressing challenges that Mexico must overcome to meet the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015 (Alarcón-Herrera et al., 2020). He et al. (2021) mention that potential solutions for urban water scarcity involve increasing water availability and reducing water demand. In this case, the techniques for water utilisation and the existing water structures must be improved Sun et al. (2017).

Such improvements are especially crucial in the dry or moderately dry locations in the North of Mexico, where the water stress level is very high. However, the analysis does not indicate a high orientation towards better water supply and system improvements. Moreover, connecting drought conditions in the region (Figure 1) with the efficiency of water system improvements (Figure 4b), we can see alarmingly very low efficiency in the areas of extreme drought in Sonora. In this instance, this result can be associated with the geographic situation of the foothills of the Sierra Madre Occidental, resulting in higher rurality. Walker et al. (2019) observed inefficiencies across water companies in rural areas due to smaller treatment plants. In this context, the inefficiencies can be linked to lower infrastructure, maintenance, and energy costs (Libralato, Volpi Ghirardini and Avezzù, 2012; Salazar-Adams, 2021), i.e., the economies of scale.

Figure 7 shows the relationship between the water system efficiency and population density in each municipality to investigate this effect. In this case, the correlation is 0.180 ($p < 0.062$) in Stage 1 and 0.012 ($p = 0.904$) in Stage 2 (if a population size is considered, $r = 0.356$, $p < 0.001$ in Stage 1 and $r = 0.113$, $p = 0.244$ in Stage 2). As a result, the economies of scale effect is observed to only an extent in the northwest region. This observation is congruent with Silva Pinto, Simões and Cunha Marques (2017), who observed that water resource efficiency increases with a higher number of customers served and bigger customer density, but only to a certain level. Similarly, Salazar-Adams (2021) observed a significant positive correlation between population density and water management efficiency in Mexico. Contrary to this, our analysis does not indicate a significant correlation, and the effect of the population density is very low.

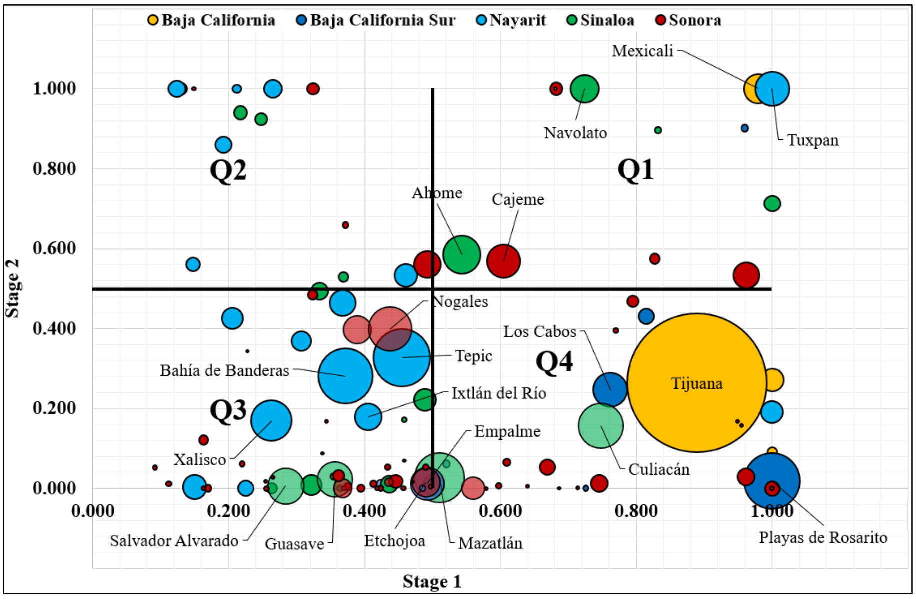


Figure 7 – Relationship between Stage 1 and Stage 2 municipality's efficiency and population density (the bubble size is proportional to the population density in each municipality)

Drinking water supply to urban areas, but especially rural areas, is a highly challenging topic. Both the efficiency of the water system management and the efficiency of the improvements of the water system management depend on several external conditions. For example, available water is related to local or regional climate conditions and meteorological events, such as the significant drought during the first semester of 2022. Limited water availability can limit the amount of water that can be entered into the water system (no matter if the economic side poses no condition).

Economic conditions are also present in the amount of work that can be done to increase the extension of the water systems and in the actions for improvements. Furthermore, not all those conditions depend on the same entity. Some expenses must be done at the municipal level (such as the distribution network extension), while others must be made with contributions from the federal government. Therefore, proactive management of natural resources to sustain dryland livelihoods must be adopted (Lopez Porras, Stringer and Quinn, 2019). Municipalities should emphasise strategic planning and risk management in water management. These actions should lead to the creation of new policies to decrease the water pressure in the region and the country. Considering the obtained results, the intention must lead to more municipalities being located in Q2 or, in the best-case scenario, Q1.

Such actions must be accompanied by strategies for improving the operational efficiency of each municipality. The water management administration should incorporate new measurement processes within the distribution network, assess possible costs and staff reductions, and involve employees' training, among others. As Salazar-Adams (2021) mentions, these actions will allow for increased coverage and continuity in the provided service, increase revenues and, consequently, intensify the level of investments in water infrastructure.

5 CONCLUSION

This article provides a municipal-level analysis to assess the public water management system in the northwest region of Mexico. Considering the high water stress in the North of Mexico, a two-stage Bootstrap DEA model was constructed to investigate the technical efficiency and improvement of the water system management. The results exposed significant space for improvements in the public water management area. More specifically, the water management efficiency can be improved by 50%, whereas the system improvement efficiency can be elevated by 72.4%. Putting this into a context within the region, only 11.01% of the analysed municipalities are in the best performing Q1, and 12.84% of municipalities belong to Q2, i.e., municipalities with low efficiency in water system management but a high orientation to water system improvements.

Therefore, proactive management of the public water system is needed. The evidence presented in the article creates an opportunity for each municipality to understand its performance, which can help policymakers to adjust their operations in public water system management and design future strategic planning. Nevertheless, caution should be taken when directly translating DEA efficiency scores into policy recommendations. The performed analysis captures only one period, during which abnormal conditions can be biased. Therefore, future research must extend the analysis by incorporating more analysed periods to capture the precise efficiency levels in the region.

REFERENCES

Alarcón-Herrera, M.T., Martin-Alarcon, D.A., Gutiérrez, M., Reynoso-Cuevas, L., Martín-Domínguez, A., Olmos-Márquez, M.A. and Bundschuh, J. 2020. Co-occurrence, possible origin, and health-risk assessment of arsenic and fluoride in drinking water sources in Mexico: Geographical data visualisation. *Science The Total Environment*, 698, 134168. https://doi.org/10.1016/j.scitotenv.2019.134168.

Alarcón-Martínez, J.E., Güemes-Castorena, D. and Flegl, M. 2023. Comparative Analysis of Innovation Districts to Set Up Performance Goals for Tec Innovation District. *Quality Innovation Prosperity*, 27(2), pp. 158-176. https://doi.org/10.12776/qip.v27i2.1873.

Ablanedo-Rosas, J.H., Guerrero Campanur, A., Olivares-Benitez, E., Sánchez-García, J.Y. and Nuñez-Ríos, J.E. 2020. Operational Efficiency of Mexican Water Utilities: Results of a Double-Bootstrap Data Envelopment Analysis, *Water*, 12(2), 553. https://doi.org/10.3390/w12020553.

Assaf, A. and Matawie, K.M. 2010. Improving the accuracy of DEA efficiency analysis: a bootstrap application to the health care foodservice industry. *Applied Economics*, 42(27), pp. 3547-3558. https://doi.org/10.1080/00036840802112497.

Avilés-Sacoto, E.C., Avilés-Sacoto, S.V., Güemes-Castorena, D. and Cook, W.D., 2021. Environmental performance evaluation: A state-level DEA analysis. *Socio-Economic Planning Sciences*, 78, 101082. https://doi.org/10.1016/j.seps.2021.101082.

Azam, M., 2022. Governance and Economic Growth: Evidence from 14 Latin America and Caribbean Countries. *Journal of the Knowledge Economy*, 13, pp. 1470-1495. https://doi.org/10.1007/s13132-021-00781-2.

Barbosa, A., de Lima, S.C. and Brusca, I. 2016. Governance and efficiency in the Brazilian water utilities: A dynamic analysis in the process of universal access. *Utilities Policy*, 43, 82-96. https://doi.org/10.1016/j.jup.2016.06.013.

Conagua, 2019. *Estadísticas del Agua en México 2019 [Water Statistics in Mexico 2019]*. [online] Comisión Nacional del Agua. Available at: http://sina.conagua.gob.mx/publicaciones/EAM_2019.pdf.

Conagua, 2022a. *Sistema Nacional de Información del Agua [National System of Water Information]*. National Water Commission of Mexico (CONAGUA). [online] Available at: http://sina.conagua.gob.mx/sina/index.php [Accessed 28 October 2022].

Conagua, 2022b. *Monitor de Sequía de México [Mexico Drought Monitor]*. National Water Commission of Mexico (CONAGUA). [online] Available at: https://smn.conagua.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico [Accessed 3 August 2022].

Cooper, W., Seiford, L. and Zhu, J., 2011. *Handbook on data envelopment analysis*. New York: Springer. https://doi.org/10.1007/978-1-4419-6151-8.

Dénes, R.V., Kecskés, J., Koltai, T. and Dénes, Z., 2017. The Application of Data Envelopment Analysis in Healthcare Performance Evaluation of Rehabilitation Departments in Hungary. *Quality Innovation Prosperity*, 21(3), pp. 127-142. https://doi.org/10.12776/QIP.V21I3.920.

Dyson, R.G., Allen, R., Camanho, A.S., Podinovski, V.V., Sarrico, C.S. and Shale, E.A., 2001. Pitfalls and protocols in DEA *European Journal of Operational Research*, 132, pp. 245-259. https://doi.org/10.1016/S0377-2217(00)00149-1.

Fitzová, H. and Matulová, M., 2020. Comparison of urban public transport systems in the Czech Republic and Slovakia: Factors underpinning efficiency. *Research in Transportation Economics*, 81, 100824. https://doi.org/10.1016/j.retrec.2020.100824.

Güngör-Demirci, G., Lee, J. and Keck, J., 2017. Measuring water utility performance using non-parametric linear programming. *Civil Engineering and*

Environmental Systems, 34(3-4), pp. 206-220. https://doi.org/10.1080/10286608.2018.1425403.

GWP, 2017. *Efficiency in Water Management*. [online] The Global Water Partnership. [online] Available at: https://www.gwp.org/en/learn/iwrm-toolbox/Management-Instruments/Efficiency_in_Water_Management/ [Accessed 20 October 2022].

Hall, P., 1986. On the number of bootstrap simulations required to construct a confidence interval. *The Annals of Statistics*, 14, pp. 1453-1462.

Hančlová, J. and Chytilová, L., 2023. Education Performance of Czech Public Higher Education Institutions Using Data Envelopment and Panel Regression Analysis. *Journal on Efficiency and Responsibility in Education and Science*, 16(4), pp. 313-328. https://doi.org/10.7160/eriesj.2023.160405.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. and Bryan, B.A., 2021. Future global urban water scarcity and potential solutions. *Nature Communications*, 12, 4667. https://doi.org/10.1038/s41467-021-25026-3.

INEGI, 2020. *Censo Nacional de Gobiernos Municipales y Demarcaciones Territoriales de la Ciudad de México 2019 [National Census of Municipal Governments and Territorial Demarcations of Mexico City 2019]*. Instituto Nacional de Estadística y Geografía. [online] Available at: https://www.inegi.org.mx/programas/cngmd/2019/ [Accessed 20 April 2021].

INEGI, 2021. *Gross Domestic Product by Federal Entity. Base year 2013*. Instituto Nacional de Estadística y Geografía. [online] Available at: https://www.inegi.org.mx/app/tabulados/default.aspx?pr=17&vr=6&in=2&tp=20&wr=1 [Accesssed 3 August 2022].

Kao, C. and Hwang, S.-N., 2008. Efficiency decomposition in two-stage data envelopment analysis: An application to non-life insurance companies in Taiwan. *European Journal of Operational Research*, 185(1), pp. 418-429. https://doi.org/10.1016/j.ejor.2006.11.041.

Libralato, G., Volpi Ghirardini, A. and Avezzù, F., 2012. To centralise or to decentralise: An overview of the most recent trends in wastewater treatment management. *Journal of Environmental Management*, 94(1), pp. 61-68. https://doi.org/10.1016/j.jenvman.2011.07.010.

Lombardi, G.V., Stefani, G., Paci, A., Becagli, C., Miliacca, M., Gastaldi, M., Giannetti, B.F. and Almeida, C.M.V.B., 2019. The sustainability of the Italian water sector: An empirical analysis by DEA. *Journal of Cleaner Production*, 227, pp. 1035-1043. https://doi.org/10.1016/j.jclepro.2019.04.283.

Molinos-Senante, M., Porcher, S. and Maziotis, A., 2018. Productivity change and its drivers for the Chilean water companies: A comparison of full private and concessionary companies. *Journal of Cleaner Production*, 183, pp. 908-916. https://doi.org/10.1016/j.jclepro.2018.02.227.

Morán-Valencia, M., Flegl, M. and Güemes-Castorena, D., 2023. A state-level analysis of the water system management efficiency in Mexico: Two-stage DEA approach. *Water Resources and Industry*, 29, 100200. https://doi.org/10.1016/j.wri.2022.100200.

Ngo, T. and Hong Tsui, K.W., 2021. Estimating the confidence intervals for DEA efficiency scores of Asia-Pacific airlines. *Operational Research: An International Journal*, 22, pp. 3411-3434. https://doi.org/10.1007/s12351-021-00667-w.

Pan, D., Hong, W. and Kong, F., 2020. Efficiency evaluation of urban wastewater treatment: Evidence from 113 cities in the Yangtze River Economic Belt of China. *Journal of Environmental Management*, 270, 110940. https://doi.org/10.1016/j.jenvman.2020.110940.

Pan, Z., Wang, Y., Zhou, Y. and Wang, Y., 2020. Analysis of the water use efficiency using super-efficiency data envelopment analysis. *Applied Water Science*, 10, 139. https://doi.org/10.1007/s13201-020-01223-1.

Reuters, 2022. *Mexico declares drought in northern state of Nuevo Leon matter of 'national security'*. [online] Available at: https://www.reuters.com/world/americas/mexico-declares-drought-northern-state-nuevo-leon-matter-national-security-2022-07-30/ [Accessed 7 September 2022].

Salazar-Adams, A., 2021. The efficiency of post-reform water utilities in Mexico. *Utilities Policy*, 68, 101153. https://doi.org/10.1016/j.jup.2020.101153.

Silva Pinto, F., Simões, P. and Cunha Marques, R., 2017. Water services performance: do operational environment and quality factors count?. *Urban Water Journal*, 14(8), pp. 773-781. https://doi.org/10.1080/1573062X.2016.1254254.

Simar, L. and Wilson, P.W., 1998. Sensitivity analysis of efficiency scores: How to bootstrap in non-parametric frontier models. *Management Science*, 44(1), pp. 49-61. https://doi.org/10.1287/mnsc.44.1.49.

SMN, 2022. *Servicio Meteorológico Nacional (Nationa Weather Service)*. Mexican Drought Monitor. [online] Available at: https://smn.conagua.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico [Accessed 22 October 2022].

Sun, Y., Liu, N., Shang, J. and Zhang, J., 2017. Sustainable utilization of water resources in China: A system dynamics model. *Journal of Cleaner Production*, 142(Part 2), pp. 613-625. https://doi.org/10.1016/j.jclepro.2016.07.110.

Tourinho, M., Santos, P.R., Pinto, F.T. and Camanho, A.S., 2022. Performance assessment of water services in Brazilian municipalities: An integrated view of efficiency and access. *Socio-Economic Planning Sciences*, 79, 101139. https://doi.org/10.1016/j.seps.2021.101139.

Tziogkidis, P., 2012. *Bootstrap DEA and hypothesis testing*. Cardiff Economics Working Papers, No. E2012/18, Cardiff University, Cardiff Business School, Cardiff.

Walker, N.L., Norton, A., Harris, I., Williams, A.P. and Styles, D., 2019. Economic and environmental efficiency of UK and Ireland water companies: Influence of exogenous factors and rurality. *Journal of Environmental Management*, 241, 263-373. https://doi.org/10.1016/j.jenvman.2019.03.093.

WWAP, 2017. *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource*. United Nations World Water Assessment Programme, Paris, UNESCO. [online] Available at: https://unesdoc.unesco.org/ark:/48223/pf000024715 [Accessed 10 November 2023].

Yang, F., Wang, D., Zhao, L. and Wei, F., 2021. Efficiency evaluation for regional industrial water use and wastewater treatment systems in China: A dynamic interactive network slacks-based measure model. *Journal of Environmental Management*, 279, 111721. https://doi.org/10.1016/j.jenvman.2020.111721.

ABOUT AUTHORS

Martin Flegl 0000-0002-9944-8475 (M.F.) – full-time research prof., School of Engineering and Sciences, Tecnologico de Monterrey, Mexico, e-mail: martin.flegl@tec.mx.

David Güemes-Castorena 0000-0002-6346-2873 (D.G.C.) – full-research prof., School of Engineering and Sciences, Tecnologico de Monterrey, Mexico, e-mail: guemes@tec.mx.

Marien Morán-Valencia 0000-0001-9059-7370 (M.M.V.) – PhD student, School of Engineering and Sciences, Tecnologico de Monterrey, Mexico, e-mail: a01420127@tec.mx.

Aldo I. Ramírez 0000-0001-8148-6820 (A.I.R.) – full-time research prof., School of Engineering and Sciences, Tecnologico de Monterrey, Mexico, e-mail: aldo.ramirez@tec.mx.

AUTHOR CONTRIBUTIONS

Conceptualisation, M.F. and D.G.C.; Methodology, M.F.; Software, M.F.; Validation, D.G.C., M.M.V. and A.I.R.; Formal analysis, M.F.; Investigation, M.F., M.M.V., Data curation, M.F.; Original draft preparation, M.F., D.G.C., M.M.V. and A.I.R.; Review and editing, M.F., D.G.C., M.M.V. and A.I.R.; Visualization, M.F.; Supervision, D.G.C. and A.I.R.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.