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System dynamics modelling of integrated urban clean water management: A case study in Padang City, Indonesia

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Abstract: Access to clean water is essential for human life and a key target of Sustainable Development Goal (SDG) 6: Clean Water and Sanitation. However, cities in developing countries, including Padang City, Indonesia, face significant challenges in meeting the growing demand due to population growth and limited water infrastructure. This study used system dynamics modelling approach with Powersim Studio 10 to develop an integrated clean water management system for Padang City. The model simulates the dynamics of population growth, water consumption, production, and distribution efficiency over a 20-year period (2022–2042). Several policy scenarios—optimistic, moderate, and pessimistic—were tested to evaluate their impact on water availability. The baseline scenario predicts a continuous decline in clean water supply due to increasing population, high leakage rates (11.99%), and water wastage (2%), which surpass the water production growth rate (5.01%). As a result, a water deficit is expected. However, under the optimistic scenario, with increased production (10%), reduced leakage (8%), and reduced wastage (3%), Padang City could achieve a clean water surplus by 2042. The moderate and pessimistic scenarios still result in a deficit. This research highlights the value of the system dynamics modelling in forecasting urban water demand and assessing policy impacts. The findings emphasize the need for integrated planning, combining technical solutions and behavioural change, to ensure sustainable water management and support the achievement of SDG 6.

Keywords: system dynamics; urban water management; policy scenario; clean water sustainability; clean water and sanitation

1. Introduction

Ensuring universal access to clean and safe water is one of the defining challenges of the 21st century, particularly in urbanizing regions of the Global South (Bishoge, 2021; Kumar et al., 2023; Randolph & Storper, 2023). Although freshwater constitutes only 2.5% of Earth's water, and less than 1% is readily accessible for human use, demand for this critical resource is growing rapidly due to population increase, urban expansion, and climate variability (Mishra, 2023). According to the 2021 United Nations World Water Development Report, more than two billion people currently reside in water-stressed areas, and this number is projected to rise in tandem with global urbanization trends (Musie & Gonfa, 2023).

Indonesia exemplifies this challenge. As urban populations surge, the development of water infrastructure often lags, creating acute pressure on local water utilities (Ferdowsi et al., 2024; Winters et al., 2014). Padang City, the capital of West Sumatra Province, illustrates this tension. With its strategic coastal location and high internal migration, Padang's clean water demand continues to grow, yet its municipal utility (in Bahasa: *Perumda Air Minum Kota Padang*) operates near capacity with limited room for expansion (Wisha et al., 2022). In 2020, the city's water demand reached 1,486.9 litters per second and is expected to surpass 1,900 litters per second by 2030, while production capacity remains around 1,555 litters per second, suggesting a looming water deficit if interventions are not urgently implemented.

Conventional water planning methods in Indonesia typically rely on deterministic models that struggle to accommodate the complex, dynamic nature of urban systems. These models often fail to reflect feedback loops, time delays, and the non-linear interactions among demographic, technical, and behavioural factors (Abujder Ochoa et al., 2025; Chan et al., 2022). In contrast, system dynamics (SD) modelling offers a powerful tool for simulating these complexities over time. SD enables planners to explore the consequences of policy decisions across interconnected subsystems, capturing both immediate and long-term effects (Fabolude et al., 2025). While SD has gained traction in fields like energy and transportation planning, its application in the Indonesian urban water sector remains limited, especially in medium-sized cities such as Padang (Forliano et al., 2024).

This study addresses that gap by developing a system dynamics model of Padang's urban water system using Powersim Studio 10. The model integrates four key subsystems: population growth, service coverage, water losses, and production capacity (Kristiadi & Herdiansyah, 2024). By simulating baseline trends and exploring three alternative policy scenarios optimistic, moderate, and pessimistic this research quantifies the long-term impacts of technical and behavioural interventions on clean water sustainability. The study contributes to academic and practical debates in three critical ways: (1) by offering a dynamic, replicable framework for water planning in secondary cities of the Global South; (2) by evaluating the long-term effectiveness of integrated policy responses; and (3) by highlighting the importance of adaptive planning under conditions of uncertainty. The novelty of this work lies in its holistic, systems-based approach that bridges technical forecasting with policy design, offering insights for more resilient and equitable urban water futures.

2. Methods

2.1 Research design and framework

This study adopts a quantitative research design that integrates a system dynamics (SD) modelling approach to explore and simulate the long-term dynamics of clean water supply and demand in Padang City, Indonesia (Bastan et al., 2022; Wang et al., 2021). The research framework follows the classical SD modelling stages introduced by (Hrehova et al., 2025), including: (1) problem identification and boundary selection, (2) system conceptualization, (3) model formulation, (4) data collection and parameter estimation, (5) simulation and validation, and (6) policy scenario analysis. These stages provide a structured process for evaluating causal relationships and feedback mechanisms affecting urban water management. The simulation spans a projection period of 20 years (2022–2042), offering a long-term lens to test and compare policy alternatives for sustainability.

2.2 Subsystem structure and algorithmic logic

The model is structured into four interconnected subsystems: (1) population growth, (2) customer connection and service coverage, (3) water consumption and losses, and (4) production and distribution capacity. Each subsystem is visualized using Causal Loop Diagrams (CLDs) to highlight reinforcing and balancing feedback loops that influence the system behaviour over time. These conceptual structures are then translated into Stock and Flow Diagrams (SFDs) in the Powersim Studio environment. The core computational logic follows the following algorithmic steps:

1. Water demand is computed as: Population × Per capita water consumption
2. Water losses are calculated as: Production × Network leakage rate
3. Net supply equals: Total production – (Losses + Wastage)
4. Water stock is updated iteratively based on inflow (net supply) and outflow (demand).

This algorithmic structure ensures transparency and reproducibility in how each policy intervention affects system behaviour across time.

2.3 Data sources and parameterization

The parameterization of the system dynamics model relies entirely on secondary data obtained from credible and authoritative sources to ensure scientific validity and replicability (Hamed et al., 2024; Schoenenberger et al., 2021). The primary data sources include the annual reports of *Perumda Air Minum Kota Padang* from 2018 to 2022, which provide operational insights and technical indicators such as production capacity, leakage rates, and service coverage. Demographic data including population growth, birth and death rates, and migration trends are sourced from the *Badan Pusat Statistik* (BPS), the official statistical agency of Indonesia. Additionally, strategic and infrastructure planning references are taken from the 2016 Master Plan for the Development of the Drinking Water Supply System (RISPAM) of Padang City, which outlines the city's projected clean water needs and infrastructure development goals. Key parameters used in the simulation are summarized in Table 1.

Table 1. Key parameters for clean water supply simulation in Padang city

Parameter	Value	Source
Birth Rate	2.46%	BPS Padang
Death Rate	1.28%	BPS Padang
Per Capita Consumption	0.15 m³/day	RISPAM (2016)
Network Leakage	11.99%	Perumda Annual Report (2022)
Water Wastage	2%	Perumda Annual Report (2022)
Production Capacity (Total WTPs)	1,555 L/s	Perumda Infrastructure Data

These parameters are critical in defining the baseline simulation and calibrating the model to reflect real-world dynamics prior to the introduction of policy scenario variations.

2.4 Tools and simulation environment

The simulation is implemented using Powersim Studio 10, a modeling software specifically designed for system dynamics applications (Ceylan & Devrim, 2021; Tanjung et al., 2022). This platform supports the creation of time-based simulations involving feedback structures, delays, and accumulations. The simulation is configured with an annual time step from 2022 to 2042, and model behaviour is governed by ordinary differential equations and lookup functions based on real-world data. Validation is performed using Absolute Mean Error (AME), comparing simulated outputs to actual historical data from 2022–2023. The model is considered valid if AME remains under 10%, consistent with thresholds in SD literature (Barlas, 1996).

2.5 Policy scenarios and testing procedure

To evaluate the potential impact of strategic interventions on the city’s clean water system, three distinct policy scenarios were formulated in Table 2.

Table 2. Policy scenario assumptions for clean water management simulation (2022–2042

Scenario	Production growth	Leakage rate	Water wastage
Optimistic	10%/year	8%	3%
Moderate	8%/year	10%	5%
Pessimistic	3%/year	15%	8%

Each scenario is simulated over the 20-year period to observe system responses in terms of the population served total demand, net water supply, and remaining stock. The outcomes guide strategic recommendations for future water infrastructure investments and policy planning.

2.6 Data acquisition and reproducibility

All data utilized in this study were retrieved from public and institutional records, with traceable documentation and date references for reproducibility. Sources are cited in the reference list, and the modelling logic follows best practices in SD research for transparency (Weiss et al., 2023). The model structure, parameters, and assumptions are fully documented and archived. Future researchers or planners aiming to replicate or extend the simulation to other cities can follow the system diagrams, equations, and parameter inputs as a reproducible base model.

3. Results and discussion

This study presents a system dynamics model that simulates the clean water supply-demand balance in Padang City over a 20-year period (2022–2042). By integrating multiple interacting subsystems such as population dynamics, water consumption behavior, infrastructure production capacity, and network performance the model enables the analysis of complex causal relationships and long-term outcomes under various policy scenarios. The model architecture begins with a Causal Loop Diagram (CLD), which visualizes Figure 1 key reinforcing and balancing feedback loops that drive the system's behavior. For example, population growth reinforces water demand, which in turn influences infrastructure stress and service delivery. Positive feedback (e.g., urban growth driving higher consumption) and negative feedback (e.g., leak reduction policies) are clearly depicted.

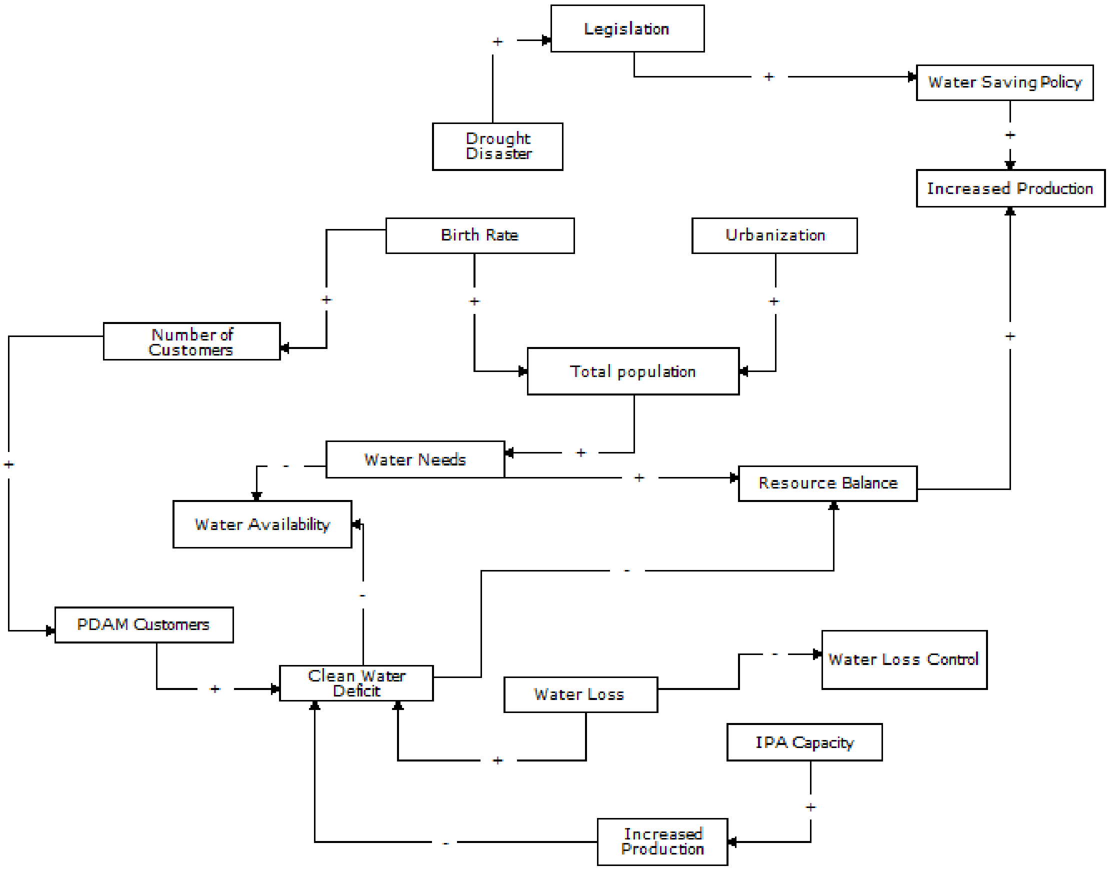

Figure 1. Causal Loop Diagram (CLD) of the integrated clean water management system

To structure the model boundaries, an Input–Output Diagram (Blackbox) was constructed in Figure 2. This diagram distinguishes controllable variables (e.g., leakage reduction, production increase) from exogenous parameters (e.g., birth/death rates, migration trends), which ultimately affect key outcomes such as water availability and system balance.

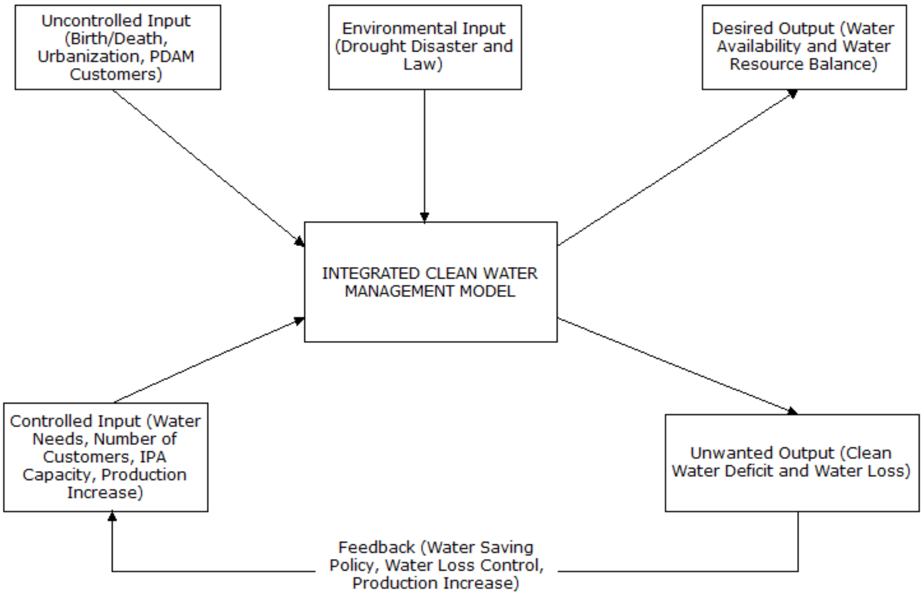

Figure 2. Input–output diagram (Blackbox)

Based on institutional sources (RISPAM 2016, BPS, and Perumda Air Minum annual reports), the model uses carefully parameterized input variables. These are summarized in Table 3, grouped into four sub models: Population, PDAM Customer Dynamics, Clean Water Consumption, and Clean Water Production.

Table 3. Key model parameters by sub model

Sub model	Parameters and values
Population sub model	- Total population in 2022 (919,145 people) - Birth rate (2.46%) - Death rate (1.28%) - In-migration rate (5.61%) - Out-migration rate (5.03%)
PDAM customer sub model	- Service coverage (71%) - Household connection growth rate (2.91%) - Household connection percentage (80%) - Public hydrant growth rate (1.83%) - Public hydrant percentage (20%) - Customer termination rate (3.49%)
Clean water consumption sub model	- Clean water consumption (HH: 0.15 m³/person/day; PH: 0.03 m³/person/day) - Network improvement rate (2%) - Water wastage rate (2%)
Clean water supply sub model	Installed capacity: - IPA Gunung Pangilun: 15,768,000 m³/year - IPA Paluki: 6,937,920 m³/year - IPA Taban: 3,153,600 m³/year - IPA Pengambiran: 157,680 m³/year - IPA Jawa Gadut: 630,720 m³/year - IPA Guo Kuranji: 1,261,440 m³/year - IPA Latung: 9,145,440 m³/year - IPA Lubuk Paraku: 4,730,400 m³/year - IPA Bungus: 1,261,440 m³/year - Water loss rate (11.99%) - Production increase rate (5.01%)

Subsequently, the conceptual model was implemented into a Stock and Flow Diagram (SFD) using Powersim Studio 10. As illustrated in Figure 3, the SFD captures the dynamic behavior of water-related variables over time by modeling the accumulation (stocks) and movement (flows) of key elements such as population, water demand, and supply. This structure allows the simulation to incorporate time delays and feedback mechanisms, enabling the analysis of how both internal policies and external factors influence clean water availability across the projection period.

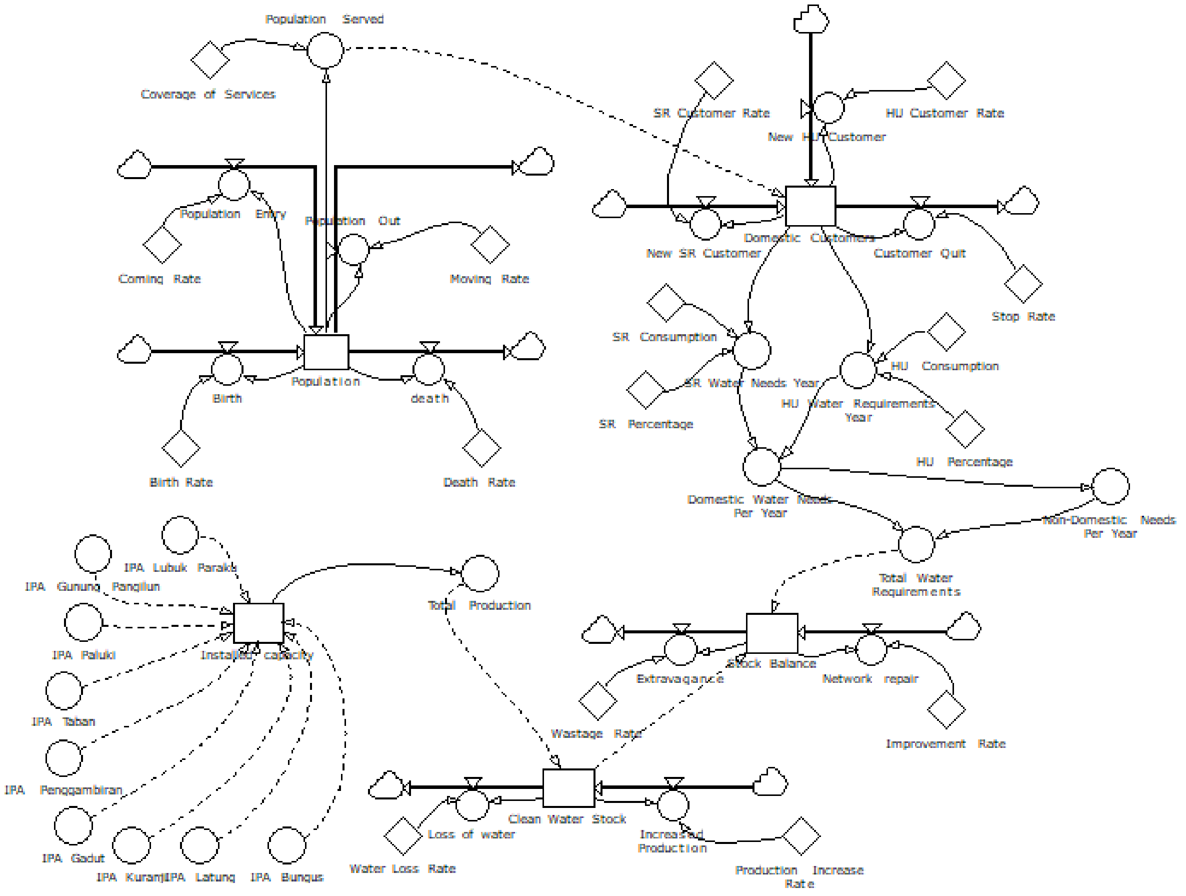

Figure 3. Stock and Flow Diagram (SFD) of the clean water supply system

After validating the model structure using the Absolute Mean Error (AME) method—which yielded a low error rate of 0.57%, well below the acceptable threshold of 10%, the simulation was run under one baseline and three policy-driven scenarios. In the baseline scenario, illustrated in Figure 4, existing trends in water production and leakage are assumed to continue without intervention. The results show a significant increase in water demand, rising from 39 million m³ in 2022 to over 50 million m³ by 2042. Meanwhile, due to cumulative losses, the water supply declines sharply from 36.8 million m³ to just 8.6 million m³ over the same period. This persistent negative balance highlights a systemic and escalating clean water deficit in Padang City.

The model testing method was conducted using the Absolute Mean Error (AME), with the population data from Padang City in 2022 and 2023. According to the AME standard, the maximum tolerable deviation is 10% (Khalil et al., 1987). The dynamic model validation test for the integrated clean water management system in Padang City resulted in an AME value of 0.57%, indicating that the model performs well, is accurate, and can be scientifically accepted as valid. The details of the model validation results are presented in Table 4.

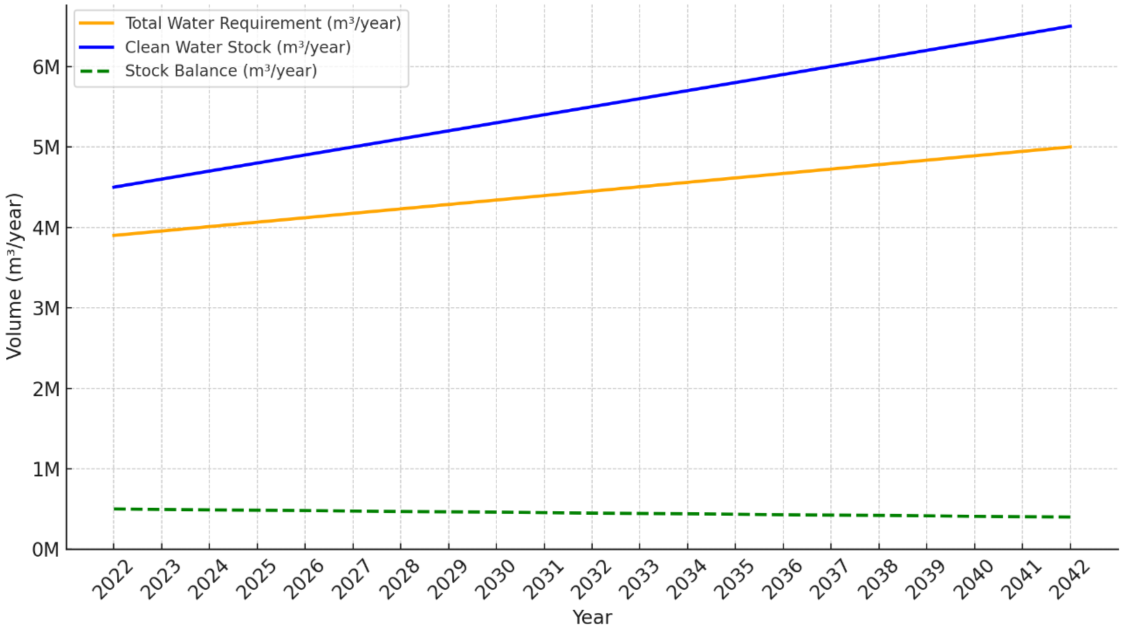

Figure 4. Simulation of clean water stock under baseline scenario (2022–2042)

Table 4. Model validation

Year	Actual population	Simulated population	AME (%)
2022	919,145	919,145	0.57
2023	935,321	930,948	

Following the validation, three strategic policy scenarios were introduced to explore potential impacts on the clean water supply system. The optimistic scenario assumes a high level of intervention through substantial investments in infrastructure, significant leakage reduction (down to 8%), and public education campaigns aimed at reducing water wastage (to 3%). Under this scenario, the model predicts a consistently surplus water supply throughout the entire simulation period. The results of this scenario are visualized in Figure 5, demonstrating the positive impact of proactive measures on maintaining a sustainable water supply.

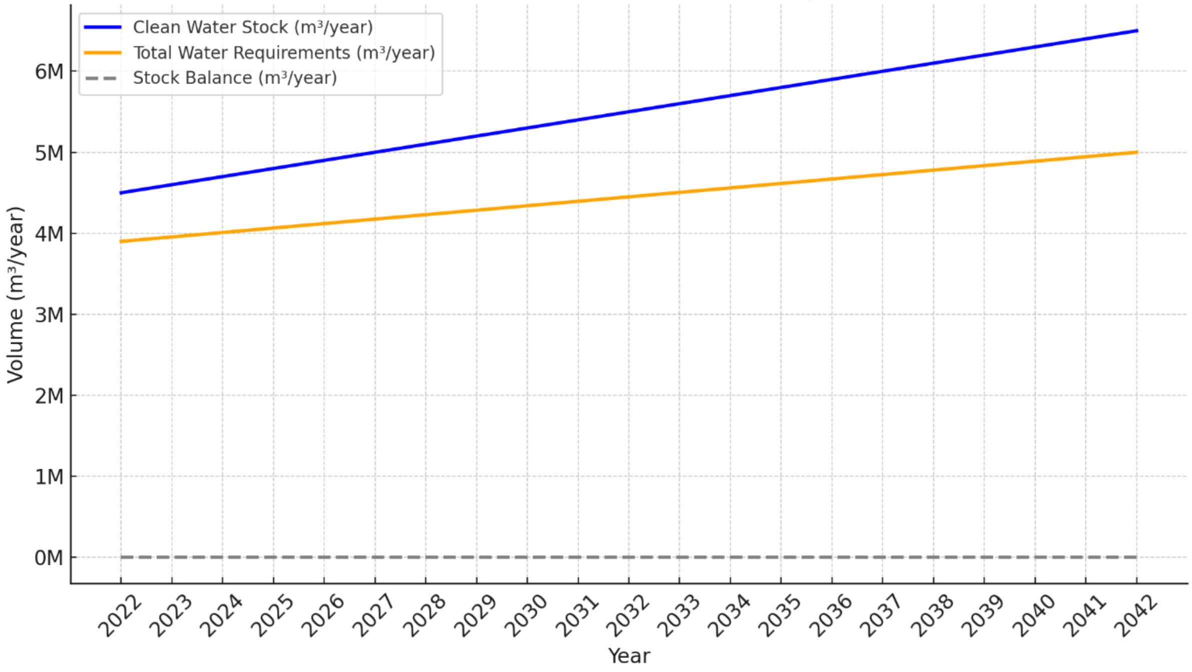

Figure 5. Simulation of clean water stock under optimistic scenario

In contrast, the moderate scenario involves moderate improvements, such as an 8% increase in production, a reduction in leakage to 10%, and a decrease in water wastage to 5%. While this scenario results in a smaller deficit compared to the baseline, it still presents a persistent gap between supply and demand. On the other hand, the pessimistic scenario, which assumes limited intervention with a mere 3% increase in production, a 15% leakage rate, and an 8% wastage rate, results in severe water shortages. This scenario highlights the significant risks associated with inaction or underinvestment in water infrastructure and management. The outcomes of both scenarios are visualized in Figures 6 and 7, illustrating the differing impacts of policy intervention on water stock.

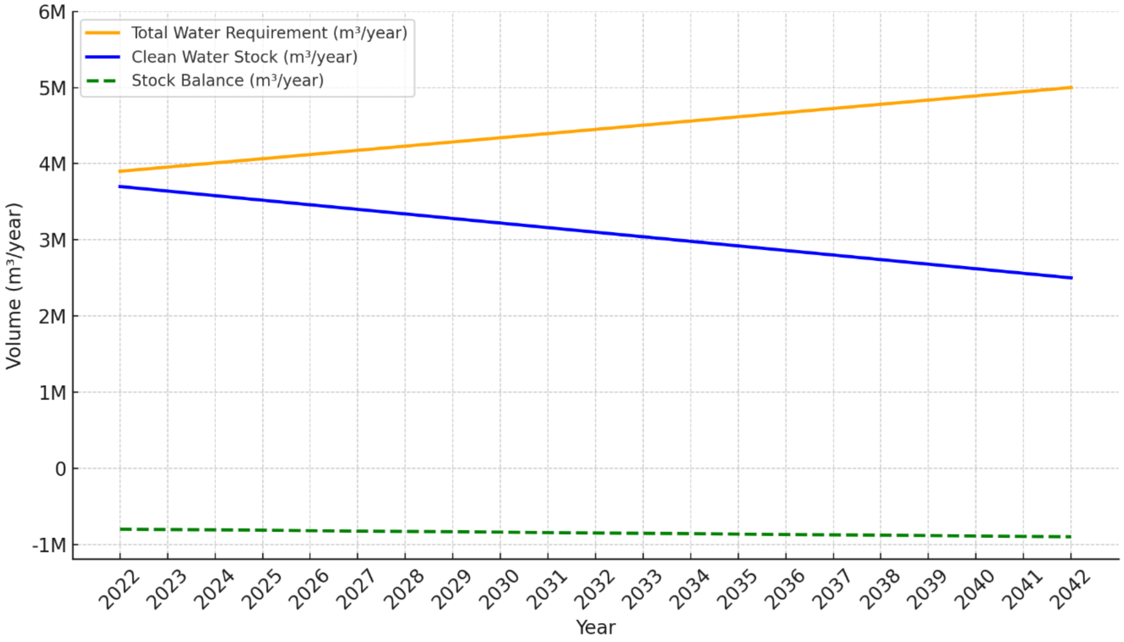

Figure 6. Simulation of clean water stock under moderate scenario

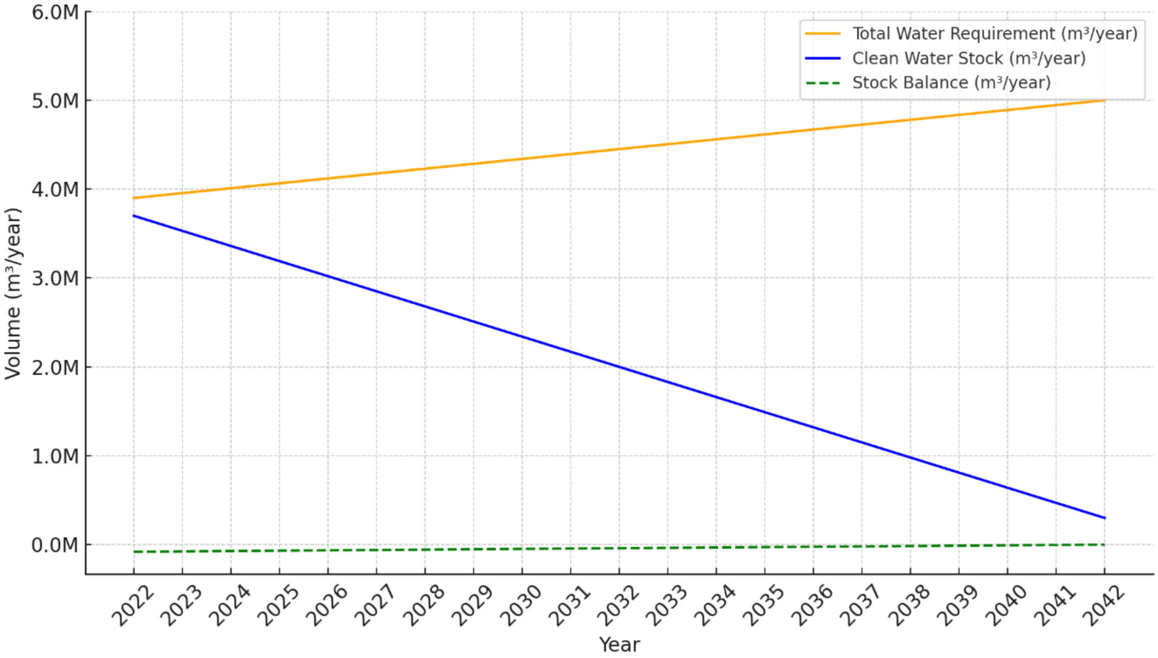

Figure 7. Simulation of clean water stock under pessimistic scenario

These results underscore the critical role of dynamic modeling in long-term urban water resource planning. The analysis confirms that a reliance on infrastructure expansion alone, without complementary behavioral change interventions, will not be sufficient to address water scarcity in urban areas. A combined socio-technical approach, integrating both technical infrastructure improvements and behavioral changes, is essential for ensuring sustainable water security. This approach is particularly important for secondary cities facing similar demographic pressures and environmental challenges. By applying system dynamics in this context, decision-makers can better assess the potential outcomes of different strategies and prioritize investments that generate both immediate and long-term benefits.

4. Conclusion

This study demonstrates the effectiveness of system dynamics modelling in analyzing and forecasting the long-term dynamics of clean water management in urban settings, using Padang City, Indonesia, as a case study. The simulation model developed using Powersim Studio 10 integrates various demographic trends, water consumption behaviour, system losses, and infrastructure capacity into a comprehensive framework. Results from the baseline simulation indicate a persistent clean water deficit driven by rapid population growth, high leakage rates, and inefficient consumption patterns. In the absence of effective interventions, water stock levels are projected to decline significantly, threatening the sustainability of the city’s water supply system.

The application of alternative policy scenarios highlights the importance of proactive and integrated strategies. The optimistic scenario, which combines increased production capacity, reduced water losses, and improved consumer efficiency, shows that Padang City can achieve water security by 2042. In contrast, the moderate and pessimistic scenarios continue to generate annual deficits, indicating that incremental improvements without structural reform may be insufficient. These findings suggest that sustainable urban water management must address both the technical and behavioural dimensions of the system. Investments in water treatment infrastructure should be complemented by leakage control programs, consumption efficiency campaigns, and improved governance mechanisms to enhance service delivery.

The key contribution of this research lies in its deployment of a system dynamics framework in a medium-sized Southeast Asian city, offering a replicable modelling approach that can support data-driven decision-making for urban water planning. Additionally, the integration of scenario-based policy testing enables local governments and water authorities to better anticipate risks and develop adaptive strategies under future uncertainties. As urban pressures and climate variability continue to grow, dynamic modelling tools such as the one presented in this study will be critical for ensuring long-term water sustainability and resilience in cities across the Global South.

Author’s Declaration

Author contribution

Yaumal Arbi: Conceptualization, methodology, writing - original draft, writing - review & editing, formal analysis, project administration, investigation, visualization. **Rumia Ramadhianty:** Data validation, validation, writing - review & editing, visualization, resources. **Shinta Rahayu:** Conceptualization, methodology, writing - original draft, data curation, supervision. **Widia Putri:** Data validation, visualization, writing - review & editing, funding acquisition.

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Competing interest

The authors declare that there are no competing interests related to the research or publication of this article.

Ethical clearance

This research does not involve human or animal as subject.

Data availability

The data will be available upon request.

AI statement

This article is the original work of the author without using AI tools for writing sentences and/or creating/editing tables and figures in this manuscript.

Publisher's and Journal's Note

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