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Optimizing Water Supply Distribution Network at Makongo in Dar es Salaam, Tanzania

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Abstract

Rapid urbanization in Dar es Salaam, Tanzania, has strained the water supply network in areas like Makongo, leading to significant challenges such as low pressure, high water losses, and poor hydraulic performance due to aging and undersized infrastructure. This study aimed to optimize the Makongo water distribution network by creating and calibrating a high-fidelity hydraulic model using EPANET. The model, which included 1404 pipes, 1250 junctions, 5 pumps, and 2 reservoirs, was built with data from DAWASA, GIS mapping, and extensive field surveys. We used an Extended Period Simulation (EPS) and skeletonization techniques to accurately capture temporal demand variations while preserving the core system's behavior. The model was successfully calibrated and validation confirmed robustness ($R^2 = 0.89$, $RMSE = 10.26$ m), demonstrating its high accuracy and robustness. Our optimization efforts led to a significant improvement in hydraulic performance. The number of nodes with pressures below the recommended 15 m head was reduced by 91%. A Wilcoxon signed-rank test showed a statistically significant improvement in pressure distribution ($Z = -3.92$, $p < 0.001$), confirming enhanced pressure regulation, reduced losses, and improved service reliability. This research provides a practical, simulation-based optimization framework that can serve as a benchmark for DAWASA and other urban water utilities in addressing water security challenges in rapidly growing cities.

Keywords

Water Distribution, Hydraulic Modeling, EPANET, Optimization, Extended Period Simulation

1. Introduction

Access to safe and reliable water is crucial for public health, economic growth, and a high quality of life. A well-functioning water supply network is the backbone of this system. However, in many developing countries, deficiencies in these networks contribute to the spread of waterborne diseases, which remain a leading cause of child mortality (Lee & Schwab, 2005).

In rapidly urbanizing areas like Dar es Salaam, Tanzania, infrastructure development often struggles to keep pace with population growth (WHO, 2024). This is particularly evident in peri-urban settlements like Makongo. Here, the water supply system faces significant challenges such as intermittent supply and low water pressure. These issues are not just an inconvenience; they pose serious public health risks. During non-supply hours, a lack of pressure can cause a vacuum in the pipes, leading to backflow and the ingress of contaminants, a direct threat to public health (WHO, 2024).

Modern water distribution networks are capital-intensive projects. The cost of the transmission and distribution network can account for as much as 80% - 85% of the total cost of a modern water supply system (Muranho et al., 2014). This high cost is largely due to the hydraulic parameters of the network, such as the size and length of pipes. Consequently, any inefficiencies in the design, operation, or maintenance of this network have a magnified impact on the overall financial viability and sustainability of the entire system (Muranho et al., 2014).

Optimizing these hydraulic parameters—specifically pressure and velocity can lead to significant operational savings, defer costly new infrastructure investments, and mitigate water losses (Al-Khaffaf et al., 2020). The fundamental objective of any water distribution network is to deliver water to consumers in sufficient quantity and at the required pressure (Rossman, 2000). Water is typically stored in elevated service reservoirs to ensure it flows under pressure. The overall performance of a system is judged by the pressure available at various flow rates (Mays, 2011). Statistical hydraulic parameter analysis using software like EPANET provides a sophisticated, data-driven strategy for optimizing these systems. This allows organizations like the Dar es Salaam Water Supply and Sanitation Authority (DAWASA) to make informed decisions for operation and maintenance, ensuring a sustainable and reliable water supply.

Despite advancements in hydraulic modeling, most studies have focused on water distribution systems in developed countries with continuous supply. This leaves a critical gap in addressing the unique challenges of intermittent supply, which are prevalent in developing urban areas like Makongo. Previous research often overlooks the crucial integration of local topographic and operational data, such as that provided by DAWASA, to optimize networks under the resource-constrained conditions typical of Sub-Saharan Africa (Makombe et al., 2017).

This study fills that gap by applying a context-specific optimization approach to the Makongo water distribution network. By integrating GIS-based mapping, field surveys, and local demand patterns, we address the root causes of intermittent supply and low-pressure issues. The novelty of this research lies in its combination of a quantitative, simulation-based approach optimizing water distribution system to improve performance and the use of Wilcoxon signed-rank test for statistical validation of the improvements.

2. Materials and Methods

2.1. Description of the Study Area

Makongo area is located in the north-western 6˚45′27″S, 39˚11′42.72″E, urban zone of Dar es Salaam city, about 17 kilometers from the city center, as shown in **Figure 1**. The area is growing rapidly with residential and commercial buildings in Dar Es Salaam City. The topography of Makongo includes gentle slopes and a plateau. It also has large valleys and streams which drain water into the Mbezi river. These valleys inhibit close movement and increase the cost of transportation. Among the different methods of population projection techniques, the study considered the overall current situation of the targeted Makongo area. The population of Makongo is approximately 35,567 according to National Bureau of Statistics (NBS), 2022. The mean yearly temperature recorded is 26.1˚C and approximately 1114 mm of precipitation descends.

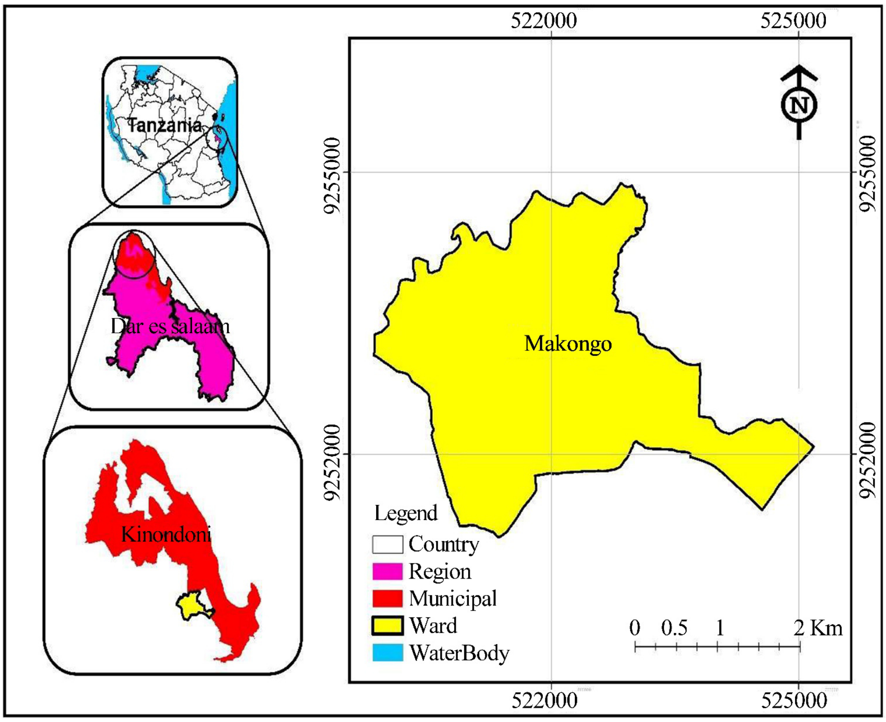


Figure 1. Map of Makongo showing the study area.

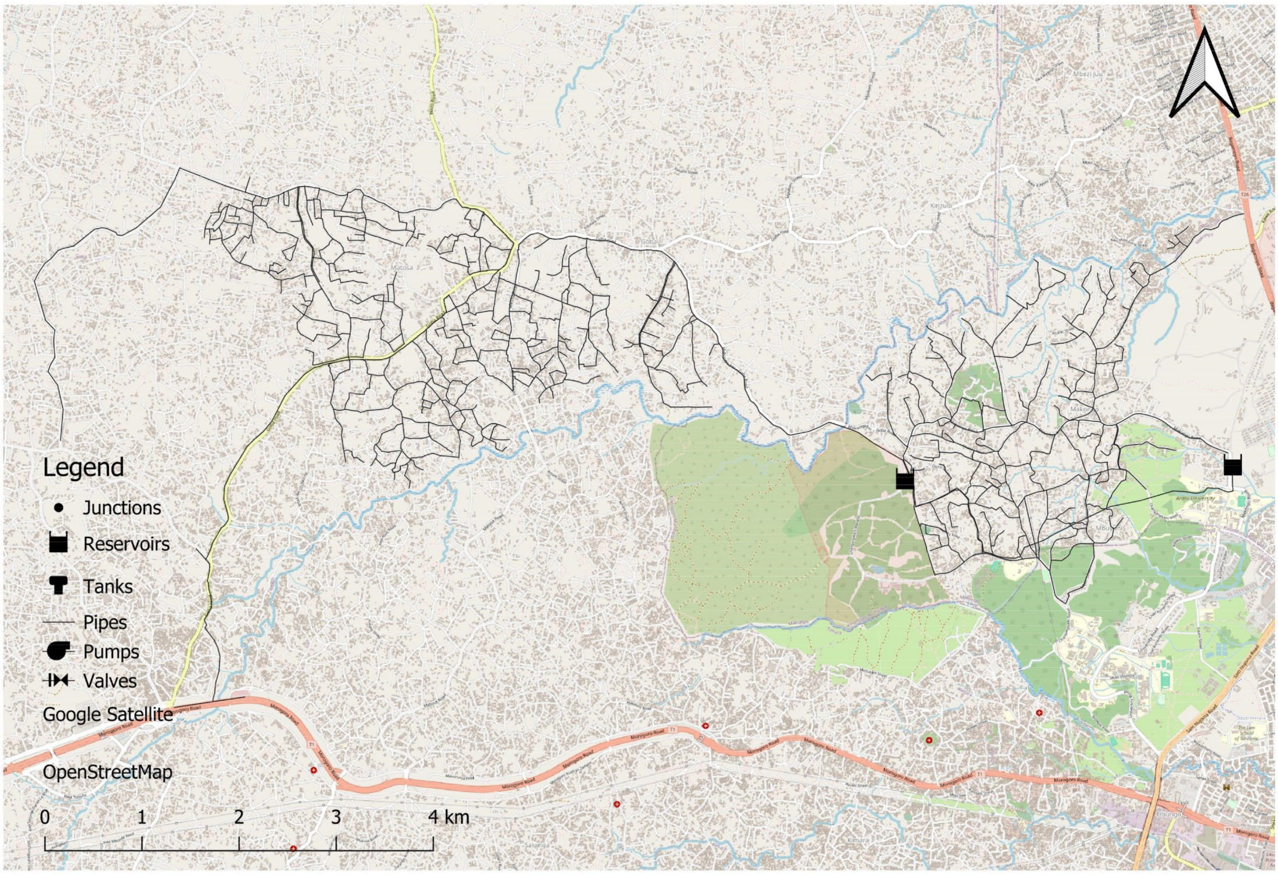
2.2. Existing Water Supply Distribution Network at Makongo Area

Currently, Makongo town was supplied from Makongo booster station, which supplied an average capacity of 1029716.00 m^3/year, but the delivered water to the customers is 666207.00 m^3/year as per the Dar es Salaam Water Supply and Sanitation Service (DAWASA, 2024). The combined water supplied, consumed, and lost in Makongo is presented in **Table 1**.

Table 1. Combined water consumed, supplied, and water loss.

Water supplied, consumption, and water loss, 2020				
Month	Supplied m³	Consumption m³	Water loss	%
January	86,975	59,939	27,036	31.08%
February	77,576	52,683	24,893	32.09%
March	89,765	62,768	26,997	30.08%
April	92,786	69,286	23,500	25.33%
May	99,879	64,467	35,412	35.45%
June	98,734	57,228	41,506	42.04%
July	88,072	58,062	30,010	34.07%
August	65,765	41,857	23,908	36.35%
September	82,647	39,230	43,417	52.53%
October	79,387	40,637	38,750	48.81%
November	79,177	54,944	24,233	30.61%
December	88,953	65,106	23,847	26.81%
Total	1029716.00	666207.00	363,509	35.30%
Average	85809.67	55517.25	55,924	35.44%

Source: (DAWASA report, 2024).



Source: Open Street Map (Google Earth).

Figure 2. Existing Makongo and Goba water supply distribution networks.

The Water Supply Distribution Network (WSDN) of Makongo town is an integrated system designed to deliver water to consumers through a combination of branched and looped pipelines, extending approximately 188.55 kilometers in total length. The network originates at a pump station, which conveys water to a reservoir, from where it is distributed to consumers throughout the town.

The pipelines are constructed from three main materials: uPVC (unplasticized Polyvinyl Chloride), a corrosion-resistant plastic; HDPE (High-Density Polyethylene), a flexible and durable plastic; and steel, which offers high strength but requires protective treatment to prevent rusting. Pipe sizes vary according to function, with Nominal Diameters (DN) ranging from 50 mm for smaller local distribution lines to 400 mm for major transmission mains. This range ensures efficient water flow and reliable service to meet the town's demand (see **Figure 2**).

2.3. Water Demand Variations

Extended period simulation analysis was used to provide a specific pattern for giving demands with respect to hourly and daily variation in water demands, as shown in Equation 1.

$$\mathrm{PF} = \mathrm{Q}_{\max} / \mathrm{Q}_{\mathrm{ave}} \tag{1}$$

where PF is the peak factor in a daily hour demand; $\mathrm{Q}_{\max}$ is the maximum hourly demand (m^3/hr); and $\mathrm{Q}_{\mathrm{ave}}$ is the average daily demand (m^3/hr).

2.4. EPANET Simulation Model for the Makongo Water Supply Distribution Network

The hydraulic model of the Makongo Water Supply system was developed in EPANET by translating physical network components and operational parameters into a digital simulation environment. The process integrated GIS data, CAD drawings from DAWASA, and field survey information. Pipeline maps and layouts in hardcopy or PDF formats were georeferenced in ArcGIS to align with topographical and satellite data. Where gaps existed, network elements were digitized manually in ArcGIS using high-resolution imagery and GPS data. This established the baseline model for subsequent calibration and hydraulic analysis.

Table 2. Lengths of pipes in the model before and after skeletonization.

	Before model skeletonization	After model skeletonization	Percentage of skeletonization (%)
Total length of pipes (m)	188,546	150,552	20

Pipe skeletonization, following USEPA (2005) guidelines, was applied to simplify the network while preserving hydraulic integrity. The criteria required retention of at least 50% of total pipe length, 75% of pipe volume, and all major transmission and distribution lines (DN50-DN400). Smaller service connections were excluded. This process reduced the modeled network length by 37,994 m (**Table**

2). This level of simplification is acceptable as it strategically removes hydraulically insignificant elements while conserving the network's core flow paths and storage capacity. As demonstrated by Saldarriaga et al. (2008), such a skeletonized model can accurately replicate the hydraulic behavior of the original full network for planning-level analyses.

2.5. Model Development

The EPANET hydraulic model of the Makongo distribution network was developed through a systematic process that translated both field and secondary data into simulation-ready inputs. The network layout was digitized using GIS and CAD drawings obtained from DAWASA, which were georeferenced against topographic maps and high-resolution satellite imagery. Junctions, reservoirs, and pumping stations were positioned using surveyed GPS coordinates, while pipeline alignments were verified through field reconnaissance.

Key hydraulic parameters were defined using a combination of literature values and locally available operational records. Pipe roughness coefficients were assigned by material type according to recommended Hazen-Williams values: 140 for HDPE, 150 for uPVC, and 120 for steel. Nodal demand was estimated from DAWASA's 2024 consumption records and projected household and commercial demands, adjusted with diurnal peak factors (morning = 1.45, evening = 1.20, off-peak = 0.65) to reflect actual usage patterns. Pump curves were generated from DAWASA operational data, with an average head-discharge slope of 0.82 m/(L/s). Reservoir head levels were fixed at 85.4 m (R1) and 78.7 m (R2), based on field measurements. Junction elevations were derived from an open-source (SRTM) 30-meter Digital Elevation Model (DEM).

This systematic parameterization ensured that the baseline model was both physically representative and hydraulically realistic. Calibration and validation were then undertaken as described in the following section.

2.6. Model Calibration and Validation

To ensure the reliability of the EPANET hydraulic model used in analyzing the Makongo water distribution network, a calibration exercise was undertaken.

Model calibration was performed based on the results of the model hydraulic parameters; pressure measured in the selected nodes was used for calibration (Walski et al., 2003). This process involved comparing simulated pressure values generated by the model with field-measured pressure data collected at selected junction nodes within the network.

To validate the EPANET model, a separate dataset independent of the calibration process was collected through field measurements at selected junction nodes. Ten (10) representative nodes, J-1263, J-803, J-862, J-1205, J-1870, J-1770, J-1624, J-1804, J-1862, and J-2129, were monitored for pressure values using portable pressure gauges. Measurements were taken at two daily intervals, at 09:00 AM high demand period and 02:00 PM low demand period, for five consecutive days to improve the quality of the results, covering both peak and off-peak conditions. These nodes were chosen because they represent a range of elevations, demand categories (domestic, commercial, institutional), and hydraulic zones within the network, making them suitable for assessing the model's predictive accuracy across different conditions.

The measured pressures were then compared with simulated pressures generated by the EPANET model under the same boundary conditions. Statistical indicators including the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Square Error (MSE) were used to evaluate the model's performance. By relying on independent field data, the validation process ensured that the model was not only calibrated to fit known conditions but also capable of accurately predicting system behavior under different operating scenarios.

The model statistical hydraulic parameters' performance was evaluated using objective functions, including the coefficient of determination, using Equation (2) and Equation (3).

2.7. Statistical Techniques for Model Evaluation

All measured and simulated pressure values obtained from the EPANET model and field surveys were exported into Microsoft Excel for statistical analysis. The following statistical techniques were applied:

2.7.1. Coefficient of Determination (R^2)

R^2 was computed to evaluate the strength of the linear relationship between measured and simulated pressures. Using Excel's built-in regression analysis tool, the correlation coefficient (R) was first obtained by plotting simulated versus measured pressures and fitting a linear trendline. The square of this correlation coefficient gave the R^2 value, which indicates how much of the variability in the measured data is explained by the model.

$$R^2 = 1 - \frac{\Sigma(x-y)^2}{\Sigma(x-\overline{x})^2}. \tag{2}$$

2.7.2. Mean Square Error (MSE)

MSE was calculated to quantify the average squared difference between the measured and simulated pressures. In Excel, this was implemented using a formula column where each error term $(x_i - y_i)^2$ was computed, summed, and divided by the number of observations (n).

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left(y - \hat{y}\right)^2. \tag{3}$$

and Root Mean Square Error (RMSE) is a frequently used measure of the differences between values predicted by a model or an estimator and the values observed. It is a standard way to measure the error of a model in predicting quantitative data.

The mathematical equation for RMSE is:

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\Sigma x_i}\ . \tag{4}$$

All evaluation statistics are embedded in the EPANET environment for calibration purposes. Calibration is a critical step in hydraulic modeling, as it enhances the model's ability to accurately reflect real-world conditions and increases confidence in subsequent simulations used for planning and operational decisions (Rossman, 2000).

3. Results and Discussion

3.1. Existing Water Distribution System

3.1.1. Water Balance

The existing water balance in the study area was assessed by calculating the difference between water production and consumption. The total water loss in Makongo's Water Supply Distribution Network accounts for 13.9% of total production. This relatively low loss is attributed to the system's recent construction in 2018. At the beginning of a system's design life, minimal water loss is expected; however, losses may gradually increase over time unless minor leakages are promptly repaired and a routine maintenance program is established and consistently implemented.

For comparison, Makombe et al. (2017) reported average water losses of approximately 49% in Dar es Salaam's older infrastructure, primarily due to aging pipelines, illegal connections, and poor maintenance. The 13.9% loss in Makongo is significantly lower, likely reflecting the newer infrastructure. According to the World Bank (Kingdom et al., 2006), well-maintained systems typically experience NRW levels of 15% - 20%, whereas developing countries often exceed 30% - 40%. The Makongo figure of 13.9% falls below this benchmark, indicating efficient operation and recent commissioning.

Mutikanga et al. (2011) found water losses of 30% - 50% in urban Ugandan systems, recommending early leak detection, real-time monitoring, and district metered areas (DMAs) for control. This supports the observation that routine maintenance and timely repairs are critical to sustaining efficient operation as the system ages. Thus, while the Makongo system currently performs well, its long-term efficiency will depend on the consistent application of maintenance, leak monitoring, and NRW management practices.

3.1.2. Network Layout

The existing network was digitized into EPANET and consisted of 1253 nodes, 1406 pipes/links, 1 pump station, and 2 storage tanks. Pipe diameters ranged from 50 mm to 400 mm, and pipe materials included HDPE and steel. Water demand was assigned to nodes based on a per capita consumption rate of 110 liters per capita per day (lpcd) and a population density of 350 persons/hectare. These demand values were distributed across the network based on demographic and land use data from NBS (2022). As shown in **Figure 3**, the existing Makongo water supply network consists of 1253 nodes, 1406 pipes, one pump station, and two storage tanks.

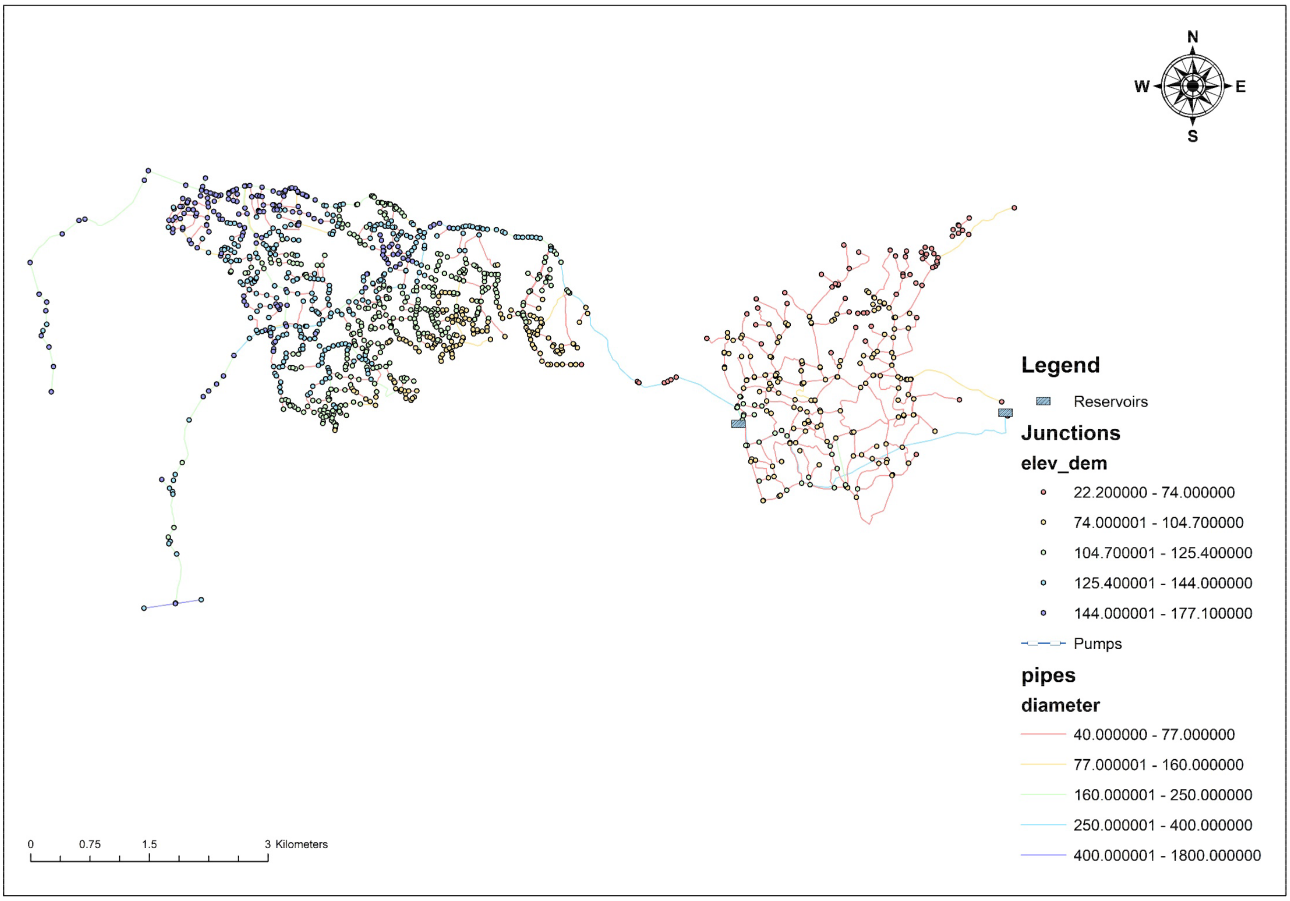


Figure 3. Existing Makongo water supply network (as built).

3.2. Simulation Results

To evaluate the performance of the Makongo water distribution system, a hydraulic simulation was conducted to examine how water demand patterns influence pressure, flow, and overall network reliability. While steady-state analysis provides a snapshot of hydraulic conditions at a specific moment, it does not account for daily fluctuations in consumption. Therefore, an Extended Period Simulation (EPS) was employed to model the system over 24 hours, capturing the diurnal variations in water demand observed in Makongo. This approach allowed for assessment of peak demand impacts on service delivery, identification of potential low-pressure zones, and support for operational optimization and water loss reduction.

Model Calibration and Validation

The hydraulic model of the Makongo water distribution system was validated by comparing measured and simulated pressures at 10 key junctions J-1263, J-803, J-862, J-1205, J-1870, J-1770, J-1624, J-1804, J-1862, and J-2129. Measured pressures ranged from 36 to 98 meters, while simulated pressures varied from 21.44 to

120.81 meters. The largest deviation was 20.15 meters at Junc J-1870, and the smallest was 4.7 meters at Junc J-803 (**Figure 4**). These differences fall within acceptable engineering limits. The close agreement indicates that model parameters including pipe roughness, demand patterns, and elevations were appropriately defined and adjusted during calibration.

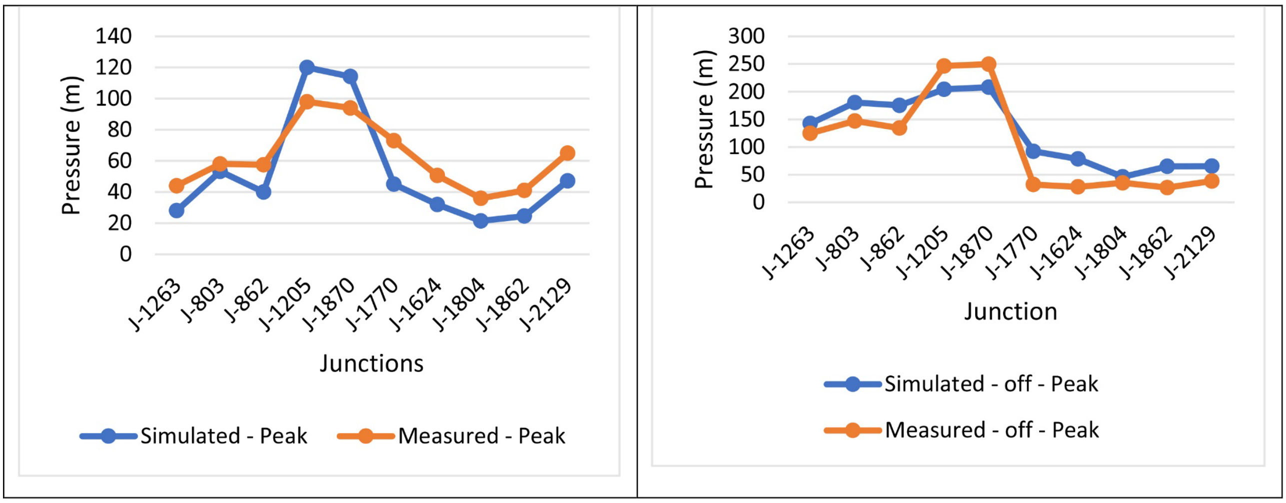


Figure 4. Simulated and measured values.

To further evaluate model performance, a correlation analysis was conducted between measured and simulated pressures at selected junctions (**Table 3**). The coefficient of determination (R^2) was calculated as 0.89, while the Mean Squared Error (MSE) and Root Mean Square (RMS) were 734 and 10.26 m, respectively. These results indicate a strong agreement between observed and simulated values, confirming the reliability of the model for further analyses, including system optimization, scenario testing, and the assessment of intermittent supply impacts.

Table 3. Calculation of root mean square as per Equation (2).

Nodes	Measured Pressure (x) m	Simulated pressure (y) m	X − Y		$(X - \bar{X})$	$(X - \bar{X})^2$
J-1263	124.83	132.07	−7.24	52.4176	19.538	381.7334
J-803	147.14	167.62	−20.48	419.4304	41.848	1751.255
J-862	134.27	158.3	−24.03	577.4409	28.978	839.7245
J-1205	246.5	204.4	42.1	1772.41	141.208	19939.7
J-1870	249.74	217.04	32.7	1069.29	144.448	20865.22
J-1770	32.24	70.34	−38.1	1451.61	−73.052	5336.595
J-1624	27.98	54.71	−26.73	714.4929	−77.312	5977.145
J-1804	24.64	44.37	−19.73	389.2729	−80.652	6504.745
J-1862	20.3	42.36	−22.06	486.6436	−84.992	7223.64
J-2129	45.28	65.42	−20.14	405.6196	−60.012	3601.44
	105.292			7338.628		72421.2

Figure 5 illustrates the scatter plot of measured versus simulated pressures, with a fitted trendline. The strong linear relationship, with $R^2 = 0.89$, indicates that over 89% of the variation in simulated pressures is explained by measured values. The points closely align along the 1:1 trendline, demonstrating minimal deviation and high consistency between field measurements and model outputs.

Comparable results have been reported in other hydraulic modeling studies. Morley and Tricarico (2008) achieved an R^2 of 0.95 during EPANET-based calibration of a municipal water network in Australia. Sitzenfrei et al. (2011) reported R^2 values exceeding 0.96 in automatic calibration studies, while Rico-Ramirez et al. (2007) recorded R^2 values of 0.97 in real-time modeling. These findings reinforce the robustness of the current calibration process and its alignment with internationally accepted practices.

Overall, the calibration and validation confirm that the model reliably represents the Makongo water distribution network and can be confidently used for performance analysis, operational planning, and water distribution efficiency assessments.

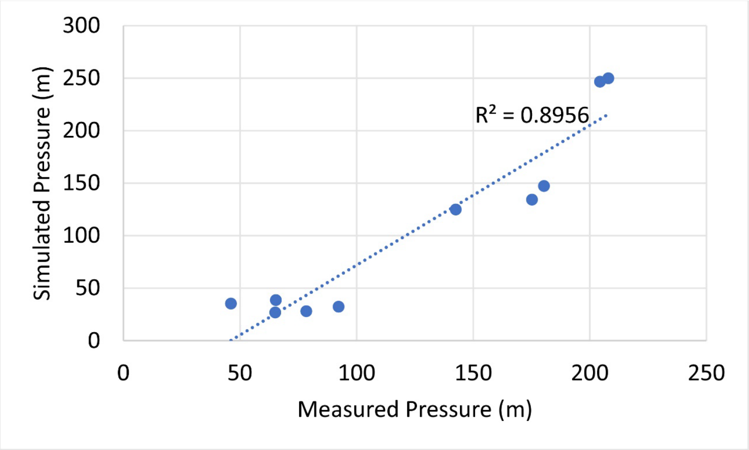


Figure 5. Correlation analysis was conducted between measured and simulated pressure.

3.3. Hydraulic Pressure and Velocity Analysis

The hydraulic performance of the existing water supply system was analyzed by evaluating pressures and velocities throughout the network. The skeletonized network considered in this study includes 1404 pipes of various materials, 1250 junctions, 5 pumps, and 2 water source reservoirs, as shown in **Figure 6**. Following model calibration, current water production was assessed in relation to the observed demand patterns in the Makongo and Goba areas.

The results align with previous studies. Muranho et al. (2014), using EPANET to evaluate a Portuguese urban water network, observed low-pressure zones at high-elevation nodes and high velocities in undersized or corroded pipes. Kapelan et al. (2005) highlighted that growing urban water distribution networks often experience increased pressure variability, necessitating pipe re-sizing and re-zoning to maintain reliability. In Dar es Salaam, Makombe et al. (2017) reported that pressure loss and pipe friction from aging infrastructure significantly impacted water delivery, consistent with the findings in Makongo-Goba. Furthermore, Behzadian et al. (2009) demonstrated that optimizing pipe diameters and pressure zones through hydraulic modeling can reduce water losses by 12% and achieve 15% energy savings, underscoring the importance of pressure-velocity analysis as conducted in this study.

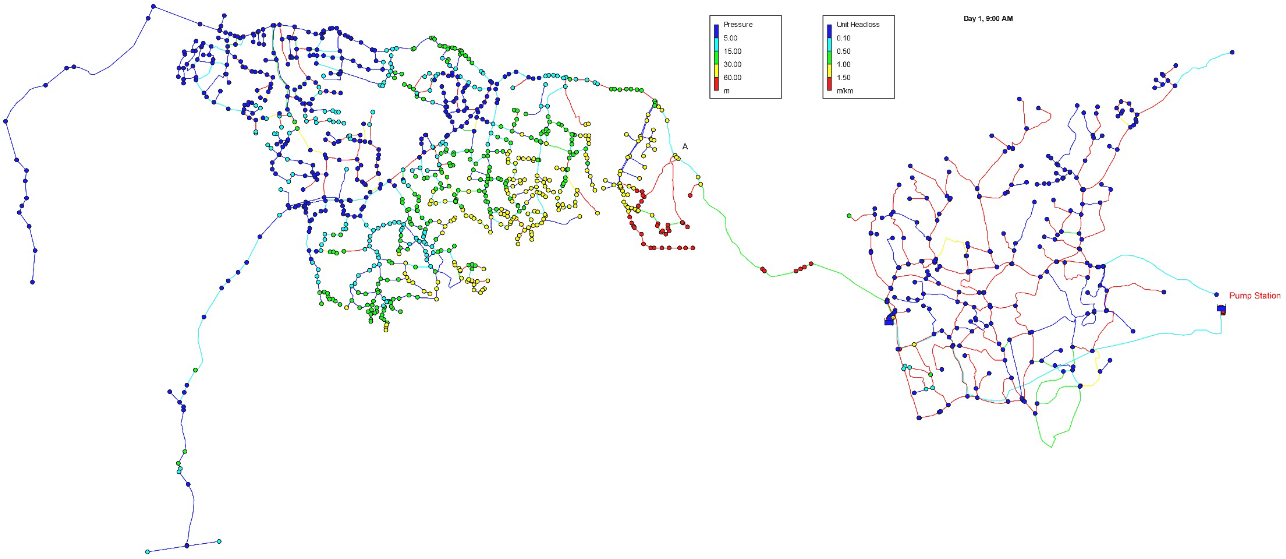


Figure 6. Map of pressure in the existing distribution system at peak hour demand.

Table 4. Hydraulic pressures before optimization.

Pressure (m)	Nodes	Percentage (%)
<−1	505	40%
1 - 5	86	7%
5 - 15	166	13%
15 - 30	243	19%
30 - 60	208	17%
>60	42	3%
	1250	

The hydraulic model results for node pressures during peak hour demand, presented in **Table 4**, provide critical insights into the performance of the existing water supply system. By comparing allowable, minimum, and maximum pressures at each junction, the analysis identifies areas where pressure may fall below or exceed recommended limits, highlighting potential service reliability issues. Maintaining pressures within the acceptable range is essential to ensure adequate water delivery to consumers, prevent pipe damage from excessive pressures, and minimize water losses. The peak-hour assessment specifically reflects the network's ability to meet the highest demand periods, indicating whether pumps, reservoirs, and pipeline capacities are sufficient. These results serve as a basis for identifying low-pressure zones, prioritizing network upgrades, and optimizing operational strategies to enhance system performance and ensure consistent, safe water supply throughout the service area.

It was observed that 493 nodes (39%) in the existing water supply system satisfied the recommended pressure range of 15 - 60 m, as specified in the Ministry of Water Design Manual (MoW, 2020). Farley and Trow (2003) emphasize that high-pressure zones (>60 m) can lead to pipe bursts, joint failures, and increased leakage. Even a small proportion of over-pressured nodes, such as the 42 nodes (3%) identified in this system, can significantly amplify water losses if left unmanaged. Conversely, a substantial number of nodes 757 (61%) were found to be below the recommended pressure range. This indicates that large portions of the study area, particularly the low-pressure nodes, may not receive sufficient water during peak hour demand (PHD), notably around 9:00 AM.

The hydraulic model results for pipe velocities at PHD are presented in **Table 5**, showing the allowable, minimum, and maximum velocities in the network. These results are critical for identifying areas with potential flow constraints, assessing the risk of pipe erosion or sedimentation, and supporting decisions for network optimization and operational management.

Table 5. Hydraulic velocity before optimization.

Velocity (m/s)	Number of Pipes	Percentage (%)
<0.6	1249	88.96%
0.6 - 1	57	4.06%
1 - 1.5	42	2.99%
1.5 - 2	29	2.07%
>2	27	1.92%
	1404	

Studies of urban water distribution systems (WDSs) in developing countries have shown that under-designed networks often suffer from low velocities and non-uniform pressures, leading to service disruptions and low efficiency (Sharma & Vairavamoorthy, 2009). They highlighted the importance of optimizing pipe diameters and upgrading critical network links.

Analysis of the Makongo distribution network indicates that the majority of pipes approximately 89% operate at very low velocities below 0.6 m/s. This pattern is typical in systems with intermittent supply, where long periods without flow result in minimal water movement in dead-end or low-demand areas once supply resumes. Such conditions increase the risk of sediment buildup, stagnation, and microbial growth. About 7% of the pipes, mainly in main distribution lines or high-demand areas, exhibit moderate velocities between 0.6 and 1.5 m/s, sufficient to maintain water quality. A small fraction, roughly 4%, experiences high velocities above 1.5 m/s, typically during peak usage or in critical pipeline segments.

The model results revealed that the existing system's pressure and velocity distribution are insufficient to meet the full water demand of the study area. Low velocities contribute to inadequate flow, siltation, and increased pipe wear, which exacerbate leakage and pipe bursts, further reducing water delivery to consumers. These findings underscore the need for optimizing pipe diameters and re-evaluating the network design to improve flow, reduce non-revenue water, and ensure reliable water supply.

3.4. Optimized Pipe Diameters

The optimization of the pipe diameters of the Water Supply system was carried out based on commercially available pipe sizes. The optimized pipe diameters skeleton in the study area is illustrated in **Figure 7**, whereby pipe optimization was undertaken during the PHD (9:00 AM) at the nodes, since it satisfied the required demands in the distribution systems, which means that other water demands were also fulfilled (Ali et al., 2015).

All hydraulic parameters before and after optimization were analyzed using nonparametric tests since the data populations were not normally distributed. The Wilcoxon signed-rank test was applied, and the results showed statistical significance ($p < 0.05$) for pressure. This indicates that the optimization process had a measurable impact on these parameters. The significance of the optimization was further analyzed based on desired performance criteria and their relative importance, as discussed in subsequent sections. **Figure 7** illustrates the optimized pipe diameter skeleton of the study area's water supply system.

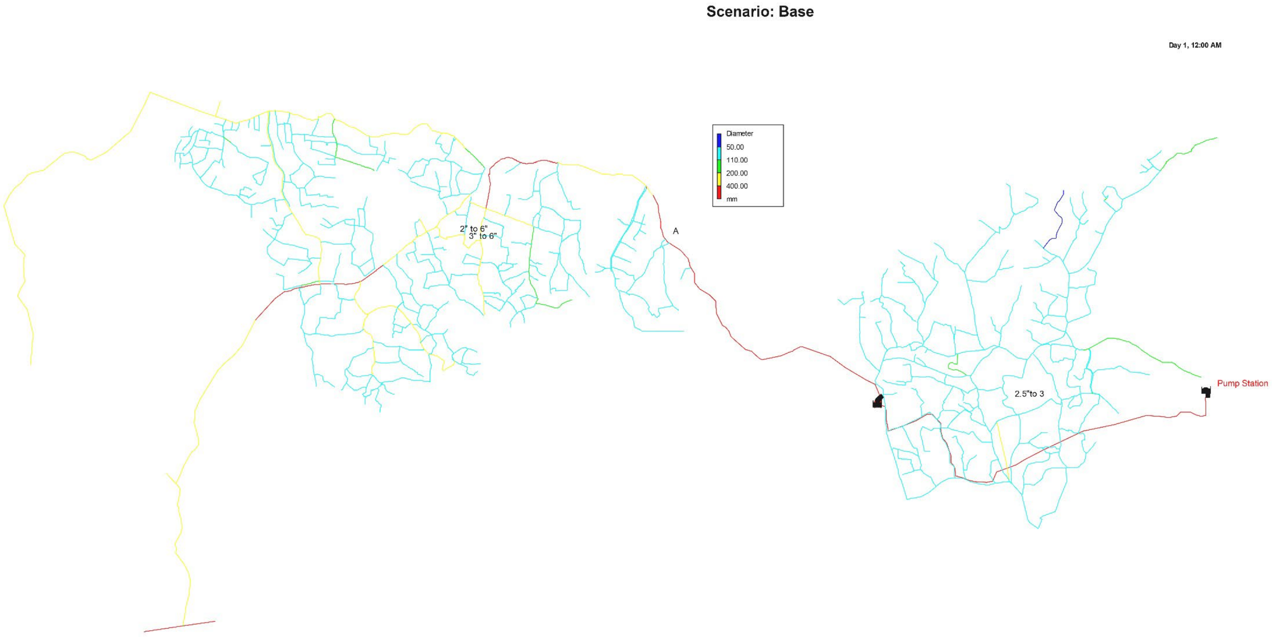


Figure 7. Optimized pipe diameter of the study area water supply system.

Pressure

A statistical comparison of node pressures before and after optimization was conducted using the Wilcoxon signed-rank test, with the results presented in Table 6. This non-parametric test was selected to evaluate whether the optimization process produced significant changes in pressure distribution across the network. The results indicate a statistically significant improvement in pressures ($p < 0.05$), confirming that the optimized pipe diameters effectively increased low-pressure node values and reduced the occurrence of over-pressured nodes. These improvements enhance the overall reliability of the water supply system, ensuring that all areas receive adequate pressure during peak demand periods and reducing the risk of pipe bursts or excessive leakage. Consequently, the statistical analysis validates the effectiveness of the optimization strategy in improving hydraulic performance and supporting sustainable water delivery.

Table 6. Wilcoxon signed-rank test results for pressure at nodes.

Metric	Value
Sample Size (N)	20
Sum of Ranks (W^+)	210
Sum of Ranks (W^-)	0
Test Statistic (W)	0
Critical Value ($\alpha = 0.05$)	52
Z-Score	−3.92
p-value	< 0.001
Concluding Remark	Significant increase in pressure (reject H_0)

Using 20 critical nodes, the sum of positive ranks ($W^+ = 210$) far exceeded the sum of negative ranks ($W^- = 0$), with a test statistic $W = 0$, well below the critical value of 52 at $\alpha = 0.05$. Normal approximation yielded a Z-score of −3.92 and a p-value < 0.001, confirming that pressure increases were not due to chance.

3.5. Optimization Makongo Water Supply System

3.5.1. Optimized Pipe Diameters

Pipe diameter optimization for the Makongo water supply system was conducted using a simulation-based approach with EPANET with objective function of minimize head loss, maximize pressure with key constraints of minimum pressure of 5 m, minimum velocity of 0.6 m/s. Commercially available pipe sizes were evaluated to meet peak demand while maintaining pressures within 20 - 80 m and velocities between 0.6 - 2 m/s, and to minimize construction and operational costs. Multiple iterative simulations were performed using EPANET's optimizer, and each configuration was assessed against hydraulic constraints.

The final optimized network, shown in Figure 7, successfully met peak hour demand at 9:00 AM, ensuring reliable supply throughout the day. Statistical analysis using the Wilcoxon signed-rank test confirmed significant pressure improvements ($p < 0.05$), demonstrating that the optimization process effectively enhanced overall network performance.

3.5.2. Pressure and Velocity Improvements

A detailed statistical evaluation of nodal pressures (**Table 7**) confirmed the effectiveness of optimization. 95% of the nodes after optimization had a pressure within the recommended range (15 - 60 m). These improvements enhance network reliability during peak demand, reducing the risk of pipe bursts, overpressure, and non-revenue water (NRW).

Table 7. Pressure at the Nodes after optimization.

Pressure (m)	Nodes	Percentage (%)
<−1	1	0%
1 - 5	9	1%
5 - 15	44	4%
15 - 30	82	7%
30 - 60	307	25%
>60	807	65%
	1250	

Velocity analysis showed reductions in high-flow sections and increased flow in low-velocity segments. Approximately 12% of pipes achieved improved velocities, helping prevent stagnation, reduce siltation, and maintain water quality. Statistically, these velocity improvements were validated ($Z = -6.13$, $p < 0.00001$), demonstrating that diameter optimization and layout adjustments contribute to better hydraulic performance and operational efficiency.

Comparative studies reinforce these results. Siew, Tanyimboh and Seyoum (2014) observed pressure improvements of up to 40% at key nodes during peak hours, while Berardi, Giudicianni and Santonastaso (2009) reported a 12% reduction in pipe velocities post-optimization, improving energy efficiency and reducing pipe failure risk. Creaco and Franchini (2012) found that increasing pressure by 10 m at low-pressure nodes reduces water loss by 6% in aged systems. The Makongo study confirms these findings and couples hydraulic modeling with rigorous statistical validation, providing a scientifically robust benchmark for water distribution optimization in Tanzanian urban contexts.

4. Conclusions and Recommendations

This study successfully developed and optimized the Makongo water distribution network using EPANET. A detailed hydraulic model was created using physical, topographical, and operational data from DAWASA. Extended Period Simulation (EPS) captured temporal variations in demand, while skeletonization simplified the model without compromising hydraulic behavior. Calibration and validation demonstrated high accuracy ($R^2 = 0.89$ and RMSE = 10.26 m). Initial analysis revealed that 61% of nodes operated below recommended pressures (15 - 60 m), and 88.96% of pipes had velocities below 0.6 m/s, indicating areas at risk of stagnation and poor water quality.

Optimization of pipe diameters leads to statistically significant pressure improvements with over 95% of node operate within the recommended rang of 15 - 60 m and sported by analysis using Wilcoxon signed-rank test, which shows $Z = -3.92$, $p < 0.001$. The optimized network resulted in better pressure regulation and improved reliability, confirming the effectiveness of the applied methodology. It is recommended that water utilities implement the optimized pipe diameters and pumping schedules, integrate routine hydraulic monitoring to maintain system performance, and consider future optimization, including water quality parameters such as chlorine decay. This study provides a benchmark for evaluating and improving other urban water distribution systems in similar settings, contributing to more efficient, reliable, and sustainable water supply operations.

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Conflicts of Interest

The authors declare no conflict of interest regarding this research. All findings, analyses, and interpretations presented in this study are independent and unbiased.

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