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Original Article

Modeling of Clean Water Distribution Networks in Blang Oi and Punge Ujong, Banda Aceh, Indonesia

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Abstract: Clean water distribution systems are essential for public health and urban sustainability, yet many developing urban areas face challenges related to uneven service quality and hydraulic inefficiencies. This study aims to evaluate the performance of the clean water distribution network in Blang Oi and Punge Ujong Villages, Meuraxa District, Banda Aceh, and to assess its ability to meet community water demand. A quantitative descriptive approach was employed, integrating hydraulic modeling with EPANET 2.2 and field data on pipeline characteristics, population demand, and customer water consumption patterns. The network model consisted of 137 junctions, 144 pipes, one reservoir, and one booster pump, and was simulated over a 24-hour period to capture variations in pressure, flow, velocity, and headloss. The results indicate that, in general, the system meets acceptable pressure standards, with values ranging between 41.44 and 63.78 mH_2O during peak hours. However, significant hydraulic issues were identified, including low flow velocities in several pipes (below 0.3 m/s), uneven flow distribution, and localized high headloss exceeding recommended limits. The system also exhibits a bimodal demand pattern, with peak factors reaching 2.94, placing stress on the network during the morning and evening periods. These findings suggest that while the infrastructure is functionally adequate, it is not yet hydraulically optimized. Therefore, improvements in pipe sizing, network configuration, and demand-based operational management are necessary to enhance system efficiency and service reliability.

Keywords: Water distribution network; EPANET; Hydraulic performance; Clean water infrastructure; Urban water supply.

1. Introduction

Clean water is a fundamental human necessity that underpins public health, socio-economic development, and environmental sustainability. Ensuring equitable access to safe drinking water remains a global challenge, particularly in rapidly urbanizing regions where population growth exerts increasing pressure on existing infrastructure systems. The sustainability of water supply systems is closely linked to their ability to maintain reliable hydraulic performance under dynamic demand conditions, which is essential

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for achieving broader development objectives, including those outlined in the Sustainable Development Goals (SDGs) (Dadebo et al., 2023). In urban water systems, the efficiency of distribution networks is critical to determining service quality. However, many developing regions continue to face significant challenges, including aging infrastructure, leakage, pressure imbalances, and insufficient system capacity. Hydraulic modeling has emerged as a key tool for addressing these challenges, enabling engineers and policymakers to simulate network behavior, evaluate system performance, and identify optimal solutions for improving efficiency and sustainability (Kumar et al., 2024; Trębicka, 2023). Modern approaches, including digital twins and data-driven modeling, further enhance the capability to monitor and optimize water distribution systems in real time (Ramos et al., 2023; Garzón et al., 2022).

Banda Aceh City, Indonesia, exemplifies these challenges, particularly in Meuraxa District, which is categorized within Zone IV of the municipal water supply system managed by PERUMDAM Tirta Daroy. This district faces multiple structural and operational constraints, including its distance from water treatment facilities, post-disaster infrastructure vulnerabilities, and uneven hydraulic performance. These issues are consistent with findings from other developing regions, where water distribution systems often suffer from high levels of non-revenue water (NRW), frequently exceeding 30%, primarily due to leakage and inefficient pressure management (Negese & Kebede, 2023; Tian et al., 2023). A key factor exacerbating these challenges is population growth.

Table 1. Population Projection in Meuraxa, Jaya Baru, and Kuta Raja (2017–2032)

Year	Meuraxa	Jaya Baru	Kuta Raja	Total Population
2017	20,134	25,554	13,667	59,355
2018	20,680	26,057	14,166	60,903
2019	21,225	26,560	14,665	62,450
2020	21,771	27,064	15,165	64,000
2021	22,316	27,567	15,664	65,547
2022	22,862	28,070	16,163	67,095
2023	23,407	28,573	16,662	68,642
2024	23,953	29,076	17,161	70,190
2025	24,498	29,579	17,660	71,737
2026	25,044	30,083	18,160	73,287
2027	25,589	30,586	18,659	74,834
2028	26,135	31,089	19,158	76,382
2029	26,680	31,592	19,657	77,929
2030	27,226	32,095	20,156	79,477
2031	27,771	32,598	20,655	81,024
2032	28,317	33,102	21,155	82,574

As shown in Table 1, the combined population of Meuraxa, Jaya Baru, and Kuta Raja is projected to increase steadily from 59,355 in 2017 to 82,574 in 2032, representing approximately 39% growth over 15 years. This trend reflects ongoing urban expansion and increasing demand for basic services. Jaya Baru consistently records the highest population, indicating a higher demand concentration in this district, followed by Meuraxa and Kuta Raja. Such demographic trends significantly influence water consumption patterns and infrastructure requirements, as highlighted by previous studies that emphasize the importance of integrating population projections into water system planning (Mekonnen, 2023). The implications of this population growth are clearly reflected in the projected domestic water demand presented in Table 2. On the basis of a standard consumption rate of 90 liters per person per day, total water demand is projected to increase from 5.34 million liters per day in 2017 to 7.43 million liters per day in 2032. This represents a substantial increase in system load, requiring corresponding improvements in infrastructure capacity and operational efficiency. The steady increase in demand across all three districts underscores the need for proactive planning and system optimization to ensure a sustainable water supply. Similar trends have been observed in other case studies, where inadequate infrastructure expansion has led to reduced service coverage and declining system performance (Kuma & Abate, 2021; Mohammed & Mohammed-Ali, 2025).

Table 2. Projected Domestic Water Demand (2017–2032)

Year	q (L/person/day)	Meuraxa (L/day)	Jaya Baru (L/day)	Kuta Raja (L/day)	Total Water Demand (L/day)
2017	90	1,812,060	2,299,860	1,230,030	5,341,950
2018	90	1,861,200	2,345,130	1,274,940	5,481,270
2019	90	1,910,250	2,390,400	1,319,850	5,620,500
2020	90	1,959,390	2,435,760	1,364,850	5,760,000
2021	90	2,008,440	2,481,030	1,409,760	5,899,230
2022	90	2,057,580	2,526,300	1,454,670	6,038,550
2023	90	2,106,630	2,571,570	1,499,580	6,177,780
2024	90	2,155,770	2,616,840	1,544,490	6,317,100
2025	90	2,204,820	2,662,110	1,589,400	6,456,330
2026	90	2,253,960	2,707,470	1,634,400	6,595,830
2027	90	2,303,010	2,752,740	1,679,310	6,735,060
2028	90	2,352,150	2,798,010	1,724,220	6,874,380
2029	90	2,401,200	2,843,280	1,769,130	7,013,610
2030	90	2,450,340	2,888,550	1,814,040	7,152,930
2031	90	2,499,390	2,933,820	1,858,950	7,292,160
2032	90	2,548,530	2,979,180	1,903,950	7,431,660

Source: PERUMDAM Tirta Daroy, Banda Aceh City Public Works and Spatial Planning Agency (PUPR)

Despite this predictable growth in demand, existing infrastructure systems often fail to adapt accordingly. Studies have shown that insufficient pipe capacity, low flow velocities, and pressure deficiencies can significantly impair system performance, leading to sediment accumulation, reduced water quality, and inadequate service delivery (Mohammed & Mohammed-Ali, 2025). In addition, excessive pressure in certain network segments can accelerate leakage and increase maintenance costs, further exacerbating inefficiencies (Price et al., 2022). These challenges highlight the importance of balanced hydraulic design and effective pressure management strategies. Furthermore, water loss remains one of the most critical issues affecting the efficiency of distribution networks. High levels of NRW, often exceeding acceptable thresholds, result in significant economic and resource losses. Advanced modeling techniques, including optimization algorithms and smart water grid systems, have demonstrated substantial potential in reducing leakage and improving system efficiency (Ramos et al., 2022; Ramos et al., 2024). The integration of such technologies into water management practices can significantly enhance decision-making and long-term planning.

Hydraulic modeling tools such as EPANET have been widely used to simulate water distribution systems and evaluate key performance parameters, including flow velocity, pressure, and headloss. These tools provide valuable insights into system behavior under various operational scenarios, enabling the identification of critical bottlenecks and inefficiencies (Kherouf & Goita, 2023; Kępa & Deska, 2025). By incorporating real-world data and demand patterns, hydraulic models can support the development of optimized network designs and operational strategies that ensure a reliable and efficient water supply. In the context of Meuraxa District, the combination of rapid population growth, increasing water demand, and existing infrastructure limitations necessitates a comprehensive evaluation of the water distribution system. The disparities in service quality, including intermittent supply, low pressure, and unequal distribution, highlight the urgent need for system optimization.

Moreover, the area’s geographical and historical context, including its exposure to natural disasters, further complicates infrastructure management and requires resilient, adaptive solutions. Therefore, this study aims to model and analyze the performance of the clean water distribution network in Blang Oi and Punge Ujong villages using EPANET. By integrating population projections and water demand analyses with hydraulic simulation, this research seeks to identify system inefficiencies and propose practical recommendations to improve network performance. The findings are expected to enhance service quality, reduce water losses, and support sustainable water resource management in Banda Aceh, Indonesia.

2. Literature Review

2.1 Hydraulic Modeling in Water Distribution Systems

Hydraulic modeling has become an essential tool for analyzing, designing, and optimizing water distribution systems (WDS). It enables engineers to simulate flow behavior, pressure distribution, and system performance under varying demand scenarios. Studies consistently show that modeling tools such as EPANET and WaterGEMS provide reliable insights into system inefficiencies and support data-driven decision-making (Kherouf & Goita, 2023; Mohammed & Mohammed-Ali, 2025). For instance, Dadebo et al. (2023) demonstrated that hydraulic modeling can predict long-term system performance under demographic changes, revealing issues such as low flow velocities and negative pressure zones. Similarly, Trębicka (2023) emphasized the role of numerical modeling in optimizing operational decisions, particularly in identifying pressure imbalances and energy inefficiencies. These findings highlight that hydraulic modeling is not merely a design tool but also a strategic instrument for sustainable water management. However, while many studies focus on technical performance indicators such as pressure, velocity, and headloss, they often overlook the integration of socio-demographic variables such as population growth and demand dynamics. This creates a gap between engineering analysis and real-world service challenges.

2.2 Water Demand Growth and Infrastructure Pressure

Population growth is a key driver of increasing water demand, significantly affecting the performance and sustainability of water distribution systems. Mekonnen (2023) found that rapid population growth can render existing infrastructure insufficient, resulting in reduced service coverage and declining water supply reliability. Similarly, Kuma and Abate (2021) showed that even when hydraulic performance appears acceptable, future demand growth can push systems beyond their operational limits. The projections presented in this study (Tables 1 and 2) align with global trends, in which urban areas experience steady increases in both population and water demand. As demand rises, systems must accommodate higher flow rates while maintaining pressure stability and service continuity. Failure to adapt infrastructure accordingly results in inefficiencies such as low flow velocities, sediment accumulation, and reduced water quality (Mohammed & Mohammed-Ali, 2025). Despite this well-established relationship, many previous studies treat demand as a static parameter rather than a dynamic variable influenced by demographic and behavioral changes. This limitation reduces the accuracy of long-term planning and underscores the need for integrated modeling that combines hydraulic simulation with demand forecasting.

2.3 Water Loss and Pressure Management

Water loss, commonly measured as non-revenue water (NRW), is a major issue in water distribution systems, particularly in developing countries. High NRW levels, often exceeding 30%, indicate inefficiencies in system design, maintenance, and operation (Negese & Kebede, 2023). Leakage, driven by excessive pressure and aging infrastructure, is a primary contributor to water loss. Pressure management has been widely recognized as an effective strategy for reducing leakage and improving system efficiency. Tian et al. (2023) demonstrated that optimized pressure-reducing valve (PRV) control strategies can significantly reduce leakage while maintaining adequate service pressure. Similarly, Price et al. (2022) proposed optimization algorithms for PRV placement, highlighting the importance of balancing pressure reduction with service reliability. While these studies provide valuable technical solutions, they often focus on isolated interventions rather than holistic system optimization. In practice, water loss is influenced by multiple interacting factors, including network design, demand variability, and operational management. Therefore, a more integrated approach is required to address these complexities.

2.4 Advances in Smart Water Systems and Digital Modeling

Recent advancements in digital technologies have introduced new opportunities for improving water distribution system performance. Smart water grids and digital twins enable real-time monitoring, predictive analysis, and adaptive management of water infrastructure (Ramos et al., 2023). These technologies integrate hydraulic models with real-time data, allowing for more accurate and dynamic system evaluation. Pesantez et al. (2022) demonstrated how digital twins can capture changes in water consumption patterns and assess their impact on system performance. Similarly, Ramos et al. (2024) showed that implementing digital twins can significantly reduce water demand and improve energy efficiency, thereby contributing to sustainability goals. Despite their potential, the adoption of these advanced technologies remains limited in many developing regions due to financial, technical, and institutional constraints. As a result, conventional modeling tools such as EPANET remain the most practical and widely used solutions for system analysis and planning.

2.5 Optimization of System Performance and Energy Efficiency

Optimization of water distribution systems involves balancing multiple objectives, including hydraulic performance, energy efficiency, and cost-effectiveness. Świętochowska et al. (2021) highlighted the importance of optimizing pumping systems to reduce energy consumption while maintaining adequate pressure levels. Similarly, Kumar et al. (2024) emphasized the need to consider multiple design parameters, such as pipe diameter, flow velocity, and headloss, in achieving efficient system performance. These studies demonstrate that system optimization requires a comprehensive understanding of hydraulic behavior and operational constraints. However, many optimization studies focus on theoretical or controlled environments, limiting their applicability to real-world conditions where uncertainties and data limitations are prevalent.

3. Materials and Methods

This study adopts a quantitative descriptive design integrated with hydraulic modeling to evaluate the performance of clean water distribution infrastructure and its relationship with community satisfaction. The approach combines technical system analysis using simulation tools with perception-based evaluation via a structured survey, enabling a comprehensive assessment of both engineering performance and service quality. By integrating these two perspectives, the study provides a more holistic understanding of how infrastructure conditions influence user satisfaction. The research was conducted in Blang Oi Village and Punge Ujong Village, located in Meuraxa District, Banda Aceh City, Indonesia. These locations were selected because they are part of the Distribution Network Development and Household Connection Program implemented by the Banda Aceh City Government through the Public Works and Housing Agency (PUPR). The area has been identified as having relatively high levels of public complaints regarding clean water services, making it a relevant case for investigation.

In 2024, the allocated budget for this program in Meuraxa District was approximately IDR 4.44 billion, covering activities such as pipeline procurement and installation, accessory installation, pipeline connections, testing, rehabilitation, and household connection improvements. The study was conducted over a period of nine months, concluding in November 2025, and included stages of data collection, processing, analysis, and reporting. The population of this study consists of all customers of PERUMDAM Tirta Daroy in Meuraxa District whose household connections were upgraded from old pipelines to new pipelines in 2024, totaling 350 households. A stratified random sampling technique was employed to ensure proportional representation across the population. The sample size was determined using the Slovin formula, with a 10% margin of error, yielding a total sample of 78 respondents. This level of error tolerance was selected to balance statistical accuracy with practical feasibility, as lower error margins would require a substantially larger sample size.

Data collection was carried out using multiple techniques to ensure data validity and completeness. Primary data were collected using a structured Likert-scale questionnaire (1–5) to assess community satisfaction across key service indicators, including water quality, availability, cost, responsiveness, and accessibility. In addition, field observations were conducted to evaluate the physical condition of the water distribution infrastructure, including pipelines, joints, and supporting components. Secondary data were collected from PERUMDAM Tirta Daroy and the Banda Aceh City PUPR Office, including population statistics, water consumption data, network maps, and infrastructure specifications. To assess the technical performance of the water distribution system, hydraulic modeling was conducted using EPANET 2.2. The model was developed based on actual network conditions, incorporating parameters such as pipe diameter, length, elevation, and demand patterns. Simulations were performed over a 24-hour operational period, with particular attention to peak demand hours.

The analysis focused on key hydraulic parameters, including flow velocity, pressure distribution, and headloss, to identify inefficiencies such as low flow velocity, excessive pressure, and system imbalances. Community satisfaction was analyzed quantitatively using a Likert scale, with responses aggregated to calculate average satisfaction levels for each indicator. The indicators assessed include water quality (clarity and suitability), water availability (continuity of supply), service cost (affordability), responsiveness (complaint handling), and accessibility (ease of access to services). These indicators provide a comprehensive measure of perceived service quality from the user perspective. To ensure the quality of the research instrument, validity and reliability tests were conducted. The questionnaire items' validity was assessed using the Pearson Product–Moment Correlation; items were considered valid if the correlation coefficient exceeded 0.30. Reliability testing was performed using Cronbach's Alpha, with a threshold value of 0.70 indicating acceptable internal consistency.

Finally, hypothesis testing was conducted using the Chi-Square (χ^2) test to examine the relationship between clean water infrastructure and community satisfaction. This non-parametric test compares observed and expected frequencies to determine whether any differences are statistically significant. The calculated Chi-Square value was compared with the critical value based on the degrees of freedom; the null hypothesis is rejected if the calculated value exceeds the critical value. The hypotheses tested in this study are: H_0, which indicates no relationship between water infrastructure and community satisfaction, and H_1, which indicates a significant relationship between the two variables.

4. Results

4.1 Condition of Clean Water Distribution Infrastructure

The condition of the clean water distribution infrastructure in Blang Oi Village and Punge Ujong Village, Meuraxa District, Banda Aceh City, indicates a noticeable imbalance between the availability of physical network infrastructure and the quality of water distribution services. In general, the pipeline network has been constructed and covers most residential areas; however, it has not yet provided optimal service to the community. The Banda Aceh City Government, through PERUMDAM Tirta Daroy in collaboration with the Public Works and Housing Agency (PUPR), has expanded the distribution network by installing pipelines up to the household level. This development is based on Mayor Regulation No. 4 of 2022 concerning Policies and Strategies for the Implementation of the Drinking Water Supply System (SPAM) of Banda Aceh City for 2022–2026, which includes planning, construction, and installation of pipeline networks as well as direct household connections. In 2024, the Banda Aceh City Government, through the PUPR Office and PERUMDAM Tirta Daroy, implemented the installation of new distribution networks in Meuraxa District. This initiative aims to improve network performance and enhance the quality of clean water services for the community. The types of pipes, diameters, and installation lengths for Blang Oi Village and Punge Ujong Village are presented in the following Table 3:

Table 3. Installation of New Pipeline Network

No	Pipe Type	Diameter	Length	Unit	Description
Blang Oi Village					
1	HDPE PN 10 SDR 17	Ø 160 mm	880	m	Installed
2	HDPE PN 10 SDR 17	Ø 110 mm	1,982.00	m	Installed
3	HDPE PN 10 SDR 17	Ø 90 mm	1,373.00	m	Installed
Punge Ujong Village					
1	HDPE PN 10 SDR 17	Ø 200 mm	909	m	Installed
2	HDPE PN 10 SDR 17	Ø 160 mm	587	m	Installed
3	HDPE PN 10 SDR 17	Ø 110 mm	2,377.00	m	Installed
4	HDPE PN 10 SDR 17	Ø 90 mm	2,622.00	m	Installed

Table 3 presents the installation of new clean water distribution pipelines in Blang Oi Village and Punge Ujong Village, both located in Meuraxa District, Banda Aceh. The infrastructure development uses HDPE PN 10 SDR 17 pipes, widely recognized for their durability, flexibility, corrosion resistance, and suitability for medium-pressure water distribution systems. The use of this pipe type indicates that the network is designed to support reliable long-term operation under varying hydraulic conditions. In Blang Oi Village, the total pipeline length is dominated by Ø 110 mm pipes (1,982 m), followed by Ø 90 mm pipes (1,373 m) and Ø 160 mm pipes (880 m). This distribution suggests that the network design prioritizes secondary and tertiary distribution lines, where medium- and small-diameter pipes are used to deliver water directly to residential areas. The relatively shorter length of Ø 160 mm pipes indicates their role as primary or feeder pipelines, responsible for transporting water from main distribution points to smaller branch networks. The dominance of Ø 110 mm pipes reflects the need to balance flow capacity and pressure stability within the residential distribution system.

In contrast, Punge Ujong Village exhibits a more extensive and complex pipeline network. The largest proportion of the network consists of Ø 90 mm pipes (2,622 m) and Ø 110 mm pipes (2,377 m), indicating a strong emphasis on tertiary distribution and household-level service connections. Additionally, the presence of Ø 200 mm pipes (909 m) and Ø 160 mm pipes (587 m) suggests a more developed primary and secondary distribution system than at Blang Oi. The inclusion of larger-diameter pipes enhances the system's ability to convey higher flow rates and maintain pressure across a wider service area. Comparatively, Punge Ujong has a longer total pipeline length and a wider range of pipe diameters, reflecting higher demand or a more dispersed settlement pattern. The significant use of smaller-diameter pipes (Ø 90 mm) in both villages indicates a focus on expanding service coverage to individual households, which aligns with the objectives of the household connection program. However, an excessive proportion of smaller pipes may also pose challenges, such as reduced flow velocity or pressure drops in certain parts of the network if not properly balanced with larger feeder pipes.

From a hydraulic perspective, variations in pipe diameters across both villages play a crucial role in determining system performance. Larger pipes (Ø 160–200 mm) function as main transmission lines, ensuring sufficient flow capacity and reducing headloss, while smaller pipes (Ø 90–110 mm) distribute water to end users. An optimal combination of these pipe sizes is essential to maintain adequate pressure, minimize energy loss, and prevent sedimentation caused by low flow velocity.

4.2. Water Consumption Pattern

The water consumption pattern of PERUMDAM Tirta Daroy in Meuraxa District exhibits significant hourly fluctuations, suggesting that water use is not constant throughout the day and is strongly influenced by community habits and daily activities. Two primary peak periods are observed, in the morning and evening, with peak-hour factors ranging from 1.17 to 1.29 times the average demand. Based on survey results and supporting literature in Zone IV of PERUMDAM Tirta Daroy's service area, these peak periods occur at 06:00–07:00 AM and 05:00–06:00 PM. During these times, water consumption increases substantially due to routine activities such as bathing, washing clothes and utensils, preparing for work and school, as well as performing religious practices. Analysis of customer water usage data indicates that the total consumption in December 2024 reached 25,182 m³. Further processing of this data using Microsoft Excel shows an estimated average daily water demand of 812.323 m³/day and an average hourly demand of 33.847 m³/hour. These figures reflect the overall demand characteristics of the study area and provide a basis for hydraulic modeling and system evaluation. Detailed customer consumption data for Blang Oi Village and Punge Ujong Village in Meuraxa District are presented in Table 4.

Table 4. Customer Water Consumption Data in Blang Oi and Punge Ujong Villages, Meuraxa District, Banda Aceh (December 2024)

Customer ID	Usage (m³)	Month	District	Blang Oi (m³)	Punge Ujong (m³)
493172	0	Dec-24	Meuraxa	0	0
486492	41	Dec-24	Meuraxa	-	41
486430	50	Dec-24	Meuraxa	-	50
486529	24	Dec-24	Meuraxa	-	24
486729	18	Dec-24	Meuraxa	-	18
493684	12	Dec-24	Meuraxa	12	-
481085	15	Dec-24	Meuraxa	15	-
493594	51	Dec-24	Meuraxa	-	51
481258	13	Dec-24	Meuraxa	13	-
486578	0	Dec-24	Meuraxa	-	0
491309	15	Dec-24	Meuraxa	15	-
480972	16	Dec-24	Meuraxa	16	-
480796	0	Dec-24	Meuraxa	0	-
480878	0	Dec-24	Meuraxa	0	-
480848	22	Dec-24	Meuraxa	22	-
481241	24	Dec-24	Meuraxa	24	-
481242	0	Dec-24	Meuraxa	0	-
481229	28	Dec-24	Meuraxa	28	-
480779	0	Dec-24	Meuraxa	0	-
480778	21	Dec-24	Meuraxa	21	-
481139	24	Dec-24	Meuraxa	24	-
480849	28	Dec-24	Meuraxa	28	-
480792	26	Dec-24	Meuraxa	26	-

Table 4 presents detailed customer-level water consumption data for Blang Oi and Punge Ujong Villages in Meuraxa District, Banda Aceh, for December 2024. The dataset provides important insights into household water-use patterns, the spatial distribution of demand, and potential service inefficiencies within the clean water distribution system. The table shows significant variation in water consumption among customers, ranging from 0 m³ to 51 m³ per month. This variation reflects differences in household size, lifestyle, water-use behavior, and possibly the level of access to and reliability of the water supply. Customers with higher consumption levels (e.g., 41–51 m³/month) are likely to represent households with greater water needs or better access to a continuous supply. In contrast, lower or zero consumption may indicate supply interruptions, inactive connections, or reliance on alternative water sources. From a spatial perspective, the data indicate a clear distinction between the two service areas. Customers in Punge Ujong Village exhibit relatively high individual consumption, with several users exceeding 40 m³ per month. In contrast, Blang Oi Village shows a more evenly distributed consumption pattern, typically ranging between 12 m³ and 28 m³ per month, suggesting more moderate but consistent usage. This difference may be attributed to variations in network performance, population density, or socio-economic conditions between the two villages.

A notable feature of the dataset is the presence of multiple zero-consumption records across both villages. These entries may indicate several possible conditions, including: (1) temporary service interruptions due to low pressure or supply instability, (2) inactive or unoccupied households, (3) malfunctioning meters, or (4) behavioral adaptation where residents rely on alternative water sources such as wells or water storage systems. From an operational perspective, these zero values highlight potential inefficiencies in the distribution system and warrant further investigation. In terms of distribution system performance, the variation in consumption also suggests inconsistencies in water availability and pressure across the network. Households with higher consumption are likely located in areas with more stable pressure and better connectivity, whereas lower consumption may reflect areas experiencing pressure drops or intermittent supply. This aligns with common issues in water distribution systems, where uneven hydraulic performance results in unequal service delivery.

Furthermore, the dataset provides a useful basis for estimating average household water demand. Based on the observed values, the typical monthly consumption for active users ranges from 15 to 30 m³, corresponding to approximately 0.5–1.0 m³/day per household. This range is consistent with standard domestic water use in urban residential areas, though the variability suggests that not all households receive uniform service. From a planning and modeling perspective, this consumption data is critical for developing accurate demand patterns in hydraulic simulations (e.g., EPANET). The presence of peak users, low users, and inactive connections must be considered when calibrating the model to ensure a realistic representation of network behavior. Ignoring such variability could lead to inaccurate predictions of flow, pressure, and system performance.

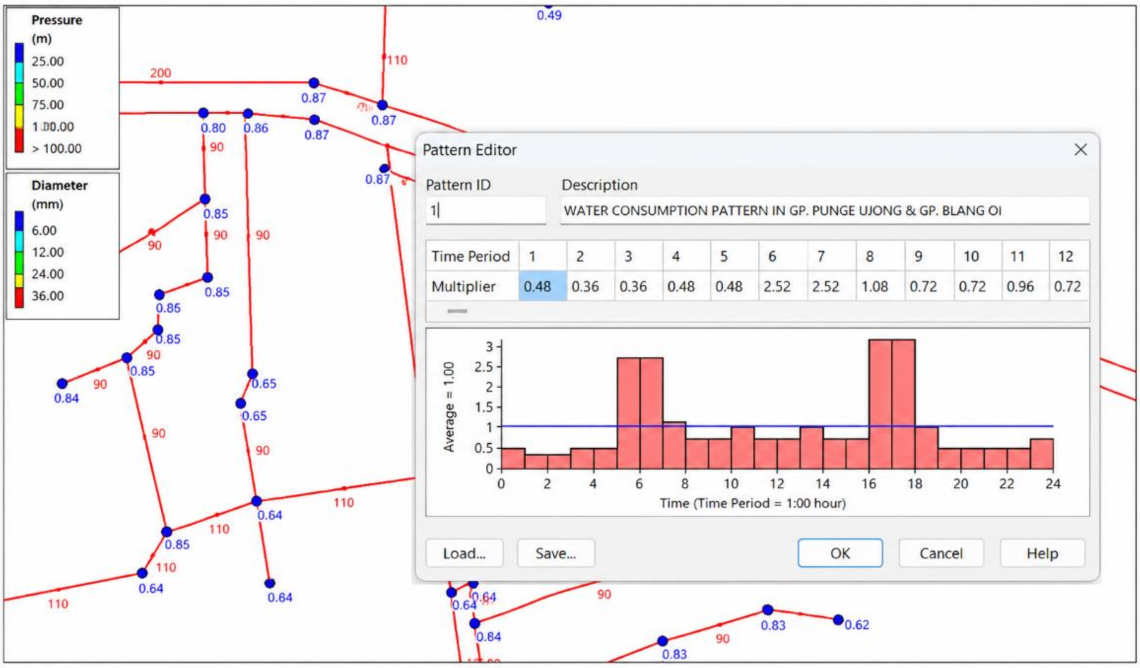
Table 5. 24-Hour Water Consumption Pattern in Blang Oi and Punge Ujong Villages, Meuraxa District, Banda Aceh

Hour	Water Consumption (Liters)	Percentage (%)	Multiplier
23:00–24:00	24,369.68	3	0.72
00:00–01:00	16,246.45	2	0.48
01:00–02:00	12,184.84	1.5	0.36
02:00–03:00	12,184.84	1.5	0.36
03:00–04:00	16,246.45	2	0.48
04:00–05:00	16,246.45	2	0.48
05:00–06:00	85,293.87	10.5	2.52
06:00–07:00	85,293.87	10.5	2.52
07:00–08:00	36,554.52	4.5	1.08
08:00–09:00	24,369.68	3	0.72
09:00–10:00	24,369.68	3	0.72
10:00–11:00	32,492.90	4	0.96
11:00–12:00	24,369.68	3	0.72
12:00–13:00	24,369.68	3	0.72
13:00–14:00	32,492.90	4	0.96
14:00–15:00	24,369.68	3	0.72
15:00–16:00	24,369.68	3	0.72
16:00–17:00	99,509.52	12.25	2.94
17:00–18:00	99,509.52	12.25	2.94
18:00–19:00	32,492.90	4	0.96
19:00–20:00	16,246.45	2	0.48
20:00–21:00	16,246.45	2	0.48
21:00–22:00	16,246.45	2	0.48
22:00–23:00	16,246.45	2	0.48

Table 5 illustrates the hourly distribution of water consumption in Blang Oi and Punge Ujong Villages over 24 hours, providing a detailed representation of daily demand fluctuations. The data reveal a highly variable consumption pattern, strongly influenced by household routines and socio-cultural activities. This variability is reflected in the percentage distribution and multiplier values, which indicate the relative intensity of water demand compared to the daily average. During the late-night to early-morning hours (00:00–05:00), water consumption remains relatively low, ranging from 12,184.84 to 16,246.45 liters per hour, equivalent to 1.5–2% of total daily demand, with multipliers of 0.36-0.48. This period represents minimal household activity, as most residents are inactive or asleep. Consequently, these hours are characterized by stable hydraulic conditions, low flow velocities, and reduced pressure fluctuations within the distribution network.

A sharp increase in water demand occurs between 05:00 and 06:00, marking the start of the morning peak period. Consumption rises significantly to 85,293.87 liters (10.5%), with a multiplier of 2.52, and remains at this level until 06:00–07:00. This surge is driven by routine morning activities such as bathing, cooking, washing, and preparation for work and school. The morning peak places substantial stress on the distribution system, requiring adequate pressure and flow capacity to maintain service quality. Following the morning peak, water demand gradually decreases from late morning to early afternoon (07:00–15:00). consumption stabilizes at 24,369.68-32,492.90 liters per hour, corresponding to 3–4% of daily demand. This period reflects more moderate, evenly distributed usage as households transition into daytime activities. The relatively stable demand during these hours helps maintain balanced hydraulic performance within the network. A second, more pronounced increase in demand occurs during the afternoon-to-evening peak period (16:00–18:00). The highest consumption values are recorded during this time, reaching 99,509.52 liters per hour (12.25%), with a multiplier of 2.94. This represents the day's maximum peak demand, exceeding the morning peak. The evening peak is associated with activities such as bathing, cleaning, cooking, and religious practices after completing daily work. From a system perspective, this period represents the most critical operational condition, requiring optimal network performance to prevent pressure drops and service interruptions.

After the peak period, water consumption declines again during the evening to late-night hours (19:00–23:00), with usage ranging from 16,246.45 to 32,492.90 liters per hour (2–4%). This decline reflects reduced household activity as residents prepare for rest. However, demand remains higher than early morning levels, indicating continued but moderate water use. The result demonstrates a typical bimodal (dual-peak) consumption pattern, with significant peaks in the morning and evening. The peak-hour factors (2.52–2.94) indicate that demand during peak periods can be nearly three times the average, with important implications for system design and operation. Such variability requires the distribution network to be designed with sufficient capacity to handle peak loads while maintaining efficiency during low-demand periods. From a hydraulic modeling perspective, this demand pattern is critical for accurately simulating network behavior in tools such as EPANET. The presence of high peak multipliers suggests potential risks of pressure drops, increased headloss, and uneven flow distribution during peak hours, particularly in areas with smaller pipe diameters or longer distribution lines. Conversely, low-demand periods may lead to reduced flow velocities, increasing the risk of sedimentation and water quality degradation.



Pattern ID: 1

Description: WATER CONSUMPTION PATTERN IN GP. PUNGE UJONG & GP. BLANG OI

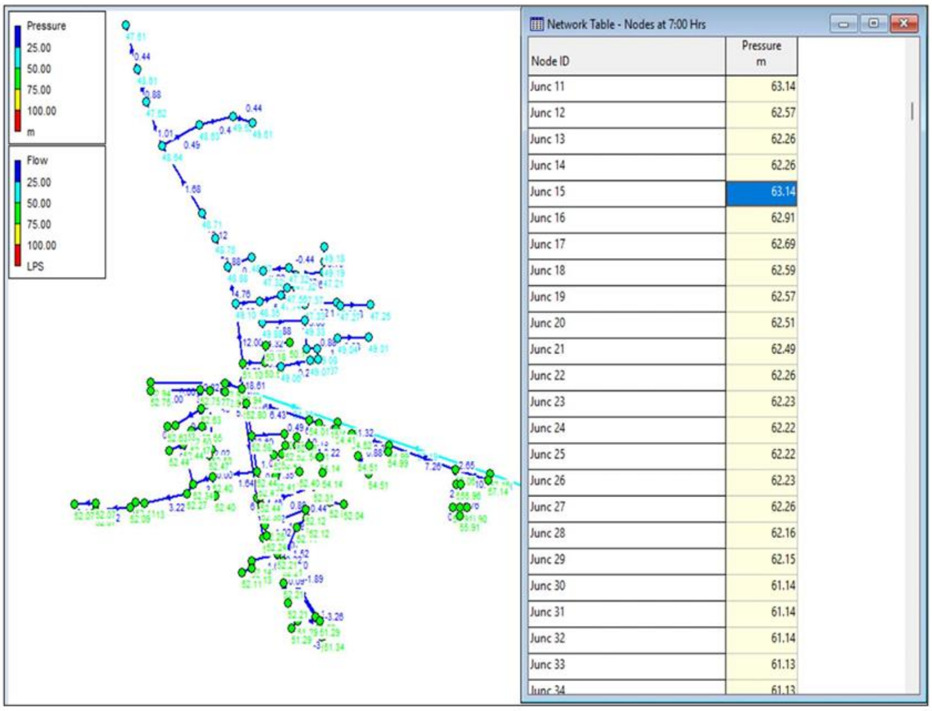
Time Period	1	2	3	4	5	6	7	8	9	10	11	12
Multiplier	0.48	0.36	0.36	0.48	0.48	2.52	2.52	1.08	0.72	0.72	0.96	0.72

Figure 1. Water Consumption Pattern Diagram

4.3. Clean Water Distribution Network Performance Using EPANET 2.2

The analysis of the clean water distribution network's performance in this study was conducted using EPANET 2.2. The network model was developed based on existing data, including pipeline network maps, ground elevations, pipe lengths and diameters, and community water demand patterns. The modeled system comprises 137 junctions, 144 pipes, one reservoir unit, and one booster pump unit, reflecting the actual configuration of the distribution network in the study area. The water consumption pattern was defined based on the average daily demand of the population in Meuraxa District, estimated at 150 liters per person per day. To capture the system's dynamic behavior, the simulation was run over 24 hours, enabling analysis of pressure and flow variations under both peak and normal demand conditions.

The network layout was developed using an online drawing system with the Auto Length feature activated, ensuring accurate representation of pipe lengths. The reservoir, defined as junction 1, is located at coordinates X: 756,907.393 and Y: 614,065.400, with an elevation of 4 meters above sea level. The furthest service point in the network is junction 108, located approximately 2,948.41 meters from the reservoir, at coordinates X: 754,177.362 and Y: 615,178.980, with an elevation of 3 meters above sea level. The elevation difference between nodes ranges from 1 to 2 meters, indicating that the study area has relatively flat topography. As a result, elevation differences have a minimal influence on pressure distribution, and the system's hydraulic behavior is primarily governed by energy losses in the pipes rather than by gravity.



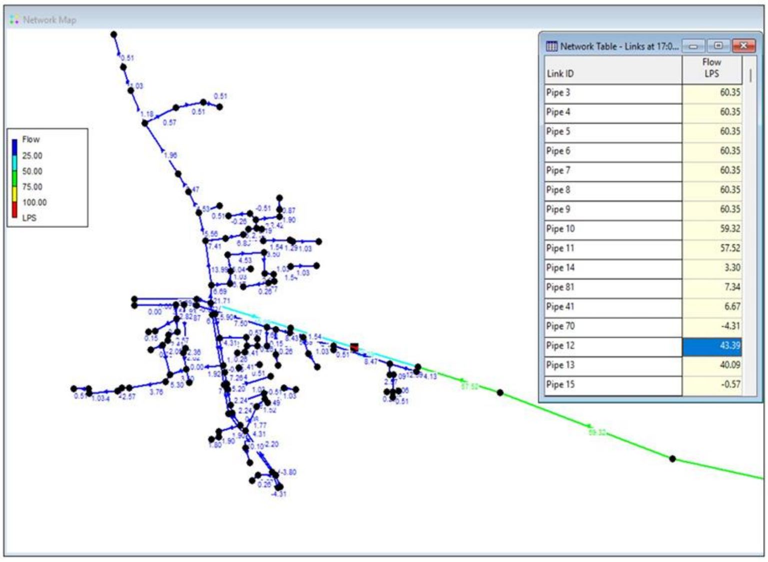
Node ID	Pressure m
Junc 11	63.14
Junc 12	62.57
Junc 13	62.26
Junc 14	62.26
Junc 15	63.14
Junc 16	62.91
Junc 17	62.69
Junc 18	62.59
Junc 19	62.57
Junc 20	62.51
Junc 21	62.49
Junc 22	62.26
Junc 23	62.23
Junc 24	62.22
Junc 25	62.22
Junc 26	62.23
Junc 27	62.26
Junc 28	62.16
Junc 29	62.15
Junc 30	61.14
Junc 31	61.14
Junc 32	61.14
Junc 33	61.13
Junc 34	61.13

Figure 2. Maximum Pressure at 06:00–07:00 AM

The pressure simulation results show that pressure values vary across different nodes within the network. However, in general, the pressure levels at most nodes fall within the acceptable service standards as specified in the Regulation of the Minister of Public Works No. 8/PRT/M/2007. This indicates that the distribution system can deliver clean water effectively under normal operating conditions. During the morning peak period (06:00–07:00 AM), the highest pressure is observed at junction 15, reaching 63.14 meters of water column (mH_2O), while the lowest pressure occurs at junction 124, with a value of 47.21 mH_2O. Similarly, during the evening peak period (17:00–18:00), the maximum pressure is recorded at junction 125 at 63.78 mH_2O, whereas the minimum pressure is recorded at junction 119 at 41.44 mH_2O. These findings indicate that although the overall pressure distribution meets the required standards, there is still noticeable variation across the network, particularly during peak demand periods. This variation suggests the presence of localized hydraulic imbalances, which may be influenced by pipe characteristics, flow distribution, and network configuration.

4.3.1. Flow Simulation

Figure 4 shows the flow rate simulation in the clean water distribution network using EPANET 2.2, indicating that flow distribution within the pipes is strongly influenced by water demand at each node, network configuration, and pipe dimensions. Some pipes exhibit flow rates below the minimum allowable limit, while others exceed the maximum permissible limit. During the morning peak hours (06:00–07:00 AM), the maximum flow rate occurs in pipe 12 at 37.19 L/s, while the minimum flow rate is observed in pipe 63 at 0.07 L/s. Meanwhile, during the evening peak hours (17:00–18:00), the maximum flow rate is again recorded in pipe 12, increasing to 43.39 L/s, whereas the minimum flow rate is recorded in pipe 104, at 0.05 L/s.

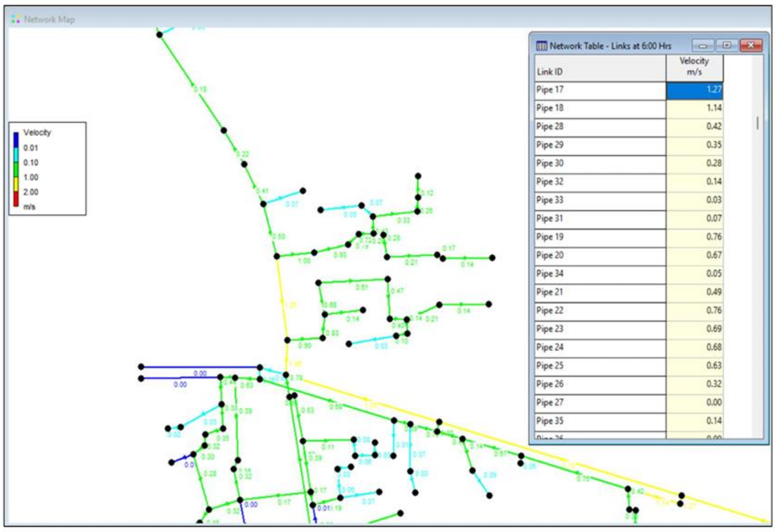


Link ID	Flow LPS
Pipe 3	60.35
Pipe 4	60.35
Pipe 5	60.35
Pipe 6	60.35
Pipe 7	60.35
Pipe 8	60.35
Pipe 9	60.35
Pipe 10	59.32
Pipe 11	57.52
Pipe 14	3.30
Pipe 81	7.34
Pipe 41	6.67
Pipe 70	-4.31
Pipe 12	43.39
Pipe 13	40.09
Pipe 15	-0.57

Figure 3. Maximum Flow Rate at 05:00–06:00 PM

4.3.2. Flow Velocity Simulation

Flow velocity is a key parameter for evaluating the hydraulic performance of a clean water distribution network. In general, several sections of the distribution pipeline network in Blang Oi Village and Punge Ujong Village exhibit flow velocities below 0.3 m/s, a condition that may lead to sedimentation within the pipes. Figure 4 shows the simulation results using EPANET 2.2; the maximum flow velocity in the distribution network during the morning peak hours (06:00–07:00 AM) occurs in pipe 17, at 1.27 m/s. Meanwhile, the minimum flow velocity is observed in pipes 39, 53, 63, and 76, with values as low as 0.01 m/s. During the evening peak hours (17:00–18:00), the maximum velocity again occurs in pipe 17, increasing to 1.49 m/s, while the minimum velocity remains in pipe 63, with a value of 0.01 m/s.

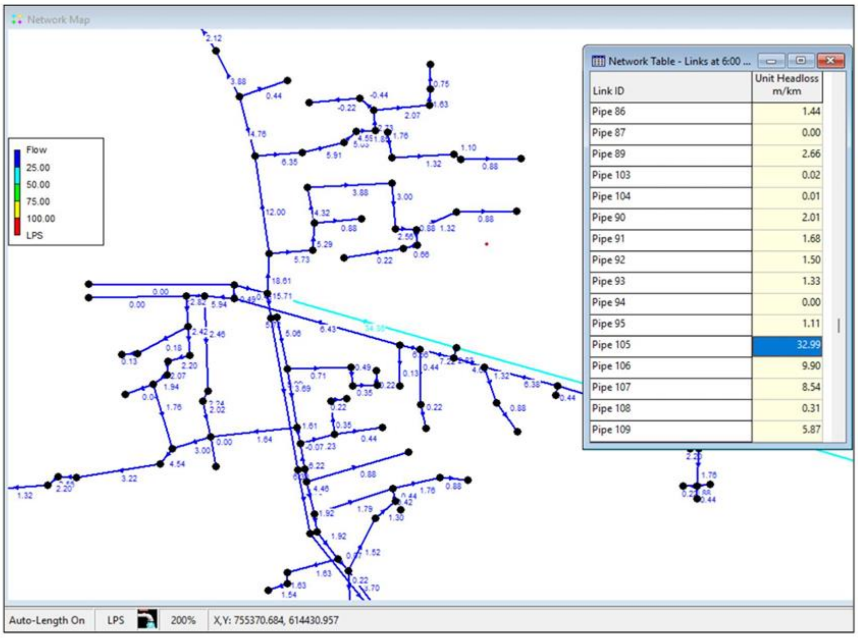


Link ID	Velocity m/s
Pipe 17	1.27
Pipe 18	1.14
Pipe 28	0.42
Pipe 29	0.35
Pipe 30	0.28
Pipe 32	0.14
Pipe 33	0.03
Pipe 31	0.07
Pipe 19	0.76
Pipe 20	0.67
Pipe 34	0.05
Pipe 21	0.49
Pipe 22	0.76
Pipe 23	0.69
Pipe 24	0.68
Pipe 25	0.63
Pipe 26	0.32
Pipe 27	0.00
Pipe 35	0.14

Figure 4. Maximum Flow Velocity at 06:00–07:00 AM

4.3.3. Headloss Simulation

Figure 5 shows the simulation results from EPANET 2.2: the headloss values in the distribution network vary across pipes. The normal range of headloss is 2–10 m/km, in accordance with Regulation No. 27/PRT/M/2016 of the Ministry of Public Works and Housing. During the morning peak hours (06:00–07:00 AM), the highest headloss occurs in pipe 105, with a value of 32.99 m/km, while the lowest headloss is observed in pipes 15, 16, 27, 39, 53, 63, 76, 87, and 94, with a value of 0.00 m/km. During the evening peak hours (17:00–18:00), the highest headloss again occurs in pipe 105, with a value of 5.52 m/km, whereas the lowest headloss is found in pipes 15, 16, 33, 27, 38, 39, 52, 53, 73, 75, 76, 87, 94, 103, 104, 117, and 130, all with values of 0.00 m/km.



Network Table - Links at 6:00 ...

Link ID	Unit Headloss m/km
Pipe 86	1.44
Pipe 87	0.00
Pipe 89	2.66
Pipe 103	0.02
Pipe 104	0.01
Pipe 90	2.01
Pipe 91	1.68
Pipe 92	1.50
Pipe 93	1.33
Pipe 94	0.00
Pipe 95	1.11
Pipe 105	32.99
Pipe 106	9.90
Pipe 107	8.54
Pipe 108	0.31
Pipe 109	5.87

Figure 5. Maximum Headloss at 06:00–07:00 AM

5. Discussion

This study aims to evaluate the hydraulic performance of the clean water distribution networks in Blang Oi and Punge Ujong and assess their ability to meet community water demand based on observed consumption patterns and projected growth. By integrating EPANET-based simulation with empirical data, the findings provide important insights into system functionality, efficiency, and areas requiring improvement. First, the results confirm that hydraulic modeling is an effective tool for evaluating water distribution systems, as widely supported in previous studies (Kherouf & Goita, 2023; Mohammed & Mohammed-Ali, 2025). The developed model, comprising 137 junctions and 144 pipes, accurately represents real network conditions and enables analysis of pressure, flow, velocity, and headloss under varying demand scenarios. This aligns with Dadebo et al. (2023), who emphasized that simulation-based approaches are essential for predicting system performance and supporting sustainable water management.

In terms of pressure performance, the simulation results indicate that most nodes meet the acceptable standards set by national regulations, suggesting the system can deliver adequate service under normal conditions. This finding is consistent with Kuma and Abate (2021), who reported that well-calibrated hydraulic models can ensure that most nodes operate within acceptable pressure ranges. However, the observed pressure variation between nodes, particularly during peak hours, reflects localized imbalances within the network. Similar patterns were identified by Mekonnen (2023), who found that uneven pressure distribution is common in systems experiencing rapid demand growth and infrastructure limitations. The flow rate analysis further highlights disparities in network performance. While some pipes carry high flow rates (up to 43.39 L/s), others exhibit extremely low flows (as low as 0.05 L/s), indicating underutilization or weak connectivity. This imbalance suggests that the network is not hydraulically optimized, a finding supported by Kumar et al. (2024), who emphasized the importance of proper pipe sizing and network design in ensuring uniform flow distribution. Additionally, low-flow conditions may contribute to inefficiencies such as stagnation and reduced water quality.

A critical issue identified in this study is the low flow velocity in several pipeline segments, with values falling below the recommended minimum of 0.3 m/s. According to Mohammed and Mohammed-Ali (2025), low velocities can lead to sediment accumulation and deterioration of water quality, which may ultimately affect service reliability. This is further supported by Negese and Kebede (2023), who found that a significant proportion of pipes in underperforming systems operate below recommended velocity thresholds, contributing to high water losses and reduced efficiency. Although maximum velocities in this study remain within acceptable limits, the prevalence of low velocities indicates a need for system optimization. The headloss analysis reveals additional insights into network efficiency. While most pipes operate within the standard range of 2–10 m/km, certain segments, particularly Pipe 105, exhibit excessively high headloss values. This suggests localized energy losses due to friction, likely caused by inappropriate pipe diameter selection or high flow concentration. Similar findings were reported by Świętochowska et al. (2021), who highlighted that improper system design can lead to increased energy consumption and reduced hydraulic efficiency. Conversely, the absence of headloss in several pipes indicates minimal or stagnant flow, further reinforcing the issue of uneven flow distribution.

Another important factor influencing system performance is the relatively flat topography of the study area, with elevation differences of only 1–2 meters. As noted by Trębicka (2023), in flat terrains, hydraulic performance is primarily governed by pipe characteristics and network configuration rather than elevation differences. This explains why pressure remains generally adequate, while velocity and headloss exhibit significant variation. It also underscores the importance of optimizing pipe layout and diameter to improve overall system efficiency. The water consumption pattern observed in this study follows a typical bimodal distribution, with peak demand occurring in the morning and evening. This pattern is consistent with findings by Pesantez et al. (2022), who demonstrated that daily human activities strongly influence water demand fluctuations. The peak hour factors (2.52–2.94) indicate that demand during peak periods can be nearly three times the average, placing significant stress on the distribution system. Such demand variability must be carefully considered in system design and operation to ensure reliability during peak conditions.

From a broader perspective, the study's findings highlight the gap between infrastructure availability and service quality. Although significant investments have been made to expand the pipeline network, the system still faces challenges due to hydraulic inefficiencies and uneven service delivery. This issue has been widely documented in developing regions, where infrastructure expansion often outpaces optimization and maintenance (Ramos et al., 2023). Furthermore, high water loss and inefficiency remain common challenges, as reported by Tian et al. (2023), underscoring the need for improved pressure management and leakage control. The results also suggest that advanced approaches, such as digital twins and smart water systems, as discussed by Ramos et al. (2024), could enhance network monitoring and optimization. However, given the practical constraints in many developing contexts, the use of accessible tools such as EPANET remains highly relevant for improving system performance. Integrating such tools with real-time data and demand forecasting could further enhance decision-making and operational efficiency. This study demonstrates that while the clean water distribution network in Meuraxa District meets basic service requirements, it is not yet fully optimized. Key challenges include low flow velocities, uneven flow distribution, and localized headloss issues. Addressing these challenges requires a combination of infrastructure improvement, hydraulic optimization, and better demand management. By aligning technical performance with actual consumption patterns, the system can be improved to provide more reliable, efficient, and sustainable water services.

6. Conclusions

This study evaluated the performance of the clean water distribution network in Blang Oi and Punge Ujong Villages, Meuraxa District, Banda Aceh, by integrating hydraulic modeling using EPANET 2.2 with empirical water consumption data. The findings indicate that the existing network infrastructure is generally capable of meeting community water demand under normal operating conditions, as evidenced by pressure levels that largely comply with national service standards. However, despite adequate pressure performance, several hydraulic inefficiencies were identified. These include uneven flow distribution across the network, low flow velocities in multiple pipe segments (below the recommended 0.3 m/s), and localized high headloss values in certain pipes. Such conditions may lead to operational issues, including sedimentation, reduced water quality, and energy inefficiency. The results also reveal that the system experiences significant demand fluctuations, with peak-hour factors reaching 2.94, placing considerable stress on the network during the morning and evening peak periods.

The relatively flat topography of the study area minimizes the influence of elevation on hydraulic performance, indicating that system behavior is primarily governed by pipe characteristics, network configuration, and demand distribution. Furthermore, although infrastructure expansion has improved service coverage, it has not fully translated into optimal service quality, highlighting a gap between physical development and hydraulic efficiency. This study concludes that while the clean water distribution system in Meuraxa District is functionally adequate, it requires targeted optimization to enhance performance and sustainability. Key improvements should focus on rebalancing pipe dimensions, improving flow distribution, managing pressure more effectively, and incorporating demand-based operational strategies. The integration of hydraulic modeling with real consumption data is a valuable approach for supporting evidence-based planning and improving the reliability of water supply systems in urban areas.

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