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Performance Evaluation and Optimization of Existing Water Supply Distribution System Using WATERGEMS: Case of Sekota Town

Demelash yenesew Kassahun * and Teshale Dargie

Hydraulic and water resources Engineering, bule hora university; teshaledargie2581@gmail.com
* Correspondence: Deme20094ever@gmail.com

Abstract: Everyone should therefore consistently get access to enough and safe water. The operation of the existing distribution network as well as the proper optimization and implementation of the new distribution systems are required for a sufficient and safe water supply. In Sekota town sufficient amount of water was not reached to the beneficiaries due to shortage of water at the source. The primary goal of this study was to evaluate the performance and optimize the existing Sekota water supply distribution system using Bentley Water GEMS. The system's hydraulic modeling is carried out by considering as a continuous supply system, and the evaluation procedure used the extended period simulation approach after calibration was done. Calibration is used to ensure the performance of the model using the observed pressure values. The output of the existing system shows pressure is very high means above the maximum pressure and velocity is very low at peak hour demand. The results of velocity and pressure before optimization have negative effect on the performance of the system. The number of pipes and junctions their velocities and pressures which were in admissible ranges are 15 and 42 pipes for velocities and zero and 59 junctions for pressure before and after optimization were evaluated respectively.

Keywords: Water GEMS; optimization; water distribution system; performance

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1. Introduction

Water is one of the most vital natural resources, and it is essential for life to exist and it is also required for practically all human activities, including industrial use, household use, irrigation, power generation, navigation, recreation, and animal consumption purposes and worldwide water scarcity is the most difficult problem to solve. Water distribution network is part of the water supply distribution system to transport water from the service reservoir to point of users. A water distribution system comprises of pipe, nodes and pump (sometimes link sometimes node), reservoir, junctions, valves (the same as pump), and storage tanks. The primary problem for water authorities around the world is not ensuring that the water distribution system (WDS) operates to users' satisfaction. Water distribution systems are difficult to build and maintain, and they need a significant investment from asset owners. Around 80 % of the total cost of a water supply project is invested for water distribution system (Sangroula et al., 2022), this implies huge amount of investment is applied to construct for a WDS for a planned town.

According to Tiwari, (2016) water consumption is affected by population increase, urbanization, and climate fluctuation, putting additional strain on water systems. There has been developed a big imbalance between the supply and demand of water as a result of population growth, and shortage of source, improving the living standard of the customer in Sokota town. The most significant aspect of a lifetime of projected loading circumstances are the design and operation of a water distribution system.

Optimization of a water distribution network aims to find the optimal pipe diameters in the network for the given layout and demand requirements. Due to these reasons implementing optimization of water distribution system using Bentley Water GEMS Darwin Designer is safe. This

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software is easy and simple to use, most water engineering experts should know the application and use of Water GEMS to optimize the pipe diameter using Darwin Designer. WDN optimization can be divided into several categories, including design, operation and rehabilitation, calibration, level-of-service, monitoring system, and network testing. This paper is concerned with evaluation of water distribution system performance and determining the optimal diameter of pipes in a predetermined water distribution network.

2. Material and methods

2.1. Description of the study area

Sekota town is located in Amhara region at 720km from Addis Ababa via the road of Addis Abeba-Weldiya-Alamata, or from regional state of Bahir Dar via Lalibela at approximately 440km (source from www.distancesto.com). It is a zonal state of Wag-Himra and lies between 12°33′30″-12°41′00″N and 38°58′00″-39°06′00″E.

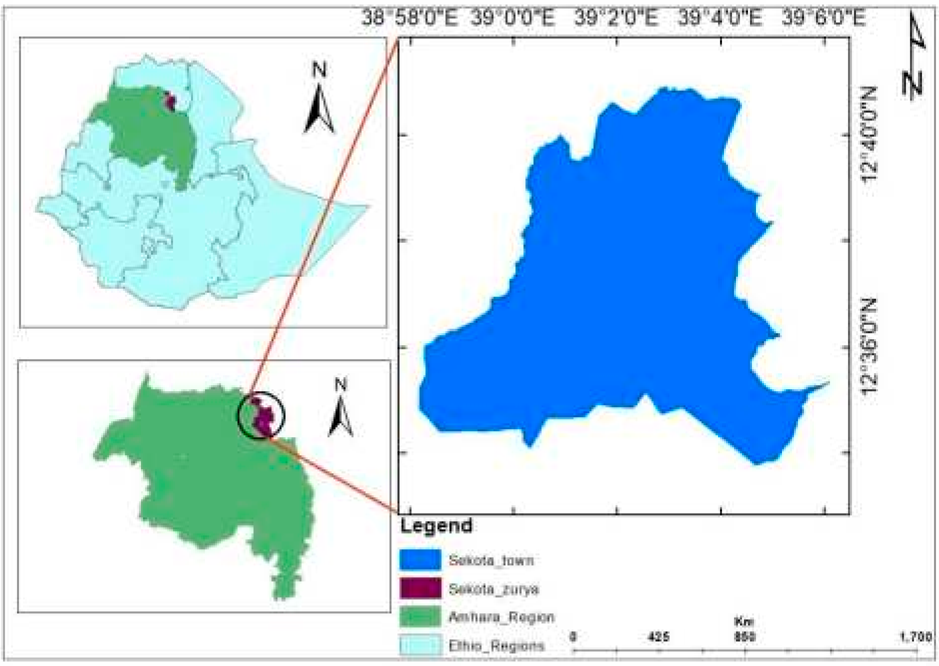

Figure 5. Map of the study area.

2.2. Materials used

The materials used in this research to achieve the research goal. Because of materials are key elements to facilitate the research work. Materials, which were used in this research topographical map, computer, Mobile camera, and GPS.

Table 1. Material used and their functions.

No	Material used	Function
1	Water GEMS for ArcMap	Use to extracted elevation of junctions, prepare the map of the study area, make shapefiles
2	Gauge pressure	Used to measure the pressure for the selected sample points
3	Water GEMS	To analyze the hydraulic and optimize the hydraulic parameters like pressure, velocity and from the beginning to the end design water distribution network.
4	GPS	Used to find the x and y coordinate of the storage tank, sources (reservoirs), and collection chambers.

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5	AutoCAD LT 2016-English	Used for convert for the layout from "dwg" format to DXF format
6	Google Earth pro	Used for connect the source and collection chamber with the distribution network

2.3. Methods of data analysis

2.3.1. Hydraulic modeling

Using physical characteristics and equations, a pipe network is represented through the process of hydraulics modeling. In a hydraulic model, the fluid or water is moved through the network by gravity or pressure difference. The SWSDS model has 63 demand nodes, 98 pipe links from the source to distribution network, 1 storage tank, 2 collection chambers, 3 sources (reservoir), 3 submersible pumps and 2 booster pumps. Water GEMS Connected Edition V10.02.03.06 is a hydraulic software, which was used for water distribution modeling and optimization, and made it simple to design and optimization a distribution network for continuous and intermittent water supply.

Nodal elevation extraction

The elevation of each junction was extracted using TRex in Water GEMS and it is integrated with ArcMap. Using the following steps extract the elevation of each node.

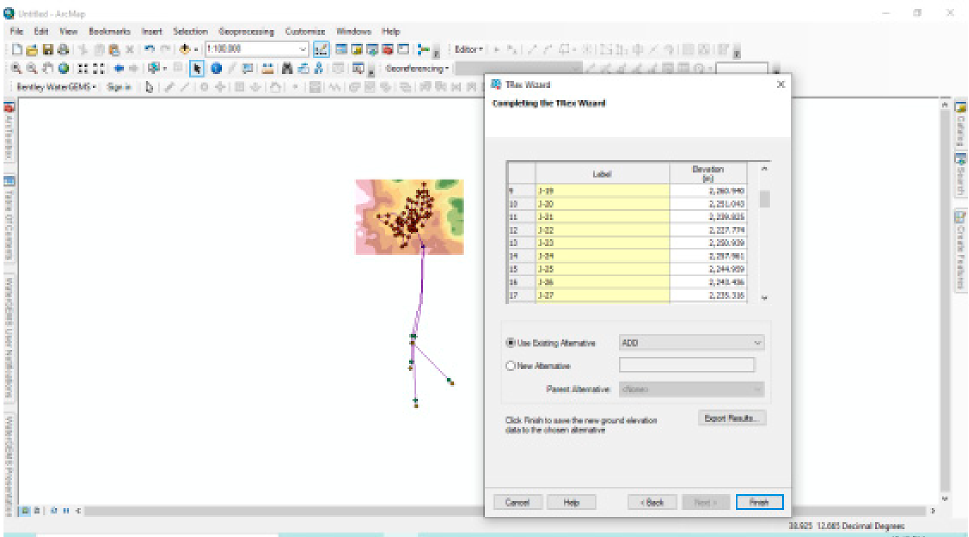

Figure 8. Extraction of nodal elevation.

2.3.2. Calibration and Validation

A model's reliability is ensured if its output or simulated value is accurately corresponding to the values observed in the field. Therefore, a model needs to be calibrated in order to have confidence in its results. Calibration was implemented using Darwin Calibrator for the measured pressure value.

Coefficient of determination (R^2): -The degree of the association between the observed and simulated values is indicated by the coefficient of determination (R^2). R^2 's description of the linear relationship between the two data sets is one of its main limitations, therefore using a faulty model that continually overestimates or underestimates the observations may result in a high R^2 value (Dufour, 2011).

$$R^2 = \frac{(\sum_{i=1}^{n}(\mathrm{Pob,i} - \mathcal{P}\mathrm{ob})(\mathrm{Psim,i} - \mathcal{P}\mathrm{sim}))}{\sqrt{\sum_{i=1}^{n}(\mathrm{Pob,i} - \mathcal{P}\mathrm{ob})\hat{}2\,(\sum_{i=1}^{n}(\mathrm{Psim,i} - \mathcal{P}\mathrm{sim})\hat{}2)\hat{}2}}$$

Where: - *Pob, i*= observed pressure for junction i

$\mathcal{P}ob$= mean observed pressure for sample junction

Psim, i= simulated pressure for junction i

Psim= mean simulated pressure for sample junction

Mean error (ME): The difference between the measured and computed pressures is the mean error. Values closer to zero demonstrate better agreement between simulated and observed values, and the ranges from -∞ to +∞ (ATSDR, 2000).

$$ME = \frac{\sum_{i=1}^{n}(|\text{Pob, i} - \text{Psim, i}|)}{n}$$

Pob,i = observed pressure for junction i

Psim,i = simulated pressure for junction i

n = number of sample points

Root means square error (RMSE): The difference between observed and simulated values is measured on an individual basis using the simulation error's standard deviation (RMSE) (based on individual residues). Its values vary from 0 to +∞, with values nearer zero indicating better agreement between simulated and actual values. More values of RMSE imply poorer model performance, whereas lower values show higher accuracy of the model performance (Chai & Draxler, 2014).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\text{Pob, i} - \text{Psim, i})\ 2}{n}}$$

Pob,i = observed pressure for junction i

Psim,i = simulated pressure for junction i

n = number of sample points

As Hunter, (2002) explained a good data set should have a pressure average difference of ±1.5m to a maximum of ±5.0m, and a poor data set should have a pressure average difference of ±3.0m to a maximum difference of ±10m

The sample points for the study area are listed in Table 3.

Table 3. Measured and simulated results of pressure at selected nodes.

Junction	Date	Time	observed (khalifeh et al.)	Observed (mH2O)	simulated	difference
J-14	6/12/2022	8:00:00 AM	11.8	118	120.8	2.8
J-15	6/12/2022	8:30:00 AM	12.2	122	119.77	-2.23
J-22	6/13/2022	8:30:00 AM	13.15	131.5	129.78	-1.72
J-47	6/14/2022	7:00:00 PM	7.2	72	74.2	2.2
J-54	6/15/2022	7:00:00 PM	7.5	75	77.59	2.59
J-56	6/15/2022	8:00:00 AM	7.8	78	81.2	3.2
J-60	6/16/2022	8:00:00 AM	7.9	79	74.57	-4.43
J-62	6/16/2022	7:00:00 PM	12.6	126	123.73	-2.27
Summation of absolute value deference						21.04

The average difference of the observed and simulated value is 2.63, which is less than the ±3, that is good.

2.4. Water supply coverage analysis

The total annual consumption divide by the number of days of year (365) is called average day demand.

$$\text{Average day demand } = \frac{\text{total annual water consumption}}{365}(\frac{l}{d})$$

2.5. Average day demand by mode of service

The annual consumption by mode of service for Sekota town was gathered and shown in Table 4 for Sep. 2020 to Aug. 202.

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Table 4. Water consumption based on mode of service for Sep. 2020 to Aug. 2021.

Type of connection	No of people served	Total water consumed (l/day)	Per capita demand (l/c/d)
House connection	2374	106,830	45
Yard shared (Brownlee et al.)	6935	242,725	35
Yard connection (shared)	6498	178,695	27.5
Public fountain	3830	95,750	25
Total	19637	624,000	

Source: From Sekota water supply and sewerage office.

2.6. Distribution system analysis

2.6.1. Model performance evaluation

Running the model for the current year, Sep. 2020 to Aug. 2021, average daily demand, at demand peaks, and at temporal variations with extended period simulation allowed for the analysis of the existing system's model.

2.6.2. Sustainability analysis using hydraulic performance

As Genetie, (2019) studies the sustainability index, that explain, is the product of reliability, resilience, and vulnerability.

$$\text{sustainability index} = \sqrt[3]{\text{Rel} * \text{Res} * (1 - \text{Vul})}$$

Where: - Rel= reliability, Res = resilience, and Vul = vulnerability Reliability: the probability that the WDN is in a suitable state is known as reliability (Rel), and it is defined as follows:

$$Rel = \frac{\text{number of satisfactory pressure (velocity)junctions}}{\text{total of number of junctions}}$$

Resilience: reflects how quickly the system recovers from failure. The capacity of a system to recover back after a breakdown and carry on with respectable operation is known as resilience (Res). If there is no failure on the system resilience is one, otherwise it is below one (Jalal, 2008).

$$\text{Res} = 1 - \frac{\text{total unsatisfactory}}{\text{total junction or pipe}}$$

The vulnerability is calculated by dividing the total amount of unsatisfactory values by the total amount of values across the simulation time.

$$Vul = \frac{\text{summation of unsatisfactory values}}{\text{total values}}$$

Pressure analysis

The pressure of water supply distribution system for Sekota town was estimated or calculated using Water GEMS.

Velocity analysis

The analysis of the pipe velocity is the same as pressure analysis. The boundary of the pipe flow velocity is, minimum 0.3m/s and maximum 3m/s MoWR, (2006).

Head loss analysis

Flow velocity, length and diameter of pipe, roughness coefficient and Reynolds number all these affects how much head loss happens in a pipe. Head loss is reduction of total head of water as moves through the system and it is not avoidable. Head loss has direct relationship with velocity. Water GEMS calculated the head loss using the Hazen-Williams formula.

$$hl = 10.67 * \frac{Q^{1.85} * l}{C^{1.85} D^{4.87}}$$

Where: -

hl = head loss (m), Q = flow in pipe segment (m3/s), L = length of the discrete pipe (m), D = diameter of the pipe (m), C = Hazen-William's roughness coefficient

2.6. Optimization of water distribution network

Water GEMS is one of the most popular and user-friendly hydraulic modeling and optimization software package (Sonaje & Joshi, 2015). In this study, Darwin designer will be used to optimize WDN based on genetic algorithm in Water GEMS model. In order to solve optimization problems with very vast solution spaces that cannot be solved using more conventional optimization techniques within the GA parameters, Darwin Designer was utilized (Ali, Abozeid, Darweesh, & Mamdouh, 2015).

Objective function

The goal of this thesis is to reduce the economic cost of pipe while meeting the minimum pressure, velocity and tank volume requirements.

Minimize Cost of pipe

$$Z = \sum_{i=1}^{n} k(d_i)L_i$$

Where: - z = total pipe cost (birr), k = unit cost of pipe i which has specific diameter (birr/m), L = length of a pipe (m), d = diameter of a pipe i (mm)

Hydraulic constraints

Water distribution system must be constrained with pressure, velocity, and diameter in case of **pipe, junction.**

Pipe constraints

Any "n" pipe associated with velocity over time interval t may be limited by minimum and maximum value denoted as:

$$\mathrm{Vmin} \leq \mathrm{Vn(t)} \leq \mathrm{Vma}x$$

Where: Vn(t) is the flow velocity of pipe "n" at time t and Vmin and Vmax represents the minimum and maximum allowable flow velocity for any pipe respectively.

Node constraints

The pressure at any junction "j" may be limited between a maximum value and a minimum value for each operating time interval. This can be stated as follows:

$$\mathrm{Pmin} \leq \mathrm{Pj(t)} \leq \mathrm{Pmax}$$

Where: - Pmin = allowable minimum pressure Pj(t) = simulated pressure at junction j at time t Pmax = maximum allowable pressure

Mass balance constraints

$$\sum \mathrm{Qi} - \sum \mathrm{Qo} - \mathrm{q} = 0$$

Where: - Qi and Qo discharge in and out of the junction whereas q = is external demand at a junction.

Energy balance constraints

$$\sum \mathrm{hfi} = 0$$

Where: hf = is the conservation of energy state that the head loss for a loop as in equation above described the summation energy balance for a loop is equals zero.

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3. Result and Discussion

3.1. Hydraulic modeling

Due to rapid population growth and high-water losses from the distribution network, the system's total water demand in Sekota Town exceeds the water supply at the moment. Higher pressure systems, that are regularly employed to limit overall demand and encourage unequitable distribution of the water supply.

Demand pattern

As SWSSO yearly reported, the hourly water demand pattern in the existing WDS as shown Figure 12. Examining the present water demand pattern in the area is critical for simulating and optimizing the WDS in Water GEMS using EPS.

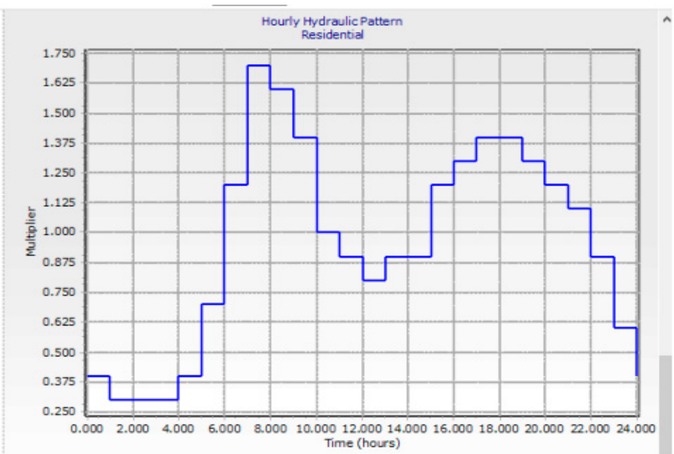

Figure 12. Hourly demand factor for Sekota town.

Calibration and validation

Figure 13 shows a strong correlation between the simulated pressure values using Bentley Water GEMS with measured values obtained from the sample points using pressure gauge.

And the fitness value of this graph is 1.96, thus it indicates the model is best and accurate to run hydraulic model and got ready to analysis.

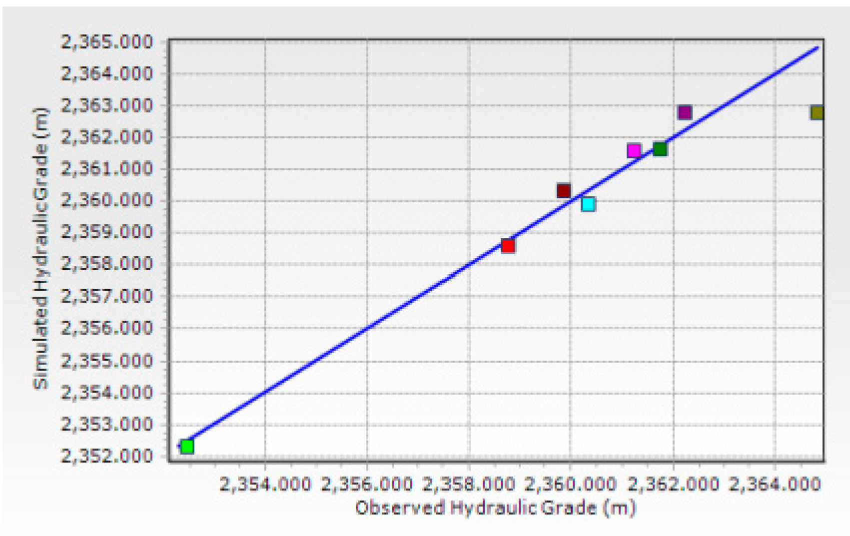

Figure 13. Calibration of hydraulic model using Darwin Calibrator.

Model performance evaluation criteria

The Water GEMS model performance was evaluated using statistical evaluation methods such as R^2, ME, and RSME, the obtained results are presented in Table 10. Table 11 Summery of performance criteria.

Performance criteria	Results
R^2	0.988
ME	0.0175
RSME	2.79

The performance evaluation results revealed that the Water GEMS has a promising approach to simulate the water pressure at nodes in the WDS. As explained in ATSDR (2000) an ME of pressure difference of ± 15.2kPa (± 1.52 m) with a maximum difference of ± 50.3 kPa (± 5.03 m) characterizes a good performance set. The ME of the Sekota, on the case, is 0.0175. As a result of these calculated pressures, the Water GEMS model has a very good pressure performance in the research area.

3.1.1. Pressure analysis

For water supply distribution network's minimum and maximum operating pressures are 10 m and 70 m respectively with regard to MoWR, (2006) guideline.

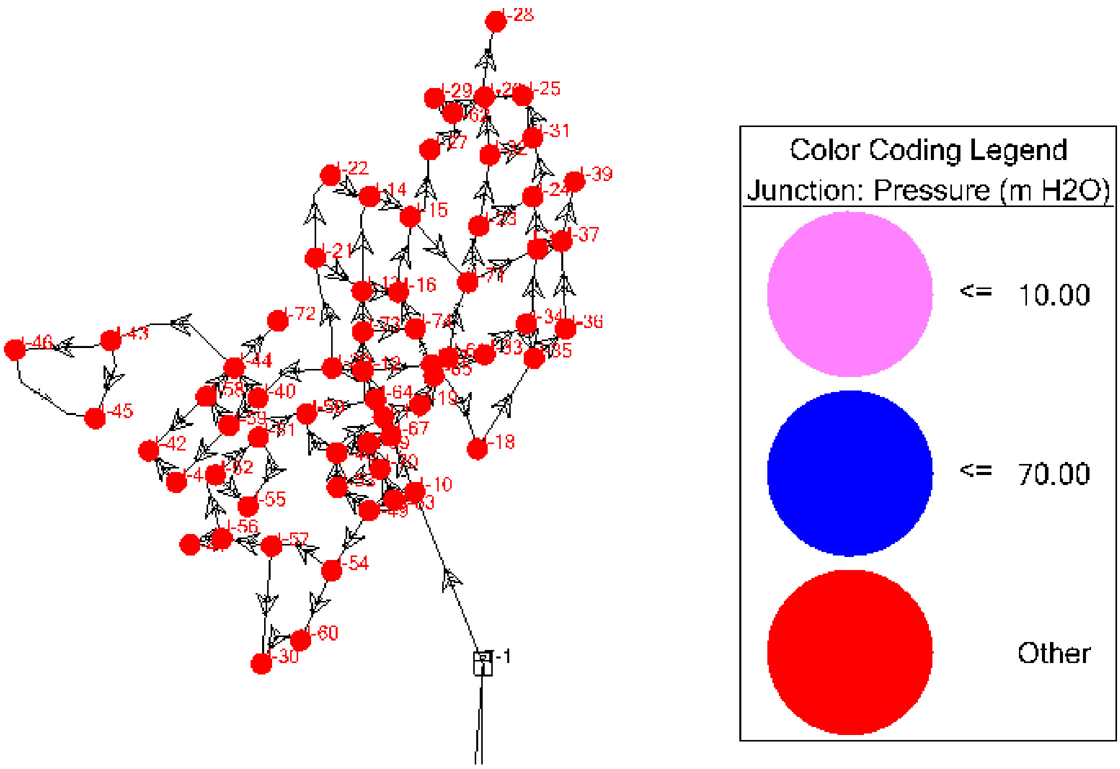

Figure 16. Existing SWDN pressure analysis.

This result indicates 100% of the system is under risks, therefore it should be improved for good performance and to get permissible pressure using Water GEMS.

3.1.2. Velocity analysis

In order to prevent structural problems or undesirable hydraulic regimes brought on by high flow rates or to lessen the detrimental impact of extremely low flow rates on delivered water quality, it is required to control flow velocities in water distribution networks.

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3.2. Hydraulic performance analysis

The first and most obvious activity to focus on when enhancing hydraulic performance is performance evaluation.

Sustainable analysis

The sustainable index of the system is below 0.5, due to this result the performance of SWDN is very low.

3.3. Optimized pipe diameter

Based on objective function and commercially available pipe sizes, the WDS's pipe diameter optimization was completed.

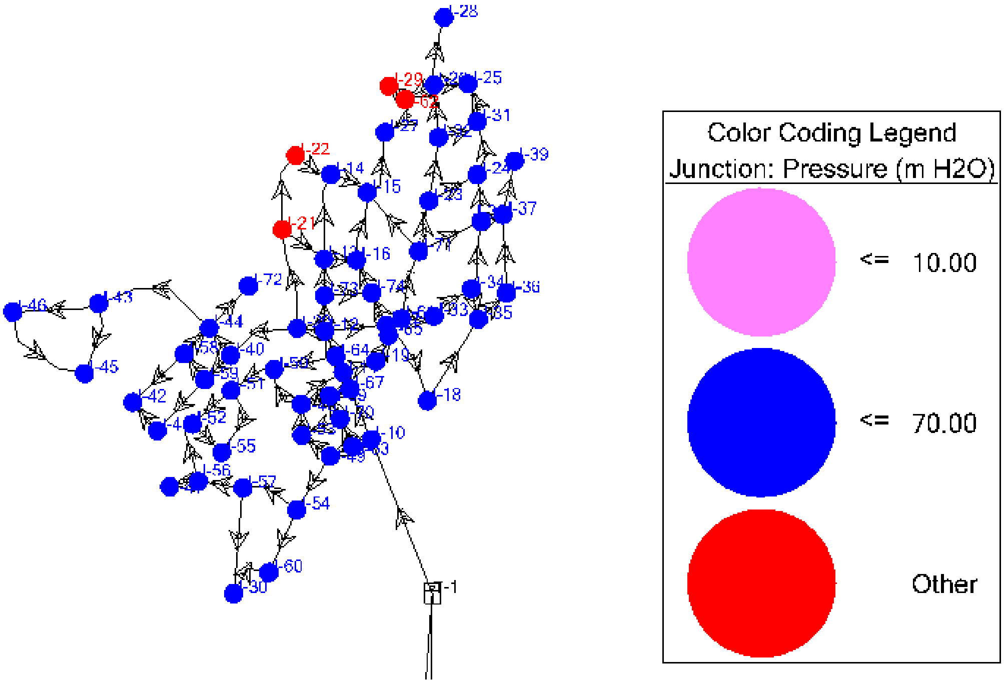

Figure 18. Pressure value for optimized water distribution system.

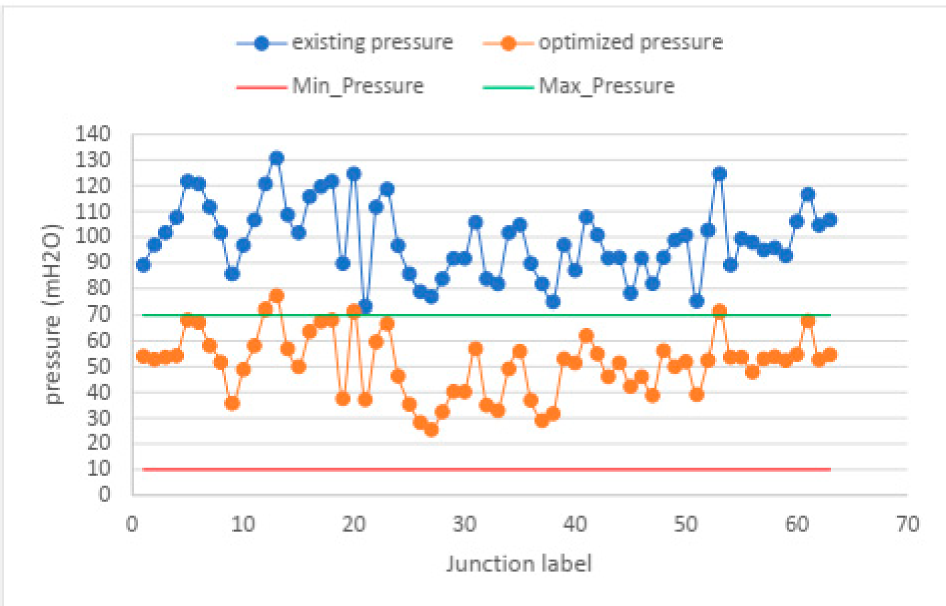

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Figure 19. pressure before and after optimized using scatter graph.

Velocity analysis after optimization

Making sure that water flow velocity is appropriate in water distribution system for its functioning correctly.

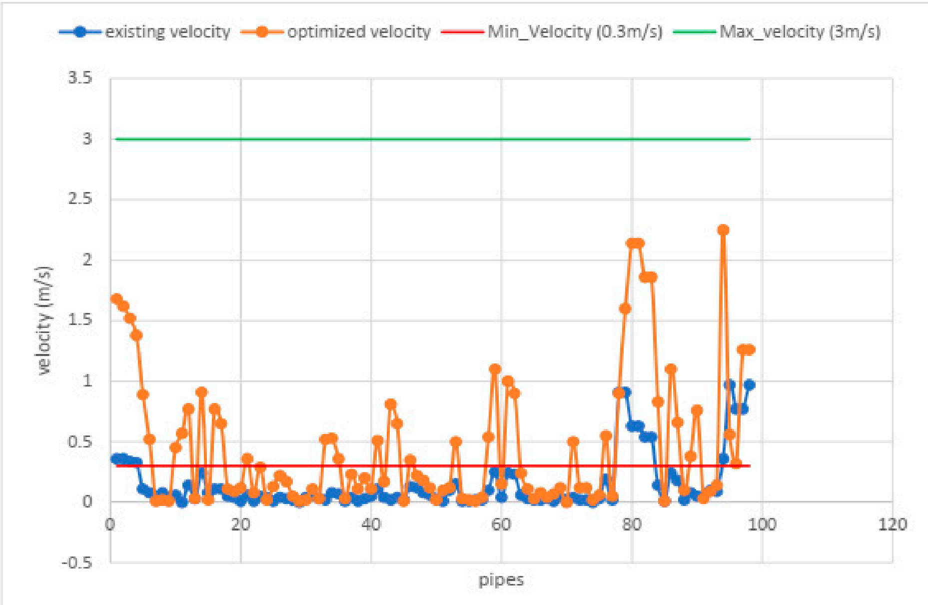

Figure 21. velocity after and before optimization using scatter graph.

Pipe cost

The total pipe length of existing and optimized of Sekota water supply distribution system is the same, which is 30,229m. When decreasing pipe diameter during optimization, its unit cost also decreasing with somehow proportion at the same time. Pipe cost and pipe diameter haven't directed proportion but have positive relationship. The optimized was accomplished only for the existing one not added any system.

Table 14. Unit and total cost for existing pipe diameter.

Diameter (mm)	Length (m)	Cost per unit length (Birr/m)	Total cost (Birr)
HDPE Pipes			
37	635	39.29875	24954.70625
50	335	69.37	23238.95
80	2281	178.86	407979.66
100	6330	286.49	1813469.04
DCI Pipes			
150	4111	2915	11983565
200	15886	3922	62304892
250	651	5088	3312288
Total length (m)	30229	Total cost (Birr)	79,870,387.36

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Table 15. Total cost of optimized pipe diameter.

Diameter (mm)	Material	Total length each diameter (m)	Cost per unit length (Birr/m)	Total cost (Birr)
32	HDPE	5780	29.73	171,839.4
40	HDPE	1562	45.04	70,352.48
50	HDPE	1295	69.37	89,834.15
63	HDPE	190	110.59	21,012.1
75	HDPE	653	156.09	101,926.8
80	HDPE	197	178.86	35,235.42
100	HDPE	134	286.488	38,389.39
140	HDPE	100	534.84	53,484
150	HDPE	88	616.48	54,250.24
100	DCI	19813	1939.8	38,433,257
125	DCI	126	283.29	35,694.54
150	DCI	15	2915	43,725
160	DCI	85	698.12	59,340.2
180	DCI	161	883.11	142,180.7
200	DCI	30	3922	117,660
	Grand length (m)	30,229	Grand cost (Birr)	39,335,188

The total cost of the existing and optimized system is 79,870,387.36 Birr and 39,335,187.56 Birr respectively.

$$Decrease\ pipe\ cost\ in\ percent\ = 79{,}870{,}387.36 - \frac{39{,}335{,}187.56}{79{,}870{,}387.36} * 100$$

Decrease in pipe cost = 50.75%

This result indicated the optimized pipe is decreased its total cost by 50.75% that approximately half of the existing pipe cost.

4. Conclusion

Water GEMS software was used in this study to create the optimal water supply network design for a specific area of Sekota town. To perform this thesis first evaluated the water supply coverage and performance of Sekota water distribution network using Water GEMS, second, optimizing the existing water distribution network for least cost while not violating the hydraulic parameters especially pressure constraint for the existing network. The pressure values for the existing WSDS of Sekota town are greater than the permissible pressure value. As MoWR, 2006 guideline, the maximum pressure value of water distribution network is 70mH2O, above this value the pressure made risk on the pipe system. In case of velocity analysis, the velocity values of the system ,85% of the system, are below 0.3m/s. For branched system velocity below the value 0.3m/s is impossible, whereas in looped system like Sekota water supply distribution system, even zero velocity is possible, (MoWR 2006). For the optimal network, the findings demonstrated that the least cost solutions were discovered that somehow met the nodes and pipes requirements for pressure and velocity respectively. However, for the result of pipe velocity it is very small even in optimized network. This small value is due to small in supply water to the customer, even the water production from the source is very small. For the pipes that have small velocity values need treatment using chlorin because stagnant of water is occurred. The ratio of the existing pipe cost to the optimized cost is 36.66%, this indicated that the existing pipe network cost has been increased by 36.66%.

Generally, there were some assumptions to conduct this study, like head loss calculation was estimated using Hazen Williams formula and to calculate the cost of each pipe was used the dollar currency as birr.

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