Rehabilitation aspects of oversized water distribution networks

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Abstract

The main problems in the exploitation of oversized water distribution networks are related to the deterioration of water quality in the network pipes. The changes in water quality are evoked primarily by the ageing of water and different sedimentations. Therefore the flow velocities and their optimisation are essential factors for the rehabilitation of water networks. The dependence of water age on the time in network pipes is investigated. The differential equation for the determination of water age in the typical cases of daily water demands is solved. The problem of optimal flow velocity in pipes is discussed. The topology of urban water distribution system with optimal flow velocities is considered, the number of water mains determined and their supply sectors defined. The diameters of mains for the cases of optimal flow velocities and different consumption of water are determined. With regard to these aspects the detailed investigation of water distribution network of the City Centre of Tallinn is carried out and possibilities for the rehabilitation of the network are explained.

1 Introduction

Optimisation of the design, rehabilitation and operation of water distribution network includes water quality considerations. Water quality changes during transport through the distribution network due to complex physical, chemical and biological processes which are taking place in the water and between the water and sediments on the walls of the pipes in the network. Water quality could deteriorate substantially in network (Clark et al. [1]). Strong influence of water quality on the corrosion processes of metal pipes had been observed by Engelhardt et al. [2]. Encrustation of pipes will decrease pipe diameters and
head losses. Computer modelling of water quality in water networks is widely used nowadays. The simplest way to estimate water quality is to calculate the consumed water age over the network. Water age could forecast changes in water quality and should be considered in the development of the rehabilitation strategy of networks. Sægrov et al. [3] and Engelhardt et al. [2] in their reviews on the rehabilitation of water networks have paid only casual attention to water age, but it would provide a simple and general measure for the overall quality of water. Therefore full consideration of water quality can be of great benefit.

2 Diurnal change of water age

Let us consider how water age changes in the water network over time. As the simplest model we can investigate the diurnal change of water age in a pipe depending on the consumption of water or velocity of flow. The equation of the conservation of mass in pipe has the form

\[
\frac{\partial a(x,t)}{\partial t} + v(t) \frac{\partial a(x,t)}{\partial x} = 1,
\]

where \( a(x,t) \) is the age of water as a function of distance from the inlet of pipe and time in days and \( v(t) \) is the velocity of flow. At the beginning of the pipe

\[
a(0,t) = 0.
\]

The velocity of flow can be approximated using typical diurnal consumption of water (Obradović [4]). Here for the approximation we use the function

\[
v(t) = \alpha - \beta \cos 2\pi \left( \frac{1}{8} + t \right),
\]

where \( \alpha \) and \( \beta \) are some constants, and \( \beta \leq \alpha \). Solution of eqns (1)-(3) can be written as

\[
a + y \sin 2\pi \left( \frac{1}{8} + t - a \right) = \frac{x}{\alpha} + y \sin 2\pi \left( \frac{1}{8} + t \right),
\]

where \( y = \frac{\beta}{2\pi \alpha} \). For some values of \( \frac{x}{\alpha} \) and \( \gamma \) the water age \( a \) is shown in Figure 1. As we can see in Figure 1 the water age may substantially change during the day. Together with monitoring the location (Le and Deininger [5]) this fact must be considered when taking water samples for quality purposes.
Resulting from the changes in the structure of the society, the water consumption regime has substantially changed in Estonia in the recent years. Decrease in water consumption has led to a situation when water networks in all towns are oversized. This has caused critical decrease in water quality. Therefore, extensive rehabilitation programme for water networks should be introduced. The number of inhabitants in Tallinn has decreased and overall water consumption has decreased during the last 10 years approximately 2.7 times. The network geometry of the City Centre of Tallinn is given in Figure 2, where pipes with the diameter ≥ 300 mm are indicated and mains with the diameter ≥ 500 mm are presented with bold lines. The water supply system of Tallinn uses mainly the surface water of Lake Ülemiste. Before injection into the network the lake water is treated in Water Treatment Works. The network of the City Centre is the most complicated part of the network of Tallinn. The velocities of flow and the age of water in the pipes of City Centre network are shown in Figure 3.

Water age is a parameter which is directly dependent on the capacity of the distribution network. The whole capacity 81,000 m³ is distributed between pipes with different diameters d (mm) as follows: 75 ≤ d ≤ 175 – 8.3 %, 200 ≤ d ≤ 280 – 8.3 %, 300 ≤ d ≤ 400 – 16.6 %, 500 ≤ d ≤ 1000 – 66.8 %. From here we can see that if we want to decrease water age in the network, the water mains with diameter ≥ 500 mm are most important in the rehabilitation process. From the aspect of water quality these percentages are different. If we assume that contamination takes place at the wall of the pipe, then pipes with different
Figure 2: The network geometry of the City Centre of Tallinn.

Figure 3: Velocities, m/s (A) and the age of water, hours (B) in the network pipes of the City Centre of Tallinn.

diameters have different relative contamination factors. Using these factors we obtain the following percentage for different pipe groups: \(75 \leq d \leq 175\) – 28.1 %, \(200 \leq d \leq 280\) – 14.5 %, \(300 \leq d \leq 400\) – 19.9 %, \(500 \leq d \leq 1000\) – 37.5 %. The percentage are obtained by multiplying the reciprocal value of the hydraulic radius of the pipe by the percentage of the capacity distribution. As we can see the influence of different groups of pipes is considerably even. The simulated water age in the existing City Centre Network according to the water network
model developed for the winter 2001 mean consumption, on the basis of EPANET 2.0 software, is given in Figure 4. The water age is naturally smaller close to the main pipes with bigger diameter. In addition the water age has been influenced by the phenomenon of backflow to the WTW direction in some mains, which should be eliminated during the network rehabilitation process. The water consumption in summer time decreased by 7 % in the whole City Centre Area of Tallinn in 2001. The reduction of water consumption was unevenly distributed over the network geometry. The difference between water age in mean winter and summer consumptions in the City Centre Network is given in Figure 5. The highest difference could be seen in the oldest part of the City Centre.
4 Configuration of main system

The network of the City Centre of Tallinn is supplied with water from WTW which is situated at the border of the City area (Figure 2). The logical scheme for this network mains is represented by a batch of pipes starting from WTW. The looped network is formed by connecting mains with smaller diameter pipes in some distances from the WTW. In this simplified network water will be delivered to all consumers by the shortest way, first by the main pipe and then by radial direction pipes. Consequently, the ideal geometry of the City Centre water mains could be represented by the scheme given in Figure 6. The mean water age coefficient $r$, in the network, covering a semicircular town area, could be determined from the following equation in polar coordinates.

Figure 5: The difference between water age in mean winter and summer consumptions in the City Centre network (WTW – Water Treatment Works).
\[ \tau_i = \frac{4i}{\pi} \int_0^\varphi \int_0^\rho (1 + \varphi) d\varphi d\rho, \quad (5) \]

where \( i \) is the number of water mains, \( \rho \) is the nondimensional length of the main and \( \varphi \) is the angle (Figure 6). If we solve the equation (5), we have the coefficient of mean water age in the network dependent on the number of water mains as

\[ \tau_i = \frac{2}{3} + \frac{\pi}{6i}. \quad (6) \]

The mean water age coefficients for different number of water mains in the semicircular town area are given in Table 1.

Table 1: Mean water age coefficient \( \tau_i \) for different number of water mains \( i \).

<table>
<thead>
<tr>
<th>( i )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_i )</td>
<td>1.189</td>
<td>0.928</td>
<td>0.840</td>
<td>0.796</td>
<td>0.771</td>
<td>0.753</td>
</tr>
<tr>
<td>( i )</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_i )</td>
<td>0.741</td>
<td>0.731</td>
<td>0.724</td>
<td>0.718</td>
<td>0.666</td>
<td></td>
</tr>
</tbody>
</table>

For the calibration of the coefficient the assumption that age \( \tau_i = 1 \) at the end of water main \( \rho = 1 \) has been used in this table. In order to get the real mean water age in the network, the coefficient \( \tau_i \) should be multiplied by the quotient of the main length and the mean flow velocity. As an example, considering the 'self-
cleansing' velocity 0.5 m/s in the water main, the water age in the network of the City Centre of Tallinn (Figure 6), consisting of three main pipes with the length of 6,000 m, would be approximately 2.8 hours. In Table 1 we can see that the optimal number of mains is 4. Further increase in the number of mains will not essentially influence the age of consumed water.

5 Optimal main diameter

Every main is supplying a sector of town with water and the optimal main diameter should be calculated on the basis of water consumption in the sector. Let the consumption of water in the sector $0 \leq r \leq R$, $\varphi_1 \leq \varphi \leq \varphi_2$ be $q(r, \varphi)$, (m/s). Then the outflow from the main at $r$ is equal to

$$q_1(r) = r \int_{\varphi_1}^{\varphi_2} q(r, \varphi) d\varphi .$$

Therefore the flow in the main at $r$ is

$$Q(r) = \int_0^r q_1(r) dr .$$

Now for determination of the diameter of main we proceed from optimal flow velocity. Assume that optimal flow velocity $v$ can be expressed as

$$v = v_0 (1 + \lambda d^2) ,$$

where $d$ is the main diameter and $v_0$ and $\lambda$ are suitably selected parameters. Then

$$Q(r) = \frac{1}{4} \pi v_0 \left(1 + \lambda d^2\right) d^2$$

and

$$d(r) = \sqrt{\frac{1}{2\lambda} \left(1 + \frac{16\lambda Q(r)}{\pi v_0} - 1\right)} .$$

For example, if $\varphi_1 = 0$, $\varphi_2 = \pi/4$, $q(r,\varphi) = 4.38 \cdot 10^{-8}$ (m/s), $v_0 = 1.37$ (m/s), $\alpha = 0.6$ (1/m²) (i.e. that by $d = 0.2$ (m) $v = 1.4$ (m/s) and by $d = 1.0$ (m) $v = 2.2$ (m/s)) and $R = 10 000$ (m) then
The main diameter given by eqn (12) is shown in Figure 7.

\[ d = \sqrt{0.833 \left( \sqrt{1 + 3.83(1 - r^2 \cdot 10^{-8})} - 1 \right)}, \text{ (m).} \]  

(12)

In Figure 7 we can see that the optimal main diameter is almost constant over the whole pipe length because the consumption area is increasing, going further. The existing and optimum diameters obtained by eqn (11) for one of the mains of the City Centre of Tallinn are shown in Figure 8.
The difference between the existing and optimum situation in main diameter is obvious.

6 Conclusions

The diurnal change of water age in network pipes is investigated. The differential equation for the determination of water age in a typical case of daily water demand is solved. It is shown that great differences in water age during the day are possible. The problem of optimal flow velocity in pipes is discussed. The topology of urban water distribution system with optimal flow velocities is considered and the optimal number of water mains determined. The diameters of mains for the cases of optimal flow velocities and different consumption of water are determined. With regard to these aspects the detailed investigation of the water distribution network of the City Centre of Tallinn was carried out and possibilities for the rehabilitation of the network are outlined.

Acknowledgment

Financial support by the Estonian Science Foundation (Grant No 4847) is greatly appreciated.

References