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Hydraulic and Water Quality Modelling of Water Distribution Networks Using EPANET Software

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ABSTRACT

In this study, hydraulic analysis of two water distribution networks was carried out using EPANET 2.0 software developed by the US Environmental Protection Agency. The study networks are: a hypothetical 65-pipe water distribution network that had been solved by the Linear Theory method; and an existing water distribution network serving the University of Benin Ekehuan campus, for which hydraulic analysis and study for the system improvement had been previously carried out using WaterCAD software. This present study was therefore undertaken to investigate EPANET's capability in executing hydraulic analysis and deploying it for water quality simulation studies of the campus' water distribution system, which was not part of the scope of the previous study.
The hydraulic analysis results showed that the average of deviations from solved values for total head, pressure head, and flow are 4.23%, 7.69%, and 7.15% respectively, which falls within an acceptable range. Results from the water quality analysis study in which water age and optimum residual chlorine dosage required were used as surrogates for water quality indicate that the existing water distribution network of the campus has a water age and optimum residual chlorine of 1.68 hours and 0.220mg/L respectively, while same for the proposed improved water distribution network of the campus are 5.56 hours and 0.255mg/L respectively. Expectedly, the water age and optimum residual chlorine of the improved network are higher than those of the existing network, as the pipe sizes and storage capacity in the improved network are larger to serve the increased future population of the ultimate design period. Even at that, the obtained values are within acceptable limits prescribed by the Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines. Hence, it is concluded that EPANET and WaterCAD are efficient piped-water network simulation software and can be relied on for use in developing countries.

Keywords: Hydraulic analysis, Water quality modelling, Water age, Residual chlorine, Pipe network design, Pressure head, Flow

1.0. Introduction

Water is required for life to exist. Human life, like all other animal and plant life on the planet, is water-dependent. Not only do we require water to grow our food, create electricity, and run our businesses, but we also require it as a basic component of our everyday life - our bodies require water regularly to function properly. 'On a daily basis, around 70 litres per person are required.' It encompasses the requirement for water to maintain a minimal level of personal and home cleanliness necessary to preserve health (Arjun *et al*., 2015).

An efficient supply of water is vital for businesses and industries to operate successfully in a municipal setting. All water utilities' principal purpose is to provide consumers with safe drinking water that is free of pathogenic and other undesired organisms. After leaving the treatment plant, the quality of treated water degrades as it travels through a distribution network (Gavin *et al*., 2006).

Disinfection is critical for controlling the spread of waterborne infections, and chlorine is a widely used disinfectant residue in drinking water supply systems to combat microbial contamination and proliferation. Maintaining an adequate residual disinfectant concentration while minimizing the production of disinfection by-products is essential for the water's safety (Monteiro *et al*., 2014).

Water age is also a significant influence on the decline of water quality inside the distribution system. While bulk water is being distributed, it undergoes a variety of chemical, physical, and aesthetic modifications, affecting the water's quality. 'These changes will occur to a greater or lesser amount depending on the water flow rate, final water quality, pipe materials, and deposited materials (i.e. sand, iron, manganese)' (U.S Environmental Protection Agency, 2002).

Modelling is a continual process of generating models in response to the growth of available information and knowledge about the simulation system, which becomes more able to depict the actual process. Developing models is just the first step, another key aspect is calibration. This is defined by Walski *et al*. (2003) as 'the process of comparing the results of a model to field observations in order to adjust the data describing the system, if necessary, until the predicted behaviour agrees reasonably well with the observed behaviour under a wide range of operating conditions'. Hydraulic modelling of water distribution systems enables the determination of system pressures and flow rates under a variety of different conditions without having to go out and physically monitor the system.

The performance of a water distribution system is judged on the basis of the pressure available in the system for a given rate of flow. The components of a water distribution system are a network of pipes and the appurtenances for transporting water from the treatment plant to the consumers' taps. Other components include the design and operation of storage, service, or balancing reservoirs. An adequate water distribution system should meet the following requirements (Punmia *et al*., 1995):

i) It should be capable of supplying water to consumers' taps at a reasonable pressure head and the pressure should not be excessive.
ii) It should be capable of meeting the fire demand simultaneously.
iii) It should be easy to operate and maintain.
iv) It should be reliable i.e.; water should be available even when there is a breakdown or during emergencies.
v) The initial cost should be as low as possible.

For a distribution system to satisfactorily meet the above requirements, its hydraulics design must be adequate and should be properly constructed and operated to reduce the chances of water contamination in the system to a minimum.

Around the world, significant sums of money are invested in developing or upgrading piped water delivery infrastructure. Even then, a sizable portion of the world's population lacks access to clean piped water. Almost 80% to 85% of the total cost of a water supply system is spent on water transmission and distribution network; therefore it must be properly designed and constructed by applying logical approaches in order to achieve significant cost savings in building a water distribution system (Shwarme and Sharma, 2008).

Water quality modelling provides a means of assessing the water quality at the point of treatment and the point of consumption. The University of Benin Ekehuan Campus has a growing population of students annually and as such requires water quality modelling to ensure that the water at the point of consumption is free from physical, chemical, and biological contamination, thereby making it fit and safe for drinking and to determine if there is any need for system upgrade.

Hydraulic analysis of a water distribution network was carried out in order to determine the available pressures and flow pattern of the system, and it involved determining the flow rate and head loss of each pipe in the network, as well as the pressures at critical points in the system under different demand or loading conditions.

This study therefore utilized EPANET software in conducting hydraulic analysis of water distribution networks and water quality analysis of the existing water distribution system using water age and optimum residual chlorine as surrogates for water quality in the network to determine the adequacy of the distribution networks and the water quality status of the studied existing water distribution system. This information is critically important to the water engineer in ascertaining whether the system under study has the capability to meet the demands for which it is being designed or has been designed.

2.0. Methodology

2.1. Hydraulic modelling and analysis

An EPANET model of a hypothetical network obtained from Jeppson (1974) was constructed using the tool palette. The Jeppson (1974) network consists of 64 pipes, 29 nodes, 5 pumps, and 6 reservoirs as given in Figure 1.

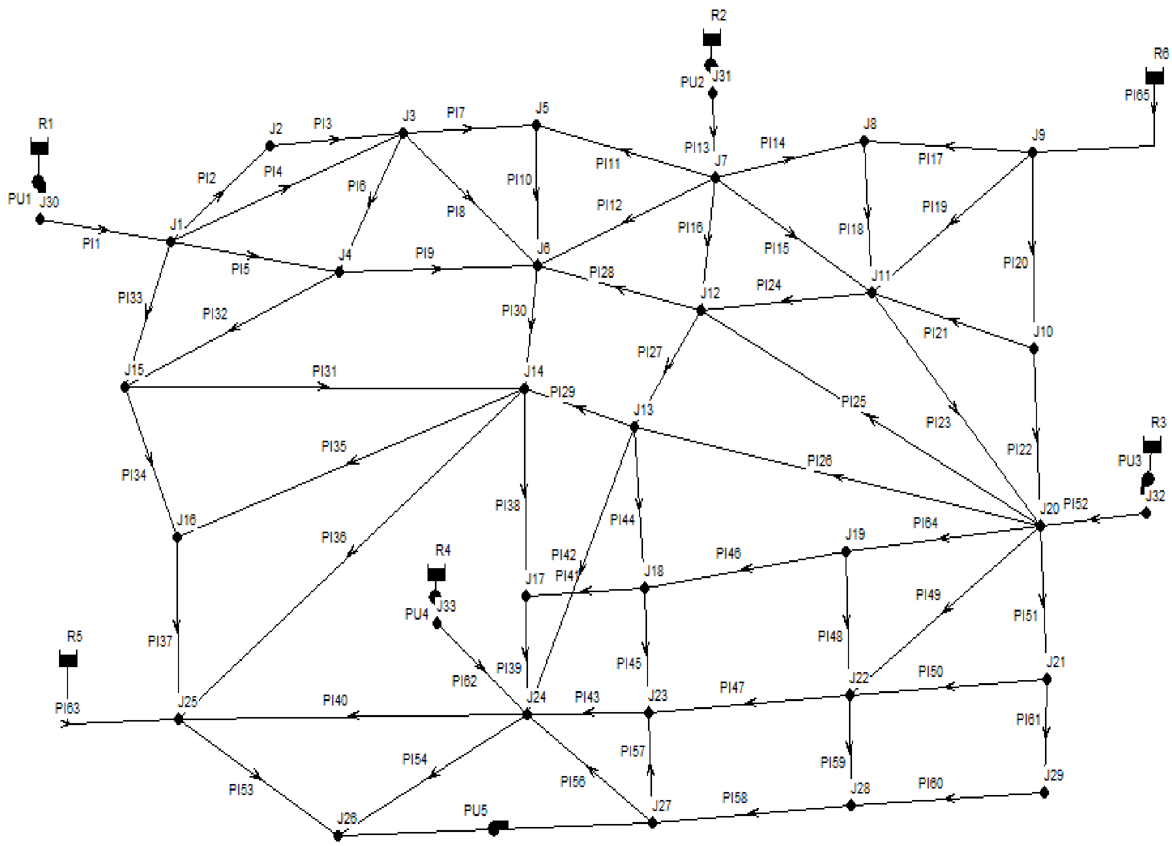

Figure 1: Hypothetical network for hydraulic modelling and analysis (Jeppson, 1974)

The input data used for the analysis obtained from Jeppson (1974) include nodal elevation, nodal demand, pipe length, pipe diameter, pipe wall roughness, minor loss coefficient, pump curves, and reservoir head. The flow unit used was cubic metre per hour (CMH) and the Darcy-Welsbach formula (see Equation 1) was used to compute frictional head loss.

$$h_f = \frac{fLV^2}{2gD} \tag{1}$$

where,
h_F = frictional headloss
f = friction factor
L = length of pipe (m)
V = velocity of flow (m/s)
D = diameter of pipe (m)

The model was constructed and a steady-state simulation was run on the network to obtain values for flow rates in pipes, pressure head, and total head at nodes. The purpose of this part of the study was to investigate the capability and adequacy of EPANET 2.0 in conducting hydraulic analysis of a water distribution network and to compare the simulation results or output obtained from the analysis with those results for the hypothetical network solved by using the Linear Theory method as given in Jeppson (1974). Deviations and average deviation (from solved values) were computed using Equations (2) and (3) respectively.

$$Deviation = \left(\frac{Solved\ Value - EPANET\ Value}{Solved\ Value} * \frac{100}{1}\right)\% \tag{2}$$

$$Average\ Deviation = \frac{\sum Deviations}{Number\ of\ Junctions/Pipes} \tag{3}$$

2.2. Water quality modelling and analysis

Water quality modelling and analysis was conducted for the University of Benin Ekehuan Campus, Benin City water distribution network using data obtained from a previous study conducted on the network by Omosigho (2017) using Water CAD hydraulic analysis and design software (see Figure 2). The data utilized for the water quality analysis includes nodal elevation, nodal demand, pipe length, pipe diameter, pipe wall roughness, tank elevation, volume curve, and boreholes data.

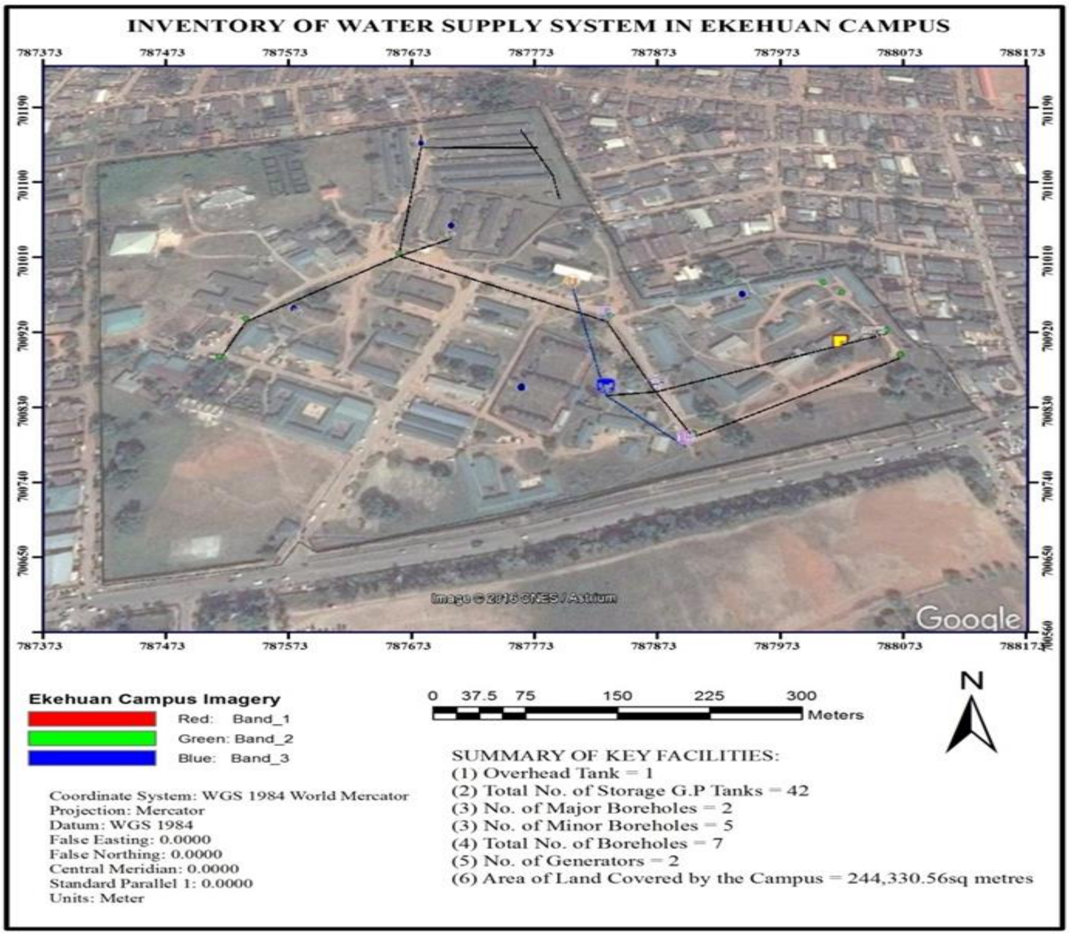

Figure 2: Map of the University of Benin Ekehuan campus (Omosigho, 2017)

The network is a dead-end layout system consisting of two boreholes, one elevated storage tank, 12 nodes, and 14 pipes as shown in Figure 3. The groundwater-pump system for the two boreholes (BH1 and BH2) was modelled as nodes with negative demands representing the borehole yield (as guided by EPANET 2.0 User Manual). All pipes are made of Polyvinyl Chloride (PVC). The flow unit used was cubic metre per hour (CMH) and the Hazen-Williams method was used to compute frictional head loss.

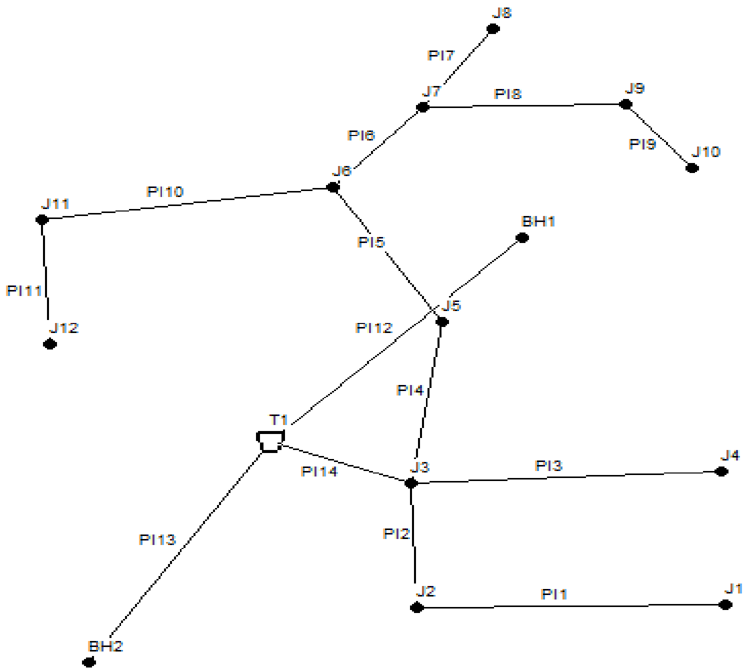

Figure 3: UNIBEN Ekehuan campus network for water quality modelling and analysis

A steady-state simulation was first run on the constructed model to ascertain that the values obtained are comparable to those obtained in Omosigho (2017). Thereafter, an extended period simulation was run on the constructed model using EPANET 2.0 using Water Age and Residual Chlorine parameters. For the residual chlorine modelling, the bulk chlorine decay coefficient was selected based on the guidance of Ogbeifun (2015) who had conducted a similar study using groundwater supply source in the same aquifer system, that is, the Benin Formation. The decay constant values were obtained from Akodwaa-Boadi (2012) because the pipes were of the same material (PVC) and the ages of the PVC pipes in the networks were similar.

Simulations were performed on two different scenarios to assess the water quality situations in both the existing and improved water distribution network of the University of Benin Ekehuan campus.

Scenario 1 involves the assessment of the existing network of the Study Area.

Scenario 2 involves the assessment of the improved network proposed in Omosigho (2017) of the Study Area, which was designed to take care of the negative pressures experienced in the existing network by increasing the sizes of some existing pipes (from 75 m to 100/200 m) and increasing the existing storage capacity (from 58 m^3 to 1100 m^3).

3.0. Results and Discussion

3.1. Hydraulic modelling and analysis

For the hypothetical network, the simulated values (EPANET) obtained were compared with the solved values provided in Jeppson (1974). The maximum, minimum, and average deviations for total head were 7.26%, 2.91%, and 4.23% respectively. The maximum, minimum, and average deviations for pressure head were 12.29%, 4.96%, and 7.69% respectively. The maximum, minimum, and average deviations for flow were 18.14%, 0.20%, and 7.15% respectively. These indicate that the simulated results obtained compare favourably with solved values and suggest that EPANET is suitable for design purposes without loss of accuracy.

The observed deviations in the values could be due to the fact that EPANET uses the Hardy Cross procedure for network analysis while Jeppson (1974) used the Linear Theory Method. The mean deviation for all results is less than 10% which is acceptable value indicating that EPANET is an adequate, efficient, and reliable tool for conducting hydraulic and water quality analysis of a water distribution network.

3.2. Water quality modelling and analysis

The dead ends of the network consist of nodes J1, J4, J8, J10, and J12. These extreme nodes were selected to be assessed because they are the critical nodes having the longest distances from the point of treatment (Tank T1). They are the nodes that would suffer the worst water quality deterioration because of their long distances of trace of water.

In the existing network, the water age modelling indicate that the stalest water occurred at J12 with an age of 1.68 hours during age peak hours and the least stale water (among extreme nodes) occurred at J4 with an age of 0.3 hours during age dip hours (see Figure 4). With the stalest water having an age of 1.68hours, which is less than the 24 hours acceptable limit for water age, hence the water is deemed safe. For residual chlorine modelling (see Figure 5), 0.220mg/L at the tank gave peaks between 0.212mg/L and 0.218mg/L and dips between 0.208mg/L and 0.211mg/L which are within the permissible limits stated in NSDWQ guideline (0.20-0.25mg/L).

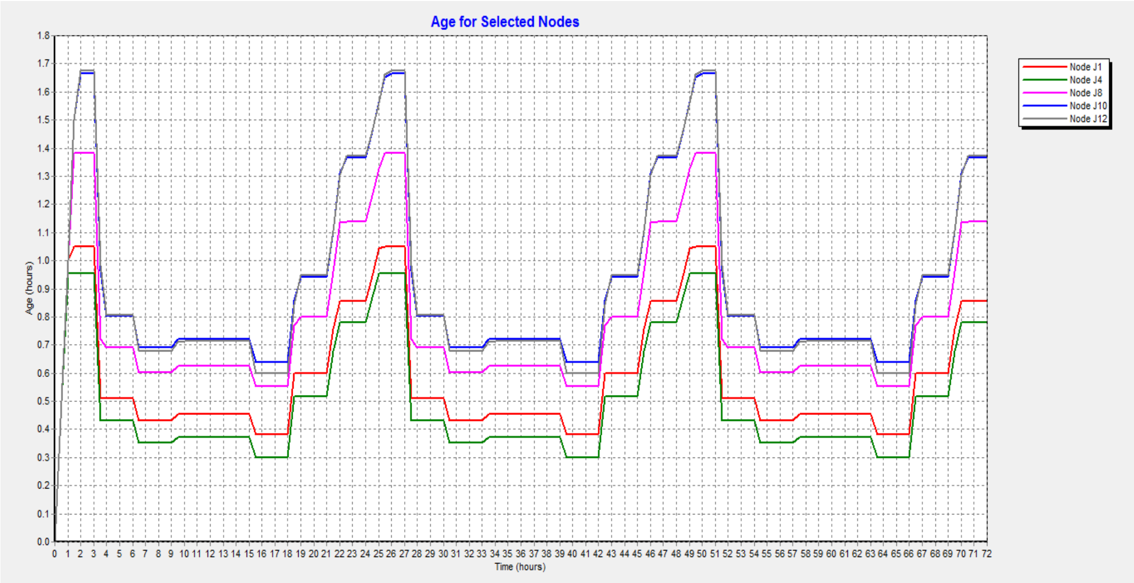

Figure 4: Time series plot of water age for extreme nodes of existing network

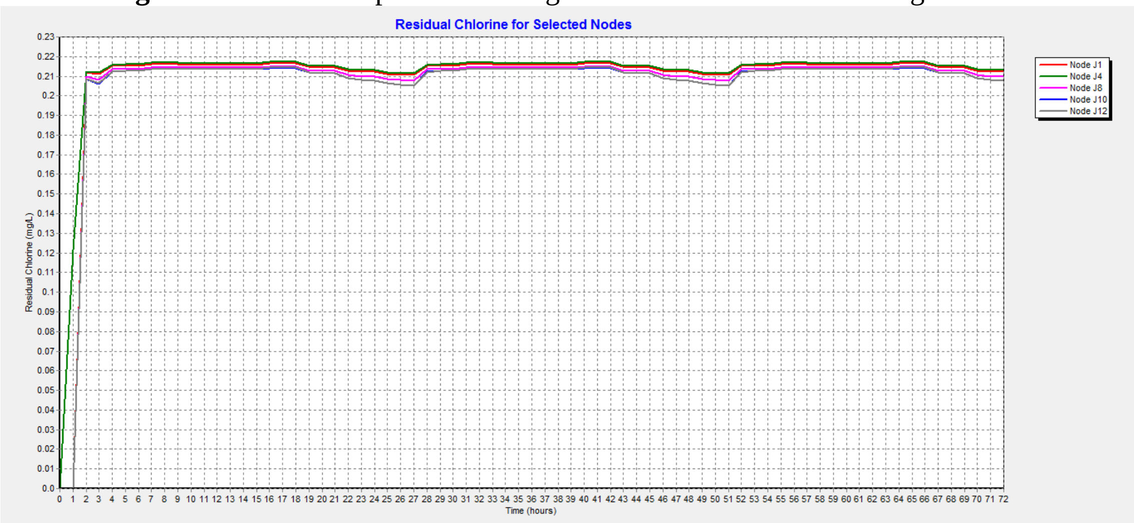

Figure 5: Residual chlorine of 0.22mg/L at tank of existing network

For water age modelling in the improved network (see Figure 6), the stalest water occurred at J12 with an age of 5.56 hours during age peak hours, and the least stale water (among extreme nodes) occurred at J4 with an age of 0.5 hours during age dip hours. With the stalest water having an age of 5.56 hours, which is less than the 24 hours acceptable limit for water age, the proposed improved network is deemed safe for water supply purposes. The residual chlorine modelling (see Figure 7) results indicated that 0.255mg/L at the tank gave peaks between 0.240mg/L and 0.250mg/L and dips between 0.202mg/L and 0.238mg/L, which are within the permissible limits in the NSDWQ guideline

(0.20-0.25mg/L) suggesting adequacy of water quality within the study network using the surrogates for water quality.

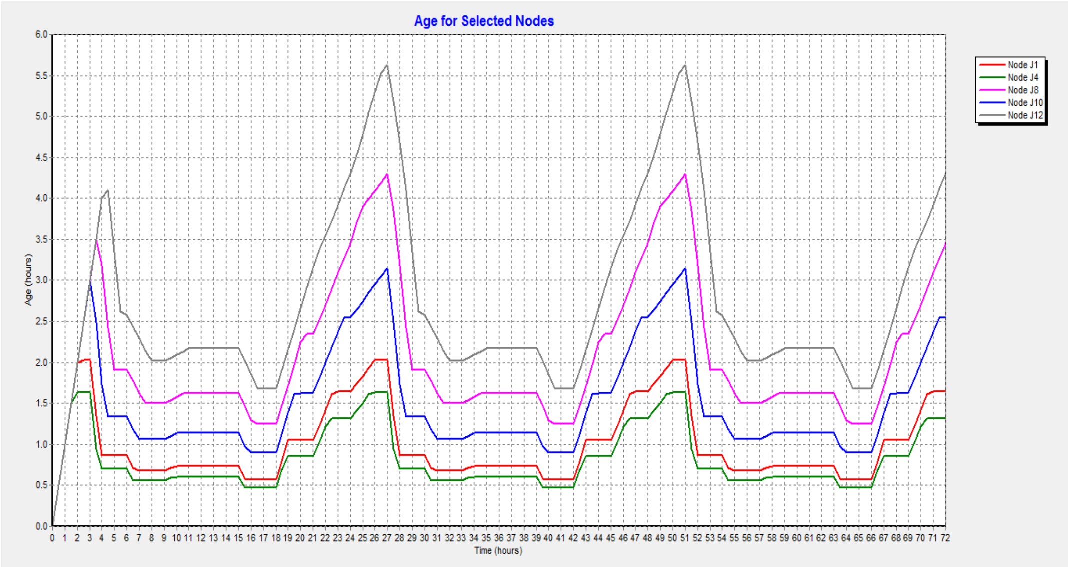

Figure 6: Time series plot of water age of extreme nodes of improved network

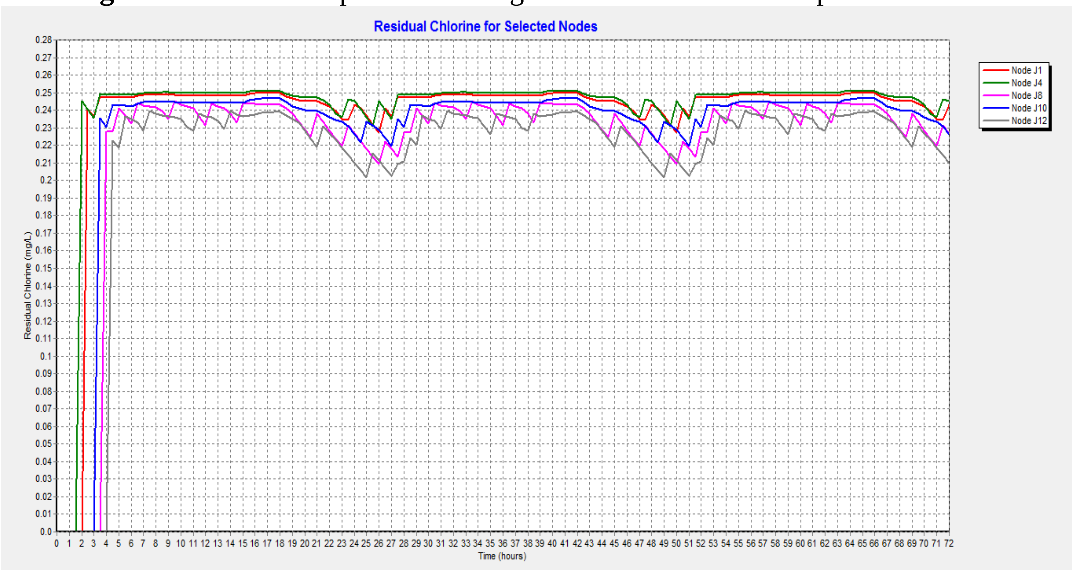

Figure 7: Residual chlorine at 0.255mg/L at tank of improved network

4.0. Conclusions

The following conclusions are drawn based on the findings from this study;

i) The values obtained from EPANET 2.0 are reliable and satisfactory for hydraulic simulations as it is a faster, more accurate, and easier means of carrying out hydraulic computations.
ii) The steady-state simulation on the University of Benin network from Omosigho (2017) gave similar results as obtained in this study. Therefore, EPANET and Water CAD hydraulic simulating software give comparable results for hydraulic analysis and design.
iii) The water age in both the existing and proposed improved UNIBEN Ekehuan campus water distribution networks at all nodes fall within satisfactory limits.
iv) Using a chlorine dosage of 0.220mg/L at the tank of the existing UNIBEN Ekehuan campus water distribution system will ensure that the quality of water at all nodes will satisfy the NSDWQ standards.
v) Using a chlorine dosage of 0.255mg/L at the tank of the proposed improved UNIBEN Ekehuan campus water distribution system will ensure that the quality of water at all nodes always will be satisfactory.

EPANET 2.0, a public-domain software, has proved to be an efficient software for hydraulic and water quality modelling. Hence, it is recommended to be adopted for these purposes especially for designing a proposed water distribution system in developing countries to ensure that an economic and time-saving design is achieved. This is in line with the position of Ekenta (2002) and Walski *et al.*, (2003) that hydraulic network modelling of a water distribution system is very useful in water distribution system planning and design because it reduces design time since tedious and iterative calculations are removed, thus enabling the engineer to focus on design decisions while guaranteeing the accuracy of computations. The ease and speed of using the models enable the engineer to explore more alternatives during design resulting in a more efficient, cost-effective, and robust design.

It is further recommended that the upgrades proposed in Omosigho (2017) of the UNIBEN Ekehuan Campus water distribution network should be implemented, and in addition, a chlorine dosage of 0.255mg/L should be used at the tank to ensure satisfactory water quality at all nodes within the network.

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