Research Paper

Performance evaluation of a municipal water distribution system using WaterCAD and Epanet

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ABSTRACT

Population explosion in urban settings usually exerts enormous pressure on existing water supply systems. The result is that overall water demand is usually not satisfied. This study evaluated the performance of Wadata sub-zone water distribution system with respect to pressure, velocity, hydraulic head loss and nodal demands using WaterCAD and Epanet. There was no statistical difference between the results of Epanet and WaterCAD, however, Epanet produced slightly higher results of pressure and velocity in about 60% of all cases examined. About 19 percent (18.52%) of the total number of nodes analyzed had negative pressures while 69 percent (69%) of the nodes had pressures less than the adopted pressure for the analysis. These negative pressures indicate that there is inadequate head within the distribution network for water conveyance to all the sections. About 88 percent (87.7%) of flow velocities in the pipes were within the adopted velocity while around 12 percent (12.3%) of the velocities exceeded the adopted velocity. These excess velocities are partly responsible for the leakages and pipe bursts observed at some points within the system. The results in this study revealed that the performance of the water distribution system of Wadata sub-zone under current demand is inefficient.

Key words | demand, Epanet, pressure, velocity, water distribution system, WaterCAD

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INTRODUCTION

Water supply systems are among the most important public utilities, because safe supply of potable water is the basic necessity of mankind in any given municipality (Swamee & Sharma 2008). In 2010, an estimated amount of about 85% of the world's population (i.e. 6.74 billion (10^9) people) had access to piped water supply through house connections (Anisha *et al.* 2016). These connections form an integral part of the master plan for communities, countries, and municipalities. Abdulkadir & Sule (2012) noted that a distribution system must supply water of good quality, in adequate quantities and at sufficient pressure to meet system requirements to the users. Generally, a water supply system comprises of intake works, treatment works, transmission mains, storage and distribution network (Swamee & Sharma 2008). The components of a distribution system are pipes, valves, hydrants and appurtenances used for distributing the water, elevated tanks and reservoirs used for fire protection and for equalizing pressure, and pump discharge and meters (Ayanshola *et al.* 2013). The cost of setting up a water distribution system is largely influenced by the accuracy of the hydraulic design and analysis, accounting for up to 80% of the total cost of the system (Garg 2005). As a result, the hydraulic modeling and analysis of a water distribution network should be given pre-eminence.

Modeling of a water distribution network is required for accurate and efficient design as well as optimal performance of a water distribution system both immediately after construction and in the future. The availability of increasingly

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sophisticated and accessible computer models allows these goals to be realized more fully than ever before. Computer-aided modeling and analyses is the new trend in the analysis of water supply systems, which took advancement from the initiative that started two millennia ago when the first piped system for fluid conveyance was constructed by the Minoans (Viyakesparan 2015). Walski *et al.* (2001) as cited by Adeniran & Oyelowo (2013) traced the development of water distribution systems and methods of analysis from wood pipes to modern piping materials; and from crude rule of thumb analysis to the lengthy long-hand iterative Hardy-Cross method to modern computer-aided design.

Many water distribution network modeling packages require input data from many sources, some of which cannot be measured directly and are not determined precisely. The main parameters considered in the hydraulic design of a water distribution system are pressure and hydraulic gradient (Abdulkadir & Sule 2012). However, as the system of pipes becomes increasingly complex, getting a precise estimate of the parameters mentioned becomes cumbersome. This has necessitated the quest for methods that can effectively and efficiently analyze the system (Henshaw & Nwaogazie 2015). The most commonly used theories for analyzing a water distribution network are Hardy-Cross, Newton-Ralphson and linear theories (Henshaw & Nwaogazie 2015). Most software for water distribution network analyses and design are based on these methods. While computer models enable fast and efficient analyses and design of water distribution networks, they can also be used to ascertain the performance of existing systems. Hence the aim of this work is to undertake a performance evaluation of Wadata water distribution system in Makurdi, Benue State, Nigeria.

METHODOLOGY

Study area

Makurdi is the capital of Benue State, Nigeria. It lies between longitude 8°31′17″ E and latitude 7°44′01″ N. Makurdi lies in the tropical savanna zone of central Nigeria, with a tropical climate of two distinct seasons. The area has an annual rainfall of 1,000 mm and temperature ranges from 27 °C to 34 °C. The main water supply source of the Makurdi metropolis is the River Benue. Water is pumped into the treatment plant by two 400 m^3/h capacity pumps installed at the river bank. After the process of treatment which involves screening, sedimentation, coagulation, flocculation, filtration, aeration and chlorination, the water is conveyed to a reservoir. Thereafter, the treated water is then transported to the central reservoir of 1,000 m^3 capacity for distribution via gravity. The pumping of water into the reservoir is done by high-lift pumps of 800 m^3/h capacity. The high-lift pumps at the pump station can supply water at a flow rate of 800 m^3/h at a pressure head of 75 m. For the purpose of analysis, the pumps were represented as single point pump-curve data in the models used.

Data collection

Data used for analyses include the population data of the sub-zone, general layout map of the area under study, and elevations of nodal junctions in the water distribution system from the topographic map and water demand at each node in the distribution network. The population of the study area as obtained from Nigeria Population Commission and projected for 2016 is 74,452 using a growth rate of 3.2%. Population demand, fire demand, minor losses, and unaccounted-for water (UFW) were used to estimate nodal demands. Population demand was obtained by multiplying the population served by each node with the annual average amount of water used per day for an individual. The per capita demand, daily peak and hourly peak factors used are 120 lpd and 1.5 for each peak factor (National Water Supply Policy (NWSP) 2000). According to Adeniran & Oyelowo (2013), a provision of 10% of the population demand is added as fire demand in the case of fire outbreak. To account for minor losses where there are bends, valves, and fittings, 5% of the total demand was used. UFW consists of two basic components: water lost from the system and water used beneficially but not sufficiently documented (Male & Walski 1990). It is practically impossible to eliminate UFW losses in a distribution system, especially in developing countries where water distribution systems perform at sub-optimal levels. Therefore, an acceptable level of 15% UFW was used. The losses mostly include flushing and blow offs for water quality reasons, gardening and draw-offs by water tankers. The total length of pipes was 4,313 m.

WaterCAD and EPANET simulating model

WaterCAD is a windows-based software developed by Haestad Methods Inc. of Cincinnati, Ohio, USA (Izinyon & Anyata 2006). WaterCAD makes use of gradient algorithms as presented by Todini & Pilati (1987) for solving systems of equations that model both head and discharge in the pipe networks (Haestad Methods 2003). The gradient method utilizes matrix formulation of the network problems in order to take advantage of the full power of the modern-day computer. In the formulation, individual energy equations for each junction node are provided for a simultaneous solution for both nodal heads and individual pipe flows (Ormbee 2006). This method is capable of solving both looped and branched networks directly. It is numerically stable when the system becomes disconnected by check valves, pressure regulating valves, or modeler's error and the structure of the generated equations allows for the use of extremely fast and reliable sparse matrix solvers (Haestad Methods 2003). EPANET is an open-structured, public domain hydraulic and water quality model developed by the United States Environmental Protection Agency (USEPA) and is used worldwide (Rossman 2000).

Skeletonization of water distribution network and model construction

Skeletonization is a procedure used to reduce the complexity of a water distribution network in order to make it amenable to analysis. Generally, a water distribution system may consist of the combination of one or two of series, parallel, and branching pipes. In addition, elbow valves, meters, and other devices which cause local disturbances and minor losses may exist in pipes. All of the above should be combined with or converted to an 'equivalent pipe' in defining the networks to be analyzed (Mohamed 2000). Paluszczyszyn *et al.* (2013) noted that a typical hydraulic simulation model may contain thousands of pipes but only few reservoirs, pumps or control elements. Therefore, the reduction of some of the hydraulic appurtenances such as pipes and nodes while maintaining important elements is a common supplication strategy. Eggener & Polkowski (1976) also found that a large number of pipes under normal demands can be removed while maintaining sufficient pressure in the system. The skeletonized water distribution network of Wadata sub-zone consists of 39 pipes with diameter ranging from 50–375 mm, 29 nodes, two reservoirs, and six valves. The simulation models used in this work describe the network elements which include pipes, junctions, valves, pumps, and reservoirs, and model calibrations were based on physical and operational data of the network collected/assembled. The arrangement of elements in the computer simulation packages follows the link–node connectivity using the tool palette available in the computer models. The outputs of these models are meant to predict pressures in the system, velocities, head losses/energy dissipated, pipe flow rates, reservoir level, inflows, outflows, and hydraulic grade.

Parameters such as pipe flow rate, roughness coefficient, pipe discharge and junction hydraulic grade line (HGL) were considered for calibration. An initial pipe carrying capacity factor of $C = 130$ for the aged network and nodal demands computed on the basis of per capital demand of 120 lpcd (NWSP 2000) were assumed. For effective analysis of the water distribution network, the results obtained were compared with the design criteria to ascertain the functionality of the system. The design criteria adopted for this study are the service pressure, flow velocities, and hydraulic loss gradients. The pressure criterion is usually given as the minimum/maximum pressure required or allowed, at the most critical point in the system (Abdulkadir & Sule 2012). Pressures of 5–10 m remaining above the highest tap usually leads to a pressure of 20–30 m above the street level (Nemanja 2006). Pressure within the system must be adequate in order to protect against contamination by the ingress of polluted water. The pressure adopted for this study is at minimum 20 m, while the maximum pressure is 66.2 m. Vreeburg *et al.* (2008) stated that the standard design velocity for self-cleansing drinking water in a distribution system is set at 0.4 m/s but that a velocity of 0.2 m/s or less may be sufficient. For the purpose of this study a maximum value of 2 m/s and minimum of 0.2 m/s was adopted (Adeniran & Oyelowo 2013). In this research, the Hazen-Williams head loss equation was adopted.

RESULTS AND DISCUSSION

Results and comparison of the two models

The results obtained from the simulation of the network using both models are discussed here. Figure 1 shows the pressure distribution at various nodes within the distribution system. Figures 2 and 3(a) and 3(b) clearly show that the predicted nodal pressures and velocities of both WaterCAD and Epanet were almost identical. Analysis of variance (ANOVA) confirmed that there was no significant difference between the values of hydraulic parameters predicted by Epanet and WaterCAD at 95% confidence level (Table 1). However, there was a significant difference among the pressure and demand at the nodes with *p*-values of 0.03 and 0.00 respectively (Table 2). There was also a significant difference among velocity and head loss in the pipes with *p*-value of 0.00. Nodes J-9, J-11, J-14, J-16, J-20, J-21, J-22, J-23, J-24, J-25, J-26, J-27, J-29 accounting for 68.9% of all nodes analyzed fell below the minimum adopted system pressure of 20 m while nodes J-15, J-17, J-18, J-19 and J-29 had negative pressures. In the contour plots produced by the models, the nodes and links were identified by the prefixes J- and *P*- respectively but in the graphs, only the node and link numbers were used. It was observed that out of the 29 nodes analyzed only nine nodes had pressure head above 20 m. Consequently, this indicates that the pressure within the distribution system was low and not sufficient for optimal system performance. Izinyon & Anyata (2006) attributed low distribution pressure to rough pipes, equipment failures, leakages and properties on high elevation. However, with respect to this study, the most prevailing factor causing this pressure fluctuation is the severe leakage resulting from dilapidated pipes observed within the distribution system during collection of field data. The sizes of pipes used at some points within the system as well as the pipe roughness also influenced the pressure in the system. The presence of negative pressures in a system could possibly lead to contamination of the water in the distribution system.

Velocity fluctuation of WaterCAD/EPANET simulators

It is crucial to maintain adequate velocity of flow in a water distribution system. Figure 2 presents the results of velocity

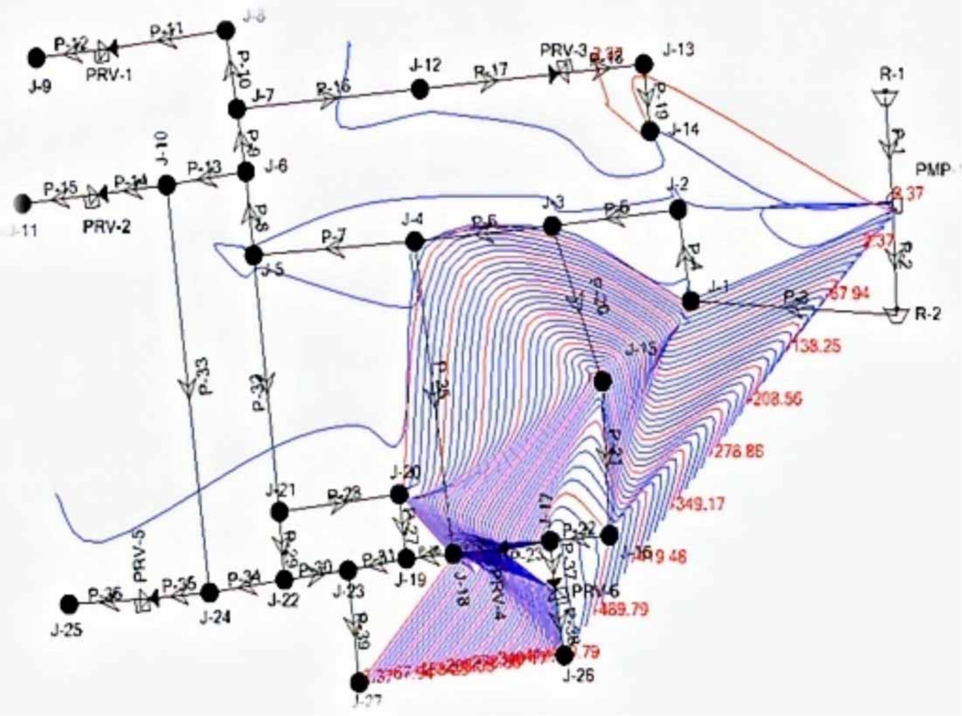

Figure 1 | Contour plot for pressure distribution produced by WaterCAD.

Table 1 | Summary of ANOVA result for WaterCAD and Epanet output

Parameter	$F_{critical}$	F	P-value	Remark
Velocity	4.16	1.13	0.3	No significant difference in velocity predicted by Epanet and WaterCAD
Pressure	4.22	1.11	0.3	No significant difference in pressure predicted by Epanet and WaterCAD
Head loss	4.16	0.04	0.85	No significant difference in head loss predicted by Epanet and WaterCAD
Nodal demand	4.22	0.17	0.68	No significant difference in nodal demand predicted by Epanet and WaterCAD

at various links/pipes including those with velocities above 2 m/s. There was no statistically significant difference between the velocity values obtained using Epanet and WaterCAD. However, the average velocity of the system simulation with Epanet (1.39 ± 1.36) was slightly greater than that of WaterCAD (1.38 ± 1.35). Forty-nine percent of Epanet velocity results were greater than those of WaterCAD while 10% of the values were the same to two decimal places. The same trend was also observed for the areas that violated the velocity range specified for this analysis where 60% of Epanet velocity results were greater than those of WaterCAD. It was observed that very high velocities occurred in pipes 1, 5, 7, 8, 16, 19 and 27 within the system. Janis *et al.* (2007) observed that high velocity supply causes shear forces between the pipe walls and water flowing, therefore reducing the microbial growth or any form of deposit. Janis *et al.* (2007) added that high velocity is an important factor for flushing pipes in the systems and distribution networks. However, a few pipes had velocity exceeding the adopted system velocity. These pipes are located where water demand is high resulting from commercial activities. Another cause of abnormally high velocities are under-sized pipes ranging from 50 mm to 75 mm diameter. These high velocities may be responsible for corrosion and subsequent bursts of pipes in the distribution system. Cohen (2002) also observed that velocity changes in a distribution system can cause turbidity. There is high tendency for hydraulic changes to occur in large transmission lines. On the other hand, when the velocity in the system is low, it could result in deposition in the system (Castorina & Jegatheesan 2002). Low velocity can result in the alteration of water quality in a distribution system (Hossein *et al.* 2013). The most eminent causes of velocity fluctuations in this study are: (i) valve opening and closing, (ii) changes in transmission conditions (pipe breaks or line freezing) and (iii) changes in customers' demand over time. About 81.2% out of the total number of pipes had flow velocity within the range adopted in this study which should be adequate for self-cleansing.

Pressure distribution with and without valves

Figure 3(a) and 3(b) show the result of pressure for the following scenarios: (i) with valves and (ii) without valves for Epanet and WaterCAD, respectively. The distribution system with valves proved to be more efficient, with 24 (89%) of the nodes having positive pressure, than the system without valves, with 20 (74%) of the nodes having positive pressure. There was a significant difference between the distribution system with and without valves in terms of pressure, with $p = 0.11$ and $p = 0.08$ for Epanet and WaterCAD respectively ($\alpha = 0.05$). Though there was no statistically significant difference between the pressure values with valves obtained from Epanet and WaterCAD, 59% of Epanet results were greater than those of WaterCAD, while 41% of WaterCAD results were greater than those of Epanet. A similar scenario was observed for pressure values without valves where 56% of

Table 2 | Summary of ANOVA for hydraulic parameters

Parameter	Source of variation	$F_{critical}$	F	P-value	Remark
Velocity	Pipes	1.82	940.72	0.00	Significant variation of velocity between pipes
Pressure	Nodes	1.93	20.37	<0.01	Significant variation of pressure between nodes
Head loss	Pipes	1.82	14,567,645	0.00	Significant variation of head loss in pipes
Nodal demand	Nodes	1.92	149,432.2	0.00	Significant variation of nodal demand

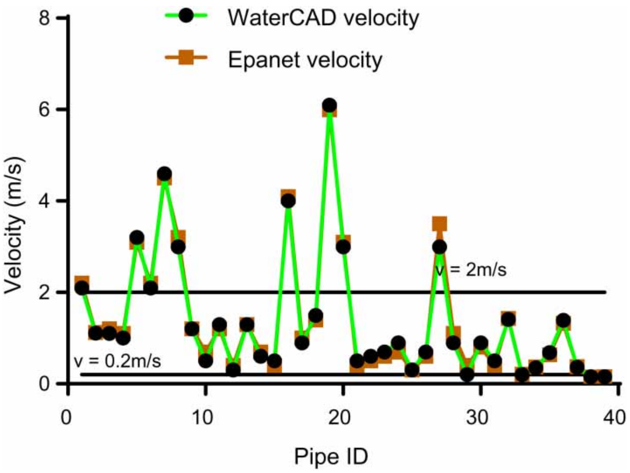

Figure 2 | Velocity of flow within the distribution system.

Epanet results were greater than WaterCAD results, and 3% of the results were the same for both models. A comparison of the results of the two models was further performed with respect to the sections of the network that failed the minimum pressure specification of 20 m. It was found that 58% and 56% of Epanet results were greater than those of WaterCAD for with and without valve scenarios. The simulated results without valves differed from the system with valves due to some deficiencies noticed in the distribution system with valves. These valves are meant to control and automate pressure and flow and protect pipelines, pumps, and other components from damage. However, in the case of the distribution system under study, the valves were subjected to high velocities and extreme temperature within the region. Moreover, some valves in the distribution system were not used in this analysis because they could not be located. The location of valves in a distribution system can severely affect the performance of the entire system. Ozger & Mays (2004) recommended that no more than four valves should require closing to isolate a pipe. They also pointed out the difficulty involved in finding optimal locations for valves in terms of the number of permutations to consider. Goulter *et al.* (2000) recommended that valves be provided at all critical points such as each hydrant lateral and at the end of each city block.

Nodal demand at various junctions

Figure 4 shows the plot of the results of nodal demand at various junctions, while Figure 5 shows the contour plot of these demands as computed by WaterCAD. The contour plot illustrates vividly the various areas where there are high draw-outs from the system. Nodes 4, 6, 8, 12, 15, and 23 are areas with particularly high draw-outs with node 23 having the highest demand. Nodal demands are mainly obtained on the basis of population served by a particular node. Node 23 happened to have the highest population which was reflected in the amount of draw-outs at that node. In order to reduce the effect of these demands on pipes, it is adequate to install pipes with a diameter that can withstand the velocity resulting from these demands.

Output of flow rates in the system

Figure 6(a) presents the results of flow rates in the system, while Figure 6(b) shows the results of flow rates on the Epanet interface. The system recorded high flow rates at

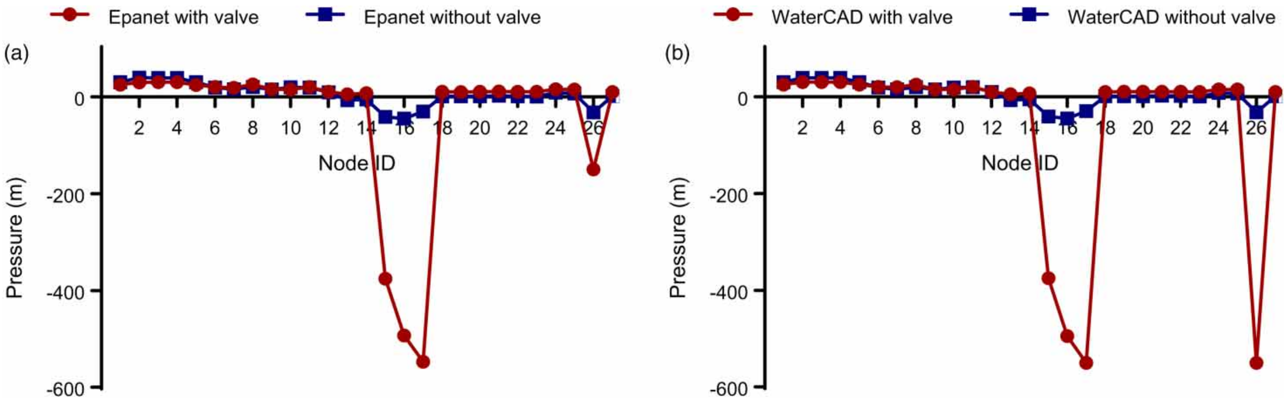

Figure 3 | (a) Pressure results with/without valves (WaterCAD). (b) Pressure results with/without valves (Epanet).

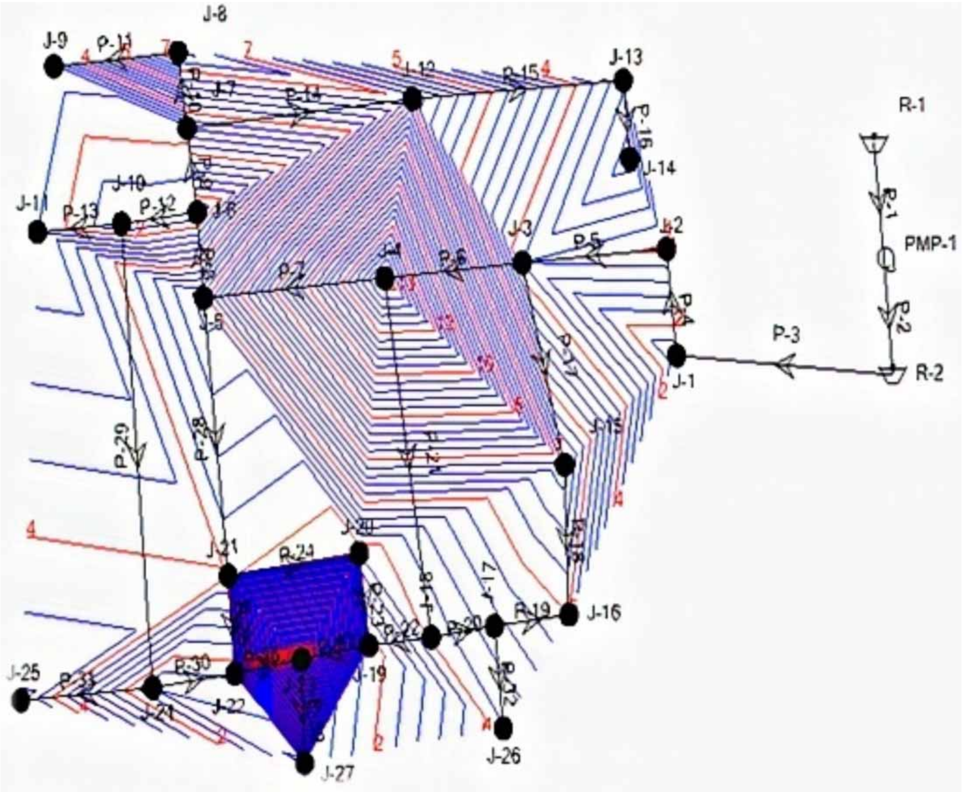

Figure 4 | Contour plot of nodal demands produced by WaterCAD.

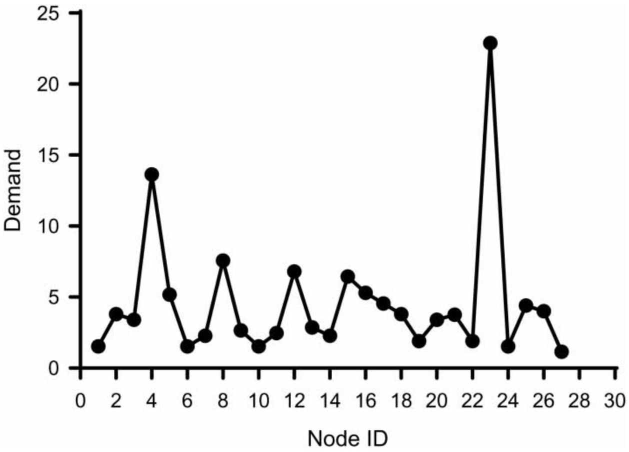

Figure 5 | Results of nodal demand at various junctions.

the beginning (i.e. source points) and gradually reducing as the water flows through the system. The reduction in flow rate can be attributed to branching of the pipes and nodal demands. Figure 6(b) clearly shows areas (pipes 1 to 6) with the highest velocity in red. In order to maintain an adequate flow velocity in the system, the step-down approach should be employed. This requires a progressive decrease in the size of the pipes so that a higher flow velocity can be achieved in the entire loop or system. This would also help to maintain a consistent pressure throughout the system.

Improvement of the water distribution network

Results presented so far show that the water distribution system in Wadata is not performing efficiently. Pipes 1, 5, 7, 8, 16, 19 and 27 had very high velocity mostly due to undersized pipes, while nodes J-15, J-17, J-18, J-19 and J-29 exhibited negative pressure as a result of insufficient reservoir head. Several scenarios were explored in the analysis in order to rectify velocities that fell outside the stipulated range of $0.2 \leq v \leq 2$ m/s. The adjusted pipe diameters that gave rise to acceptable velocities within the distribution system are shown in Table 3 while the corresponding velocities are given in Figure 7. To eliminate negative pressure within the system, various scenarios were

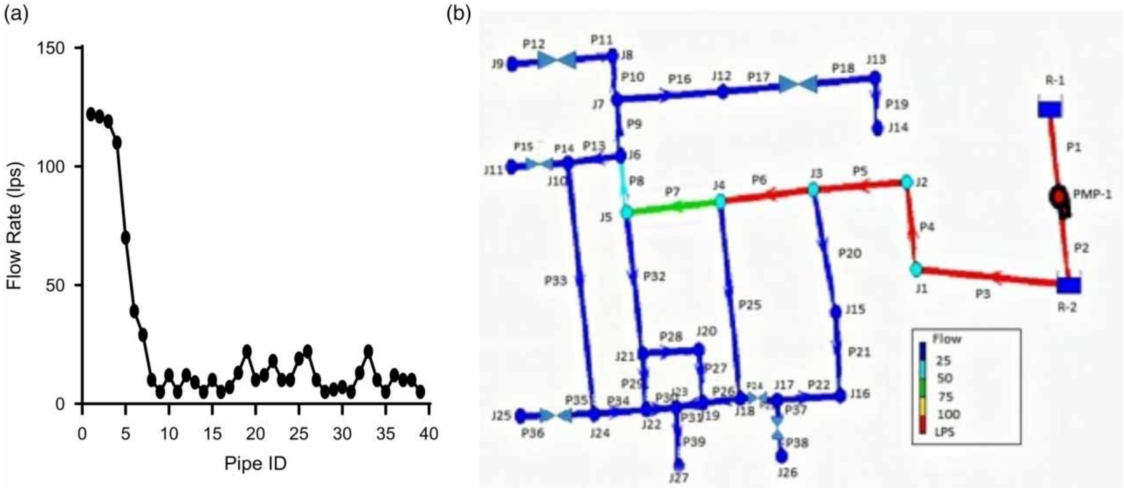

Figure 6 | (a) Flow rate (litres per second, LPS) in the system. (b) The distribution system highlighting areas of high flow rate by Epanet. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/washdev.2018.262.

Table 3 | Diameters of pipes that were improved

Pipe ID	Diameter (mm)	Adjusted diameter (mm)
Pipe 1	375	400
Pipe 5	160	200
Pipe 7	200	250
Pipe 8	100	150
Pipe 16	100	100
Pipe 19	100	100
Pipe 27	200	250

simulated with different reservoir heights. A height of 135 m was found to provide adequate head for water supply by gravity and at the same time produced zero violations of design specifications. This height is 4 m above the 131 m height of the existing reservoir.

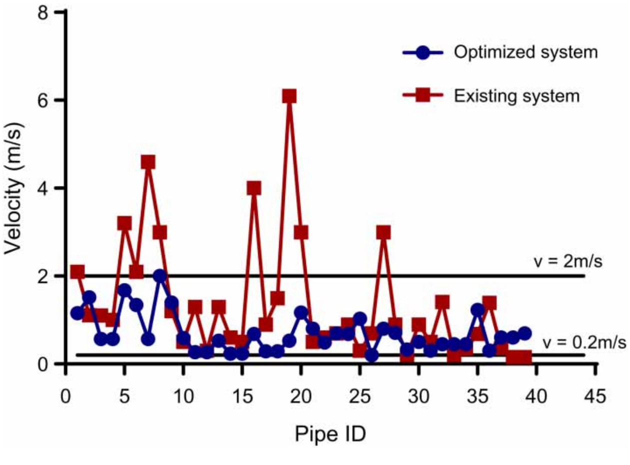

Figure 7 | Comparison of velocities of existing system with the adjusted one.

CONCLUSION

This study employed WaterCAD and Epanet to evaluate the hydraulic performance of Wadata water distribution network. Inadequate placement of valves in the system was found to be responsible for poor system performance in terms of pressure control, resulting in the valves having little or no impact on the system. Quite a number of pipes in the system are inadequate, resulting in very high velocities at some points in the system where nodal demands were high. This is responsible for the enormous pipe leakages and bursts in the distribution system, thereby reducing the system performance. Besides, inadequate reservoir height gives rise to negative pressures within the distribution system. Hence, the Wadata distribution network is not functioning adequately as negative pressures were recorded for some of the nodes in the system.

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