Dynamic management of water distribution networks based on hydraulic performance analysis of the system

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Abstract In this paper the hydraulic performance of water distribution networks is evaluated by assessing the head values in demand points and velocities in pipes. To obtain the hydraulic parameters a head-driven simulation method is used. In this method, nodal outflows are not fixed and vary with nodal heads. Considering the possibility of a range of demand variations and mechanical and hydraulic failures in the system, nodal heads and pressure dependent outflows are obtained. Then, by using a mathematical function, the performance of the system is realistically evaluated. As expected, the level of service in the system is decreased when head and velocity values are out of the standard ranges. Also, the reliability of a water distribution network is calculated using the ratio of the pressure-dependent outflows to the demand values considering the probability of pipe failures. Comparing the level of service index and reliability applications on a test network, it can be concluded that the reliability method is not sensitive to high-pressure values in the system. However, in this situation the performance index shows a lower level of service in the network. This means that high reliability values guarantee a good connectivity and enough pressure to satisfy the required nodal outflows, although pressure values higher than the standard codes, which lead to more leaks and bursts, are not acceptable in water supply systems. Therefore, the existing definitions of reliability are not comprehensive enough to realistically evaluate performance of the system. Using the level of service index and the head-driven simulation method, the network performance under different normal and abnormal conditions can be appropriately evaluated for water companies.

Keywords Head-driven simulation; hydraulic performance; level of service index; pipe failure; reliability; water distribution networks

Introduction
Hydraulic performance or level of service in water distribution networks is a main criterion to evaluate the efficiency of the water system. Knowledge about actual network performance during different operating situations is a key tool to control and manage the existing water systems or design new networks. This concept has been reviewed as reliability or level of service in the literature. Reliability is the ability of the system to satisfy the required demand under sufficient pressure during normal and abnormal operating conditions. Abnormal conditions can occur due to pipe failure, outage of pumps, excess of demands, fire fighting, leakage, outage of reservoirs, etc. Many researchers have evaluated the level of service under the reliability context in water supply networks (For example, Germanopolous et al., 1986; Wagner et al., 1988; Cullinane et al., 1992; Tabesh, 1998).

At first the concept of reliability was considered to be the probability of an existing path between a source and a demand node (Tung, 1985). But, because of the strong inter-relationship between pipe flow rate and head loss, it has been established over recent years that reliability should be defined as the ratio of the actual flow delivered to the required flow. Unfortunately, there was no satisfactory method to analyse water networks with head-dependent consumptions. Most of the existing hydraulic models and algorithms for network analysis are based on the demand-driven simulation method. These models generally treat nodal outflows as constants with predetermined values regardless of pressure variations at demand nodes. Therefore, these models are not suitable to evaluate
the quantity of flow actually delivered by water distribution systems with less than the satisfactory pressure. Under special situations such as pipe breaks, leakage and excess of demands, the pressure will be reduced and pressure-dependent demands would be less than the required values. These conditions can be analysed based on the head-driven simulation method (HDSM), which relates the outflow to nodal pressures. Only a few researchers have used the head-driven simulation method to evaluate reliability and level of service accurately (Germanopolous et al., 1986; Cullinane et al., 1992; Fujiwara and Ganesharajah, 1993; Tabesh, 1998).

Using random analysis, Germanopolous et al. (1986) evaluated the hydraulic performance of water distribution networks by the head-driven simulation method. Reliability was assumed to be the same as the level of service and obtained by the frequency and duration of critical failures of the network equipment. They used a Poisson distribution to analyse the frequency-duration and probability of component failure. An exponential distribution was used to evaluate the duration of failure. This approach was complicated and no independent definition was suggested for level of service.

Coelho (1996) and Jowitt and Coelho (1997) proposed a method for performance assessment in water supply and distribution networks. They used a three-step performance assessment framework. The method was defined by three types of entities: a network variable such as pressure or velocity; a penalty curve which plotted the values of a level of service index, credited to the network variable at a network element level, over a given range; and finally a network operator which allowed the performance values at element level to be aggregated across the network or parts of it. Although this framework defines a criterion to evaluate the system performance using the demand-driven simulation method, it cannot assess the real performance of the system under abnormal situations. In this approach only demand variations are considered and effects of other abnormalities, such as any pipe failure on the hydraulic performance, are not discussed. Also, to compare the results the entropy concept, which is just a surrogate measure for reliability, was used. Weaknesses of the entropy method in comparison with the reliability concept can be seen in Tabesh (1998).

In this paper using the head-driven simulation analysis the actual value of hydraulic parameters such as nodal pressures and velocities in pipes are obtained. Then considering the effects of demand variations and pipe failures on the hydraulic parameters, the system level of service is evaluated using some penalty functions and network operators.

Methodology
Hydraulic analysis
The head-driven simulation of the hydraulics of pipe systems (HDSM) is considered to produce the available nodal heads and, consequently, available outflows. The method which has been described in detail by Tabesh (1998), uses the following nodal head-outflow relationship to calculate the value of nodal outflows (Tabesh, 1998; Wagner et al., 1988).

\[
Q_j^{\text{avl}} = Q_j^{\text{req}}; \quad \text{if } H_j \geq H_j^{\text{des}}
\]

\[
Q_j^{\text{avl}} = Q_j^{\text{req}} \left( \frac{H_j - H_j^{\text{min}}}{H_j^{\text{des}} - H_j^{\text{min}}} \right) \left( \frac{1}{n} \right); \quad \text{if } H_j^{\text{min}} \leq H_j \leq H_j^{\text{des}}
\]

\[
Q_j^{\text{avl}} = 0; \quad \text{if } H_j \leq H_j^{\text{min}}
\]

where \(Q_j^{\text{avl}}\) and \(Q_j^{\text{req}}\) are available outflow and demand at node \(j\), respectively, \(H_j^{\text{des}}\) is the desired head pressure to satisfy the demand, \(H_j\) is the available head and \(H_j^{\text{min}}\) is the
absolute minimum head at node $j$. $n$ is an exponent usually between 1.5 and 2. Herein a value of 2 is applied for $n$.

The head-dependent outflow term can be added to the continuity equation at node $j$, $(F_j)$, as follows:

$$F_j = \sum_{i=1}^{NJ} \left( \frac{H_i - H_j}{K_{ij}} \right)^{0.54} \text{sgn} \left( H_i - H_j \right) + Q_{j\text{req}}^{\text{eq}} \left( \frac{H_j - H_{j\text{min}}}{H_{j\text{des}} - H_{j\text{min}}} \right)^{0.5} = 0$$

(2)

in which $H_{j\text{min}} \leq H_j \leq H_{j\text{des}}$, $NJ$ is the number of nodes directly connected to node $j$, $K_{ij}$ is the resistance factor of pipe $ij$ and sgn denotes the sign of $(H_i - H_j)$.

According to Eq. (1), the second term of Eq. (2) is equal to $Q_{j\text{req}}^{\text{eq}}$, if $H_j = H_{j\text{des}}$ and it is equal to zero when $H_j = H_{j\text{min}}$. Eq. (2) is solved based on the Newton–Raphson method and choosing the nodal piezometric heads as unknown parameters (see Tabesh, 1998).

**Level of service index**

Level of service index is a criterion that introduces the hydraulic performance in the system. Using the results of the hydraulic model this index is calculated at both element and network levels.

**Level of service index for network elements.** Two main hydraulic parameters of nodal pressures and velocities in pipes are considered to evaluate the network performance. According to Zia (2000) two penalty functions are introduced in Figures 1 and 2, which plot the level of service index against the pressure and velocity values. An index of 0.25 is considered an unacceptable level of service and 0.5, 0.75 and 1 are regarded as acceptable, fair and excellent level of service, respectively. In Figure 1, $H_{\text{des}}^{\text{opt}}$ is the minimum desired pressure above which the demand is satisfied completely and $H_{\text{max}}$ is the maximum required pressure which is recommended by the standard codes. Also values of $H_1$, $H_2$ and $H_3$ represent outflows equal to 0.25, 0.5 and 0.75 of nodal demands ($Q_{j\text{req}}$), respectively. In Figure 2, $V_{\text{min}}$ and $V_{\text{max}}$ are the minimum and maximum velocity values introduced by the standard codes. $V_{\text{optl}}$ and $V_{\text{optu}}$ also show the domain of optimum or economical velocity in pipes, respectively. According to the nodal head and pipe velocity values produced by the hydraulic model, the level of service for each node and pipe can be evaluated by Figures 1 and 2.

**Network level of service index.** Applying two functions of $W_1$ and $W_2$, results of the level of service for each element are developed for the network. To assess the network level of service index due to the nodal pressures (LSIP) the following function is introduced:

$$\text{LSIP} = W_1(LSIPE_j) = \sum_{j =NJ} Q_{j\text{req}}^{\text{eq}}(LSIPE_j)$$

(3)

where $LSIPE_j$ is the level of service index based on pressure values at each node. Also, the network level of service index due to the velocities in pipes (LSIV) is defined as follows:

$$\text{LSIV} = W_2(LSIVE_{ij}) = \sum_{j =NP} V_{ij}(LSIVE_{ij})$$

(4)

in which $LSIVE_{ij}$ is the level of service index based on the velocity in pipe $ij$ and $NP$ is the number of pipes. $D_{ij}$, $L_{ij}$ and $V_{ij}$ are the diameter, length and volume of pipe $ij$, respectively.
Reliability assessment

Recently the concept of reliability has been widely used to assess the performance of the water system. In this paper reliability the index is introduced to compare the level of service index results. Considering the more recent and widely accepted definition of reliability as the ratio of the available flow to the required flow (demand) in conjunction with link failure probabilities, component and network reliability is assessed as follows.

Component (pipe) availability can be taken as the ratio of the mean time between failures to the mean time between failures and the mean failure, including repair and duration. This can be calculated using Cullinane et al. (1992):

\[ a_l = \frac{0.21218 D_l^{0.462131}}{0.00074 D_l^{0.285} + 0.21218 D_l^{0.462131}} \text{ where } l = 1, ..., NL \]  

(5)

where \( D_l \) is the diameter of pipe \( l \) in inches (1 in. = 25.4 mm) and \( NL \) is the number of links. Reliability for each node at any normal or subnormal configuration is defined as follows:

\[ r_j(M) = \frac{Q_j^{\text{avl}}(M)}{Q_j^{\text{req}}} \text{ where } M = 0, ..., NP \]  

(6)

where \( r_j(M) \) is the nodal reliability with \( M \) specified links (pipes) unavailable and \( Q_j^{\text{avl}}(M) \) is the available flow at node \( j \) when the \( M \) specified links (pipes) are unavailable. Taking all network configurations into consideration, the overall nodal reliability \( R_j \) is:

\[ R_j = \frac{1}{Q_j^{\text{req}}} \sum_{l=0}^{NP} p(l) Q_j^{\text{avl}}(l) \]  

(7)

where \( p(0) \) is the probability that all links are available and \( p(l) \) is the probability that only
Application test
To evaluate the results of the proposed methodology the test network of Figure 3 is chosen. Nodal and pipe data are shown in Table 1. In this example the parameters of Figures 1 and 2 are as follows: $H_j^\text{min}$ is the topographical level of each node (herein $H_j^\text{min} = 0$), $H_j^\text{des} = 27$ m, $H_{\text{max}} = 62$ m, $V_{\text{min}} = 0.3$ m/s, $V_{\text{max}} = 2.5$ m/s, $V_{\text{optl}} = 0.8$ m/s and $V_{\text{optu}} = 1$ m/s.

The level of service and reliability of this network are assessed under three different conditions. First, the level of service is evaluated based on demand variations during 24 hours a day (Figure 4). The results are presented in Figure 5. In this figure, the level of service index for pressure is below, but close to, the acceptable level of 0.5. The reason for low values of pressure index is that during this period nodal pressures are high (more than $H_j^\text{des}$ and even $H_{\text{max}}$). Consequently, pressure management is required to improve the pressure index in the system. On the other hand, the variations of the level of service index for velocity and reliability are the same. Also, fluctuations of the velocity index are opposite to the demand variation during 24 hours a day. This means that during peak demand times the velocities are out of the optimum domain.

Reliability is decreased during the peak demand period because of pressure reduction at nodes 6, 8 and 9 to below $H_j^\text{des}$. This situation leads to decreasing available nodal outflows at these nodes. Only at 3 am the reliability is 1, because total demands are satisfied at all demand nodes. However, in some periods, at some nodes (especially the critical one; node 9), the total required demand cannot be satisfied.

<table>
<thead>
<tr>
<th>Node no.</th>
<th>Demand m$^3$/min</th>
<th>Pipe no.</th>
<th>Diameter (mm)</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>1.248</td>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>1.248</td>
<td>2</td>
<td>175</td>
</tr>
<tr>
<td>4</td>
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<td>115</td>
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<tr>
<td></td>
<td></td>
<td>12</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 3 Layout of the test example ($H_1 = 100$ m, CHW = 130 and $L_{ij} = 1,000$ m)
In the second step, the level of service index and reliability of the system are assessed due to variations of demand values from \(0.25 \ Q_j^{\text{req}}\) to \(4 \ Q_j^{\text{req}}\) with steps of \(0.25 \ Q_j^{\text{req}}\). This analysis evaluates the reaction of the network performance to the exceptional demands. The results are shown in Figure 6. It can be seen that the velocity index is decreasing until 2 \( Q_j^{\text{req}}\) and then remains constant. For 0.5 \( Q_j^{\text{req}}\), the velocity index is at an excellent level because the velocity in the pipes are near the optimum level. Therefore, with higher demands, the velocity in the pipes is higher and the velocity index tends to lower values.

Reliability faces a decreasing situation. For all demands above 0.5 \( Q_j^{\text{req}}\), the pressure at node 9 and, in some situations, the pressure at nodes 6 and 8 are less then \(H_j^{\text{des}}\). This leads to unsatisfying the full demands at these nodes and therefore, reliability is less than 1. The pressure index is again near, but below, the acceptable level of 0.5 because, with an increase of demands, head losses would be higher and nodal pressures would be lower.

In the third step, the level of service and reliability due to pipe breakage and bursts during the operational situation in the network are compared. Results of each pipe break are represented in Figure 7. Again the pressure index fluctuates between 0.25 and 0.5 and shows unacceptable pressure performance. The velocity index and reliability vary around 0.75 due to each pipe break, which shows a good performance. The effects of break in pipes (1, 7), (2, 10), (3, 8), (4, 11), (5, 9), and (6, 12) are the same for all parameters, because the layout of the network is symmetrical. Breakage of pipes (6, 12) and (1, 7) are critical for the pressure index, and velocity index and reliability, respectively. Also, the variations of pressure and velocity indices are opposite to each other.
As an overall discussion, it can be said that in this network, velocity index and reliability under different operational situations are at an acceptable level. The pressure index is unacceptable because in different situations the nodal pressures in some parts of the network are very high, and in the critical part it is lower than the minimum standard level. To improve the situation a pressure management programme can be applied. For example, using PRV after reservoir or change of pipe diameters and using the pump in the critical part of the network, may improve the pressure index of the system. A very valuable observation from the results is the considerable difference between reliability and pressure index. The reason is the weakness of the reliability formulation, which is not sensitive to the pressure values more than $H_{j}^{des}$ and $H_{max}$.

**Conclusion**

In this paper, using the head-driven simulation method the level of service for water distribution networks is evaluated. Introducing two pressure and velocity indices based on the standard codes, the hydraulic performance of the system is assessed in different operational situations such as demand variations in 24 hours, demand fluctuations up to four times the required demands and pipe breakages. The results are compared with the reliability values that today are used to assess the network performance. The results show the similarity of reliability and velocity index and the difference of velocity and pressure indices. From the results, some decisions can be made as to how to improve the system performance.

In addition, insensitivity of the existing reliability formulation to the pressure values higher than $H_{j}^{des}$ and $H_{max}$ is highlighted. In this situation, pressure index indicates lower performance of the network. Therefore, the existing definition of the reliability needs to be modified. In this condition higher values of reliability just guarantee the satisfaction of total nodal demands, without considering the side effects of high pressures. However, high pressure is not acceptable because it leads to more bursts, breaks and leakage in the system. Finally, it can be concluded that the level of service concept is a valuable tool to evaluate the hydraulic performance of the water distribution networks. It can identify weaknesses of the system and can help to determine possible scenarios to improve the system performance.

**References**


