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Hydraulic performance evaluation of Yeka Abado supply zone of Addis Ababa's water distribution network

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ABSTRACT

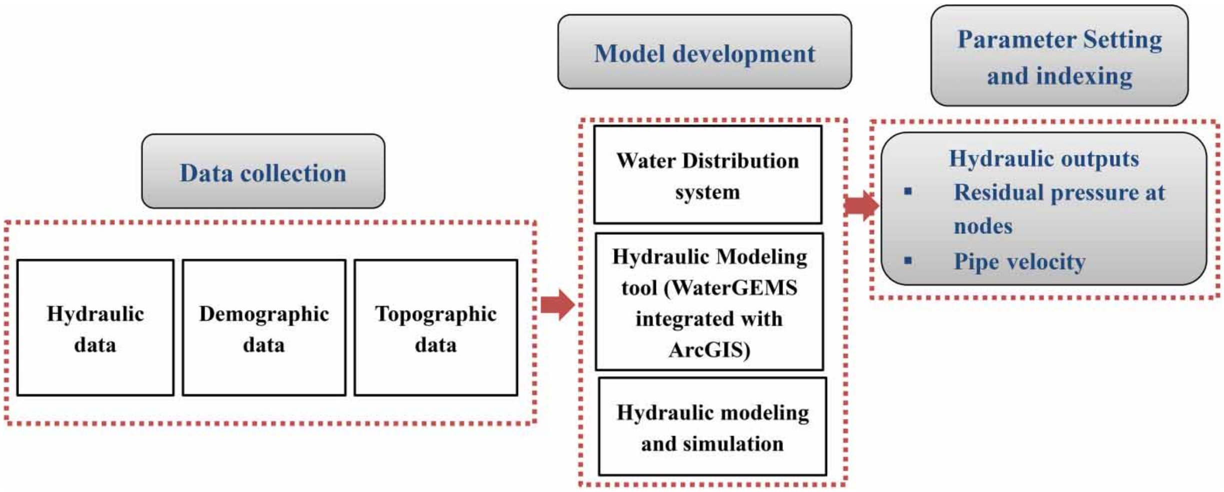
A water distribution network's crucial feature is providing adequate water to meet the required demand with satisfactory performance. The objective of this study was to evaluate the hydraulic performance of the Yeka Abado supply zone in Addis Ababa and suggest corrective measures to the problems obtained through the evaluation. A computer model was created in WaterGEMS to simulate the water distribution network. An intermittent scenario was created based on customer meter data to check the ability of the system to meet the current demand in the study area. Two scenarios were developed to evaluate the system's ability to satisfy the current and future demands in a continuous supply. The model analysis results indicated that pressure below the acceptance criteria at some junctions during peak hours, shortly after the supply, had resumed during intermittent operations. The performance remained satisfactory at other time steps. Furthermore, analysis in a continuous supply scenario for predicted future flows in 2044 indicated that the system is unable to meet the increasing demands in the study area, requiring system expansion works at some point. The results for a continuous supply model for 2021 indicated an excellent performance, with almost all the acceptance criteria being met.

Key words: extended period simulation, hydraulic performance, intermittent water supply, model calibration, steady state simulation, water distribution system

HIGHLIGHTS

- A computer model was created in WaterGems to simulate the water distribution network.
- An alternate scenario was assigned to the system to evaluate the system performance in various what-if conditions.
- An intermittent scenario was created based on customer meter data.
- Two scenarios were developed to evaluate the system's ability to satisfy the current and future demands in a continuous supply.
- Calibration and verification of the model were conducted based on field pressure tests in selected junctions of the study area.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The design of a water distribution system should be able to deliver water to the individual consumer in the required quantity and at sufficient pressure (Mays 1999). Sufficient quantity and quality of water can be maintained by adequate pressure and velocity. Keeping pipes always under pressure drastically reduces the risks of external contamination (Trifunovic 2006). It is also generally accepted that proper management of pressure in the water distribution network can lead to a more reliable operation (Dai & Li 2016).

In many older systems, the condition of the pipework may have deteriorated to such an extent that targeted renovation and replacement are necessary to maintain operability (Ainsworth 2004). Developing countries like Ethiopia have made great strides in addressing the past injustice of provision of water but, unfortunately, the focus of expanding service provision has often been at the expense of adequate operation and maintenance of the existing infrastructure (van Zyl 2014).

The capital city Addis Ababa currently gets its water from three surface water sources (Gefersa, Lagadadi, and Dire dams, which are located in the Oromia Regional state) and groundwater sources (Akaki well fields and small boreholes distributed in different parts of the city). Currently, the total water supply is 580,000 m^3 per day, while the city demand is 1.1 million m^3 per day. It is estimated that about 36.5% of this water is lost due to leakage and other system inefficiencies. The per capita distribution is estimated to be around 40 liters/day, well below the city's goal of 110 liters/day. Addis Ababa Water and Sewerage Authority (AAWSA) provides safely managed water through its piped network to less than 60% of the population in Addis Ababa. In general, even though the supply has increased in the recent decade, the coverage is still limited and there is water shortage due to an unprecedented increase in demand (City-Characterization-Report 2019).

The city water supply and sewerage authority (AAWSA) has implemented many efforts to mitigate the water shortage problem that the city is facing. One of the major projects includes the Legedadi deep well water supply project (LDWWSP), which targets the water deficit areas of the city – Eastern & North Eastern Addis Ababa. This project is based on 10 deep wells of the Legedadi well field located in the Oromia Regional state at a distance of 30 km from the city center (AAWSA-Development-Sanitation-Office 2017).

The LDWWSP project which conveys water of 53,958 m^3/day is designed to distribute water from the Legedadi well fields to the newly constructed condominium sites in Yeka and Bole subcities. The estimated population size proposed to use the project or direct beneficiaries of the project is about 450,000 with an average per capita demand of 120 l/c/d. In achieving this goal, the project plays a great role in reducing the water shortage in the city (AAWSA-Development-Sanitation-Office 2017).

Different local researchers used different techniques to undergo a performance assessment of water distribution systems. Merga & Behulu (2019) used WaterCAD to develop a model of the existing distribution system of Adama town and, by calibrating data for pressure at different locations, performed a model run for different scenarios. Similarly, Geta & Sahilu (2018) used WaterCAD to model the system as in reality for Janmeda, Teferi Mekonnen, Belay Zeleke, Entoto, and Ras Kassa sub-water distribution network of Addis Ababa city. Asmare & Sahilu (2019) used both primary and secondary data for their study and used a WaterCAD model to assess the existing system of Finote-Selam town.

Varieties of problems have been identified by those researchers after undertaking their performance evaluation. According to the findings of Ayele & Abate (2018), a maximum pressure of 284.78 m occurred at the gravity main pipeline, which is above the recommended value, leading to pipe burst at the gravity main pipeline. The model analysis result showed the different problems of the system; these are oversized and undersized pipes, zero flow velocity, and low pressures (negative 87 m up to 9 m H_2O) due to pipe size and topography of the area (Merga & Behulu 2019). As the result of intermittency and insufficient water supply, there is unreliable service and uneven distribution of water; a reduced network pressure due to the increased hydraulic losses associated with increased flows and undersized pipe diameters; and increased water leakage (Geta & Sahilu 2018).

There is a growing requirement to analyze the performance of the water distribution system by researching the hydraulic parameters, variations, and relationships between them and other elements that govern the system's performance. This enables us to give a better answer to a city's existing water crisis and enable a system design improvement of the existing network. Thus, this study aims at analyzing the hydraulic performance and capacity of the Yeka Abado supply zone of Addis Ababa's water distribution network under different scenarios.

2. MATERIALS AND METHODS

2.1. Study area

This study is conducted on the Yeka Abado supply zone, technically referred to as the LDW-T3-G zone of the Legedadi deep well subsystem of Addis Ababa's water supply network. This supply zone was chosen because of its relative isolation from the other subsystems. It has not been explored as thoroughly as the city's other subsystems/supply zones. Additionally, the supply zone delivers water to condominium units, where problems related to water scarcity are common. The impact of discontinuous supplies on hydraulic performance may be depicted since condominium units lack water.

Yeka Abado is located in Lemi Kura sub-city, in the northeastern portion of Addis Ababa, near the city's border with Oromia Region (Figure 1). The supply zone lies within the UTM coordinates of (484334, 486070) East and (1001195, 1003690) North, and the average elevation is about 2,510 m a.s.l. A location map of the study area is shown in Figure 2.

2.2. Materials

Hydraulic simulation models of water distribution networks are routinely used for operational investigations and network design purposes (Machell *et al.* 2010). In this study, the hydraulic performance of the town's water distribution system was analyzed using the WaterGEMS hydraulic model integrated with ArcGIS.

The purpose of the data collection effort is to provide sufficient and reliable field measurements to be used as data for the estimation of the model parameters (Lansey *et al.* 2001). The primary and secondary data required for modeling the existing water distribution system generally fall under system/network component data, elevation data, population data, water demand/supply data, or field test primary data. In addition to the data types listed above, interviews with local experts and site visits/inspections were done for additional information. Digital data related to water demand/supply and network components were collected from AAWSA's distribution network, I.T., and non-revenue water departments. Field measurements were made to ensure the primary data quality and calibrate the hydraulic model. To characterize and describe the study area, online sources were used with some modifications. The specific data collected for undertaking the study are presented in Tables 1–3.

To determine nodal demands (Figure 3), a standard per capita demand value was used for continuous supply modeling, while a Thiessen polygon shapefile was created in the WaterGEMS hydraulic model to define the service area of each

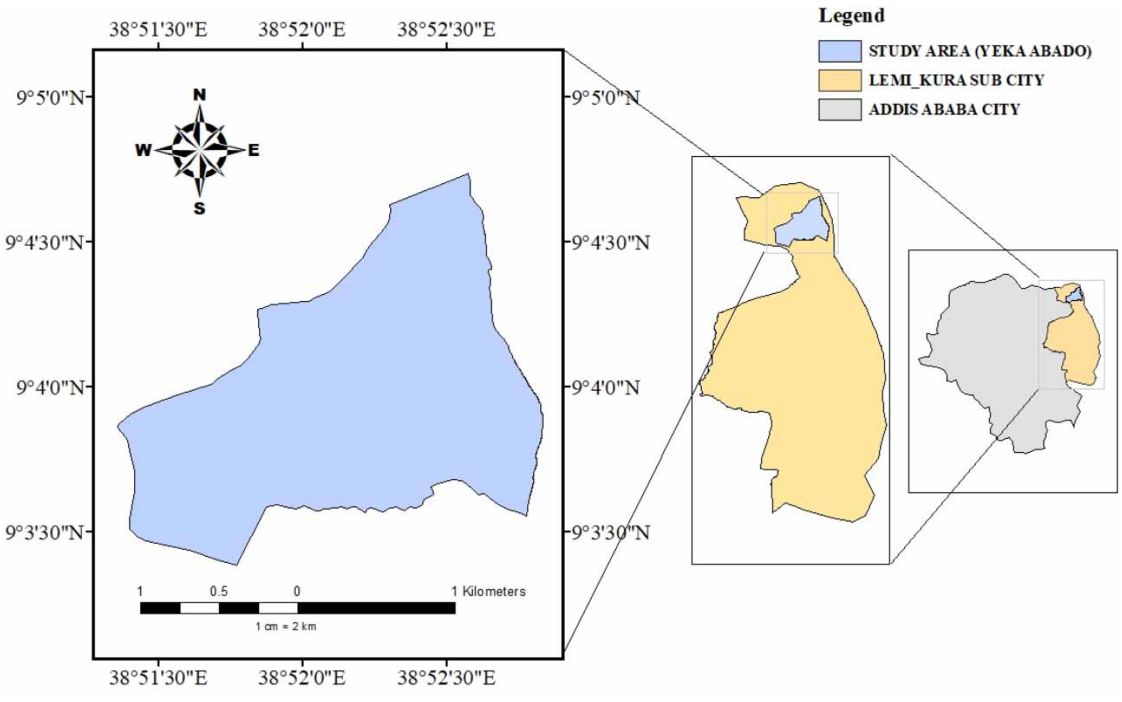


Figure 1 | Location map of the study area.

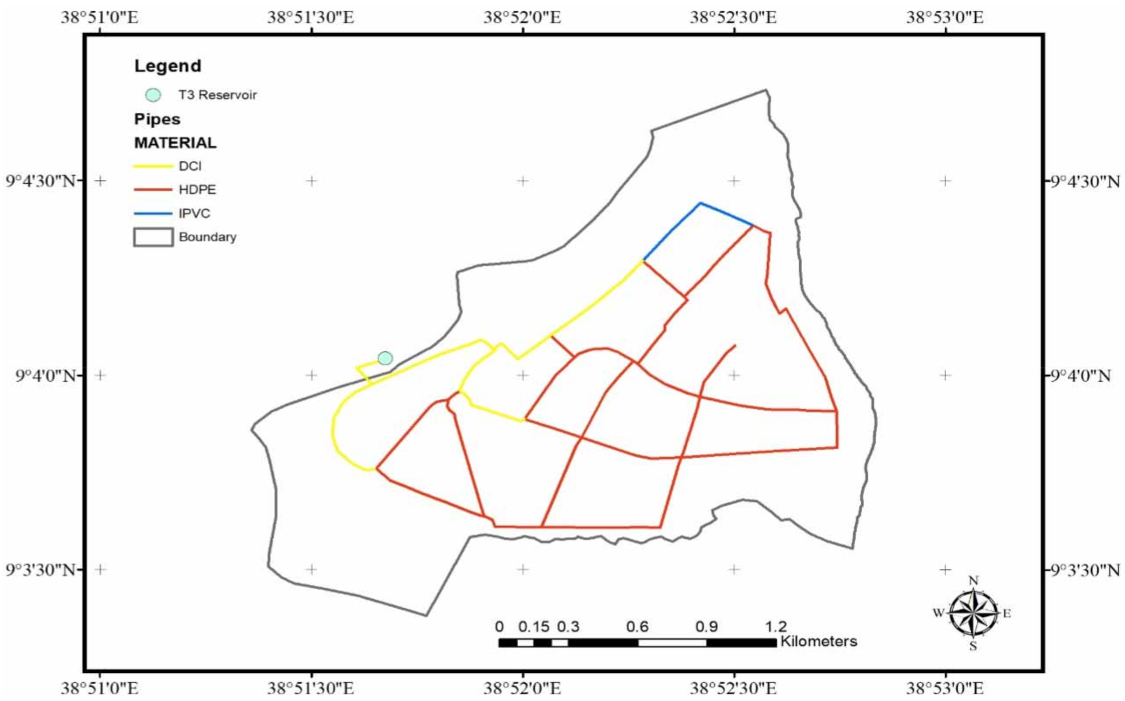


Figure 2 | Pipe network map of the study area.

Table 1 | Demand allocation based on customer meter

		Consumption (l/s)				
Junction	**Label**	**DOM**	**Non-DOM**	**PF**	**UFW**	**Total**
0	J-0	3.365	0.306	0.000	1.156	4.826
1	J-1	6.382	0.564	0.000	2.192	9.137
2	J-2	8.374	1.103	0.044	2.876	12.398
3	J-3	4.395	0.828	0.238	1.510	6.970
4	J-4	7.034	0.965	0.000	2.416	10.415
5	J-5	6.918	1.476	0.000	2.376	10.771
6	J-6	6.525	0.946	0.000	2.241	9.712
7	J-7	6.337	0.443	0.394	2.177	9.352
8	J-8	5.276	0.740	0.000	1.812	7.829
9	J-9	5.729	0.914	0.000	1.968	8.611
10	J-10	0.912	0.123	0.031	0.313	1.378
11	J-11	7.206	0.306	0.000	2.475	9.987
12	J-12	3.206	0.090	0.043	1.101	4.440
13	J-13	8.312	0.562	0.428	2.855	12.158
14	J-14	1.823	0.172	0.262	0.626	2.882
15	J-15	3.566	0.041	0.000	1.225	4.831
16	J-16	6.738	0.874	0.051	2.314	9.976
17	J-17	2.471	0.443	0.000	0.849	3.763
18	J-18	2.453	0.186	0.000	0.843	3.482
19	J-19	2.458	0.239	0.000	0.844	3.541

DOM, domestic demand; Non-DOM, non-domestic demand; UFW, unaccounted for water; PF, peaking factor.

Table 2 | Location of calibration nodes

		Coordinates		
Calibration node No.	**Meter key**	***X***	***Y***	***Z***
1	APW-12585267	484883.547	1002152.700	2554.08
2	MET-34101751	485423.204	1001812.524	2499.87
3	BAY-10786671	486227.889	1002416.523	2463.48

Table 3 | Summary of total domestic demand and peak hour demand for continuous supply modeling

	Year	
Demand type (LPCD)	**2021**	**2044**
Average day demand	149.43	231.73
Non-domestic demand (11.38%)	17	26.37
Unaccountable for water (34.36%)	51.34	79.622
Total domestic demand	217.77	337.72

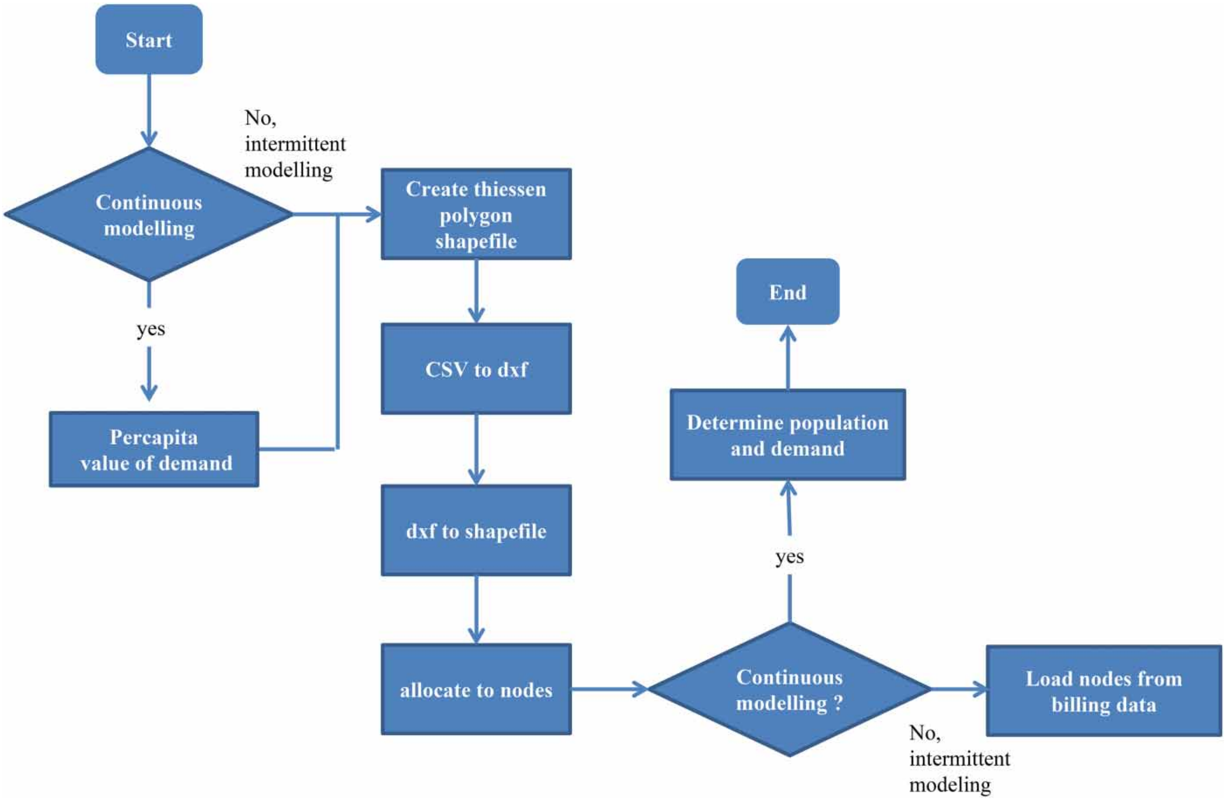


Figure 3 | Flowchart for nodal demand allocation.

node for intermittent supply modeling. Customer meter data was then converted from CSV to AutoCAD DXF format, and the resulting DXF file was turned into a shapefile with relevant attribute information. Using ArcMap's spatial analysis tool, the customer meters located within each Thiessen polygon were allocated to their respective nodes. For continuous supply modeling, the number of households assigned to each node was multiplied by the average population-to-household ratio to calculate the total population served. For intermittent supply modeling, the total nodal demand was determined by using the monthly bill data of the customer meters located within each Thiessen polygon. Provisions were made for non-domestic demand and non-revenue water.

Yeka Abado's water distribution system was designed and installed in the year 2014, and has a 30-year lifespan (AAWSA-Development-Sanitation-Office 2017). With this base, water demand projection was conducted for the year 2024.

2.3. Network modeling procedures

- *Import files*: Import shapefiles of pipes and create a model using a model builder tool in WaterGEMS.
- *Elevation*: Assign elevations to nodes.
- *Loading nodes*: Load nodes with demands.
- *C-factor assignation*: Assign Hazen Williams C-factor for pipe materials based on their age.
- *TCV adjustments*: Adjust settings for throttle control valves.
- *Demand multipliers for EPS*: Input demand multipliers for extended period simulation.
- *Scenario management*: Create scenarios (what if's) for different model runs (continuous and intermittent).
- *DDA run*: Run a demand-driven analysis.
- *Check for pressure*: If results of a demand-driven analysis indicate low residual pressures, change to a pressure-driven analysis.
- *Model calibration*: Calibrate the hydraulic model from field measurements. Industrial criteria for calibrating hydraulic models are as follows:
  - ✓ Hydraulic grade line of a model is within 5–10 ft. of field data. The water level is within 3–6 ft. (AWWA & ANSI 2016).
  - ✓ ±5% of maximum head loss for 85% of readings. ±7.5% of maximum head loss for 90% of readings (WSDOH 2009).
  - ✓ Predict the hydraulic grade line to within 5–10 ft. at model calibration points during peak demands, such as fire flows (Walski *et al.* 2003).
- *Final assessment*: Make interpretations/decisions based on the acceptance criteria for performance measure parameters and finalize the performance assessment. The primary purpose of a continuous model is to check the ability of the system to run sufficiently at the end of the design year. The set of design criteria considered for the analysis of pressure and velocity results of the proposed model of the continuous supply system is as follows (OWWDSE 2008):

  - ✓ As a rule, a minimum of 15 m manometric head is considered adequate during peak hour demands. However, in exceptional and rural water supply cases, depending on the topography of the area, lower pressure levels may be permitted, but not less than 5 m.
  - ✓ A maximum of 100 m manometric head to avoid leaks and bursts in the distribution system, particularly during minimum flow conditions and when the static pressure would be dominant. If necessary, the distribution system is divided into separate pressure zones so that the maximum possible pressure does not exceed 100 m.
  - ✓ Based on experience, in many cases, pipes designed to flow velocities of 0.8–1.2 m/s are quite at optimum conditions, and for long lines, the acceptable flow velocities are as follows: minimum: 0.5 m/s and maximum: 2–2.5 m/s.

3. RESULTS AND DISCUSSION

3.1. Intermittent modeling

3.1.1. Model calibration

Design engineers may use various criteria to evaluate model accuracy. A relative pressure difference is the preferred criterion. Simulations over extended periods involve comparing predicted to observed flow rates, pressures, and tank water levels (WSDOH 2009). The hydraulic model simulating the current intermittent supply operation was calibrated to make better decisions and interpretations using the primary data collected from field measurements.

The initial model before calibration showed no erroneous discrepancies but still did not show a perfect resemblance with the existing situations.

In order to calibrate the WaterGEMS model and validate the results, discussions were held with experts from the AAWSA to determine the status of the intermittent supply valves across an extended period. This information was used to simulate the routine operation of the valves in the network, which was an important factor in accurately modeling the water distribution system. Additionally, demand multipliers for the extended period simulation were collected from AAWSA and adjusted until a perfect agreement between model and field values was found. These demand multipliers were used to simulate the water demand in the network over an extended period. The values were adjusted until the model accurately reflected the measured field values.

With changes to adjustable attributes, the model showed a perfect agreement between predicted and real-life parameters with an R^2 value of 0.9692 (Tables 4 and 5).

3.1.2. Results for intermittent modeling in peak hours

The results of intermittent supply modeling at peak hour demand are summarized in Table 6. The study area's customers rely heavily on water buckets, instead of roof tanks, as storage means. The supply resume time, the transitional time from the day of no supply to the day of full operation, usually occurs during the study area's peak hours (morning). The water bucket filling pattern is high, shortly after the supply has resumed after days of no water. Since the water withdrawal pattern is the sum of the consumption pattern and the filling pattern, a higher withdrawal (more than the usual case of consumption) occurred in the morning, leading to a higher flow rate and a lesser residual pressure at nodes.

3.1.3. Results for intermittent modeling at off-peak hours

Table 7 implies that 40% of the nodes are liable to excessive pressure. There is no node with negative pressure, and only one node failed to meet the minimum allowable pressure acceptance criteria. The table also shows that 55% of the nodes are

Table 4 | Initial values for model calibration parameters

Initial demand pattern								
Time (HRS)	0–2	3–5	6–8	9–11	12–14	15–17	18–20	21–23
Demand pattern	0.3	0.8	1.7	1.3	1.2	1.2	1	0.5
Initial relative valve closure pattern								
Time (HRS)	0–2	3–5	6–8	9–11	12–14	15–17	18–20	21–23
Demand pattern	0.5	0.5	0.5	0.3	0.5	0.5	0.5	0.5
Remark	Midnight		Morning					

Table 5 | Summary of modeled and measured pressure value at test nodes

				Residual pressure (m)		
Test junction ID	***X***	***Y***	***Z***	**Measured field value**	**Model value before calibration**	**Model value after calibration**
TJ-1	484883.54	1002152.7	2550.96	8.08	9.44	8.57
TJ-2	485423.20	1001812.52	2507.45	15	18.45	16.01
TJ-3	486227.88	1002416.52	2461.48	11.22	11.43	10.28

Table 6 | Summary of residual pressure values at peak hour for intermittent supply modeling

Pressure (m)	Number of nodes	Percentage
>100	0	0
80–100	0	0
60–80	1	5
15–60	14	70
0–15	5	25
<0	0	0

Table 7 | Summary of residual pressure values at off-peak hours for intermittent supply modeling

Pressure (m)	Number of nodes	Percentage
>100	3	15
80–100	5	25
60–80	6	30
15–60	5	25
0–15	1	5
<0	0	0

supplied with optimum pressure. As compared to the peak hour demand conditions, fewer nodes are being provided at an optimal pressure, but the presence of minimum pressure is reduced in the off-peak demand conditions.

As discussed above, excessive pressure in the system is high. High pressure during low demand conditions is usually caused by serving customers at too low an elevation for the pressure zone or due to an oversized piping main. The presence of excessive pressure within the system leads to pipe bursts in the pipe that can increase leakage losses.

The result obtained in this study is similar to other hydraulic performance studies made in various subsystems of the city. Similar problems were identified within the Legedadi subsystem's nodes by Belay & Seleshi (2012), after conducting a hydraulic performance evaluation. Problems identified include low-pressure values in junctions trying to serve customers at too high an elevation for that pressure zone. And high-pressure problems are caused by serving customers at too low an elevation for the pressure zone. Furthermore, problems arising from undersized and oversized piping were also discussed in the study.

Another case study conducted by Geta & Sahilu (2018) on the hydraulic performance of selected water subsystems in Addis Ababa identified junctions with minimum pressure during peak hour demands. The presence of minimal pressure in the studies was linked to elevation difference, remoteness from the source, inadequate capacity of pumps, equipment failures, and pipes of inadequate capacity (old pipes). Furthermore, the study's off-peak hour demand condition analysis indicated that the system would have excess pressure in those hours, leading to pipe bursts and leakage problems.

3.2. Continuous modeling

Continuous modeling allows studying the system's ability to satisfy the demand of the projected future population in 24 h supply with the required quality that accounts for an increase in demand, development in the area, and socio-economic changes.

3.2.1. Continuous modeling in 2021

The system was modeled in WaterGEMS for 2021 to analyze the system's ability to satisfy the current demand of the study area for a continuous supply scenario. The pressure head and velocity results obtained from WaterGEMS are summarized in Table 8.

From the table, the following inference can be made:

- 90% of the nodes are provided with pressure between 15 and 80, which falls under the desirable pressure for allowable minimum and maximum values. This indicates that water reaches almost all taps with sufficient pressure.
- Table 8 indicates that all nodes have pressure less than 100 m. This indicates that pipe bursts in the pipe and related leakage are avoided in the current system.
- Two nodes in the system have a pressure of less than 15 m, indicating that water cannot be supplied to those regions sufficiently. The low pressure at J-15 arises from the relatively close elevation between the reservoir (2,564 m) and J-15 (2,552 m). Since the system is designed to use gravity for the distribution of water from the reservoir to junctions, areas with similar heights to the reservoir will obtain water with less pressure.
- 60% of pipes have velocity between 0.5 and 2.5, which indicates that water is being supplied to those regions sufficiently, and around 11% of velocity results have velocity between 0.8 and 1.2, indicating that water is being supplied at an optimal velocity to those nodes.

Table 8 | Residual pressure at nodes and pipe velocity (2021)

Residual pressure at nodes			Pipe velocity		
Pressure (m)	**Number of nodes**	**Percentage**	**Velocity (m/s)**	**Pipe**	**Percentage**
>100	0	0	<0.5	7	11.3
80–100	0	0	0.5–0.8	2	3.2
60–80	1	5	0.8–1.2	7	11.3
15–60	17	85	1.2–2	23	37.1
0–15	2	10	2–2.5	5	8.1
<0	0	0	>2.5	18	29.0

Table 9 | Residual pressure at nodes and pipe velocity (2044)

Residual pressure at nodes			Pipe velocity		
Pressure (m)	**Number of nodes**	**Percentage**	**Velocity (m/s)**	**Pipe**	**Percentage**
>100	0	0	<0.5	2	3.23
60–80	0	0	0.5–2	5	8.06
15–60	1	5	2–2.5	2	3.23
0–15	0	0	>2.5	53	85.48
<0	19	95			

3.2.2. Continuous modeling in 2044

The primary purpose of a continuous model is to check the ability of the system to run sufficiently at the end of the design year. The supply system was modeled in WaterGEMS for 2044 to verify the performance at the end of the design year. The model's pressure head and velocity results are presented in Table 9.

The results of the pressure head summarized in Table 9 show that 95% of the nodes have negative pressure. A large number of negative pressures indicate that the demand for 2044 is beyond the system supply capacity. The forecasted population for 2044 is 184,996, which is twice more significant than the current population. This increases demand in the system. The WaterGEMS model result shows that the flow demand grows from 285 to 1,024 l/s between the 2 years. Expanding and connecting a new source with the system should be considered to mitigate the problem.

4. CONCLUSION

The study examined the hydraulic performance of Yeka Abado's water supply zone in Addis Ababa. Analyzing the system capacity for a continuous supply scenario in 2021 and 2044 (end of design year) indicates that the system was able to meet the capacity requirement in the year 2021, but would be limited in satisfying the future demand in the study area, as the flow requirement increases significantly between 2021 and 2044. The model analysis result shows that the flow demand in the system increases significantly from 285 to 1,024 l/s. The negative results for the year 2044 indicate that the demand is beyond the system capacity. This problem is related to a large amount of flow passing through each pipe. As flow is directly related to head loss in the pipe, an increase in flow would increase the head loss in the pipes. One solution to the problem could be an expansion of the system. Expanding the system would reduce individual flow within the pipe and, hence, limit head loss and stabilize pressure.

ACKNOWLEDGEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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