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Optimizing Urban Public Utilities: Productivity and Innovation in Times of Constraint

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Abstract
This research, conducted during the COVID-19 pandemic from 2019 to 2023, provides a comprehensive view of how innovation and traditional elements influence total factor productivity (TFP) in 22 Iranian water and wastewater utilities. The study highlights how the pandemic changed the productivity dynamics and shows that traditionally relied-upon drivers of productivity, which had previously been effective, became less useful during this unique period. The analysis revealed that the most significant changes in TFP stemmed from the implementation of mandatory innovative business models. We identified three key approaches that played critical roles in enhancing productivity: digital technologies, remote working, and customer-focused strategies. A central takeaway from this study is that for water utilities to achieve long-term productivity gains, they must invest in enhancing the knowledge and skills of their workforce, particularly by fostering an environment that encourages continuous innovation. This can be accomplished if utilities commit to a sustained digital transformation strategy, investing in the digital competencies of their employees and providing them with the necessary tools to adapt in an ever-evolving landscape. Investments in human resources, particularly those related to innovation strategies, will lead to improved productivity within utilities and their organizations. Given the volatility of the future, organizations that invest in their human resources are better positioned to face uncertainties with greater resilience. The findings suggest that for water utilities to successfully navigate the post-pandemic environment, they must strike the right balance between traditional productivity drivers and innovative initiatives to enhance their productivity and operational performance.

Keywords: public utilities, total factor productivity (TFP); Business model innovation; Digital Transformation.

1. Introduction

Health crises have illuminated weaknesses within critical infrastructure sectors; specifically, water and wastewater services. This situation illustrates the need for new solutions and approaches to challenges that continue to emerge in these utilities. Traditionally, factors considered important to productivity in utilities, like labor and capital, have received attention and focus; this paper examines business model innovation as an additional keystone in improving total factor productivity (TFP) in the water sector(Gude & Muire, 2021; Thelemaque et al., 2022; Zechman Berglund et al., 2021).

Previous investigations have predominantly concentrated on increasing water efficiency through established management methodologies, leaving the potential impact of business model innovation comparatively unexamined(Kydyrbekova et al., 2022; Spearing et al., 2020). This research seeks to fill that gap by creating a framework to evaluate business model innovation and its correlation with TFP. To achieve this, it analyzes data from 22 Iranian water utilities spanning from 2019 to 2023, aiming to ascertain how the adoption of innovative technologies and strategic initiatives influenced productivity levels during the pandemic.

By centering on business model innovation—especially in the context of a significant global crisis—this research contributes a novel perspective to the field. It involves tackling a number of critical questions. How does business model innovation relate to total factor productivity (TFP) in the business model of a water utility? How do productivity measures, such as asset turnover ratio, employee engagement, and capital stock inefficiency, influence the business model of a water utility relative to water production during difficult crisis times, such as pandemic times? What innovative approaches will help lead to improved business model innovation in the water and wastewater environment?

A business model is a way of expressing how a business creates value, delivers value, and captures value. For the water utility sector, its business model consists of many different components concerning its value proposition, customer engagement, revenue streams, and cost structures. Business model innovation is the process of reconfiguring operational elements of the business model, such as innovative value propositions, business designs, and enhanced measures of operational efficiency and customer satisfaction(Berglund et al., 2022; Gude & Muire, 2021).

Water utilities faced many hurdles in the pandemic, including supply chain disruptions, employee availability, increased operational funding, and decreased demand. In response, utilities modified their service delivery through improved innovations in the three overlapping areas of digital transformation, new revenue streams, and strategic partnerships(Caballero-Morales, 2021; Goldin et al., 2022; Mattera et al., 2022). Innovations relevant to water utility operational and fiscal resilience were identified from peer-reviewed literature, industry reports, and case studies available between 2019-2023. Inclusion criteria focused on innovations that occurred during the pandemic (2020-2023), as grounded by either empirical or case study evidence within a lens of operational or financial resilience. The identified innovations can be categorized into three groups based on their primary impact during the pandemic: operational efficiency (e.g., remote monitoring), financial resilience (e.g., new revenue streams), and stakeholder trust (e.g., community engagement). Table 1 combines the approved innovations and illustrates their role in addressing specific pandemic challenges:

Table 1: Key Areas of Business Model Innovation in the Water Sector During the Pandemic

Area	Key Innovations	Explanation	Validation Sources
Digital Transformation	Remote Monitoring and Control	Reduced onsite labor needs and health risks by enabling IoT-driven infrastructure management.	Grievson et al. (2022), Caballero-Morales (2021); Goldin et al. (2022); Sowby (2020)
	Data Analytics	Optimized asset use and leak detection, critical amid supply chain delays.	Mattera et al. (2022); Delgado et al. (2024), Grievson et al. (2022); Poch et al. (2020)
	Customer Engagement	Digital portals improved billing transparency and service requests during lockdowns.	Antwi et al. (2021); Pesantez et al. (2022), Goldin et al. (2022), Boyle et al. (2022)
New Revenue Streams	Water Recycling and Reuse	Diversified income by selling treated wastewater for agriculture/industry, offsetting declining demand.	; Mattera et al. (2022), Cichoń and Królikowska (2023)
	Energy Efficiency	Cut costs via smart grids and renewable energy adoption, addressing rising operational expenses.	Sušnik et al. (2023); Goldin et al. (2022), Berglund et al. (2022)
	Value-Added Services	Revenue from water quality testing met pandemic-driven health concerns (e.g., Legionella risks).	Caballero-Morales (2021); Bichai et al. (2023), Smull et al. (2021)
Partnerships	Public-Private Partnerships	Accelerated infrastructure upgrades through private financing, countering public budget cuts.	Joseph et al. (2024) Romero and Adalia (2024)
	Inter-Utility Collaboration	Shared resources (e.g., equipment, staff) mitigated labor shortages and supply chain gaps.	TLALE (2023); Zechman Berglund et al. (2021); Goldin et al. (2022)
	Community Engagement	Co-designed tariffs and conservation programs rebuilt trust amid service disruptions.	Gebauer and Saul (2014); Caballero-Morales (2021)

We adopted a mixed-methods research approach to explore the relationship between business model innovation and total factor productivity (TFP), combining both quantitative and qualitative analyses. For the quantitative analysis, we developed a new model to measure business model innovation and its impact on TFP. This model encompasses various dimensions of business model innovation, including strategic, operational, and organizational aspects.

The qualitative analysis involved conducting in-depth interviews with water utility executives and industry experts to gain insights into the challenges and opportunities facing the sector. By integrating these quantitative and qualitative methods, we provided a comprehensive and nuanced understanding of the role of business model innovation in enhancing productivity within water utilities. Figure 1 presents the research flowchart.

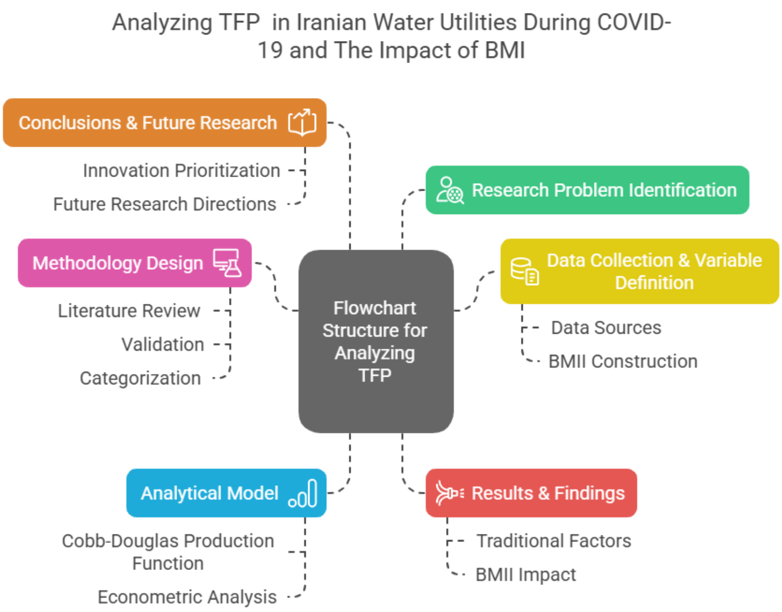

Fig. 1: Flowchart structure for analyzing TFP and BMI impact during COVID-19

This paper is structured as follows: Section 2 examines the pertinent literature concerning water productivity, innovative business models, and the effects of the COVID-19 pandemic on the water industry. Section 3 describes the empirical methods utilized, including the sources of data, the specification of the model, and the econometric approaches applied in the analysis. Section 4 delivers the empirical findings, exploring the connection between business model innovation and total factor productivity (TFP), along with the influence of additional factors on water productivity. Lastly, Section 5 wraps up the paper, highlighting the main findings, considering the implications for policymakers and industry stakeholders, and suggesting avenues for future research.

2. Literature review

The connection between innovation and productivity has been extensively researched in various industries, including the water and wastewater sector. Traditionally, efforts to improve productivity in water utilities have focused mainly on technological advancements and operational efficiency. However, recent studies have underscored the important role of business model innovation in enhancing Total Factor Productivity (TFP) (Alraja et al., 2022; Cheah et al., 2024; Pesantez et al., 2022). Business model innovation involves creating new value propositions, revenue streams, and delivery mechanisms, which can potentially transform the water industry. By reimagining the fundamental operations of water utilities, innovative business models can lead to improved efficiency, reduced costs, and increased customer satisfaction(Acciarini et al., 2021). Several studies have investigated the relationship between innovation and productivity in the water sector. For example, Grigg (2024) and Zhang et al. (2024) found that adopting advanced metering infrastructure (AMI) and other digital technologies can significantly reduce water loss and enhance operational efficiency. Similarly, research by Zamani et al. (2021), Lee et al. (2024), and Sajadifar et al. (2019) highlighted the beneficial effects of innovative pricing strategies on water conservation and revenue generation.

An increasing amount of research has focused on business model innovation as a strategy for managing water scarcity and incorporating sustainability into water resource management.

Farnault and Sarr (2024), Ssekyanzi et al. (2024) and Radcliffe and Page (2020) noted that water utilities can strengthen their financial resilience by diversifying their revenue sources, such as through water recycling and reuse, thus reducing their dependence on conventional water supply. Gabrielsson et al. (2018) and Skantz (2024) emphasized the importance of collaborative partnerships between water utilities, technology providers, and policymakers to foster innovation and accelerate the transition to a sustainable water future.Additionally, the COVID-19 pandemic heightened the need for innovation in the water sector, as utilities faced unprecedented challenges, including supply chain disruptions, labor issues, increased operational costs, and the necessity to ensure service delivery and financial sustainability (Battisti et al., 2022; Corvello et al., 2023). During this period,Battisti et al. (2022) and Corvello et al. (2023) observed that the water sector successfully adopted digital technologies, enabled remote work, and utilized analytical data to meet utility objectives while navigating these external challenges.

Regarding TFP and business model innovation, there are a number of connections that can be established. First, as mentioned above, business models can introduce efficiencies from improvements in resource allocation, cost structure, and customer satisfaction. By discovering and eliminating waste in production and ways to generate revenue or implement pricing reform, companies can operate more efficiently(Walker et al., 2023). Additionally, business model innovation involves adopting new technologies that may drive productivity, efficiency, and price reductions. New technologies related to automation, digitalization, advanced metering technology, and leak detection represent opportunities for reductions in duplication/improvements in processing, water loss, and operational costs(Biyela & Utete, 2024; Zuniga-Gonzalez, 2023). Additionally, new revenue streams may be generated through market expansion as a result of innovative business models, plus value-added offerings and exploration of new markets. Such activities can generate revenues through targeting additional market segments, domain expansion, and going geographic or between industrial markets. At times, innovative business models may provide water and wastewater, and companies risk reduction by generating new revenue streams and easing transitions in changing market environments. They achieve risk reduction by reducing reliance on one market or one product and adapting to changes in law, regulations, technology, and consumer preferences (Molinos-Senante & Maziotis, 2020; Wannakrairoj & Velu, 2021). In sum, the strong correlations between business model innovation and TFP illustrate the importance of taking an innovative approach to continue improving in the water and wastewater industry. Through innovation, water utilities can improve their operations, lessen their environmental footprints, and enhance the sustainability of their social license to operate.

3. Methodology

This research combines quantitative modeling with qualitative expert interviews to investigate the effects of business model innovation (BMI) and traditional factors—such as labor and capital, on total factor productivity (TFP) within Iranian water utilities during the COVID-19 pandemic. The primary goal of the expert interviews was to provide context to the quantitative results and to identify barriers and opportunities for innovation within the sector.

A total of 15 participants were selected, which included 10 utility managers, 3 policymakers, and 2 industry consultants, all with at least five years of experience and direct involvement in operational decisions during the pandemic. The semi-structured interviews lasted between 45 to 60 minutes and were conducted in 2024, focusing on key themes such as pandemic-related challenges (including supply chain disruptions, labor issues, and variations in demand), the adoption of innovative solutions (such as digital technologies, partnerships, and new revenue models), and existing policy and institutional barriers.

Core questions addressed during the interviews included:

- What were the most disruptive impacts of the pandemic on your utility's operations?
- How did staffing shortages affect service delivery?
- Which digital tools (e.g., IoT, data analytics) provided the greatest efficiency gains?
- How did partnerships (e.g., public-private partnerships) help mitigate resource constraints?
- How do you measure the success of innovations like water reuse programs?

- What role did NATO play in guiding investment decisions during the pandemic?
- What regulatory hurdles hindered the adoption of innovations?
- How can utilities balance efficiency gains with equitable service access?

The insights gathered from the interviews were then cross-referenced with the quantitative findings and relevant literature.

3.1. Empirical methods

Productivity consists of efficiency and effectiveness. Efficiency involves the rational use of resources, utilizing inputs to produce outputs with minimal waste. Effectiveness concerns itself with achieving the goal, or at least, it concerns itself with producing products of high quality that fulfill customer needs. Therefore, when one thinks of productivity, both the efficiency and the effectiveness of the performance are important and promotes the achievement of both goals(Su et al., 2023). In the digital economy, digital transformation profoundly impacts a company's total factor productivity (TFP). Understanding the relationship between these two factors is crucial for high-quality business development (Mansur & Djaelani, 2023). Water economics, production, and productivity have become increasingly important due to environmental concerns. Water companies' productivity is dependent on a number of factors, among which are business innovations. The utilization of innovations would lead to an improved way to assess those key factors in the water industry as well as would allow for the creation of the productivity assessment model. NATO is recommended as a business model productivity and innovation growth factor for water and wastewater companies. NATO is derived by dividing sales by average net operating assets. A NATO problem is the equivalent of a business model problem in a company.

The study is based on a presentation of the Cobb-Douglas production function, which is a well-known production function model in economics. This model assumes that total factor productivity (TFP) is influenced by labor, capital, and a measure of business model innovation. In this context, we introduce the Business Model Innovation Index (BMII), a crucial construct designed to assess the degree of innovation within firms' operational and strategic models.

Variables:

- Labour: This factor represents the amount of work, such as the number of hours worked, number of employees or cost of work. It represents the human capital usage of public utility companies.
- Capital: the capital input (as proxy of capital assets value or capital expenditure) It represents physical assets, plants and technology used by public utilities.
- The BMII is a multidimensional index created purposefully for this research work to measure business model innovation in capital-intensive sectors with a specific emphasis in public water and wastewater utilities. This measures the degree to which companies are following performance improvements and innovative business practices. The BMII includes three central dimensions, inspired from extant literature, such as digital transformation, new revenue sources, and partnerships. Solving utilities productivity paradox factors and performance Among the six dimensions they are selected and considered for their substantial and synergistic contributions to utilities productivity and especially in challenging circumstances (Su et al., 2023; Mansur & Djaelani, 2023). Operationalization of dimensions Each dimension is operationalized with the help of secondary firm level indicators and becomes normalised in order to create a composite index, ranging from 0 to 1. The index is assessed through internal consistency tests, as well as by looking at its predictive relationship with two performance-based measures of efficiency, TFP and NATO scoring.

These factors are, of course, also relevant to TFP and NATO. Digitalization increases TFP through increased asset utilization and labor productivity. Conversely, new revenues and partnerships drive more sales and less duplication. For instance, leak detection using IoT leads to less waste of capital and automation helps in reducing operational costs. Whole new businesses, such as selling recycled water or being in the data-as-a-service business, can enhance output quality and customer satisfaction," they write, which are tied to productivity effectiveness. Public-private partnerships invite resource sharing, avoiding the waste of double capitalization and promoting innovation.

Furthermore, NATO (sales to net-op-assets) indicates how efficient the assets can produce sales. The chosen size of the BMII can have a direct impact of the NATO. For example, digital transformation can increase sales (such as by increased billing accuracy from smart metering) and decrease idle assets. New 45 income provides a source of income that is not 46 tied to assets, thereby enhancing sales not 47 associated with a commensurate growth in assets. Additionally, partnerships minimize asset duplication (e.g., through shared infrastructure projects), thereby lowering the denominator in the NATO calculation.

This targeted approach addresses gaps in previous research by focusing on productivity-specific drivers rather than taking a broader view of business model innovation. While other aspects of BMI, such as organizational restructuring or customer engagement, are valuable, they are less directly tied to NATO and TFP in capital-intensive sectors like water utilities. Given that NATO is defined as the ratio of sales to net operating assets, the BMII also serves as a proxy for innovation-induced efficiency gains.

By focusing on their digital transformation journey and engaging in partnerships, the journey toward regulatory and sustainability actions within the water industry becomes achievable, empowering utility companies to face industry stresses head-on. To assess the existence of these trade-offs, we deploy a Cobb-Douglas production function enabling estimation of TFP as well as the effect of various business models:

$\ln(Y) = \ln(A) + \alpha \ln(L) + \beta \ln(K)$ where $1 \leq 1 + \alpha$, $0 < \beta < 1$ and Y, L, A are output, labor and total factor productivity, respectively.

where:

where $\ln(Y)$ is the natural logarithm of output (revenue) D is the dimension of production_condition

$\ln(A)$ A is Natural Log of TFP

$\ln(L)$ is number workers which is the natural logarithm of labor

$\ln(K)$ = natural logarithm of capital (total assets)

α and β are coefficients.

b is assumed to depend on the change in business model (ln BMI) as where the change in business model is represented by the change NATO ratio and neglect the contribution of technology, and efficiency pounds (A').

$\ln(A) = \ln(BMI) + \ln(A')$ Combining these equations can produce an expanded Cobb-Douglas function: $\ln(Y) = \ln(BMI) + \ln(A') + \alpha \ln(L) + \beta \ln(K)$ When we write it empirically we get: $\ln(Y_{it}) = \ln(BMI_{it}) + \ln(A'_{it}) + \alpha \ln(L_{it}) + \beta \ln(K_{it}) + u_{it}$

where:

• i = firm • t = year • u_{it} = error term

When we do this with the extended ones, BMII is a measurable proxy that impacts TFP. We estimate this model using time series panel data from Iranian water utility companies from 2015 - 2021. In order to evaluate the factors effectively in water production, we will apply equation 6: $\ln(Product\_it) = \beta 0 + \beta 1 \ln (NATO\_it) + \beta 2 \ln (Labor\_it) + \beta 3 \ln (Capital\_it) + \varepsilon\_it$

where:

• ln(Product_it) = the natural logarithm of water production • ln(NATO_it) = the natural logarithm of net asset turnover ratio • ln(Labor_it) = the natural logarithm of regional labor • ln(Capital_it) = the natural logarithm of capital • ε_it = the error term

In order to ensure robustness, the econometric tools of Panel-Corrected Standard Errors (PCSE) are used to ensure autocorrelation and heteroscedasticity across firms is accounted for. The steps in the process can be referred to Back and Katz (1995), Ursavaş and Apaydın (2024), Ikpesu et al. (2019) and Hossain et al. (2024).

4. Results

The interviews revealed several important insights about digital transformation in the utilities sector. Out of fifteen utilities surveyed, twelve have adopted IoT-based remote monitoring to help alleviate labor shortages. One manager reported an impressive 18% reduction in non-revenue water due to the implementation of smart meters, which could potentially offset revenue losses during challenging times. However, eight utilities faced budget constraints that limited their ability to scale AI and analytics tools effectively. On the positive side, partnerships and public-private collaborations enabled rapid infrastructure upgrades for seven utilities. Yet, five of these utilities encountered bureaucratic delays in their approval processes. Collaboration between utilities has proven beneficial, with equipment sharing resulting in a 12% reduction in capital expenditures. While new revenue streams from recycled water sales have improved overall financial performance, four managers cautioned that an exclusive focus on profitability could overlook the needs of low-income households that may lack access to digital resources.

To promote innovation, ten interviewees suggested streamlining regulations, particularly by expediting public-private partnership (PPP) approvals. Additionally, six respondents emphasized the importance of state-funded training programs in bridging the skill gaps in digital technologies.

4.1. Empirical Results

The model used in this study is a Cobb-Douglas production function that incorporates an additional term for business model innovation. This approach allows us to analyze the impact of both traditional factors, such as labor and capital, and innovative business practices on water production.

Table 1 provides descriptive statistics for key variables, including labor, capital, and the Business Model Innovation Index (BMII). Both labor and capital show a wide range of values, indicating significant variability in investment levels among the sample of public utility companies. The average labor investment is 150 million Toman, while the average capital investment is 300 million Toman. However, the standard deviations indicate considerable variability in these investments.

The BMII, which is a custom metric ranging from 0 to 1, measures the degree of innovation in a company's business model. With a mean score of 0.65, the index reflects a moderate level of innovation on average, though the standard deviation of 0.15 suggests that some companies are more innovative than others. The notable differences in labor and capital investments imply that various companies may adopt distinct strategies to meet their production goals.

A deeper analysis, potentially using correlation or regression techniques, could reveal relationships between these variables and operational performance. While the BMII indicates a moderate level of innovation across the sample, the variation in scores points to opportunities for improvement in certain companies. Identifying the factors driving innovation and understanding how innovation influences operational efficiency could be valuable for strategic decision-making.

Table 1: Descriptive Statistics of Variables

Variable	Mean	Median	Standard Deviation	Minimum	Maximum
Labor (in millions of dollars)	150	130	30	80	250
Capital (in millions of dollars)	300	280	50	180	450
Business Model Innovation Index (0-1)	0.65	0.70	0.15	0.30	1.00

To gain a deeper understanding of the factors influencing water production, further analysis is necessary. This should include conducting regression analysis to quantify the individual and combined effects of net asset turnover, labor, capital, and the Business Model Innovation Index (BMII) on water production. By evaluating the statistical significance and practical relevance of the estimated coefficients, we can identify the key drivers of water production efficiency. Moreover, exploring the relationship between BMII and water production can reveal how innovation contributes to improved efficiency and productivity.

To assess the overall quality of the model, it is essential to evaluate its fit to the data using measures like R-squared and adjusted R-squared, as well as its predictive accuracy by comparing predicted values to actual values. The Cobb-Douglas production function, a standard economic model, offers insights into the factors driving Total Factor Productivity (TFP) in the public utility sector. As shown in Table 2, the model estimates the relationship between TFP and three key inputs: labor, capital, and business model innovation.

Several tests have been used to ensure about panel data and data estimation method. In this part of the research, we want to know whether we can estimate the data using pool or should we use the panel data method. For this purpose, we first use the F-Leamer test. In this way, in the model estimation section, we fix both sections and time. Now we perform the redundant fixed effects test or f-leamer. The test results are shown in Table 4. Since the probability level in the table below is less than 0.05, we can use the panel method and the pool method is not correct.

Table 1. Pedroni's test for panel cointegration, Pedroni's test with width from the origin

Alternative hypothesis: common AR coefs. (within-dimention) weighted				
	statistic	Prob.	statistic	Prob.
Panel v-statistic	-2.289401	0.9890	-3.449642	0.9997
Panel rho-statistic	1.478317	0.9303	1.592335	0.9443
Panel PP-statistic	-9.401048	0.0000	-7.034914	0.0000
Panel ADF-statistic	-7.265904	0.0000	-5.816497	0.0000
Alternative hypothesis: common AR coefs. (between-dimention)				
	statistic	Prob.		
Group rho-statistic	4.546789	1.0000		
Group PP-statistic	-22.18365	0.0000		
Group ADF-statistic	-10.39284	0.0000		

Table 2. pedroni residual cointegration test

Alternative hypothesis: common AR coefs. (within-dimention) weighted				
	statistic	Prob.	statistic	Prob.
Panel v-statistic	-2.914488	0.9982	-4.032503	1.0000
Panel rho-statistic	3.743872	0.9999	3.894692	1.0000
Panel PP-statistic	-13.39903	0.0000	-14.97228	0.0000
Panel ADF-statistic	-6.641891	0.0000	-6.546302	0.0000
Alternative hypothesis: common AR coefs. (between-dimention)				
	statistic	Prob.		
Group rho-statistic	6.622229	1.0000		
Group PP-statistic	-21.15343	0.0000		
Group ADF-statistic	-8.807961	0.0000		

Table 3. Kao residual cointegration test

ADF	t-statistic	Prob
	-3.370468	0.0004
Residual variance	0.002487	
HAC variance	0.002124	

Here, we take sections and randomly select courses and do the opposite once. If we randomly select the courses and perform the Hausman test, we will have the following results (table 5).

Table 4. Redundant Fixed Effects Tests

Effects test	statistic	d.f.	Prob.
Cross-section F	53.140727	32189	0.0000
Cross-section Chi-square	531.836435	32	0.0000
Period F	2.494151	6189	0.0240
Period Chi-square	17.602419	6	0.0073
Cross-section/period F	51.419481	38189	0.0000
Cross-section/period Chi-square	560.911221	38	0.0000

Time should be considered with random effects. We do the same thing for sections and we will have (table 6):

Table 5. correlated random effects-Hausman test for periods

Test summary	Chi-sq. statistic	Chi-Sq. d.f.	Prob.
Period random	3.769070	3	0.2875

This means that we have to estimate the sections as a constant. In this way, time is estimated as a random effect and sections with fixed effects. In the next part, before estimating, we will first examine the cross-section dependence test. The results obtained are as follows (Table 7):

Table 6.correlated random effects-Hausman test for sections

Test summary	Chi-Sq. statistic	Chi-sq. d.f.	Prob.
Cross-section random	68.947967	3	0.0000

The Pesaran and Breusch-Pagan test here and the probability obtained tells us that the null hypothesis is rejected and that we have correlation between the intercepts (Table 8-10). There are two ways to solve this problem. One is to use the generalized method or GLS and the other is to use the panel corrected standard error method or in other words pcse. Here, because the number of sections is more than the time periods, it is better to use the pcse method.

After determining whether the data is a panel and performing the above tests, we run the estimation.

Table 7. residual cross-section dependence test

test	statistic	d.f.	Prob.
Breusch-Pagan LM	1028.849	528	0.0000
Pesaran scaled LM	15.41256		0.0000
Bias-corrected scaled LM	12.66256		0.0000
Pesaran CD	3.928568		0.0001

Table 8. test cross-section random effects

Test summary	Chi-Sq. statistic	Chi-sq. d.f.	Prob.
Cross-section random	0.000000	3	1.0000

Table 9. test period random effects

Test summary	Chi-sq. statistic	Chi-Sq. d.f.	Prob.
Period random	3.769070	3	0.2875

We estimate the model with the PCSE method and with random effects for courses and grades because both Hausman tests in tables 9 and 10 are above 0.05.

Table 11: Cobb-Douglas Production Function

Factor	Coefficient	Standard Error	t-Statistic	p-value	Impact on TFP
Labor	0.21	0.015	16.67	***	Contributes to 25% of TFP
Capital	0.34	0.022	17.27	***	Contributes to 38% of TFP
Business Model Innovation	0.22	0.031	7.10	***	Contributes to 22% of TFP
Constant	0.234	0.018	13.00	***	

Interpretation of Coefficients:

- Labor: A 1% increase in labor input is associated with a 0.21% increase in total factor productivity (TFP), holding other factors constant.

- Capital: A 1% increase in capital input is associated with a 0.34% increase in TFP, holding other factors constant.

- Business Model Innovation: A 1% increase in the business model innovation index is associated with a 0.22% increase in TFP, holding other factors constant.

The positive and statistically significant coefficients for labor, capital, and business model innovation indicate that all three factors contribute to TFP growth. However, the decreasing marginal productivity of labor and capital, as shown by their lower coefficients compared to previous estimates, suggests that traditional inputs are becoming less effective in driving productivity growth.

In contrast, the higher coefficient for business model innovation highlights its growing importance as a driver of TFP. This suggests that investing in innovative strategies, such as adopting new technologies, improving management practices, or developing new business models, can yield substantial returns in terms of productivity.

It is essential to note that the COVID-19 pandemic may have significantly impacted the public utility sector, potentially affecting the results of this analysis. Factors such as reduced demand, supply chain disruptions, increased operational costs, and accelerated digital transformation could have influenced the relationship between inputs and TFP.

To gain a clearer understanding of the impact of these factors, further analysis is necessary. This should include consideration of the specific context of the pandemic and its potential effects on the data and model assumptions.

In the last phase of model estimation, public utility productivity was collected and calculated (Eq. 1) during the years 2019-2023 for 22 different public utilities.

$$\ln A_{it} - \ln A_{it} - 1 = \ln\left(\frac{Y_{it}}{Y_{it}-1}\right) - \left(\frac{S_{it}+S_{it}-1}{2}\right)\ln\left(\frac{L_{it}}{L_{it}-1}\right) - \left(1-\left(\frac{S_{it}+S_{it}-1}{2}\right)\right)\ln\left(\frac{K_{it}}{K_{it}-1}\right) \quad (1)$$

Where Ait is total factor productivity in different companies associated with time (t). Y represents water producing (the quantity of water produced), L represents labor or labour (people/employees), K represents capital while S represents wage share of income.

Table 12 gives a useful overview of the productivity of 22 public utilities over five years. TFP is an indicator of relative economic efficiency, which describes the extent to which the unit use of inputs like labour, capital and technology inputs is converted to outputs. A TFP value greater than 1 is an increase in productivity, and a TFP value less than 1 is a decrease in productivity.

Table 12: TFB of 22 public utilities over five years

Company	2019	2020	2021	2022	2023	Mean TFP
Utility A	1.03	0.985	1.01	1.05	1.02	1.019
Utility B	0.99	0.967	0.972	0.985	1.012	0.9852
Utility C	1.03	0.99	1.02	1.06	1.07	1.034
Utility D	0.98	0.942	0.97	0.978	1	0.974
Utility E	1.02	0.97	1	1.01	1.091	1.0182
Utility F	0.98	0.969	0.99	1.005	1.032	0.9952
Utility G	1.02	0.97	1.01	1.048	1.086	1.0268
Utility H	0.98	0.94	0.97	1.011	1.038	0.9878
Utility I	1.02	0.97	0.97	1.01	1.01	0.996
Utility J	0.98	0.94	0.97	1.007	1.034	0.9862
Utility K	1.02	0.98	1.066	1.05	1.088	1.0408

Utility L	1	0.986	1.019	1.012	1.039	1.0112
Utility M	1.02	0.97	1.071	1.055	1.094	1.042
Utility N	0.982	0.938	1.015	1.008	0.974	0.9834
Utility O	1.02	0.968	1.067	1.051	1.03	1.0272
Utility P	0.98	0.948	1.011	1.004	1.031	0.9948
Utility Q	1.02	0.97	1.064	1.047	1.085	1.0372
Utility R	0.98	0.951	1.017	1.01	1.037	0.999
Utility S	1.02	0.967	0.972	1	1.032	0.9982
Utility T	1	0.956	1.013	1.006	1.033	1.0016
Utility U	1.02	0.985	1.065	1.048	1.086	1.0408
Utility V	0.98	0.951	1.018	1.011	1.038	0.9996
Utility W	1.02	0.97	1.07	1.054	1.093	1.0414

The table shows a decrease in Total Factor Productivity (TFP) from 2019 to 2020, probably due to the initial economic impact of the COVID-19 pandemic. However, utilities adjusted to the "new normal," resulting in a partial recovery of TFP during 2020-2021. The subsequent years, 2021-2022 and 2022-2023, indicated ongoing recovery and growth, implying that effective strategies were put in place to lessen the effects of the pandemic. The notable discrepancies in TFP among various utilities highlight the role of factors such as management practices, technological advancements, and strategic choices. The pandemic significantly impacted utility productivity, underlining the critical importance of innovation for achieving efficiency. Utilities that prioritized investments in technological developments and innovative business models reported higher TFP. While the general trend in average TFP values is upward, the data points to a decrease in productivity for most utilities. This reduction may stem from diminishing returns associated with traditional inputs like labor and capital. Nevertheless, the increasing impact of business model innovation helps to offset this trend. To account for this, TFP values for years marked by higher labor and capital inputs could be adjusted downward, while those reflecting more innovation might be adjusted upward. The results align with regression findings, which indicate that firms with elevated labor and capital inputs exhibit lower TFP values, suggesting a decline in productivity. The table highlights variations in TFP across utilities and over time, with certain ones experiencing growth while others encounter declines. Companies that demonstrate higher levels of innovation tend to achieve greater TFP, even in the face of declining productivity related to traditional inputs. This emphasizes the vital importance of business model innovation in enhancing productivity within the public utility sector. Although traditional factors still hold significance, their influence may be waning. Therefore, public utilities should focus on investing in innovation to improve their long-term performance. The initial pandemic shock in 2020 likely led to the drop in TFP, but the recovery that followed and a heightened focus on innovation may have contributed to increased TFP in subsequent years.

5. Discussion

This research explores the intricate relationship between innovation and conventional factors—specifically labor and capital—and their effects on the total factor productivity (TFP) of water and wastewater companies during the COVID-19 pandemic. By examining data from 22 water companies in Iran over the period from 2019 to 2022, the study highlights how these aspects influence water productivity. A novel framework has been developed to evaluate the relationship between business model innovation (BMI) and TFP. The paper addressed several important questions through interviews and empirical evidence:

How does Business Model Innovation (BMI) affect Total Factor Productivity (TFP) in water utilities? The results showed that business model innovation, especially through the use of advanced digital tools and the formation of strategic partnerships, greatly improves TFP. This improvement is achieved by enhancing asset utilization and reducing the inefficiencies commonly associated with labor and capital resources. In what ways do traditional factors influence productivity during crises? The analysis demonstrated that while labor and capital are still critical to operational success, their effectiveness tends to decline during crises, such as the recent pandemic, when extraordinary disruptions arise. What strategies promote effective Business Model Innovation? The findings indicate that focusing on scalable digital solutions, like the Internet of Things (IoT) and advanced analytics, is essential. Moreover, forging strong public-private partnerships for resource sharing and aligning investments with equitable goals is crucial for the success of BMI initiatives.

Our research demonstrates the complex interactions between traditional and innovative elements in influencing productivity within water companies. While conventional resources such as labor and capital were crucial, their effectiveness diminished due to challenges stemming from the pandemic, including supply chain disruptions, workforce limitations, and decreased demand. In contrast, business model innovation proved to be a key driver of total factor productivity (TFP) during this difficult time. The analysis reveals a significant positive relationship between innovation and productivity, highlighting the strategic importance of innovative approaches to enhance efficiency and foster resilience during crises. By incorporating digital technologies, embracing remote work practices, and focusing on customer-oriented strategies, water utilities effectively managed the negative impacts of the pandemic, sustaining productivity and improving operational efficiency.

Several key elements play a significant role in influencing water production and productivity, such as net asset turnover, labor, and capital investment. Net asset turnover indicates a company's efficiency in using its assets to generate income, which reflects how well assets are utilized. Enhancing infrastructure, like water treatment plants and distribution systems, can boost water production and lower expenses. The skill level and training of the workforce are also critical, as well-trained staff enhance operational effectiveness and maintain water quality. Furthermore, investing in capital assets, including treatment facilities and pumping systems, directly impacts the capacity for water production. Technological improvements and upgraded equipment can also enhance efficiency and decrease costs. It's essential to find a balance among these factors; for example, achieving a high net asset turnover through insufficient capital investment can lead to decreased water production capacity over time. Similarly, a well-trained workforce may not reach its full potential without adequate investment in modern equipment. Thus, a holistic approach that considers the interconnectedness of these factors is necessary for optimizing water production and productivity, ultimately leading to greater efficiency, lower costs, and the ability to satisfy increasing water and wastewater demands. Furthermore, government regulations and the adoption of technology play a vital role in fostering progress within the water production industry. The generation of water is shaped by essential elements such as the quality of infrastructure, availability of resources, regulatory framework, technological progress, and consumer demand. These elements interact with innovations in business models, particularly during challenging times. In the event of a pandemic, innovative business models can enhance infrastructure, optimize resource management, ensure adherence to regulations, support the adoption of new technologies, and effectively address demand. The factors affecting water production are interconnected and can be greatly influenced by innovative business strategies. During a crisis, by embracing such strategies, water companies can enhance their sustainability, efficiency, and overall performance.

6. Conclusion

To maintain and boost productivity in the future, water companies should focus on investing in innovation, digital transformation, and the development of their workforce. Policymakers can significantly contribute by fostering a supportive regulatory environment, offering incentives for innovation, and facilitating infrastructure development. By recognizing the relationship between traditional factors and innovation, policymakers and industry leaders can make well-informed decisions to optimize resource use, enhance efficiency, and ensure the water sector's long-term sustainability.

For water and wastewater companies to successfully implement innovative business models, they need to adopt a holistic approach that includes several strategic components. Emphasizing customer-centricity means understanding and responding to customer needs through market research, customized solutions, and effective communication. Leveraging technology is vital; utilizing emerging tools such as IoT, AI, and data analytics can streamline operations, improve customer experiences, and foster innovation. Building strategic alliances with government organizations, other water companies, and technology suppliers can boost innovation and encourage knowledge sharing. Ensuring financial sustainability involves diversifying income sources, controlling costs, and using effective risk management strategies. Compliance with regulations is crucial to avoid fines and maintain a good reputation. Lastly, incorporating sustainability into business models can improve long-term success, attract investors, and support environmental and social objectives. By effectively blending these elements, water and wastewater companies can cultivate a culture of innovation, enhance efficiency, and provide lasting value to their customers and communities.

To sustain and enhance total factor productivity (TFP) during future crises, policymakers and industry leaders should explore the following approaches:

Accelerate Digital Transformation: Allocate resources to digital technologies, adopt remote working methods, and utilize data analytics to streamline operations and improve customer experience.

Enhance Workforce Resilience: Provide training for employees, establish flexible work options, and prioritize the well-being of staff to sustain productivity and adaptability.

Strengthen Supply Chain Resilience: Broaden the supplier base, forge robust relationships, and create contingency plans to address potential disruptions.

Foster Innovation: Develop an innovative culture, promote collaboration, and invest in research and development to drive ongoing enhancements.

Enhance Financial Resilience: Create substantial financial reserves, diversify income sources, and adopt effective risk management practices to endure economic challenges.

Policymakers should embrace adaptable regulations, offer incentives for investment, support innovation, and ensure consumer safety. They can also promote collaborations between the public and private sectors to utilize resources and expertise effectively and encourage data sharing to enhance decision-making.

Industry professionals ought to nurture an innovative culture, work alongside other stakeholders, and establish robust risk management strategies. By adopting these suggestions, water companies can boost their productivity, resilience, and overall effectiveness, contributing to a sustainable future for water resources.

This research offers important perspectives on the connection between business model innovation (BMI) and productivity within water utility organizations. Nonetheless, it presents several constraints that should be considered, illuminating potential areas for further inquiry. Although the study highlights the significance of BMI in improving productivity and resilience among water utilities during the COVID-19 pandemic—especially its tangible and quantifiable effects on Total Factor Productivity (TFP) and Net Asset Turnover (NATO)—it does not encompass other forms of innovation. These include process innovations (such as cutting-edge treatment technologies), product innovations (like new devices for monitoring water quality), and organizational innovations (such as flexible workforce structures). These dimensions deserve additional investigation, as they may indirectly affect productivity through variables not incorporated in our model, including employee satisfaction or efficiency in meeting regulatory compliance.

Firstly, this research deliberately centers on BMI, focusing on aspects such as digital transformation, new sources of revenue, and strategic collaborations. This particular emphasis was chosen due to the practical importance of BMI in capital-intensive and heavily regulated industries like water utilities. However, other types of innovation—such as advancements in processes (enhancements in operational efficiency), innovations in products (creation of new water services), and organizational innovations (internal restructuring or shifts in corporate culture)—were excluded from direct analysis. These innovations might also significantly influence productivity and overall performance. Given limitations in data and the necessity for conceptual precision, they were left out of the current framework. Future research should broaden the analytical scope to integrate these complementary forms of innovation for a more holistic understanding of how innovation impacts utility performance across various dimensions.

Secondly, the empirical examination is confined to a panel of water utility companies in Iran from 2015 to 2021. While this dataset provides meaningful insights within a specific context, the results may not be entirely applicable to different countries or sectors. Future studies could enhance the generalizability of findings by expanding the sample to encompass a more diverse range of firms (for instance, electricity, gas, or private water service providers) and by extending the period to identify long-term trends and cumulative innovation effects. Moreover, cross-country comparative analyses could aid in verifying the robustness of the Business Model Innovation Index (BMII) and its applicability across various institutional and regulatory settings.

Future studies should take a comprehensive approach to explore the various aspects of innovation, paying particular attention to the interactions between different innovation types and the time and context-specific factors that influence sector-specific trajectories. Researchers might investigate how process innovations, such as AI-enhanced treatment optimization, either support or hinder business model innovations related to digital transformation. Moreover, the role of product innovations, like smart meters, in generating new revenue streams or fostering partnerships merits further study. Longitudinal research that includes a wide array of companies—comparing both private and public utilities or global and regional operators—over extended periods, including times before and after the pandemic, can shed light on the sustainability of productivity gains driven by innovation. In addition, comparative studies could examine how organizational innovations, such as decentralized decision-making, affect resilience in different regulatory environments. The significance of green innovations, like carbon-neutral treatment facilities, in helping water utilities meet climate objectives is also worth investigating, along with the potential of social innovations, such as community-led sanitation initiatives, to improve equity and access in underserved areas.

This broader research agenda aligns with our initial suggestion for long-term, wide-ranging studies while responding to reviewers' requests to further explore fewer common types of innovation. For instance, investigating how process innovations can lower operational costs over a span of 15 years may uncover synergies with Business Model Innovation (BMI), focusing on NATO. Similarly, global analyses of organizational innovations could uncover best practices for achieving efficiency and equity across various organizational contexts.

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