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Modelling Water Age as Surrogate for Water Quality in a Distribution System

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Abstract. Extended period simulation study of the water quality was made through construction of a waterCAD model of the existing Ikpoba Hill water distribution system to simulate the age of water as surrogate for water quality throughout the network. The average age of water in the network fluctuated between 0.5 and 4 h during 24 h; applying literature values of 0.00007/min and 0.00003/min for chlorine decay coefficients to the most critical time (4 h), it was indicated that the chlorine residual could degrade in the network by 1-2% only. This suggests that areas presently served by the network are not likely to suffer water quality problems on account of travel time. However, considering the age of the network, adequate attention should be paid to the possible unaccounted reasons for water problems in a network for maintaining the water quality integrity of the network *viz.*, management of metering, billing and collection, and illegal connections and theft which create higher chances of drinking water contamination and outbreak of water-borne diseases.

Keywords: extended period simulation, water age, calibration, waterCAD

Introduction

The safety of drinking water depends on a number of factors including quality of source water, effectiveness of treatment and integrity of the distribution system that transports water to consumers (Stevens *et al.*, 2004). In most cities of the world, there have been years of neglected maintenance of water storage, treatment and distribution system leading to deterioration in these water infrastructures thereby threatening the quality and reliability of water services. These deterioration processes are more severe in developing countries due to ageing of the systems, poor construction practices, little or no maintenance and rehabilitation activities due to limited financial resources, and operation at higher capacities than permissible by the design.

Hence, the quality of treated drinking water may vary considerably both from system to system and within a system as a result of deterioration after water leaves the treatment plant and comes in contact with the distribution piping thereby affecting the quality of water available to the end user (Hughes, 2002). This has necessitated the global emphasis on conforming to the water quality standards at the point of use (consumer taps) rather than at the source treatment plant (USEPA, 2005); the scenario has thus shifted the focus to water quality within the distribution system. This is why a disinfectant is added typically at the end of water treatment at plant to provide some protection against microbial growth and limit the effects of contamination while the water is being conveyed through the distribution system.

A disinfectant residual is normally consumed by exposed surfaces of materials in the network, deposits in the pipes, microorganisms and chemical species in the water. It may also be consumed by contaminants entering the network. Consequently, at the end of long networks or networks with long transit times, the disinfectant residual concentration can be zero and in this circumstance many water utilities consider it prudent to maintain adequate residual to the extremities of the system by ensuring a high residual concentration as water leaves the treatment works or by establishing booster or relay disinfection station(s). However, the earlier method may mean that consumers immediately downstream of treatment works receive concentration of disinfectant that is undesirable because of taste and odour.

The water quality within the distribution system (at the consumer taps) can be measured by sampling for bacteria or positive coliforms, chlorine residual, discolouration, taste, odour and other indicators (Hughes, 2002). Each of these attributes or surrogate values can be correlated to determine the effectiveness of the distribution system in meeting water quality performance expectations. Since, water quality sampling can be difficult on a routine basis and very expensive or cost prohibitive exercise to sample in sufficient density to assess the whole of a network, the need for computer based

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water quality modeling has become more compelling (USEPA, 2005). Disinfectant residual across the whole of the network can be modelled and areas can be identified where disinfectant residual is likely to be inadequate. Examples of such models include EPANET and WaterCAD. While EPANET is a public sector model that performs extended period simulation (EPS) of hydraulic and water quality behaviour within pressurized pipe network developed by USEPA, WaterCAD is a commercial model with similar capabilities developed by Haestad Methods (2002) of Waterbury, Connecticut, USA.

This paper focuses on the construction of an extended period Simulation (EPS) model (WaterCAD) and demonstrates its application in modelling the changes in water age throughout a real (Ikpoba Hill) distribution network in Benin City, Nigeria. Water age or time spent by a parcel of water in the network has been used as a surrogate for water quality in the network. The main objective of the investigation is to undertake assessment of the water quality and water contamination potential of the network with a view to making recommendations for necessary improvement.

Study network of water age modelling of water distribution system. The network utilized for this study is the Ikpoba Hill water distribution network, Benin City, Nigeria. Benin City is located approximately within latitudes 5°-30′ N and 5° 45′N and longitudes 6° – 15′E and 6° – 30′E. Benin City is the capital of Edo State, Nigeria. The study network is one of the five major networks serving the City. It is an independent water supply system incorporating areas some 3.5 km east of Benin City across Ikpoba River. Areas covered by the system are Federal Housing Estate, Aduwawa Quarters, Agbor Road, Old Army Barracks, Auchi Road and environs with an estimated population of 29,000 persons, land area of 180 hectares with 1734 consumer connections.

Basic theory of water age modelling and chlorine residual decay in water distribution network. The chemical processes that can affect water quality of the distribution system are a function of water chemistry and physical characteristics of the distribution system itself (Walski *et al.*, 2001). These processes occur over time, thereby making residence time in the distribution system a critical factor that has the greatest overall effect on water quality (Chambers *et al.*, 2004). Hence, the cumulative residence time of water has come to be regarded as a reliable surrogate for water quality (Haestad Methods, 2002; Walski *et al.*, 2001).

Water age gives general indication of the overall water quality at any given point in a distribution system. It gives a simple non-specific measure of the general water quality of delivered water (Rossman, 2000). Water age is typically measured from the time that the water enters the system from a tank or reservoir until it reaches a junction. The age of water may differ from point to point of destination. Where the age of water has increased substantially, water quality may deteriorate and therefore residence time in the distribution system should be minimized to reduce loss of disinfectant residual and age of water at the outlet.

Water age is computed using the following equation (Bentley, 2001):

$$A_j = A_{j-1} + \frac{X}{V} \tag{1}$$

where:

A_j = Age of water at the j^{th} node
A_{j-1} = Age of water at node j-1
X = Distance between node j-1 and node j
V = Velocity from node j-1 to node j

If there are several paths of water to the j^{th} node, then the water age is computed as a weighted average using the following equation (Bentley, 2001):

$$A_j = \frac{\Sigma Q_i \left[A_i + \left(\frac{X}{V}\right)i\right]}{\Sigma Q_i} \tag{2}$$

where:

Q_i = flow rate to the j^{th} node from the i^{th} node
A_i = average age immediately upstream of node j

Chlorine residual decay in a distribution network is modelled as a first order reaction as follows (Rossman, 2000; Hart *et al*, 1992):

$$C_t = C_o e^{-kt} \tag{3}$$

where:

C_t = concentration at time t
C_o = initial concentration
k = decay constant

Materials and Methods

An extended period simulation (EPS) model of Ikpoba Hill Benin City water distribution network was constructed for this study using WaterCAD Version 6 software. The computer model was composed of two parts, (i) the network data which describes the infrastructure, demands and operational characteristics of the system and (ii) a computer programme (WaterCAD) that solves a set of energy continuity, transport or optimization equations to solve for pressure, flow, tank level, water age or water chemical concentration, the results of which are presented in graphical and tabular forms. The model was constructed in 3 steps of minimal model skeletonization

(Walski *et al.,* 2001) model building and model calibration based on the network's physical and operational data applying rules available in the literature (Pilipovic, 2004; Haestad Methods, 2002; Walski *et al.,* 2001). Physical network data consisting of pipe length, alignment, connectivity, material of manufacture, diameter, age, location, geometry and size of tank and information on valves, meters were obtained from water system map, acquired from Edo State Water Board, the operator of the distribution system. System operational data were also obtained from the Water Board.

Water demand analysis and computation was carried out to determine nodal demands for the present and future requirements of the system using standard methods available in the literature e.g., Griffith and Williams (1980).

In addition to the information required for steady state model, additional information required for the EPS model include detailed tank information, water usage pattern and operational rules for pumps and valves. The water demand pattern utilized for the study is shown in Table 1 and was obtained from the previous study undertaken by Tahal Consultants, Nigeria (1980).

Table 1. Typical residential water demand pattern for Benin City

Time from start (h)	3	6	9	12	15	18	21	24
Multiplier	0.4	1	1.3	1.2	1.2	1.6	0.8	0.5

The skeletonized model of the network consisted of 15 nodes, 25 pipelines ranging from 100 mm to 300 mm diameter, 3 functional boreholes and an elevated storage tank. To use the base model as a predictive tool, it was calibrated using calibration data consisting of pressure and flow measurements at 3 locations in the network, tank water levels and operating condition for selected test days (Pilipovic, 2004; Hammer, 2001). The model was validated using independently collected data.

Application of the model for water age simulation. The model of the network constructed as a link-node connectivity of the network using WaterCAD tool pallete was based on the field data collected and the skeletonization exercise carried out. Data were entered into the model for each of the network element - pipe size, type, length, roughness coefficient for each pipe element. Elevation, demand data and pattern were entered for each junction. Tank and pump information were entered based on actual condition and capacity. The entered data were checked (Pilipovic, 2004) to ensure that potential errors were corrected and checked to ensure its correct functioning. The constructed EPS model was utilized to evaluate water age, i.e. to predict the changes in the age of water throughout the network in order to assess if the residence time within the tank was excessive which can contribute to water quality degradation. To run the water age analysis, an initial age of zero (0) was assumed for all nodes in the network (Haestad Methods, 2002).

The water from the reservoir will be an infinite supply of fresh water so the age of water elsewhere in the entire system will be a reflection of the time, from the start of the run till water leaves the reservoir. The analysis was run for 2-week period (336 h) in order to determine the equilibrium point of the system. The simulation was undertaken for 4 different tank sizes in order to predict the effect of tank capacity on water age-an important water quality parameter in a distribution system.

Results and Discussion

Figure 1 presents the result of water age analysis for the existing tank in the system while Fig. 2, 3 and 4 present the the water age analyses for different-tank sizes. The summary of the result of the analysis is presented in Table 2.

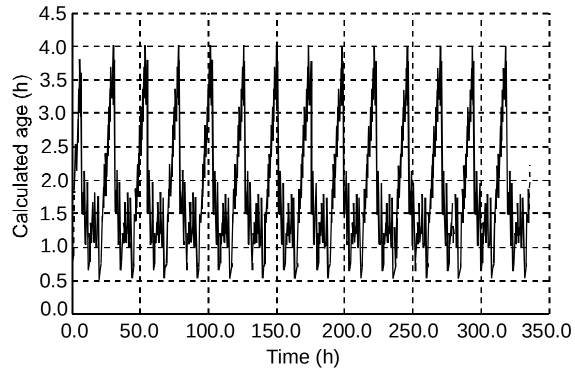

Fig. 1. Calculated age *vs* time for 8 m diameter tank.

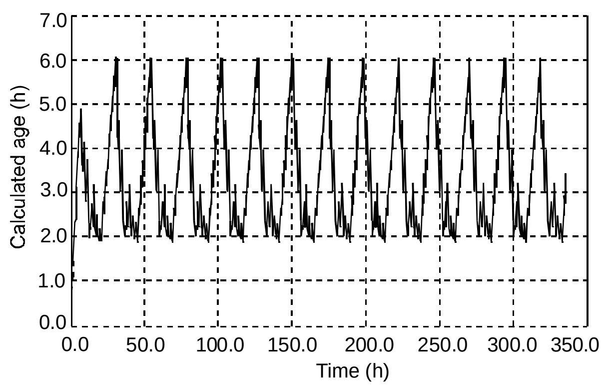

Fig. 2. Calculated age *vs* time for 10 m diameter tank.

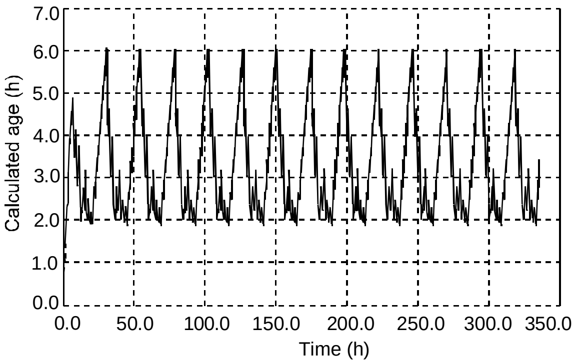

Fig. 3. Age analysis for 12 m diameter tank.

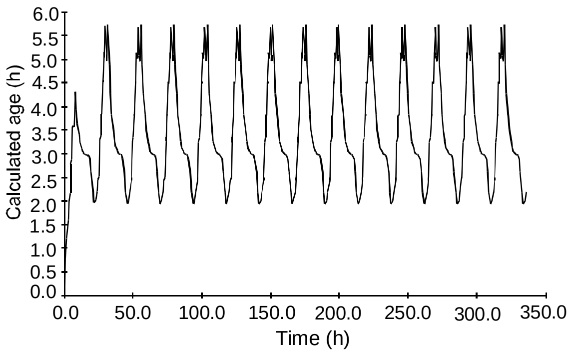

Fig. 4. Calculated age *vs* time for 17.4 m diameter (1300 m^3) tank.

Table 2. Summary of water age analysis

Storage tank diameter (m)	Active volume of tank (m^3)	Simulated water age (h)
8 (existing)	270	0.5 – 4 h
10	430	1.2 to 5 h
12	622	2 to 6 h
17.4	1300	2 to 6 h

Table 2 shows that the existing network with the existing tank size has a water age that varies between 0.5 and 4 h during 24 h. Based on the assumption that chlorine decay follows a first order equation, $C = C_o e^{-kt}$, and using decay constant (k) values of 0.00007/min and 0.00003/min as suggested by Hart *et al.* (1992), these water age values are not excessive and may lead to only 1% to 2% loss of chlorine residual in the network on account of travel time.

Table 2 also shows that for all tank sizes of the network studied, the water age values obtained were not excessive and cannot be a cause of low chlorine residual in the network if adequate treatment is given to water prior to distribution. Water age analyses is thus important in water distribution system planning, operation and maintenance since the primary goal of water distribution system is to deliver potable water when and where it is needed. Ideally, there should be no change in the quality of water from the time it leaves the treatment plant until the time it is consumed.

Conclusion and Recommendations

WaterCAD EPS model was utilized to analyze the water age of the existing Ikpoba Hill, Benin City water distribution network which was used as surrogate for water quality in the network. From the study, the following conclusions are made:

(i) The travel time from the reservoir to the nodes in the network are not excessive.
(ii) Excessive water age cannot be a cause of low chlorine residual in the network.
(iii) Areas served by this network are not likely to suffer water quality problem on account of travel time.
(iv) Water age can be used as surrogate for water quality in a distribution system since chlorine level decays over time and disinfection by product levels tend to increase with time as chlorine reacts with organic compounds. Hence, water age modelling can be used to improve the performance of distribution system modification meant to reduce hydraulic residence time and as a tool for improving the management of disinfectant residual and other water quality operation.

To maintain water quality within a water distribution system, water utilities should strive to minimize water age by ensuring that water in reservoirs turns over regularly so that it does not become stagnant.

However, in view of the age of the studied network (greater than 30 years) and the inherent vulnerability to water quality problems associated with unaccounted-for-water issues, the following possible measures for unaccounted-for-water problem should be considered:

- Poor engineering construction,
- Poorly managed metering, billing and collection and
- Illegal connection and theft.

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