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Hydraulic Performance Analysis of Existing and Revised Water Supply Distribution Network, a case of Dukem Town in Ethiopia

Boki Tesfaye Geleta [1,*] and Andinet Kebede Tekile[2]

[1]Haramaya University, Department of Water Supply and Environmental Engineering, P.O.Box:138, Dire Dawa, Ethiopia (E-mail:bokitesfaye342@gmail.com)
[2]Adama Science and Technology University, P.O. Box: 1888, Adama, Ethiopia (E-mail: andinetm@gmail.com)[*]Corresponding author

ABSTRACT

Analysing the status of a town's water distribution network is necessary to monitor its current and future management patterns. Dukem Town's existing water distribution system is not properly functioning; as the result, the utility is unable to deliver the required demand to customers. Thus, the main goal of this study was to analyse the town's water distribution system's hydraulic performance and the users' perceptions. Sample size of 376 households was used to assess the level of consumer satisfaction with the utility water delivery services. WaterGEMS software was used for the hydraulic performance analysis and the model was calibrated using eight nodal data points at minimum and peak hour consumptions, with corresponding R^2 of 0.97 and 0.99, respectively. The result of the analysis at steady state simulation indicated that 45.11% of the nodes had pressure above the desired limit, at average daily demand. At peak hour demand, the nodes with pressure within the desired limit reduced from 50% average demand to 34.3%. The analysis of pipe velocity showed that only 45.71 and 48.57% of pipes had a desired limit of velocity (0.5-2 m/s) at average daily and peak hour demands, respectively. The extended-period simulation showed only 45.36% of the nodes to have pressure within the desired limit. Moreover, 62.86% of pipes had less than the allowable velocity limit for the extended period. By applying pressure reducing valves, it was possible to keep 99% of the nodal pressures within the desired range. Even though there are recurrent water supply interruptions, the customers' satisfaction with the existing service is 55.4%. Generally, by integrating the findings from the hydraulic performance analysis and customer satisfaction assessment, decision-makers can make informed choices regarding infrastructure investments, operational strategies, and policy interventions.

Key Words: Customers Perceptions, Dukem Town, Hydraulic performance, *WaterGEMS,* Distribution Networks

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1. INTRODUCTION

One of the critical factors in ensuring public safety and the smooth normal urban activities is the efficiency of water distribution systems (WDSs) (Ataoui & Ermini, 2015)**.** A water distribution system (WDS) is created and maintained in order to deliver a dependable water supply, that is, to adequately meet water user demands, especially under crucial operational conditions such as periods of peak demand (Vicente et al., 2016). Consequently, an essential requirement in the framework of WDS reliability is the study of the influence of water demand parameters (Zhan *et al*., 2020).

In developing countries like Ethiopia, most water distribution networks (WDNs) cannot fulfil their aim of providing sufficient water due to the frequent failure of their elements associated with poor design, construction, operation, and maintenance (Workneh et al., 2023). Generally, the focus of urban water management is to build infrastructure, with prime attention of augmentation; however, the distribution network hydraulics are usually ignored, and this does not lead to sustainable services (Jaiswal et al., 2021). An assessment of the hydraulic performance of a WDN could show if the system can provide consumers with the necessary amount of water at all times and locations (Shah, 2021). WaterGEMS is one of the preferred hydraulic modelling programmes used for the analysis and design of water distribution networks (Mehta et al., 2017). Its robust design method enables it to meet the standards for accuracy in the design of water distribution networks, control of distribution network variables including flow, pressure, and velocity, as well as their optimisation (Ostfeld et al., 2013). It is far superior to other WDN model software, especially EPANET, because to its integration with several platforms graphic applications (GIS tools, AutoCAD, and Micro Station tools).

On the other hand, customer satisfaction level is strongly linked to the four fundamental components of water service: quality, quantity, continuity, and price. Therefore, to ensure that water is delivered at a safely managed service level, rigorous assessments of piped water service providers should be conducted (Ajeng et al., 2018). However, according to Beker & Kansal (2023), more than 55% of urban Ethiopians have no access to water from safely managed services, and this is lower than the average for Sub- Sahara African countries and the world by 9% and 41%, respectively.

Dukem Town's water distribution system sometimes fails due to poor hydraulic performance of the distribution elements and in some places, there are prolonged disruptions of drinking water for unknown reasons. The town also does not have appropriate wastewater disposal systems, and if the leaking pipes are not promptly maintained, pollution may make its way into the network system (Mohammed et al., 2013). Consequently, it is important to use hydraulic computational tools, which are effectively combined with GIS tools, to assess and then improve the efficiency of the water distribution system (Tabesh et al., 2010). Thus, this study focused on hydraulic performance analysis of existing and optimized water distribution network of the town by using WaterGEMS software and assessment of costumers' satisfaction to existing water supply service. The study was limited to hydraulic performance analysis in terms of pressure, flow, and velocity within the existing water supply system. For the customer perception only the issues which are relevant to the topic and could be meaningful for good decision-making were considered. Thus, to address the main concerns always raised with water distribution systems in developing countries, daily water availability (per capita demand), distance travelled, water quality, adequate pressure in the system, and overall customer satisfaction with the existing system were considered the core issues. In this research, by carrying out a hydraulic performance analysis, the improvement and optimisation the current infrastructure of Dukem Town utility to deliver adequate water to the community, with sufficient pressure and velocity, was studied.

2. MATERIALS AND METHOD

2.1 Description of the Study Area

Dukem town is located 37 km South-East of Addis Ababa along the Adama-Dire Dawa-Djibouti transport axis. Geographically, the study area is located between latitudes of 8^o 45' 25" N and 8^o 50' 30" N and longitudes of 38^o 51' 55" E and 38^o 56' 5" E, covering a total area of 35.96 km^2 (Figure 1). It is located at an average altitude of 2100 m above sea level. The total population of the town was about 121,240 and the coverage of potable water was 65.7%, in 2020. The town's average annual temperature is 15.6 °C.

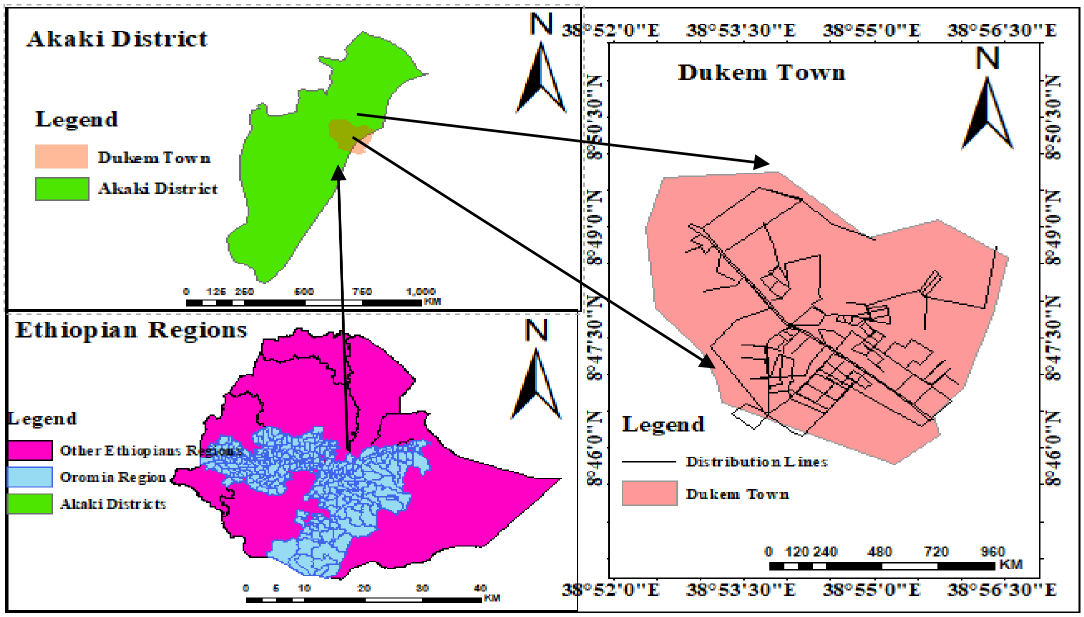


Figure 1: Location map of the study area

2.2 Existing Water Supply Condition of the Town

The water supply system of Dukem Town is fed by groundwater and has source from nine well field areas of deep boreholes. Currently, the total production of clean water in the town is 61.8 L/s. The average water supply of the utility for the 2020 year was 5,330 m^3/d. This average water production of the town was used to evaluate the performance of the existing distribution system based on the estimated water demand within the required water patterns. The average water demand was projected at 7,458.83 m^3/d in 2023 and the population number was 152,103. Thus, the average per capita consumption was 49.8 l/d. However, according to Ministry of Water Resource and Irrigation to GTP-II, the per capita consumption standard set for category-one towns, such as Dukem Town, was 100 l/d (MoWIE, 2022). Data recorded by the utility was used to estimate the water loss of the town and the result showed that, annual water loss of the town decreased somewhat from 2014–2018 (36 - 17%) and increased back to 30% in 2021. The water utility has not yet technically and for sure identified the main causes of water loss in the system.

The utility has five storage tanks, which are used to equalise flow to each service area. The municipality uses these storage tanks as a pressure zone boundary based on the topography to manage the distribution network. However, the geographical conditions and reservoirs location as well as the performance of water distribution network indicated that the main reason for water loss in this town is high pressure of water in some areas. Comparing the total water billed against the total production, the average water loss of Dukem Town water supply system was 39.5 %, which is well above the World Bank's expected maximum of 25 % and that is common in Ethiopian cities (Beker & Kansal, 2023). The network has 133 junctions, 176 pipes, 7 reservoirs, and 3 pumps, which were used in the analysis of the of Dukem town water supply system. The pipe materials of the network are HDPE, DI, UPVC and GS with internal diameter of 20-200 mm.

2.3 Data Collection Methods and Materials Used

Primary data was collected through observations and measuring nodal junction pressure for the calibration purpose in March and April 2023. From the field survey, x and y coordinates of nodes, tanks, and boreholes were collected. The data collected was transferred to WaterGEMS and simulated at Extended Period to compare the simulated result with the observed data. On the other hand, secondary data were collected from Dukem Town's water supply and sewerage service. Thus, population data, water demand, water consumption, water production, water loss, and borehole history data like depth, static water level, dynamic water level, discharge, pump head, and pumping hours, as well as existing pipe materials, junction, pump, and tank data, were all collected from the office. The equipment and materials used for the data collection were a pressure gauge to measure pressure at the selected nodes and GPS to collect the required elevation data during the pressure reading as well as to identify the exact location of the sample points. Google Earth for pre- and post-processing was used to collect, organise, and analyse the data. ArcMap v10.7.1 was used to display the overlapped shape file of the distribution network on the topographic map of the town and also for delineation of the study area. Global Mapper v20 was used to check the elevation of the junction, storage tank, water source, and coordinates of each node. IBM SPPS v21 and MS Excel were used to analyse the customers’ responses.

2.4 Data Preparation and Analysis Methods

The baseline for the overall performance assessment of the water supply system depends on base demand. To project future demand, the geometric increase method was employed to estimate the future population from 2023–2030. The data for the existing water distribution network of the town was generated in QGIS and Excel. Since the data from QGIS was lacking visuals, Google Earth Pro was used to relocate the distribution network, and all data relocated were added to Global Mapper v2022 to generate X and Y coordinates of junctions and reservoirs. The coordinates for each point were generated in Global Mapper v20 and then exported to Microsoft Excel 2013. Then data exported to Excel was transferred to WaterGEMS 10.2.3 software through the model builder toolbar to prepare setup for the network. The processed data in WaterGEMS was assessed and upgraded, then transferred to ArcGIS for further mapping of the network.

The existing demand data can be assigned to the network nodes in WaterGEMS software by point load data, area load data, or population (land use) data. In this study, to assign demand to distribution network, point data method, which is unit line option and the best to assign demand data to model especially in developing countries, was used. The unit line flow method divides the total demand in the system (or in a section of the system) into two parts: known demand (metered) and unknown demand (leakage and unmeasured user demand) (Momenzadeh et al., 2018). Dukem Town's utility records total water demand and not the demand of each junction, rather than locating the position of junctions. So, the base water demand of the town, which is 5338 m^3/d, was brought into the model by using WaterGEMS to load the building bar using the point data method. The demand scenario for peak hours was used for modelling, and demand was calculated for each supply node using the demand multiplier factors for a 24-hour flow period.

2.4.1 Population forecasting

According to the town's administration, the total population of the town was 121,240 in 2020 and projected up to 2030. The appropriate method for forecasting Dukem Town's population was the geometric increase method (equation 1), which was selected by comparing it with the Ethiopian Central Statistical Authority forecasting method using percentage error.

$$Pn = Po(1+r)^n \qquad \text{……………………………………………………………………}1$$

where Po is base population, Pn is population at n decades or year, n = decade or year, r = rate (percent increase).

2.4.2 Demand projection

The projection of water demand was based on the estimated population for a defined year. According to the town water service office reports, there are three major modes of service for domestic water consumers: house connections (HC), yard connections (YC) shared, and public fountains (PF) or communal taps. Base per Capita Water Demand by Mode of Service was set within national standards (MoWR, 2006). Running the model under scenarios of peak hour demand and average daily demand for the current year allowed for an investigation of the present system's hydraulic performance.

2.4.3 Model calibration and Validation

Firstly, the nodes of the network used for calibration and validation were junctions, which were added. Then, during the initial run, the model was calibrated using the Darwin calibrator toolbar on WaterGEMS by modifying flow-related sensitive parameters, including the water demand and pipe roughness coefficient, until they fell within an acceptable range. Both the correlation coefficient and the scatter plot were used to verify the validity.

Thus, by using a portable pressure gauge to take readings at 2-10% of all junction nodes, from low pressures to high pressures, calibration was carried out in accordance with USEPA water distribution system calibration guideline. Pressure from eight sample nodes of junctions (J-7, J14, J-30, J-44, J-61, J-71, J-109, and J-113) was measured near the corresponding location using a pressure gauge to calibrate and validate the model. The calibration of the model was performed at peak hour consumption in the morning (6.30–8.00 AM) and minimum hour consumption in the afternoon (2.30–4.00 PM). The sensitive parameters (pipe roughness and nodal demand) were then mildly adjusted until the simulated results resembled actual or field results. The validation was done manually using the correlation coefficient equation (R^2), which is:

$$R^2 = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2} * \sqrt{\sum(Y-\bar{Y})^2}} \text{--} 2$$

where: R^2 is coefficient of determination, X and Y are the computed and observed pressure values, and $\bar{X}$ and $\bar{Y}$ are mean value of computed and observed pressure, respectively.

2.4.4 Customer satisfaction assessment

Interviews were carried out by using sufficient sample size to represent the population to answer the questions about per capita water consumption, frequency of water supply, accessibility to water sources, and overall satisfaction with the existing water supply system. Thus, for the customer satisfaction assessment, the sample size (n) was determined using Yamane (1967) equation, which is:

$$n = \frac{N}{(1+Ne^2)} \quad \text{------} 3$$

where N is the total number of households (21,595) and e is level of precision (5% is taken).

3. RESULTS AND DISCUSSIONS

3.1 Hydraulic Performance Analysis of Town Distribution System

3.1.1 Model Calibration and Validation

The calculated values are within an average error at peak demand of 2.36 m and at minimum demand of 1.06 m of pressure simulated and observed values. As a result, the model's calibration was acceptable since it has met the calibration and validation standards for establishing pressure calibration and validation (average error 1.5 m to maximum 5 m). According to AWWA (2012), the liner regression relationship of pressure, which showed a typical difference error of between ±1.5m and ±5m, is considered an acceptable level of model performance. The observed values at minimum hour demand and peak hour demand are shown in Figure 2 respectively.

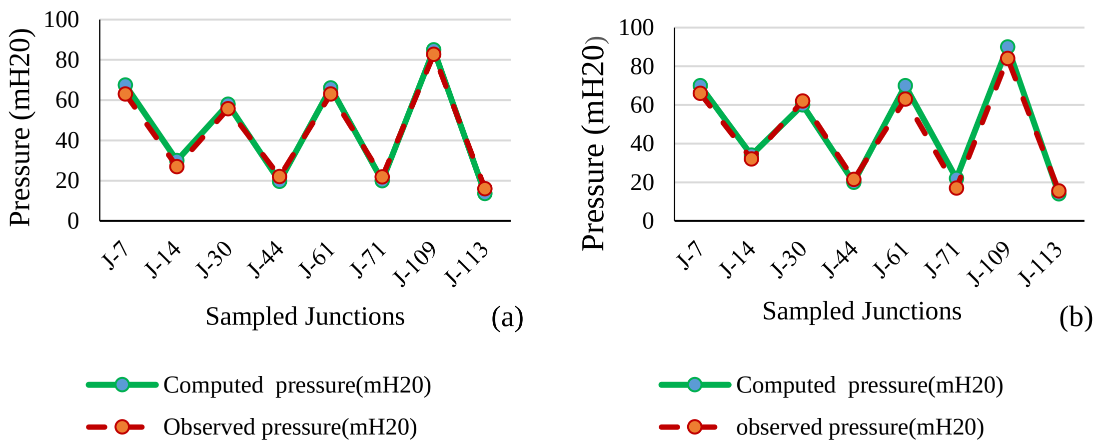


Figure 2: Computed and observed pressures at (a) minimum and (b) peak hour consumptions

On the other hand, the statistical correlation between the measured and simulated pressure during calibration for peak hour demand and minimum demand recorded R^2 of 0.98 and 0.97, respectively. R^2 of greater than 0.50 is considered acceptable for model performance (AWWA, 2012), and the result indicated existence of strong relationship between computed and observed values. The summarised validations at minimum and peak hour consumptions are shown in Figure 3.

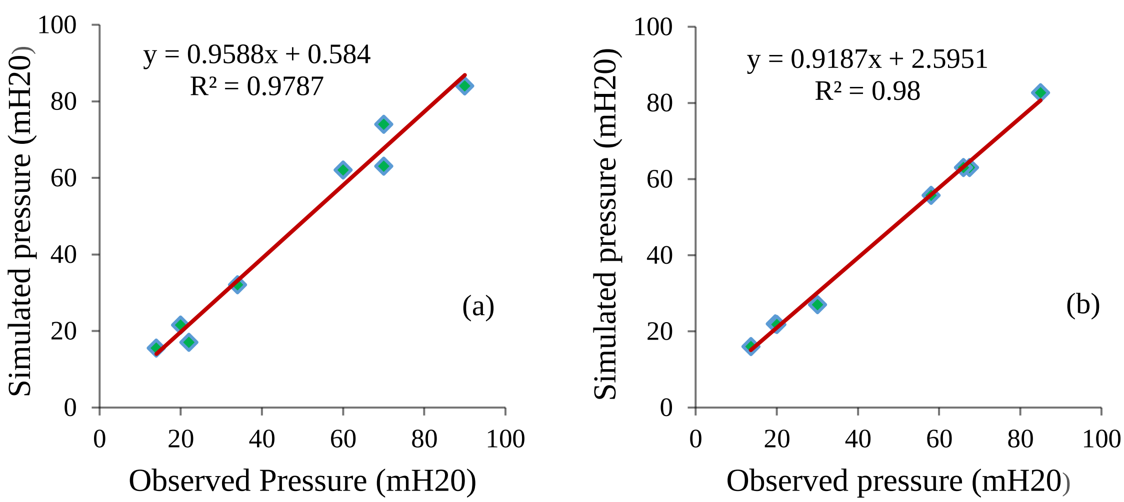


Figure 3: Validation at (a) minimum hour and (b) peak hour consumptions

3.1.2 Pressure and Velocity Analysis in Steady State Simulation

The pressures at average daily demand showed that 45.11% of the junctions had excess pressure (>70 mH20), especially at J61, J85, and J94-J111, which have significantly high pressure due to elevation of the reservoirs compared to the distribution area, as well as J125, J126, J217, J128, and A129, which have excess pressure due to lower elevations to the distribution line. In total, 50.38% of the junctions had pressure within the recommended limit, including acceptable in special conditions (10 to 70 m), and only 4.51% had undesirable pressure (<15 mH20). According to the national standard, the operating pressure in the distribution network should be (15–60 m) under normal conditions and (10–70 m) under exceptional conditions, and water velocity should be between 0.6 and 2 m/s, although one can find pipelines with zero velocity in the looped system (MoWR, 2006). The analysed values of junction pressures at average daily demand are shown in Figure 4.

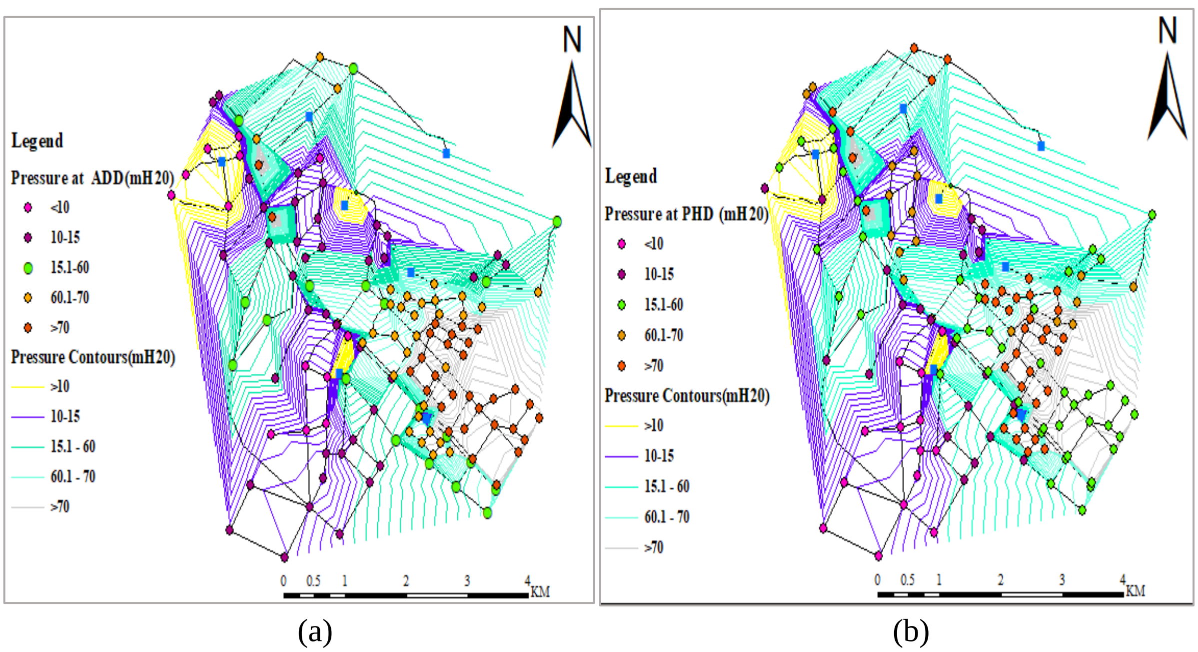


Figure 4: Nodal pressure of the existing distribution system (a) at average daily demand and (b) at peak hour demand

The scenario of pressures at peak hour demand indicated that only 20.81% of the junctions had pressure >70 m H20, and 34.3% of junctions had pressure within the recommended limit (10 to 70m). 44.89% of the nodes have less than the allowable limit (15 mH20). The detail map of pressure at peak hour demand is indicated in Figure 4.

At average daily demand, no pipe had above allowable limit of velocity, 45.71% of the pipes were within acceptable velocity limit (0.5 - 2.0 m/s) and 54.29% of them were under acceptable limit (< 0.50 m/s) of velocity. This indicates that pipe velocity was very low at minimum hour consumption since there is high pressure in the system (Figure 5. But at peak hour demand (Figure 5), 8.57 % of pipes had above allowable limit (>2m/s), 48.57% had velocity within acceptable limit (0.5 - 2.0 m/s) and 42.86 % pipes were under acceptable limit of velocity (<0.5 m/s).

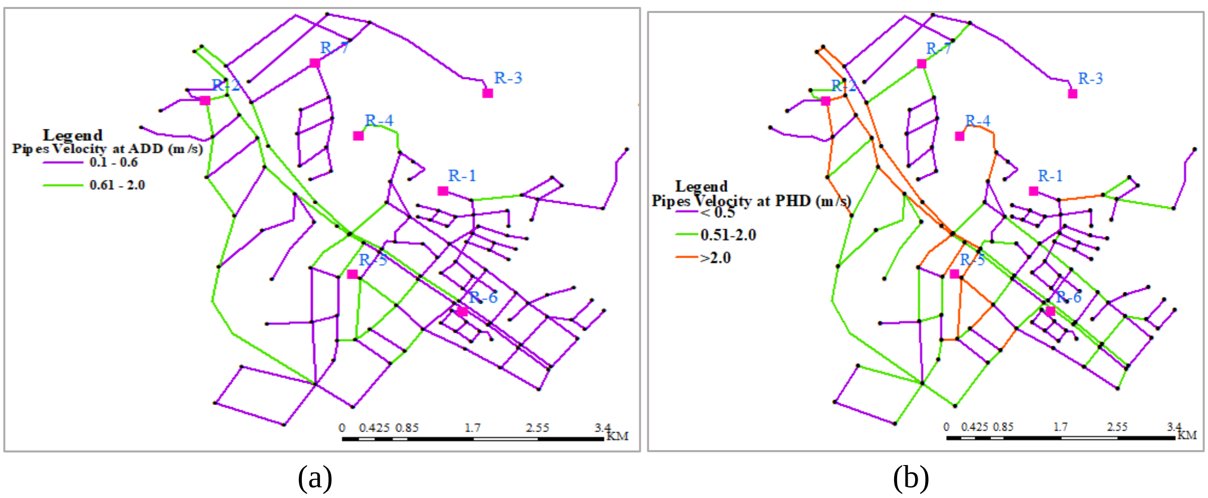
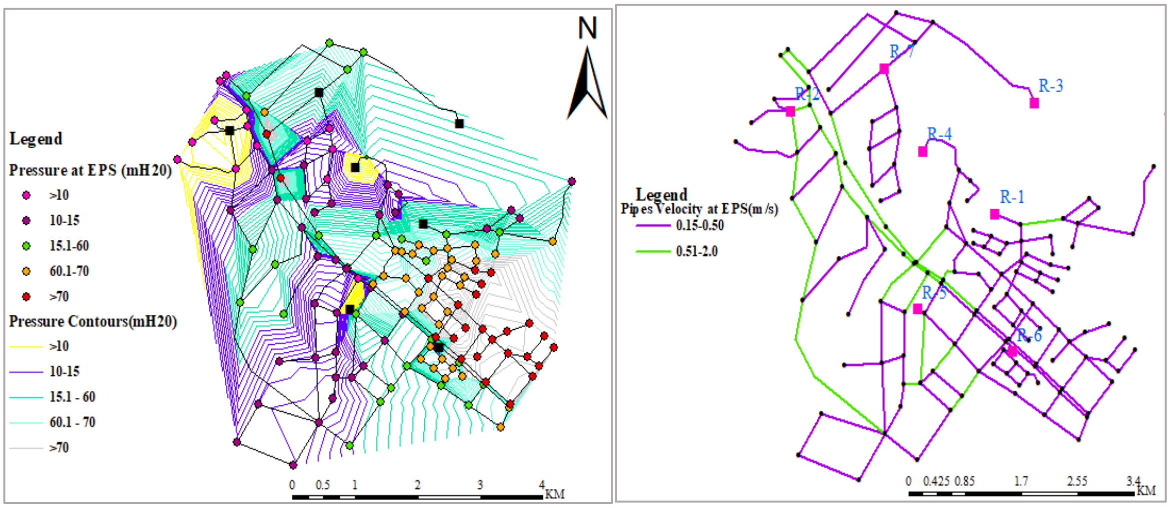


Figure 5: Pipe flow velocity of the existing distribution system (a) at average daily demand (ADD) and (b) at peak hour demand (PHD)

3.1.3 Pressure and Velocity Analysis in Extended Period Simulation

For every hour over a 24-hour period, the model was simulated, where pressure and flow velocity changed in the system in response to variable demand. Demand patterns were used to simulate this fluctuation in demand over time. Demand patterns are temporally variable multipliers added to a base demand, most typically the average daily demand (Bentley, 2014). Therefore, average daily demand was used for pressure and velocity analyses in the extended-period simulation of this work. Most junctions had high pressure as demand fluctuated over 24 hours. 51.88, 45.36 and 3.76% of junctions had above allowable limits, within allowable limits and below allowable limits of pressures, respectively, at average daily demand (Figure 6.

The pipe velocity was also analysed at extended period simulation through 24-hours with respect to average daily demand. As a result, 62.86% of the distribution system had a pipe flow velocity less than 0.5 m/s, 37.14% of the pipes had a velocity of 0.6 to 2 m/s, which is the optimum adopted velocity, and there was no pipe with a velocity greater than 2 m/s in the distribution system (Figure 6.



(a) (b)

Figure 6: Extended period simulation maps the existing distribution system for (a) junctions pressure and (b) pipes velocity

Based on analysis performed in both steady-state and extended-period simulations, there were two identified major problems. The first main problem in the water distribution system of the town was that there were large number of nodes with pressure in excess of the permissible values due to the relatively high elevation of the reservoirs. Especially, during low consumption hours, the pressure level was significantly higher than the maximum allowable limit (>70 mH20). So, the high water loss in the system every year is understood to be caused by the excessive pressure in the distribution system. However, during high consumption hours, the water pressure was occasionally below the required level. The other main problem observed in the existing water supply system was that pipe velocity getting outside the recommended values. This means that when the pressure increased significantly, the pipe velocity become much below the minimum requirement of less than 0.5 m/s, to the extent of causing no flow conditions in some of the pipes. Therefore, to improve the observed problem, works related to adjusting the pressure to the allowable limit is required, say by applying additional elements to the system.

3.2 Optimization of the Existing Water Distribution Network

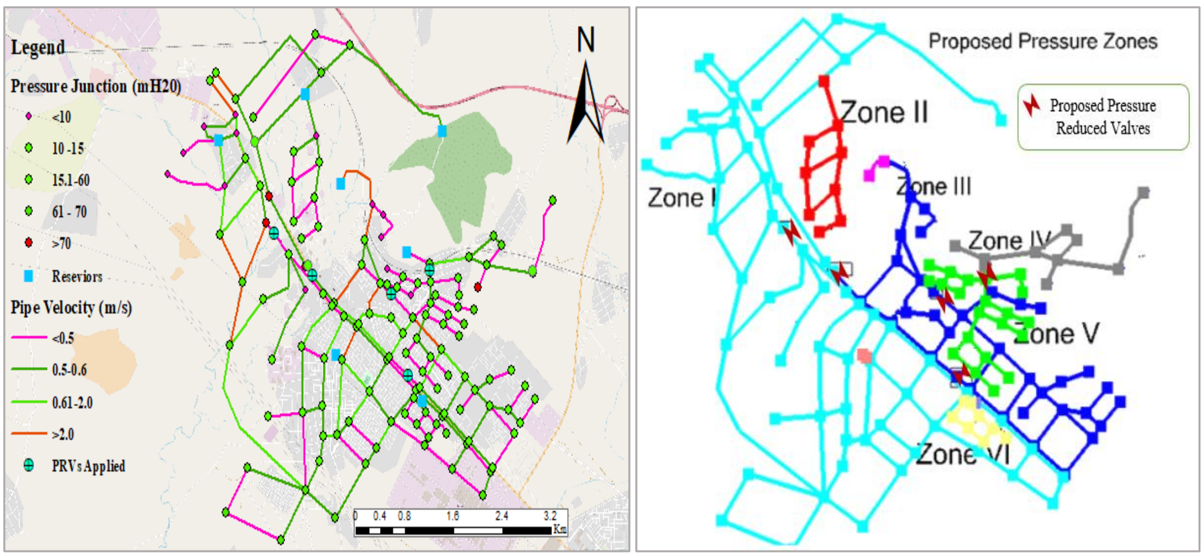
The distribution system can be adjusted to minimise the observed high pressure and to boost low pressure and velocity based on the results of model simulation. For this, a new pressure zone was created by applying pressure reducing valves (PRV) to decrease the high pressure observed in the system, and a pipe size arrangement was proposed to normalize pipe velocities and pressure to overcome the overall problem observed in the system. Even though there are several other options and techniques available to reduce pressure in a water distribution system, such as pressure-regulating pumps, flow control valves, changing pipe diameter, and demand-side management, the PRV was applied because the pressure from the elevated reservoirs is so high at lower elevations of the area, and the topography of the area does not allow for other options of pressure management. Thus, PRV were introduced as appropriate devices to control high pressure in this area. The pressures reducing valves were assigned to the system by considering high pressure observed (Table 1). Five PRV were introduced to pipes P-119, P-127, P-88(2), P-102(2), P-85(2), P-5 (2) and P-79 to decrease the high pressure observed in these areas.

Table 1: Location and description of the proposed pressure reducing valves

Label	Elevation (m)	Y (m)	X (m)	Valve Dia. (mm)	Pressure (mH_2O)	
					From	To
PRV-1	1,952.33	972,553.01	490,668.05	100.0	73	28
PRV-2	1,977.68	972,497.65	488,739.75	100.0	131	22
PRV-3	1,957.56	973,006.09	488,109.79	100.0	91	26
PRV-4	1,949.88	972,260.54	490,027.25	100.0	60	44
PRV-5	1,934.00	971,262.84	490,309.42	80.0	62	33

As pressure of junctions has been adjusted, velocity of pipes also improved and lower pressure junctions become within the standard pressure ranges. As a result, 95.36% of the nodes had pressure within the desired limit, whereas only 1.88 and 2.76% of nodes had pressure above and below the desired limit, respectively. Correspondingly, 37.14% of pipes had less than the allowable velocity limit, and 62.86% of them were within the desired limit. The modified junctions pressure and velocity of pipe are shown in Figure 7.

Allocating nodes to their proper pressure zoning gave the chance for the nodes to receive better flow and pressure head. Pressure zones were set up to regulate pressure in locations where large grade changes could create too much pressure at the lower end of the system and not enough pressure in the higher ends. The boundaries of the six pressure zones were suggested for Dukem Town's water supply system based on PRV placement and consideration of dispersed water sources in the town (Figure 7.



(a) (b)

Figure 7: (a) Modified pressure and velocity of the System and (b) pressure zones of the modified system

3.3 Customer Satisfaction Level with Existing Water Supply System

The sample size of 376 was randomly selected to investigate the level of customer satisfaction with the town's water supply services. Based on the demographic characteristics of the respondents, 63.9% of them were female. The main age groups were 31–40 and 41–50 years, making 39.1 and 25.9%, respectively, of the total sample size. More than half (54.3%) of the contacted consumers had an education level of at least a secondary school graduate. The income sources of the respondents were daily labour, business/trade, and farming, which are 26.6, 24.73, and 24.23%, respectively.

Figure 8 shows the number of households with and without access to adequate water to be 59.50, and 40.50 %, respectively. Two-third of respondents were satisfied with pressure in the pipe; specifically, those householders residing at lower areas of reservoir location were benefited as they always receive water of sufficient pressure. More customers of the town speak unfavourably of the cost of water. The mode of water service has shown that 35.6 and 34.1 % of the households use yard connection (YC), and public fountain (PF), respectively. But the proportion of households that use House Connection (HC) was only 24.1%. This shows that most households are currently using communal pipes and they need additional water supply to upgrade the system of piping inside their house.

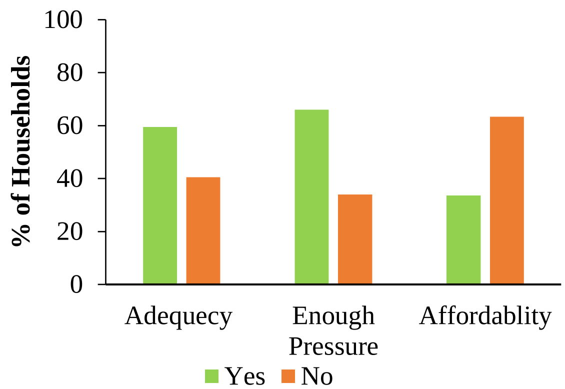


Figure 8: Customer responses to adequacy, pressure and affordability of water

With respect to the quantity of water collected from the source, only 5% of households get above 60 l/d (Figure 9 . Based on the average family size of 3 people, the average per capita water consumption of the town was 12.58 l/d, which is far below the World Health Organization criteria of at least 20 l/p/d for a basic household use. Regarding the accessibility of customers to water sources, more than half of the households (56.2%) have access to water at a distance of less than 100 m. Only 1.6% of households have to cover more than half a kilometre to fetch water (Figure 9 .

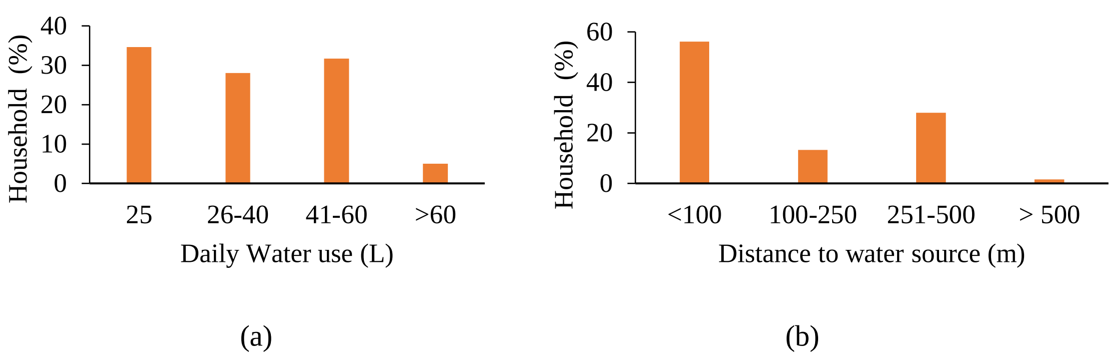
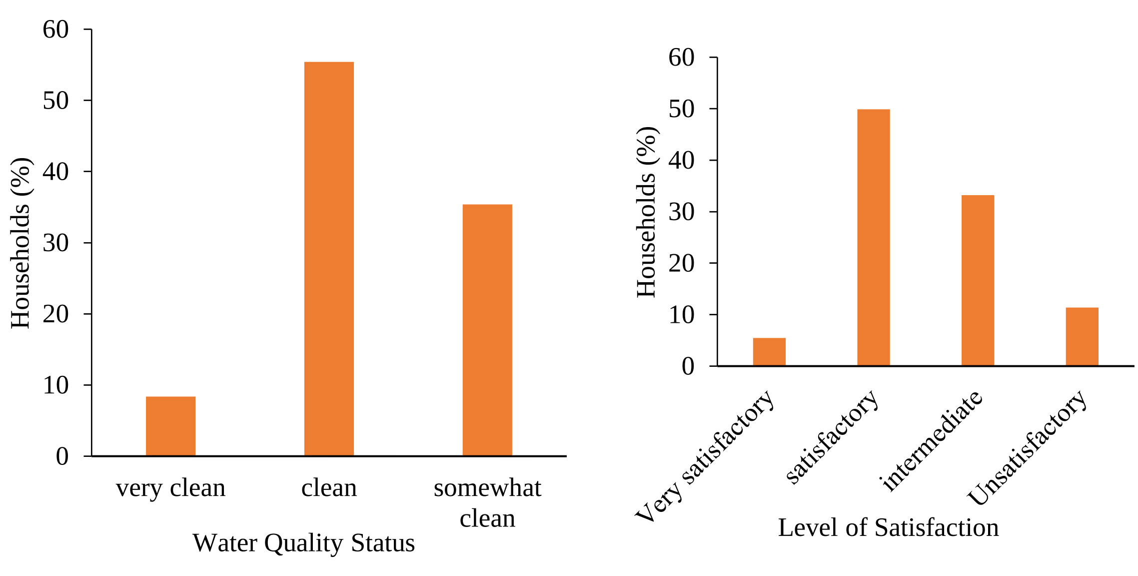


Figure 9: Customer responses to (a) daily water consumption and (b) distance to water sources (m)

For improved supply with respect to distance travelled to fetch water, 29.6% of customers yet to be served according to the standards (maximum distance) set by Growth and Transformation Plan-II (MoWIE, 2022). According to the standard, urban population must have access to urban water supply with a GTP-II minimum service level of 100 l/c/day for category-one towns and cities at a distance of 250 m. However, 39.21% of the households walk more than 500 m to get water due to drought (winter), water scarcity, and nearby community pipes that are sometimes closed. Regarding the continuity of supply, 43.5% of households get water once a day, which stays for 1-3 hours, 41.7% gets water once in two days, which stays for 3-5 hours, and the others get it twice a week, which stays for more than 5 hours.

Related to the water quality status, most households are satisfied with the clean water from the sources (Figure 10. Overall, more than half of the population are satisfied with the water supply system and 11.4% of them were discontented (Figure 10 . According to Kassa et al. (2017), the overall satisfaction of a town with the existing water supply service should be at least in average 50%, which agree with this level of satisfaction with the existing water supply service of Dukem Town.



(a) (b)

Figure 10: Customer responses to the water quality and (b) the overall customers' satisfaction

4. CONCLUSIONS

The main objective of this study was to model the existing water distribution system in Dukem Town and then, based on the identified problems, to propose modifications. Moreover, the customer's perception of the existing system was assessed. The estimated current total average water demand is 5953.37 m^3/d, and the utility needs to provide additional sources that produce 2044.37 m^3/d to satisfy demand by 2030, which is projected to be 7997.74 m^3/d. Moreover, 51.88 and 3.76% of nodes had pressure above and below the desired limit, respectively. Correspondingly, 62.86% of pipes had less than the allowable velocity limit. The modifications to the existing water distribution system were proposed by creating pressure zones and by introducing pressure-reducing valves to manage the excess pressures. As a result, 95.36% of the nodes could have pressure within the desired limit, and 62.86% of the pipes had velocity within the desired limit. From the customer perception study, the average amount of water collected per household was 37.5 l/d. Most households have access to water at a distance of less than 250 m, and only 28 and 1.6% of households access water at 251–500 m and >500 m, respectively. However, the majority of the householders were dissatisfied with the affordability of water. Overall, even though the water supply system had shown low hydraulic performance, more than half (55.4%) of the customers were satisfied with the existing service. In order to minimise the high pressures and reduce water loss in the system, it is recommended to implement the proposed improvement. Moreover, the utility needs to gather customers's perceptions of the water distribution system from time to time to know their attitudes and then to take necessary decisions. In addition, the resilience and sustainability of the water supply system should be examined by combining hydraulic performance analysis with risk assessment models, climate change projections, and infrastructure resilience planning. These steps will allow for a thorough assessment of the system's overall water losses as well as revenue and non-revenue water in the town.

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