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Water quality deterioration modeling in aged distribution mains: A case study in Addis Ababa, Ethiopia

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Abstract

Background: Water quality deterioration is becoming a serious challenge for water utility corporations supplying treated water through the use of a centralized distribution system. After water leaves the treatment plant and enters the distribution system, it is subjected to numerous complex physical, chemical, and biological changes. This study aimed to investigate the major physical factors deteriorating water quality in an aged distribution system.

Methods: Deterioration modeling was undertaken using an EPANET computer program. For model calibration processes, data collected from field measurements were used. Descriptive statistics were employed to analyze the data. Water age and residual chlorine were selected parameters to investigate the deterioration level. The identification of major factors posing water quality changes was undertaken by examining distinct physical and operational settings.

Results: The maximum water-age variation obtained between two extreme water-use periods was 21.97%. In the same way, the maximum residual chlorine concentration variation obtained was 11.68%. On the contrary, with tested extreme pipe sizes in the study, the maximum water-age variation obtained was only 0.93%. Whereas, the obtained maximum residual chlorine concentration variation between the two extreme pipe sizes was 21.03%.

Conclusion: Water use variation poses more water quality degradation than pipe geometry. Water age in aged distribution is rarely influenced by conditions of pipe geometry.

Keywords: Calibration, Chlorine, Computer simulation, Water-age, Water quality

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Introduction

Water quality deterioration in a distribution main is becoming a serious challenge for drinking water utilities (1). when water leaves the treatment plant and enters the distribution system, it is subjected to numerous complex changes (2) affecting water quality one way or the other (3,4). Changes in quality may be caused by chemical or biological transformations, by a loss of system integrity, or by blending of waters from different sources (2). Depending on the inflow rate, treated water quality, pipe materials, and stored materials (i.e., sand, iron, manganese), these changes will continue to a more significant or lesser degree (5,6). For water quality maintenance to be compromised, particular responses must take place that introduce objectionable compounds or organisms into the bulk liquid of the water distribution system (1).

Degradations and changes in water quality may be physical, chemical, or microbiological characteristics (7). Vital chemical reactions include the leaching of poisonous compounds from pipe materials, inner corrosion (8), scale development and disintegration, and the decline of disinfectant residual (Figure 1) through the distribution mains (3,9,10). These reactions can happen either at the solid-liquid interface of the pipe wall or in solution (11,12). Three chemical reactions that were identified well are bulk liquid reactions, reactions that happen on a surface (ordinarily the pipe wall) (13), and formation reactions including a restricting reactant (14). Moreover, the interaction between the pipe wall and the water, and reactions inside the bulk water itself are the two primary causes of water quality deterioration (12,15). Noticeable microbiological changes include the development of biofilms and disintegration of microbes inside water distribution systems and the expansion of nitrifying life forms (11).

Factors impairing water quality in distribution mains are still complex and debating, a few of which are ineffectively caught on, and most of which are not well-identified (16). Recently, however, they have been better trapped with the

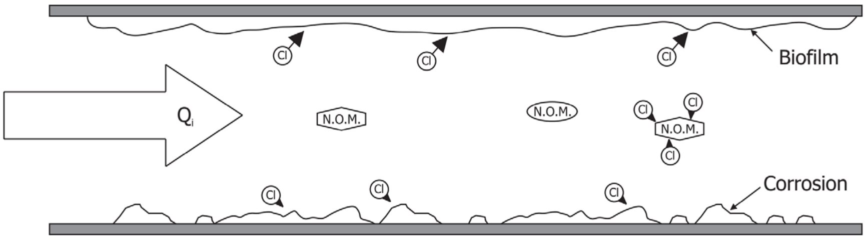


Figure 1. Disinfectant reactions in distribution main (16)

development of water quality modeling techniques (9,17). Furthermore, water quality modeling has been employed for numerous applications including solving multi-source mixing issues, determining blending percentage for high total dissolved solids, chlorine booster station location, reducing disinfection-by-product formation, cutting back excessive flushing, understanding taste and odor complaints, and determining contamination sources (18,19).

The two chemical processes frequently modeled are constituent and water age modeling (13). Various water quality constituents modeled are generally classified into conservative and non-conservative constituents. Modeled conservative constituents include salinity, fluoride, and lead. Non-conservative constituents include nitrates/nitrites, metals, chlorine, chloramines, organics, and means Disinfection bi-products (DBP's) Trihalomethanes (THM) (20). The main objective of this study was to model water quality deterioration in aged distribution mains to accurately identify physical factors impairing water quality, using EPANET.

Materials and Methods

Description of the study area

Addis Ababa is the capital city of Ethiopia (Figure 2). Geographically, the city is located at 9º01'29" to the north and 38º44'48" to the east. It is the most important city in Ethiopia with a population of more than 3 107 423 as per census report of the central statistical authority (21). The city is situated in the center of Ethiopia; covering an area of 540 km^2 of which 18.174 km^2 is countryside, with an altitude ranging from 2000 to 2800 meters above sea level (asl).

The water distribution system in Addis Ababa city is drawing closer by a century. It is the oldest water system in Ethiopia. Over its long service years, it has undergone several physical, operational, and environmental changes. A baseline survey conducted over several periods indicated a repeated loss of safeguarding residual chlorine in most parts of this distribution system.

Modeling tool

EPANET is an open-structured, open-space hydraulic and water quality model created by the Environmental Protection Agency (EPA), and is extensively utilized around the world for the analysis, design, and modeling of distribution systems (22,23). It has flexible features that suitably interface with other CAD software. For the present study, this modeling program was chosen as an analyzing tool due to its colossal hydraulic and water quality modeling capabilities (24,25). Moreover, it is a client-friendly and accessible modeling computer program (26).

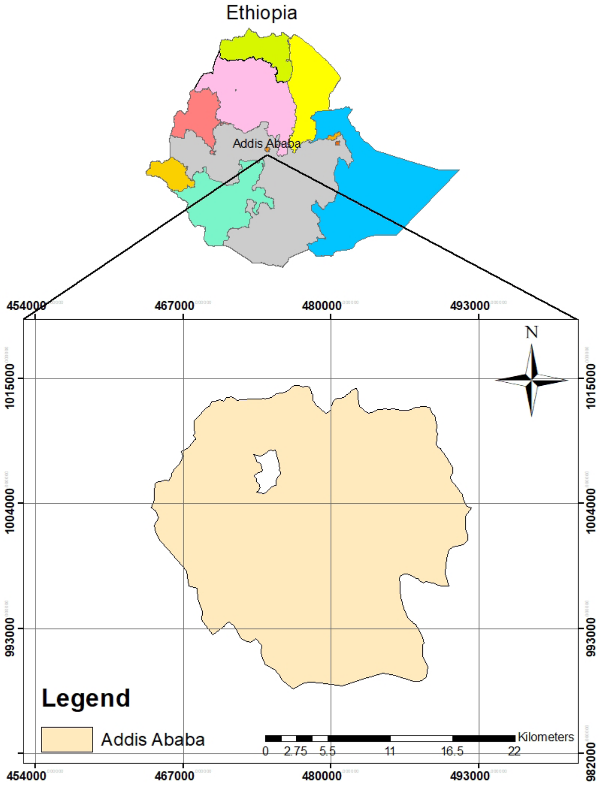


Figure 2. Location map of the study area

Data sources and collection methods

Both primary and secondary data were distinctively collected in the present study. The primary data were directly collected from field surveys and measurements. The secondary data were collected from utility databases and official records. The primary data collected includes tank water levels, residual chlorine within the distribution main, and rate constant for the bulk flow (bulk coefficient) by performing a bottle test within the laboratory facility. The secondary data collected include system maps, topographic maps, water utilization records, water charging records, borehole data, pump data, and valve setting data.

Schematic map development

The physical characteristics of the distribution system were presented within the model by nodes and pipes (or ‘elements’). The nodes, joined together by pipes, denote pipe intersections, changes in pipe sizes, and the areas of network traits such as valves and high demands. The node and pipe information sets contain geographic coordinates, ground levels, basic water demand data, pipe nominal diameter and friction coefficients, pump bends, benefit store geometry, valve execution characteristics, initial water quality, and bulk and wall reaction coefficients (16) (Figure 3).

The simulation time step employed for hydraulic analysis was 60-minute intervals over 24 hours. Besides hydraulic simulation, water age, and retention time were analyzed by setting initial measures of water age in reservoirs and tanks. The calculated water age was utilized to settle extreme hours to run bottle tests for the assurance of bulk reaction coefficient in water quality research facilities.

Water quality simulations were conducted after hydraulic simulation. In the process, initial water quality status was assigned to reservoir and tank nodes. Later, bulk, and wall reaction coefficients were assigned to each pipe in the system.

Sample location determination

The sampling location was determined based on the permissible access points and main entrance locations within case study distribution mains.

Laboratory equipment, apparatus, and chemicals

The equipment and apparatus used in this study were a sampling kit for sample handling, sampling bottles (200 ml), test tubes, a standard incubator, and a comparator test kit. Diethyl-p-phenylenediamine was the only chemical employed to bring color changes throughout tested samples. A notebook for recording experimental conditions and results was also used.

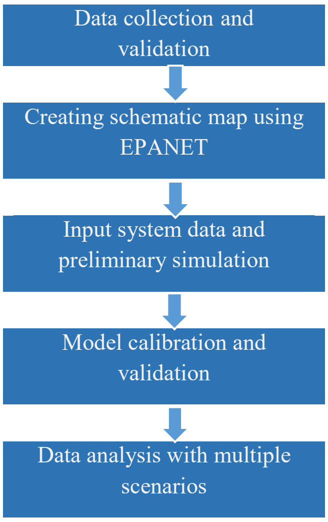


Figure 3. Study design

Bulk coefficient determination

Disinfectant modeling requires the determination of two water quality coefficients including bulk and wall coefficients. Bulk coefficients are determined by performing bottle tests in the laboratory. While the wall coefficient is straightly determined as a part of water quality calibration.

For tests conducted in the laboratory, a maximum of 72-hour experimental period was employed. Sampling bottles were washed and prepared using chlorine-demand-free procedure. Distilled water was used to rinse the bottles and test tubes. To decide bulk reaction coefficients, water samples were placed in golden bottles and kept at a steady temperature. Within a few time intervals, each bottle was chosen and analyzed in terms of available free chlorine residual. At the end of the test, the normal logarithms of the proportion of measured chlorine to initial chlorine (Ct/Co) values were plotted against time (19). The rate constant was determined as the slope of the straight line through these points (16). The wall reaction coefficient was determined differently by trial and error through model calibration and validation efforts.

Model calibration and validation

Actual field measurements were taken from selected parts of the case study distribution system. These data include tank water level, pump flow, and residual chlorine. For each parameter, records were taken over several days. Pipe roughness was selected and employed as an adjusted model parameter in the process of model calibration and validation endeavors (5).

Model calibration and validation were performed using various requirements that previous literature suggested. At calibration and validation data points, the model must predict the hydraulic grade line to be inside (1.5-3 m) for extended period simulation runs. For disinfectant modeling, the model must replicate the pattern of measured disinfectant concentrations over the time tests are undertaken to an average error of generally 0.1 to 0.2 mg/L, depending on the complexity of the system (3,16).

Model simulations

Single and extended-period simulations were conducted sequentially in the study. The former simulation was intended to examine model conditions under snapshot situations. Whereas, overall analysis including model calibration and validation has been solely done with the later simulation-extended period simulation.

Possible scenarios for water quality deterioration

To get the overwhelming factor contributing to water quality degradations in the distribution system of Addis

Ababa city, the following two distinctive scenarios were surveyed.

Scenario 1. Demand pattern

a. Water age at peak and low hour flow

b. Residual chlorine at peak and low hour flow

Scenario 2**.** Pipe geometry

a. Water age for existing and modified pipe sizes

b. Residual chlorine for existing and modified pipe sizes

Results

Schematic model presentation

The physically appearing distribution systems in the study area were schematically modeled as interconnections of numerous nodes and links. On the EPANET platform, nodes denote junctions, reservoirs, and tanks in the scheme. Whereas, links refer to pipes, pumps, and valves in the scheme. Figure 4 illustrates the schematic layout of the sub-distribution system under consideration in the present study.

Bulk coefficient tests

Tests for bulk coefficient determination were conducted in three test periods. These test periods were preferred to avoid any possible error and ensure that each test's result was essentially the same.

Accordingly, three test samples were collected for each test period; and measurements were taken starting from collection time. Then, samples were brought to the laboratory and stored in complete darkness with the temperature held constant. The samples were pulled at designated times and measured.

Based on test outcomes, several graphs were plotted through the proportion of concentration at any time (C_t) to initial concentration (C_o) as ordinate and time as abscissa (Figure 5). The slope of the best-fitted line drawn through the charted result was determined — the bulk reaction coefficient. Accordingly, for test 1, test 2, and test 3, the slope of the line was -0.0201, -0.017, and -0.02054, respectively.

Tested scenarios

Two realistic scenarios were set and tested in the present study. These were fluctuations in water use or water demand (Scenario 1) and pipe geometry (Scenario 2). Accordingly, Scenario 1 was surveying water quality conditions within a case study distribution system under the impact of water use variations. Water quality circumstances at a peak and a low-flow hour were evaluated distinctly, considering water age and residual chlorine water quality parameters as indicators (17). Scenario 2 was surveying the effect of pipe geometry on water quality in the distribution mains. Two distinct cases were created and evaluated about water quality circumstances of actual pipe size. The first case was with the use of downsized pipe conditions and the second one was with the use of upper-sized pipe conditions.

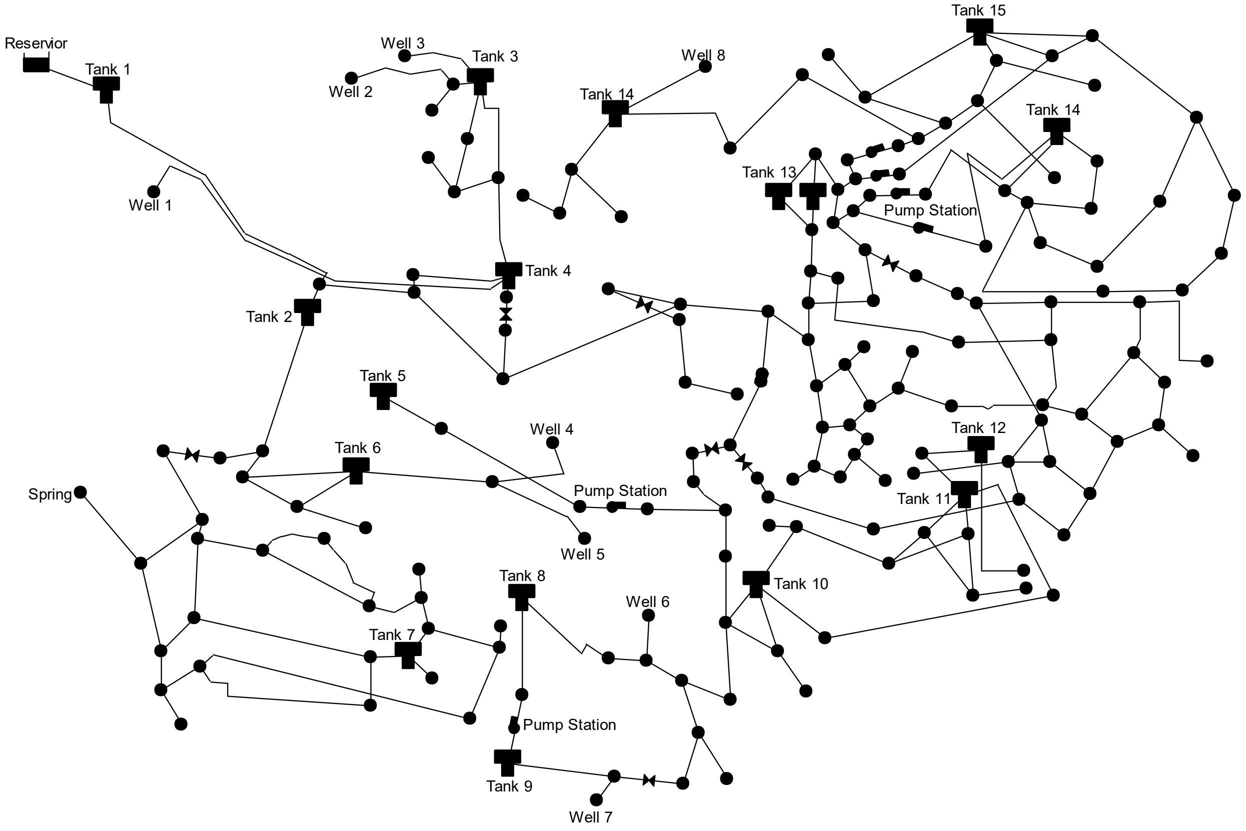


Figure 4. Schematic model for case-study distribution mains

Model outputs

Modeling efforts within 72 hours were carried out to investigate possible factors posing water quality degradations in case-study distribution systems.

Extended period simulation (Table 1 and Table 2) with multiple scenarios was carried out to understand how far water residence time and residual chlorine concentration were responding to various physical factors.

Water age reaching water mains during peak-flow hour is seemingly lower than the corresponding low-flow hour period (Figure 6).

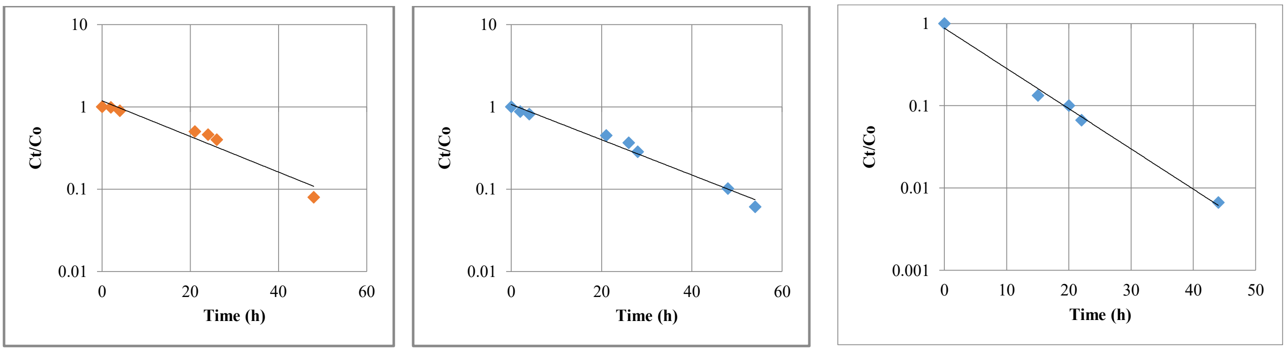
Residual chlorine concentration reaching water mains during peak-flow hour is somewhat lower than the corresponding low-flow hour period (Figure 7).

Water age reaching water mains for actual, downsized, and upper-sized pipe conditions are overlapping with each other (Figure 8). Changes in pipe sizes do not affect the water residence time.

For various pipe-size conditions, residual chlorine concentrations reaching water mains are very distinct (Figure 9). For the downsized condition, it is higher when compared to the upper-sized condition.

Discussion

Water utilization over different hours of a given day is subjected to change. Sometimes it peaks and other times it becomes low. Frequently peak water consumption is exhibited in the early morning (near 8:00 am); and in contrast, the minimum utilization is recorded at midnight. These fluctuations in demand lead to the utilization of large pipes and storage tanks. Despite their benefits, huge pipes and storage tanks have negative impacts on water quality (27,28).



Plot for **test 1** Plot for **test 2** Plot for **test 3**

Figure 5. Plots of residual chlorine tests

Table 1. Simulation outputs - Scenario 1

Peak demand hour period				Low demand hour period			
Water age		Residual chlorine		Water age		Residual chlorine	
Age (h)	Nodes (%)	Concentration (mg/L)	Nodes (%)	Age (h)	Nodes (%)	Concentration (mg/L)	Nodes (%)
<12	12.15	0	10.75	<12	14.95	0	10.28
12-24	0.93	0.01-0.1	1.4	12-24	0.93	0.01-0.1	2.34
24-48	3.27	0.1-0.2	3.27	24-48	1.4	0.1-0.2	20.09
48-60	26.63	0.2-0.5	73.83	48-60	3.74	0.2-0.5	62.15
>60	57	>0.5	10.75	>60	78.97	>0.5	5.14

Table 2. Simulation outputs - Scenario 2

Actual Pipe				Down Sized Pipe				Upper Sized Pipe			
Water Age		Residual Chlorine		Water Age		Residual Chlorine		Water Age		Residual Chlorine	
Age (h)	Nodes (%)	Concentration (mg/L)	Nodes (%)	Age (h)	Nodes (%)	Concentration (mg/L)	Nodes (%)	Age (h)	Nodes (%)	Concentration (mg/L)	Nodes (%)
<12	12.62	0	17.76	<12	11.68	0	15.89	<12	12.15	0	16.82
12 - 24	0.47	0.01-0.1	31.78	12-24	1.4	0.01-0.1	21.96	12-24	0.9	0.01-0.1	6.54
24 - 48	5.14	0.1-0.2	32.71	24-48	5.14	0.1-0.2	56.07	24-48	5.14	0.1-0.2	49.53
48 - 60	20.09	0.2-0.5	16.82	48-60	21.03	0.2-0.5	5.14	48-60	20.09	0.2-0.5	26.17
>60	61.68	>0.5	0.93	>60	60.75	>0.5	0.93	>60	61.68	>0.5	0.93

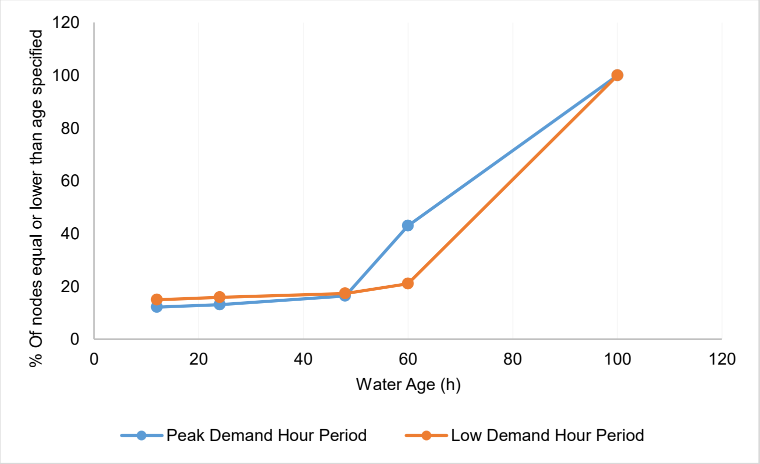


Figure 6. Water-age distribution at peak and low-hour flow

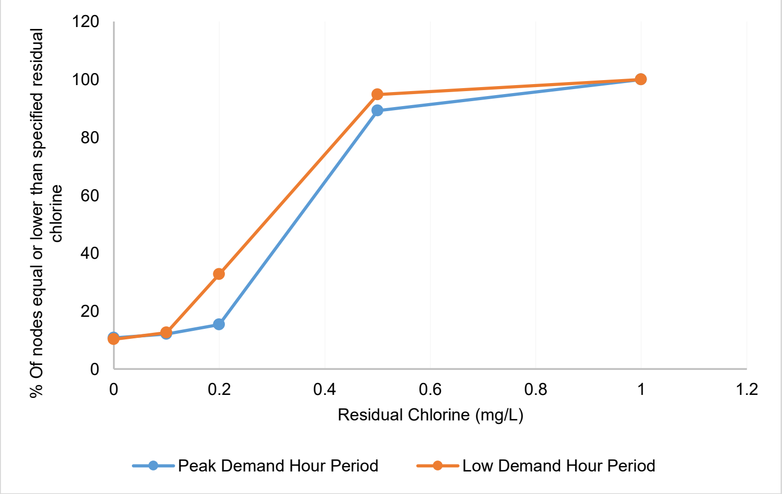


Figure 7. Residual chlorine distribution at peak and low hour flow

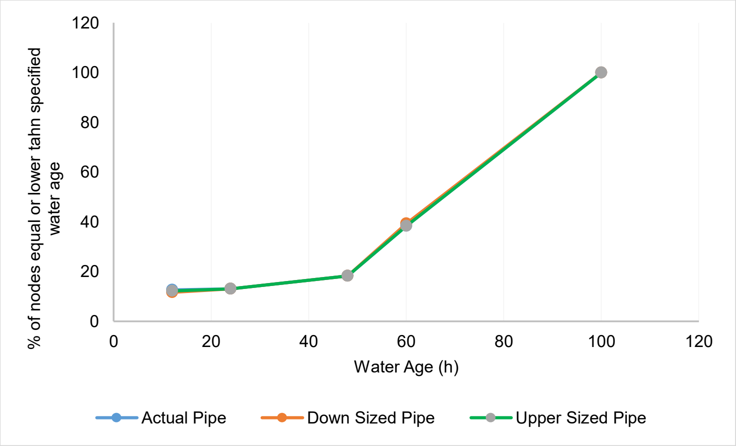


Figure 8. Average water-age distribution for actual, downsized, and upper-sized pipes

Water age at peak and low flow hours

The investigation for water age was based on the fact that the case study distribution system is constantly loaded with continuous flow. Thus, any discoveries for this parameter are constrained to this presumption.

At a low-flow hour period, most nodes (78.97%) received water with age surpassing 60 hours (Figure 6). However, 14.9% of all nodes received water at less than 12 hours of age. Whereas, at peak-flow hour, nodes receiving water with age surpassing 60 hours were reduced to 57%. There

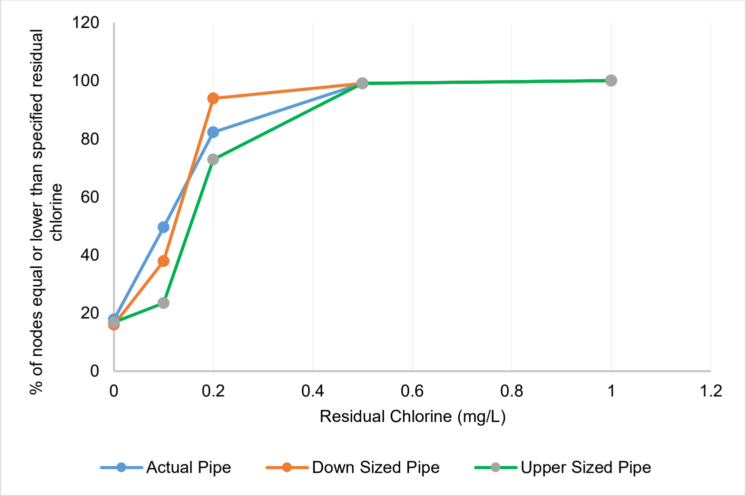


Figure 9. The minimum residual chlorine distribution for actual, down-sized, and upper-sized pipes

is a big difference between water status in terms of age-reaching nodes during peak and low water utilization time.

Nodes in the vicinity of water wells likely received water with age less than 12 hours. Increases in water age were exhibited for the areas a bit far away from water wells including those located in close vicinity of storage tanks. The majority of nodes located nearer to storage tanks were likely to receive water with an age exceeding 60 hours. The remaining nodes were receiving an age of less than 60 hours during the low-flow hour period. At a peak-flow hour period, nodes in the vicinity of the storage tank were served with an age exceeding 60 hours. Moreover, in areas where storage tanks slightly concentrate, the average water age reaching each node showed a significant increment. Entirely all nearby nodes were receiving water of high residence time. Thus, the liability of these parts of the distribution mains for declined microbiological water quality is expected to be higher 18 (29).

Residual chlorine at peak and low flow hours

Recontamination of water in a municipal distribution mainly happens due to different reasons, and their corresponding result might be different. No matter what the reason it might be, microbiologically risky water should not be tolerated. Its implication on public health is extremely dangerous (30). The broad technique to handle the likely recontamination is assuring residual chlorine in distribution mains (31,32). Suggested residual chlorine at the taps of the clients as a rule lies between 0.2 to 0.5 mg/L (33,34).

At a low-flow hour period, only 62.15% of all nodes were receiving water with residual chlorine of (0.2-0.5 mg/L) margin (Figure 7). Only 10.28% of all nodes received water with nil residual chlorine. However, at a peak-flow period, 73.83% of all nodes were served with residual chlorine concentration (0.2–0.5 mg/L). These depicted that the quality of water in the case study distribution system is much better during a peak-flow hour than the corresponding low-flow hour.

Water age for actual and modified pipe sizes

Figure 7 depicts normal water age distribution at nodes for various pipe size conditions. For the case of actual pipe sizes, the lion's share of nodes, 61.68% of all nodes, were receiving water with an age surpassing 60 hours. As it were, 12.62% of all nodes received age less than 12 hours. Similarly, for the case of downsized pipes, 60.75% of all nodes received an average water age exceeding 60 hours (Figure 8). Almost 11.68% of nodes were loaded with a mean water age lower than 12 hours. In the same manner for the case of upper-sized pipes, 61.68% of all nodes received an average water age exceeding 60 hours. Only 12.15% of nodes were served with a mean age lower than 12 hours. There were no substantial water-age variances for the cases of actual and modified pipe sizes.

Residual chlorine for actual and modified pipe sizes

As depicted in Figure 9, only 16.82%, 5.14%, and 26.17% of all nodes were served with residual chlorine in the recommended margin of 0.2–0.5 mg/L for actual, downsized, and upper-sized pipes, respectively (Figure 9). Furthermore, 17.76%, 15.89%, and 16.82% of all nodes of actual, downsized, and upper-sized pipes were served with nil residual chlorine. For the case of downsized pipes, those getting optimal residual chlorine declined in percentage in comparison with actual pipe sizes. For the case of upper-sized pipes, those getting residual chlorine within the margin of 0.2 – 0.5 mg/L reduced in percent with comparison to actual pipe sizes.

For the most parts, both scenarios were distinguished as variables contributing to water quality degradations in a case study distribution system. In any case, Scenario 1 was recognized as the principal factor— due to critical variations of evaluated parameters (water age and residual chlorine). Since critical variation was only identified for the case of residual chlorine examination, Scenario 2 has been recognized as a minor factor contributing to water quality degradation in a case study distribution system. Scenario 2 showed no critical variation for the case of water age.

Conclusion

To identify major factors affecting water quality status in aged distribution mains, modeling endeavors were carried out for the case study of the water distribution system. An adequately calibrated and validated model was employed.

Model outcomes for the case study considered showed that fluctuation in water use (water demand pattern) is the principal factor contributing to water quality degradation in aged distribution mains. Changes in pipe geometry have a minor effect on the status of water quality in aged distribution mains. Establishing booster disinfection stations is found a fitting intervention to manage microbiological water quality status in aged distribution mains.

Future studies are required to examine the possible effects of additional physical, operating, and environmental factors such as pipe materials, operating pressure, and external environmental conditions. In addition, future studies are needed to investigate water quality changes under flow conditions apart from continuous flow.

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Competing interests

The author declares that there is no conflict of interests.

Ethical issues

The author hereby verifies that all data composed in the field of study were designated in the manuscript and no data from the study have been or will be published separately elsewhere.

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