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Hydraulic Modelling of Water Distribution System of Aksum Town, Ethiopia

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Abstract

Intermittent water distribution is the key problem of many water authorities in developing countries including Ethiopia. Hence, this research was conducted to carry out the hydraulic modeling of the Aksum town water distribution system which is located in the Central Tigray region of Ethiopia. The objectives of this research were to evaluate the hydraulic performance of the water supply distribution system by assessing the situation of the existing water supply distribution system. Water GEMS V8i software was used as a tool to model the water distribution system. The model can be used to identify the high pressure and low pressure in the junctions and the magnitude of velocity through pipes was used as a base to evaluate the hydraulic performance. Modeling results showed a violation of maximum and minimum pressure and low-velocity requirements. High pressures in the system occurred both during low demand and peak demand have to be identified. The simulation result of the existing system about 38.6% of the junctions was failed to satisfy the allowable pressure and the velocity of about 34.9% was failed out of range during the peak consumption hour. The model performance measures were checked based on the coefficient of determination. In general, it was concluded that the existing water distribution network systems of Aksum town categorized under satisfactory hydraulic performance situation and were not supply adequate water to various demand categories of the town. In the modified system, the network runs hydraulic parameters are radically improved using the Pressure Reducer Valve added in the system to reduce high-pressure impacts on water distribution system. The results of the simulation show that the hydraulic simulation about 43.4% of pipes of diameter from the total water distribution system pipe diameters needed to be upgraded.

Keywords: Water GEMS • Water distribution system • Hydraulic modelling • Maximum pressure • Minimum pressure • Aksum • Tigray • Ethiopia

Introduction

The expansion of urbanization, population increment, and others are the cause which puts increasing pressure on the local water distribution system and water planers to satisfy the growing urban water and sanitation demands in developing countries. According to the World Health Organization WHO (2014) the report, the global drinking water target was met 91% in 2010 while Central Asia, Northern Africa, Oceania, and sub-Saharan Africa did not achieve this landmark.

The water problem is a growing worldwide concern and that has an impact on countries' economic prospects. Rising water stress, large supply variability, and lack of access to safe and adequate drinking water is a common problem in many parts of the world. Especially, developing countries face greater challenges of adequate water distribution because of their larger population growth rate, poor infrastructure, lower income levels, and less developed policy and institutional capacity.

Intermittent piped water networks were found all over the developing world. And it is estimated that one third of urban water supplies in Africa were operated intermittently. As result of; high population growth rate, scarcity of source water, treatment plant size, reservoirs, and storage tank capacity, power outages to run water pumps, high leakage problems, or some combination of these conditions were the primary causes for intermittent water distribution in the water system.

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Aksum town is a serious shortage of water in the distribution system due to the high growth rate of population expanded economic activities, and uncontrolled urban expansion of the town. A water-shortage condition would cause an unbalance in water supplies and demands. This could occur when the water supply decreases and is no longer sufficient for satisfying demand. Water shortage is accelerated by undesirable pressure within distribution systems [1].

Statement of the problem

Currently, Aksum town facing inadequacies and intermittent water distribution systems are the major challenge all over the town due to population growth and town expansion. This research intends to determine the extent to which the hydraulic performance of the Aksum water distribution network is affected by the intermittent supply, operational ways, and management system. To propose appropriate recommendations, we have to study the hydraulic parameters, the variations, and the relations between them and other factors, which control the hydraulic performance of the water supply distribution networks.

Also, it is advisable to evaluate the effects of local conditions and improve them for increasing the efficiencies of the water distribution systems. So, in order to address the overall of Aksum town water supply distribution problem and to give remedial measures, there is a need to evaluate the hydraulic performance of water distribution systems and to define the appropriate design requirements [2].

General objective

The general objective of this research is to model and improve the hydraulic characteristics of the water distribution system using Water GEMS software.

Specific objectives

- To evaluate the existing design, operation, and maintenance facilities of the water distribution system.

- To evaluate the balance of supply and demand in the water supply system.
- To evaluate the existing hydraulic performance of the water distribution system.

Materials and Methods

Description of the study area

Aksum town is located in the Northwestern Highlands Physiographic Unit and administratively belongs to the Central Zone of Tigray Region. Aksum is a historical place where the Ethiopian overall history began before 3000 years. It almost all comprises the center of the Aksumite Kingdom where it was among the four famous kingdoms in the world. Astronomically, Aksum is located at 470520 m E and 1561532 m N at a distance of about 1043 km from the North of Addis Ababa and 245 km away from the capital of Tigray, Mekelle. The town is located at the principal road which connects Adwa to the Shire -Enadasilassie. The town is subdivided into five kebeles and has a woreda status with the urban administration [3] (Figure 1).

Materials and Tools

Based on the research objectives the materials that were used for this study. Among the many commercially available hydraulic software, water GEMSV8i is chosen for modeling pressure in the systems for many reasons. Materials that were used in the study are Arc GIS 10.7 for delineating and locating the study area, Excel Spread sheet: For data preparation, analysis, and interpretation of results, a Pressure gauge to measure the pressure at the nodes and pump outlet, water meter to measure the flow of the pipe, handheld GPS to measure the coordinate's points.

Data analysis

To analyze the data which is collected from different sources, both qualitative and quantitative methods was used. From the quantitative methods, the descriptive statistical methods like percentage, graphs, and cross-tabulation was used in order to come up with the appropriate result. In addition to this, qualitative methods like narration were employed in the study. The computer software application excel was used to analyse the data obtained from the office. The field survey data for the distribution system was evaluated by using the engineering software called Water GEMS V8i.

Population projection

A census record of the population size of Aksum town for different years has been collected from the Central Statistical Agency. CSA method of population forecasting has been adopted for this research. Because of this, a method is mostly practiced to produce comprehensive, timely, reliable, and standardized statistical information using scientific statistical methods like Aksum town [4].

$$Pn = Po * e^{rt}$$ ----------eq. 3.1

Where,

Pn = Design population (after n years)

Po = Present population (at the start of design period)

r = Annual population growth rate in %

t = Design period in years

Per capita water consumption

The per-capita water consumption for various demand categories varies depending on the size of the town and the level of development. In Aksum town, the growth of the socio-economic activity in both the governmental and private sectors, there was a high water demand in the town. Using the annual water consumption and population in (2020), the average per capita consumption of the town was identified as equation 3.2 below.

$$percapitalconsumption(1/person/d) = \frac{AnnualConsumption(m^3)*10001/m^3}{CurrentPopulationoftown*365days}$$ -------- eq. 3.2

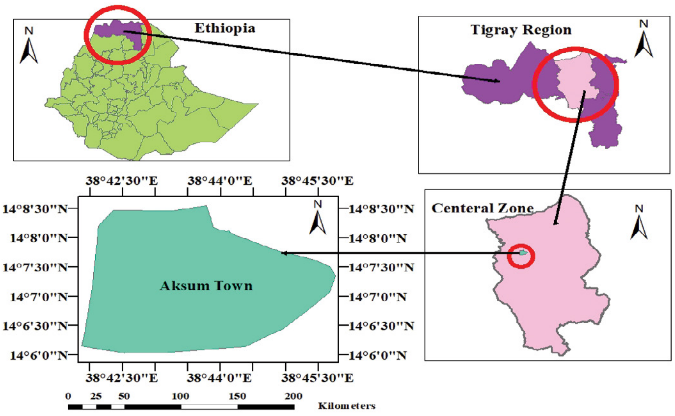

Figure 1. Location map of the study area.

Domestic water demand

Domestic water demand includes the water requirement for drinking, food preparation, washing, cleaning, and various domestic uses, like Aksum town per capita water requirement, is 60 l/c/day (MoWR, 2006).

DWD= Population* per capital water demand--------eq. 3.3

Climatic adjustment factor

According to the literature review National Meteorological Agency the climatic condition for Aksum town the mean Temp is 26.50C -300Cwas grouped with the corresponding adjustment factor of 1.1.

Socio-economic adjustment

The adjustment factor usually is based on the ministry of water resource the case of Aksum town was taken with a socioeconomic factor of 1.1

Adjusted Domestic Water Demand (ADWD) = DWD × Climatic factor × Socio economic factor…………eq. 3.4

Factor Uncounted Water loss

Unaccounted for water (UFW) is expressed as a percentage of the total water produced for the system. UFW arises from system leakage, water taken by illegal connections, inaccuracies in metering, overflowing of reservoirs, and legitimate unmetered use such as firefighting, flushing, etc.

$$UnaccountedWater\% = \frac{Water\ Produced - Meteredwaterused*100}{Water\ Produced}$$ -----------eq. 3.5

Therefore the total non –domestic water demand can be:

Non-domestic water demand (NDWD) = Institutional + Commercial and industrial + Livestock +Uncounted water loss………….eq. 3.6

Average daily water demand

Average daily water is the sum of domestic and non –domestic water demand. Therefore average daily water demand:

Total average water demand (TWD) = ADW + NDWD…………..eq. 3.7

Maximum daily water demand

Maximum daily demand is the deviation of consumption from average daily water demand. This can be computed by using maximum day factor. From water sector development manual the factor is 1.2.

Maximum day demand = 1.2 × TWD……….eq. 3.8

Peak hour demand

The peak hour demand is obtained by applying a factor of 2-5 to the average daily demand.

Peak hour demand = 1.8 × TWD………eq. 3.9

Demand classification based on land use

Different types of customers and their water use patterns must be considered in this process and customer types are classified as a residential, commercial, industrial, and public institutions. Land use (2020) data of Aksum town was collected from the municipality of town in the form of an AutoCAD file and was prepared using ArcMap GIS tools. The prepared land use of the town has been changed to the shape file with the same coordinate of the network system of the town for the overlying purpose [5] (Figure 2).

Allocating base water demand to each node

To assign base demand to each service node, it is necessary to determine the houses around each supply node. It is a multi-step procedure to allocate water demand to the node, which is as follows:

A. Classification of land use type

The water distribution system is classified into supply areas according to land use, such as residential, commercial, and industrial area, and public service. The map of the town was taken from the municipality of Aksum in AutoCAD file format prepared in ArcMap to change urban land use.

B. Identify the number of the house around each supply node

The urban land uses the town based AutoCAD format was obtained from the municipality of Aksum town. Then the urban land use was prepared in ArcMap. The land use map and the town WDN, which is display in Water GEMS. The number of houses in each census block was physically counted, and assigned to the nearest supply node. An Excel sheet was created for demand allocation.

$$Averagepeopleperhouse = \frac{Totalcurrentpopulation}{Totalnumber}$$ ---- eq 3.10

C. Population served to each node

To calculate the population served to each node was used the physical counting the number of a house near to the node multiply with the average people per house.

Population served to each node = number of a house near to the node * Average people per house------------ eq.3.11

D. Conversion of the number of houses into the amount of water

The amount of existing water consumption and water loss of the town is 45.7 l/s based on the actual design and based on revised design the base demand of 2020 is 73 l/s. The water Consumption and water loss were taken from Jun 2017-May 2020. Then the fraction of the demand required for those houses around a particular supply node was calculated by the following equation:

$$Basewaterdemandfora\sup plynode = (\frac{Populationservedbythatnode}{Totalpopulationofthetown}) * ADD$$ ----------eq 3.12

To assigning the industrial, commercial and institution, consumption to each node was calculated using the following formula:

$$IWD = \frac{Numberofinstitutionservedbythenode}{Tota\ln umberofcustomer\sin theinstitution} * consumedwaterdemand$$ ---------eq 3.13

Results and Discussion

As per the collected information and field observation, the operation and maintenance facilities of the Aksum town WDS operation system was controlled by the utility guards (non-skilled workers), who protect the powerhouse and collection chamber. Recently there are no controlling and operating mechanisms at the service reservoir due to chlorine dose adding. The overall maintenances of system components were not checked by schedule and it was maintained during failure or damage is occurring. Valves and all accessories installed in the main were not properly used and maintained regularly. Such as, the PRV in the WDS was not functional all the operation time, and it made challenges to limit pressure in the network (Figure 3).

Diurnal curve for water demand analysis

The water consumption relatively low usage at night when most people sleep, increased usage during the early morning hours as people wake up and prepare for the day, decreased usage during the middle of the day, and finally, increased usage again in the early evening as people return home. It is more appropriate to analyze this system under the daily flow conditions to understand its dynamics. Thus, a daily flow pattern is applied to every node. Figure 2 shows the pattern for water usage over the course of 24 hours.

Water demand estimation

Water demand estimation is one of the basic inputs to select source of water supply and to find the amount of water required to fill the gap between supply and demand of the subsystem. According to the water supply service of Aksum town, the existing design has the per capita demand that had been adopted as 60 l/c/d. However, this study estimated the per capita consumption

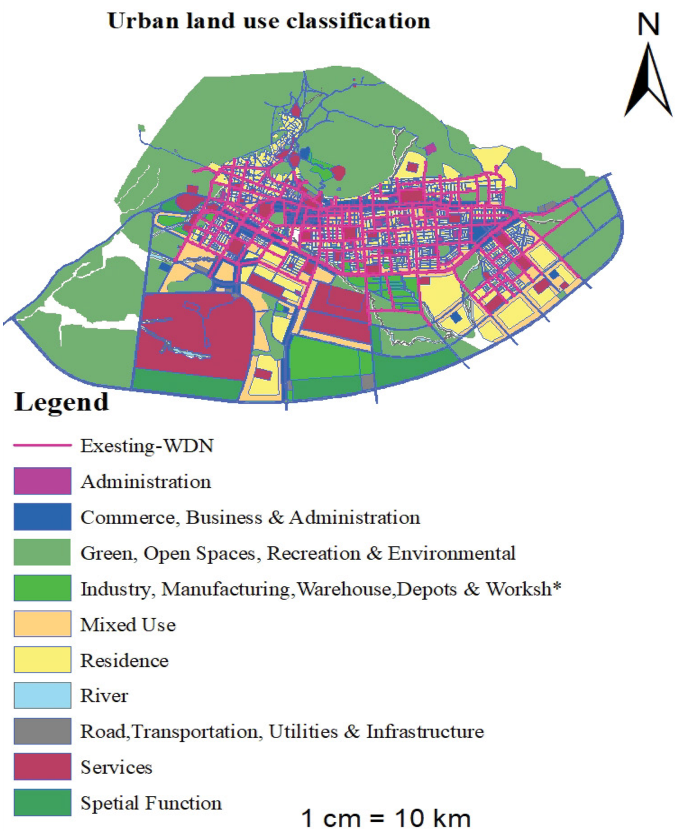

Figure 2. Urban land use map overlying with existing WDN of Aksum town.

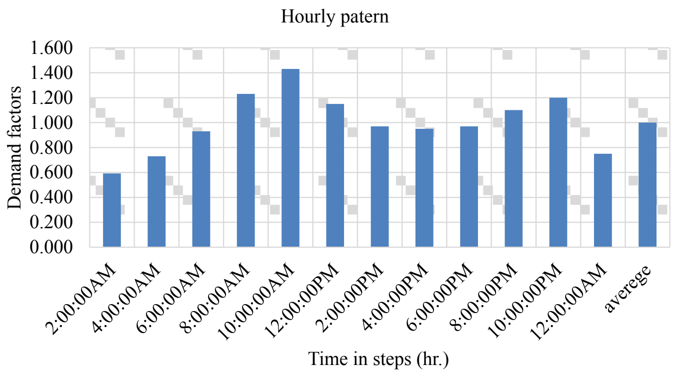

Figure 3. Hourly hydraulic pattern of Aksum town.

is 36.6 l/c/d based on the data Jun 2019- May 2020. The present domestic per capita consumption in Aksum town is low showing that the demand is suppressed due to the inadequacy of the existing water supply. Therefore, it is clear that the current per capita consumption is far below the recommended rate for towns in the water sector development program 60 l/c/d.

Water supply and demand gap between production and demand= Supply–Demand= (3950.6-6456.6) m^3/day= (-2506) m3/day. The negative sign indicates that there is a shortage of water supply (source). So, additional water must be required in the system per day to meet the supply and demand gap.

Model results

The WDN of Aksum town was classified using a pressure contour browser, which area is high, medium, and low-pressure areas. With regard to current simulation, the result for pressure using the estimated average daily demand during peak hour consumption is summarized in Table 1.

As shown in Table 1 shows that 38.6% of junctions are failed to satisfy desirable minimum pressure during minimum peak consumption. There are no nodes exceeded to maximum allowable pressures of 70m. While 61.4% of junctions are in the allowable pressure ranges of minimum 10m and maximum 70m (Figure 4).

Figure 4 expressions pressure distribution contour map during peak hour flow. As shown in Figure 4 above, junctions have located at the red color marked area are liable to lower pressure less than 10m. The rest color shows the allowable pressure in the study area.

As described in Table 2 shows 9.1% of junctions are responsible for extremely high pressure during the minimum consumption hour. 13.3% of the junctions are liable to a minimum pressure. While 77.6% of junctions are in the permissible pressure ranges of minimum 10m and maximum 70m pressure. Aksum town also affected the town by higher pressure (Figure 5).

Velocity

The velocity of water flow in a pipe is also one of the important parameters in hydraulic modeling performance evaluation of the efficiency of water supply distribution and transmission line. Velocity distribution is also varying with demand pattern changes. At the peak hour demand, the values are different as compare to the minimum consumption hours. The water distribution network velocity during peak hour demand is summarized in Table 3 below.

As shown in Table 3 during the peak hour demand conditions the no pipes that are failed to satisfy permissible velocity due to the maximum velocity in distribution and transmission line (>3 m/s). In addition to that, 34.9% of pipes also below the minimum velocity. While only 65.1 of pipes are in the permissible velocity ranges (average 0.3 m/s-3 m/s) (Table 4).

Pressure calibration and validation

Twelve representative samples measurement location have been selected for the calibration. The measurements were taken at a location other than the direct connection to the water mains, nearer to the supply main nodes at homes faucet. For the calibration, the head loss between the supply main nodes and the site where pressure is measured had been considered (Table 5).

As shown in the above Table 5, measured values are within an average error of + 0.975 m pressure simulated. Hence, the model is acceptable calibrated which is satisfied the setting pressure calibration and validation criteria under average level (average ±1.5 m to the maximum ±5 m).

Model performance evaluation

There are many ways to evaluate the performance of model calibration. The evaluation was made by calculating the squared relative difference between observed and simulated pressure for each test. Coefficient of determination (R^2) describes the degree of co linearity between simulated and measured data. The coefficient of determination, R^2 which ranges between 0 and 1, describes the proportion of the variance in the measured data, which is explained by the model, with higher values indicating less error variance. Typically, R^2>0.5 is considered acceptable (Table 6) (Figure 6 and Figure 7).

A comparison of results indicated that there is a significant difference between the measured and simulated data before calibration, but it is significantly close to the measured data after calibration. Comparison of results before and after calibration indicates that the average error of the test data (J-240) was improved from 2.41 to 0.53, which showed also optimal performance calibration model.

Validation

Model validation is the steps that follows calibration and uses an independent observed data set to verify that the model is well calibrated. In the validation step, the calibrated model is run under conditions differing from those used for calibration and the results compared to field data. If the model results closely approximate the field results (visually) for an appropriate time period, the calibrated model is considered to be validated (Figure 8).

Table 1. Summary of Borana livestock watering calendar in normal seasons of a year.

Pressure range in (m)	Junctions in peak hour consumption	Percentage %
>70	0	0
60 -70	24	8.4
50-60	4	1.4
40-50	20	7.0
30-40	27	9.5
20-30	41	14.4
10-20	59	20.7
< 10	110	38.6
Total	285	100

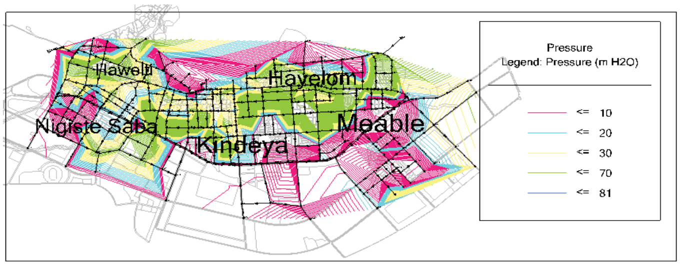

Figure 4. Actual junctions pressure contour at peak hour.

Table 2. Distribution of actual junction pressure at minimum consumption hour.

Pressure range in (m)	Junctions in minimum hour consumption	Percentage %
>70	26	9.1
60 -70	10	3.5
50-60	26	9.1
40-50	40	14.0
30-40	75	26.3
20-30	46	16.1
10-20	24	8.4
< 10	38	13.3
Total	285	100

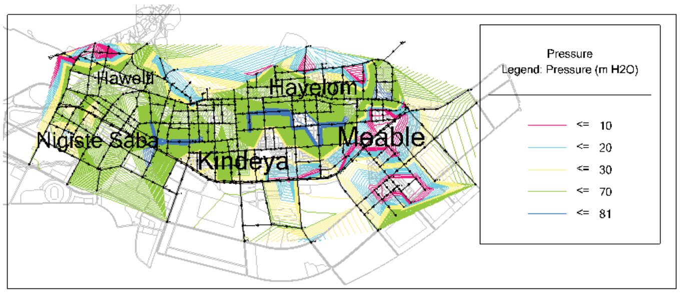

Figure 5. Actual junction pressure contour map at minimum consumption hour.

Table 3. Distribution of actual velocity pipe at peak hour demand.

Velocity in (m/sec)	Pipe (number)	Percentage %
>3	0	0
2.5-3	2	0.5
2-2.5	8	1.9
1.5-2	29	6.8
1.5-1	80	18.9
1-0.5	59	13.9
0.5-0.3	98	23.1
0-0.3	148	34.9
Total	424	100

Table 4. Distribution of actual velocity at minimum consumption hour.

Velocity in (m/sec)	Pipe (number)	Percentage %
>3	6	1.4
2.5-3	4	0.9
2-2.5	4	0.9
1.5-2	3	0.7
1.5-1	36	8.5
1-0.5	63	14.9
0.5-0.3	136	32.1
0-0.3	172	40.6
Total	424	100

Table 5. Pressure calibration at junction based on measured pressure and simulated.

Time (hrs.)	Pressure Junction id	Simulated Pressure head (m)	Observed Pressure (m)	Difference Pressure Error (m)
	J-1	23	20.5	2.5
	J-37	44	43.55	0.45
	J-41	52	50.6	1.4
	J-81	54	55.5	-1.5
	J-143	33	32.5	0.5
8:00 AM	J-151	21	19.51	1.49
	J-162	73	71.15	1.85
	J-240	63	61.5	1.5
	J-242	44	43.05	0.95
	J-247	27	25.44	1.56
	J-251	16	15.5	0.5
	J-284	53	52.5	0.5
			Average	**0.975**

Table 6. Measured and simulated pressure before and after calibration at J-240.

Time (hr.)	Measured Pressure	Simulated pressure after calibration	Simulated pressure before calibration	Error before calibration	Error After calibration
8:00	63.5	61.5	61.75	1.75	1.5
10:00	76.6	75.45	73.06	3.54	0.55
12:00	83.1	83.46	81.07	1.93	-0.46
Average error				2.41	0.53

As shown in Figure 6 and 8; it explains the results of correlation value (R^2) for both peak hour and minimum day demand time was represent as 0.9969 and 0.9953 respectively. Therefore, the calibrated pressure value was validated within the recommended standard.

System model modification

A WDS is designed at peak hour and minimum hour demand flow. By observing what is going on the system as a result of peak hour solutions have been given to the problems faced (pressures and velocities out of the design limit) within the network. Modification to the drawbacks of the hydraulic characteristics is made by creating new alternatives and scenario, trial and error procedure until a solution appeared to meet the design criteria at peak and low consumption hour. The pressure junctions are negative or low during the peak consumption hour had been created. Therefore, the kind of problem has modified or upgraded by increasing the diameter to increase the pressure head in the junctions to achieve the allowable pressure (Table 7).

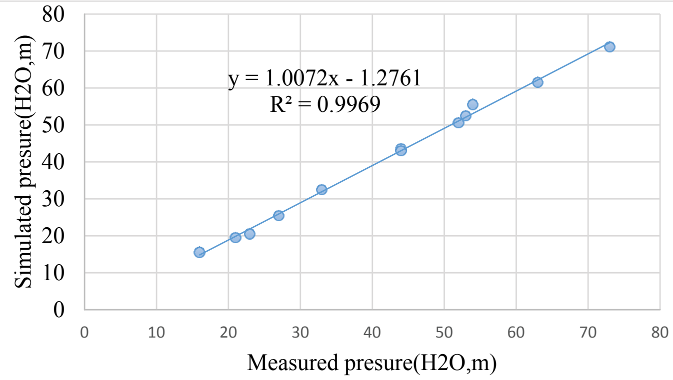

Figure 6. Borana indigenous water management cycle for ponds, Adadi and Tula.

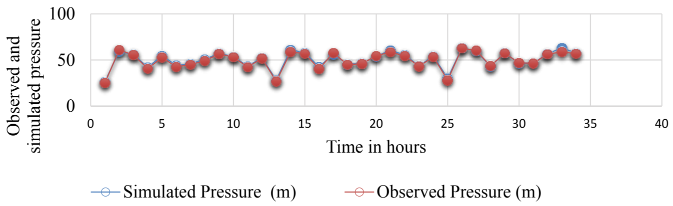

Figure 7. Shows that pressure calibration fitness test.

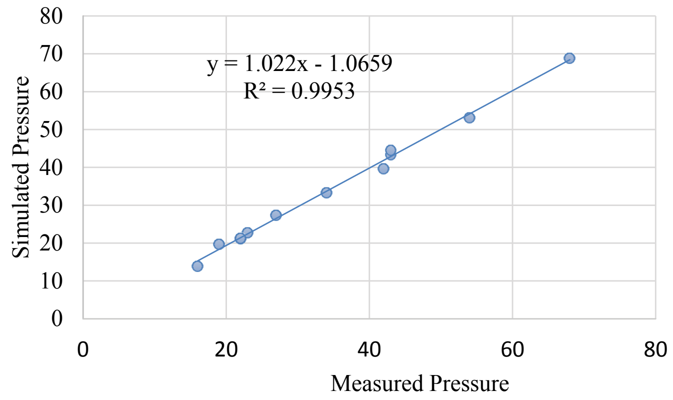

Figure 8. Correlated plot during minimum day demand for validation.

There are 26 junctions that have maximum pressure during low consumption. Thus, junctions are failed to satisfy the allowable maximum pressure and modified using the adding of PRVs in the actual system. This means not only reduce the pressure but also increase was entering the value pressure to sustain the pressure of the actual system (Table 8 and Figure 9).

The expression of the above table is for scenario comparison with regard to SSS and EPS during minimum and maximum consumption. For instance, in the current scenario base demand (Jun 2019-June 2020) the pressure greater than 70 is about 24.5%. Allowable pressure and adequate velocity the existing scenario is 71.7% and 70.17% respectively.

Table 7. Actual and modified pressure at minimum consumption hour.

Label	Existing Pressure (m H_2O)	Modified Pressure (m H_2O)	Label	Existing Pressure (m H_2O)	Modified Pressure (m H_2O)
J-246	76	64	J-251	72	56
J-249	76	69	J-186	72	65
J-285	76	70	J-168	72	69
J-255	75	62	J-95	72	68
J-252	74	68	J-220	71	62
J-73	73	66	J-247	71	58
J-112	73	45	J-116	71	62
J-253	73	60	J-27	71	60
J-115	73	67	J-241	71	64
J-110	73	65	J-160	71	65
J-224	73	64	J-106	71	63
J-31	73	69	J-182	71	62
J-244	73	63	J-145	71	45

Table 8. Hydraulic comparison in different scenarios.

S.no	Scenarios/Alternatives	Pressure (m)			Velocity (m/s)		
		P>70m	P<10	P (10-70)	V>=3	V <=0.3	V (0.3- 3)
1	Current demand (Jun 2019-May 2020) SSS	24.50%	3.80%	71.70%	0.00%	29.83%	70.17%
2	Base ADD SSS based on Design (2020)	9.10%	3.20%	87.70%	0	15.06%	84.94%
3	Base ADD at 2:00:00 AM EPS	9.10%	13.30%	77.61%	1.40%	40.60%	58.00%
4	Peak hour (10:00:00 AM) EPS Analysis	0.00%	38.60%	61.60%	0.00%	34.90%	65.10%
5	Modified model -EPS Analysis low	0%	0.00%	100.00%	0%	0%	100.00%
6	Modified model -EPS Analysis at peak hour	0%	0%	100%	0%	0%	100.00%

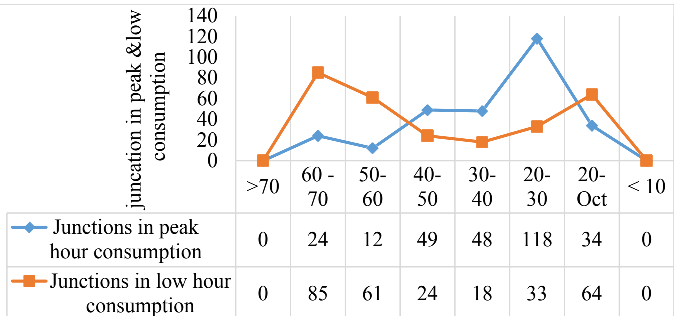

Figure 9. Relationship between modified system at minimum and peak pressure (mH_2O).

Conclusion and Recommendations

In this research, the existing WDS is simulated through the construct of a model using Bentley Water GEMS V8i. The actual system was evaluated for the existing design, operation, and maintenance of the network, especially in various abnormal situations. The result evaluated the design, operation, and maintenance facilities were poor due to the wrong model result implementation without modifying, and due to the poor technician. Finally, we can conclude that there is no clear Operation &Maintenance system for the WDS in Aksum town, which ensures the needed for establishing an effective Operation &Maintenance system for Aksum town Most of these problems are created in kebele Meable and Hawelti. After computing the existing system, about 9.1% of junctions are failed to satisfy desirable minimum pressure during steady-state simulation and 13.3% of junctions are failed due to extremely high pressure during the steady-state simulation. Generally, the condition or a situation of the actual water distribution system of the study area is inadequacies. The result of the modified hydraulic parameter is the required allowable design criterion range, especially for Pressure and Velocity [6-9].

The researcher has annoyed to recommend some of the very important issues to improve the hydraulic modeling of the water system.

1. The universal peak factors, which are used in the design of water distribution systems, should be modified and adjusted in the design of new water systems in Aksum town according to the local conditions of operating and managing the distribution networks.
2. Installing pressure reducing valve devices, which decrease pressure, is recommended as a solution to control the occurrences of maximum pressures during low consumption hour for desirable pressure range.
3. Install a Supervisory Control and Data Acquisition system (SCADA). SCADA should be installed at each borehole, valves, and reservoir. Data control signals and system status are transferred to and from the central system employing a bidirectional antenna at the center.

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