J. Sci. Univ. Kelaniya 16 (1) (2023): 01 - 14 http://doi.org/10.4038/josuk.v16i1.8070

Optimizing the water distribution network of community water supply using different computer simulation techniques

M.E. Sutharsan

Regional Support Centre (North), National Water Supply and Drainage Board, Vavuniya, Sri Lanka

edsutharsan@yahoo.com

https://orcid.org/0000-0001-8171-3894

Received: 24.08.2022 Revised: 23.01.2023 Accepted: 02.02.2023 Online: 15.05.2023

Abstract The appropriate operation of a water distribution network (WDN) of any water supply scheme is vital to supply sufficient potable water to consumers at sufficient pressure. However, the performance of the WDN may vary from the original design in the long run. In this study, a WDN network model was built using WaterGEMS and WaterCAD computer simulators, and hydraulic analyses were conducted to obtain an optimal WDN for a community water supply scheme of a village in Sri Lanka. A series of steps such as; selection of models, network representation, simulation of network, problem identification, network configuration finalization, and results analysis were carried out in developing the WDN simulation model. The hydraulic parameters such as pressure, flow velocity, and flow rate were analyzed under extended period simulation. The result indicated that the nodal pressure head in the junctions (100%) is above the required pressure level of 10 meters H_2O, which is adequate for the effective performance of the water distribution system (WDS) during peak and off-peak demand hours. The elevated water tower was optimized with a 10 m height to supply water at satisfactory pressure. Nodal pressure is negatively correlated with ground elevation. The flow velocity was observed within the range of 0.1-0.4 m/s in 67% of the pipe network, while 17% of the pipe network velocity was below 0.1 m/s. The low daily water demand of the small community could be the reason for the low-velocity scenario, which shall lead to silt deposition in the pipelines; hence frequent line washout to eliminate the silt deposition in the system is recommended. The WDN was designed for optimized pipe sizes with availability in the market.

Keywords: Optimization, Simulation, WaterCAD, WaterGEMS, Water network model

Introduction

Drinking water is a crucial component of human sustenance. In addition, water is a vital element as the basic need to carry out day-to-day activities (Sonaje & Joshi, 2015). The water supply scheme mainly supplies potable water to houses, organizations, and commercial and industrial institutions. The appropriate operation of a water distribution network (WDN) of any water supply scheme is vital to supply sufficient potable water to consumers at sufficient pressure. The drastic change in the water demand during operation due to the increase in population is considered one of the prime factors affecting the performance of a WDN which may lead to the complete augmentation or rehabilitation of the water supply system. In designing the optimal water distribution system, the analysis and designing play vital roles that contribute to curtailing the capital cost incurred during construction and maintenance costs during operation (Agunwamba et al., 2018).

A water distribution system (WDS) is a system that caters to the water demand of consumers with an adequate quantity of water with good quality, at satisfactory pressure throughout the hour, day, week, month, and year (Agunwamba et al., 2018). However, potable water distribution is not an easy task to implement and maintain in terms of the technical perspective of quantitative and qualitative aspects. Maintaining invariable water flow with adequate quantity and acceptable quality is vital for the proper function of any water supply scheme. It was reported that many water supply schemes in India deliver a few hours of water supply to the consumers, without adequate pressure and insufficient level of water quality (Bhave & Lam, 1983).

According to the design manual of the National Water Supply and Drainage Board (NWSDB)

This work is licensed under a Creative Commons Attribution 4.0 International

(National Water Supply & Drainage Board, 1989), the minimum allowable pressure at every consumer point is 10 mH_2O, while maximum working pressures should be within the stipulated pressure limit depending on the pressure class of the pipes. As per the American Water Works Association, a water supply scheme should have the minimum water pressure in the junction throughout the water network system depending on the water consumption category, which is usually in the range of 275.8 – 689.5 kN/m² (AWWA, 1974).

The minimum flow velocity in WDN is specified as 0.6 m/s to eliminate the chance of silt deposition which may occur due to the low velocity. In addition, the maximum flow velocity range is stated as 1.8 - 2.5 m/s to eliminate the occurrence of excessive water hammer, which may create additional pressure in the system thereby pipe failure may occur. There are a few factors such as population growth, pipe length, pump capacity, and pipe diameter shall influence the performance of the WDS, because WDS is designed for a long period, often 25 years.

A user-friendly interface to analyze, design, and optimize WDN is provided by both WaterGEMS V8i and Water CAD software. There are a few important attributes namely; hydraulic analysis, water quality analysis, extended period simulation, and steady-state simulation. Simplified model building, water quality modelling, fire flow analysis, optimization, and scenario management are some benefits of WaterGEMS V8i over other software (Bentley Communities, 2013).

A user-friendly interface to create, analyze, design, and, optimize water networks is provided by waterGEMS V8i software. Time series hydraulic results, system data, future and current scenarios, and other important data with GIS application are some of the benefits of waterGEMS V8i software (Schneiter et al., 1996).

WaterGEMS and WaterCAD feature a powerful design algorithm that satisfies the requirements for accuracy in water distribution network designs, regulating water flow, velocity, and water pressure and optimizing them. The algorithm used to obtain the solution in Water GEMS and Water CAD is Genetic Algorithm. These software include state-of-the-art genetic algorithm optimization engines for automated calibration, design, rehabilitation, and pump operations (Mehta et al., 2017).

The use of genetic algorithms in non-linear optimization-related problems is becoming more popular among designers and engineers of water resources. A manual run in Calibrator, for instance, will still permit comparison of model results to actual data gathered in the field. However, model parameters are manually adjusted by trial-and-error and guesswork, instead of using the WaterGEMS's built-in Genetic algorithm: *eg.* minor loss roughness coefficient is added as 4.8 in the pipe section if the gate valve is in a half-open position. The adjustment of model parameters until reaching the field measured data or set designed value by the designer is the advantage of automatically processed calibration and designs in WaterCAD and WaterGEMS software. This shall lead the calibration and design process much faster (Bentley Communities, 2015).

The designer enters the input parameters such as pipe material, pipe diameter and length, hydraulic constraints, allowable unit cost, and design mode as manual or automatic. While performing automatic design, the methodology of the genetic algorithm shall analyze and assess hundreds of thousands of design approaches depending on minimizing the cost, benefits maximization, and multi-objectives. WaterGEMS and WaterCAD have these automated design features by using a genetic algorithm. Further, this method has numerous other advantages than the other algorithms methods to obtain pipe network systems solutions

- Both partially and looped branched networks shall be solved directly, which can provide computational benefit than other loop-based algorithms like the Simultaneous Path method, for which network re-formulation pseudo-loops or into equal looped networks is required.
- A post-computation phase of path and loop definition shall be avoided by this algorithm, and thereby system's computation overhead shall be significantly reduced.
- The stable network system can be maintained even when the system gets disconnected due to the modeler's error or due to introduction valves.

In a previous study, a water supply network was investigated, designed, and developed effectively using the waterGEMS program. To curtail the gap between the simulated and observed junction pressure, a model was calibrated. The distribution system was optimized in terms of cost and performance. Finally, it was concluded by the authors that, waterGEMS software has more advantages to perform effective hydraulic modelling and designing water distribution systems (Dhumal et al., 2018).

Thorough analysis and proper design are vital to obtaining an optimized WDN not only to perform a smooth operation but also to optimize the investment cost, operational efficiency, and operation cost (Mehta et al., 2017). Therefore, the principles of designing a WDN need to be well understood.

The problems commonly faced by WDS are categorized as new water network design, modification of the existing network, and existing system operation (Izinyon & Anyata, 2009). In addition, the prominent problems faced by water supply utility entities with respect to water distribution network are; (i) service area expansion beyond the project area, (ii) water connections escalation than estimated, (iii) sudden pipe burst due to high water pressure, (iv) water hammer issue due to high velocity and (v) increased pipe internal surface's roughness due to aging. Hence, the objective of this study is to design and analyze the optimized existing water distribution network of a community water supply scheme, by paying special attention to sufficient design horizon, proper population growth forecast, system pressure, and system velocity by using two different computer simulation software namely; Bentley WaterGEMS and WaterCAD. The significance of the study is to assist water utility managers to perform not only smooth operations but also to optimize the investment cost, operational efficiency, and operation cost. In addition, this will also assist to understand the important parameters needed to be considered while designing the WDN of the community water supply scheme.

Methodology

Study area

The study area is in a rural village in the Mannar district in the Northern Province of Sri Lanka as shown in Figure 1. The population in the area is over 500. Topographically, the ground elevation has a 10 m difference within the area. The area falls under the dry zone area. The average temperature is 29.9^{o}C and the average annual rainfall is 903.7 mm in the area.

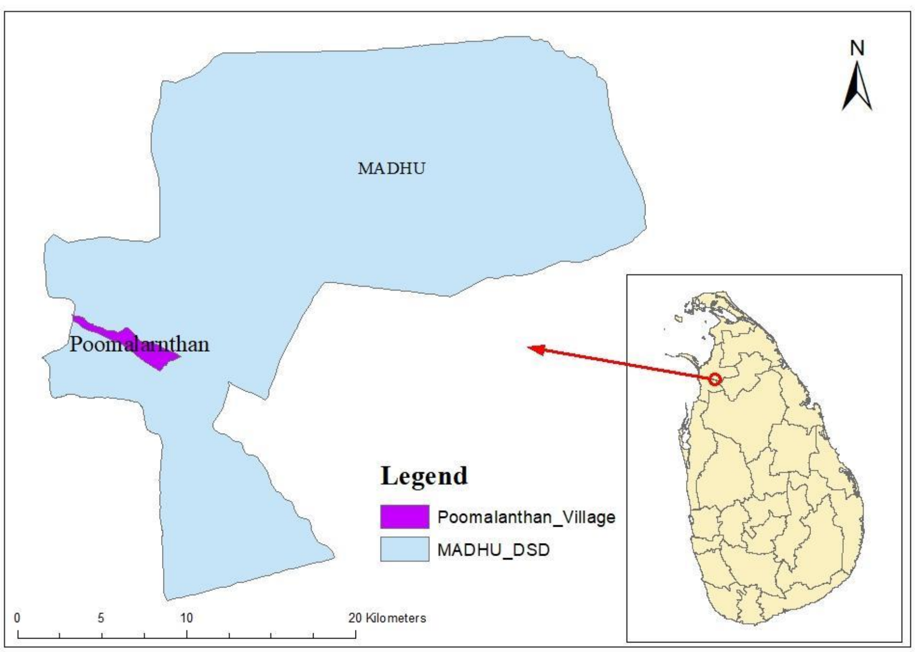


Figure 1: The study area

Methods of Analysis

The water distribution network model was created with the relevant elements such as pipes, nodes, bends, valves, and tower by using both WaterGEMS and WaterCAD programs. The methodology adopted in the study is shown in Figure 2.

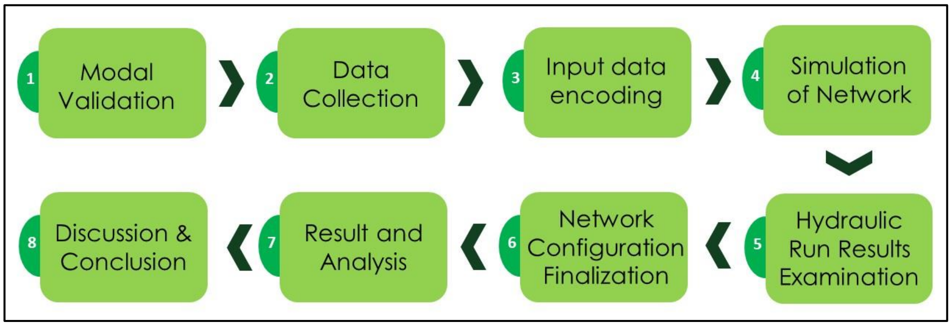


Figure 2: Methodology flow chart

The demand for domestic, industrial, commercial, and unaccounted-for water was taken into consideration while calculating the system demand by considering the design horizon as 25 years as tabulated in Table 1.

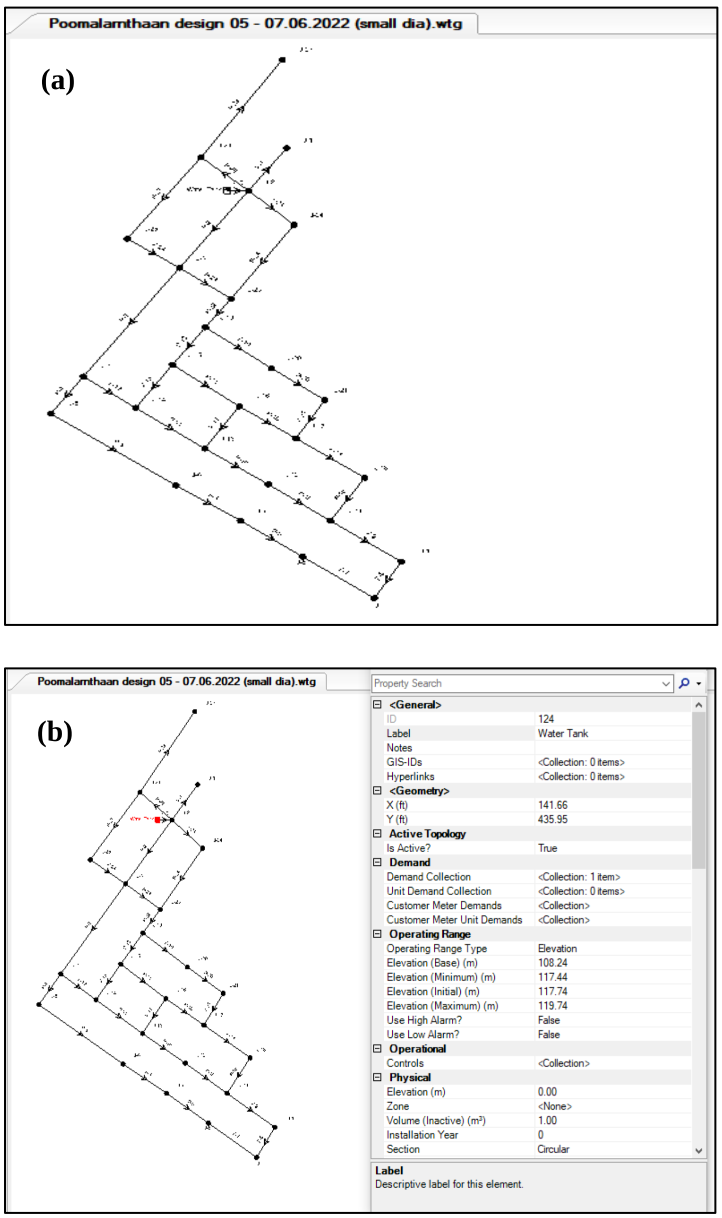
Table 1: Water demand calculation

Start	End	Population	Per	Domestic	Commercial	Industrial	NRW	Total
J-1	J-2	27	100	2.7	0.27	0.27	0.49	3.73
J-2	J-3	27	100	2.43	0.24	0.24	0.44	3.35
J-3	J-4	74	100	6.66	0.67	0.67	1.20	9.20
J-4	J-5	20	100	1.8	0.18	0.18	0.32	2.48
J-5	J-6	27	100	2.43	0.24	0.24	0.44	3.35
J-6	J-7	20	100	1.8	0.18	0.18	0.32	2.48
J-7	J-8	20	100	1.8	0.18	0.18	0.32	2.48
J-8	J-9	20	100	1.8	0.18	0.18	0.32	2.48
J-9	J-10	13	100	1.17	0.12	0.12	0.21	1.62
J-10	J-11	20	100	1.8	0.18	0.18	0.32	2.48
J-11	J-12	20	100	1.8	0.18	0.18	0.32	2.48
J-12	J-13	13	100	1.17	0.12	0.12	0.21	1.62
J-13	J-14	34	100	3.06	0.31	0.31	0.55	4.23
J-14	J-4	34	100	3.06	0.31	0.31	0.55	4.23
J-14	J-15	34	100	3.06	0.31	0.31	0.55	4.23
J-15	J-16	40	100	3.6	0.36	0.36	0.65	4.97
J-16	J-17	40	100	3.6	0.36	0.36	0.65	4.97
J-17	J-18	20	100	1.8	0.18	0.18	0.32	2.48
J-15	J-19	13	100	1.17	0.12	0.12	0.21	1.62
J-19	J-20	34	100	3.06	0.31	0.31	0.55	4.23
J-20	J-21	34	100	3.06	0.31	0.31	0.55	4.23
J-19	J-23	13	100	1.17	0.12	0.12	0.21	1.62
J-23	J-24	27	100	2.43	0.24	0.24	0.44	3.35
J-25	J-26	27	100	2.43	0.24	0.24	0.44	3.35
J-26	J-27	40	100	3.6	0.36	0.36	0.65	4.97

The following steps were carried out to create the computer model of the WDN using WaterGEMS and WaterCAD Simulator program.

Step 01 - Input data encoding

The input of required data for analysis is the first step in any hydraulic analysis program, especially in WaterGEMS and WaterCAD. The input data are categorized into four types namely; pump data, tank data, junction data, and pipe data. However, the pump data part is not included in the methodology, since the system is fed by the elevated water tower. The most important data such as reservoir number, capacity (m^3), base elevation (m), water level (m), and inactive volume (m^3) were input under tank input data. Pipe diameter (mm), pipe material, pipe number, dimensionless roughness coefficient, pipe length (m), and minor losses were assigned as pipe data. Under junction data, important data such as junction number, elevation (m), junction demand (l/s), and demand pattern were assigned. The procedure for creating the model and data input is in Figure 3.



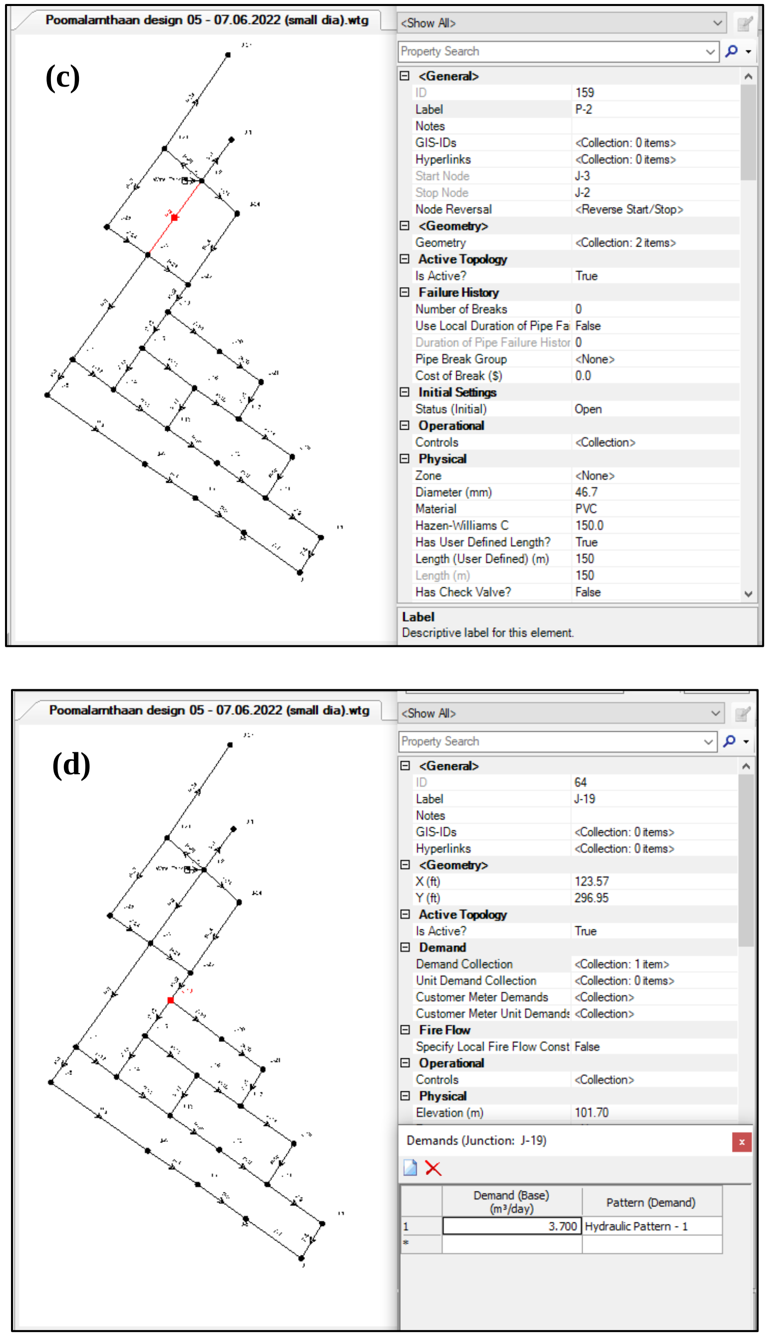


Figure 3: The procedure of (a) creating the model, (b) water tank data input, (c) pipes data input, and (d) nodal data input

Step 02 - Simulation of Network

This is a vital part of the hydraulic analysis in WaterGEMS and WaterCAD software. The model was checked for errors after creating the model and input data through a process called the "validate" option. Then the model was simulated with a hydraulic run after inputting all the required data as shown in Figure 4. Nodal pressure (m), flow velocity (m/s), pipe headloss (m), and headloss gradient (m/km) were computed by the software which is vital for decision-making during hydraulic analysis. As per Bentley Communities (2013), waterGEMS V8i program has a reliable design algorithm to produce precise network design since the WDN parameters namely, junction pressure, velocity, and water flow along with their optimization are controlled by the program.

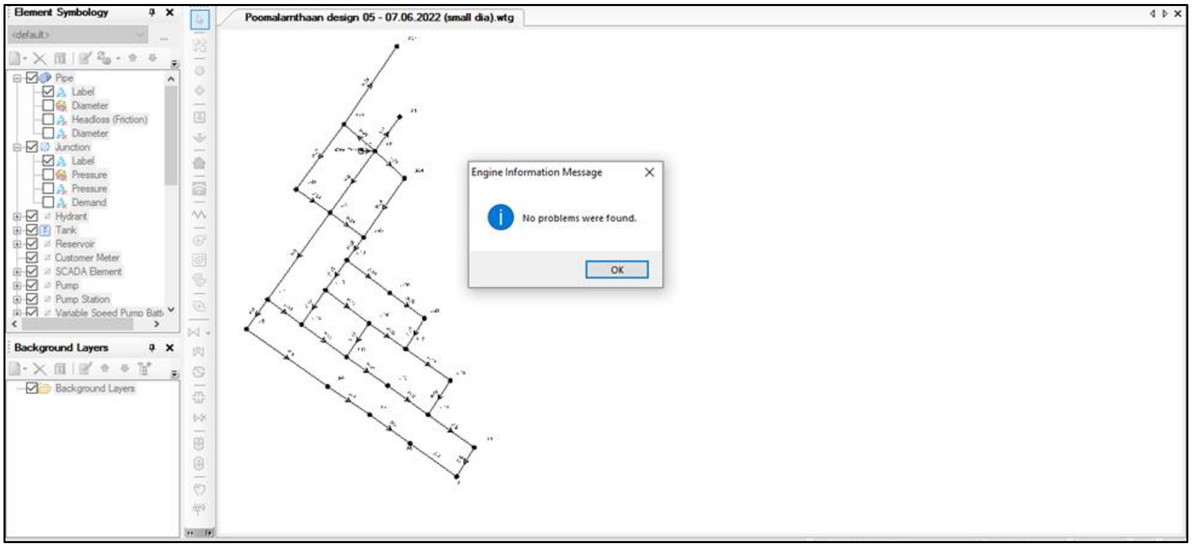


Figure 4: Model validation process

Step 03 –Hydraulic Run Results Examination

The hydraulic run was performed as shown in Figure 5 and the required hydraulic output parameters were extracted from the report section of the software. The important output parameters such as pressure at every junction and the flow velocity in every pipe were checked to have within the acceptable range.

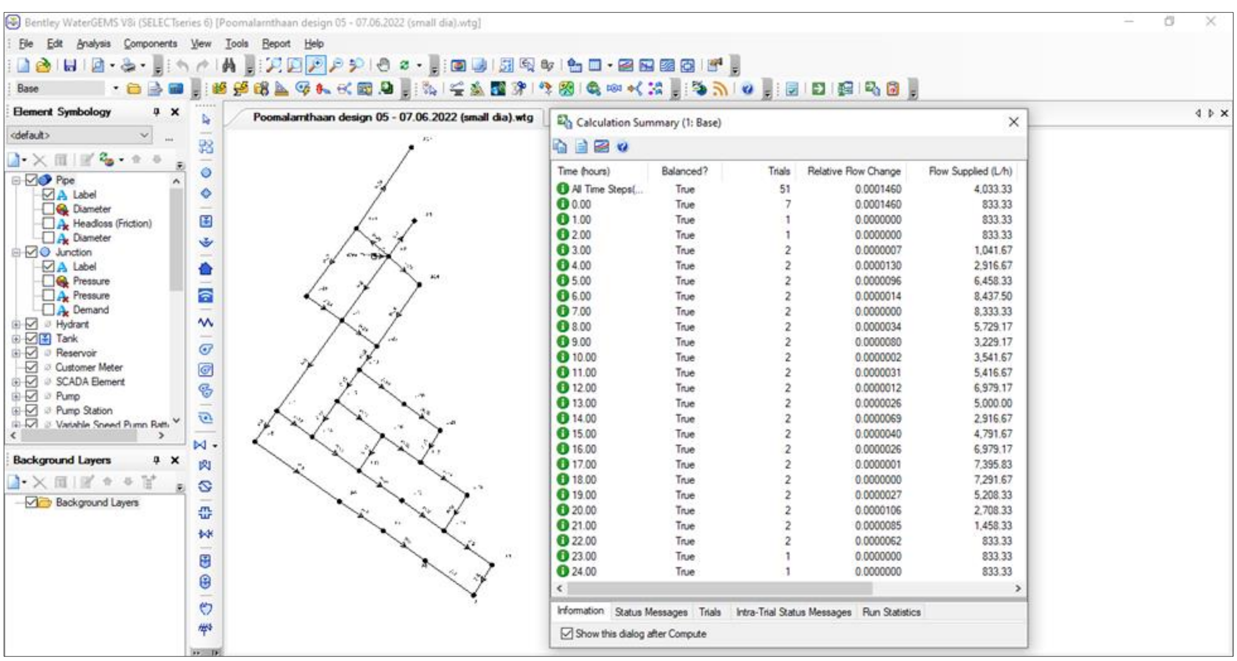


Figure 5: Hydraulic run for 24 hours

Step 04 - Network Configuration Finalization

The model was simulated repetitively for several trials by adjusting the data until a satisfactory water network configuration is reached.

Step 05 - Result and Analysis

The modal was run for the last time once the water network configuration is accepted. The required tables and graphs were extracted from the generated results as shown in Figure 6. The pipe results and junction results extracted from the computer simulation are shown in Figure 7 and Figure 8 respectively.

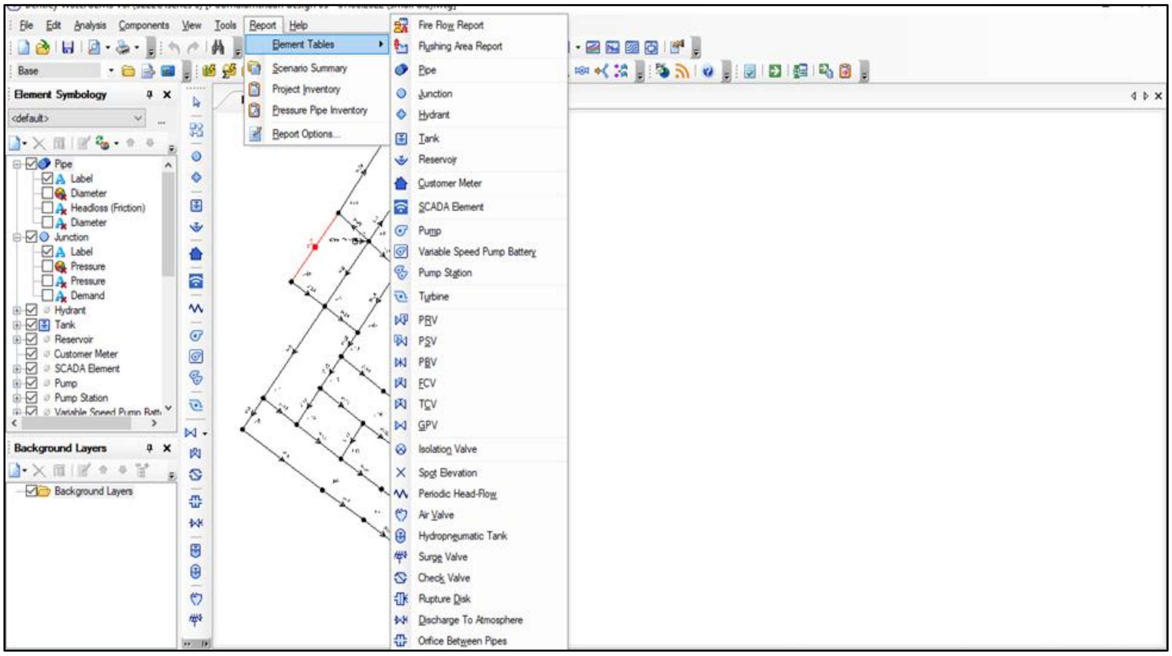


Figure 6: Generating results

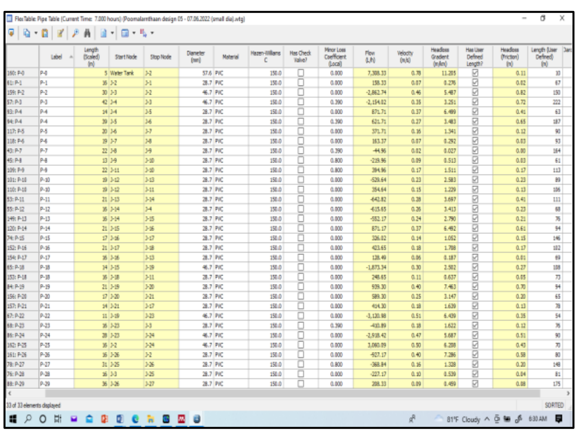


Figure 7: Pipe results

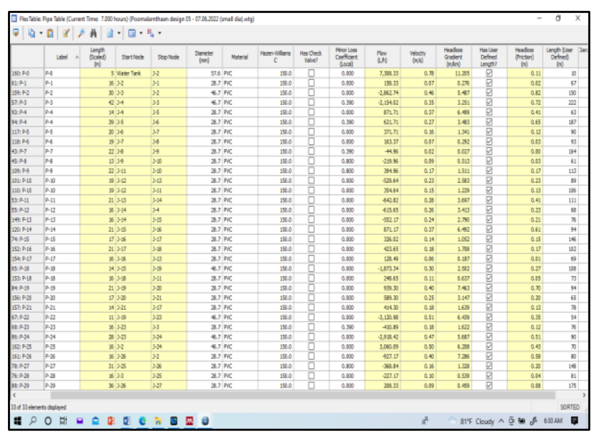


Figure 8: Junction results

There are two friction methods widely used in WaterGEMS and WaterCAD software namely; Hazen –Williams formula and the Darcy Weisbach formula. However, the hydraulic analysis is carried out by using the Hazen-Williams friction method (1) with extended period simulation in this study.

$$\frac{H_L}{L} = \frac{10.67\ Q^{1.852}}{C^{1.852}\ D^{4.8704}} \quad (1)$$

where;
Q = Fluid flow rate (m^3/s)
C = Dimensionless HW roughness constant
D = Pipe internal diameter (m)
H_L = Head loss (m)
L = Pipe length (m)

Hydraulic pipe design is one of the governing factors in the production of pipes for water supply. The hydraulic efficiency and conformity to the principles of flow of the water pipes have to be ensured before manufacturing and using in the water supply scheme. The friction head loss per meter or feet and characteristics of the flow should be inside the stipulated range to use the pipes in water transmission. Even though various formulas are existed to compute the pipe friction head loss, the Hazen-Williams equation has been extensively recognized in the arena of fluid mechanics simply due to its proven accurateness over the other formula (Jamil & Mujeebu, 2019).
Equation 1 shows the empirical Hazen-Williams formula in SI units, which relates the slope gradient of the energy line to the flow velocity of the fluid flowing in the pipe and the hydraulics radius. The pipe's inner surface roughness is characterized by the constant in the equation. It is still widely utilized in water supply engineering, even though introduced in 1902 (Liou, 1998). Regardless of a few limitations in the formula, the equation is still being used for many years since the availability of a reliable database for the roughness coefficient of new, and old pipes (Hudson, 1966).
The pattern of the hourly water demand is shown in Figure 9. The WDN consist of an elevated tower and a 3300 m length of uPVC pipe network with different nominal diameter of 63 mm, 50 mm, and 32 mm which have internal diameter of 57.6 mm, 46.7 mm, and 28.7 mm respectively.

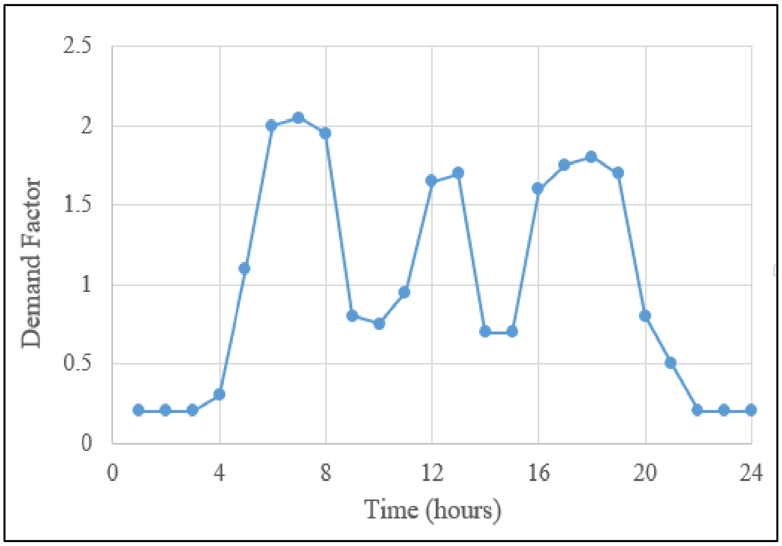


Figure 9: Hourly demand factor of the system

Results and Discussion

There are few significant output parameters required to analyze the optimizing options to design the WDN, in terms of investment cost, operational efficiency, and operation cost. Those output parameters namely; nodal pressure, flow rate, and flow velocity were extracted from both WaterGEMS and WaterCAD simulation models and discussed in this chapter. Single Factor ANOVA test at $\alpha = 0.05$ was used to compare the level of significant difference in results obtained from both simulators and found to be no significant difference between WaterCAD and WaterGEMS. Hence WaterGEMS was used to find the optimum solution in the water network distribution system.

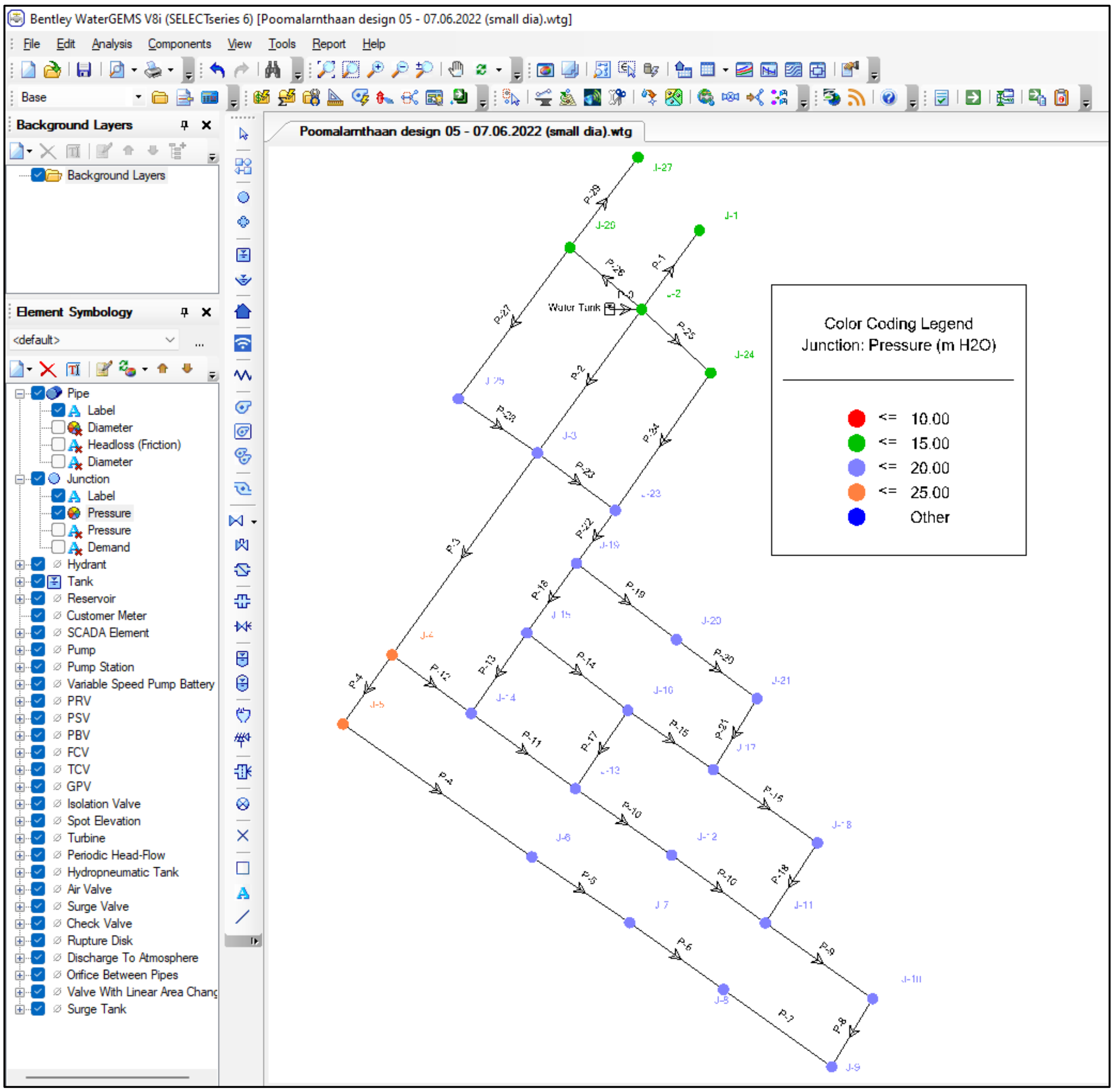


Figure 10: WDN computer model

Nodal pressure and Elevations of WDS

Figure 11 shows the nodal pressure at peak and off-peak hours when simulating using WaterGEMS and WaterCAD simulators. There are many water network simulation software namely; WaterGEMS, WaterCAD, EPANET, HydrauliCAD, Branch, etc. which are public domain software. The commercial software is WaterGEMS, and WaterCAD. However, WaterGEMS, and WaterCAD are being used as commercial software due to their important attributes namely; hydraulic analysis, water quality analysis, extended period simulation, steady-state simulation simplified model building, water quality modelling, fire flow analysis, and optimization. These operations can be performed by commercial software (Bentley Communities, 2013). In addition, it is recorded that, WaterGEMS software has more advantages to perform effective hydraulic modelling and designing water distribution systems (Dhumal et al., 2018). A user-friendly interface to analyze, design and optimize WDN is provided by both WaterGEMS and Water CAD software. Hence WaterGEMS and WaterCAD were used to simulate to optimize the water distribution network.

The pressure heads at the delivery points during peak and off-peak hours are not constant, because the demand in the system is not constant throughout the day, (as presented in Figure 9), instead, it varies with the time of the day, and normally the peak demand arises in the morning and late evening hours when people consume water for bathing, washing, and cooking. Hence, the pressure during peak hours is the critical output factor which shall give an idea of ensuring the supply of water to every consumer at an adequate pressure.

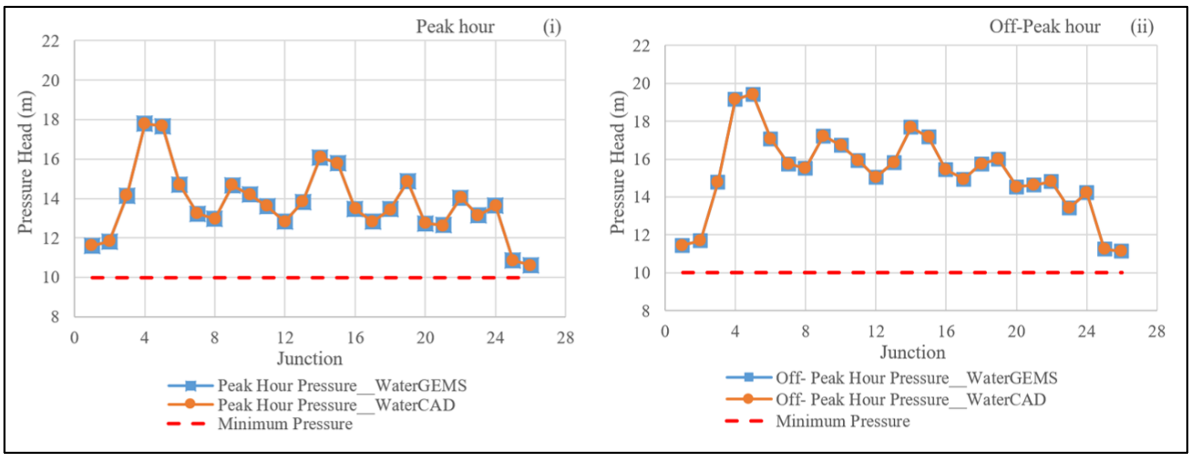


Figure 11: Pressure head vs elevation of nodal junctions (i) Peak, (ii) Off-peak hours

The pressure in the WDN mainly depends on pipe diameter, roughness coefficient of pipe material, and elevation. As mentioned in the D2 manual of NWSDB (National Water Supply & Drainage Board, 1989), the minimum pressure is to be maintained above 10m H_2O. Similarly, during the present study, the result indicates that the nodal pressure within the WDS is above the minimum level and adequate for the effective performance of the WDS, this may be due to little elevation difference in the ground level of the study area. It is can be observed that the nodal pressure is negatively correlated with the ground elevation as illustrated by Figure 12, simply the reason for the total head depends on the elevation head as explained in the theory of Bernoulli (Shields, 1973)

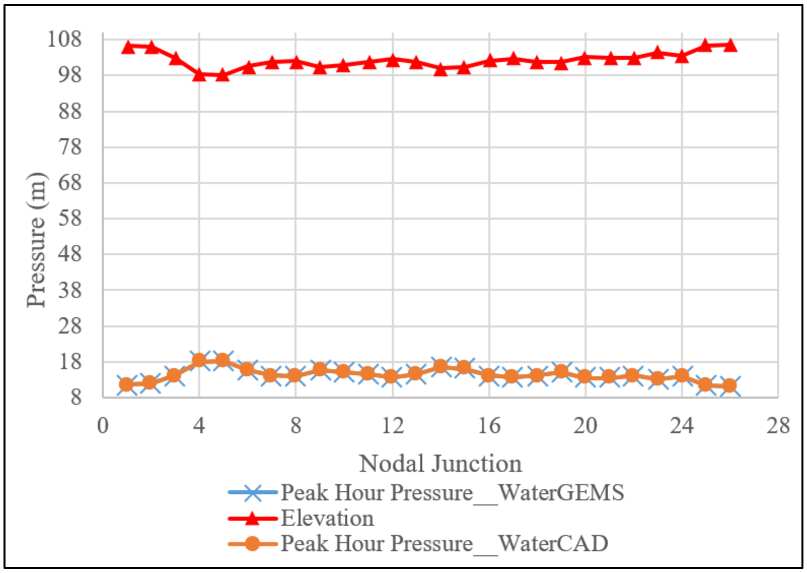


Figure 12: Pressure head vs elevation of nodal junctions

Flow rate variation of WDS

The water flow rate hourly variation in pipe P-2 is plotted in Figure 13. It can be observed that the flow rate is not constant throughout the day (Figure 13). This is because models were analyzed for the extended period simulation to suit the practical scenario of the WDS since the variation in the WDS hourly demand. The demand in the system is not constant throughout the day, instead, it varies with the time of the day, and normally the peak demand arises in the morning and late evening hours when people consume water for bathing, washing, and cooking. Further, the WDS model can be also simulated by taking sessional water demand which mainly depends on rainfall and atmospheric temperature.

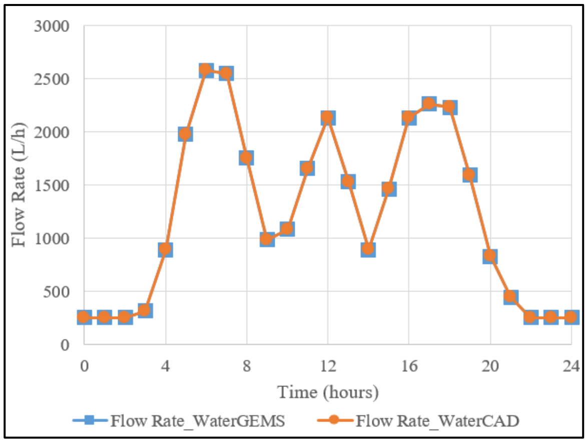


Figure 13: The hourly flow rate in pipe P-2

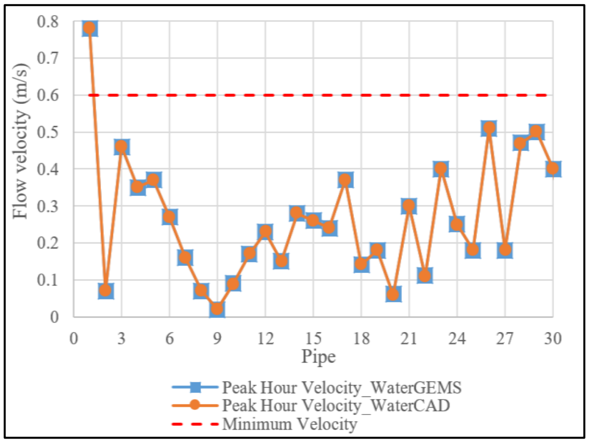


Figure 14: Flow velocity in pipes

Velocity Fluctuations of WDS

The velocity during peak hours in all the pipes is shown in Figure 14. The minimum flow velocity in WDN is specified as 0.6 meters per second to eliminate the chance of silt deposition which may occur due to the low velocity as specified in the design manual of NWSDB (NWS & DB, 1989). However, only one pipe velocity is observed to be above the minimum level, whereas all others are below the minimum velocity limit. Very low-velocity values are observed in 10 pipes. The flow velocity is attributed to the factors such as pipe internal diameter and flow rate or water demand.
Therefore, the velocity solely depends on the pipe's internal diameter when the demand is fixed. Velocity shall be increased by reducing the internal diameter. However, the diameter is inversely proportionate to the friction loss in the pipes as elaborated by the Hazen-Williams formula. Hence reduction in the pipe diameter can cause insufficient pressure in WDS. This scenario shall lead not only to customer dissatisfaction and complaints but also to additional pumping costs to boost the WDS and complexity in day-to-day operations. By considering the above, this type of WDS shall have frequent line washouts to eliminate the silt deposition in the system, thereby having a low velocity in the system is no more a big deal.

Conclusions

Based on this study, the nodal pressure head in the junctions (100%) is above the required pressure level of 10 meters H_2O, which will ensure a sufficient supply of water based on the customers' demand during off-peak and peak demand hours within the study area. The flow velocity was observed within the range of 0.1-0.4 m/s in 67% of the pipe network, while 17% of the pipe network velocity was below 0.1 m/s. The low-velocity scenario that occurred may be due to the low daily water demand of the small community. The low flow velocity shall lead to silt deposition in the pipelines, hence this type of water distribution network shall have frequent line washouts to eliminate the silt deposition in the system and to eliminate low-velocity issues. The designed and optimized pipe sizes of the WDS are adequate to meet the future demand and peak hour water demand while maintaining adequate pressure in the WDS. There is no significant difference in the nodal pressure, flow velocity, and flow rate results derived from WaterGEMS and WaterCAD simulation techniques. Those simulators used for this design can handle various WDS network problems. Computer-aided WDN simulation techniques provide great advantages over conservational computations in terms of optimization, results in accuracy, monitoring of the system during operation, time consumption, and room for future modification.

Acknowledgements

The National Water Supply & Drainage Board is gratefully acknowledged by the author for providing data.

Conflicts of interest

The authors declare no conflicts of interest.

References

Agunwamba, J. C., Ekwule, O. R., & Nnaji, C. C. (2018). Performance evaluation of a municipal water distribution system using waterCAD and Epanet. *Journal of Water Sanitation and Hygiene for Development*, *8*(3), 459–467. https://doi.org/10.2166/washdev.2018.262

American Water Works Association (1974). Water Distribution Research and Applied Development Needs. Journal *American Water Works Association*, 6, 385–390.

Bentley Communities. (2013). https://communities.bentley.com/products/hydraulics___hydrology/m/hydraulics_and_hydrology_gallery/272257

Bentley Communities. (2015). https://communities.bentley.com/products/hydraulics___hydrology/m/hydraulics_and_hydrology_gallery/272257

Bhave, P. R., & Lam, C. F. (1983). Optimal Layout for Branching Distribution Networks. *Journal of Transportation Engineering*, 109(4). https://doi.org/10.1061/(ASCE)0733-947X(1983)109:4(534)

Dhumal, J. R., Danale, M. S., & Jadhav, G. H. (2018). Design of continuous water supply system by using WaterGEMS. *8th National*

Conference on Emerging Trends in Engineering and Technology, 147–152.

Hudson, W. D. (1966). Studies of Distribution System Capacity in Seven Cities. *Journal American Water Works Association*, *58*(2), 157–164. https://doi.org/10.1002/j.1551-8833.1966.tb01568.x

Izinyon, O. C., & Anyata, B. U. (2009). Water distribution network modelling of a small community using watercad simulator. *Global Journal of Engineering Research*, 10(1–2), 35–47.

Jamil, R., & Mujeebu, M. A. (2019). Empirical Relation between Hazen-Williams and Darcy-Weisbach Equations for Cold and Hot Water Flow in Plastic Pipes. *Water*, 10, 104–114. https://doi.org/10.14294/WATER.2019.1

Liou. (1998). Limitations and Proper Use of The Hazen-Williams Equation By Chyr Pyng Lion,. *Journal of Hydraulic Engineering*, 124(9), 951–954.

Mehta, D. J., Yadav, V., Waikhom, S. I., & Prajapati, K. (2017). Design of Optimal Water Distribution Systems Using WaterGEMS: A Case Study of Surat City. *E-Proceedings of the 37th IAHR World Congress*, 1–7.

National Water Supply & Drainage Board. (1989). *Design Manual D2, Urban Water Supply and Sanitation* (1st ed.). National Water Supply & Drainage Board. Sri Lanka

Schneiter, C. R., Haimes, Y. Y., Li, D., & Lambert, J. H. (1996). Capacity Reliability of Water Distribution Networks and Optimum Rehabilitation Decision Making. *Water Resources Research*, 32(7), 2271–2278. https://doi.org/10.1029/96WR00357

Shields, P. C. (1973). *The theory of Bernoulli Shifts* (1.01). University of Chicago Press edition.

Sonaje, N. P., & Joshi, M. G. (2015). A Review of Modeling and application of water distribution networks (Wdn) Softwares. *International Journal of Technical Research and Applications*, 3(5), 174–178. https://doi.org/10.3390/w10060756