Water Supply System Performance for Different Pipe Materials Part I: Water Quality Analysis

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Abstract The quality of potable water has been a major issue in the water industry for the last few decades. The deterioration of treated water can be due to physical, chemical or microbiological changes that occur in the water during distribution. In addition, pipe material and decay of a disinfectant agent can affect the quality of the water being distributed. In this study the purpose was to simulate the decay of chlorine in two networks, one made of old cast iron (CI) pipes and another of polyethylene (PE) pipes. In addition the performance of the network considering chlorine concentration, velocity, water age, and an intrusion of a contaminant – in this case organic material – into the network was evaluated. The simulations were performed with EPANET software using as the simulation network an example network from the program. It was found that the CI network requires higher initial chlorine concentrations than the PE network to maintain the required minimum chlorine concentration throughout the whole network. To maintain the chlorine concentrations required by WHO (Cl must be greater than 0.2 mg/l and lesser than 0.5 mg/l) re-chlorination stations were necessary to add into both networks. The performance of both networks before re-chlorination was low due to high initial chlorine concentrations, but after the addition of the re-chlorination stations it was 100% throughout the networks. The performance of the velocities was good in both networks. The performance of the water age was dependent mainly on the tank usage, and the performance of contamination by organic material depended on the coefficient that defines the decay rate of the organic material in the bulk phase.

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1 Introduction

Several factors can contribute to the deterioration of water quality during distribution, such as interactions between the distributed water and pipe material or interactions within the bulk water (Kirmeyer et al. 2001). In addition, the decay of a disinfectant agent, such as chlorine, can degrade the microbial conditions of a distribution system causing thus a possible health risk to the consumers (Clark and Haught 2005).

Pressure variations caused by sudden changes in the flow velocity (LeChevallier et al. 2003), originated from basic distribution system operations such as starting or stopping of a pump (Gullick et al. 2004) can lead to the external pressure of the pipe exceeding the internal pressure (Kirmeyer et al. 2001). In such situation, there is a chance of non-potable water entering the distribution system from the surrounding environment (Loureiro 2002; Gullick et al. 2004) through leakage points, faulty seals or joints *etc.* (Kirmeyer et al. 2001), giving thus an opportunity for contaminants to enter the distribution system degrading the quality of the water (Gullick et al. 2004). It has also been found that flow velocity and chlorine decay rates in the bulk water correlate significantly, higher flow velocities leading to higher decay rates (Menaia et al. 2002).

Increased residence time, especially in reservoirs, increases the turbidity and the bacterial numbers of the distributed water (Kerneis et al. 1995; Power and Nagy 1999). Chlorine residuals decrease rapidly with distance from the treatment plant causing the furthest parts of the distribution system remaining with virtually no chlorine residuals leading thus to high bacterial numbers (Lu et al. 1995; DiGiano 2005). Also, the material of water piping affects the chlorine decay. Free chlorine can be consumed by the internal walls of the piping, by reactions with the fixed biomass on the pipe walls and with the pipe material itself (Frateur et al. 1999). In fact, pipe materials can be classified either having high reactivity, such as unlined iron, or low reactivity, such as PVC or MDPE (Hallam et al. 2002). The high reactivity of iron pipes might be due to the fact that free chlorine reacts readily with ferrous iron to produce ferric hydroxide (Lu et al. 1995). Corrosion scales can also increase the chlorine demand and offer a good environment for micro-organisms enhancing thus the growth of biofilms (Sander et al. 1996; Volk et al. 2000; Sarin et al. 2004; Clark and Haught 2005).

Chlorine is one of the most important disinfectant agents in water treatment. Chlorine is used either as free chlorine or as monochloramine to disinfect the bulk water in drinking water distribution systems and to control the growth of biofilms (Jegatheesan et al. 2000; Maier et al. 2000; Vikesland et al. 2001). It is important to maintain adequate chlorine residual throughout the whole distribution system in order to sustain the chemical and microbial quality of distributed water (Vasconcelos et al. 1997; Munavalli and Mohan Kumar 2003). However, being a strong oxidiser, chlorine reacts readily with organic and inorganic compounds and thus decays inside the distribution system through reactions both in the bulk phase and at the pipe wall (Vasconcelos et al. 1997; Kiéne et al. 1998; Powell et al. 2000a; Clark and Sivaganesan 2002; Munavalli and Mohan Kumar 2003; Clark and Haught 2005). In addition, chlorine can be consumed by the corrosion process of the pipe material (Vasconcelos et al. 1997; Clark and Haught 2005) as well as due to the biofilm attached to the pipe wall. The decay caused by biofilms varies largely, however, and the interactions between biofilms and disinfectants are still inadequately understood (Kiéne et al. 1998; Jegatheesan et al. 2000).

2 Mathematical Model for Chlorine Decay

Chlorine decay in distribution systems can be characterised as a combination of first-order reactions in the bulk liquid and first-order or zero-order mass transfer-limited reactions at the pipe wall (Vasconcelos et al. 1997). In water quality modelling tools chlorine decay is often simplified to first-order kinetics:

$$C(t) = C_0 e^{-kt} \quad (1)$$

where t is time, C the chlorine concentration after time t , C_0 the initial chlorine concentration, and k the decay coefficient. The advantage of the first-order reaction scheme is its simplicity and available analytical solution (Kastl et al. 1999; Loureiro 2002) and the fact that there is need for only one decay coefficient, k (Maier et al. 2000). The decay of chlorine in a distribution system is due to both bulk and wall decay (Munavalli and Mohan Kumar 2003) and the easiest method to define the overall decay coefficient is to use the sum of these two coefficients (Powell et al. 2000b; Loureiro 2002):

$$k = k_b + k_w \quad (2)$$

where k_b is the bulk decay coefficient and k_w is the wall decay coefficient. The bulk decay is due to chlorine reacting with chemicals in the bulk phase and the wall decay is due to chlorine reacting with biofilms, consumption of chlorine in the corrosion process and mass transport of chlorine between the bulk flow and pipe wall. The decay coefficients should describe these factors, thus they are site specific and are required to be verified by field measurements (Vasconcelos et al. 1997).

However, a more complex kinetic model for wall and bulk decay is used within the EPANET network modelling package. The kinetic model of EPANET tries to include to the decay model the mass transfer mechanism by which the chlorine is transferred from the bulk flow to the pipe wall. Thus, k_w turns into a function of velocity, pipe diameter, pipe length, diffusivity, and viscosity (Powell et al. 2000b). The decay coefficient used in EPANET modelling package (Maier et al. 2000):

$$k = k_b + \frac{k_f k_w}{R_H (k_f + k_w)} \quad (3)$$

Where k_f is a flow dependent mass transfer coefficient, k_b and k_w are parameters representing bulk and wall demand, respectively, and R_H is the hydraulic radius. The decay rate coefficients, both the bulk decay and the wall decay, for chlorine can have a large variability. In literature values between $0.02\text{--}0.74 \text{ h}^{-1}$ (Powell et al. 2000a; Hallam et al. 2003) and $0.01 \text{ h--}0.78 \text{ h}^{-1}$ (Hallam et al. 2002) have been reported for bulk decay coefficient (first order) and wall decay coefficient (first order), respectively. The variation in the bulk decay coefficient is due to quality changes in the water and the wall decay coefficient varies according to the material and the condition of the pipe (Powell et al. 2000a; Hallam et al. 2002, 2003).

The aim of this work was to simulate chlorine decay in two different networks – a network that consists solely of CI pipes and a network consisting of PE pipes – in order to estimate the necessary chlorine dosage to maintain the required chlorine concentrations throughout the network. In addition, the performance of the networks regarding chlorine concentrations, velocity, water age and an intrusion of a contaminant into the network was evaluated. The modelling tool used was the EPANET program that is available on the internet at the page of USEPA (www.epa.gov).

3 Application Example

3.1 Introduction and Input Values

The network used in the simulations was an example network from the EPANET program, *net3.net* (Fig. 1) that consists of two reservoirs (RIVER, LAKE), two pumps and 3 tanks, 117 pipes with diameters between 20 and 76 cm and 92 nodes. The added input values for the water were bulk decay coefficient, wall decay coefficients and initial chlorine concentrations in the reservoirs. Besides the chlorine concentration, the quality of the water in the two reservoirs was identical, and it was not possible to set any other characteristics for the water. The input characteristics for the network tanks included only dimensional characteristics without possibility of choosing their material.

The roughness coefficients were adjusted to fit a network made of 30 years old slightly corroded CI pipes and another one of PE pipes. As bulk decay coefficient an average value of the values from the literature (Powell et al. 2000a; Hallam et al. 2003) was used, i.e. 0.36 h^{-1} . As wall decay coefficients average values obtained by Hallam et al. 2002 were used, i.e., 0.67 h^{-1} for CI pipes and 0.05 h^{-1} for PE pipes. 1st order kinetic reactions for both bulk and wall decay were used. The roughness coefficients for CI pipes were calculated from Walski 1984 and the roughness coefficients for PE pipes were adjusted using the values from Walski 1984 and Rossman 2000. The roughness coefficients (Hazen-Williams, C) for the CI network varied between 108 and 118 and for the PE network between 140 and 144 depending on the pipe diameter.

According to the WHO the concentration of chlorine in a distribution network should remain between 0.2 and 0.5 mg/l (Loureiro 2002). Thus, three sets of simulations were run for both networks. The first simulation was done to find out the lowest initial chlorine concentrations necessary to maintain the minimum required chlorine concentration throughout the whole distribution system. The second simulation was done to find the necessary locations for re-chlorination to maintain the chlorine concentration between the recommended limits. Thirdly, the water age of the two systems was simulated. For the chlorine levels, the simulation was run for 6 weeks (1,008 h) and for the water age for 36 weeks (6,048 h) for the network to reach equilibrium.

Fig. 1 General layout of the simulation network

Fig. 2 Reaction report for CI pipes (*left*) and PE-pipes

3.2 Results and Discussion

3.2.1 Chlorine

For the CI network the initial chlorine concentrations necessary to maintain the minimum chlorine concentration were 3.7 mg/l for the RIVER-reservoir and 2.6 mg/l for the LAKE-reservoir and for the PE network the corresponding values were 0.5 mg/l and 1.6 mg/l. When comparing the reaction rates (Fig. 2) for the two networks it can be seen that in the CI network majority of the chlorine decay occurs in the pipe wall (69.25%) and in the PE network in the bulk water (62.37%). This is due to the fact that the wall decay coefficient for CI pipes is much higher than for PE pipes the bulk decay coefficient being same for the two.

The consumption in the network system is based on five demand patterns (Fig. 3), which are defined for 4 nodes presented in Fig. 4 (nodes 123, 15, 35 and 203), and the general default demand pattern, which is defined for the rest of the nodes. The multiplier of the patterns is the value that the base demand of each node is multiplied to generate effective demand. In nodes that have a specified demand pattern the base demand is 1 and the rest of the nodes have variable base demand. The system flow plot shows the overall consumption in the network during a period of 24 h and this figure (Fig. 5) shows the peak and the lowest consumption hour. By drawing the contour plots for the chlorine concentration for the hours of peak and lowest consumption, the differences between the behaviours of CI and PE networks considering chlorine decay can be seen. The contour plots (Figs. 6 and 7) show that majority of the network area in both networks has chlorine concentrations above the WHO recommendation limit 0.5 mg/l. At the peak hour 97% and 80% of the nodes have chlorine concentrations above 0.5 mg/l in CI and PE networks, respectively. At the lowest consumption hour the corresponding percentages are 98% and 74%.

In the CI network the chlorine concentrations during maximum consumption are lower than the concentrations during minimum consumption. As EPANET includes the mass transfer mechanism to the chlorine decay and thus the decay is influenced by the rate chlorine is transferred from the bulk flow to the pipe wall; since most of the decay of chlorine in the CI network occurs in the pipe wall; and since the decay coefficient is a function of velocity, pipe diameter, pipe length, diffusivity, and viscosity (Powell et al. 2000b) the higher chlorine concentrations during maximum consumption might be explained with higher flow velocity and thus more efficient transport of chlorine to the pipe wall. It has been suggested that in pipes that react readily with chlorine (e.g. CI pipes) the wall decay is limited by the transfer of chlorine to the pipe wall and, in addition, a positive relationship between flow velocity and wall decay has been found (Hallam et al.

Fig. 3 From left to right General default demand pattern, demand pattern for node 123, node 15, node 35 and node 203

Fig. 4 Demand pattern nodes

Fig. 5 System flow plot

2002). Thus, in the high consumption times the velocity of the fluid in the network is higher and chlorine is transported more efficiently to the pipe wall increasing the chlorine decay at the pipe wall and resulting in lower chlorine concentrations.

In the PE network the situation is opposite the peak hour having higher chlorine concentrations than low consumption hour. This is probably due to the chlorine decay in the bulk phase, which has much higher consumption of chlorine than the pipe wall. In low consumption periods the flow velocity is low giving thus time for the bulk reactions to occur. It should be noted that the area with chlorine concentrations below 0.2 mg/l in the contour plots of the PE-network are due to a tank (TANK 2), which stops functioning having thus no in- or outflow and consequently chlorine levels constantly at zero.

By plotting the chlorine concentration with the demand in a single node the behaviour of the chlorine concentration compared to the demand can be seen (Figs. 8 and 9). These plots were drawn for four nodes in different parts of the network (Fig. 10) and they show that the biggest influence on the chlorine concentration is the fact whether the water in the node originates from a tank or directly from a reservoir. These figures show that in node 253 there are big variations in the chlorine concentration which are due to the fact that water, at the low chlorine concentration hours, enters the node from a tank (TANK 3).

In node 211 in the CI network chlorine concentration correlates with the demand, low demand hours having high chlorine concentrations and vice versa. This behaviour is probably due to the low flow velocity at low demand hours and thus smaller wall decay. This behaviour can not be seen in the PE network, probably due to the less significant wall decay. However, in the PE network the chlorine concentrations are high with high demand and low with low demand. This might follow from the fact that at low consumption hours there is time for the bulk decay to occur which in the PE network is the main reason for the chlorine decay.

Fig. 6 Contour plot of chlorine concentrations in CI network at peak consumption (*left*) and at lowest consumption hour

Fig. 7 Contour plot of chlorine concentrations in PE network at peak consumption (*left*) and at lowest consumption hour

In the PE network in node 121 the chlorine concentration does not change much, which is probably due to the fact that the node is close to the reservoirs and there are no tanks feeding water to this node. However, in the CI network there can be seen similar correlation between demand and chlorine concentration as in node 211.

The figures for node 131 are very different in the two networks. In CI network the chlorine concentration varies according to the fact whether the water in the node originates from the tank (TANK 2) or directly from the reservoir. However, since this tank stops functioning in the PE network, chlorine concentrations in this node do not have significant variations.

When the chlorine concentrations between the nodes are compared it can be seen that the furthest nodes i.e. nodes 131 and 253 have the lowest chlorine concentrations, the tanks, however, affecting the chlorine concentrations in these nodes the most. Node 121 is influenced only by the

Fig. 8 From left to right Flow–chlorine concentration plot for node 121,131, 211 and 253, CI network

Fig. 9 From left to right Flow–chlorine concentration plot for node 121, 131, 211 and 253, PE network

RIVER reservoir and has thus, in both networks, chlorine concentrations that are still reasonably close to the initial chlorine concentrations in the reservoir. On the other hand, node 211 is influenced by both reservoirs and has thus, in the PE network, higher chlorine concentration than node 121, even though it is further in the distribution system, which is evidently due to the fact that the initial chlorine concentration in the LAKE reservoir is somewhat higher than in the RIVER reservoir. This behaviour does not take place in the CI network since the RIVER reservoir has higher initial chlorine concentration than the LAKE reservoir.

Fig. 10 Scheme of the simulation network with the nodes in question

Fig. 11 Re-chlorination nodes in CI network (*left*) and in PE network

3.2.2 Re-chlorination

With EPANET it is possible to add chlorine into selected nodes of the network to maintain a sufficient chlorine concentration throughout the network. This was done by using set point booster chlorination. This method sets the chlorine concentration in the water leaving a node to a defined level, which in this case was 0.5 mg/l in order to keep the chlorine level between the recommended levels. Through trial and error the nodes that required re-chlorination were specified. In the CI network 10 nodes and in the PE network 3 nodes (Fig. 11) needed re-chlorination.

From the chlorine concentration contour plots (Figs. 12 and 13) can be seen that after setting the re-chlorination locations the chlorine concentration remains between 0.2 and 0.5 mg/l throughout the whole network, unlike in the situation without re-chlorination with initial chlorine concentrations in the reservoirs set to the maximum acceptable (0.5 mg/l). The contour plots before re-chlorination are drawn at the critical hour, i.e. at the hour when the chlorine concentration is at its lowest. The plots after re-chlorination are drawn at the same hour. In both networks re-chlorination was needed in the nodes that receive water from tanks, which is due to the fact that water stagnates in the tanks for a long time giving thus time for chlorine decay to occur. In addition, there was need for re-chlorination mainly

Fig. 12 *Left* Chlorine concentration in the CI network before re-chlorination (initial chlorine concentrations 0.5 mg/l). *Right* Chlorine concentration in the CI network after re-chlorination

Fig. 13 *Left* Chlorine concentration in the PE network before re-chlorination (initial chlorine concentrations 0.5 mg/l). *Right* Chlorine concentration in the PE network after re-chlorination

in the remote nodes of the network. It should be noted, though, that the most remote nodes of the network are not dead ends, but instead nodes with demand from where water is distributed further to the consumers, which is why re-chlorination in these nodes is justifiable.

3.2.3 Water Age

Water age is the time that a water parcel spends in the network. New water entering the network from reservoirs is considered to have water age of zero (Rossman 2000). It is important to know the water age of a distribution system in order to estimate the extent of chlorine decay or disinfection by-product formation. If the residence time is known it is easier for water utilities to e.g. decide the location of sampling stations (DiGiano et al. 2005). The water age simulations were done to compare the chlorine concentrations and the water age in the network. The obtained water ages are presented in the contour plots (Figs. 14 and 15) at peak and low consumption hour.

The average water ages at the peak and low consumption hour in the CI network are 33.14 h and 13.48 h, respectively. The high water age at the peak consumption hour is due to the fact that all three tanks are providing water with high age to the network. On the contrary, at the low consumption hour, the tanks are filling up and water to the network is

Fig. 14 Contour plot of water age in CI network at the peak consumption hour (*left*) and at the lowest consumption hour

Fig. 15 Contour plot of water age in PE network at the peak consumption hour (*left*) and at the lowest consumption hour

provided directly from the reservoirs with small water age. For PE network the average water ages are 7.50 and 16.93 h, for peak and low consumption, respectively. The tank usage in PE network is not as significant as in the CI network and it does not have such an effect on the water age. Thus, the water age in the PE network is low when the consumption is at its highest and vice versa.

By comparing the plot of water age and chlorine concentration of the CI network at peak hour it can be seen that where the water age is highest, the chlorine concentrations are lowest since the distributed water is originating from the tanks. This is the case at the low consumption hour as well. For PE network similar behaviour can be seen. In the PE network, however, longer stagnation times lead to higher chlorine decay due to the decay in the bulk phase.

4 Performance Evaluation

4.1 Introduction

The level of service provided by water supply and distribution systems is one of the key issues facing the water industry today. However, measuring the performance of a distribution network is not a straightforward task, given the multiple factors involved, and the lack of a unified approach or a single clear-cut definition of performance. In order to evaluate the service of a water supply there has been developed a Performance Evaluation System. The Performance Evaluation System is a technical analysis tool based on a system of penalty curves, providing standardised means of diagnosis (Coelho 1997).

The method is defined by three types of units. Firstly it is defined by the numerical value of a network property or condition variable, which is considered to be showing the

Fig. 16 Penalty function for chlorine

Fig. 17 Performance of chlorine in the CI network in minimum hour (*left*) and peak hour

particular aspect being examined. Secondly, it is defined by the penalty curve which plots the value of a performance attributed to the condition variable or network property. The performance index varies between a no-service (0%) and an optimum-service (100%) situation, and the curves are supposed to penalise any deviation from the latter. The convention adopted in this work uses a 0 to 100% scale, with the following meanings: 100% – optimum service, 75% – adequate service, 50% – acceptable service, 25% – unacceptable service and 0% – no service. Thirdly, the method is defined by a network operator which allows the performance values at element level to be aggregated across the network or parts of it (Coelho 1997).

Thus, in order to aggregate the performances at element level across the network an aggregation function is defined (Eq. 4). This function represents the importance of each element related to the system as a whole.

$$P = W(pm_i) = \sum_{i=1}^N (w_i \cdot pm_i) \quad (4)$$

where P is the global value of performance, pm_i the performance in each element i , and w_i the weight of each element according to Eq. 5:

$$w_i = \frac{z_i}{\sum_{i=1}^N z_i} \quad (5)$$

where z_i is the element used (Araujo 2005).

Hence, this method yields values of performance evaluation for every element of a network as well as for the network as a whole. There is a global value (P) which is achieved through a particular function in order to represent the performance assessment of the network, and, on the other hand, a population of elementary values (pm_i) which lends itself to a basic statistical treatment. The two are combined together graphically in diagrams where performance is plotted against simulation period, typically a 24-h simulation in steady state conditions. The main curve represents the global performance, whereas the shaded areas are 25% demand percentile bands which should be read as follows: if (t, y) are the coordinates of a given point in the $P\%$ demand percentile curve it means that at time t $P\%$ of the total demand are being supplied with a performance that is smaller or equal to y (Coelho 1997).

Fig. 18 Performance of chlorine in the PE network in minimum hour (*left*) and peak hour

4.2 Performance Analysis before Re-chlorination

4.2.1 Chlorine

The performance analysis before re-chlorination was done with initial chlorine concentrations in the RIVER and LAKE reservoirs, for the CI network 3.7 and 2.6 mg/l, and for the PE network 0.5 and 1.6 mg/l, respectively. The penalty function was adapted from Coelho and Alegre (1999) and it can be seen in Fig. 16. Since the chlorine concentration should maintain between 0.2 and 0.5 mg/l throughout the network, the performance in the penalty function maintains at 100% with these chlorine concentration values. Chlorine concentration values below the minimum limit 0.2 mg/l yield a performance of 0%. When the chlorine concentration values exceed the recommended upper limit 0.5 mg/l the performance descend to 25% and maintains in this value.

The performance of the network with the above mentioned initial chlorine concentrations is very low especially in the CI network. This is because majority of the CI network has chlorine concentrations above the accepted upper limit, 0.5 mg/l. In the PE network the situation is better due to lower initial chlorine concentrations.

In the CI network (Fig. 19) the performance maintains always equal or above 25% since the initial chlorine doses are set so that the chlorine concentration does not fall under 0.2 mg/l. However, the performance of the network is only 25% throughout the whole simulation cycle with low and average demand (<75%), which is due to chlorine

Fig. 19 Performance simulation diagram for chlorine in the CI network (*left*) and in the PE network

Fig. 20 Penalty function for velocity

concentrations above 0.5 mg/l. With high demand ($>75\%$) the performance varies between 25% and 100% falling at times below the 75% performance limit. From the contour plots of the performance in the CI network (Fig. 17) can be seen that majority of the nodes have a performance of 25%. However, almost throughout the whole simulation cycle there are also nodes in the network with performance of 100%. This leads to a broad percentile band in the performance graph that reaches from 25% to 100% performances. However, regardless of the high performance values, the global performance of the system (index curve) is low and it is running barely over the 25% performance limit.

In the PE network (Figs. 18 and 19) the situation is better. However, the fact that there are performances lower than 25% is due to the fact that TANK 3 in the PE network stops working and the tank and the corresponding node have thus zero chlorine concentration and 0% performance throughout the simulation. In the PE network the performance varies considerably. The global performance is, however, much higher than in the CI network; in the PE network the index curve runs between 50% and 75% performance limits. The variations in the performance are due to the fact that the network – at a certain hour and with certain demand percentile – has nodes with very different performances and is thus fairly heterogeneous leading to percentile bands that are very wide at times.

4.2.2 Velocity

Control on the flow velocities in water distribution networks should be maintained in order to avoid structural problems or undesirable hydraulic regimes caused by high velocities, or in order to minimise the unfavourable consequences of too low velocities on the quality of the transported water. It is common to use project criteria in which the reference velocity V_{ref} is calculated according to the diameter of each pipe (Coelho and Alegre 1999). The reference

Fig. 21 Performance simulation diagram for velocity in the CI network (*left*) and in the PE network

Fig. 22 Performance of velocity in the CI network in minimum hour (*left*) and peak hour

velocity is considered to be the optimum velocity for a certain pipe, thus the performance for the reference velocity is 100% (Fig. 20). The following expression (Eq. 6) according to DR 23/95 (1995), Article 21 is proposed for the reference velocity of a pipe with diameter D .

$$V_{ref} = 0.1274D^{0.4} \quad (6)$$

where D is the diameter of the pipe (in mm) and V_{ref} is in m/s (Coelho and Alegre 1999). The minimum norm velocity is 0.3 m/s (DR 23/95 1995), returning thus a performance of 75%. V_{ref} being the ideal velocity returns performance of 100%.

When considering the flow velocity the performance graphs are fairly similar for the two networks the differences being probably due to roughness coefficients. The global performance curve in both networks is in the region of 75% performance limit, therefore the performance in both networks can be considered good. It can be seen from Fig. 21 that the performance with higher (>50%) demand is, in both networks, always clearly over 75%. In the PE network the performance reaches 100% limit, unlike in the CI network, which indicates that the reference velocity is not obtained in the CI network. Also, with lower (<50%) demand the performance maintains always above 25%, which means that velocities that are three – or more – times the reference velocity are never reached in neither of the networks (Figs. 22 and 23).

Fig. 23 Performance of velocity in the PE network in minimum hour (*left*) and peak hour

Fig. 24 From left Penalty function I, II and III for water age

4.3 Performance Analysis after Re-chlorination

In the performance analysis with re-chlorination stations the performance of both networks considering chlorine concentrations was 100% throughout the whole simulation period. The performance considering velocities maintained identical to the performance before re-chlorination.

4.4 Performance Analysis for Water Age

Since the water age of a network depends on many variables such as length of the network, consumption, and the presence of tanks there are no explicit penalty functions for water age. Thus, in order to see the performance of the water age in the network, the analysis was done with three different penalty functions to perform sensitivity analysis. The three penalty functions are presented in Fig. 24.

Fig. 25 From left Performance simulation diagram for water age in the CI network according to penalty function I, II and III

Fig. 26 From left Performance simulation diagram for water age in the PE network according to penalty function I, II and III

By comparing the graphs in Figs. 25 and 26 it can be seen that the performance changes a lot more in the CI network than in the PE network. In the CI network the changes occur mainly at times of higher consumption whereas in the PE network the performance maintains virtually identical with different penalty functions. This is most likely due to the fact that in the CI network at the peak consumption hours the tanks are providing the network water with very high water age while in the PE network the tanks are less used. In the PE network the performance is good throughout the simulation cycle the global performance maintaining in all three situations above 75% performance limit and in the two latter cases constantly at 100% with average and high demand (>25%). In the CI network

Fig. 27 Performance simulation diagram for chlorine in the CI network (left) and in the PE network with leak in node 203

Fig. 28 Performance simulation diagram for velocity in the CI network (*left*) and in the PE network with leak in node 203

with penalty curve I the global performance at high consumption hours descends below the performance limit of 50% maintaining nevertheless above 75% performance limit at times of low consumption. These drops in the global performance obviously lessen when the water age in the penalty curves increases i.e. in the two latter cases. In the last case the performance in the CI network is already very good; the index curve stays close to 100% and the performance with average and high demand (>25%) maintains at 100%.

4.5 Performance Analysis with Leak

4.5.1 Introduction

In these simulations a leak was created in three nodes. The purpose was to see, whether a leak will cause changes in the chlorine concentration or flow velocity of the network. The penalty functions used in these simulations were identical to the ones in previous simulations. A leak was simulated in three nodes; in the node with the highest elevation (node 153, elevation 22.18 m), the node with lowest elevation (node 167, elevation

Fig. 29 Network map with the intrusion nodes

Fig. 30 From left Penalty function I, II and III for organic material contamination

−1.52 m) and the node with biggest demand (node 203, elevation 0.61 m). Each of the leaks was simulated separately i.e. only one of the nodes had a leak at a time.

In order to simulate a leak in the EPANET program it is necessary to introduce an emitter in a node. Emitters are devices that can be used to model flow through an orifice that discharges to the atmosphere and they can thus be used to simulate leakage in a pipe connected to the node. The flow rate through the emitter can be calculated with: (Rossman 2000)

$$q = Cp^{\alpha} \quad (7)$$

where q is the flow rate, p is pressure, C is the emitter coefficient of the orifice, which depends on the shape and the diameter of the orifice and α is the pressure exponent (Colombo and Karney 2002; Araujo et al. 2006). When an emitter is used to simulate leakage it is necessary to introduce the emitter exponent, α , and the emitter coefficient C as input values. For nozzles and sprinkler heads the emitter exponent α is often assigned a value of 0.5 to reflect flow through a fixed size orifice (Colombo and Karney 2002). However, other values have been suggested. Araujo et al. (2003) used the value 1.18. They suggest that even though this value is quite a bit higher than the expectable 0.5 it is nevertheless found by experimental results that it can be applied and that the difference in α may be caused by changes in the shape and size of the cracks and orifices due to the internal or external pressure differences.

Thus, when performing the simulations with the leak, a leak of 25% was simulated in each node (Colombo and Karney 2002). With emitter exponent of 1.18 and demand of 125% the emitter coefficients for each situation were found. The emitter coefficients for node 153 were 0.1 and 0.1 for CI and PE network, respectively, for node 167 0.03 and 0.02

Fig. 31 Organic material propagation in CI (left) and PE network at critical hour (node 101, Bulk coeff. −0.1)

Fig. 32 Performance in the CI network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function I

and for node 203 9.1 and 8.9. The simulations considering the chlorine concentrations and velocities were done only when the emitter coefficients were established. In the cases of the highest and lowest node (nodes 153 and 167) the differences in the chlorine concentrations or velocities in the network were not significant, which is probably due to the fairly low consumption in these nodes leading thus to small leak flows. In the case of the leak in the node with the highest demand (node 203), there were already differences in the chlorine concentrations and the velocities in the network.

4.5.2 Chlorine

By comparing the graph of the chlorine concentration in the CI network before and after the occurrence of the leak (Figs. 19 and 27) it can be seen that the performance of the system with the leak is actually a bit better. This is probably due to the fact that the chlorine concentrations are lower with a leak raising thus the performance slightly. In the case of PE network, when a leak is introduced, with lower ($<50\%$) demands the performance is diminished. However, with higher demands the performance maintains roughly at the same level. The diminution of the performance might be due to the fact that with the higher demand caused by the leak a tank that in the initial situation is not functioning returns to function. Thus, since the initial chlorine concentrations were adjusted without the functioning of the tank they are not high enough anymore to maintain the minimum requested chlorine concentration.

Fig. 33 Performance in the PE network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function I

4.5.3 Velocity

Considering the velocities the changes in the CI network are small (Figs. 23 and 28). With higher ($>50\%$) demand the performance maintains virtually identical. The changes happen in the lower percentiles; the performance with low ($<25\%$) demand improves slightly. In the PE network there are changes even in the higher demand percentiles. The performance with higher ($>50\%$) demand improves slightly. The changes with lower ($<50\%$) demand can be considered insignificant. The global performance maintains virtually at the same performance level in both networks.

4.6 Performance Analysis with an Intrusion of Organic Material into the Network

4.6.1 Introduction

Simulating contaminant intrusion into the network in EPANET can be done by either simulating a contaminant that is non-reactive or a contaminant that is reactive. When a contaminant that is reactive is simulated it is necessary to know the reactions that the contaminant has with the bulk water and the pipe wall in order to adjust the reaction kinetics and reaction coefficients. In this case the purpose was to simulate an intrusion of organic material that reacts with the chlorine present in the network. First order reaction kinetics were used for the bulk water and the reactions at the pipe wall were neglected. The simulations were done with three different bulk coefficients; -0.1 , -5 and -10 to see the different behaviour of the contaminant. The intrusion was done using the setpoint booster

Fig. 34 Performance in the CI network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function II

source which sets the water leaving the node to have a certain concentration of contaminant which in this case was 50 mg/l.

The intrusion of organic material into the network was simulated in two nodes: node 101 which is a node that is located close to the LAKE reservoir and has a fairly high elevation (12.8 m) and node 153 which is the node that has the lowest pressure in the network. Node 101 was selected to have the intrusion for its elevation and the fact that it provides water nearly to the whole network. This way the contamination spreads to a large part of the network. Node 153 was chosen because of its low pressure and thus the risk of having a rupture and further easy access of the organic material to enter the distribution system. The nodes are presented in Fig. 29. Due to the lack of an explicit penalty function the performance analysis was done with three different penalty functions to perform sensitivity analysis. The penalty curves for the organic material intrusion are presented in Fig. 30.

4.6.2 Intrusion in Node 101

The propagation of the organic material in the network is presented in Fig. 31. From the performance graphs (Figs. 31, 32, 33, 34, 35, 36 and 37) can be seen that the global performance in both networks improves when the bulk coefficient decreases *i.e.* with bulk coefficient -10 the performance is better than with coefficient -0.1 . This is due to the fact that the contaminant with smaller bulk coefficient is consumed faster in the network.

When the situation with penalty function I is considered, in the CI network with coefficient -10 and -5 the global performance of the network is above the limit of 75%,

Fig. 35 Performance in the PE network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function II

Fig. 36 Performance in the CI network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function III

Fig. 37 Performance in the PE network with contaminant intrusion. *From left* Bulk coefficient -0.1 , -5 and -10 . Penalty function III

whereas with coefficient -0.1 it remains between 50% and 75% performance limits. In the PE network the performance is very similar than in the CI network. With coefficient -0.1 the performance is a bit lower than in the CI network, but with smaller coefficients the performance is similar. This behaviour repeats in the situations with penalty functions II and III. The differences between the two networks are most likely due to the different flow velocities and different tank usage.

When comparing the different penalty functions, penalty function II yields the best performances and penalty function I the lowest performances. This is evidently due to the fact that in penalty function I already concentration 20 mg/l gives performance of 0% whereas in penalty function II only 40 mg/l gives performances of 0%.

Fig. 38 Organic material propagation in CI (*left*) and PE network at critical hour (node 153, bulk coeff. -0.1)

Fig. 39 Performance in the CI network (*left*) and PE network with contaminant intrusion. Bulk coefficient -0.1 . Penalty function I

4.6.3 Intrusion in Node 153

When the organic material intrusion is simulated in node 153 the organic material doesn't spread in a broad area in the network which can be seen in Fig. 38. Therefore, since the contamination is only local the performance of the network maintains very high. Additionally, regardless of the penalty curve the performance in both networks maintains very similar. As an example in Fig. 39 there are presented the performance of both networks with bulk coefficient -0.1 and penalty curve I. Changing the penalty curve or the bulk coefficient doesn't cause significant changes to the performance of the networks. Thus, from the contour plots and the performance graphs it can be seen that the performance in majority of the network is 100%, and thus the global performance curve runs close to 100% performance limit. However, since there are also some nodes in the network that have high organic material concentration and therefore 0% performance, the 25% demand percentile band is very wide reaching from performances of 0% to performances of 100%.

5 Conclusions

The current paper presents mathematical model analysis for the calculation of water supply system performance with different pipe materials, as well as the developments regarding the water quality assessment. The analysis of the results allows the following conclusions to be drawn:

- For the CI-network higher initial chlorine concentrations are necessary compared to PE network in order to maintain the minimum acceptable chlorine level throughout the network.
- The need for higher initial chlorine concentrations in the CI network is possibly due to higher wall decay rates.
- The fact that the CI network has low chlorine concentrations during maximum consumption hours may be due to flow velocities enabling more efficient transportation of chlorine to the pipe wall leading thus to higher chlorine decay rates.
- The low chlorine concentrations of the PE network during low consumption hours are probably due to bulk reactions that in low consumption periods have more time to occur. The wall decay in PE pipes is not such a significant factor.

- The most significant factor for the chlorine concentration in a specific node is whether the water in the node originates from a tank or directly from a reservoir. However, when there is no effect of a tank the chlorine concentration correlates with the demand in the node; for CI network the chlorine concentration is low in high demand hours and vice versa, and for PE network the chlorine concentration is low in low demand hours and vice versa.
- In order to maintain the chlorine concentration between the recommended limits in the network, when the initial chlorine concentration in the reservoirs is 0.5 mg/l, re-chlorination is required in certain nodes. In CI network the need for re-chlorination is bigger than in the PE network. Re-chlorination is needed in both networks in the nodes that receive water from tanks and in some nodes in the furthest parts of the network.
- The performance considering chlorine concentrations in CI network is bad due to high chlorine consumption on the pipe wall and thus low chlorine levels throughout the network. In the PE network chlorine levels maintain higher due to lower decay at the pipe wall and thus the performance maintains higher. After the addition of re-chlorination stations the performance maintains at 100% throughout the whole simulation time in both networks.
- The water age in both networks corresponds logically with the chlorine concentrations; at high water ages the chlorine concentrations are at lowest in both networks. The performance of water age is mostly dependent on the usage of the tanks, which is why, due to lesser tank usage, the PE network has better performance. In the CI network, however, the performance is low mainly at the times of peak consumption hours, when the water to the network is largely provided from the tanks.
- The performance of the velocities of both networks is good throughout the whole simulation without significant differences between the networks. This indicates that the network is not over- or under-dimensioned.
- Introduction of a leak into the network does not cause big changes in the performance regarding the chlorine concentrations or velocities.
- The performance of the organic material intrusion is dependent on the bulk coefficient, lower bulk coefficient leading to faster reaction rates, and thus lower organic material concentrations in the network.

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