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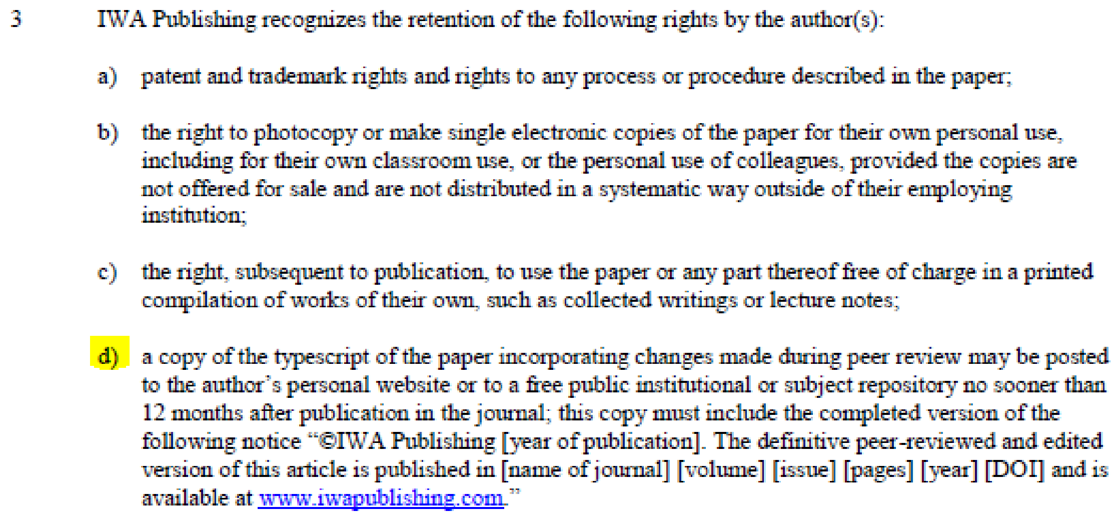

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Failure monitoring in water distribution networks

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Abstract
An algorithm for the burst detection and location in water distribution networks based on the continuous monitoring of the flow rate at the entry point of the network and the pressure at a number of points within the network is presented. The approach is designed for medium to large bursts with opening times in the order of a few minutes and is suitable for networks of relatively small size, such as district metered areas (DMAs). The burst-induced increase in the inlet flow rate is detected using the modified cumulative sum (CUSUM) change detection test. Based on parameters obtained from the CUSUM test, the burst is simulated at a number of burst candidate locations. The calculated changes in pressure at the pressure monitoring points are then compared to the measured values and the location resulting in the best fit is selected as the burst location. The EPANET steady-state hydraulic solver is utilised to simulate the flows and pressures in the network. A sensitivity-based sampling design procedure is introduced to find the optimal positions for pressure monitoring points. The proposed algorithm is tested on a case study example network and shows potential for burst detection and location in real water distribution systems.

Keywords
Pipe networks; monitoring; instrumentation; burst detection and location

INTRODUCTION

A pipe burst is a common type of failure in water distribution systems. It is an undesirable, expensive and, unfortunately, relatively frequent event. A pipe burst can be defined as the rupture of a pipe wall or other element in the network that is usually followed by a significantly large discharge of water. Due to the high discharge, bursts can have dramatic consequences, including damage to surrounding infrastructure, flooding of properties, interrupted supply, and consumer complaints.

Since many water supply systems are old and in poor condition, it is practically impossible to prevent pipe failure. Nevertheless, the damage and losses associated with bursts can be reduced by minimising the burst detection and location time. Although most bursts result in the appearance of water on the ground surface and are detected by customers or water company personnel (passive burst detection), the average location time can be still quite long. In Morrison (2004) the awareness and location of a 4 $m^3/hour$ burst is estimated to be 5 days. Obradovic (2000) reported burst location times of around 18 hours. Experience from the oil and gas industries shows that the determination of a burst's location can be made more efficient and accurate by continuous monitoring of the system. Recent developments in instrumentation and data acquisition have reduced the cost of monitoring systems and made continuous monitoring of water supply systems feasible. However, most burst (and leak) detection techniques consider single pipelines and cannot be directly applied to a network situation (Silva *et al.* 1996; Zhang 2001; Misiunas *et al.* 2003). In fact, the complicated topology found in water distribution networks requires special attention for burst detection and location methods to be successfully applied.

The majority of pipe network monitoring approaches found in the literature focus on the assessment of leakage that is present in the system. The most common and straightforward technique is the concept of district metering area (DMA) (WRc 1994). A district is an area of the pipe network that is hydraulically isolated from the rest of the network by the permanent closure of valves. A DMA typically comprises 300-2000 properties and has a metered incoming flow and pressure at the entry point. The leakage level can be determined by performing a simple mass balance analysis of the flow that is entering the DMA. Manual techniques are then used to locate the leak point, such as listening devices and correlators. Since the DMA concept was introduced in the 1980s, a considerable amount of research has been directed towards finding a more efficient way to detect and locate leaks (Andersen and Powell 2000; Mounce *et al.* 2003; Buchberger and Nadimpalli 2004). Most of leakage detection and location techniques described in the literature target the whole range of leak sizes and types (i.e. burst, background leakage) and usually do not determine the exact leak location.

THE SCOPE OF APPLICATION

In this paper, pipe bursts of medium to large size that develop within the period of minutes and have a substantial influence on the pressure within the network are considered. Misiunas et al. (2004) presented a methodology for the detection and location of sudden bursts in pipe networks based on the continuous monitoring of pressure at two (or more) points within the network and hydraulic transient theory. The approach is efficient for pipe failures that induce transient waves into the system. In some cases, a pipe break can develop over a longer period of time causing little or no observable transient behaviour and therefore cannot be located by the transient-based technique. This paper describes an approach that can be referred to as an extension of the technique presented in Misiunas et al. (2004) for slower bursts. The flow rate and steady state pressure readings at a relatively low sampling rate are used to detect and locate the break. The proposed technique is applicable on a scale of a DMA. To simplify the description of the method, two basic assumptions are made: (1) there is only one flow entry point in the DMA analysed and (2) the demand within the DMA is purely residential and the total demand is assumed uniformly distributed between all nodes.

MODELLING OF STEADY-STATE FLOW IN PIPE NETWORKS

A water distribution network basically consists of set of nodes (junctions) that are joined to each other by links (pipes). The principles of conservation of mass at nodes and conservation of energy between nodes and in loops are used to model pressure, flow and hydraulic elements in the network.

Conservation of mass dictates that the fluid mass entering any node will be equal to the mass leaving the node:

$$\sum_{j=1}^{pipes} Q_j - D_M = 0 \tag{1}$$

where Q_j is the inflow to node from j^{th} pipe and D_M is the demand at the node. The conservation of mass equation is applied to all nodes in a network, resulting in one equation for each node in the network.

Conservation of energy dictates that the difference in energy between two points must be the same regardless of the path that is taken (Bernoulli 1738):

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + \sum h_a = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + \sum h_f + \sum h_m \tag{2}$$

where: Z = elevation; P = pressure; γ = fluid specific weight; V = velocity; g = gravitational acceleration constant; h_a = head added by pumps; h_f = head loss due to pipe friction; h_m = head loss due to minor losses. When a series of links and nodes constitute a closed path, they form a loop. In a distribution network, the sum of all energy losses in an independent closed path or loop must equal zero. Additionally, energy must be conserved between two nodes of known energy. As a result, one energy equation must be developed for each pipe (or loop) depending on the method used. In this paper, the EPANET hydraulic solver (U.S. Environmental Protection Agency 2000) is used to simulate the flows and pressures in a pipe network.

From Eqs. (1) and (2) it can be seen that change of demand at one node (i.e. due to a burst) will influence the flow rates and pressure at that node and the distribution of pressures and flow rates at other nodes. Since a network with measured inflow rate (DMA) is considered in this study, the burst flow rate will be fully realised in the flow rate measurement at the entry point of the system.

MONITORING OF SYSTEM FLOW FOR A BURST EVENT

In this paper it is proposed that the burst event may be detected from the continuous flow rate measurement at the entry point of the network. The burst discharge will increase the measured total flow rate, Q^m, entering the network. The increase of Q^m may be detected using a cumulative sum (CUSUM) change detection test (Page 1954). The CUSUM test has been extensively applied for change detection in different time series analysis problems (Basseville and Nikiforov 1993). If the flow rate data contains a high level of measurement noise pre-filtering is applied using the adaptive Recursive Least Squares (RLS) filter. The filter estimates the signal θ_t from the measurement $Q^m{}_t$ (containing noise) as

$$\theta_t = \lambda\theta_{t-1} + (1-\lambda)Q_t^m = \theta_{t-1} + (1-\lambda)\varepsilon_t \tag{3}$$

where $\varepsilon_t = Q^m{}_t - \theta_{t-1}$ is the prediction error and the parameter $\lambda \in [0,1)$ is the forgetting factor. The value of the forgetting factor determines the smoothing effect of the filter. The prediction error values ε_t are fed into the CUSUM test to determine whether a change has occurred in the measured signal. Mathematically, the CUSUM test is formulated as the following time recursion

$$\begin{aligned} &G_0 = 0 \\ &G_t = \max(G_{t-1} + \varepsilon_t - \nu, 0) \\ &\text{if } G_t > h \text{ then issue alarm and set } t_a = t,\ G_t = 0 \end{aligned} \tag{4}$$

where G_t is the cumulative sum value at a time t, h and ν are threshold and drift parameters respectively. For every sample of data, the part of the change in signal ε_t that exceeds the drift value (the expected variation) is added to the cumulative sum G_t. When G_t reaches the threshold value h, an alarm is issued and the time of change t_a is recorded. In the classical form of the CUSUM algorithm G_t is then reset to zero. A modified CUSUM test is presented in this paper. Instead of resetting G_t directly after t_a (when $G_t > h$), the cumulative sum is calculated until its value starts decreasing. The reason for such a modification is due to the uncertainty of the burst parameters – the burst size and development time (from the burst event until the maximum burst flow is established). Figures 1a and 1b show the idealized burst flow and total flow rate traces. The maximum burst flow rate $Q_{B,max}$ and the time $t_f - t_s$ that is taken for Q_B to reach $Q_{B,max}$ are unknown and can vary considerably for different bursts. As it will be shown later in the paper, for the determination of the burst location it is beneficial to register the maximum change in pressure induced by the burst. To achieve that, pressure measurements before the burst event ($t=t_s$) and after the burst flow has reached its maximum value ($t=t_f$) have to be determined. As shown in Figure 1c, t_s corresponds to the time when dG/dt becomes positive and t_f corresponds to the time when dG/dt becomes zero or negative. Based on these observations times t_s and t_f can be found.

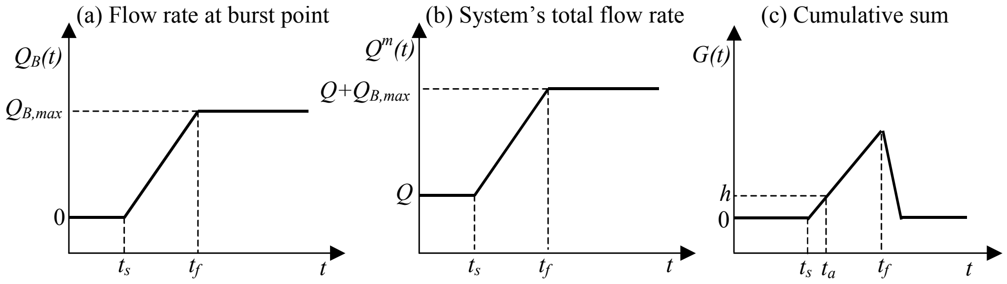

Figure 1. The generalised traces of (a) flow rate at burst point, (b) total flow rate ant the entry point and (c) cumulative sum.

The drift ν is chosen so that it is larger than typical operational flow rate oscillations in the system, which can be determined from the historical flow rate data. Usually water demand changes quite rapidly during certain periods of the day and can be rather stagnant at other times, especially during the night hours. Thus, variable drift selection can be introduced to improve the performance of the burst detection and location technique. The specific drift set points can be derived for every hour or peak/off-peak periods based on the observed fluctuations of flow rate in a particular network. Theoretically, threshold h can have a small positive value (resulting in $t_a \approx t_s$). However, in reality, the fluctuations in flow rate due to demand can exceed drift value which would result in $G > 0$. To prevent false alarms triggered by such situations, h is set to be larger than drift, i.e. $h = 2\nu$.

BURST LOCATION ALGORITHM

The schematic view of the complete burst detection and location algorithm is shown in Figure 2.

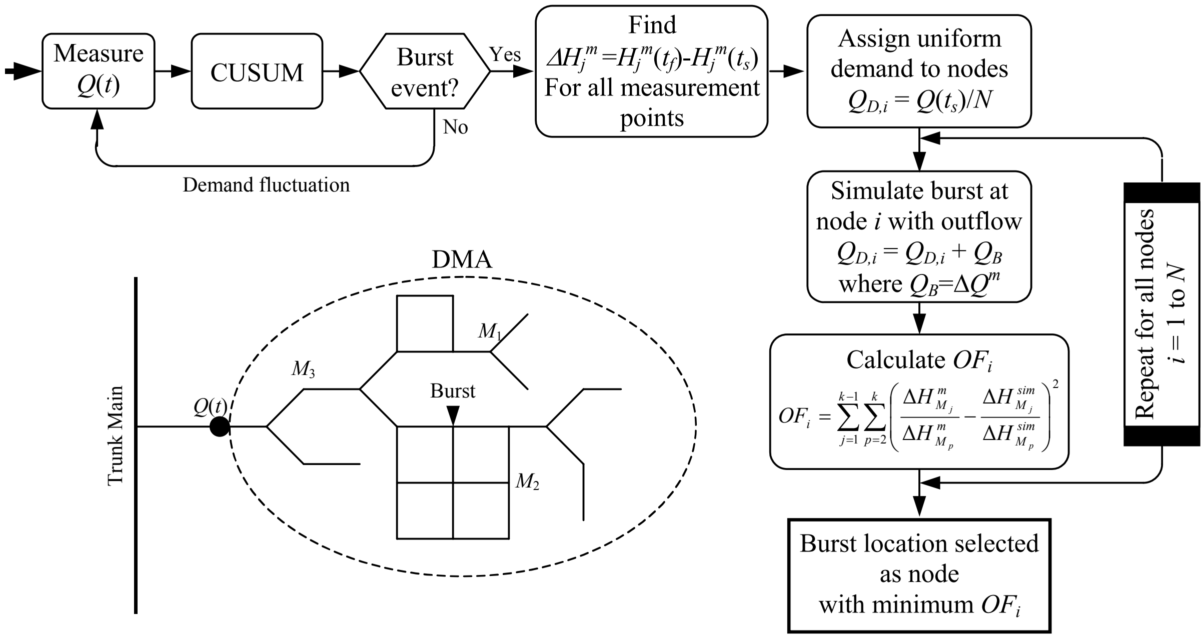

Figure 2. The structure of the continuous burst monitoring algorithm

Once the presence of a burst is detected in the flow rate measurement at the entry point of the network, the location of the burst is found by searching for the burst node based on the observed changes of pressure at a number of measurement points throughout the network. Using the burst start time t_s and the time when burst flow has reached its maximum t_f, as identified by the CUSUM change detection test, the total change in flow rate due to the burst and the changes in pressure at the monitoring points can be calculated:

$$\begin{aligned}\Delta Q^{m} &= Q^{m}(t_f) - Q^{m}(t_s) \\ \Delta H^{m}_{M_j} &= H^{m}_{M_j}(t_f) - H^{m}_{M_j}(t_s)\end{aligned} \tag{5}$$

The demand value for an individual node is assigned as a proportion of $Q^m(t_s)$ based on historical demand information at that node. If no demand information is available, an average demand of $Q_{D,i}=Q^m(t_s)/N$ is assigned uniformly to all nodes. The burst of size $Q_B=\Delta Q^m$ is simulated by assigning $Q_{D,i} = Q_{D,i} + Q_B$ to one burst candidate position and calculating the pressure and flows in the network. In this study, all the nodes in the network are nominated as burst candidate locations. Simulated pressure values at the measurement points are used for calculating the objective function:

$$OF_i = \sum_{j=1}^{k-1} \sum_{p=2}^{k} \left(\frac{\Delta H^{m}_{M_j}}{\Delta H^{m}_{M_p}} - \frac{\Delta H^{sim}_{M_j}}{\Delta H^{sim}_{M_p}} \right)^2 \qquad \forall i \in [1, N] \tag{6}$$

where ΔH^m is the measured change in pressure, ΔH^{sim} is the simulated change in pressure, k is a number of pressure measurement points in the system and $M_{1,\dots,}M_k$ are the nodes where the measurement points are located. The objective function is calculated for all burst candidate locations and the node having smallest OF_i value is declared to be the burst position. The burst size is equal to the detected change in the flow rate observed at the inlet point of the network ($Q_B=\Delta Q^m$).

MEASUREMENT LOCATION ALGORITHM

The optimal placement of the pressure monitoring points is an important factor that influences the performance of the proposed technique. A large number of measurement positioning (also called sampling design) approaches are described in the literature (Liggett and Chen 1994; Bush and Uber 1998; De Schaetzen *et al.* 2000; Lansey *et al.* 2001; Kapelan *et al.* 2003; Vítkovský *et al.* 2003). Most are based on sensitivity analysis. The sensitivity matrix can be derived using a perturbation method (Bush and Uber 1998; De Schaetzen et al. 2000) where every element represents the change in a state variable due to the change of a single parameter:

$$S_{i,j} \cong \left| \frac{\partial H_j}{\partial Q_{D,i}} \right| = \left| \frac{H_j(Q_{D,i}) - H_j(Q^{*}_{D,i})}{Q_{D,i} - Q^{*}_{D,i}} \right| \qquad \forall i \in [1, N], \forall j \in [1, N] \tag{7}$$

where $H_j(Q_{D,i})$ is the computed head at node j for the assumed demand $Q_{D,i}$ at node i and $H_j(Q_{D,i}^*)$ is the computed head at node j after alternating the assumed demand $Q_{D,i}$ at node i to $Q_{D,i}^*$. The value of Q_D depends on the average demand in the system that can be determined from the historical data. The demand perturbation Q_D^* is set depending on the expected size of the burst.

A sampling design can be defined as a set of monitoring points $X=(M_1,\dots,M_k)$ where M_j is the position of j^{th} monitoring point. The task is to optimally distribute k monitoring points among N nodes. Two performance indicators may be used to measure the merit of a particular sampling design:

(1) The sum of sensitivities at all monitoring points in sampling design X for every possible burst location:

$$\eta_{1,X} = \sum_{i=1}^{N} \sum_{j=1}^{k} S_{i,M_j} \tag{8}$$

The upper limit $\eta_{1,max}$ can be derived from the sensitivity matrix by setting $k=N$. The lower limit $\eta_{1,min}$ is zero.

(2) The probability that a unique burst location will be derived using the objective function from Eq.(6) for every burst candidate location:

$$\eta_{2,X} = P\left(\frac{S_{i,M_j}}{S_{i,M_v}} - \frac{S_{p,M_j}}{S_{p,M_v}} > \beta\right) \qquad \forall i \in [1,N], \forall p \in [1,N], \forall j \in [1,k-1], \forall v \in [2,k] \tag{8}$$

where β depends on the resolution of pressure measurements. The limits $\eta_{2,max}$ and $\eta_{2,min}$ are assumed to be 1 and 0 respectively. To combine the two performance indicators (Eq.(8) and (9)) into one objective function a compromise programming approach is used. Compromise programming is a multi-criterion distance-based technique designed to identify compromise solutions. The following objective function is used:

$$OF_X = \sqrt{\sum_{n=1}^{2} w_n \left(\frac{\eta_{n,X} - \eta_{n,\max}}{\eta_{n,\min} - \eta_{n,\max}}\right)^2} \tag{9}$$

where w_1 and w_2 are the weights for η_1 and η_2 respectively. The sampling design X that has the smallest value of OF_X is selected as optimal sampling design.

CASE STUDY

The example network model shown in Figure 3 is used to verify the proposed method for burst detection and location. The network has 108 pipes and 79 nodes. Pipes have diameters between 100 and 200 *mm*, lengths between 70 and 210 *m* and a roughness height of 0.2 *mm*. The node elevations are in the range of 140 to 160 *m*. The network is fed from a fixed head (56 *m*) reservoir.

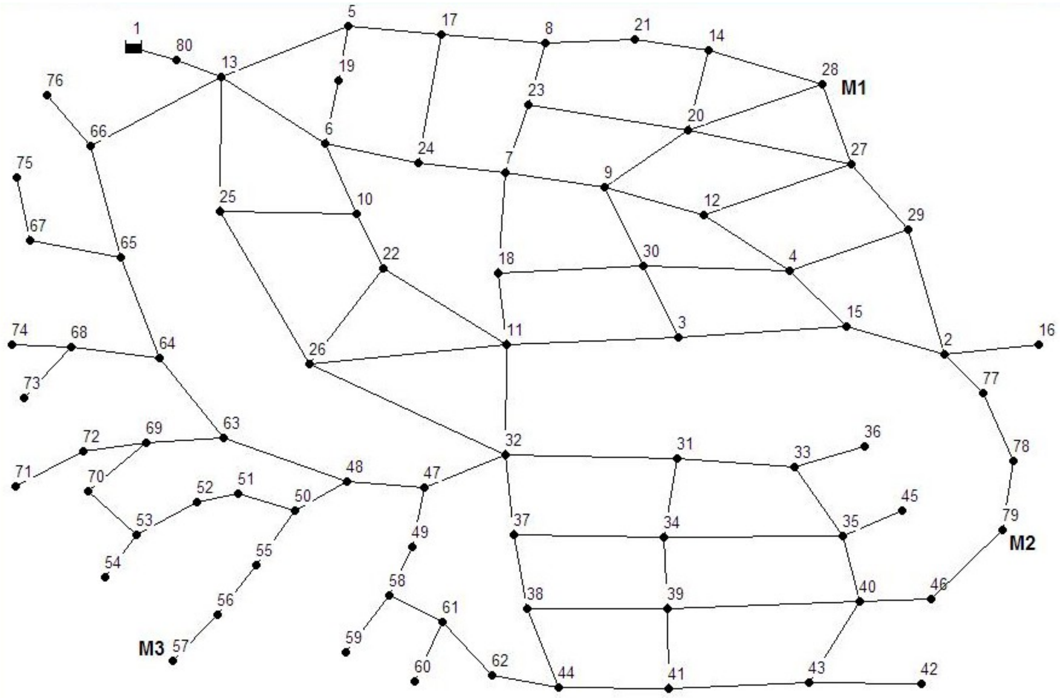

Figure 3. The layout of the pipe network used for the case study.

The 24-hour incoming flow rate “measurement” (Figure 4a) is artificially generated at 1 minute intervals based on the data presented in Guercio et al. (2001) assuming that 300 households are connected to the network. Noise is added to the flow rate pattern as shown in Figure 4b to represent discrete demand changes corresponding to household appliance use as described by Buchberger and Nadimpalli (2004).

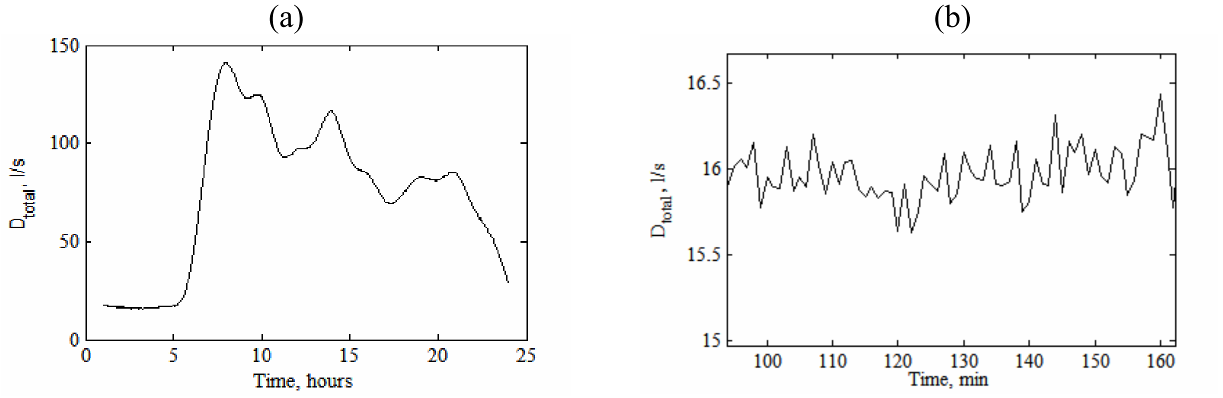

Figure 4. (a) 24-hour demand curve and (b) zoom in on the demand curve to show noise characteristics. 1 minute sampling time.

The burst was simulated as an increase in the measured flow rate (Figure 1a,b) with size corresponding to the actual size of the burst and the slope being proportional to the burst opening time. The pressure was monitored at nodes 28, 57 and 79 (M1, M2 and M3 in Figure 3) which were selected using the sampling design procedure described earlier in the paper (with $w_1=0.8$ and $w_2=0.2$). The measured pressure changes at monitoring points were obtained by simulating the burst of the actual size at the actual location and subtracting pressure values before and after the burst event: $\Delta H^{m}_{Mj}=H^{m}_{Mj}$ *(after burst)*-H^{m}_{Mj} *(before burst)* for all measurement sites $j\in[1,k]$.

The variable drift value for CUSUM test is obtained by dividing a 24-hour period into two parts – night (22:00-06:00 hours) and day (6:00-22:00 hours). The drift was chosen to be larger than the maximum changes in flow rate during the night and day time intervals as 0.939 and 1.763 *L/s*. The threshold has been set to twice the drift value, i.e. 1.878 and 3.526 *L/s* for night and day parts respectively.

Three sets of tests were performed to evaluate the performance of the proposed technique:

(1) *Detection of bursts that occur at different times of the day, with different sizes and opening times* (see Table 1). Five different bursts with sizes between 5 and 20 *L/s* and opening times in the range of 1 to 8 minutes were successfully detected. Errors in the estimated size of the burst were less than 2.5%.

Table 1. Burst detection tests and results.

Burst No.	Actual burst parameters			Detected burst parameters		
	Time of burst	Opening, *min*	Size, *L/s*	Time of burst	Opening, *min*	Size, *L/s*
1	4:20	3	10	4:20	3	10.2
2	6:00	2	15	6:00	2	14.76
3	9:00	8	20	9:00	8	19.07
4	20:00	5	12	20:00	5	12.21
5	22:30	1	5	22:30	1	4.78

(2) *Location of bursts that occur at burst candidate locations*. The actual burst was placed at the node of the network (all nodes were tested, one test for each location) and the search for the burst location was performed using the proposed technique. The five different bursts from the first set of tests were tested and results are summarised in Table 2. Around 70% of all tested burst locations

were identified uniquely and in other cases, two or more nodes (including the actual burst location) clearly identified the part of the network where the failure has occurred.

Table 2. Burst location tests and results when bursts occur at network nodes.

Test No.	Actual burst location	Burst No.	Burst location found (tests)	More than one location had same *OF* value (tests)
1-79	Nodes 1-79*	1	78	24
80-158	Nodes 1-79*	2	79	24
159-237	Nodes 1-79*	3	79	22
238-316	Nodes 1-79*	4	79	25
317-385	Nodes 1-79*	5	79	23

*79 tests were performed with one burst node per test.

(3) *Location of bursts that occur at points that were not selected as burst candidate locations, i.e. along the pipe length*. The actual location of the burst was not to one of the candidate burst locations. Although unable to determine the true burst location, the technique identified the adjacent node to the burst pipe as the burst location, as shown in Table 3.

Table 3. Burst location tests and results when bursts occur along pipes.

Test No.	Burst No.	Actual burst location	Estimated burst node
386	1	Between nodes 32 and 11	32
387	1	Between nodes 63 and 64	64
388	1	Between nodes 17 and 24,	17
389	1	Between nodes 39 and 40	40

CONCLUSIONS

The proposed burst detection and location technique has been demonstrated to be extremely promising. As shown in the case study, a range of bursts that occur at different times of the day with different sizes and opening times and at different locations within the network were successfully detected and located. One flow rate and only three pressure monitoring points are enough to find the unique location of the burst that occurs at (or in between) for up to 70% of nodes in the network that has 79 nodes and 108 pipes. The technique is based on the real-time continuous monitoring of network inflow and pressure, thus, the burst is detected and located directly after it occurs and the isolation time can be minimized preventing the large losses associated with the pipe failure. Further research, including field validation in real pipe networks, is required to make a more specific evaluation of the influence of burst parameters, network topology and measurement accuracy on the performance of the method. The proposed technique is suitable for applications on the DMA level, which would make its implementation in the real water distribution networks quite straightforward. If implemented, the proposed technique could increase the efficiency and reliability of the water supply. The cost of installation is relatively low and the investment return time is expected to be short.

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