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Exploring Technical Efficiency in Water Supply Evidence from Ecuador: Do Region Location and Management Type Matter?

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Abstract: The efficiency that drinking water suppliers have, is widely analyzed in the literature due to the importance of its proper diagnosis in the regulation of the sector. These regulations seek, via the reduction of inefficiencies, to counteract water access crises. This research calculates the level of input-oriented technical efficiency of Ecuador's potable water service providers in the period 2014–2017. It analyzes its determinants, focusing on the effect of the geographic region (Highlands, Coast, and Amazon), as well as the type of management, specifically municipal departments and autonomous public enterprises. For this purpose, the semi-parametric method of data envelopment analysis (DEA) with double bootstrap is used. The results suggest that drinking water suppliers could save the inputs used while maintaining their level of production. In addition, it was found that the level of technical efficiency differs by geographic region but not by the type of management used. The natural Highlands region is more efficient compared to the Coast and Amazon region, suggesting climatic and natural resource distribution heterogeneities that induce this difference. The result by type of management shows that the advantages indicated by some literature regarding the technical, financial, and administrative autonomy of public companies may not improve efficiency compared to municipal departments.

Keywords: drinking water supplier; technical efficiency; data envelopment analysis (DEA); location; management

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1. Introduction

Universal access to water equally and at an affordable cost is the sixth sustainable development goal expected to be achieved by 2030 [1]. Water crises are a phenomenon that affects the achievement of this goal but can be addressed by the proper management of the resource [2]. According to the United Nations, water scarcity is not only explained by the level of availability of the resource, but also by poor governance, weak policies, and poor management [3]. In this context, water providers play a crucial role in influencing not only coverage but also costs, quality, and continuity of service now and for future generations [4,5].

Yardstick regulation is commonly used as a criterion to encourage water suppliers to be more efficient [6] and is based on comparing the performance of service providers—the idea being that, through comparison, it is possible to generate an artificial competitive market. Thus, suppliers with poorer performance than those with similar characteristics should become more efficient [7]. There is a growing body of research evaluating the efficiency of water utilities, e.g., Molinos-Senante et al. [8] in Chile; Lin [9] in Peru; Song et al. [10] in China; Mbuvi, De Witte, and Perelman [11] in Africa; Lo Srtorto [12] in Italy; and Molinos-Senante et al. [13] in England and Wales among others. Therefore, measuring the efficiency of suppliers is becoming an increasingly important practice.

Efficiency has been traditionally measured through partial productivity or performance indicators [7]. However, these are incomplete measures that do not consider market structure, location, density, water sources, and other variables preventing a practical comparison between suppliers [14,15]. The application of production frontier techniques for efficiency evaluation (e.g., data envelopment analysis (DEA) and stochastic frontier analysis (SFA)) have emerged to overcome specific problems present within the traditional technique [14].

In Ecuador, the Water Regulation and Control Agency (ARCA by its acronym in Spanish) presented a benchmarking of the efficiency level index of public providers of drinking water and sanitation services in 2018. This index is an aggregation or weighted sum (partial indicators) of the level of performance in 7 categories and 31 indicators on different aspects of service management [16]. As previously indicated, partial indicators are not complete for measuring efficiency. The level of efficiency of the drinking water supply sector in Ecuador has not yet been explored using frontier methods, probably due to the difficulty of accessing sector data at the provider level. Since 2014 ARCA has started to collect operational indicators on the drinking water service of public providers at the district level in the country, making it possible to analyze the sector's efficiency.

Once efficiency has been calculated, the identification of the factors that contribute to greater or lesser efficiency is essential to support decision-making. In the literature, a variety of studies have analyzed the factors explaining efficiency in the water sector, which have concluded that economic, natural, operational, demographic, and governance/institutional variables influence the level of efficiency. The debate on the influence of geographic regions remains to be solved due to the possibility of heterogeneity in each region, as well as the analysis of the type of management in countries where the providers are public, as is the case in Ecuador.

In Ecuador, water has been considered a constitutional human right since 2008, and its management is restricted to public and community administration [17]. Each level of government (central, provincial, and local) has different responsibilities within the water management structure in the country; where the management, control, and general regulation of the system is under the responsibility of the central government, irrigation management is under the responsibility of the provincial government, and drinking water management is under the responsibility of local governments [18].

In this context, the responsibility for drinking water management to supply drinking water to approximately 17.5 million inhabitants is decentralized and provided by 221 local municipalities distributed in the 24 provinces of Ecuador [19,20]. In addition to the municipalities, Ecuadorian regulations allow parish councils to provide drinking water services in rural parishes—known as community management [21]. The unit of analysis of this research is the municipal water providers, who generally offer their services in urban areas, since information regarding the performance of parish councils in the provision of water supply is not available, thereby hindering its analysis. Table 1 outlines the primary obstacles that need to be addressed for effective water management and efficiency analysis in Ecuador.

This research aims to analyze the efficiency in the supply of drinking water in Ecuador during 2014–2017 and the determinants that explain its variation. The double bootstrap data envelopment analysis method is applied for these purposes, using the database of indicators of drinking water providers at the municipal level constructed by ARCA during 2014–2017. Faced with the debate on the most efficient type of management—independent public company or municipal department—and on the influence of the geographic region, this study seeks to answer the research question: do the geographic location and the type of management of the drinking water supplier influence the level of efficiency? A specific analysis of efficiency for private (Guayaquil City) and joint management is not addressed because only a limited number of municipalities operate under these modalities.

Table 1. Main challenges of water management in Ecuador.

Challenges	Remarks/Discussion
Geographic diversity	Ecuador is divided into four different geographical regions (Coast, Highlands, Amazon, and Galapagos), each with distinct climatic characteristics and levels of development that could impact the effectiveness of water management. The Amazon region has lower quality water and coverage compared to the Highlands and Coast [22], which could potentially hinder the efficiency of water management. This might be due to high population dispersion and different climate conditions in each region.
Decentralization of the system	Various suppliers adopt different ways of doing their management. The majority (61.5%) use direct municipal management, while 32.1% utilize independent municipal public companies, and 5.9% employ joint or regional public companies [23]. Private operators account for only 0.5% of the total. This configuration can impact technical efficiency due to challenges in terms of access to resources and autonomy level. Direct municipal management may face a lack of autonomy, leading to potentially lower efficiency compared to public companies with greater autonomy [21]. On the other hand, pooled management, which involves multiple municipalities joining forces, may have higher levels of efficiency due to resource sharing and combined technical capabilities [24].
Political influence	Political interference in technical aspects, a common occurrence in Ecuador [21], can affect the efficiency of water management, resulting in little difference in efficiency among different types of management.

The study contributes to the existing empirical literature evaluating the efficiency of water operators in a developing country like Ecuador, where the service provided is primarily public. Specifically, it provides evidence on whether the type of management and geographic location influences the level of efficiency. The results are expected to provide information for regulators in their policy formulation.

The paper is organized into five sections. Section 2 describes the theoretical framework on which the hypotheses are based and a review of empirical studies related to the topic. Section 3 provides the method used to test the research hypotheses and describes the data used. The results obtained, discussion, and conclusions are presented in Sections 4 and 5, respectively.

2. State of the Art

A significant and growing number of studies have analyzed the efficiency of companies in strategic sectors such as water [12,25,26], electricity [27–29], transportation [30–32], and health [33–35], among others. The following paragraphs review the relevant literature to establish a definition of efficiency, examine the main methods used for its measurement, and establish the main determinants of efficiency in drinking water supply companies.

2.1. Efficiency and Its Measurement

Economic theory has established that a productive unit with optimizing behavior is efficient [36]. According with Worthington [37] Farell divided this economic efficiency into two types: technical efficiency (TE) and allocative efficiency (AE). Thus, a drinking water supplier will be economically inefficient if it is technically and/or allocatively inefficient [37]. There are two approaches to measuring each type of efficiency: output-oriented (or output maximization) and input-oriented (or cost minimization) [14]. Output-oriented TE is defined as the ability to obtain the maximum possible output or outputs given a set of inputs [36,37], while input-oriented TE measures the extent to which a productive unit can reduce the use of inputs to produce a given level of outputs or production, within the feasible production set [14].

Input-oriented allocative efficiency is defined as the ability to select an optimal combination of inputs given their respective prices (or relative costs) and available production technology [38]. While output-oriented AE is achieved when the productive unit selects the optimal quantity of output, all the while keeping relative output prices equal to the marginal cost ratio [14]. Note that the difference between EA and ET is because the former, considering information on relative prices, addresses the problem of selecting an optimal combination of inputs. In contrast, ET focuses on the possibility of reducing the use of inputs to produce a given quantity of outputs without considering whether the input mix is optimal.

The water industry has specific characteristics under which inefficiency may be present. For example, water utilities that operate as natural monopolies [8,39], by presenting entry barriers, do not face pressure from market competition and as a result tend to be inefficient [5]. Moreover, if drinking water is provided by the public sector, efficiency may be even lower due to possible budgetary constraints, financial problems, and/or possible organizational slack [36]. Consequently, regulatory bodies have taken an interest in assessing efficiency in this sector worldwide [37].

The most recent literature has focused on analyzing input-oriented technical efficiency [4,40,41]. This is because, given the nature of the sector, the use of inputs is endogenous to the productive unit. At the same time, outputs are determined exogenously [42] due to the existence of legal regulations according to which the supplier must satisfy demand [43]. Studies of input-oriented allocative efficiency are less frequently observed (e.g., Molinos-Senante and Maziotis [44]), given the low availability of data related to input prices [45].

Since Farrell's seminal work [45] the traditional ways of measuring efficiency (e.g., through labor productivity, efficiency indexes) were considered unsatisfactory due to the lack of an adequate representation of efficiency in economic terms. The current form of measurement is based on production possibilities, where the technically efficient production combinations at a given point in time are presented [38]. For this purpose, both parametric and non-parametric methods have been used in the literature; for example, stochastic frontier analysis (SFA) [46] and data envelopment analysis (DEA) [7,8,37,47,48], respectively.

Each approach has its specificities and has been applied by multiple studies in each case; for example, Morán-Valencia et al. [48], Benito et al. [49], lo Storto [12], Cetrulo et al. [25] for DEA; Molinos-Senante and Maziotis [8], Ferro and Mercadier [42],and Ferro et al. [50] within SFA. Finally, few studies have applied both approaches, e.g., Estruch-Juan et al. [7], which aims to test the robustness of the results.

Alternatively, multi-criteria decision-making methods, such as the analytical hierarchy process (AHP), can be used to measure or evaluate risk in operators. For example, Kut and Pietrucha-Urbanik [51] apply the AHP technique to assess photovoltaic installation operators. This method involves evaluating a set of criteria and sub-criteria based on their relative importance, with the aim of generating an overall risk ranking [51]. Although this approach does not rely on the production possibility frontier, it can complement parametric and non-parametric methods for assessing efficiency in the drinking water sector by taking into account the criteria's relative importance, as defined by experts. It is important to note that AHP does not provide a direct measure of efficiency, but rather allows for the establishment of risk or efficiency rankings according to the assigned criteria and weights.

2.2. Determinants of Efficiency in the Drinking Water Supply Industry

A significant number of studies have focused on establishing the most important factors to explain the efficiency of drinking water supply, considering economic, demographic, operational and quality, natural, and governance/institutional determinants, among others. Within each factor, there are a variety of aspects analyzed. For example, within the operational and quality factors, it has been studied how losses in the network, the number of complaints, and other elements affect efficiency. In the case of governance and institutionality, work has been done on aspects of ownership; however, there is limited literature on efficiency according to the type of management or administration of the company. Likewise, within the natural factor, issues such as the number of extraction sources and the type of water source have been explored as determinants of efficiency, but aspects such as climate and meteorological aspects have often been neglected [10,49,52]. One possible reason for the limited analysis of this is the difficulty in quantifying and measuring these factors compared to more tangible variables. Additionally, the lack of available data and the complexity of establishing clear causal relationships between these natural factors and water management efficiency could further contribute to their limited analysis in the literature. According to the study by Goh and See [53], out of the 53 analyzed articles, temperature as a climatic factor was one of the least studied. However, geographical location has become increasingly relevant, being the fifth most used factor in studies of water management efficiency.

Table 2 summarizes the main efficiency determinants, as well as the expected signs of the coefficients, according to several empirical works. This research focuses on two of the least studied aspects, such as the type of management and the geographic location of drinking water suppliers, without neglecting the factors commonly analyzed according to data availability.

Table 2. Summary of efficiency determinants and expected signs.

Factor	Description	Sign	Detail	Authors
Economic	Per capita income	(+/−)	Increased resources for investment Less concern for achieving efficiency In the early stages of growth, signs (−) of possible waste of natural resources. After reaching a certain point, sign (+) for adopting better production practices to save resources.	Ma et al. [54] Benito et al. [49] Song et al. [10]
Demographic	Population or customer density	(+/−)	Higher density, higher number of people served per km of network Possibility of congestion Inverted U-ratio	Guerrini et al. [46] Song et al. [10] Guerrini et al. [55]
Operational and quality factors	Percentage of water loss Pumping level Complaints	(−) (+) (−) (−)	Due to cost increases Repair expenses are higher than the benefit Increased energy use (resources) Higher claims handling costs	Molinos-Senante et al. [8] Guerrini et al. [46] Villegas et al. [4] Molinos-Senante and Maziotis [56]
Natural	Number of water sources Surface water	(−) (−)	Increased inputs/costs for the use of the sources Need for further water treatment due to the existence of sediments	Walker et al. [41] Villegas et al. [4]
Meteorology	Temperature	(−)	Excessive water consumption, increased costs	See [40]
Institutional	Governance/political strength indicator Corruption rate	(+) (−)	Imposition of budget restrictions, increased resistance Use of non-technical resources	Benito et al. [49] Estache and Kouassi [57] Estache and Kouassi [57]

Within the governance factor, the type of ownership of the productive unit is widely analyzed [50,52,57,58]. A positive relationship in efficiency is expected when ownership is private since the objective of these is to maximize profits rather than public welfare [40]. According to empirical evidence, plants managed by mixed-ownership companies are more efficient than those that are entirely privately owned [52]. Currently, the public–private dilemma is not the only governance or management factor that can influence efficiency. Countries, such as Ecuador, where service supply is public—except for the municipality of Guayaquil—and involve three management models: departmental or direct, independent public company and commonwealth. Most municipalities (93.6%) operate under the first two models, so it is worth asking whether efficiency differs according to the type of public management. There are case studies that explore this topic, such as Gupta, Kumar and Sarangi [59].

Another underexplored determinant is geographic location. Romano and Gerrinzzi [60] showed that geographic location affects efficiency in Italian companies. In Ecuador, there are 79 and 137 river basins and sub-basins, respectively, but the natural distribution of these resources is unequal [61]. For this reason, access to water resources may differ for each productive unit depending on its geographic location. In addition, the different geographic regions of Ecuador (Coast, Sierra, Amazon, and Galapagos) have particular characteristics with respect to climate, topography, and available water resources that could influence the level of efficiency of water providers. Although geographic location is not a factor that can be controlled, its analysis allows us to identify which suppliers, depending on their location, require attention in decision making to enable greater efficiency.

Given the provided context, the hypothesis can be formulated as follows: The efficiency of water service providers in Ecuador is heterogeneous, depending on the type of public management and geographical location. Unique challenges and opportunities of each region, as well as the advantages of each management type, are expected to be reflected through varying levels of efficiency, ultimately allowing for a greater understanding of drinking water service efficiency in Ecuador.

3. Materials and Methods

To test the raised hypotheses, this article uses the semi-parametric DEA method with double bootstrap frequently used by the empirical literature within the water industry [4,7,56]. This method is used because it does not require the priori assumption of a production function relating inputs to outputs. In light of the strong heterogeneity in the productive structure of providers in Ecuador, using a parametric approach can be risky. In such a situation, the non-parametric method has its advantages, as it is less susceptible to specification errors and more resilient to potential inaccuracies in information quality, owing this to its independence from strict data distribution assumptions. Additionally, by incorporating the double bootstrap, the non-parametric method accounts for uncertainty in efficiency estimates, enhancing the precision and reliability of the analysis. Consequently, the risk of underestimating or overestimating efficiency due to specification errors or incorrect assumptions is minimized. As previously indicated, we analyze input-oriented technical efficiency since it is assumed that service providers aim to minimize inputs or costs in providing drinking water [5].

3.1. Data Envelopment Analysis

The DEA model proposed by Charnes et al. [62] measures the efficiency of decision-making units (DMU) by calculating an efficiency score through mathematical programming using multiple inputs and outputs [49,63]. The method consists of establishing the most efficient DMU(s) to form the efficiency frontier, and then each DMU is compared in relation to the efficient frontier [4,7].

The input-oriented DEA is expressed through the linear programming problem in Equation (1) [8]. Each DMU (j = 1, . . . , n) in each period t (t = 1, . . . , T), employs the vector $x_{jt} \in \mathbb{R}^m_+$ of inputs, which includes variables such as network length, number of employees, costs, among others, to produce the vector of outputs $y_{jt} \in \mathbb{R}^r_+$, [26]. If DMU_o is the unit under evaluation, the efficiency score is calculated by solving the following problem;

$$\begin{gathered} \min_{\delta_0,\lambda} \delta_0 \\ \sum_{j=1}^{nt} \lambda_{jt} x_{jt} \leq \delta_0 x_{0t},\ t = 1, \ldots, T \\ \sum_{j=1}^{nt} \lambda_{jt} y_{jt} \geq y_{0t} \\ \sum_{j=1}^{n_t} \lambda_{jt} = 1 \\ \lambda_{jt} \geq 0,\ j = 1, \ldots, n_t \end{gathered} \tag{1}$$

where x_{0t} e y_{0t} specifies the inputs and outputs of DMU_o at time t, δ_0 represents the technical efficiency score calculated for the DMU_o [8]. When $\delta_0{}^{op} = 1$ the productive unit is efficient, while if $\delta_0{}^{op} < 1$ this is inefficient, since it means that there is a possibility that from λ_{jt} a virtual DMU with better performance than DMU_o is built [64]. The expression $1 - \delta_0$ measures the proportion of inputs that can be reduced given the production level [4,60]. The estimated weight of each production unit j within the efficiency frontier is symbolized by λ_{jt} [65].

The constraints $\sum_{i=1}^{n_t} \lambda_{jt} = 1, \lambda_{jt} \geq 0$ refer to the returns to scale of the technology, indicating $\lambda_{jt} \geq 0$ constant returns to scale (CER), while both expressions for variable returns to scale (VSR) [65]. CER states that a proportional increase in inputs leads to an increase in outputs [63], while RVE does not assume proportionality [66]. The returns to scale of the technology are not known a priori, so the Simar and Wilson test [67] is applied, which tests the null hypothesis that returns to scale are constant.

This methodology does not make assumptions about the functional form of the relationship between inputs and outputs [68], unlike parametric methods, but it is deterministic in nature and sensitive to outliers [49,63]. Outliers are identified and treated (i.e., corrected or removed) as a step prior to the application of DEA [4] through the Wilson statistical method [69]. Wilson's method allows for identifying outliers in non-parametric frontier models [69], taking into account that certain outliers may not be measurement errors but represent sections of the efficiency frontier [49].

On the other hand, to address or overcome the deterministic limitations of the method, Simar and Wilson [70] point out that the bootstrap technique can be applied to correct biases in DEA efficiency estimates and provide information on bias and variance. This study applies the two-stage semi-parametric method with double bootstrap, as proposed by Simar and Wilson [71]. In the first stage, technical efficiency is estimated through DEA and employs bootstrap for bias correction [68], while in the second stage, a truncated regression model with bootstrap is applied to establish the determinants of efficiency [72]. The procedure of the Simar and Wilson algorithm [71] is summarized in seven steps. Steps 1 to 4 make up the first stage, and steps 5 to 7 constitute the second stage [26].

First stage: calculation of the technical efficiency through DEA with bootstrap.

First step: calculation of $\widehat{\delta_{jt}}$ using (1), for each DMU_j in each period t, evaluated as a grouped boundary [4].

Second step: using the maximum likelihood method, the regression is estimated between 0 and 1 (Equation (2)) obtaining $\widehat{\beta}, \widehat{\gamma}$ and $\widehat{\sigma_u}$ [8];

$$\widehat{\delta_{jt}} = Z_{jt}\beta + D_t\gamma + u_{jt},\ j = 1, \ldots,\ n_t\ y\ t = 1, \ldots, T \quad (2)$$

where Z_{jt} are the factors that could influence the efficiency level [68]. D_t is a vector of dummy variables for each time period analyzed. β, γ represent the coefficient vectors measuring the effect of covariates and time on the efficiency variations, respectively, and u_{jt} is the residual. Based on the data generation of the mathematical programming problem, in this step, the observations with spurious efficiency do not meet the bounds of $\widehat{\delta_{jt}}$ between 0 y 1 [72]. Consequently u_{jt} presents a truncation on the left tail at $(-Z_{jt}\beta - D_t\gamma)$ and on the right at $(1 - Z_{jt}\beta - D_t\gamma)$ and it is assumed that $u_{jt} \sim N(0,\ \sigma_u^2)$ [73].

Third step: a bootstrap procedure is performed following steps 3.a–3.d with B1 replicates for each $(j = 1, \ldots,\ n_t)$, and $(t = 1, \ldots, T)$, obtaining bootstrap estimates for $\left\{\widehat{\delta_{jt}^b}\right\}_{b=1}^{B1}$ [4].

3.a. Artificial residues are generated $\widehat{u_{jt}} \sim N\left(0,\ \widehat{\sigma_u^2}\right)$ with left truncation at $(-Z_{jt}\widehat{\beta} - D_t\widehat{\gamma})$ and to the right at $\left(1 - Z_{jt}\widehat{\beta} - D_t\widehat{\gamma}\right)$ for each DMU_j at t [72].

3.b. Artificial efficiency scores are calculated $\widetilde{\delta_{jt}} = Z_{jt}\widehat{\beta} + D_t\widehat{\gamma} + \widehat{u_{jt}}$.

3.c. A single set of data $({x_{jt}}^*, {y_{jt}}^*)$ is obtained where ${x_{jt}}^* = x_{jt}\left(\frac{\widehat{\delta_{jt}}}{\widetilde{\delta_{jt}}}\right), {y_{jt}}^* = y_{jt}$.

3.d. Through the set $(x_{jt}{}^*, y_{jt}{}^*)$, we estimate $\hat{\delta}_{jt}^b$ by DEA (Equation (1)) [26].

Fourth step: calculate $\hat{\hat{\delta}}_{jt}$ presenting the bias-corrected efficiency score for each DMU_j and period t, by means of $\hat{\hat{\delta}}_{jt} = \hat{\delta}_{jt} - \hat{s}_{jt}$, where $\hat{s}_{jt} = \left(\frac{\sum_{b=1}^{B1} \hat{\delta}_{jt}^b}{B1}\right) - \hat{\delta}_{jt}$ represents the estimation bias [68].

Second stage: determinants of efficiency through truncated normal regression with Bootstrap.

Fifth step: the truncated regression $\hat{\hat{\delta}}_{jt} = Z_{jt}\beta + D_t\gamma + u_{jt}$, is estimated via maximum likelihood, obtaining $\hat{\hat{\beta}}$, $\hat{\hat{\gamma}}$ y $\hat{\hat{\sigma}}_u$ [26].

Sixth step: process 6.a–6.c is replicated in B2 times to obtain $\left\{\hat{\hat{\beta}}^b, \hat{\hat{\gamma}}^b, \hat{\hat{\sigma}}_u^b\right\}_{b=1}^{B2}$ [72].

6.a. Starting from the fifth step, we generate the artificial errors $\hat{\hat{u}}_{jt} \sim N(0, \hat{\hat{\sigma}}_u^2)$ with left truncation at $(-Z_{jt}\hat{\hat{\beta}} - D_t\hat{\hat{\gamma}})$ and right truncation at $(1 - Z_{jt}\hat{\hat{\beta}} - D_t\hat{\hat{\gamma}})$ for each DMU_j at t [68].

6.b. Calculate $\tilde{\tilde{\delta}}_{jt} = Z_{jt}\hat{\hat{\beta}} + D_t\hat{\hat{\gamma}} + \hat{\hat{u}}_{jt}$.

6.c. We estimate the truncated regression between 0 and 1 via maximum likelihood using $\tilde{\tilde{\delta}}_{jt}$ as the dependent variable and Z_{jt}, D_t as explanatory variables to estimate $\hat{\hat{\beta}}^b$, $\hat{\hat{\gamma}}^b$, $\hat{\hat{\sigma}}_u^b$ [8].

Seventh step: calculate confidence intervals and standard errors for the vector of $\hat{\hat{\beta}}^b$, $\hat{\hat{\gamma}}^b$, $\hat{\hat{\sigma}}_u^b$ with a confidence level of $(1 - \alpha)\%$ [26].

Research Hypothesis

The non-parametric Mann–Whitney test is applied to test the null hypothesis (H0), which states that the level of technical efficiency is equal between a provider that manages the service through an independent public company versus a municipal department, and between an operator that provides its services in the Highlands versus the Coast, Highlands versus the Amazon region, and Coast versus the Amazon region.

Additionally, the influence of Z_{jt} on the variation of inefficiency is analyzed through the null hypothesis (H0) that $\hat{\hat{\beta}}^b = 0$. If H0 is rejected at a significance level of 1%, 5%, or 10%, it is concluded that the exogenous variables Z_{jt} influence the level of technical efficiency.

3.2. Data and Variables

3.2.1. Data Description

This research uses the database called "Indicadores de evaluación del servicio de agua potable y alcantarillado" (Drinking water and sewerage service evaluation indicators) for the period 2014–2017, for 221 cantons of Ecuador, which has been developed by ARCA. This base constitutes an unbalanced panel made up of 221 productive units and 845 observations. The unit of analysis is the drinking water service provider in each of the municipalities.

Prior to obtaining the results, data cleaning was performed, which consisted of (1) eliminating observations with no information (110 observations); (2) eliminating observations with a variable that does not fall within a logical range; for example, variables such as the number of employees and drinking water coverage cannot take negative values; (3) eliminating miscoded data; in addition, observations that are ±2.5 standard deviations from the mean of the cost variable and miscoded data, (4) six outliers were identified, applying Wilson's method [69], which were removed from the base. As a result, we obtained an unbalanced panel consisting of 180 production units with a total of 493 observations.

The pooled sample consists of 50.9% of water providers located in the Highlands, 27.9% and 20.1% in the Coast and Amazon, respectively; the rest operate in Galapagos. According to the type of management, the majority (67.3%) is managed directly by a municipal department, 29.4% through a municipal public company, and the remainder through private management (0.6%) or a commonwealth (2.6%).

An analysis of the missing information, using the Pearson's test of independence, shows that there is no randomness in the sample at a significance level of 5%, indicating that the missing information is related to the geographic region and the type of management. It was found, for example, the existence of a higher proportion of missing data in the coastal region and from suppliers that are managed under commonwealth during 2014. Therefore, the results presented are inferred at the sample level without making generalizations, considering that the sample is biased and represents the reality of the productive units used in the study.

3.2.2. Specification of Variables and Descriptive Data

This section describes the variables that are configured as inputs (x) and outputs (y) used to calculate efficiency and the exogenous variables (Z) that explain the variation in efficiency, as well as the descriptive variables that make it possible to identify how the sample is constituted.

Inputs y Outputs

According to See [40], the selection of the inputs and outputs variables used for the construction of the frontier influences the results. In the present research, the three inputs and the two outputs most frequently used in the literature are employed (see Table 3) [4,7,8,25,41,50,58,74,75].

Table 3. Inputs and outputs used to measure the level of efficiency.

Variable	Description	Measuring Method	Unit of Measurement	Input/Output
coc	Operating expenses per connection	Operating costs per connection deflated by PPI 2017=100	USD/connections	Input
lrd	Kilometers of network length	Kilometers of distribution network length per connection	Km/connections	Input
etcap	Number of employees	Total employees per drinking water connection	No. employees/No. connections	Input
vapc	Volume of water supplied	Volume of drinking water per connection	m^3/No. connections	Output
csap	Coverage	Drinking water service coverage	% of total housing	Output

The inputs considered are operating costs per connection (coc), network length per connection (lrd), and number of employees per connection (etcap). The outputs, on the other hand, are volume of water per drinking water connection (vapc) and level of service coverage (csap). The variable coc includes production and maintenance costs, not only for drinking water but also for sewerage service, according to the data provided by ARCA. However, given the availability of information, the analysis of the efficiency of the sewerage service has not been considered in this study, leaving its analysis for future research.

Table 4 presents the main descriptions of inputs and outputs, by geographic region and type of management. Lower efficiency is expected in the Coast and Amazon regions compared to the DMUs located in the Highlands, since these regions have approximately double the operating costs per account (coc) (See Figure 1) and have a lower coverage. In addition, the number of employees per account of the production units operating in the Amazon region is approximately 55% higher than in the Highlands and 40% higher than in the Coast. This possible inefficiency can be explained by the length of the extensive network compared to the low density of clients they have (see Tables 4 and 5 below).

Table 4. Descriptive variables inputs (x) and outputs (y).

Variable	Full Sample			Geographic Región			Type of Management	
	Obs	Mean	Std. Dev.	Highlands (50.9%)	Coast (27.9%)	Amazon (20.1%)	EP Independent (29.4%)	Municipal Dep. (67.3%)
coc	487	6.59	12.34	4.52	8.11	9.86	7.11	6.23
vapc	493	39.03	41.88	32.75	40.66	52.83	35.80	40.77
etcap	493	9.80	11.14	8.60	9.51	13.34	9.13	10.23
lrd	490	2.06	12.68	2.58	0.80	2.64	1.44	2.44
csap	493	0.89	0.15	0.92	0.87	0.84	0.89	0.89

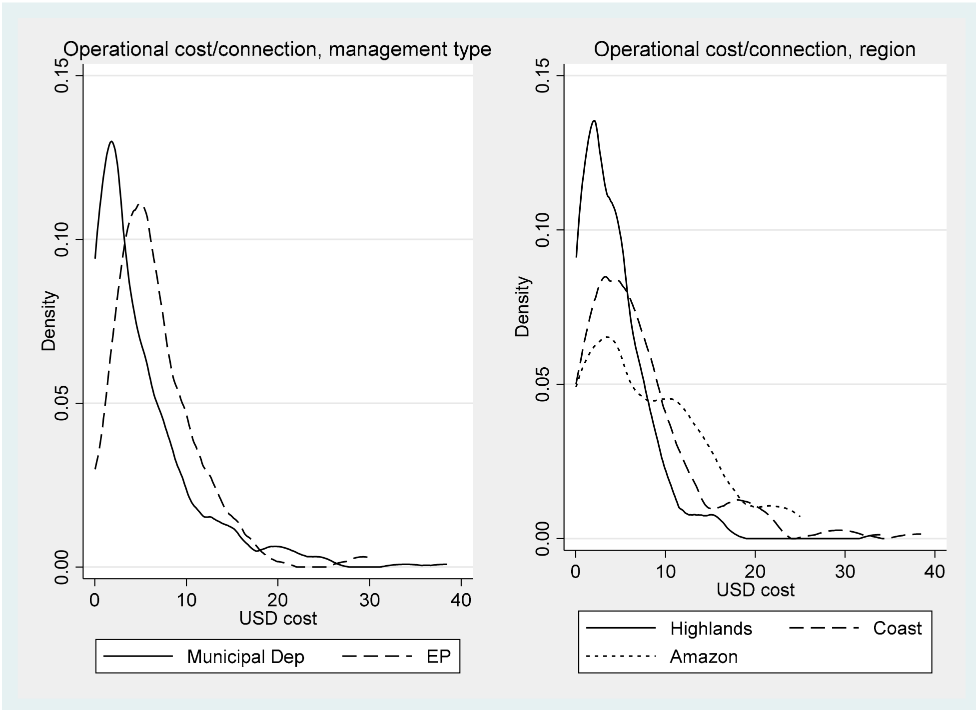

Figure 1. Operating cost per connection.

Table 5. Descriptive data of the independent variables.

Variable	Description	Full Sample			Geographic Región			Type of Management	
		Obs	Mean	Std. Dev.	Highlands	Coast	Amazon	EP Independent	Municipal Dept.
lvabpc	GVA per capita	493	7.82	0.55	7.82	7.83	7.75	8.00	7.73
ldenc	Customer density	493	3.59	1.88	3.66	3.90	2.97	3.54	3.57
lvpr	Water loss	427	5.84	2.37	5.55	6.31	5.95	5.70	5.85
drt	Complaints	493	0.10	1.07	0.15	0.03	0.09	0.03	0.13
tfa	Water sources	491	5.53	12.93	6.63	4.34	4.61	8.72	4.34
ias	Groundwater	490	0.22	0.37	0.22	0.30	0.08	0.29	0.20
ep	Public company	493	0.29	0.46	0.30	0.41	0.12	1.00	0.00
mu	Municipality	493	0.67	0.47	0.70	0.47	0.88	0.00	1.00
Highlands	Highlands Region	493	0.51	0.50	1.00	0.00	0.00	0.52	0.53
Coast	Coastal Region	493	0.28	0.45	0.00	1.00	0.00	0.39	0.20
Amazon	Amazon region	493	0.20	0.40	0.00	0.00	1.00	0.08	0.26
Scope	Scope	488	0.97	0.17	0.99	0.92	0.99	0.94	0.98

When comparing the type of management, it is observed that, on average, suppliers managed directly through a municipal department use a greater length per connection (lrd) and number of employees per account (etcap) than the average provided by independent public companies. The difference is significant at 5% only for the case of the lrd variable (*p*-value = 0.0351); however, the municipal departments have a slightly lower operating cost per account than the independent public companies.

Explanatory Variables or Determinants of the Technical Efficiency Level

The dependent variable is the technical efficiency score calculated by the DEA method with double bootstrap, while the explanatory variables were established according to the specification of Villegas et al. [4], Carvalho and Marques [74], Carvalho and Marques [58], Marques et al. [75], Walker et al. [41], Cetrulo et al. [25], Estruch-Juan et al. [7], Molinos-Senante et al. [8], Ferro and Mercadier [42], and Ferro et al. [50], from data availability and according to the hypotheses put forward.

To capture the differences in the level of efficiency, along with the type of management and geographic location, we considered economic, socio-demographic, operational, and natural factors (see Table A1). In order to control the results for the possibility of scope effects [76], a dummy variable is incorporated that takes the value of 1 if the unit offers sewerage and potable water services, and 0 if it only offers the second service. In general, there is a low correlation between the explanatory variables (see Table A2), which is adequate for the analysis due to the multicollinearity problem.

According to Table 5, the Amazon region has a lower level of economic development and a low density of clients compared to suppliers located in the other regions. The Amazon and Coastal regions tend to present operational deficiencies by exhibiting a higher volume of water lost per km of network in comparison to suppliers in the highlands. These regions also show a lower density of complaints, which is consistent with the hypothesis that a supplier is more efficient to the extent that it has a higher number of complaints due to the pressure this generates for service improvement. On the other hand, suppliers in the Coast and Amazon regions use, on average, fewer sources of water extraction compared to the Highlands region. In the Amazon, it should be added that they use a low proportion of groundwater, implying a greater use of surface or imported water, which in turn results in higher costs.

There are important differences in the type of company management when compared by geographic region, with the municipal department predominating in the highlands and Amazon, while on the coast, this aspect is much more balanced. Furthermore, the relationship between efficiency and type of management is less clear. On the one hand, independent public utilities use a higher proportion of groundwater, inducing lower costs compared to municipal departments, but use twice as many water sources for service provision, increasing costs and thus suggesting lower efficiency.

4. Results and Discussion

A total of B1 = 1000 and B2 = 2000 replications are used in the application of the Simar and Wilson method [71]. The empirical literature applies this methodology for panel data structures in their pooled form [4]. Under this context, it is assumed that technology does not change between periods and is feasible when the period under analysis is short [72]. The results are presented in two subsections: the first one analyzes the technical efficiency scores obtained, with and without bias, both for the complete sample and by geographic region and type of management; the second part details the findings regarding the factors that explain the level of efficiency, within the analyzed sample.

4.1. Input-Oriented Level of Technical Efficiency

According to the Simar and Wilson test [67], the returns of the potable water sector in Ecuador are variable (*p*-value = 0.000), which demonstrates the non-existence of proportionality between inputs and outputs [66]. This result is consistent with the literature, as evidenced by Guder [77] for Germany, Benito et al. [49] for small municipalities in Spain, and Villegas et al. [4] for England and Wales.

The technical efficiency with bias correction estimated over the period 2014–2017 was 44.3% on average, suggesting that productive units could decrease their inputs by 55.7% and remain within the feasible production set. This value was lower than the estimated technical efficiency without bias correction (59.2%), implying that the uncorrected analysis leads to overestimating technical efficiency by 14.9%, on average (see Table 6). In addition, as already indicated (see Figure 2), the uncorrected estimate assumes the existence of completely efficient productive units. This figure shows two broken lines that limit the DMUs with less than 10% bias (43.8% of the total) and with less than 20% bias (36.3% of the total).

Table 6. Technical efficiency full sample.

Descripción	Obs	Mean	Std. Dev.	Min	Max
Ef without correction	400	59.23%	0.2602	0.0643	1.0000
Bias	400	14.94%	0.1422	0.0148	0.9324
Ef with correction	400	44.29%	0.1986	0.0407	0.8665

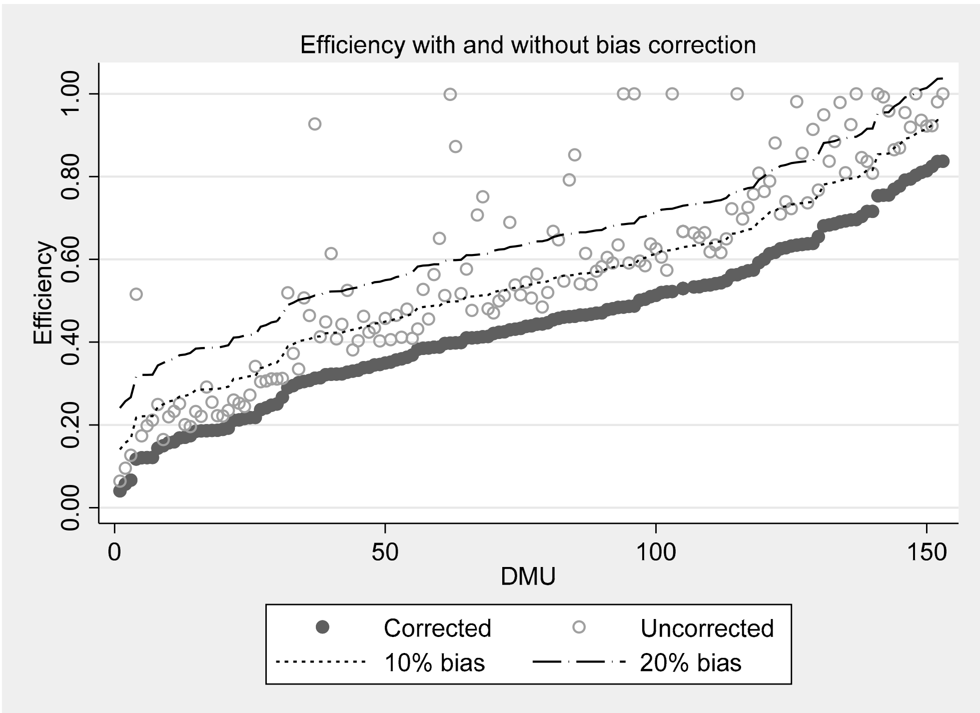

Figure 2. Technical efficiency with and without bias correction.

Table 7 and Figure 3 present the descriptive data and the distribution of technical efficiency by region and type of management. The productive units in the Amazon region are much less efficient than those located in the Coast and Highlands regions, a difference that is corroborated by the Mann–Whitney test (p-value = 0.00). This fact can be explained mainly in two ways. The first is client density. In the Amazon region, users are widely dispersed [22], causing the need for greater inputs for drinking water connection; on the other hand, in the Coast region the density is higher compared to the other regions (Table 5), generating possible congestion problems in the service. In addition, there is a high volume of water loss in this region, which results in an increase in service costs [8,49].

Table 7. Technical efficiency by region and type of management.

Sample	Obs	Eff. Unbiased	Std. Dev.	Eff. with Bias	Bias
Highlands	208	49.43%	0.1878	63.21%	13.77%
Coast	102	44.29%	0.1898	59.39%	15.10%
Amazon	81	31.19%	0.1718	45.68%	14.49%
PE independent	116	41.51%	0.1823	53.12%	11.61%
Municipal Dept.	267	45.77%	0.2038	61.21%	15.44%

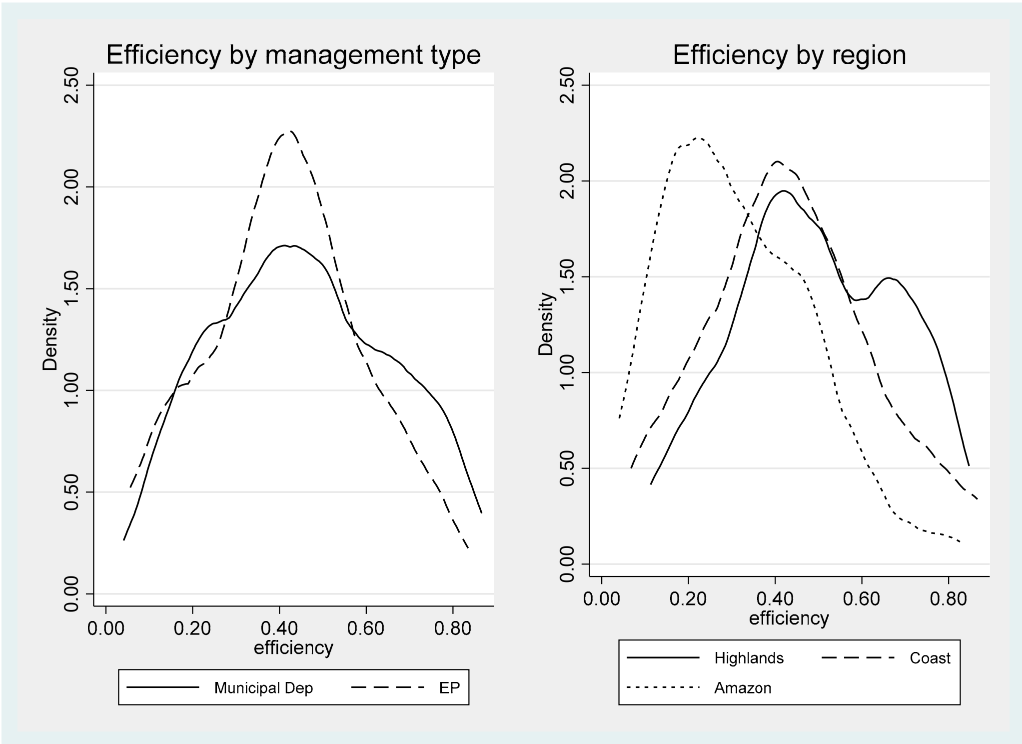

Figure 3. Distribution of technical efficiency with bias correction, by type of management and region.

The second reason is related to the climate that characterizes each region of Ecuador. The temperature of each region can help explain the difference in efficiency levels, as high temperatures are associated with humid areas with higher water consumption, negatively influencing efficiency, unlike the study by See [40], where high temperatures are associated with drought. In Ecuador, the highland region is characterized by temperatures between 3.8 and 24.2 °C, while in the coastal region, it is between 18.8 and 33 °C, and in the Amazon, between 21.5 and 33.4 °C. Moreover, the natural distribution of the river basins between regions is unequal, so that, in real terms, the difference in the availability of water resources influences the inputs needed to supply drinking water services to the population.

Regarding the type of management, the average efficiency of drinking water suppliers operating under a municipal department is approximately 4 percentage points higher than those operated under an independent public company, although according to the Mann–Whitney test this difference is not statistically significant (p-value = 0.22).

However, Figure 4 shows that the level of technical efficiency starts to differentiate in favor of suppliers managed by a municipal department from the fourth decile onwards. According to the Kolmogorov–Smirnov test, the hypothesis that the two distributions are equal is not rejected for deciles 1–5 of the distribution (p-value = 0.367), but it is rejected for deciles 6–10 (p-value = 0.021). Furthermore, according to Levene's test, the hypothesis that variances are equal is rejected (p-value = 0.033). Consequently, for less efficient units, there is no significant difference between the two types of management, but as units become more efficient, this difference becomes significant.

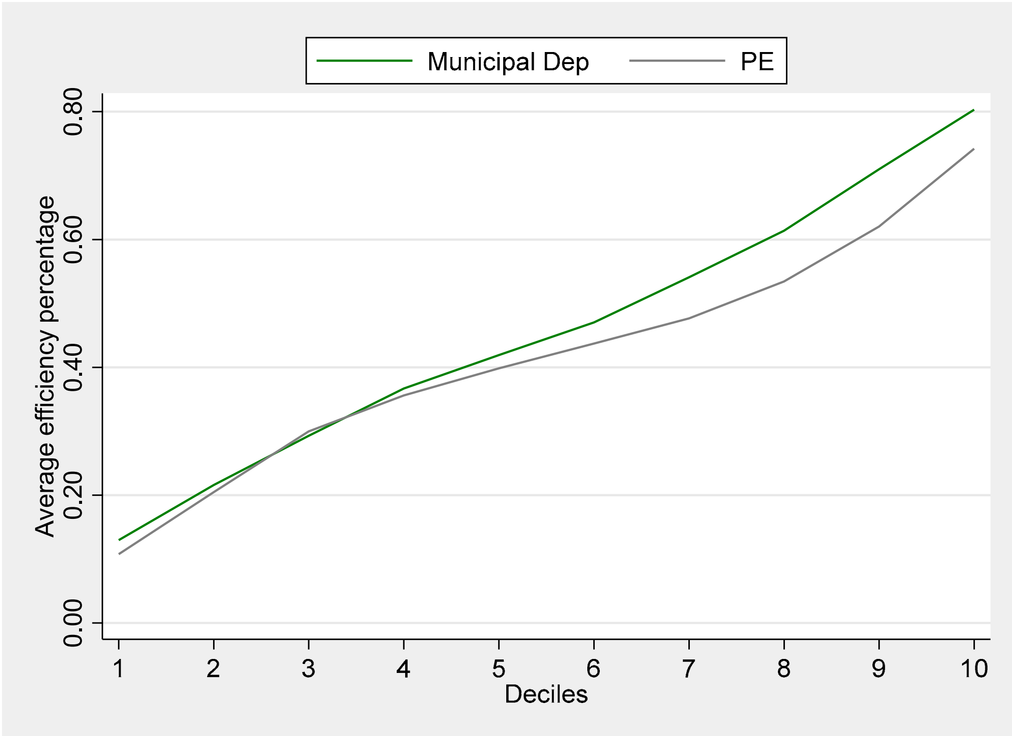

Figure 4. Bias-corrected technical efficiency deciles by management type.

Contrary to what the literature indicates, in the Ecuadorian case, there is no gain in technical efficiency when the supplier is managed through an independent public company instead of a municipal department. This result suggests that a possible gain in efficiency given by financial, administrative, and technical autonomy is offset by the additional costs that the productive unit must assume when it is formed as an independent public company, for example, administrative expenses. Authors such as Martínez et al. [78], suggest that the results may not differ between these two modalities if political decisions take precedence over technical ones, indicating that in independent public companies, there may be restricted technical autonomy, which makes it difficult for them to achieve greater efficiency in relation to their counterpart

4.2. Determinants of Technical Efficiency in the Provision of Drinking Water Service

Table 8 presents the results of the regressions to establish the determinants of technical efficiency. Column (2) considers the complete sample; columns (3), (4), and (5) show the estimates by geographic region, and columns (6) and (7) by type of management. The following sections analyze the determinants of technical efficiency by economic, demographic, operational, management, and geographic factors.

Table 8. Factors explaining the input-oriented technical efficiency of drinking water supply (full sample).

Variables	Full Sample (2)	Highlands (3)	Coast (4)	Amazon (5)	Independent PE (6)	Municipal Dept. (7)
lvabpc	0.0317 *	−0.0020	0.1099 ***	0.0197 ***	0.1113 ***	0.0116
	(0.0164)	(0.0247)	(0.0254)	(0.0583)	(0.0271)	(0.0230)
ldenc	0.1183 ***	0.0684 ***	0.1104 ***	0.0082	0.0190	0.1270 ***
	(0.0116)	(0.0136)	(0.0173)	(0.0254)	(0.0123)	(0.0154)
lvpr	−0.0165 ***	−0.0348 ***	−0.0165 *	0.0365 *	0.0109	−0.0260 ***
	(0.0063)	(0.0096)	(0.0100)	(0.0213)	(0.0108)	(0.0085)
drt	0.0130	−0.4613	0.4629	−1.3819	0.0656	−0.2857
	(0.2580)	(0.4282)	(0.2855)	(3.0277)	(0.2690)	(1.2036)
tfa	0.0009	0.0034 ***	−0.0024	−0.0197 ***	0.0036 ***	−0.0108 ***
	(0.0006)	(0.0013)	(0.0028)	(0.0046)	(0.0014)	(0.0028)
ias	0.0925 ***	0.0695 *	0.1505 ***	0.0184	0.1512 ***	0.1650 ***
	(0.0249)	(0.0405)	(0.0371)	(0.1099)	(0.0384)	(0.0376)
mu	0.0752 ***	0.0865 ***	0.1668 ***	−0.1655 ***		
	(0.0195)	(0.0313)	(0.0309)	(0.0551)		
highlands	0.1024 ***				0.1151 ***	0.1000 ***
	(0.0171)				(0.0295)	(0.0229)
scope	0.0253	0.0675	0.0365	0.2526	0.0489	0.0226
	(0.0624)	(0.1120)	(0.0743)	(0.3120)	(0.2292)	(0.0727)
cons	−0.3296	0.3415	−0.8361 ***	0.0764	−0.7065 **	0.0321
	(0.1499)	(0.2288)	(0.2192)	(0.5838)	(0.2937)	(0.1964)
Sigma	0.1582 ***	0.1763 ***	0.1321 ***	0.1563 ***	0.1430 ***	0.1715 ***
	(0.0062)	(0.0102)	(0.0096)	(0.0130)	(0.0100)	(0.0086)
Year	yes	Yes	Yes	yes	Yes	yes
N.obs	410	209	109	88	117	278
Wald chi	192.86	43	93.32	60.9	85.93	135.6
Prob > chi2	0	0	0	0	0	0

Note: bootstrap std. err in parentheses; *p*-value: $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *.

4.2.1. Economic Factors

We will first focus on analyzing the results of column (2). We note that according to the literature, the signs were as expected, besides the fact that several coefficients were significant at 1%. The economic level of the locality (lvabpc) positively influenced technical efficiency ($p < 0.10$), a result that is congruent with that of Ma et al. [54] but contrary to that of Benito et al. [49]. Narbón-Perpiñá and De Witte [79] argue that municipalities with high-income residents face increasing pressure from the population to provide efficient services. Moreover, residents with higher income may pay more taxes increasing the municipal budget and, with it, the possibility of funding to improve service quality. However, analyzing columns (3)–(5), it can be observed that a population with a higher level of resources did not help explain efficiency in the highlands. In this region, the higher efficiency can be explained by a cultural factor, since, in general, it tends to provide better services and have more efficient public companies due to a more demanding population involved in public affairs, regardless of their level of income [22].

Regarding the type of management, it is observed that in municipal departments, efficiency is not affected by the economic level of the population, as opposed to the independent public companies. Since the municipal departments are not autonomous, it is likely that for those municipalities where income is higher due to higher revenues, these resources are not reflected in greater efficiency due to the possibility that they may be diverted to other services and not to reinvestment in the drinking water system.

4.2.2. Demographic Factors

Another factor that is directly related to technical efficiency is customer density (ldenc), a result that is in line with the findings presented by Guerrini et al. [55] and Song et al. [10]. The level of technical efficiency can increase in the face of an increase in the number of users by making use of economies of scale, characteristic of the sector [49]. However, it is observed that the increase in customer density does not improve efficiency in the Amazon, as is the case in other regions. Amazonian operators failed to reach a minimum threshold above which higher density increases efficiency through economies of scale. This can be seen from the quadratic term of density (see Table A3 column 5); according to these results, from a density of two, efficiency increased (natural logarithm of the density of clients).

4.2.3. Operating Factors

Within the operational factor, the volume of water loss (lvpr) negatively influenced efficiency, a finding that is corroborated in other studies such as Molinos-Senante et al. [8]. The presence of water leaks, clandestinely, among other elements that cause losses in the network, implies that the supplier produces additional potable water, which leads to a higher use of inputs [40]. This means that the benefit of reducing losses would be greater than the cost associated with their reduction, thus increasing technical efficiency. However, unlike what happens in the highlands, the great extension of the Amazon areas means that there is no benefit in the efficiency of reducing water losses, since their reduction is very costly. On the other hand, there is no evidence of scope effects, which can be explained by the fact that 97% of the suppliers also offer sewerage services, showing that this is a common characteristic of these areas.

Regarding the type of management, a decrease in water losses did not generate benefits or costs on technical efficiency for the independent companies, contrary to what happens in the municipal departments. One possible explanation is that once a public company is created, the first thing that is undertaken is to generate the bureaucracy and infrastructure for its operation, leaving aside or neglecting the aspects related to the service provision. Whereas, in the case of the Municipal Department, its ultimate purpose is focused on service provision.

4.2.4. Management and Geographic Location Factors

The type of management and geographic location had a significant influence on technical efficiency. We observed that efficiency increased when the company was in the highland region. Romano and Gerrini [60] also found that geographical location influenced efficiency.

Regarding the type of management, the one in a municipal department showed greater efficiency in comparison with the other types of management. However, in the case of the Amazon region, it is preferable is operated through a public company. Given the level of competencies available to each municipality, it is likely that despite the additional costs incurred to form an independent public company, it is beneficial for providers in this region to operate under this modality due to the large area they must cover. Thus, under these conditions, an independent PE generates specialization and is more efficient than a municipal department.

4.2.5. Natural Factors

The number of extraction sources (tfa) was not relevant in explaining efficiency at the level of the whole sample and in the Coastal region. An important difference is that a greater number of sources increases efficiency for suppliers in the Highlands, contrary to what is indicated in the literature. Considering the relief of the Highlands region, it may be less costly for suppliers located in this area to have several sources than in other regions. This is because the mountain range feature helps the pressure and fall of water to fall naturally, which does not require additional infrastructure for water distribution. In contrast, this is not the case in the Amazon region, where the relief is flat and, therefore, a greater number of water sources implies higher costs and lower efficiency.

There was also a discrepancy in the sign expected from the literature for the number of water sources in the case of independent PEs. Considering that 39% of independent PEs are located on the coast, this fact could be explained by the fact that the greater availability of water sources is a benefit rather than a cost in more desert areas.

The incidence of groundwater in the extracted water (ias) positively influenced the level of efficiency, a result in line with the literature, since the groundwater source requires fewer inputs for its potabilization compared to the surface source [4]. However, the incidence of groundwater did not affect the operators in the Amazon region. This large region is characterized by abundant flora and fauna with parks under conservation, indicating that surface water is not significantly contaminated compared to groundwater and therefore does not incur high costs compared to groundwater.

Based on the results from Table 8, it is concluded that the factors influencing technical efficiency in water management differ among various regions and management types. It is important for providers to ensure they have the necessary personnel and resources to successfully manage an autonomous company before making any changes to their management structure.

The results of this article are confined to the year 2017 due to the unavailability of data for the variables employed in our model in the 2020 INEC survey. Notably, the 2020 survey omits key variables such as network length and water loss volume, thereby restricting the evaluation of sector efficiency for more recent years using the current model. Nevertheless, given the methodological disparities, we referenced ARCA's efficiency indicators to track the evolution of efficiency during the 2019–2021 period. Our findings reveal that the percentage of providers deemed efficient or of high quality declined from 36.65% to 31.22% between 2019 and 2021, signaling a deterioration in the sector's efficiency.

5. Conclusions

This research has provided the first technical efficiency analysis of the potable water sector in Ecuador using frontier methods. The findings for the sample used during the period 2014–2017 evidenced that suppliers presented significant efficiency gaps, presenting potential savings in the use of their inputs while still maintaining the current level of production in terms of volume of water supplied and coverage. In terms of representativeness and inference, it is expected that future research can address all the counties of Ecuador.

The efficiency score results were heterogeneous according to geographic location, with suppliers operating in the Highlands region showing the highest level of efficiency on average. Possible explanations are centered on demographics, operations, and climate. No significant differences were found in the level of technical efficiency by type of management in the lowest efficiency deciles, but significant differences were found in the last deciles of their distributions. The findings show that there are no benefits of operating under an independent company modality in relation to the municipal department. In fact, the latter show significant positive differences when analyzing the most efficient productive units between the two types of management.

The findings have interesting implications for public policy. In operational terms, it is not possible to address efforts to reduce water losses for the Amazon region, since the costs are greater than the benefits that would be generated by the reduction. In this case, to improve efficiency, strategies should be sought to take advantage of economies of scale. On the other hand, the results indicate that the use of groundwater influences the level of technical efficiency, so suppliers should encourage the use of this type of source. Nevertheless, it is recognized that this factor is not under the direct control of the drinking water service providers. However, the finding indicates the need to take care of the quality of the water sources, for example, through investment in green infrastructure in order to incur lower inputs for drinking water treatment.

An additional implication is related to the type of management. The results reveal the need for greater financial funding for independent companies, as they require additional resources for their operations. However, in the Amazon region, efficiency increases if it is managed by a public company. This implies that, in this region, productive units can increase efficiency if they achieve greater administrative, technical, and financial autonomy.

In methodological terms, although variable returns to scale (VRS) were used for the calculation of efficiency under DEA double bootstrap because of the non-existence of proportionality, the use of VRS has been criticized for the possibility that there is some proportionality between certain inputs and outputs, and thus, it overestimates the efficiency scores [66]. New hybrid approaches combining CER and SVR have emerged to overcome this problem. There are other aspects that can be analyzed to contribute to the knowledge of the sector. For example, those related to the financial factor, such as budgetary issues, tariffs, or other financial indicators, such as the management of overdue accounts. Additionally, considering that data quality is an important aspect of efficiency studies, future research could apply methods to control data quality.

So far, technical efficiency has been analyzed, but it would be interesting to include the analysis of the scale efficiency of water service providers and the type of increasing or decreasing scale to shed light to policymakers on which operators have an optimal scale or are under- or over-utilizing the productive scale. Alternatively, efficiency could be analyzed by separating service operators by size [80], allowing for a comparison of efficiency between units of different sizes. A dynamic analysis of efficiency and technical change, in conjunction with the analysis of sector productivity, is a pending task. Finally, the analysis of allocative efficiency and a combination of technical and allocative efficiency can be performed to have the full picture of economic efficiency.

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Appendix A

Table A1. Form of measurement of the explanatory variables of technical efficiency.

Variable	Description	Measuring Method	Unit of Measurement	Source
lvabpc	GVA per capita	Natural log of non-oil gross value added by county deflated with CPI 2017 = 100	USD	BCE
ldenc	Customer density	Natural log number of connections per km of network	connections/km	INEC
lvpr	Water loss	Natural log of the volume of drinking water losses per km of network	m^3/km	
drt	Complaints	Total complaints density	N° PQRs/N° accounts	
tfa	Water sources	Number of extraction sources	N°	
ias	Groundwater	Incidence of groundwater on extracted water	%	ARCA
ep	Public company	1. When the supplier is a Public Company, 0. otherwise	dummy	
mu	Municipality	1. When the Municipality is directly in charge of the service provision, 0. otherwise	dummy	
Highlands	Highlands Region	1. if the supplier belongs to the Highlands region, 0. otherwise	dummy	
Coast	Coastal Region	1 if the supplier belongs to the Coastal region, 0. otherwise	dummy	
Amazon	Amazon Region	1 if the supplier belongs to the Amazon region, 0. otherwise	dummy	
scope	Scope	1 if drinking water and sewerage coverage is greater than 0, 0 if only drinking water is provided	dummy	

Table A2. Correlations between explexplanatory variables.

	Variables	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
[1]	lvabpc	1										
[2]	ldenc	−0.008	1									
[3]	lvpr	0.034	0.787	1								
[4]	drt	0.136	0.022	0.053	1							
[5]	tfa	0.259	0.036	0.008	0.098	1						
[6]	ias	0.180	0.024	−0.020	0.151	0.112	1					
[7]	ep	0.228	0.004	−0.043	−0.045	0.195	0.127	1				
[8]	mun	−0.258	−0.044	0.011	0.045	−0.166	−0.087	−0.918	1			
[9]	Highlands	−0.063	0.014	−0.139	0.048	0.095	0.042	0.045	0.035	1		
[10]	Coast	0.053	0.157	0.138	−0.043	−0.060	0.089	0.124	−0.249	−0.610	1	
[11]	Amazon	−0.028	−0.193	0.018	−0.010	−0.044	−0.200	−0.173	0.208	−0.538	−0.314	1
[12]	scope	0.076	−0.023	−0.024	0.013	−0.022	−0.047	0.048	−0.057	0.038	−0.075	0.031

Table A3. Quadratic effects of the economic factor and customer density on technical efficiency.

Variables	Full Sample (2)		Highlands (3)		Coast (4)		Amazon (5)		Independent PE (6)		Municipal Dept. (7)	
lvabpc	−0.0965		0.1208		2.0764	***	−3.0934		2.7597	***	0.0982	
	(0.2065)		(0.2544)		(0.4832)		(1.9473)		(0.6954)		(0.2399)	
lvabpc × lvabpc	0.0073		−0.0058		−0.1293	***	0.1922		−0.1653	***	−0.0046	
	(0.0126)		(0.0153)		(0.0304)		(0.1241)		(0.0432)		(0.0146)	
ldenc	0.0497	***	0.0316	***	−0.0178		−0.0311		−0.0042		0.0663	***
	(0.0091)		(0.0106)		(0.0160)		(0.0265)		(0.0150)		(0.0107)	
ldenc × ldenc	0.0243	***	0.0279	***	0.0299	***	0.0312	***	0.0159	***	0.0299	***
	(0.0017)		(0.0025)		(0.0033)		(0.0059)		(0.0039)		(0.0021)	
lvpr	−0.0067		−0.0219	***	0.0027		0.0467	**	0.0117		−0.0226	***
	(0.0049)		(0.0071)		(0.0081)		(0.0230)		(0.0104)		(0.0062)	
cons	0.1945		−0.4804		−8.2259	***	12.3446		−11.2195	***	−0.5603	
	(0.8358)		(1.0472)		(1.9031)		(7.6280)		(2.7828)		(0.9823)	
sigma	0.1326	***	0.1382	***	0.1110	***	0.1798	***	0.1444	***	0.1397	***
	(0.0050)		(0.0073)		(0.0080)		(0.0167)		(0.0103)		(0.0065)	
Year	Yes		Yes		Yes		Yes		Yes		Yes	
N.obs	418		209		112		86		120		275	
Wald chi	522.84		196.91		205.2		58.45		87.02		398.54	
Prob > chi2	0		0		0		0		0		0	

Note: bootstrap std. err in parentheses; *p*-value: $p < 0.001$ ***, $p < 0.05$ **. The lvabpc × lvabpc and ldenc × ldenc variables indicate the multiplication of variables.

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