Performance assessment of leak detection failure sensors used in a water distribution system

A. Khan, P. D. Widdop, A. J. Day, A. S. Wood, S. R. Mounce and J. Machell

ABSTRACT

This paper presents a performance assessment of two failure sensors for the detection of events in a pipeline distribution system. These sensors identify abnormal events on the basis of water opacity and differential temperature. The opacity sensor measures the cloudiness of the water, which is assumed to be dependent on water flow rate and turbulence caused by local events, while the second sensor measures water temperature difference. Both sensors, installed in the same housing, have been deployed at ten strategic locations in one zone of a local water company's distribution network. An isolated section within the zone has been selected for monitoring by the two sets of sensors. Detailed analysis for the flow measurement has been conducted in the isolated section using modelling software. The analysis is supported by a series of flushing trials organised for the performance assessment of both sensor locations in the pipeline network. A comparison is also made with data from established pressure loggers, which were located at various strategic locations in the zone during these trials.

Key words | flushing, leakage, monitoring, sensors, water distribution systems

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INTRODUCTION

The problem of leakage within distribution systems is of operational, economic and political significance to water companies everywhere. An accurate assessment of water loss must be obtained in order to develop and implement an appropriate action plan for the management of distribution systems. Previous research has reported that up to 30% of water assets was wasted in transit for a number of reasons of which leakage was considered to be the major component (Bridges & MacDonald 1994). Consequently, at the UK's 1997 Water Summit, tough action for water conservation and leakage prevention was called for. This resulted in an overall leakage reduction of 25% in the last 4 years and in just 2 years after the summit, 900,000 m^3 (200 million gallons) of water per day were saved, enough for all Yorkshire Water's customers (Wateronline.com). This significant achievement was made by using leak detection techniques already deployed in water distribution systems. These techniques can be divided into three categories.

1. Action is instigated either by customers' complaints or by abnormal pressure problems in the system. In other words, a situation where water appears on the surface. This is the most inefficient policy of leakage control as in some cases water will cause a lot of damage to infrastructures before appearing on the surface (David & Keeling 1999).
2. Leakage detection accompanies other types of maintenance work (for example the repair of hydrants) in the distribution system. This technique may not be economical, as the network may be in good repair, with few leaks, which results in a waste of resources (David & Keeling 1999).
3. The minimum night flow (MNF) is used as the measuring tool for leakage identification. It is an economical, effective and more systematic mechanism of analysing the distribution network for leakage. District meter areas (DMAs) in which flow levels are significant in terms of the MNF are

> labelled as 'problematic areas' and are put forward for detailed analyses. A priority list is compiled on the basis of leak levels in the network. These DMAs are searched manually by leakage inspectors using listening sticks at curb stops, hydrants, valves and other convenient places (Hunaidi *et al*. 1999).

Leaks not detected by the established techniques can be sought using sophisticated instrumentation such as acoustic emission, cross-correlation methods, ground penetrating radar, hydrophones and tracer gas. Every method of leak detection has merits and limitations, which are addressed, together with a comparison, in Hunaidi & Giamou (1998), Hunaidi & Chu (1999) and Hunaidi *et al*. (1999).

Despite substantial savings on water resources from previous years, 20% of water is still lost from the supply and 18 out of 24 water companies in the UK do not achieve an economic leakage level for their distribution systems (Water News, www.waterplace.co.uk). Detailed analysis of the leakage detection methods currently used has shown that they are expensive, unreliable and time consuming.

The high cost of conventional sensors has precluded their widespread use for water pipeline monitoring at a density allowing accurate leakage detection. Hydraulic (e.g. pressure and flow) sensors are used for district-based asset management, typically in urban areas or strategically important trunk mains. Global indicators from sensors located, for example, at the entry to and exit from a district, can, with associated local knowledge and expertise, only give an estimate of the location or importance of an 'event'. The accuracy of event detection and location can be improved by analysing signals from a greater number of sensors in a district, but the installation, operation and analysis resource costs are prohibitive.

In research at the University of Bradford, two new sensors using the concept of 'failure' have been designed and developed. Both sensors have been extensively tested in the laboratory and have subsequently been deployed in strategic locations in the field (Khan *et al*. 2002*a*). These sensors have provided encouraging results and their potential for use in a comprehensive water monitoring and management system based on an artificial neural network (ANN) has been presented (Mounce *et al*. 2002). Promising results from the first set of sensors have paved the way for the development of a set of ten sensors along similar principles which have been installed in an isolated DMA of a UK water company. Later, two sets of burst trials were organised in the same zone in order to assess the performance and integrity of both sensors. In both trials, the failure that occurred in close proximity to the sensor was easily identified (Khan *et al*. 2002*b*, *c*).

In this paper, the assessment of both sensors is further narrowed to a sub-zone where two out of ten sensors are located. A series of aggressive flushes was organised to evaluate the failure response of the sensors at a street level. A simulation study has been conducted of the same sub-zone to assess water quality characteristics and flow characteristics. Several hydraulic sensors were also placed at various strategic locations for a comparative analysis. The following section describes the flushing trial, followed by an analysis of the flushing trial based on the results of the failure sensors, hydraulic sensors and simulations with the modelling software. The paper ends with conclusions relating to the outcomes and interpretation of the trial.

FLUSHING TRIALS

It has been observed that there is a 3°C temperature difference along the experimental network from the reservoir to the customer delivery point (Khan *et al*. 2002*c*). During a failure event, the lower temperature of the reservoir pervades the network which makes the temperature difference across the network negligible. After the event, water in the network required a reasonable time in order to re-establish a temperature difference with the reservoir water (the slow moving water in the pipeline is warmed up and develops a temperature difference of 3°C). In the flushing trial where one aggressive flush after another was conducted at several locations across the network, the reservoir and the network remained at the same temperature during the whole trial. This made the flushing trial different from a real burst event which explains why it was difficult to check the performance of the temperature-based sensor for individual flushes. However the failure (differential temperature) sensor recorded the whole trial

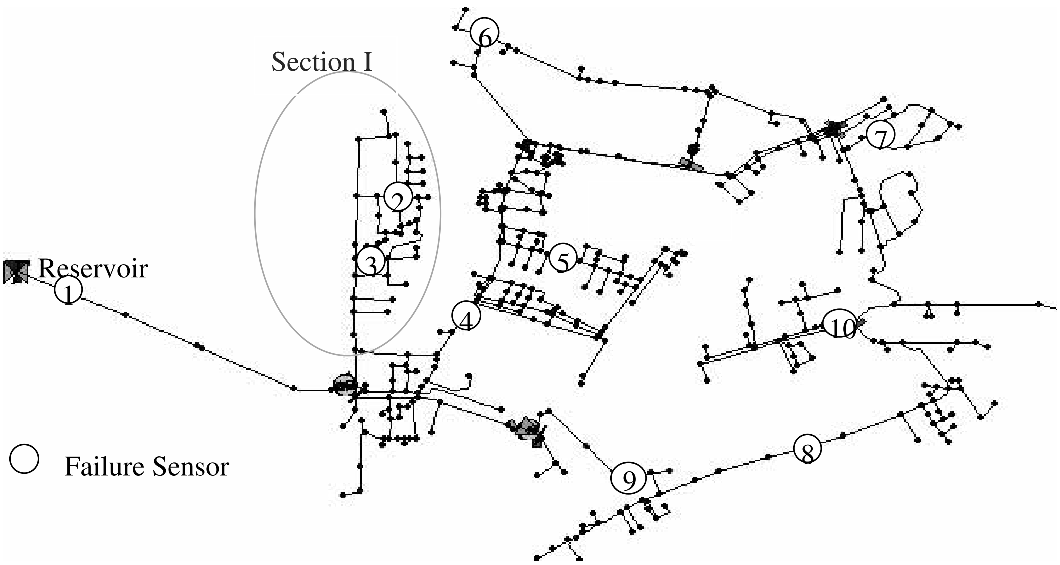

Figure 1 | Ten failure sensor locations in one district meter area.

as a single failure event in the network. An analysis of the other failure sensor (opacity), the hydraulic sensors (pressure and flow) and the simulations is presented in the following sections

Failure sensor description

Two types of failure sensor have been designed, calibrated, tested, installed and used to generate useful data for an ANN leak detection approach. One failure sensor was designed to measure the opacity of water flow in a pipe, and the second was designed to measure the temperature difference between the water flowing in the pipe and that of the surrounding soil. Both failure sensors have given repeatable results in the laboratory (Khan *et al*. 2002*a*).

Initially one arrangement was designed to house both sensors, with a dual-channel data logger for downloading data at the sensor location to a laptop computer. Later, ten sensors of the same design were constructed and placed at strategic locations in one highly instrumented DMA. Two trials each of four independent bursts were conducted on separate nights in order to achieve maximum benefits of the MNF. The performance of both sensors during the trials have been analysed separately (Khan *et al*. 2002*b*, *c*).

The DMA was divided into three sections in such a way that two sensors (1 and 4) were placed close to the reservoir, five sensors (2, 3, 5, 6, 7) were located in the central section and three sensors (8, 9, 10) were placed in the end section of the network (Figure 1). In the burst trials, organised by the water company, the performance of two sensors (2 and 3) in a separate branch of the network were found to show the most significant response. It was therefore decided to analyse the performance of both sensors in more detail, particularly at the street level. A separate section (Section I) within the DMA was selected for this purpose and a flushing trial was organised where two sensors (2 & 3) were located.

Sub-zone selection

The trial was divided into a number of aggressive flushes that were conducted in sequence during a single night. In these trials, the main concern for the water company was to clear the pipes of sediment in this particular section of the network. During each flush, a number of valves were closed and the flow was routed in the direction of flush in order to clear sediment from the pipes. The scheduled flushing trial is presented in Figure 2 where a separate route for each flush is shown in grey (section b–l).

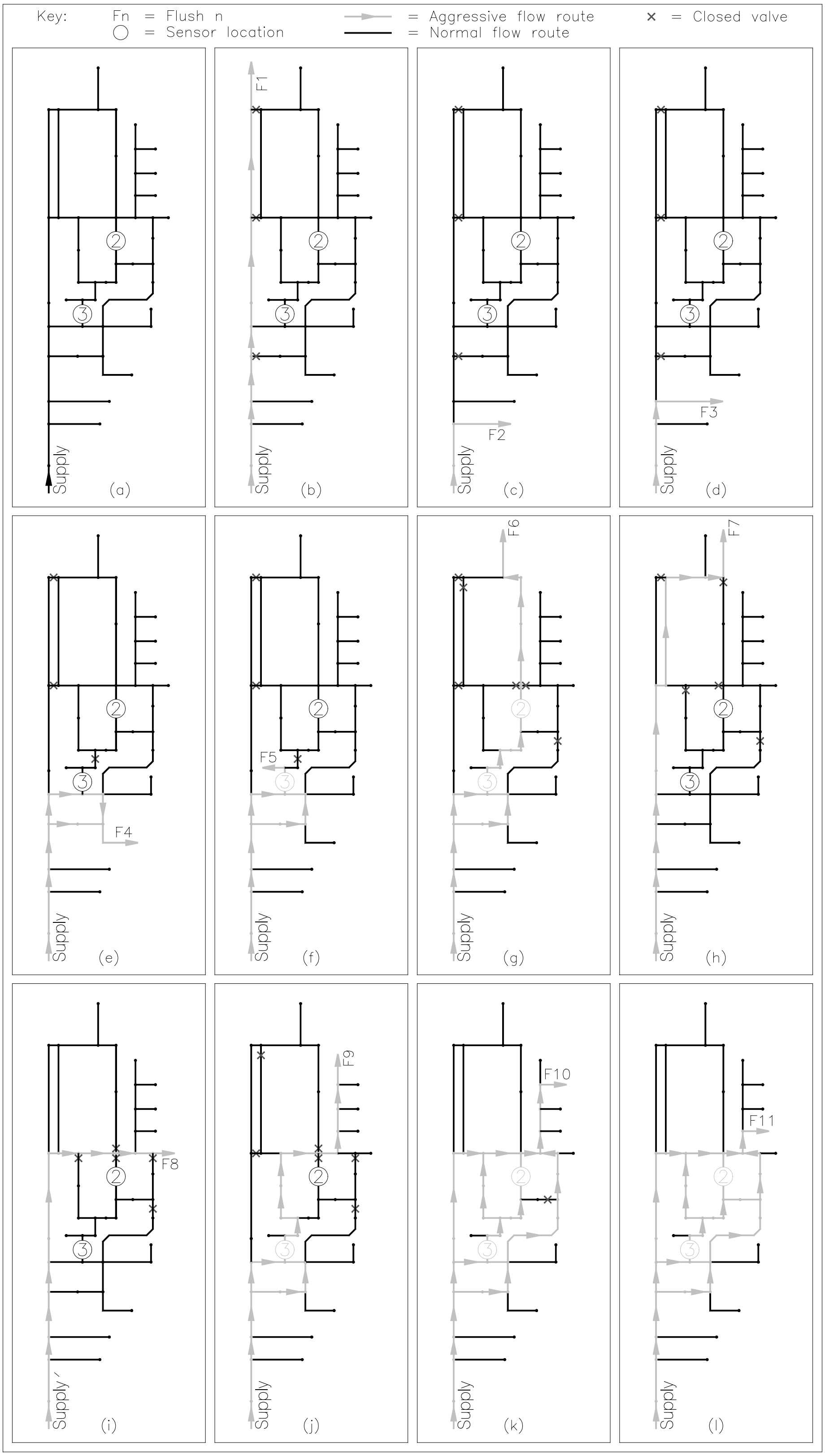

Figure 2 | Scheduled flushing trial.

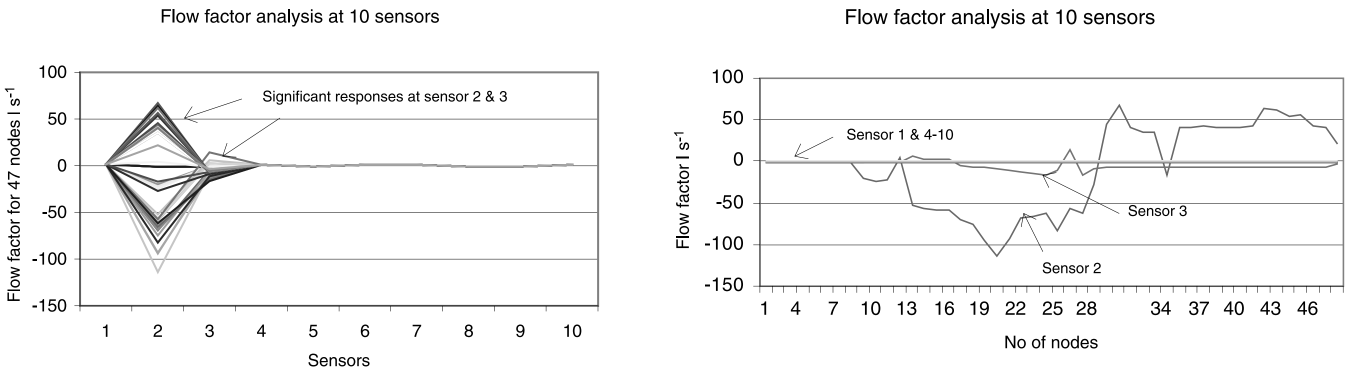

Figure 3 | Significant responses at sensors 2 and 3 to independent leak at 47 points.

Sub-zone flow analysis

The failure sensors' functions are based on opacity and differential temperature of the water flow, which is assumed to be dependent on the water flow characteristics (e.g. flow velocity). In order to test the validity of this assumption, a hydraulic water network modelling software program has been used to model the small, isolated branch of the network (containing 47 nodes) where sensors 2 and 3 are located (Figure 1).

A similar leak (20 mm diameter hole) was simulated separately and individually at each node in the section, keeping each leak independent from the others, and the effect of flow rate on all ten sensor locations was monitored. Forty-seven runs were simulated, one for each independent leak at each node, and the flow rate was monitored for 24 hours at 1 hour intervals. A flow factor was determined which compared the relative effect of each leak at the sensor locations with no leak. From the study, it was found that the sensor locations 2 and 3 responded most significantly to all simulated leaks in the section, whereas response at the remaining eight sensors was negligible (Figure 3).

A detailed analysis of the flow directions from these two sensors indicated that the proposed section of the network could be further divided into three sub-sections (Figure 2). These sub-sections are (a) nodes above both sensors, (b) nodes in between the two sensors and (c) nodes below both sensors. A leak created at any node in sub-section (a) will cause flow rate to be increased at both sensors. A leak created at any node in sub-section (b) will cause flow to increase at sensor 3 and to decrease at sensor 2 whereas a leak in sub-section (c) will decrease the flow rate at both sensors. This behaviour of the flow rate in three sub-sections of the network is displayed in Figure 3.

FLUSHING TRIAL ANALYSIS

The scheduled trial was divided into 11 flushes that were conducted consecutively in one night. Before each flush, some valves were closed (shown in Figure 2 for each flush) to direct the flow to a particular flush location. This operation affects the flow regime within the pipeline and hence the opacity of the water. The response of failure sensors during this period (in between the flushes) was attributed to the build-up of pressure, reverse flow or flow redirection in the system. The overall analysis of the flushes is presented in the following sections.

Failure sensors analysis

Analysis from the two failure sensors (2 and 3) that were located in the selected network section is considered here (Figures 4 and 5). As the trial was conducted during the night with the purpose of clearing the network section of sediment, the flow of this section was isolated from the

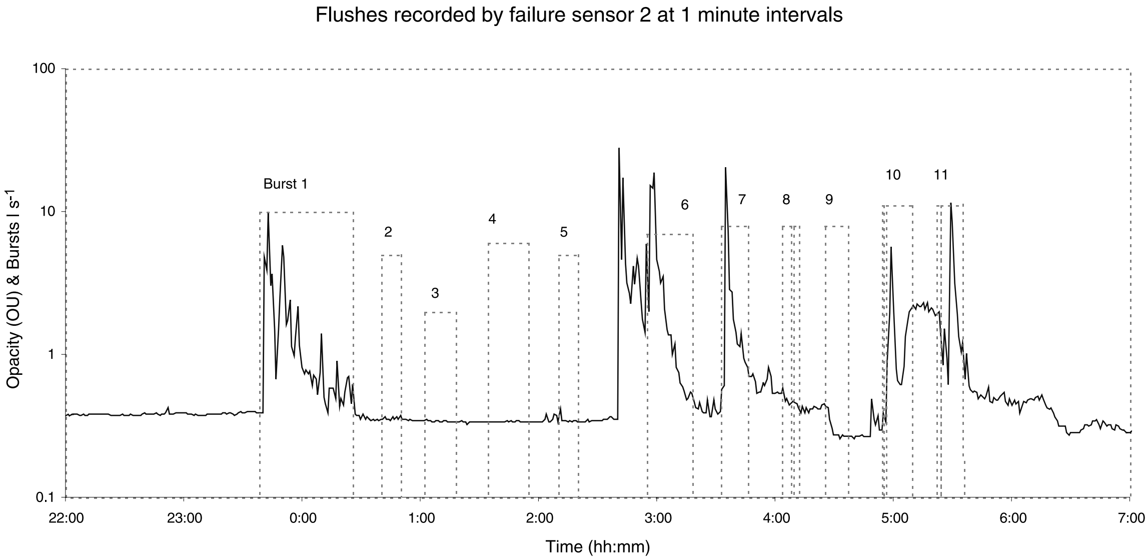

Figure 4 | Output o\f failure sensor 2.

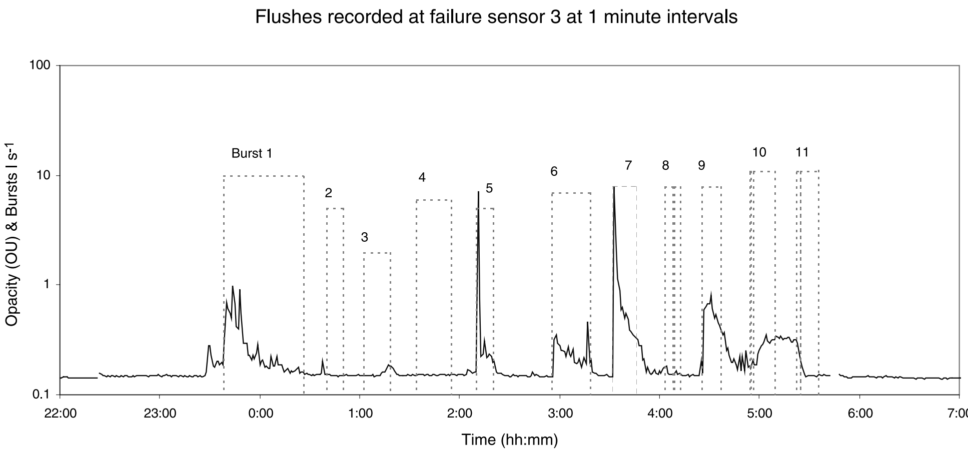

Figure 5 | Output of failure sensor 3.

rest of the zone. The remaining eight failure sensors located in the rest of the zone have obviously not responded to any of the flushes during the trial. However the responses of these sensors were recorded as one combined event in the system when the flow was normalised at the end of the flushing trial.

Flush 1

Both sensor 2 and sensor 3 appeared to respond significantly to Flush 1 (Figure 2 (b)), each showing a sharp rise in opacity within a few minutes of the burst being created, before steadily falling to their initial values over three-quarters of an hour (Figures 4 and 5).

It is possible that the sudden change in pressure could have set up a short duration high flow pulse of 'disturbing' sediment in the pipes, at and around these sensors, causing a sudden rise in opacity. It is also noticeable that the opacity at sensor 2 takes longer to reduce to its initial value than the opacity at sensor 3; this is due to the additional route for sediment to travel from sensor 3 to sensor 2.

Flushes 2–4

Neither sensor responded to any of these flushes since they did not affect the flow at the sensors due to the closure of valves in this particular section of the network (Figure 2 (c–e)).

Flush 5

Sensor 3 showed a very significant response to Flush 5 (Figure 2 (f)). Within 1 minute of the start of the flush the opacity rose to 35 times its original value and then fell to twice its original value after a further 5 minutes, subsequently falling steadily back to its original value over a further 5 minutes. Sensor 2 did not respond to the flush but both sensors recorded very small changes in opacity before the flush which were probably due to the adjustment of valves. It is understandable that sensor 3 should respond, as Flush 5 is immediately downstream of this sensor.

The change in flow direction of the water in the pipe feeding sensor 2 was expected to cause a rise in opacity. This can be seen prior to Flush 5 in the data from sensor 2, though the modelling analysis shows that at the low flow rate it should take at least 30 minutes for any sediment to reach sensor 2.

There is a very sharp increase in opacity to about 100 times the original value at a time between Flushes 5 and 6 at sensor 2, but there is no corresponding change in opacity at sensor 3. This may be due to changes in flow direction in the pipe feeding sensor 2 because of valve operations that are applied before a flush (in this case prior to Flush 6).

Flush 6

Flush 6 (Figure 2 (g)) caused a very large flow through both sensors that can be seen in the simulation plots (Figures 4 and 5). Sensor 2 responded, seemingly instantaneously, to about 100 times its normal value whereas a smaller response was recorded by sensor 3 within 2 minutes. The pipes leading to sensor 3 had already been flushed which explains why the opacity recorded at sensor 2 was much higher than that recorded at sensor 3, even though the flow rates were similar. Responses on both sensors returned to their normal values over the same period of time.

Flush 7

Both sensors responded to Flush 7 (Figure 2 (h)) with a sharp increase in opacity to about 65 times its normal value (Figures 4 and 5). The response at sensor 3 occurred immediately after the start of the flush while the response of sensor 2 occurred some 3 minutes later due to redirection of the flow in the system.

Flush 8

There is no response at either sensor (Figures 4 and 5) to Flush 8 (Figure 2 (i)), as the aggressive flushing is not directed past either sensor.

Flush 9

The opacity data for sensor 3 (Figure 5) shows a sharp and instantaneous rise in response to Flush 9 (Figure 2 (j)), to about six times its normal value, followed by a steady fall. There is no very high value opacity peak however, and it is likely that this is due to the fact that all of the pipes leading to sensor 3 have previously been flushed. The opacity data for sensor 2 (Figure 4) shows a distinct reduction in opacity which seems to start at the same time as Flush 9.

Between Flushes 9 and 10 (Figure 2 (k)) there was a single peak in which opacity at sensor 2 suddenly increased by a factor of four, and then decayed fairly slowly to its original value; this was due to the adjustment of the valves. The flushes were not expected to have had much effect on the flow at sensor 2, and the measured response was probably a result of the small flow of water past sensor 2 (Figure 2 (j)).

Flushes 10 and 11

Only sensor 2 has responded to Flush 10 (Figure 2 (k)) and Flush 11 (Figure 2 (l)), though both sensors recorded an increase in between Flush 10 and Flush 11 (Figures 4 and 5). The responses at sensor 2 were greater than 30 times the normal value which indicated that the sediment in the remaining non-cleaned section of the pipeline was being routed through sensor 2. Flush 10 was recorded as a single peak, and Flush 11 as two peaks. Both flushes were stopped and restarted after 2 minutes. In both cases there

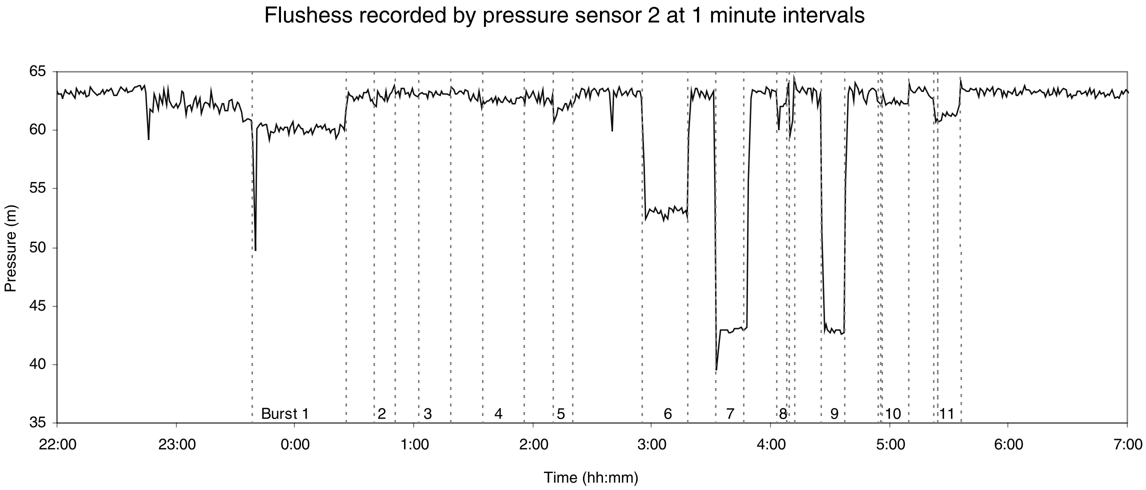

Figure 6 | Output of pressure logger located near failure sensor 2.

is an indicated delay of about 3–4 minutes between the start of the flush and local rise in opacity, which at the velocity of water at sensor 2 corresponds to about 50 metres travel (by the simulations); that is, from the start of the pipe where sensor 2 is located.

Between Flushes 10 and 11 there is a change in the measured opacity: a slow build up and then rapid decline which coincides with the start of Flush 11 for both sensor sites. The delay between the start of Flush 10 and the start of the build up is 5 minutes for sensor 3 and 10 minutes for sensor 2. It is likely that the high flow velocity in the main pipeline disturbed the sediment there. Simulations showed that it takes 6 minutes to reach sensor 3 and 15 minutes to reach sensor 2. These seem to be the times at which the opacities peak. It should be noted, however, that after 15 minutes Flush 11 ended and the flow rate reduced dramatically in the main pipeline and at the pipeline where sensors 2 and 3 were located. The opacity did not reduce during this period, but it did reduce at the start of Flush 11 which may indicate a clean pipeline system.

Hydraulic sensors analysis

Various pressure loggers were strategically located during the trial. The analysis presented here is for the two pressure loggers that were located close to sensors 2 and 3 (Figures 6 and 7). The pressure simulations for both sensors showed a 5% drop in pressure for the duration of Flush 1. This was also observed in the recorded pressure data at these two sites. The pressure loggers at both sites also recorded a pressure drop of about 22%, of very short duration (~1 minute), at the start of the flush.

There were no recorded pressure changes at all loggers for Flushes 2–5, although small changes in pressure due to Flush 2 and 4 at sensor 3 were recorded. Similarly both pressure loggers responded to Flushes 6 and 7 in a manner that exactly matches the failure sensor responses.

Due to the isolated flow during Flush 8, the pressure simulations showed no change in pressure at any sensors, but the actual pressure loggers across the entire DMA all picked up a short duration pressure drop of about 2–3 minutes at each site for both of the times that Flush 8 was started. However the failure sensors have shown some correlation with the actual pressure loggers for that duration.

Generally the flushing operation caused a drop in pressure and a rise in the flow rate, which subsequently increased the failure sensor response. During Flush 9 when the pipeline pressure reduced, the flow rate decreased (due to the closure of valves in the particular section of the network; Figure 2 (j)) and, hence, a drop in the failure sensor reading can be seen at that point.

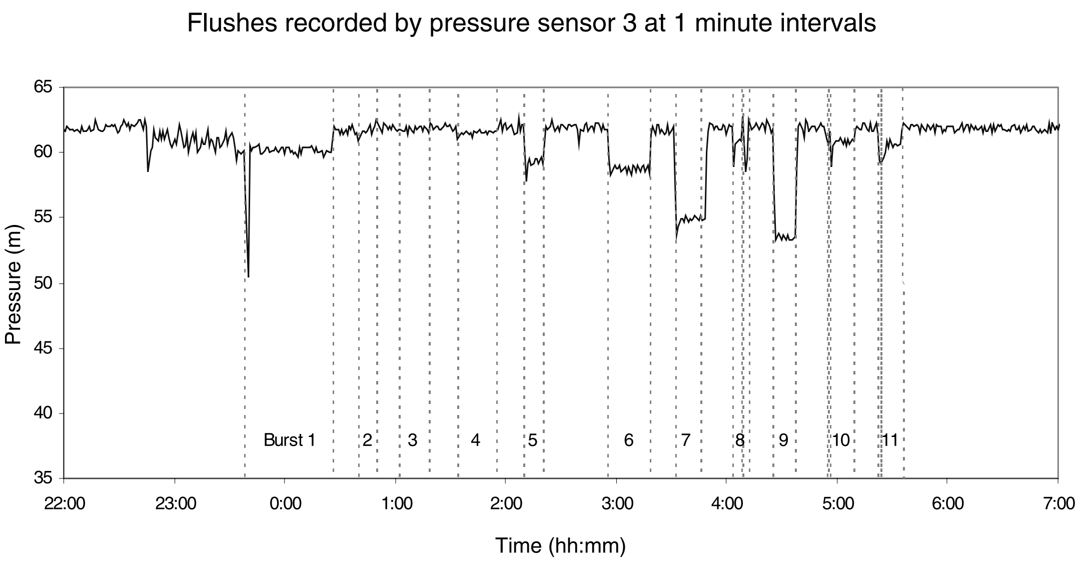

Figure 7 | Output of pressure logger located near failure sensor 3.

Analysis by modelling software

Simulations at 1 minute intervals for pressure, velocity and flow were carried out using modelling software for the DMA network for each flushing operation with the valve setting and simulated leak flow rates set to those which were used during the actual flushing trial. Each simulation was then repeated without any leakage. The simulated flow data before, during and after each flushing operation for the entire trial at sensors 2 and 3 is shown in Figures 8 and 9, respectively.

Simulations for these sites showed no change in the flow rate with the exception of the main pipeline where Flush 1 was created. However, as sensors 2 and 3 are fed via the main pipeline, any sediment that was disturbed could be carried to these sensors. From the simulation data, it was calculated that it took 15 minutes for water to travel from the main pipeline to sensor 3, and then a further 44 minutes to reach sensor 2, whereas sensors 2 and 3 showed sharp rises in opacity 3 minutes and 1 minute, respectively, after the start of the trial. This large discrepancy in timing showed that, although the failure sensor could be directly related to the flow rate, it did not require the flushing water to reach the sensor location. The sensor responded as soon as the local sediment was disturbed due to flushing elsewhere in the network.

Little change was observed in simulated velocity and flow for Flushes 2–4 due to the closure of valves in that section. A reduction in simulated flow was predicted when flow through sensor 3 is shut off between Flush 3 and Flush 4 but this did not appear to cause a rise in opacity. For Flush 5 the flow was directed in such a way to cause the sediment in the main pipeline to pass via sensor 3. This arrangement showed a significant change in velocity during the simulation which has a strong correlation with the failure sensor response (Figures 5 and 9).

The simulations for sensor 2 and sensor 3 show no increase in flow (or velocity) due to Flush 7 or 8, as there was very little flow through these sensor locations. Flow (and velocity) simulations show a very significant flow through sensor 3 due to Flush 9 and no change in flow for sensor 2.

DISCUSSION

The data features that are of interest are the ‘peaks’, which indicate the occurrence of events in the pipeline. The sensors were designed to be low-cost (ultimately a few pounds or less if manufactured in volume) and to provide

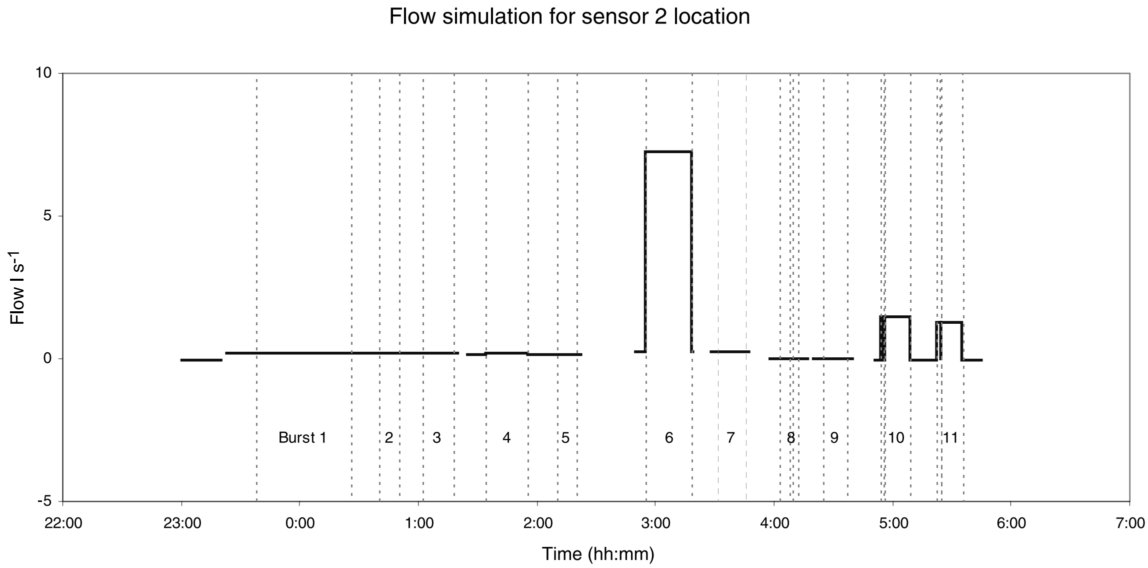

Figure 8 | Output of flow simulation near failure sensor 2.

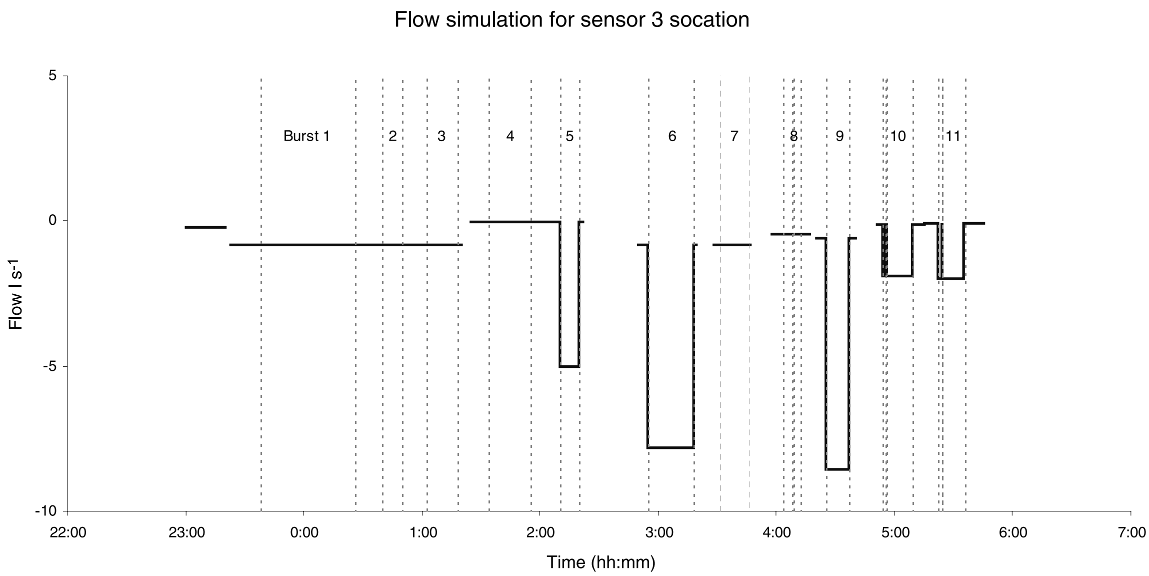

Figure 9 | Output of flow simulation near failure sensor 3.

a signal which was not necessarily proportional and which could have a low signal to noise ratio. It is clear from the results presented here that the 'events' are quite distinguishable from the noise. When the sensor site is sufficiently remote from the event location, the magnitude of the event signal will be reduced, possibly to an extent where it becomes indistinguishable from the noise.

Data collection and transfer remain major issues. Technologies for data collection from low cost sensors were not within the remit of this research programme.

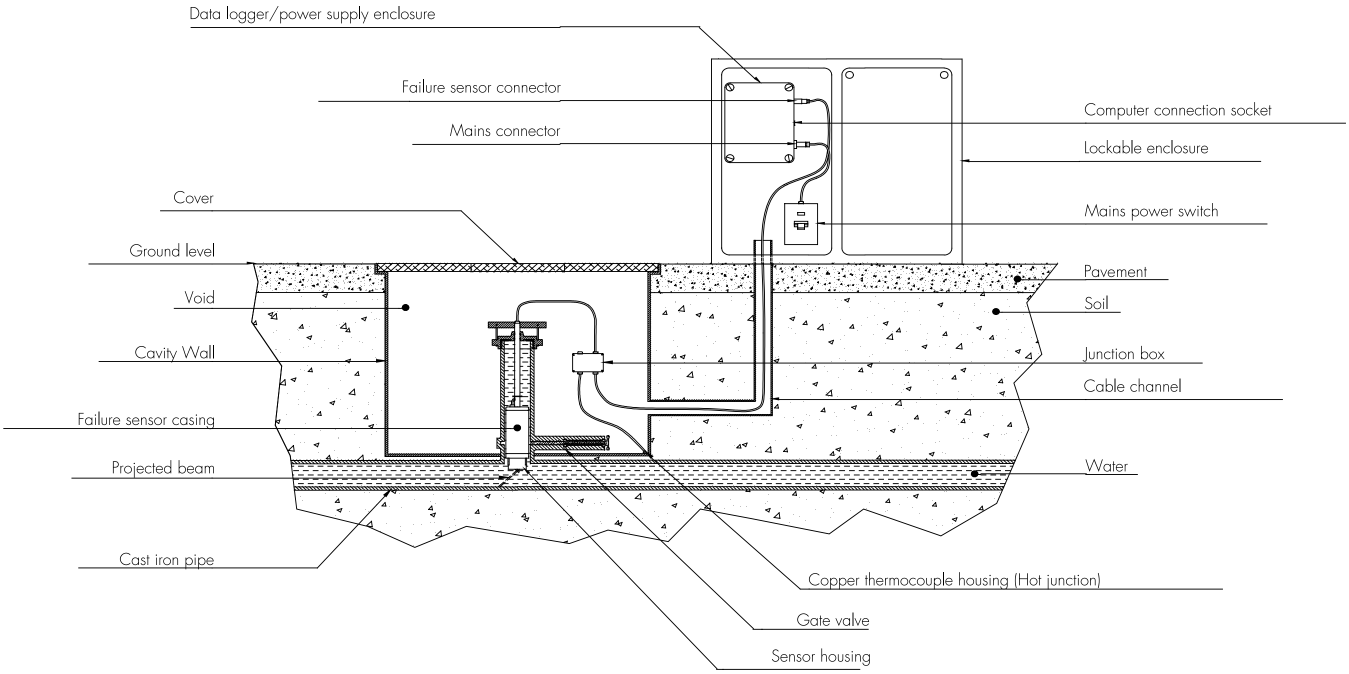

Figure 10 | Trial prototype failure sensor site installation.

However, the importance of an efficient method for data collection is understood, for which the rapidly developing technologies associated with mobile communications are of great interest. This must represent a subsequent stage of the research. There will be the possibility of using a PSTN (public switched telephone network) link as a data download solution.

CONCLUSIONS

This paper has assessed the performance of two low-cost sensors that were deployed for 'failure' detection in a water distribution system. Both sensors were installed in a housing that was then installed at ten strategic locations in one DMA of a UK water company (Figure 10). An isolated section of the DMA (covered by two failure sensors) was selected for the analysis described and a flushing trial with the purpose of clearing pipes of sediment was organised for the particular section.

During the trial, pressure loggers were used to monitor the pressure at various strategic locations. Modelling software was also used for estimating the flow rate, flow speed and pressure in the required section and water quality characteristics have been assessed with the flow characteristics.

The first (differential temperature) failure sensor required a significant time between changes of state (with and without failure state), and 11 consecutive flushes organised aggressively in a single night made it difficult to differentiate between individual flushes of the trial. However the authors are confident of its performance in a real failure situation (Khan *et al*. 2002c). The second failure sensor based on water opacity has provided useful information during the flushing trial where every flush for which the flow was directed past the sensor can be distinctly recognised. Due to the isolation of the flushing section, failure sensors located in the remaining portion of the DMA have recorded the trial as a single event in the system.

The analysis showed that the maximum peak responses of flow (simulations) and pressure readings (loggers) are maintained from the start to the finish of the flush, whereas failure (opacity) sensors have responded with a sharp rise that steadily dropped to its original value even while the flush continued. It is also noticeable that between flushes, the peak responses of failure sensor alone could be attributed to the closure of valves, which caused flow reversal or redirection in the network. This confirmed the direct relationship of the failure sensor response to the 'disturbance' of sediment in the system.

The information collected from the three different sources (failure sensors, pressure loggers and simulation) has been examined carefully for events that have occurred in the system. The abnormal flow directed past the opacity sensor is measured with confidence as a 'failure' in the system. The pressure loggers located near failure sensors have shown a strong correlation for all events occurred during the trial. Similarly, data from the flow simulation has also provided significant evidence to support a claim for robustness of the developed sensors, which is potentially a valuable asset management tool.

Failure sensor technology can usefully indicate the state of a water pipeline distribution network and can thus contribute to a system for monitoring and leak detection in water distribution pipelines. Such technology can be deployed alongside more costly sensors to measure hydraulic parameters.

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