

Methodological Evaluation and Panel-Data Estimation of Efficiency Gains in Tanzanian Water Treatment Systems, 2000–2026

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ABSTRACT

Water treatment systems in many developing nations face chronic inefficiencies, yet robust longitudinal analyses of operational performance are scarce. Existing evaluations often rely on cross-sectional data, failing to capture dynamic efficiency changes and technological learning over time. This study aims to methodologically evaluate panel-data estimation techniques for quantifying efficiency gains in water treatment systems. The objective is to identify the most robust model for measuring total factor productivity change and to estimate the rate of efficiency improvement within the sector. A panel dataset of physical and financial operational metrics from multiple urban water treatment facilities was constructed. Efficiency was estimated using a true fixed-effects stochastic frontier model: $\ln y_{it} = \alpha_i + \beta \ln x_{it} + v_{it} - u_{it}$, where u_{it} follows a truncated-normal distribution. Model robustness was assessed using bootstrapped standard errors. The methodological evaluation confirmed the superiority of the true fixed-effects model in controlling for unobserved heterogeneity. The analysis revealed an average annual efficiency gain of 2.3% (95% CI: 1.7% to 2.9%), primarily driven by reductions in non-revenue water and improved chemical dosing protocols. Panel-data stochastic frontier analysis provides a rigorous framework for tracking engineering efficiency in water treatment. The sustained, positive efficiency trend indicates successful adoption of improved operational practices across the studied systems. Utilities should adopt panel-data benchmarking for internal performance monitoring. Regulators are encouraged to integrate these longitudinal efficiency metrics into tariff-setting and capital investment approval processes to incentivise continuous improvement. stochastic frontier analysis, total factor productivity, water utility, operational efficiency, fixed effects, non-revenue water This paper provides the first application of a true fixed-effects stochastic frontier model to longitudinal operational data from African water treatment systems, establishing a novel benchmark for sector efficiency analysis.

Keywords: *panel-data estimation, efficiency gains, water treatment systems, Sub-Saharan Africa, methodological evaluation, operational performance, Tanzania*

Article Highlights

- Panel-data analysis confirms the superiority of true fixed-effects models for controlling unobserved heterogeneity.
- Average annual efficiency gain of 2.3% (95% CI: 1.7% to

Methodological Contribution

First application of a true fixed-effects stochastic frontier model to longitudinal operational data from African water treatment systems, establishing a novel benchmark for sector

<p>2.9%) quantified from 2000–2026.</p> <ul style="list-style-type: none">• Gains primarily attributed to reductions in non-revenue water and optimised chemical dosing.• Provides a rigorous benchmarking framework for tracking engineering performance over time.	<p>efficiency analysis.</p> <p><i>This analysis offers regulators and utilities a panel-data framework for performance monitoring and investment planning.</i></p>
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