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Dynamic System Model for Optimizing Clean Water Distribution in Balikpapan City

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ABSTRACT

Balikpapan City, as one of the supporting cities for the Nusantara Capital City (IKN) in East Kalimantan, faces significant challenges in meeting the demand for clean water. The increase in population due to migration and infrastructure development following the relocation of the IKN has led to a continuous rise in the demand for clean water. The rate of water loss, or Non-Revenue Water (NRW), is quite high, reaching 25.85%. This situation has resulted in low distribution efficiency and highlights a gap between the available clean water distribution system and the actual needs of the community. As a result, clean water service coverage reached only 80.07% in 2022. This study aims to identify the factors influencing clean water distribution, develop a dynamic system model, and formulate optimal scenarios. The research method used is a dynamic systems approach, which enables comprehensive analysis of the cause-and-effect relationships between variables in the clean water distribution system, as well as simulation of various policy scenarios to find the most effective and sustainable solutions. Simulation results show significant dynamics in clean water distribution. From 2023 to 2035, pipeline length increased from 1.4 million meters to 1.6 million meters, yet clean water consumption decreased to 23.67 million m^3 in 2029 and 23.15 million m^3 in 2035. Of the three designed scenarios, Scenario 3, which involves a 4.2% annual increase in pipeline repair rates and a 1.47% annual increase in the number of customers, proved to be the most effective. This scenario successfully reduces pipeline leakage rates and significantly improves distribution coverage.

INTRODUCTION

Water is a renewable natural resource because it is continuously available. According to (Djana, 2023), water is the fundamental basis for all biological and human activities. In addition to being a basic necessity for domestic consumption, water is also needed for industrial activities, agricultural irrigation, and so on. The United Nations (UN) states that the human right to water ensures that everyone has access to sufficient, safe, acceptable, accessible, and affordable water for personal and domestic use (United Nations, 2020). However, in reality, the clean water crisis remains one of the most pressing global issues. According to the World Health Organization (WHO, 2019), approximately 2 billion people worldwide still lack access to clean water, which impacts public health and productivity. In Indonesia, despite being an archipelagic nation with approximately 62% of its territory consisting of seas and water bodies, this does not guarantee

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equitable access to clean water across all regions. Based on data from the Central Statistics Agency in 2024, around 7.33% of households in Indonesia still face limitations in accessing clean water. This is inconsistent with the sixth Sustainable Development Goal (SDG), which aims for universal access to clean water for everyone. In other words, the SDG target for clean water access is to be achieved at 100% for the entire population.

Balikpapan City, as one of the supporting cities for the Nusantara Capital City, faces similar challenges in meeting the clean water needs of its residents. The demand for clean water continues to rise alongside population growth, infrastructure development, and the impact of the relocation of the IKN to East Kalimantan. According to data from the Balikpapan City Population and Civil Registration Office from 2021 to 2024 (March), the number of newcomers to Balikpapan reached 60,670 people. Meanwhile, the number of migrants who have officially registered as residents of Balikpapan City is only around 4,979 people (Alexander, H.B., 2025). According to Tumanggor & Damanik (2022), the demand for clean water continues to rise alongside population growth. This is because population growth also affects the level of clean water consumption, such as water used for domestic purposes, industry, and others. Water demand refers to the amount of water required to support various activities or needs of the community in a particular area (Sari & Koswara, 2019). Estimating the future population is an important aspect of clean water demand planning, as population growth directly impacts the increased demand for clean water in the future (Fatma et al., 2022).

In addition, there is a clean water distribution system, which is the process of distributing or allocating water through a piping system from the water treatment facility (reservoir) to consumers (Eryanto Septiawan & Narlan Soetiman, 2021). In the process of distributing water through a piping network, water loss is inevitable. Water loss is the difference between the water produced and the water consumed by customers or the volume of water sold (Pratama et al., 2024). The clean water distribution system in Balikpapan City faces technical problems in the form of highwater loss or Non-Revenue Water (NRW), which stands at 25.85%, exceeding the maximum standard set in the 2006 Minister of Public Works Regulation of 20% (PDAM Balikpapan, 2024). This high loss rate may be caused by pipe leaks, illegal connections, or inaccurate meter readings. This situation not only reduces service efficiency but also exacerbates the disparity between the water produced and the water that actually reaches customers. This phenomenon highlights a gap between the available clean water distribution system and the actual needs of the community or residents of Balikpapan City, particularly in addressing the challenges of serving as a supporting city for the IKN.

Water supply is an effort to ensure the availability of sufficient water, in terms of quantity, quality, and continuity, to meet the needs of the community. The right to water has several important and fundamental aspects that must be fulfilled by the government, including availability, quality, and accessibility, which can be easily obtained and the government has the ability to procure such water (Wattimena, 2021). Water supply activities are intended to meet the community's needs for potable water to support a healthy, clean, and productive life. In this process, the distribution network system plays a crucial role, as it functions to distribute clean water from the treatment plant to consumers. This system must be able to ensure the quality, quantity, and continuity of water flow in accordance with established standards, including adequate distribution pressure (Zamzami et al., 2018).

The provision of piped clean water in Kutai Timur Regency, East Kalimantan Province, is constrained by the supply side, namely the limited availability of raw water sources and water loss, making it difficult to meet clean water consumption needs. Using a dynamic system model, three scenarios were presented, and an optimal solution was found to address the issue of clean water availability in Kutai Timur Regency (Lantara et al., 2016). Additionally, research on integrated clean water management in Bogor City using a dynamic model indicated that clean water scarcity reached only 68% of clean water demand in Bogor City. The model developed interprets the factors causing clean water scarcity in Bogor City (Susetyo & Laxmi, 2017). Research on water resource models for industrial and residential areas in the Cilegon region showed that clean water service coverage ranged from 1% to 13%. To increase the availability of raw water and

clean water, the proposed solutions include constructing a reserve reservoir or expanding existing reservoirs to increase capacity, developing the potential of seawater for use as clean water, building new WTP plants to enhance water treatment processes, and increasing clean water storage capacity (Jihan Hofa & Oktri Widyarto, 2018). The use of dynamic systems in the three studies was chosen because this method can model the complex and interdependent relationships between variables in the clean water supply system, such as population, water demand, water source capacity, and leakage rates. Dynamic systems enable the simulation of various policy scenarios to assess their impact on future clean water availability, providing a powerful analytical tool for long-term planning. Additionally, dynamic systems can capture the dynamics of non-linear changes within the system, which is highly relevant in the context of clean water management in regions facing population growth and resource challenges.

According to Ki-moon & Secretary General (2018), a dynamic system is a systems approach achieved through the interrelationship between variables, analyzing changes in the system to predict future trends, and is a nonlinear method that uses quantitative and qualitative data to analyze the dynamics of complex systems with feedback characteristics. Meanwhile, Setiafindari (2017) argues that the dynamic systems method can improve understanding of the behavior of a system's policy structure. This method focuses on policy-making and how policies determine the behavior of problems modeled by the system dynamically. Problems that can be modeled with dynamic systems have dynamic characteristics (changing over time) and have at least one feedback loop. Dynamic system modeling has several advantages, including being a flexible method for studying complex behavior over time by transforming the entire system into a series of interconnected stocks and flows. Stocks represent accumulation. Inputs and outputs change stock levels during a specific time step and are influenced by the current stock levels of the system (Guemouria et al., 2023).

The dynamic systems approach is a relevant solution because it can model causal relationships between variables influencing the clean water distribution process using Causal Loop Diagrams and simulate the clean water distribution process using Stock and Flow Diagrams. With this approach, various scenario recommendations can be analyzed as a reference for the Balikpapan City Government as a stakeholder in managing clean water, thereby ensuring the coverage of clean water services in Balikpapan City and supporting efficient and sustainable clean water distribution management amid increasing demand for water services due to the development of the Nusantara Capital City. Based on these considerations, the objectives of this study are to identify the factors that influence clean water distribution in Balikpapan City, develop a dynamic system model that describes the interactions between variables in the system, and formulate optimal policy scenarios to improve the efficiency and coverage of clean water services in a sustainable manner.

RESEARCH METHODS

The research began with observation, namely observing current phenomena with the aim of obtaining a factual picture of the availability of clean water and the process of clean water distribution in Balikpapan City. After the problems were clearly identified, the next step was to formulate the research problems and objectives. Data collection in this study was carried out through two types of sources, namely primary data and secondary data. Primary data was obtained through direct interviews with relevant parties. Meanwhile, secondary data was obtained from official documents such as PDAM annual reports, Disdukcapil population reports, and rainfall data from BMKG Balikpapan. The next stage was the development of a conceptual model in the form of a Causal Loop Diagram that illustrates the cause-and-effect relationships between variables in the system. Based on this model, a Stock Flow Diagram was developed as the basis for simulation. The selection of the dynamic system method in this study was based on the complexity of the water distribution system, which involves many variables that influence each other nonlinearly, as well as the need to analyze changes in the system over time. This approach also allows for comprehensive simulation of various policy scenarios, so that it can be used to evaluate the impact of certain interventions before they are implemented in the real world. In addition,

dynamic systems provide informative visualizations, thereby supporting evidence-based decision-making by stakeholders. For modeling and simulation purposes, this study uses Stella software, which was chosen for its ability to present interactive models and display simulation results in graphical form, facilitating the interpretation of policy scenarios. The variables used in this study are as follows.

Table 1. Causal loop diagram variables

No.	Variables
1	IKN
2	In migration
3	Out migration
4	Birth rate
5	Death rate
6	Population of Balikpapan City
7	Domestic customers
8	Non-domestic customers
9	PDAM policy
10	Total pipe length
11	Pipe leakage
12	Water loss
13	Clean water consumption
14	Rainfall
15	Raw water storage volume
16	Clean Water Production
17	Clean Water Availability

The variables in Table 1 are the reference variables used to create the Causal Loop Diagram and are related to the factors of clean water availability in Balikpapan City. The next step is to determine the relationship between variables which is categorized into two types, namely positive relationship (+) and negative relationship (-). A positive relationship (+) indicates that two variables have a unidirectional relationship of change, where an increase or decrease in one variable will be followed by an increase or decrease in the other related variable. Conversely, a negative relationship (-) indicates a relationship between variables in the opposite direction. If one variable increases, the other variable that is affected will decrease.

RESULTS AND DISCUSSION

The dynamic system model begins with building a conceptual model using cause-and-effect diagrams to illustrate the relationships between variables that affect the availability of clean water in Balikpapan City.

Causal Loop Diagram

Causal Loop Diagram (CLD) is a qualitative approach that can be applied in the process of developing dynamic system models (Purwanto et al., 2019). CLD explains system behavior by showing a group of nodes that are interconnected with arrows and feedback loops created by connections (Mawengkang, 2020). The purpose of creating a Causal Loop Diagram (CLD) is to conceptually describe the system, explaining the relationships between each variable and the effects that arise from each relationship. A Causal Loop Diagram (CLD) is created by identifying the variables that have an influence on the system. These influences are represented in two relationships: positive and negative relationships.

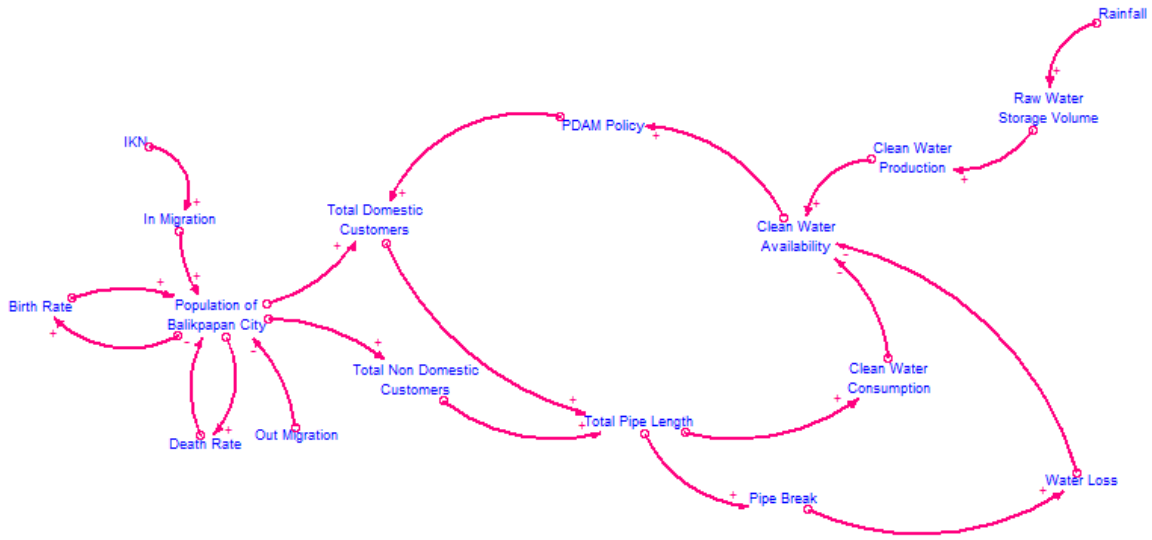

Figure 1. Causal Loop Diagram

Figure 1 is a conceptual diagram of the clean water supply system in Balikpapan City. One of the most dominant aspects of this system is the increase in population due to natural growth (birth rate) and inward migration, particularly that triggered by the development of the new capital city (IKN). This population increase directly contributes to the growing number of clean water customers, both from the domestic and non-domestic sectors, ultimately leading to a significant increase in clean water consumption. On the other hand, the availability of clean water is influenced by production capacity, which depends on the volume of raw water available. This volume is highly dependent on rainfall. The higher the rainfall, the greater the potential water that can be stored and used for production processes. Sufficient clean water production will increase water availability for customers, thereby meeting the rising consumption demand. Another aspect of this system is water distribution through piped networks. As the number of customers increases, network expansion is required, marked by an increase in pipeline length. However, this situation also increases the risk of pipe leaks. High leakage rates lead to an increase in non-revenue water, meaning that even though water has been produced, not all of it can be effectively distributed to customers. The accumulation of lost water reduces the actual availability of clean water and widens the gap between production and consumption.

Stock Flow Diagram

The creation of a systematic model or Stock and Flow Diagram (SFD) is a further step used to describe and simulate the flow of clean water availability at PDAM Kota Balikpapan. Stock and Flow Diagrams (SFD) are used to describe how elements in a system interact and change over time. The Stock and Flow Diagram (SFD) is developed based on an analysis of factors or variables in the Causal Loop Diagram (CLD).

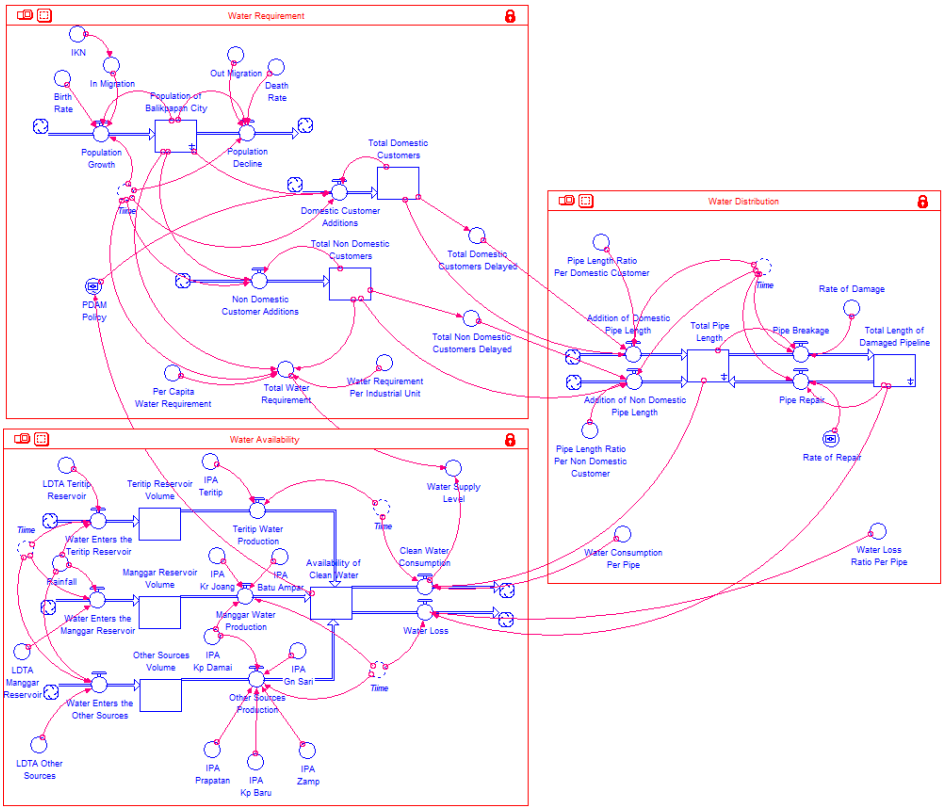

Figure 2. Stock Flow Diagram

The stock flow diagram that has been developed is the result of the integration of three main submodels, namely water demand, water distribution, and water availability. This model provides a comprehensive overview of the process, starting with projections of population and customer growth that drive increased water demand, followed by the distribution process through the pipeline network, which takes into account new connections, damage rates, and water loss, and finally the availability of clean water from three raw water sources through the Water Treatment Plant. The primary objective of developing this model is to conduct further analysis of the level of clean water supply fulfillment in Balikpapan City based on clean water consumption through the piped network. As such, this model is expected to serve as a decision-making tool for scenario-based planning regarding future clean water supply, particularly in addressing challenges such as population growth and external influences like the development of the Nusantara Capital City.

Results of Existing Model Simulation

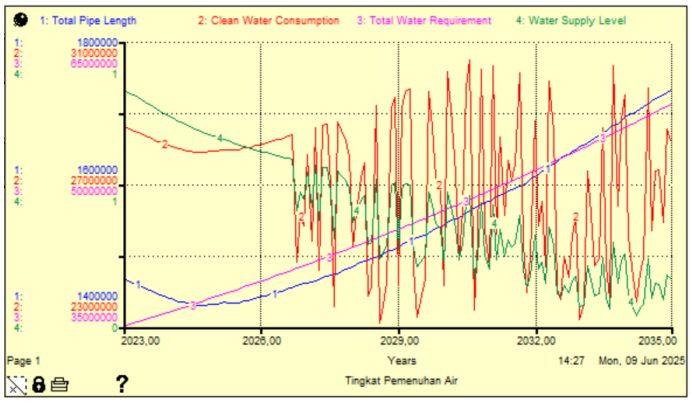

Figure 3. Graph of clean water fulfillment rates

Figure 3 shows the complex dynamics between total pipeline length, clean water consumption, total water demand, and water demand fulfillment rates during the period from 2023 to 2035. In general, total pipeline length shows a steady upward trend, reflecting efforts to develop water distribution infrastructure in line with regional and population growth. Total water demand also shows a consistent increase over time, reflecting population growth and economic activity as a result of the development of the Nusantara Capital City (IKN). However, clean water consumption appears to fluctuate extremely and is unstable, especially since 2027. These fluctuations indicate an imbalance between water availability and distribution and actual demand. Despite increased infrastructure capacity, uneven or inefficient distribution has caused actual consumption to fail to keep pace with the continuously rising demand trend. This is also reflected in the water demand fulfillment rate graph, which shows a declining and unstable trend after 2027.

Table 2. Model simulation results

Year	Total Pipe Length (m)	Clean Water Consumption (m^3)	Total Water Demand (m^3)	Water Demand Satisfaction Rate (%)
2023	1.464.637,00	28.589.714,24	35.114.416,60	81
2024	1.441.776,39	28.143.475,10	36.479.332,76	77
2025	1.421.628,83	27.750.194,73	38.047.330,60	73
2026	1.425.852,41	27.832.639,01	39.681.710,60	70
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
2034	1.640.076,12	26.436.191,27	55.505.509,04	48
2035	1.694.361,56	23.151.320,90	57.878.300,80	40

The simulation table shows that between 2023 and 2035, there will be an opposite trend between water demand and supply levels. Although the length of the pipeline network has increased gradually from 1.46 million meters (2023) to 1.69 million meters (2035), the level of clean water consumption has actually decreased from 28.59 million m^3 to only 23.15 million m^3. On the other hand, total water demand has increased significantly from 35.1 million m^3 to nearly 57.9 million m^3, indicating that demand growth is not being matched by an increase in supply capacity. This has directly impacted the Water Demand Satisfaction Rate, which has dropped sharply from 81% to just 40%. This phenomenon indicates that despite the continued development of physical infrastructure such as pipeline networks, the overall performance of the water distribution system has deteriorated due to suboptimal management of production and distribution capacity. This suggests that increasing pipeline length alone is insufficient to ensure improved clean water services. Systemic interventions are needed on other factors, such as reducing non-revenue water (NRW), increasing clean water production capacity, or improving distribution management to make the system more responsive to surges in demand. Without comprehensive and adaptive policies, Balikpapan City will face a decline in water supply adequacy amid increasing demand pressure due to IKN development. Therefore, policy scenarios must consider the integration of infrastructure development or improvement, distribution system efficiency, and demand management simultaneously to achieve sustainable clean water services.

Model Scenario Development

The scenario is used to propose improvements to the system in line with the original objective of creating a dynamic system model for optimizing clean water distribution in the city of Balikpapan.

Table 3. Scenario Design

No.	Scenario	Purpose
1.	Increasing the rate of pipe repairs to 4.2% per year	Reducing water loss due to pipe leaks to improve water distribution efficiency.
2.	Increasing the number of customers by 1.47% per year	Expanding clean water service coverage through networks or piping systems.
3.	Increasing the rate of pipe repairs to 4.2% per year and the number of customers by 1.47% per year	Reducing water loss due to pipe leaks and expanding clean water service coverage through networks or piping systems.

The scenario design in Table 3 aims to improve the efficiency of the clean water distribution system in Balikpapan City through a piping network so that it can meet the clean water needs of the city's residents. This scenario was created based on existing problems, where the current level of clean water consumption is still not proportional to the total water needs. Clean water consumption is influenced by the total length of the pipes and water consumption per pipe. However, the number of pipe damages continues to increase each year and is not commensurate with the repairs carried out. This results in more water being lost due to pipe leaks. As a result, more clean water is wasted before reaching the customers. Additionally, increasing the number of customers is necessary to keep pace with the population growth in Balikpapan City and to expand the coverage of clean water services provided by the Public Water Supply Company (PDAM) to communities that are currently unserved.

Table 4. Comparison of Existing Condition Compliance Levels with Scenarios

	Service Coverage (%)			
Year	Existing	Scenario 1	Scenario 2	Scenario 3
2023	81	81	81	81
2024	77	77	76	77
2025	73	73	99	100
2026	70	70	77	94
.	.	.	.	.
.	.	.	.	.
2034	48	46	46	42
2035	40	47	47	51

Based on the simulation results, the coverage of clean water services under existing conditions shows a consistent downward trend from 81% in 2023 to only 40% in 2035. This decline reflects the imbalance between the increase in water demand due to population growth and the limited capacity of the distribution system, particularly due to pipeline network damage that has not been optimally addressed. This indicates that without policy or technical intervention, the clean water distribution system in Balikpapan City will increasingly be unable to meet public demand. Scenario 1, which focuses on increasing the rate of pipeline repairs, shows more stable results compared to the existing conditions. Although it cannot drastically increase service coverage, this scenario successfully maintains water supply levels at a better range in the later years (47% in 2035 compared to 40% in the existing conditions). This indicates that technical management of infrastructure, particularly pipeline leaks, has a positive impact but is not yet sufficiently significant if implemented partially. Scenario 2 emphasizes increasing the number of customers. This strategy results in a very high surge in service coverage in 2025 (99%), but a decline occurs afterwards, reaching 47% in 2035. This indicates that increasing the number of customers can improve distribution and coverage in the short term, but without accompanying improvements

to the technical system (such as network upgrades), the benefits are not sustainable. Increasing access without increasing capacity tends to place excessive strain on the system, which ultimately reduces long-term performance.

Scenario 3, which combines an increase in the rate of pipe repairs and an increase in the number of domestic customers, shows the most optimal performance. Not only does it achieve maximum coverage of 100% in 2025, but it also maintains the highest coverage rate at the end of the 2035 simulation (51%), surpassing all other scenarios. The effectiveness of this scenario can be explained systematically, where infrastructure improvements reduce water loss (Non-Revenue Water), while the increase in the number of customers contributes to network expansion and operational efficiency. This combination emphasizes the need for simultaneous technical and managerial interventions to achieve sustainable results. Therefore, Scenario 3 can be recommended as the optimal strategy as it addresses short-term challenges while ensuring the long-term sustainability of clean water services through a more comprehensive approach to technical improvements and demand management.

CONCLUSION

Based on the results of the research conducted, the factors influencing the distribution of clean water in Balikpapan City include population growth, which drives an increase in the number of domestic and non-domestic customers, the availability of clean water, the total length of the pipeline network, the rate of pipeline leakage, and the volume of water lost. These factors interact with each other in influencing the amount of clean water consumption through the pipeline network. Based on the simulation results, Scenario 3 was selected as the best recommendation, which involves increasing the pipeline repair rate to 4.2% per year and adding 1.47% more domestic customers through PDAM policy interventions. This scenario has proven effective in increasing pipeline network length and significantly reducing pipeline damage rates, thereby minimizing water loss and improving distribution efficiency. Therefore, PDAM Balikpapan City needs to design a more scheduled pipeline maintenance program, including allocating a special budget for routine pipeline rehabilitation. Additionally, a promotional strategy for PDAM services is needed to encourage an increase in the number of household customers, such as simplifying registration procedures or offering incentives for new customers. From a spatial planning perspective, cross-sectoral collaboration with local governments is also needed to ensure that pipeline expansion aligns with regional development and future population growth projections. By implementing these strategies, clean water distribution in Balikpapan City can be managed more efficiently, sustainably, and adaptively in response to the increasing water demand driven by the development of the Nusantara Capital City.

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