REDUCING CUSTOMER MINUTES LOST BY ANOMALY DETECTION?

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ABSTRACT
An method which compares measured and predicted water demands to detect anomalies, was developed and tested on three data sets of water demand of three years in which and 25 pipe bursts were reported. The method proved to be able to detect bursts where the water loss exceeds 30% of the average water demand in the area. By simultaneously running the method in adjacent supply areas, and combining the monitoring results the number of false alarms could be reduced. Further analysis of the reported bursts, showed that most burst (22 of 25) were isolated within 2 hours after occurrence. The anomaly detection method could not have reduced the number of Customer Minutes Lost (CML) of those bursts. The water loss and pressure drop of the other bursts was limited and caused no CML. The detection method was able to detect the bursts, but did not reduce the CML.

INTRODUCTION

Unmanned operation of water supply systems
Water supply companies are gradually transforming their operations from local and manual operation to centralized unmanned operation (Worm *et al.*, 2010). Operators who are continuously controlling a single location are replaced by supervisors who are supervising a number of locations in a region only during office hours. This implies that the distance between the human operator or supervisor and the water production and distribution processes is gradually increasing. This increasing distance results in an increasing risk, that failures in the system will remain unnoticed especially at times when no human supervisor monitors the processes. In water production facilities the equipment (pumps, valves, blowers, et cetera) has failure alerting functionality, which alerts the consigned operator in case of a failure. Distribution networks have no such failure alerting functionality to warn operators in case of a pipe failure. In most distribution networks in the Netherlands, flow and pressure sensors are only installed at pumping facilities and not separately in the pipe networks. The monitoring of these measured flows and pressures is limited to a simple "flat-line" alerting system, of which Mounce *et al.*, 2010 showed the limitations. As a result many pipe bursts stay unnoticed in the system, and the utilities only take action after customer complaints of low pressure or customers reporting water flows on the streets.

Customer Minutes Lost
Pipe burst have an important disturbing effect in water supply (Bicik *et al.*, 2011). A pipe burst will not only lead to large water losses, but also to an interruption of water supply to customers and discolouration of the water due to disturbed pipe flows. Interruption of supply or supply of inadequate water quality can be expressed in Customer Minutes Lost (CML), which is defined as the average number of minutes per year that a customer does not receive any water or water of a quality that doesn't meet the legal standards. Blokker *et al.*, 2005, and Trietsch and Vreeburg, 2005, describe the use of CML as a performance indicator in the Netherlands. The application of CML in

the integrated risk analysis of drinking water systems is described by Lindhe *et al.*, 2009 and Rosén *et al.*, 2010.

Overview burst detection methods

For the detection of pipe bursts, various techniques can be used. Puust *et al.*, 2010, give a profound overview of different techniques for managing background leakage in distribution systems, as well as detecting pipe bursts.

Monitoring pressure transients

One of the commonly used the techniques for pipe burst detection is based on monitoring pressure transients in the distribution system, which occur after a sudden failure (rupture) of a pipe. By measuring pressure at different locations at a very high sampling rate (2000 Hz, Misiunas *et al.*, 2005a) the propagation of the pressure transient in the network can be measured, and the burst location can be approximated. Colombo *et al.*, 2009 presents a literature overview of transient monitoring techniques. Brunone and Ferrante, 2001, Misiunas *et al.*, 2005a, 2005b, Kim, 2005, Duan *et al.*, 2011, and Kwon and Lee, 2011, present theoretical research to further develop this technique. The technique is only applicable for actual bursts. Pipe failure which develops gradually will not induce a pressure transient, and will therefore not be detected by this technique.

Monitoring flow, or pressure and flow in a DMA

When flow and pressure measurements are present for off-line DMA monitoring, the measurements can be used for on-line monitoring when made available (semi) online. Stephen Mounce researched detection techniques and tested those techniques in a real water supply system in North Yorkshire, UK (Mounce *et al.*, 2002, Mounce *et al.*, 2003, Mounce and Machell, 2006, Mounce and Boxall, 2010 and Mounce *et al.*, 2011). The papers describe the application Artificial Neural Networks (ANN) combined with Fuzzy Logic to evaluate pressure and flow measurements. In Mounce *et al.*, 2011, the application of the system in practise in a six month test period is described. It was proved that the system was able to detect 7 of 18 reported bursts (11 events missed), where the system generated a total of 46 alerts (39 were not related to actual bursts).

Other promising research in the field of burst detection is carried out by Palau *et al.*, 2011, who used a multivariable statistical technique (Principle Component Analysis) to derive burst events from flow and pressure data. Bicik *et al.*, 2011, combined flow and pressure data with information from other data sources, like customer contacts and an hydraulic model to detect burst events. And Khan *et al.*, 2005, describe the application of experimental failure sensors measuring opacity or temperature for the detection pipe bursts.

Techniques for leak estimation

Poulakis *et al.*, 2003, Buchberger and Nadimpalli, 2004, Aksela *et al.*, 2009, and Wu *et al.*, 2010, present techniques for combined background leakage estimation and burst detection, based on measured hydraulic data.

Development deterministic burst detection method

In this paper a pipe burst detection method is proposed, based on an adaptive demand forecasting algorithm in combination with an adaptive threshold monitoring system. The proposed method has some similarities with the method proposed by Misiunas *et al.*, 2006, which is based on monitoring hydraulic phenomena, and anomaly detection with a cumulative sum function. The aim of implementing the method is to reduce the period between the point in time of the occurrence of the burst and the point in time that the utility is aware of the burst. This is the unawareness period in the life cycle of a burst, as shown in Figure 1 (derived from Water Research Centre, 2006, and Mounce and Boxall, 2010). The other periods, the Awareness period, the Location period, the Isolation period and the Repair period, will not be affected by detection method.

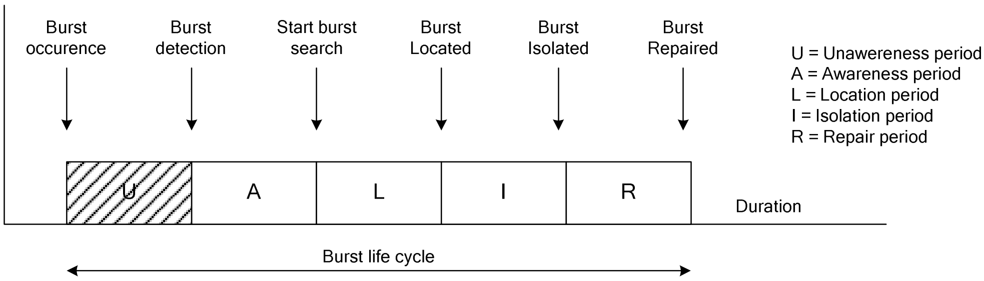

Figure 1: Life cycle of a burst.

In the current situation without a burst detection method installed, the unawareness period is determined by the time it takes for customers to experience lower or no water pressure, or to see water running over the streets – and to contact the water utility.

METHODOLOGY/ PROCESS

Burst detection by comparing predicted and measured water demand

The developed burst detection method is based on a continuous comparison between the measured water demand and the predicted water demand in an area. The method will process the unfiltered flow measurements for the detection of pipe bursts.

Measured water demand

For each area where the burst detection method is applied, the water demand must be measured. For simple areas the demand is measured directly by the flow meter at the entrance of the area. In more complex areas the readings of a number of flow meters, registering incoming or outgoing flows needs to be combined to calculated the water demand. In case there is a reservoir or a water tower in the area of which incoming and outgoing flow is not measured, this flow has to be calculated. This can be done by integrating the change in the level measurement over time:

$$F_{reservoir,t} = \frac{dL}{dt} \cdot A_{reservoir} \qquad (1)$$

Predicted water demand

The water demand to each area is predicted by an adaptive demand forecasting algorithm, described in Bakker *et al*. 2003. This algorithm automatically builds up a database with typical curves and factors which characterize the diurnal and weekly patterns of the water demand in the area. The typical curves and factors are used to predict the water demand for the next 48 hours on a quarter of an hourly basis.

Prediction error

The prediction error ($F_{error,t}$) is the difference between the measured flow ($F_{measured,t}$) and the predicted flow ($F_{predicted,t}$):

$$F_{error,t} = F_{measured,t} - F_{predicted,t} \qquad (2)$$

In case of a pipe burst, the measured flow will suddenly increase and become higher than the predicted flow. Therefore only positive prediction errors must be monitored in order to detect pipe burst. The positive prediction error ($F_{Poserror,t}$) is derived by:

$$F_{Poserror,t} = \frac{\left|F_{error,t}\right| + F_{error,t}}{2} \qquad (3)$$

Dynamic alert threshold

If the positive prediction error exceeds the threshold value during a chosen time window, the burst detection method will generate an alarm. The threshold value is dynamic in time and is calculated at time *t* with:

$$F_{Treshold,t} = C_1 \cdot F_{error,avg} + C_2 \cdot \left(\frac{F_{error,avg}}{F_{meas,avg}}\right) \cdot F_{predicted,t} + C_3 \frac{dF_{predicted,t}}{dt} \qquad (4)$$

$F_{error,avg}$ is the average absolute prediction error and $F_{meas,avg}$ is the average measured water demand in the area in the previous year. $dF_{predicted}/dt$ is de derivative of the actual predicted water demand. By calculating the threshold value as function of the predicted demand and the derivative of the prediction, the value is adjusted depending on the accuracy of the prediction: The calculated threshold will be lower when the prediction is known to be more accurate (during low flow and a low derivative of the flow), and higher when the prediction is known to be less accurate (during high flow, and high derivative of the flow). In choosing the constants C_1, C_2 and C_3 a balance must be found between quick and accurate monitoring on the one hand and, limiting the number of false alarms ("ghosts") on the other hand.

Integrating error and threshold over time value

The water demand to an area can be more or less variable. The variability depends highly on the size of the area. In larger areas fluctuations are levelled off, because of limited simultaneity of individual usages. In smaller areas the levelling off will occur only to a smaller degree, resulting in relatively larger fluctuations. This is especially true in smaller areas where 1 of more (industrial) large consumers are present. Figure 2 shows examples of variability of the water demand in a large, medium and small area. The examples show that not only the percentage of the variation can differ between areas, but also the time scale (the sudden flow increases in the medium area last 5-10 minutes, where the flow increases in the small area last nearly 1 hour).

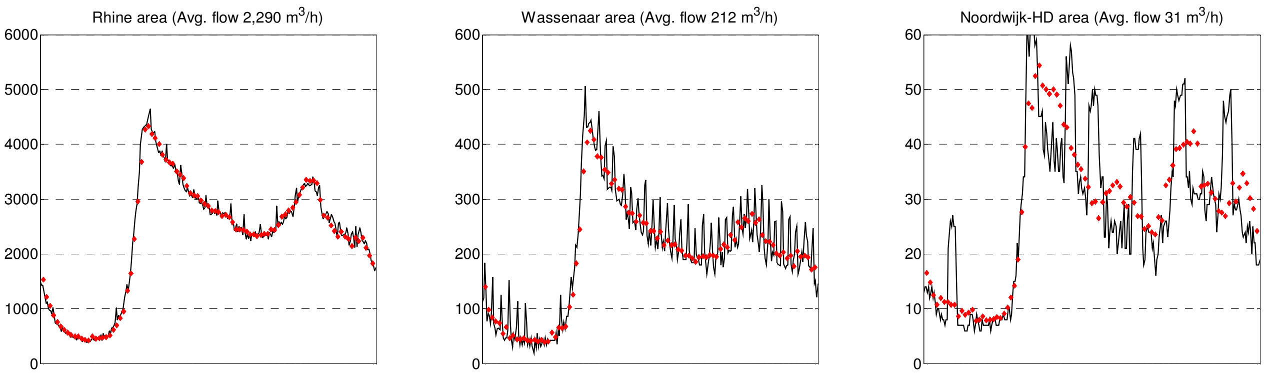

Figure 2: Variability in water demand, in a large area (Rhine area), medium area (Wassenaar area) and small area (Noordwijk-HD area), (– = measured flow, ■ = predicted flow).

For effective monitoring the variability of the flow has to be taken into account. For this purpose the integral over the monitoring time window (T_{mw}) of both the positive prediction error as well as the threshold are calculated (note that the unit of both derived values is volume (m^3), because flow values (m^3/h) are integrated over time (hour)):

$$V_{Treshold,t} = \int_{t=-T_{mw}}^{t=0} F_{Treshold} \cdot dt \quad and \quad V_{Poserror,t} = \int_{t=-T_{mw}}^{t=0} F_{Poserror} \cdot dt \tag{5}$$

The burst detection method will generate an alarm if the integrated positive error value exceeds the integrated threshold value:

$$Alarm\ if : V_{Poserror,t} > V_{Treshold,t} \tag{6}$$

In other words an alarm will be generated if (over the monitoring time window) the average positive error is bigger than the average threshold. This method enables effective monitoring using the raw measured data, without the need to filter the measurement.

"Dual monitoring": comparison with adjacent area

A potential drawback of monitoring the difference between predicted and measured flow, is that false alarms may be generated when a discrepancy between predicted and measured flow occurs. In many cases the discrepancy is a systematic error: a similar overestimate or underestimate of the water flow is made in the prediction for all areas where the flow is predicted. This can occur after a sudden change in the weather conditions or the occurrence of a special day, which is not modelled correctly in the prediction algorithm. The accuracy of the alarm detection improves when potential alarms are compared between various detection areas. Simultaneous discrepancies between measured and predicted demand indicate a 'demand-event' rather than a burst. An alarm is suppressed when:

$$Alarm\ suppressed\ if : V_{Poserror,adj,t} > C_4 \cdot V_{Treshold,adj,t} \tag{7}$$

C_4 is chosen at a value of 0.3, meaning that a much smaller prediction error in the adjacent zone is enough to suppress the alarm in the monitored zone.

Parallel monitoring for detection of different burst types

Different types of bursts require different settings for C_1 to C_4 and for the monitoring time window T_{mt}. Large bursts are characterised by sudden large increase of the flow, and those bursts need to be detected in a short time frame. Smaller burst are characterised by smaller increase of the flow, and a longer time frame for detection is acceptable. In order to detect multiple types of bursts and minimize the number of false alarms at the same time, multiple burst detection methods can be operated in parallel on the same measurement, but with different settings. In this case study the following settings are used for parallel monitoring:

Table 1: Settings for parallel monitoring to detect both large bursts as well as small bursts

Burst type	C_1	C_2	C_3	C_4	T_{mt}
Large bursts	3	2	0.02	0.3	10 minutes
Small bursts	0	6	0.20	0.3	40 minutes

Case study

Analysis of three areas

For the case study a dataset with historic data was collected. For three areas of drinking water company Dunea, the amount of supplied drinking water in 5 minutes intervals of the period 2009-2011 was collected. Dunea collects and stores all data of pressure and flow measurements in a central database system called EI-Server. As a result of the high reliability of both the meters and the database system, virtually no data gaps of data errors were present in the dataset. The three researched areas are shown in Figure 3 and the characteristics are summed in Table 2.

Table 2: Characteristics of the three researched areas (average values of 2009-2011)

Area	**# connections**	**Water demand (m^3/h)**	**Water use m^3/conn./year**	**# burst incidents**
Rhine area	130,920	2,290	145	19
Wassenaar area	11,180	212	154	5
Noordwijk HD area	650	31	391	1

In the Noordwijk HD area there is one customer with (relatively) very high water use. As a result of this high water use of one customer, the average water use per connection is in this area approximately 2.5 times higher than in both other zones.

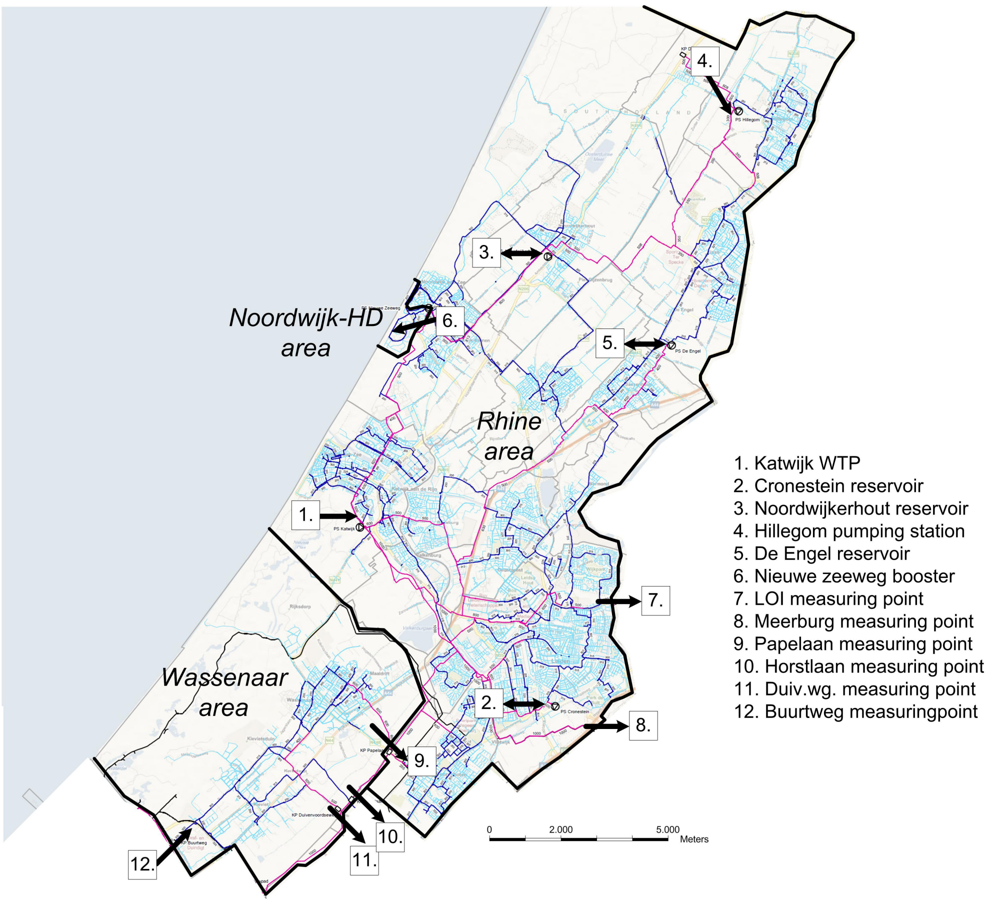

Figure 3: Areas of the case study, including all measuring points. The Rhine and Noordwijk-HD area are supplied by water from the Katwijk Water Treatment Plant (1.) and for a minor part from the Hillegom pumping station (5.). The Wassenaar area is supplied by water from an adjacent zone (12.). Cronestein (2.), Noordwijkerhout (3.) and De Engel (4.) are (low) service reservoirs. Connection points 7. to 10. are normally closed. The Nieuwe Zeeweg booster (6.) pumps the water to the higher elevated Noordwijk HD area.

Reported pipe bursts

Dunea makes reports for larger pipe bursts where the burst flow exceeds some 200 m^3/h (pipe diameter 200 mm and larger) since 2009. In the period 2009-2011 a total of 25 larger pipe burst were reported in the tree areas (see Figure 4 and Figure 5).

Simulations

In the case study the prediction algorithm was run using the original data and compared with the actually measured data. After doing the simulations the simulated alerts were compared with the reported pipe bursts. All simulations were carried out with two different settings for the detection method: "loose" with a minimum of false alarms; and "tight" with more false alarms. The settings were constructed by multiplying C_1 to C_3 from Table 1 with 1.0 for "tight" and 1.3 for "loose" monitoring. Because of the higher variability in the water demand in the Noordwijk-HD area, the factors of Table 1 were multiplied by 2 for this area.

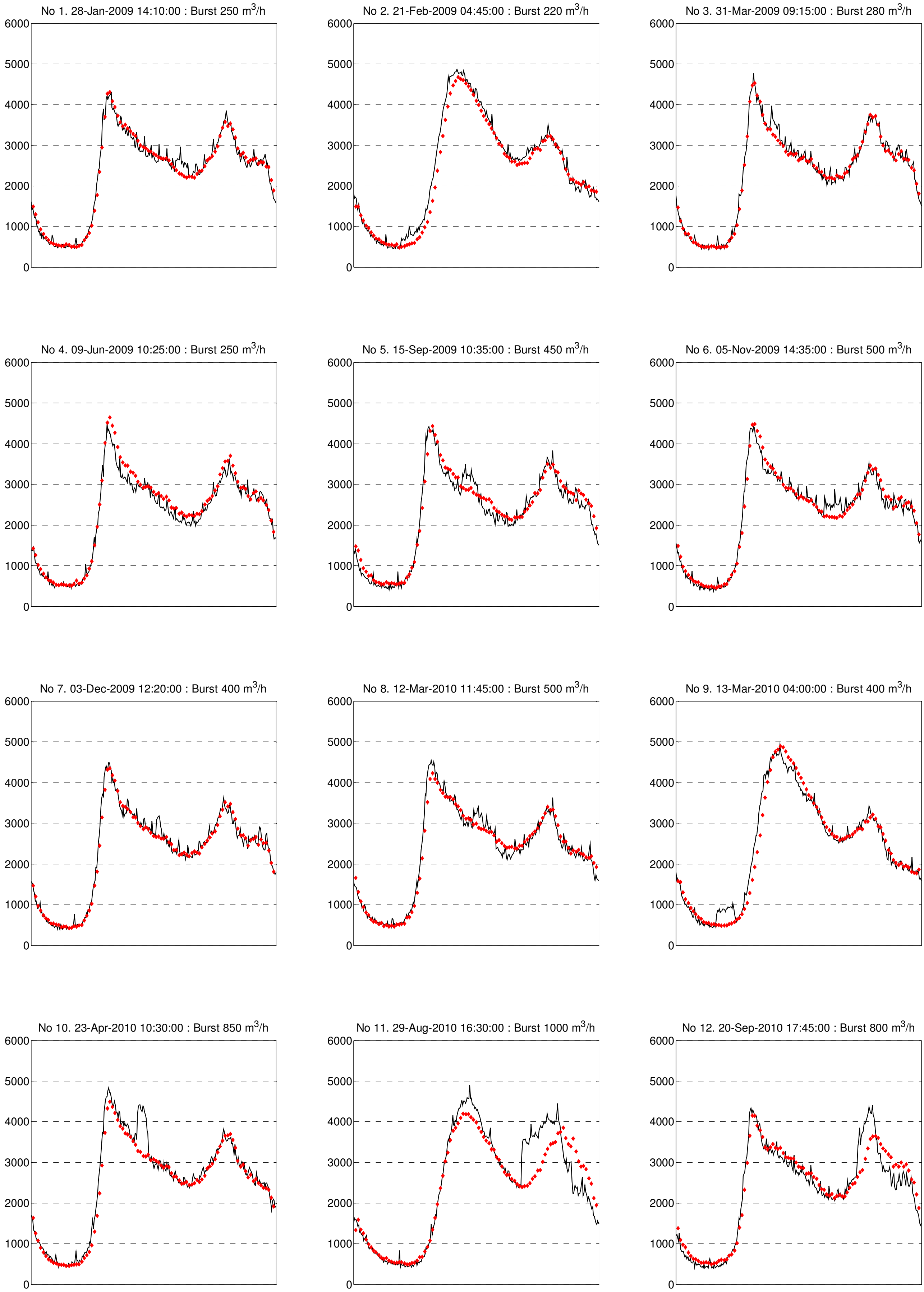

Figure 4: Measured water demand on days with reported pipe burst in 2009-2011 (– = measured flow, ■ = predicted flow).

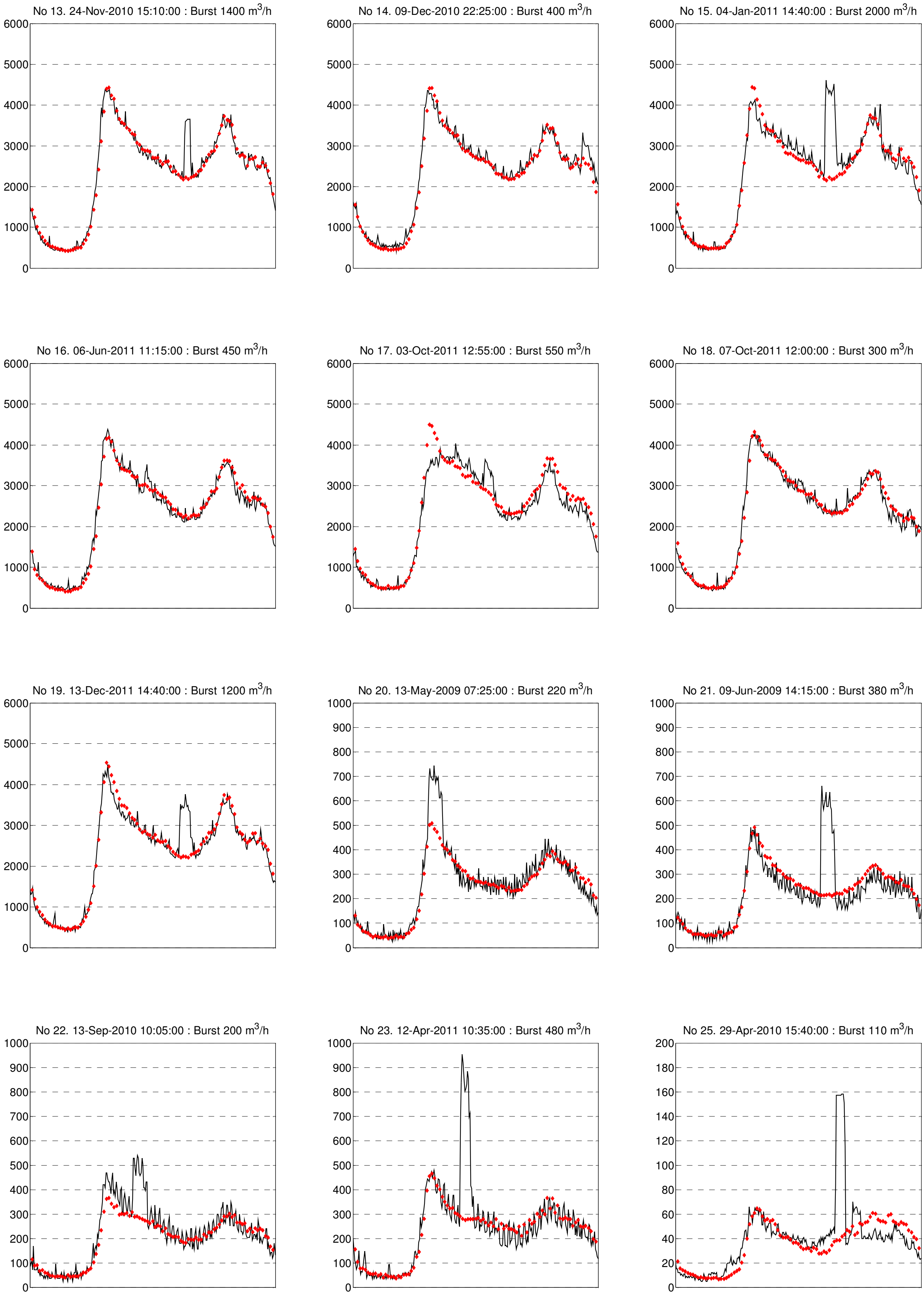

Figure 5: Measured water demand on days with reported pipe burst in 2009-2011 (– = measured flow, ■ = predicted flow). Note that events 20-23 are in Wassenaar and 25 in Noordwijk-HD area.

RESULTS

Results pipe burst detection method

The results of the simulations are summed in Table 3.

Table 3: Results of pipe burst detecting method (the table shows the elapsed time between the beginning of the burst and the generated alarm (hours:minutes), X = not detected)

No.	Date burst	Burst flow		"stand alone"		"dual monitoring"	
		m^3/h (% of avg. flow area)		Tight	Loose	Tight	Loose
Rhine area							
1.	28-Jan-09	250	(11%)	X	X	X	X
2.	21-Feb-09	220	(10%)	00:40	X	00:40	X
3.	31-Mar-09	280	(12%)	X	X	X	X
4.	09-Jun-09	250	(11%)	X	X	X	X
5.	15-Sep-09	450	(20%)	X	X	X	X
6.	05-Nov-09	250	(11%)	X	X	X	X
7.	03-Dec-09	450	(20%)	X	X	X	X
8.	12-Mar-10	500	(22%)	X	X	X	X
9.	13-Mar-10	400	(17%)	00:25	00:30	00:25	00:30
10.	23-Apr-10	850	(37%)	00:10	00:10	00:10	00:10
11.	29-Aug-10	1,000	(43%)	00:10	00:10	00:10	00:10
12.	20-Sep-10	800	(35%)	00:15	00:15	00:15	00:15
13.	24-Nov-10	1,400	(61%)	00:05	00:05	00:05	00:05
14.	09-Dec-10	400	(17%)	03:15	03:35	03:15	03:35
15.	04-Jan-11	2,000	(87%)	00:05	00:05	00:15	00:05
16.	06-Jun-11	450	(20%)	X	X	X	X
17.	03-Oct-11	550	(24%)	00:15	X	00:15	X
18.	07-Oct-11	300	(13%)	X	X	X	X
19.	13-Dec-11	1,200	(52%)	00:05	00:10	00:05	00:10
# Bursts 2009-2011 (# detected)				19 (10)	19 (8)	19 (10)	19 (8)
# False alarms per year				30	8	10	2
Wassenaar area							
20.	13-May-09	220	(105%)	0:15	X	1:10	X
21.	9-Jun-09	380	(180%)	0:05	0:05	0:05	0:05
22.	13-Sep-10	200	(95%)	0:10	0:15	0:10	0:15
23.	12-Apr-11	480	(230%)	0:05	0:05	0:05	0:05
24.	9-May-11	80	(38%)	X	X	X	X
# Bursts 2009-2011 (# detected)				5 (4)	5 (3)	5 (4)	5 (3)
# False alarms per year				8	2	5	2
Noordwijk area							
25.	29-Apr-10	110	(330%)	00:10	00:10	00:10	00:10
# Bursts 2009-2011 (# detected)				1 (1)	1 (1)	1 (1)	1 (1)
# False alarms per year				6	0	5	0

The simulations show that a small pipe burst (< 20-25% of the average water demand) generally cannot be detected by the detection method, unless the burst happens during low demand in the night (see burst Rhine area, 21 February 2009). Bursts with flow exceeding 40% of the average demand can always be detected. The detection of bursts between 20% and 40% of the average demand depends on how tight the monitoring method is configured, and at what time of the day the burst occur. When tight monitoring is applied, an unacceptable high number of false alarms occur. Therefore only loose monitoring seems to perform acceptable for practical application. In the Rhine area, the number of false alarms can be reduced by 60-80% by applying “dual monitoring” (rejecting alarms based on comparison with an adjacent zone). For the smaller zones “dual monitoring” doesn’t do much about false alarms.

Further analysis of reported pipe bursts

There was no detailed information available about the points in time of occurrence, detection, location, and isolation of the reported burst events. However from the flow data some information could be extracted. At all reported pipe burst events a sudden increase of the water flow at the point in time of the occurrence of the burst was observed. A sudden decrease of the flow was observed at the point in time of the isolation of the burst. The difference between the two points in time covers the Unawareness period (1.) + Awareness period (2.) + Location period (3.) + Isolation period (4.) in the life cycle of a burst (Figure 1). Of the 25 reported bursts the total period (1. to 4.) for 8 bursts (32%) was 1 hour or less, for 14 bursts (56%) it was between 1 and 2 hours. Of the other 3 bursts (12%) the total period (1. to 4.) was 2 hours or more, see Figure 6.

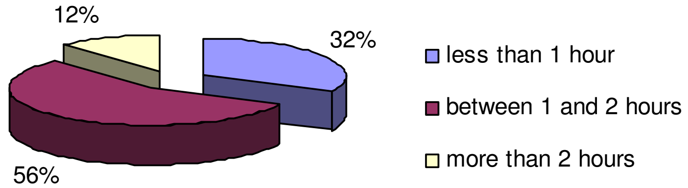

Figure 6: Time between occurrence and isolation of reported bursts

This indicates that 88% percent of the bursts were isolated in less than two hours after occurrence. All but one of theses bursts occurred during day time, between 7:00 and 22:00. To isolate a burst within 2 hours after occurrence seems a rather short time, especially because the Isolation period (4.) takes at least 30-45 minutes according to servicemen of the Dunea water company. After location, it takes time to identify the proper valves in the GIS system, to locate the valves in the field, and to close the valves slowly. The larger the diameter of the pipe to be closed, the longer closing time of the valve must be applied. The reason for this is to prevent water hammer in the distribution system which implies the risk of new pipe bursts. Given the assumption that the Isolation period (4.) takes 30-45 minutes, the time for the other periods (1. to 3.) is on average less than 1 hour for these bursts. This indicates that the bursts were discovered by customers shortly after occurrence, and reported to the water company resulting in a rather short Unawareness period (1.). After the customer call(s), the water company sends out servicemen to travel to the burst location, and to locate the exact pipe section of the pipe (period 2. and 3.). The Location period (3.) can be rather short, because the customers calling the water company give an accurate approximation of the location of the burst.

The periods 1. to 4. for the other bursts were 5 hours, 12 hours and 16 hours. The points in time when the bursts occurred were 16:30, 22:25 and 4:45 respectively. The two bursts with the longest time between occurrence and isolation (periods 1. to 4.) occurred during the night. Assuming the same Isolation period (4.) of 30-45 minutes and the same Awareness and Localisation period (2. and 3.), the Unawareness period were considerably longer. This can be explained by the fact the bursts in the night time were not noticed by customers and not promptly reported to the water company.

Reducing customer minutes lost by anomaly detection?

As shown above, most of the bursts (88%) were isolated within 2 hours after the occurrence. This indicates that the bursts were reported by customers shortly after occurrence. For those events the added value of a pipe burst detection system is limited. At the time the system generates an alarm (on average 5 – 15 minutes after occurrence), in most cases the burst were already reported by customers. The burst detection method could not have reduced the number of customer minutes lost (CML) for those pipe bursts.

Three bursts (12% of the total number of bursts) had a period between occurrence and isolation of more than 2 hours. The characteristics of those bursts are listed in Table 4.

Table 4: Characteristics bursts where the period between occurrence and isolation exceeds 2 hours.

Burst no.	Burst flow	Date	Time	Period 1-4	Detection time
2.	220 m^3/h	21 February 2009	04:45	16 hours	Not detected
11.	1,000 m^3/h	29 August 2010	16:30	5 hours	10 minutes
14.	400 m^3/h	9 December 2010	22:25	12 hours	3½ hours

The local pressure drop caused by the bursts of Table 4 is shown in the graphs of Figure 7. The graph shows that the burst on 21 February 2009 caused no (visible) pressure drop, the burst at 29 August 2010 caused a large pressure drop, and the burst at 9 December 2010 caused a medium pressure drop.

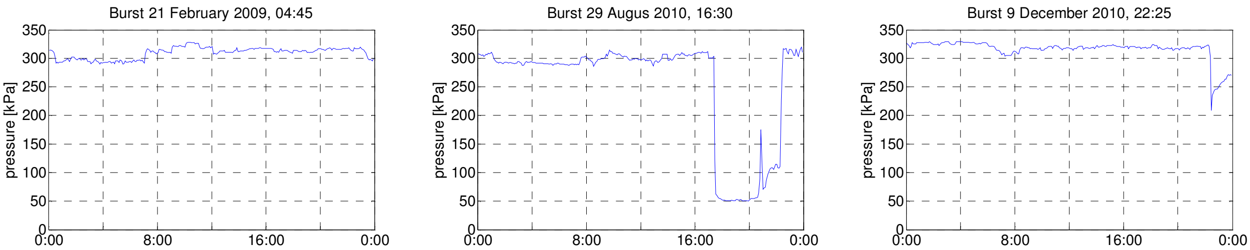

Figure 7: Pressure near burst locations during burst where the period between occurrence and isolation exceeds 2 hours

The very small and medium local pressure drop on 21 February 2009 and 9 December 2010 respectively, caused no CML because the pressure did not drop below 200 kPa. Detection by the burst detection method of these bursts could therefore not reduce any CML.

The large pressure drop on 29 August 2010 has (probably) caused CML. The pressure at the pressure measuring point approximates 50 kPa, which is defined by the Dutch water boards as limit value for CML. In a part of the supply area (which is closer to the burst location than the pressure measuring point) the pressure most likely dropped below 50 kPa. There is no information available from the call centre of the water company at what time the first customer(s) called to report low pressure. As the burst occurred at day time (16:30) on a Sunday, it's likely that people noticed the low pressure shortly after the burst and called the water company. The burst was located at 20:00, some 3½ hours after the occurrence of the burst. The Location period was relatively long in this case, because the pipe burst occurred in a rural are near to a canal, where the water flow from the burst could stay unnoticed. The burst detection method generated an alarm at 16:40, 10 minutes after the occurrence of the burst. Although this is rather quick after the occurrence, it is likely that customers called the water company earlier or around the same time. This implies that the reduction of CML by using the burst detection method can not be proved for the burst on 29 August 2010.

DISCUSSION

Value of burst detection beside reducing CML

The results show that reduction of CML by applying a burst detection method, can not be proved based on the researched dataset and reported real pipe bursts. However, applying a burst detection method can have added value. This is especially true for pipe bursts which occur at night and don't cause large pressure drops. Potentially, that type of pipe burst will stay unnoticed for many hours or even days. The water flowing out of the broken pipe can cause considerable damage to roads or other public areas. An early detection by a burst detection method can result in an early isolation of the burst, and a limitation of the damage caused. However the number of occasions of that type of bursts seems to be limited. In the researched dataset there were 2 such burst in 3 years, of which only 1 was detected by the detection method.

Application of burst detection method in smaller areas

In the case study only information was available of relatively large pipe bursts, and measurements were available for relatively large areas (the Rhine area has the size of 50-100 DMA's). If the flow is measured in smaller areas, also smaller pipe bursts can be detected. In general, smaller pipe bursts will stay unnoticed for longer. The added value of detection of smaller bursts by a burst detection method, is therefore potentially bigger. This can be achieved by installing more flow meters in the distribution network, and monitor the flow with the proposed burst detection method.

CONCLUSIONS

A pipe burst detection method was developed and tested on three data sets of 3 years, in which 25 large pipe burst events were reported. Simulations proved that the method was able to detect all pipe burst where the flow exceeds 30% of the average flow in the supply area. An important factor in monitoring the flow, is the number of false alarms which is accepted. False alarms can be reduced by combining the monitoring of two adjacent areas.

Further analysis of the reported bursts, showed that most burst (22 of 25) were isolated within 2 hours after occurrence. The burst detection method could not have reduced the number of Customer Minutes Lost (CML) of those bursts. The water loss and pressure drop of the other bursts was limited and caused no CML. The detection method was able to detect the bursts, but did not reduce the CML.

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