

# **Sustainable Operational System for Drinking Water Management PDAM Tirta Pakuan, Bogor City**

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## **Abstract**

This study examines the operational sustainability of Perumda (PDAM) Tirta Pakuan, a drinking water utility in Bogor City, through integrated environmental, economic, and social dimensions. This study aims to analyze the operational system of PDAM Tirta Pakuan through an integrated sustainability framework that includes environmental, economic, and social dimensions. This analysis is based on comprehensive valuation data conducted by Pakuan University and PDAM Tirta Pakuan, integrated with international literature on sustainable water management best practices. Serving approximately 1.2 million residents in an area of 118.5 km<sup>2</sup>, this utility faces critical challenges in achieving universal coverage, operational efficiency, and financial sustainability. Analysis of current operations shows a service coverage of 62% with 24-hour continuous supply, Non-Revenue Water (NRW) of 32%, and water quality compliance exceeding 95%. This study integrates institutional assessment data with international best practices in sustainable water management, assessing production capacity (1,850 L/s from surface and groundwater sources), distribution infrastructure (1,200 km network), and operational performance. Key findings indicate that while PDAM Tirta Pakuan demonstrates strong water quality management and contributes significantly to public health and economic development, gaps remain in infrastructure optimization, energy efficiency, and climate resilience. Recommendations prioritize the implementation of smart water technologies, improved asset management, water source diversification, and an integrated sustainability framework. This research provides empirical evidence on the transition of regional water utilities in developing countries toward sustainable operational models while balancing economic viability, environmental stewardship, and social equity.

## **Keywords**

Sustainable Water Management, PDAM, Operational Efficiency, Water Distribution Systems, Indonesia

## **1. Introduction**

Sustainable drinking water management is a critical challenge for water utilities in developing countries, particularly in the context of rapid urbanization, climate change, and resource constraints. The Regional Drinking Water Company (PDAM) Tirta Pakuan in Bogor City, as the primary water provider for 1.2 million residents, faces complex pressures to balance service expansion, operational efficiency, and environmental sustainability. Bogor City, with an area of 118.5 km<sup>2</sup> and a high population density, is experiencing significant economic and demographic growth, increasing the demand for clean water. PDAM Tirta Pakuan currently serves 62% of the population with a continuous 24-hour

supply, but 38% of residents still rely on alternative water sources that often do not meet health standards. This service gap creates disparities in access to clean water, impacting public health and economic development (Shim *et al.*, 2022).

Key operational challenges include: (1) Non-Revenue Water (NRW) of 32%, exceeding the national target of 20%, indicating significant water losses through physical leakage and commercial losses; (2) reliance on surface water sources vulnerable to climate variability and pollution; (3) aging distribution infrastructure requiring rehabilitation and modernization; (4) limited financial capacity for major infrastructure investments; and (5) the need to improve energy efficiency in pumping and water treatment operations (Gonzales and Ajami (2015); Minaei *et al.*, 2025).

## **1.1 Objectives**

This study aims to analyze the operational system of PDAM Tirta Pakuan through an integrated sustainability framework encompassing environmental, economic, and social dimensions. This analysis is based on comprehensive valuation data conducted by Pakuan University and PDAM Tirta Pakuan, integrated with international literature on best practices in sustainable water management. Specific objectives include: (1) evaluating current operational performance in a sustainability context; (2) identifying gaps and opportunities for improvement; and (3) formulating strategic recommendations for transitioning to a more sustainable operational system. The contribution of this research is to provide an empirical analytical framework for regional water utilities in Indonesia in adopting sustainable practices, with practical implications for policymakers, water utility managers, and stakeholders in the water sector.

## **2. Literature Review**

### **2.1 Sustainability Framework for Water Utilities**

Water utility sustainability is defined as the ability to provide reliable, affordable, and high-quality water services while minimizing environmental impacts and ensuring social equity (Torkomany *et al.*, 2023). Kayaga *et al.*, (2013) developed an institutional sustainability framework encompassing five dimensions: technical, financial, environmental, social, and governance. This framework emphasizes the importance of integrating operational efficiency, economic viability, and socio-environmental responsibility.

Gonzales and Ajami (2015) proposed an integrative framework for sustainable urban water management that links water resources, infrastructure, and services with sustainability goals. This approach recognizes that water utility sustainability depends not only on technology but also on institutional capacity, stakeholder participation, and adaptation to changing local contexts.

### **2.2 Water Distribution System Optimization**

An efficient water distribution system is the foundation of operational sustainability. Grigg (2024) identified an integrated approach to effective utility management that encompasses network optimization, asset management, and digital technology. Research shows that optimizing pipe topology and sizing can reduce energy costs by up to 30% while improving supply reliability (Minaei *et al.*, 2025).

Smart water technology offers solutions to improve operational efficiency through real-time monitoring, automatic leak detection, and pressure optimization (Shim *et al.*, 2022); (Ramos *et al.*, 2022). Ramos *et al.*, (2022) (Ramos *et al.*, 2023) demonstrated that implementing a digital twin in a water distribution network can improve system efficiency by up to 25% through operational scenario simulation and infrastructure failure prediction.

### **2.3 Non-Revenue Water (NRW) Management**

NRW is a critical indicator of a water utility's operational efficiency. Water losses through physical leaks and commercial losses not only reduce revenue but also increase energy consumption and operational costs [30]. International best practices recommend an NRW target below 20% for well-performing utilities, with strategies including pressure management, active leak detection and repair, and metering accuracy improvement (Savic *et al.*, 2009).

### **2.4 Water Quality and Energy Management**

Optimizing water quality and energy efficiency are dual priorities in sustainable utility operations.

## **2.5 Indonesian Context**

Research on water utilities in Indonesia highlights specific challenges related to limited service coverage, high NRW, and limited financial capacity (Roekmi, 2019); (Hermana, 2024). Hermana (2024) identified the importance of synchronization between PDAM (Regional Water Company) and community-based water supply systems (HIPAM) to improve the sustainability of water services. Wijayanti *et al.* (2023) applied the “Utility of the Future” framework to Indonesian water utilities, emphasizing the importance of technological innovation, resource efficiency, and community engagement.

A study by Suharyanto *et al.* (2015) on sustainable drinking water management in Semarang using the Rappfish method showed that the economic and institutional dimensions were the main limiting factors for sustainability, while the ecological and social dimensions performed relatively better. These findings underscore the importance of a holistic approach that integrates all dimensions of sustainability.

## **3. Methods**

This study used a descriptive-evaluative analysis approach by integrating primary data from the institutional assessment of PDAM Tirta Pakuan with international scientific literature on sustainable water management. The methodology includes three main components:

### **3.1 Operational Data Collection and Analysis**

PDAM Tirta Pakuan's operational data was obtained from a comprehensive valuation report conducted by a research team from Pakuan University and PDAM Tirta Pakuan (July 2025). The data includes: - Water production capacity and sources (flow, quality, reliability) - Distribution infrastructure (network length, pipe material, asset age) - Operational performance (service coverage, NRW, supply continuity, water quality) - Financial performance (revenue, operational costs, investment) - Social and environmental impacts (community access, water resource conservation, energy efficiency).

### **3.2 Sustainability Analysis Framework**

The analysis uses a three-dimensional sustainability framework adapted from Kayaga *et al.*, (2013) and Gonzales and Ajami (2015):

1. Environmental Dimension: Water use efficiency, water resource conservation, energy management, ecological impact
2. Economic Dimension: Operational efficiency, financial viability, regional economic contribution
3. Social Dimension: Coverage and equity of access, service quality, public health, stakeholder engagement

### **3.3 Benchmarking with International Best Practices**

PDAM Tirta Pakuan's performance was compared with international standards and best practices identified through a systematic literature review of 30 scientific publications related to sustainable water management, distribution system optimization, and water utility management. Benchmarking criteria included technical performance indicators (NRW, supply continuity, water quality), operational efficiency (energy consumption, staff productivity), and financial sustainability (operational ratio, investment capacity).

## **4. Results and Discussion**

### **4.1 PDAM Tirta Pakuan Operational Profile**

PDAM Tirta Pakuan serves the city of Bogor, with a service area of 118.5 km<sup>2</sup> and a target population of 1.2 million. This utility operates a water production and distribution system with the following characteristics (Table 1):

Table 1. Summary of PDAM Tirta Pakuan Operational Performance

Indicator	Value	Standard/Target
Production capacity	1,850 L/s	-
Average Production	1,480 L/s	-
Service coverage	62%	100% (SDG 6)
Number of customers	142,000 SR	-
Distribution network length	1,200 km	-
Non-Revenue Water (NRW)	32%	<20% (best practice)
Supply Continuity	24 hours	24 hours
Water quality compliance	>95%	100%
Per capita consumption	120 L/day	100-150 L/day

Source: PDAM Tirta Pakuan data (2025)

PDAM Tirta Pakuan relies on two categories of water sources: (1) surface water from the Cisadane and Ciliwung Rivers through a water treatment plant (IPA) with a total capacity of 1,450 L/s, and (2) groundwater from 40 deep wells with a total capacity of 400 L/s. This diversification of sources provides resilience to seasonal variability, although reliance on surface water (78% of total production) creates vulnerability to pollution and climate change (Gonzales and Ajami, 2015)

## 4.2 Environmental Dimension Analysis

### 4.2.1 Water Use Efficiency and NRW Management

The NRW of 32% indicates significant water loss that impacts environmental and economic sustainability. Of the total NRW, an estimated 20% is physical loss (leakage) and 12% is commercial loss (water theft, meter inaccuracy). This NRW level exceeds international best practices (<20%) and the Indonesian national target (20%) (Mazzolani *et al.*, 2023).

Distribution network analysis shows that 35% of pipes are over 20 years old, with PVC and asbestos cement as the dominant materials, making them prone to leaks. Suboptimal operating pressure (ranging from 1.5 to 4.0 bar) in some distribution zones contributes to leaks and water waste (Ramos *et al.*, 2022). Implementing optimal pressure management can reduce leaks by 15 to 20% (Kostner *et al.*, 2023).

### 4.2.2 Water Resource Conservation and Climate Resilience

High reliance on surface water (78%) creates vulnerability to climate variability and pollution. Raw water quality from the Cisadane and Ciliwung Rivers experiences seasonal fluctuations, with increased turbidity and organic contamination during the rainy season. Current WTP capacity is capable of handling these quality variations, but climate change, which predicts increased rainfall intensity and longer dry periods, could challenge treatment capacity (Gonzales and Ajami, 2015).

Groundwater utilization (22% of production) provides an important buffer but requires close monitoring to prevent over-extraction and groundwater level decline. Data shows that some deep wells are experiencing decreased discharge, indicating potential pressure on aquifers (Kayaga *et al.*, 2013).

### 4.2.3 Energy Efficiency

Energy consumption for pumping and water treatment operations is a significant component of operational costs (approximately 25% of total operational costs). Analysis shows that energy efficiency can be improved through: (1) optimizing pump scheduling based on demand patterns and electricity tariffs, (2) rehabilitating older, low-efficiency pumps, and (3) implementing a real-time energy monitoring system (Xie *et al.*, 2024); (S and R, 2024). A study by Xie *et al.* (2024) showed that coordinated pump scheduling can reduce energy consumption by up to 20% while improving water quality. Implementing a similar strategy at PDAM Tirta Pakuan has the potential to achieve significant energy cost savings and reduce its operational carbon footprint.

### 4.3 Economic Dimension Analysis

#### 4.3.1 Financial Performance and Operational Efficiency

PDAM Tirta Pakuan demonstrates relatively healthy financial performance with an operating ratio of approximately 0.85, indicating that operating revenue covers 85% of operating costs (Table 2). However, capacity for major infrastructure investments remains limited, with most investments relying on government loans and grants (Kayaga *et al.*, 2013).

Table 2. Operational Efficiency Indicators

Indicator	PDAM Tirta Pakuan	Best Practice
Operating ratio	0,85	<0,80
Staff per 1,000 connections	4,2	3-5
NRW	32%	<20%
Collection efficiency	92%	>95%
Production cost per m <sup>3</sup>	Rp 3,200	-
Average rate per m <sup>3</sup>	Rp 3,800	-

Source: Data from PDAM Tirta Pakuan (2025) and literature (Grigg, 2024), (Mian *et al.*, 2022)

Staff productivity (4.2 staff per 1,000 connections) is within the international best practice range (3-5 staff per 1,000 connections), indicating adequate operational efficiency (Grigg, 2024). However, the collection efficiency of 92% indicates room for improvement in billing and revenue collection.

#### 4.3.2 Regional Economic Contribution

Economic valuations indicate that PDAM Tirta Pakuan contributes significantly to the regional economy through: (1) providing water for commercial and industrial activities supporting over 15,000 businesses, (2) creating direct (600+ employees) and indirect (contractors, suppliers) jobs, (3) saving public health costs through the provision of clean water that reduces waterborne diseases, and (4) increasing property values in areas with PDAM water access (Shim *et al.*, 2022). A willingness-to-pay (WTP) analysis shows that the community values PDAM Tirta Pakuan's economic value beyond its operational costs, indicating that the utility service provides a positive consumer surplus and is considered important by the community.

### 4.4 Social Dimension Analysis

#### 4.4.1 Coverage and Equity of Access

The 62% service coverage indicates that 38% of Bogor City's population (approximately 456,000 people) does not yet have access to PDAM services. Spatial analysis shows that unserved areas are primarily located in: (1) suburban areas with steep topography that require booster pump investments, (2) informal settlements with unclear land status, and (3) low-density areas that are uneconomical for network expansion (Vizanko *et al.*, 2024)

This access gap creates social inequity, with unserved communities having to rely on alternative water sources (shallow wells, bottled water, water vendors) at often higher per-unit costs and with less guaranteed quality. Studies show that households without PDAM access can spend up to 10-15% of their income on water, compared to 2-3% for PDAM customers (Kayaga *et al.*, 2013).

#### 4.4.2 Service Quality and Customer Satisfaction

PDAM Tirta Pakuan provides continuous 24-hour service with water quality that meets national standards (>95% compliance with water quality parameters). Water quality monitoring is conducted routinely at the source, water treatment plant (WTP), and distribution points, covering physical, chemical, and bacteriological parameters (Cherchi *et al.*, 2015). Customer satisfaction surveys indicate a high level of satisfaction (>80%) regarding the continuity of supply and water quality, but complaints relate to low water pressure in certain areas and slow responses to service disruptions. Improving the customer service system and implementing information technology for reporting and handling complaints can improve customer satisfaction (Aguirre *et al.*, 2023).

#### 4.4.3 Public Health

The provision of clean water by PDAM Tirta Pakuan contributes significantly to public health by reducing the incidence of waterborne diseases such as diarrhea, typhoid, and hepatitis A. Health data shows that areas with high

PDAM coverage have a 40-50% lower incidence of waterborne diseases than areas without PDAM access (Shim *et al.*, 2022).

Health economic valuations show that the savings in health costs (medical treatment, lost productivity) resulting from the provision of clean water by the Regional Water Company (PDAM) reach billions of rupiah per year, far exceeding any government subsidies or support to utilities. A closer look at the sustainable drinking water management system (PDAM) of the Tirta Pakuan Regional Water Company (Perumda) in Bogor can be illustrated in a complete visual form, as explained in Figure 1.



Figure 1. Drinking Water Management System at Perumda Tirta Pakuan Bogor

Based on this figure, the business processes and drinking water management at Perumda Tirta Pakuan Bogor are generally good, with high water quality (95%), 24-hour service, and satisfactory public service. However, improvements are still needed: NRW is still 32%, with coverage only at 62%. Furthermore, challenges include aging infrastructure, high energy consumption, climate change, and ongoing service gaps. Therefore, solutions are needed: smart technology, asset management, source diversification, and a strategic framework. Sustainable water management requires a balance between environmental, economic, and social aspects to better serve the community.

#### 4.5 Gaps and Opportunities for Improvement

The analysis identified the following key gaps in PDAM Tirta Pakuan's operational system:

1. Infrastructure and Technology: Aging distribution network, manual monitoring system, and limited digital technology for operational optimization (Ramos *et al.*, 2022); (Ramos *et al.*, 2023).
2. Asset Management: Unsystematic asset management practices, with incomplete asset data and reactive rather than predictive maintenance planning (Mazzolani *et al.*, 2023).
3. Operational Efficiency: High NRW, suboptimal energy efficiency, and potential for operational scheduling optimization (Xie *et al.*, 2024).
4. Service Expansion: Limited financial and technical capacity for network expansion to underserved areas, particularly those with challenging topography (Vizanko *et al.*, 2024).
5. Climate Resilience: Vulnerability to climate variability and water source pollution, with limited adaptive capacity (Gonzales and Ajami, 2015).
6. Stakeholder Engagement: Limited communication and community involvement in planning and decision-making related to water services (Kayaga *et al.*, 2013).

Opportunities for improvement include:

1. Digitalization and Smart Water: Implementation of IoT sensors, SCADA, and digital twins for real-time monitoring and operational optimization (Shim *et al.*, 2022); (Ramos *et al.*, 2022); (Ramos *et al.*, 2023).
2. Data-Driven Asset Management: Adoption of integrated asset information systems and predictive maintenance strategies (Mazzolani *et al.*, 2023).

3. Energy Optimization: Smart pump scheduling, equipment rehabilitation, and renewable energy utilization (Xie *et al.*, 2024); (S and R, 2024).
4. Water Source Diversification: Exploration of alternative water sources, increasing storage capacity, and implementing water reuse (Gonzales and Ajami, 2015).
5. Partnerships and Innovative Financing: Public-private partnerships, green bonds, and performance-based financing mechanisms for infrastructure investments (Kayaga *et al.*, 2013).
6. Capacity Building: Staff training in new technologies, asset management, and sustainability practices (Grigg, 2024).

## **5. Recommendations**

Based on the analysis, strategic recommendations for PDAM Tirta Pakuan's transition to a sustainable operational system are grouped into three priorities:

### **5.1 Short-Term Priorities (1-2 Years)**

#### **5.1.1 Intensive NRW Reduction Program**

Implement a comprehensive program to reduce NRW from 32% to 25% within 2 years through: - Establishing a dedicated NRW team with clear performance targets - Dividing the network into District Metered Areas (DMAs) for leak monitoring and detection - Implementing pressure management in overpressure zones - An active leak detection and repair program using acoustic technology - Replacing old and inaccurate customer meters - Anti-water theft campaigns and legalizing illegal connections. A 7% NRW reduction (from 32% to 25%) could save approximately 100 L/s of water, equivalent to the capacity to serve 20,000 additional household connections without any new production investment (Savic *et al.*, 2009); (Mazzolani *et al.*, 2023).

#### **5.1.2 Customer Service System Improvement**

Implementation of an integrated customer information system that includes: - A digital platform for reporting disruptions and complaints (mobile app, web portal) - An automated ticketing system with target response times - SMS/WhatsApp notifications for service disruptions and billing - A call center with adequate capacity  
Improved responsiveness and communication with customers can improve customer satisfaction and collection efficiency (Aguirre *et al.*, 2023).

#### **5.1.3 Basic Operational Optimization**

- a. Comprehensive energy audit to identify efficiency opportunities
- b. Optimization of pump operating schedules based on demand patterns and electricity tariffs
- c. Rehabilitation of low-efficiency pumps
- d. Improved water quality monitoring protocols

### **5.2 Medium-Term Priorities (3-5 Years)**

#### **5.2.1 Implementation of Smart Water Technology**

Gradual adoption of smart water technology to improve operational efficiency and resilience: - Installation of IoT sensors for real-time monitoring of pressure, flow, and water quality at critical points - Implementation of an integrated SCADA system for centralized control and monitoring - Development of a digital twin for operational scenario simulation and failure prediction - Implementation of smart metering for real-time consumption monitoring and anomaly detection. Investment in smart water technology can increase operational efficiency by 15-25% and further reduce NRW (Shim *et al.*, 2022); (Ramos *et al.*, 2022); (Ramos *et al.*, 2023).

#### **5.2.2 Systematic Asset Management**

Development and implementation of a comprehensive asset management system: - Inventory and condition assessment of complete assets (pipes, pumps, reservoirs, WWTPs) - Implementation of a GIS-based asset information system - Development of predictive maintenance strategies based on asset condition and risk - Planning for asset rehabilitation and replacement based on risk priorities - Integration of asset management with long-term financial planning. Systematic asset management can extend asset life by 20-30% and reduce long-term maintenance costs (Mazzolani *et al.*, 2023).

### 5.2.3 Planned Service Expansion

A service expansion program to increase coverage from 62% to 75%: - Prioritizing expansion to areas with high density and economic viability - Implementing alternative technologies (booster pumps, local gravity systems) for challenging topographic areas - Partnerships with housing developers to integrate water infrastructure into new developments - Connection subsidy programs for low-income households.

Planned expansion should be integrated with urban spatial planning and other infrastructure development (Vizanko *et al.*, 2024).

## 5.3 Long-Term Priorities (5-10 Years)

### 5.3.1 Water Resource Diversification and Resilience

Long-term strategies to increase water resource resilience: - Exploration and development of alternative water sources (new reservoirs, deep groundwater) - Increased storage capacity (reservoirs, tanks) to buffer seasonal variability - Implementation of water reuse and recycling for non-potable uses - Regional partnerships for transboundary water resource management - Implementation of water conservation and demand management programs. Diversifying water sources can reduce vulnerability to climate change and pollution (Gonzales and Ajami, 2015).

### 5.3.2 Transition to Net-Zero Energy

Roadmap to reduce operational carbon footprint: - Installation of renewable energy systems (solar PV) at PDAM facilities - Implementation of energy recovery systems (hydroelectric turbines in transmission pipelines) - Comprehensive optimization of energy consumption at all facilities - Participation in carbon credit or green financing programs.

### 5.3.3 Integrated Sustainability Framework

Adoption of a comprehensive sustainability framework that integrates environmental, economic, and social dimensions: - Establishment of measurable sustainability targets (SDG 6 alignment) - Sustainability performance monitoring and reporting system - Integration of sustainability considerations into all operational and investment decisions - Sustainability certification (ISO 14001, water stewardship) - Public sustainability reporting for transparency and accountability (Table 3). An integrated sustainability framework ensures that the transition to sustainable operations is systematic and measurable (Torkomany *et al.*, 2023); (Kayaga *et al.*, 2013).

Table 3. Summary of Priority Recommendations

Priority	Key Focus	Target Outcome	Timeline
Short Term	NRW Reduction, Customer Service, Basic Optimization	NRW 25%, Customer satisfaction >85%	1-2 tahun
Medium Term	Smart water, Asset Management, Service expansion	NRW 20%, Coverage 75%, Energy efficiency +15%	3-5 tahun
Long Term	Water resilience, Net-zero energy, Integrated sustainability	90% coverage, Carbon neutral, SDG 6 compliance	5-10 tahun

## 6. Conclusion

This study analyzed the operational system of PDAM Tirta Pakuan in Bogor City through an integrated sustainability framework, identifying strengths, gaps, and opportunities for improvement. Key findings indicate that PDAM Tirta Pakuan has achieved good performance in water quality and supply continuity, and has made significant contributions to public health and regional economic development. However, persistent challenges in universal service coverage (62%), operational efficiency (NRW 32%), and resilience to climate change require strategic intervention.

Priority recommendations include intensive NRW reduction programs, implementation of smart water technologies, systematic asset management, planned service expansion, and diversification of water sources. The transition to a sustainable operational system requires a phased approach that balances technology investment, capacity building, and institutional strengthening. The contribution of this research is to provide an empirical analytical framework and practical recommendations for regional water utilities in Indonesia in adopting sustainable practices. Implementing the recommendations could improve operational efficiency by 20-30%, reduce NRW to <20%, and increase service coverage to 90% within 10 years, while minimizing environmental impacts and ensuring social equity.

Further research is needed to: (1) conduct detailed economic feasibility analyses for specific technology investments, (2) study the impact of climate change on water resource availability, (3) evaluate innovative financing models for infrastructure investments, and (4) assess institutional capacity for implementing operational transformations.

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