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Locating pipe bursts in a district metered area via online hydraulic modelling

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Abstract

This paper presents an online burst location method which extends the recently developed methodology [1] for online burst detection in Water Distribution Systems (WDS) at the District Metered Area (DMA) level. This is achieved by a combination of data algorithms that make use of flow and pressure residuals between the online hydraulic model predictions and corresponding WDS observations. The leak location methodology was tested on a series of simulated pipe burst events in a real-life UK DMA. The results obtained show that the new methodology is effective in determining burst locations in near real-time and satisfactorily estimates the burst flows.

Keywords: Burst Detection, Burst Localisation, Online Hydraulic Modelling, Water Distribution System

1. Introduction

The problem of pipe bursts location in Water Distribution Systems (WDSs) still remains an important issue for water companies worldwide. The expansion of water networks and the increasing demand for water due to population growth are adding more pressure on the ageing water infrastructure. Therefore, it is of paramount importance for water companies to ensure that water resources are managed effectively and that the water losses

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from pipe networks **[2]** are reduced. Water losses cause economic damages to water companies and also affect their operational performance, customer service and reputation **[3]**. The source(s) of water losses vary from illegal connection to fractures in pipelines. In the UK, up to 25% of the supply water is accounted as water loss. In recent years, hydraulic modelling technologies, burst detection and location techniques and improved leakage control have all advanced to enable industry practitioners to identify and locate leaks/bursts **[4]**. However, UK water companies are considering to combine a hydraulic model with distributed data from multiple hydraulic sensors in a WDS section to tackle and reduce water losses in near real-time.

There are many techniques which attempt to solve the pipe burst location problem by numerical analysis **[5]**. Misiunas et al. **[6]** presented a method that utilises the negative pressure-wave technique and the cumulative sum of the residual between hydraulic model predictions and WDS observations. This method was shown to work well in a small WDS network. However, the instrumentation required for implementing the negative pressure-wave technique is expensive. Wu et al. **[7]** used genetic algorithms to optimise pressure-dependent emitter coefficients as possible leakage points via an iterative, calibration based method. This method, however, can only be used for offline WDS applications. Bicik et al. **[8]** developed a decision support method to assist WDS practitioner to locate pipe bursts events in a timely fashion utilising various information sources (e.g., customer calls, pipe characteristics, etc.). This method relies heavily on customer contacts which mean hidden burst events may not be detected or located. Skworcow and Ulanicki **[9]** considered an approach that uses changes in head-loss between pressure loggers for burst detection and location analysis. The success of such approach is limited to pipe bursts occurring at night.

Farley et al. **[2]** presented a method that uses both flow and pressure meters for burst detection and location. The method is based on a predefined sensitivity Jacobian matrix to determine the hydraulic sensor most sensitive to an occurring burst. This method hasn’t been exploited for online WDS applications. Romano et al. **[3]** used several geostatistical techniques for approximate location of pipe burst events in WDS. The proposed methodology displayed some success in locating a series of flushing events in a District Metered Area (DMA). However, the authors did not use any hydraulic model to perform approximate burst location and, as a result, applying such methodology in a large urban DMA can be challenging. Kang and Lansey **[10]** presented a data driven simulation-based burst detection and location approach in WDSs using burst sensitivity matrix and control limits. The burst sensitivity matrix is developed by synthetically generating bursts and analysing the WDS hydraulic responses to the bursts. The technique worked successfully in a small and simple synthetic WDS model with less than 15 nodes. Hence, the performance of the technique in a real-life DMA model is unknown. Adachi et al. **[11]** proposed a leakage location estimation method to prioritise WDS sections for leak analysis. The estimation method combined the difference between the WDS hydraulic model predictions and observations and also asset information (i.e., pipe diameter, length).

This paper proposes a new methodology for locating burst events within a DMA in near real-time. This methodology uses a hydraulic simulation model and the observed field data for a reliable and rapid burst location area identification.

The paper is organised as follows. After this introduction, section 2 provides an overview of the new burst location methodology. Section 3 presents the case studies and the hydraulic data considered for analysis. Section 4 presents the key results and reviews the performance of the proposed burst location methodology. Finally section 5 provides concluding remarks and describes the planned future work.

2. Methodology

2.1. Burst Localisation Methodology Overview

The objective of the proposed Burst Localisation Methodology (BLM) is to approximately locate the burst within the DMA in near real-time by using observed and predicted hydraulic system states. The BLM is performed after a pipe burst is detected by using the corresponding burst detection model [1]. An overview of principal BLM procedural steps is shown in Figure 1.

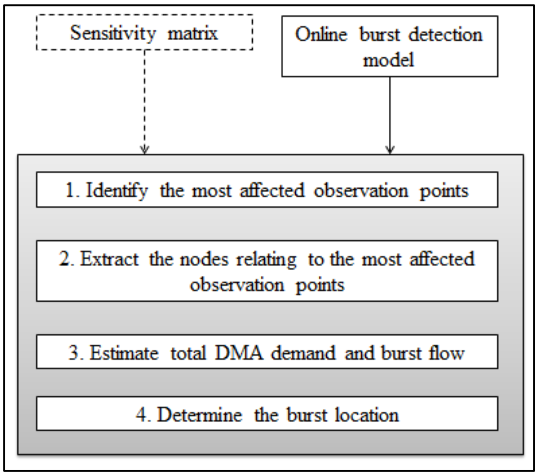


Figure 1: The flowchart of Burst Localisation Methodology

The sensitivity matrix is a matrix based on the sensitivity of hydraulic model predicted flows and pressures at observation points to bursts simulated at different DMA nodes. Sensitivity is determined by using multiple offline hydraulic simulations with the aim to identify the most sensitive hydraulic sensors' location(s) assuming potential bursts at all network nodes. This matrix is developed offline before the above BLM methodology is applied online. Once a pipe burst is detected, the second step ranks the observation points in descending order based on the burst detection metric values obtained by using the online burst detection model [1]. The order (rank) of the observation points indicates the level of observation points being affected by the burst. Therefore, the highest rank indicates the observation point that is most affected by the burst. The most affected observation points are then identified in the above matrix and are used to form a short list of likely burst locations. The third step estimates the total DMA demand and burst flow using multiple hydraulic model simulations and several data analysis techniques (see section 2.3 and 2.4). The total DMA demand is estimated assuming no burst flow in the DMA. The last step involves running the hydraulic model with the estimated total DMA demand and the burst flow simulated in turn at each network node shortlisted (as likely burst location) in the second step. Finally, the analysed candidate burst locations (network nodes) are ranked in ascending order based on the total residual error between predicted and observed flow and pressure data at the observation points. A predefined number of nodes are used to determine the burst area. The BLM procedure outlined above is repeated at each time step (e.g., every 15minutes) following a burst alarm.

2.2. Development of the sensitivity matrix

The sensitivity matrix is a binary matrix. The matrix value of 1 indicates that the observation points are sensitive to burst located at given network node and the matrix value of 0 means otherwise. The proposed method to build the sensitivity matrix offline follows four steps as summarised in Figure 2.

The first step is to check and/or calibrate the hydraulic model offline. The second step runs hydraulic simulations for 24hours with fixed time steps (i.e., 15mins) under normal conditions (i.e. assuming no bursts and by using demands from the offline calibrated model) to obtain a hydraulic system state (i.e. pressure or flow) at each sensors' location. The third step repeats the previous step but under abnormal conditions when burst flow is simulated in turn at each network node (i.e. at all possible locations). The fourth step aims to calculate the impact a burst has on the hydraulic sensors' location within the DMA by comparing the hydraulic states obtained under normal and abnormal conditions (at that location). A threshold value is used to determine whether burst simulated at a given network node affects significantly enough the hydraulic state at each sensors' location. If the hydraulic state residual error between normal and abnormal conditions is greater than this threshold then a value of 1 is assigned to the corresponding sensitivity matrix variable (0 otherwise).

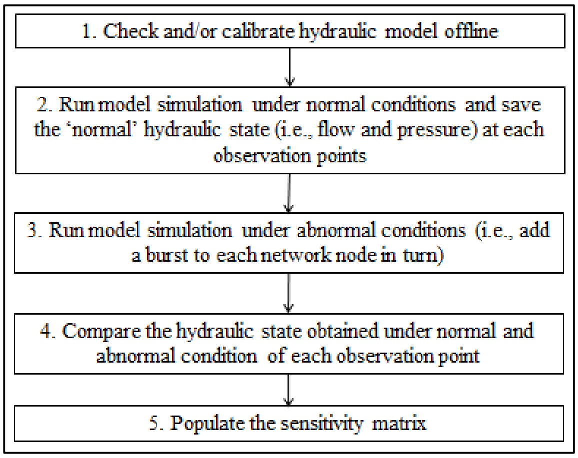


Figure 2: The flowchart of hydraulic sensors - nodes matrix

2.3. *Estimation of total DMA demand and burst flow*

The proposed method to determine a total DMA demand and burst flow in real-time is shown in Figure 3. The total DMA demand is estimated assuming no burst flow in the DMA.

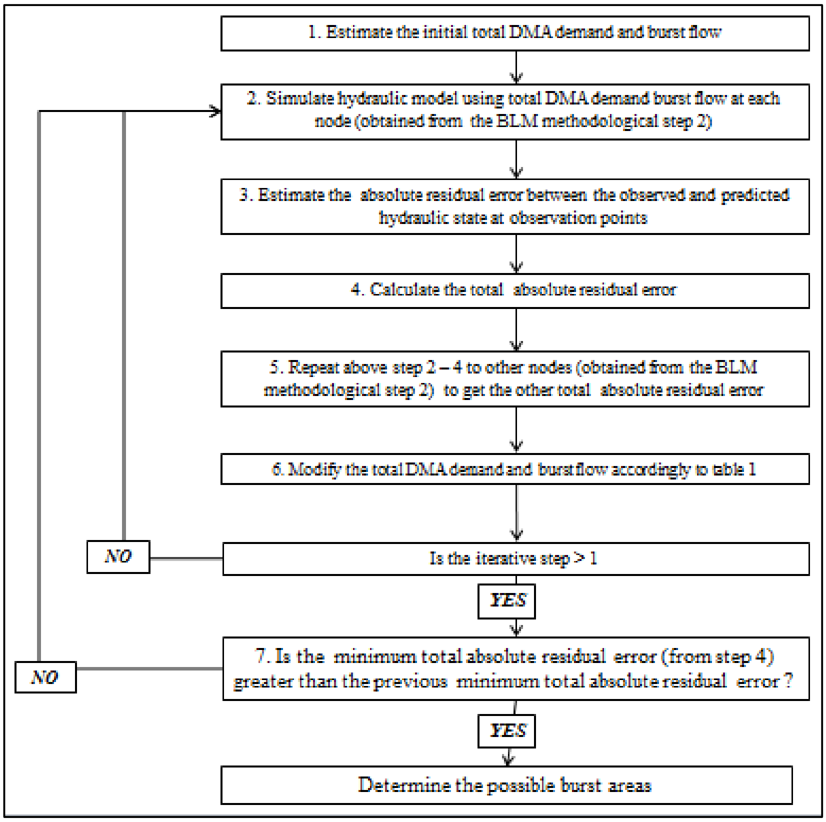


Figure 3: The flow chart of total DMA demand and burst flow estimation

The first step estimates the initial total DMA demand and burst flow. The initial total DMA demand is the forecasted DMA demand from a water demand forecasting model. The burst flow is the difference between the estimated demand based on the inlet/outlet flow observations and the forecasted DMA demand. The second step simulates total DMA demand and burst flow at each node obtained from the BLM methodological step 2 via hydraulic simulation. The third step determines the residual error between the observed and predicted hydraulic states at each sensor's location. The fourth step calculates the total residual error. The fifth step repeats step 2 – 4 for each node to obtain total residual error at each sensor's location. The sixth step modifies the burst flow and total DMA demand accordingly to objective functions in Table 1. The final step compares the lowest total absolute residual error to the previous lowest total absolute residual error. If the lowest total absolute residual error is greater than the previous lowest total absolute residual error, the process stops otherwise repeat the above steps 2 - 7.

Table 1: The procedure for total DMA demand and burst flow estimations

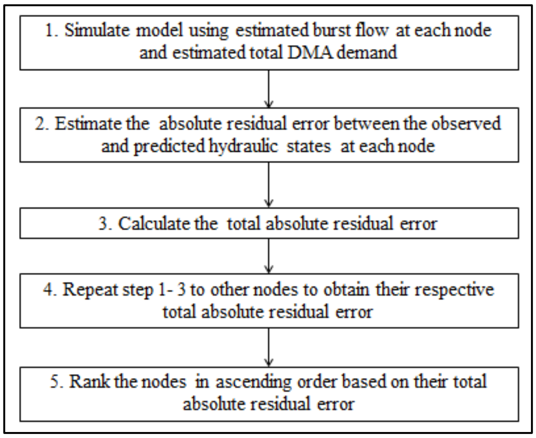
Criterions/ Iteration	$\min r_{t,i} > \min r_{t,i-1}$ & $q_{b,i} > q_{b,i-1}$	$\min r_{t,i} > \min r_{t,i-1}$ & $q_{b,i} < q_{b,i-1}$	$\min r_{t,i} < \min r_{t,i-1}$ & $q_{b,i} > q_{b,i-1}$	$\min r_{t,i} < \min r_{t,i-1}$ & $q_{b,i} < q_{b,i-1}$
i = 0	$q_{b,i} = q_{b,i} + n$ $d_i = d_i - n$			
i = 1	$q_{b,i} = q_{b,i} - 2n$ $d_i = d_i + 2n$	$q_{b,i} = q_{b,i} + 2n$ $d_i = d_i - 2n$	$q_{b,i} = q_{b,i} + n$ $d_i = d_i - n$	$q_{b,i} = q_{b,i} - n$ $d_i = d_i + n$
i > 1	$q_{b,i} = q_{b,i} - n$ $d_i = d_i + n$	$q_{b,i} = q_{b,i} + n$ $d_i = d_i - n$		

where i is the iterative step index, n is the flow (burst/demand) increment; q_b is the burst flow; d is the total DMA demand; $min\ r_t$ is the minimum total residual error between the observed and predicted hydraulic states at observation locations.

The total DMA demand is distributed across the DMA nodes based on the fraction of properties allocated to each network node. When a pipe burst is detected, both the minimum total residual error, $min\ r_{t,\ i-1}$ and the burst flow, $q_{b,\ i-1}$ are (re)set to zero at the initial iteration step. At the subsequent time step during the burst period, the initial minimum total residual error, $min\ r_{t,\ i-1}$ and the initial burst flow, $q_{b,\ i-1}$ are the same as the minimum total residual error and the burst flow from the previous time step respectively to reduce computation time.

2.4. Determination of burst location

The proposed method to find nodes that could be the possible location of the burst is summarised in Figure 4. The first step is to simulate the model by adding the estimated burst flow at each candidate node obtained from the BLM methodological step 2. The second step estimates the residual error between the observed and predicted hydraulic states (i.e. pressures and/or flows) at the sensors' location. The third step calculates the total residual error. The fourth step repeats step 1-3 at other candidate burst locations (i.e. DMA nodes). The fifth step ranks the nodes in ascending order based on their total residual errors obtained in step 3. The highest ranked node represents the most likely burst location while the worst ranked node represents the least likely burst location. A predefined number (i.e. percentage) of network nodes that are most likely to be the burst location are evaluated at each time step and the nodes that appear as frequently top ranked are used to define the likely burst area.



1. Simulate model using estimated burst flow at each node and estimated total DMA demand

2. Estimate the absolute residual error between the observed and predicted hydraulic states at each node

3. Calculate the total absolute residual error

4. Repeat step 1- 3 to other nodes to obtain their respective total absolute residual error

5. Rank the nodes in ascending order based on their total absolute residual error

Figure 4: A flow chart of determining the burst area

3. Case Study

3.1. Case study area description

The case study area is a real-life DMA. This DMA (see Figure 5) is located in the North-West of England and represents an urban area which supplies water to approximately 1864 domestic and 27 commercial properties with an average daily demand of 9 l/s. The DMA hydraulic model consists of 527 nodes, 412 pipes and 147 valves. The DMA is fed from another, upstream DMA.

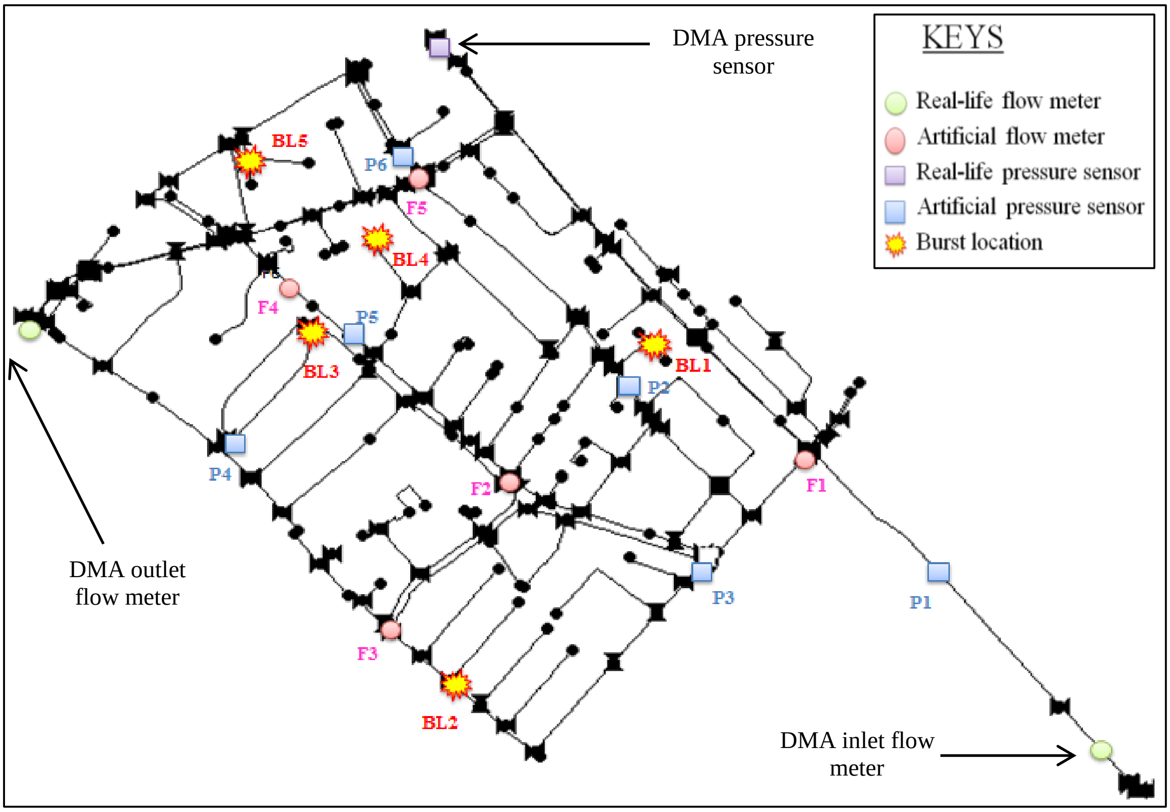


Figure 5: The overview of the studied water network including DMA.

3.2. Sensor data

The available real-life data are the DMA's inflow and outflow data, and pressure data gathered at the highest point of the DMA (see Figure 5).The flow and pressure data are gathered between 14th January and 10th February 2014 (4weeks). However, there is no other pressure sensors and flow meters within the DMA. Therefore, the artificial pressure and flow observations including pipe bursts within the pipe network are generated via hydraulic model simulation. The spatial (i.e. nodal) demand allocation is done based on the fraction of properties allocated to each network node and the total DMA demand. The 'perfect' flow/pressure observations obtained from the corresponding hydraulic model outputs are altered by adding random noise errors. The random noise error is derived from the normal distribution defined by the zero-mean and standard deviation of 0.05 $QP_{i,t}$. Where $QP_{i,t}$ represents the hydraulic data (flow and pressure) for the hydraulic sensor, *i* at time step, *t*. The location of the artificial flow and pressure sensors (see Figure 5) are selected based on optimal sensor placement method for burst/event detection [2].

3.3. Burst simulation

In this study, the bursts are simulated as pressure-dependent flows by using emitters at network nodes [9], i.e. as follows:

$$q_{i,t} = C\, p_{i,i}^{e} \tag{1}$$

where $q_{i,t}$ is the burst flow at node, i at time step, t; *C* is the emitter discharge coefficient; $p_{i,i}^{e}$ is the nodal pressure at node, *i* at time step, *t*; and *e* is the emitter pressure exponent.

To develop the sensitivity matrix offline, the emitter exponent of 0.5 in the hydraulic model is used [14] and an emitter discharge coefficients of 0.351 (corresponding to an average burst flow of 2.8l/s) are used. To test the BLM described in section 2, various emitter discharge coefficients have been tested to find the acceptable emitter discharge coefficient to represent the 5 burst flows. A total of 5 burst flows were used in this case study: 5%, 10%, 20%, 30% and 50% of the average DMA demand. The bursts are simulated at 4 different time periods: morning peak (6.00am – 10:45am); midday (11:45am – 4:30pm); evening peak (4.30pm – 9.15pm) and night (12.45am – 5.30am). All the bursts are assumed to last for 5 hours. Pipe bursts are simulated at 5 different burst locations which were selected randomly (see Figure 5).

3.4. BLM Parameters

Prior to online burst detection and localisation, the BLM parameters have to be determined offline. In the BLM methodological step 2, the nodes relating to the top two affected flow meters are used for burst localisation analysis. This is because the sensitivity matrix shows that flows at observation points are more sensitive to bursts simulated (when compared to pressures at observation points). The threshold value *(in step 2, section 2.2)* to determine if simulated burst at a node has an impact on the hydraulic sensors is the average residual error between the hydraulic state under normal and abnormal (burst) conditions. The threshold value is 1.68 l/s.

The selected value of flow increment (*in step 5, section 2.3*) is 0.1 l/s during the DMA demand and burst flow estimation process. This increment operator is chosen as small as possible to ensure the burst flow is accurately determined bearing in mind the computational constraints associated with the iterative procedure used. In the BLM methodology step 4, 10% of the DMA nodes (i.e. a total of 54 nodes here) are used as the maximum number of nodes to identify the burst area.

4. Results and Discussion

In the data analyses carried out here, the methodology behind the BLM is tested on the artificial pipe bursts. The BLM capabilities were also evaluated based on the time taken to locate bursts.

Figure 6 shows the burst (blue) areas identified for simulated bursts with a flow of 2.7 l/s taking place during the night time period at 5 different network locations. As it can be seen from this figure, each burst assumed (i.e. simulated) is located within the identified burst area. A set of 10 most likely burst locations (red dots with yellow outlines) are displayed for each of the 5 bursts simulated. Note that these locations are always close to the actual burst locations. The top 10 ranked nodes displayed in the figure have been all determined 6 time steps (i.e. 90 minutes) after the burst has been detected. Note that these can be used only to indicate the approximate area of a pipe burst as it is very difficult to pinpoint the actual burst location in near real time.

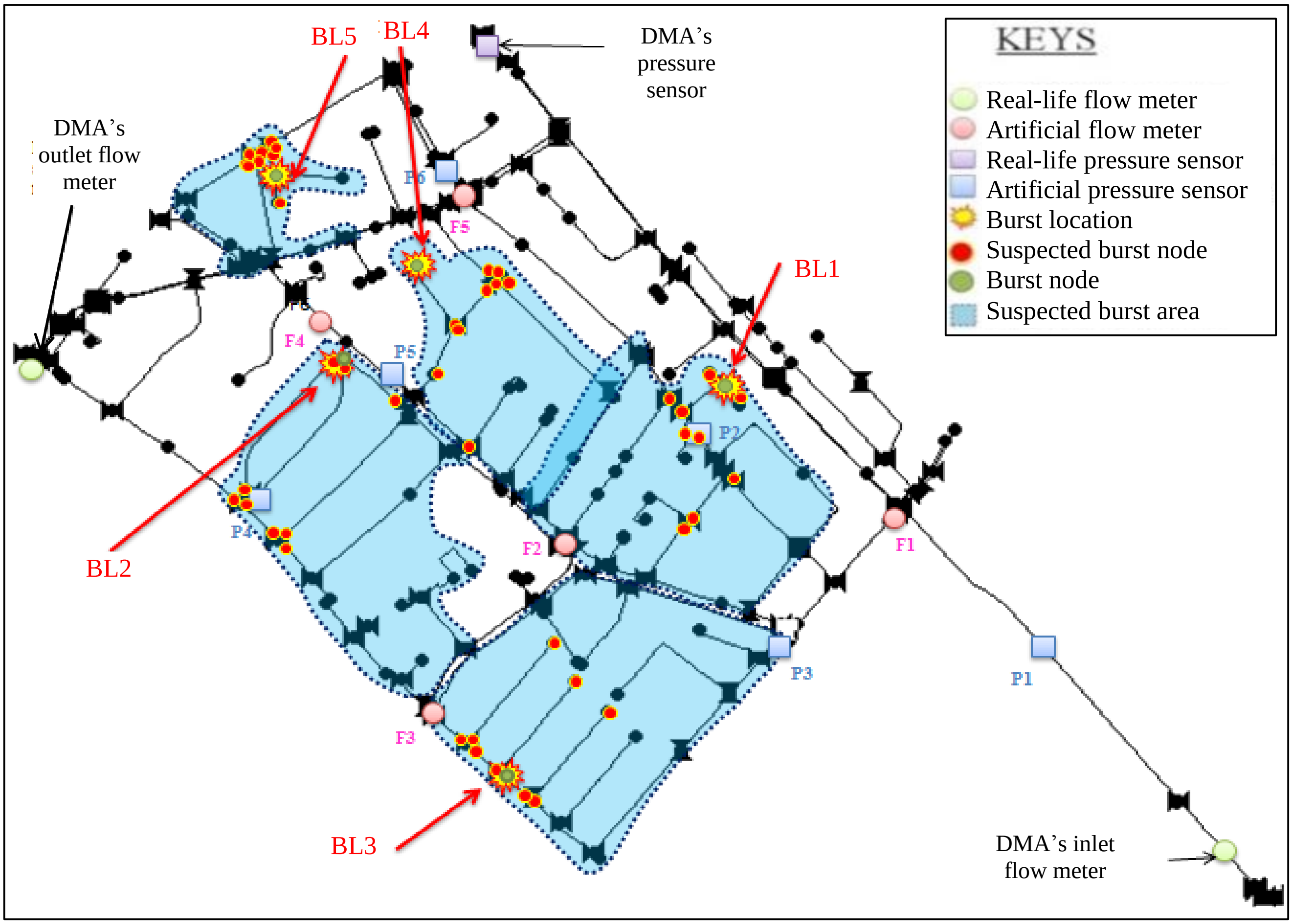


Figure 6: Illustration of the burst areas and 10 most sensitive nodes (red dots with yellow outline) for each burst location during the night time period (burst flow - 2.7 l/s)

Table 2 shows the performance of the BLM for the alternative burst time periods and magnitudes simulated at the same 5 locations in DMA004. The rank of the actual burst node during the burst period once a pipe detected are listed in the last 3 column in Table 2. This rank is based on the total absolute residual error between observed and predicted hydraulic states from the observation locations. Hence, the decrement of the total absolute residual error corresponds to the increment of the burst node's rank.

Table 2 also shows that the estimated average burst flows are close to average simulated burst flows. The rank of the burst nodes is displayed in the last 3 columns in Table 2. Note that there is no strong relationship between the actual burst node's rank and either burst time period or burst magnitude. However, the average rank of actual burst node is amongst the top 50 nodes are likely to be the burst location. . The size of burst area varies and it depends on the burst location and DMA network. For example, burst location 5 has the smallest size of burst area because it is located in a branch section of the DMA. Other burst locations' size of burst area is almost twice of the burst location 5's burst area and they are located in a looped network of the DMA.

It can take between 3 and 11minutes to run the BLM. The time taken for the BLM to output the suspected burst areas depends on 2 factors: (1) the size and configuration of the DMA and (2) initial estimated burst flow. It takes nearly 53 seconds to perform one iteration step in BLM methodological step 3 in the DMA presented above. The above simulations were performed on a personal computer with Intel core i5 processor @ 2.30GHz and 6.0 Gb RAM memory.

Table 2: The performance of BLM at 'selected' time period and burst magnitude at 5 burst locations in DMA004

Burst location	**Time period**	**Avg. simulated burst flow (l/s)**	**Burst detected? (Yes/No)**	**Burst located? (Yes/No)**	**Avg. estimated burst flow (l/s)**	**Estimated burst area (% of DMA area)**	**Avg. rank of actual burst node**	**Highest rank of actual burst node**	**Lowest rank of actual burst node**
BL1	Night	0.44	Yes	Yes	0.48	14.2	18	1	31
	Morning	0.81	Yes	Yes	0.73	15.2	42	9	71
	Mid-day	1.76	Yes	Yes	1.64	14.9	19	10	41
	Evening	2.66	Yes	Yes	2.25	14.4	14	4	27
BL2	Night	4.46	Yes	Yes	4.36	15.2	7	3	15
	Morning	0.43	Yes	Yes	0.50	16.0	16	8	20
	Mid-day	0.89	Yes	Yes	0.83	15.3	8	2	15
	Evening	1.77	Yes	Yes	1.72	15.3	9	2	15
BL3	Night	2.67	Yes	Yes	2.69	16.3	3	1	7
	Morning	4.16	Yes	Yes	4.03	17.6	4	1	4
	Mid-day	0.43	Yes	Yes	0.39	17.5	22	8	40
	Evening	0.87	Yes	Yes	0.83	18.7	14	6	36
BL4	Night	1.79	Yes	Yes	1.83	12.6	3	1	3
	Morning	2.72	Yes	Yes	2.49	13.4	4	3	11
	Mid-day	4.34	Yes	Yes	4.20	13.0	4	3	15
	Evening	0.40	Yes	Yes	0.41	13.2	5	1	8
BL5	Night	0.87	Yes	Yes	0.92	5.3	3	1	7
	Morning	1.77	Yes	Yes	1.71	6.4	13	1	52
	Mid-day	2.62	Yes	Yes	2.65	6.2	8	4	17
	Evening	4.24	Yes	Yes	4.08	5.6	13	8	20

5. Conclusion

This paper presented a novel methodology to determine the suspected burst location area in near real-time. The BLM is based on the online hydraulic modelling and has been tested and demonstrated by applying it to a real-life water distribution network (DMA) with simulated burst events. The corresponding flow and pressure observations were artificially generated from the hydraulic model. The capability of the developed BLM was assessed by simulating bursts at 5 random locations within the analysed DMA. The burst localisation results obtained correlate well with the assumed burst locations and the same is valid for the estimated burst flows. All this indicates the suitability of the proposed BLM for pipe burst location in near real time. Further work will be focused on analysing the impact of other observation noises (e.g., random and/or systematic error noise) and the number and type of hydraulic sensors used.

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