Innovative Optimization Model for Water Distribution Leakage Detection

Zheng Yi Wu*

* Haestad Methods Solution Center, Bentley Systems, Incorporated,
27 Siemon Co Dr, Suite 200W, Watertown, CT06795, USA
Zheng.Wu@bentley.com

Abstract This paper presents a new optimization methodology for leakage detection in water distribution systems. It pinpoints where leakages are and predicts how much a leakage is as a orifice flow that is modeled as flowing emitter flow dependent on the nodal pressure in addition to the volume-based demand at node. The new method then minimises the differences between the model predicted and the field observed values of flows and pressures. The optimization problem is solved by using a competent genetic algorithm. The methodology is developed as a user-friendly integrated optimization modeling tool so that engineers can readily execute leakage hotspot identification optimization as an independent task. The integrated optimization framework also permits the engineer to carry out combined leak detection and hydraulic calibration tasks. The case studies have been demonstrated by using a DMA system in UK. The results obtained illustrate the robustness and effectiveness of the developed method at predicting leakage hotspots.

Key words water loss, leakage detection, water distribution system, hydraulic model, genetic algorithm and optimization

INTRODUCTION

Water utilities provide clean water service to local communities and charge the service by the metered water consumption. However, not every drop of water produced at a water treatment plant reaches customers and generates the revenue for water companies. Instead, a significant portion of drinking water is lost, due to either water dripping away from the distribution pipelines or the unauthorized water usage. Consequently, water utilities lose the revenue within distribution pipeline networks. Water loss represents a major fraction of non-revenue water (NRW). According to the International Water Association (IWA)'s best practice recommendations (IWA 2000) for water balance studies, more than 65% of NRW arises from unauthorized water consumption, meter inaccuracies and leakages from the water mains source-to-taps infrastructure.

Water companies are losing more water than saved. On average, more than 15% of water produced is lost in UK. Water management 2005-06 report by House of Lord Science and Technology Committee states that current level of leakage from the distribution network is unacceptably high in parts of the country; this has a negative impact on the public's attitude to sensible water use. Ofwat is called on to sanction increased water company expenditure on reducing leakage. Leakage targets, taking into account of environmental and social factors, as well as economics, are set as a key part of water utilities measured performances with severe financial penalties being incurred if targets are not met.

More recently, Ontario Sewer and Watermain Construction Association in Canada reports that as much as $1 billion worth of fresh, clean drinking water disappears into the ground every year from rotting, leaky municipal water pipes, 20 to 40 per cent of all the water pumped through municipal water systems never reaches consumer taps and in some cases the loss is as high as half of all treated water. The fact that municipalities are wasting such enormous amounts of water themselves through leaky pipes undermines the water conservation message that is delivered.

Water leakage rate is high. It causes financial loss and damages public reputation to water utilities. Deteriorated water infrastructure must be proactively improved in order to control water loss to an economic level (Lambert & Frantozzi 2005). Water audit studies focus on the calculation of supply balances for water systems or their subsystems such as district meter areas (DMAs). Over the last decade, the concepts and methods developed for system wide water balance calculations (Lambert & Mckenzie 2002) have been based upon water assets' physical data and the statistics of pipe bursts, service connections and underground conditions. Performance measures and indicators are used to support the managerial approaches to minimize different components of water losses. These concepts and methods have been adopted by countries around the world. Some researchers developed an alternative approach for assessing leakage through network hydraulic simulation. In general, however, there is still a relatively low level of leakage reduction R&D funding by the industry. Water UK provided the figure on the overall spending by combined water and sewerage companies in England and Wales was just 0.3 percent of turnover in 2004-05.

A need has arisen to develop a systematic approach that identifies likely leakage hotspots so that detection crews can identify leaky mains more quickly in turn leading to quicker repairs. To meet the requirement, a number of tasks must be undertaken, first of all to assess the level of water loss (often called water balance or auditing), secondly, locate where the losses are and finally adopt reactive and proactive measures to improve the conditions of water mains.

CONVENTIONAL APPROACHES

There are several techniques currently used for detecting where leakage is occurring in a distribution system, including (1) random or regular sounding surveys; (2) step-testing of sub-systems and (3) acoustic loggers as a survey tool.

Regular or random sounding survey can be conducted for leak detection. It uses a traditional listening stick, an electronic listening stick or a systematic 'sweep' using acoustic loggers. Leak noise correlators or ground microphones are then used to pinpoint the exact location of the leak. This technique is time consuming and not very efficient in terms of focusing on areas with potential leaks because the leakage engineers or technicians often looking for leaks in sections of the network where they do not exist.

Step-testing is conducted by making temporary successive valve closure to reduce the size of a system (or supply district), typically, one step-testing area contains about 500-1500 water service connections. The valves are closed for a short duration whilst simultaneously measurements of the flow rate are being made. The resultant reduction in flow rate following the closure of a particular valve indicates the total leakage plus legitimate night consumption in that section of the distribution system. If the resultant reduction is greater than anticipated, taking into account the number and type of customers in the section isolated, then it is an indication of a leak. Step tests are generally undertaken during the period of minimum night flow (often between 2:00 AM and 4:00 AM). Carrying out such a test at this time avoids causing supply problems to the majority of customers.

To avoid night work and shutting down of various parts of a distribution system, acoustic loggers can be used to detect leakage. The acoustic or noise loggers are installed on pipe fittings by way of a strong magnet and are programmed to listen for leak characteristics. Typically, noise is recorded at one second intervals over a period of two hours during the night, when background noise is likely to be lower. By recording and analyzing the intensity and consistency of noise, each logger indicates the likely presence (or absence) of a leak. Acoustic loggers can either be permanently located in the network or they can be deployed at certain points for a user definable period, often two nights.

However, it is time-consuming and costly for a leak detection crew to apply the current leakage detection apparatuses and procedures to all the water pipelines throughout a system. Leaks are also becoming harder to find. One reason for this is pressure management. Not only is leakage being routinely suppressed by planned pressure reduction but also the same reduction leads to less acoustic disturbance from those leaks. At the same time, sounding for leaks has become more difficult as ferrous mains are replaced with less acoustically responsive plastic pipes.

LEAKAGE DETECTION MODEL

One alternative approach for achieving cost-effective leakage detection is to leverage the well-established computer-based hydraulic modelling technology. Water industry has accepted a hydraulic model as routine computer simulation tool to analyze the hydraulic characteristics of the system elements (pipes, pumps, valves and storage facilities). An innovative approach is developed by applying genetic algorithm (GA), a search technique based upon the principles of natural evolution and genetic reproduction, to identify leakage hotspots.

It is the well-known fact that leakage is pressure dependent, the greater the pressure, the greater the leakage. Leakage is one type of pressure-driven demand that can be modeled as emitter flow given as:

$$Q_i = K_i P_i^{\alpha} \tag{1}$$

Where Q_i is the leakage aggregated at node i, P_i is the nodal pressure at node i, α is the exponent (usually 0.5 for leaks as default) and K_i is the emitter coefficient. It is the emitter coefficient K_i that is to be optimized as the indication of possible leakage when its optimal value is greater than zero. An optimization model was formulated (Wu and Sage 2007) to optimize the emitter coefficient of all the nodes, but this requires for optimizing hundreds or even thousands of nodal emitter coefficients. By the nature of leakage hotspots, there are only a handful of spots that are experiencing leakages in a real system. Thus a new leakage detection optimization model is formulated to identify a given number of leakage nodes and corresponding emitter coefficients, given as:

Search for: $$\vec{X} = (LN_i^n, K_i^n); \quad LN_i^n \in \mathbf{J}^n; n = 1,...,NGroup; i = 1,...,NLeak^n \tag{2}$$

Minimize: $$F(\vec{X}) \tag{3}$$

Subject to: $$0 \le K_i^n \le K_{\max}^n \tag{4}$$

Where LN_i^n is the leakage node index for leakage node i within demand group n, K_i^n is the emitter coefficient for leakage node i in group n, $\mathbf{J}^n$ is the set of nodes within node group n, *NGroup* is the number of node groups, $NLeak^n$ is the number of the specified leakage nodes to be identified for node group n, $K_{\max}^n$ is the maximum emitter coefficient for group n, $F(\vec{X})$ is the objective function defined as a distance between the field observed and model simulated values (Wu et al. 2002).

Integrating the emitter flow pressure-driven hydraulic model with the state-of-art optimization technique allows engineers to identify where the leakage is and how big the leakage is likely to be. The method is developed and incorporated into the powerful parameter optimization tool Darwin Calibrator (Wu et al. 2002 and Bentley 2007) that searches for the leakage locations and the size of each possible leakage as part of model calibration process. One common framework for parameter identification fulfils two purposes of both model calibration and leakage detection.

EXEMPLARY CASE

This example is based on a hydraulic model of a real district meter area (DMA) in the UK with high leakage historical records (Sage 2005). The model is comprised of 1,122 pipes, 841 nodes and one variable head reservoir. The field tests were carried out by United Utility Water (UUW) with a higher density of pressure loggers than usual as part of the work to test out the leakage prediction method. UUW has also identified leakage hotspots based on field test data used for normal all-mains model calibrations, typically deploying one logger per 200 houses.

The observed data contains the time series of flows into the DMA and pressures at 28 junctions. They are processed and imported into the GA-based calibration and leakage detection tool as different field datasets with each set representing a complete snapshot of system conditions for one time step. For example, Field Date Set – Hour 6.5 contains the observed flow and the pressures at hour 6:30 AM. A total of 48 filed datasets over 24 hours have been imported into the GA-based calibration tool. One dataset at a particular time step can be used for model calibration at that time step.

This model is relatively small in comparison to many large water systems. However, leakage hotspot prediction will still present a fairly large optimization exercise. If every node is treated as an independent optimization variable this will result in a search problem of 841 decision variables. Experience to date indicates that the number of leakage hotspots for such a problem often comprises no more than dozens of nodes within the modeled DMA. So, instead of optimizing the emitter coefficient for each node in the predefined demand groups, the solution method, given as Eq.(2 to (4), reduces the optimization dimension as follows.

1. The user specifies the maximum number of possible leak nodes, noted as $NLeak^n$ for nodal demand group *n*.
2. The genetic algorithm searches for the best combination of $NLeak^n$ nodes (leakage locations) within node demand group *n*.
3. The genetic algorithm also optimizes the emitter coefficients for a total number of $\sum_{n=1}^{Ngroup} NLeak^n$ nodes to minimize the difference between the simulated and observed flows and pressures.

Comparing to the optimization formulation that just considers emitter coefficients without optimizing the leakage node locations for leakage detection given by Wu and Sage (2007), the proposed solution method has a number of advantages including:

1. Elimination of the requirement to create multiple demand groups.
2. It ensures more scalable optimization efficiency based on optimization of the given number of possible leakage spots. The proposed solution method avoids the selection by the end user of predefined demand groups for which the optimization dimension increases exponentially with the number of nodes in a system. This also avoids the need for increasing numbers of demand groups associated with larger models, In contrast, the new solution method optimizes the given number of leaks, which are independent from the size of the system (the number of nodes), so that the optimization dimension does not increase as the system size increases. Leak detection optimization for large systems can be solved for the limited number of possible leaks.
3. Allows user to flexibly perform leak detection optimization runs for the user-specified maximum number of possible leakage spots.

The only drawback of the proposed procedure is that the user now needs to prescribe the maximum number of possible leaks but this is a minor limitation. The optimization runs, based upon the competent genetic algorithm (Wu et al. 2002) can be effectively completed for a few dozen (up to hundreds) of decision variables (leak nodes), which should generally represent the leakage hotspot locations in a real network. The way forward is to restrict the number of leakage hotspots options by performing multiple optimization runs with different maximum numbers of possible leak emitters, and then compare the results to see if the similar leakage locations are identified. If the same leakage hotspots are identified over multiple runs, it is very likely that the mains in the identified areas are worthwhile candidates for site based leakage investigation.

Results

To demonstrate the application of the proposed method for leakage detection, leakage detection optimizations are conducted for the field data at low demand hours, that is, from midnight (hour 0) to 4:00 AM, this is because the pressure is high during this period of time, so is leakage. To test the robustness of the method, two optimization runs are conducted for the maximum numbers of 25 leak nodes (emitters) using two sets of pipeline roughness values respectively. Both cases have reached good correlation in between the observed pressures and flows as shown in Figure 1 and 2. To verify if the same locations are identified as leak hotspot, Figure 3 and 4 present the leakage thematic map with the optimized possible leaks. The greater the leaks, the greater the size of the node is in both Figure 3 and 4. Although both optimization runs do not identify the exact same leakage nodes, comparing both leakage thematic maps clearly indicates the very similar nodes or adjacency nodes are identified as possible leaks.

The identified leakage nodes are compared with the historical records of field leakage investigation conducted by UUW. One of the big known leakage hotspots, named Leak Site A as indicated in Figure 3 and 4, has been consistently predicted as leakage node by the optimization method. This is rather promising that the well-developed optimization tool is capable of detecting water distribution leakage using the real field data. The predicted leakage locations can be used as a good guide for field crew to better narrow down the leaky area and place the leakage detection equipment in a more target portion of the system than before, thus enable cost-effective and efficient leakage detection.

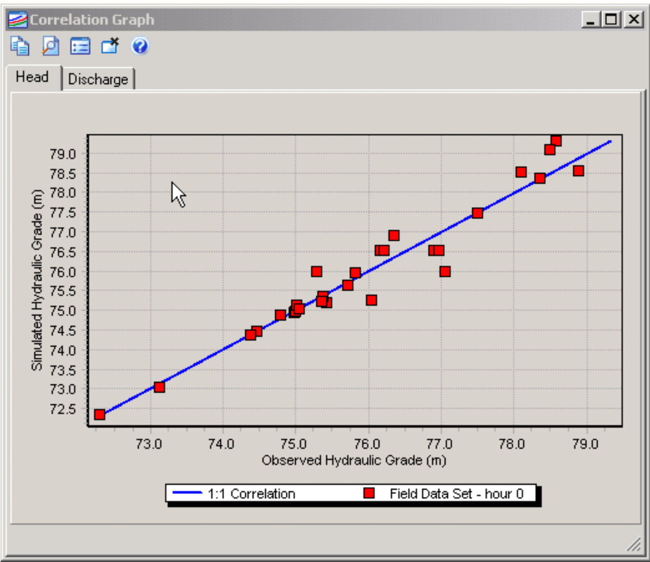

Figure 1 Correlation of predicted and observed pressures with the averaged emitter coefficients

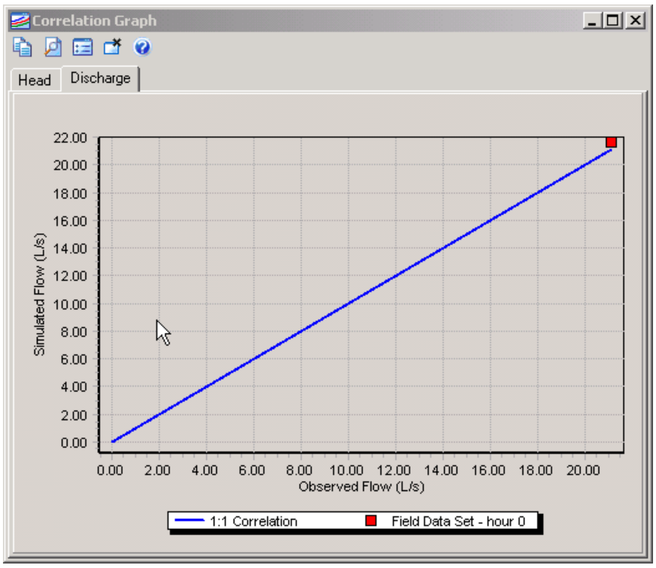

Figure 2 Correlation of predicted and observed flows with the averaged emitter coefficients

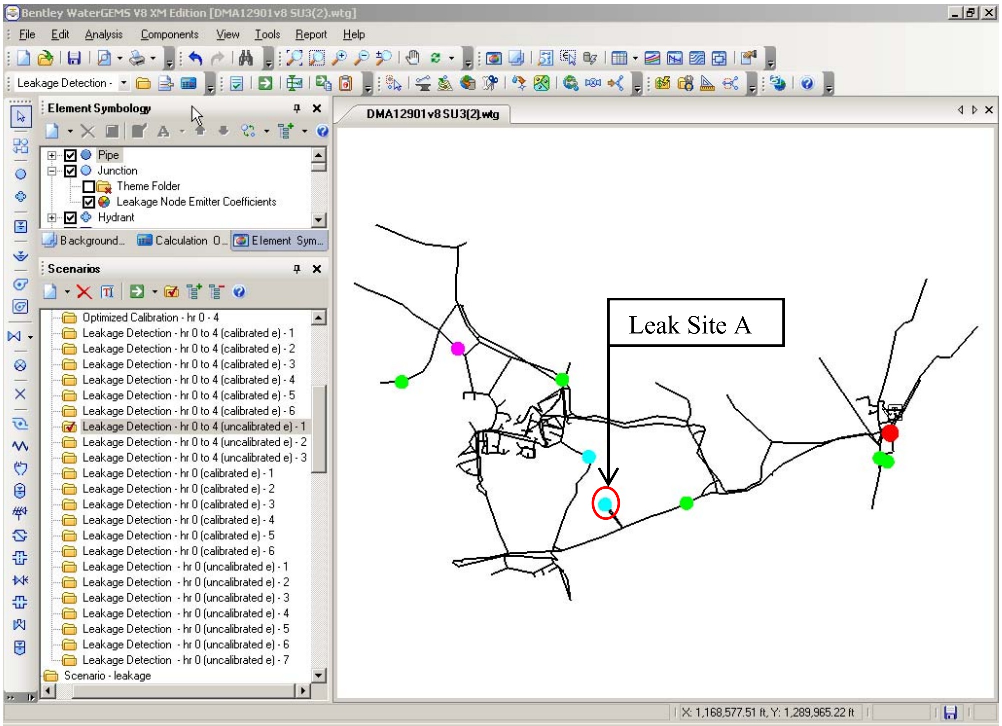

Figure 3 Detected leakage hotspots by allowing the maximum number of 25 leaks with default pipeline roughness

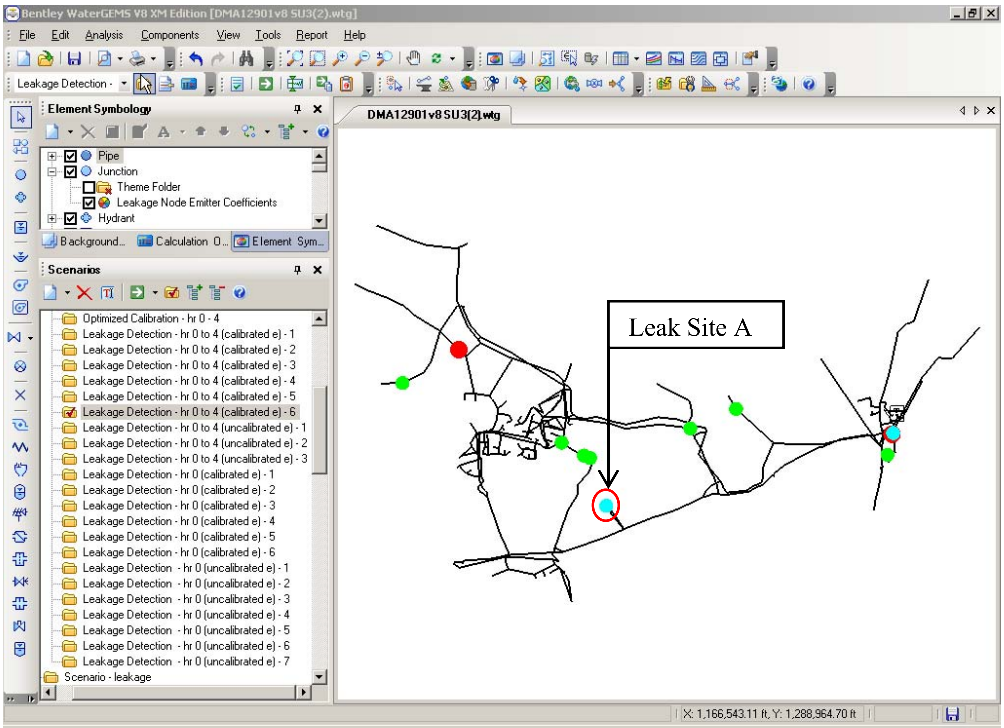

Figure 4 Detected leakage hotspots by allowing the maximum number of 25 leaks with the calibrated pipeline roughness

CONCLUSIONS

An optimization modeling method has been developed for identifying leakage hotspots and applied to a district meter area in UK. Good results are obtained for the example case study and illustrate that the integrated modeling method is a powerful tool for supporting water companies and their cost effective leakage reduction strategies. In general, it is impossible to exactly locate the water losses or leakages in a distribution system by just using the integrated optimization-simulation approach, but it is able to help engineers to narrow down the possible water loss (including leakages, un-metered and illegal consumptions etc) and thus enable more efficient leakage reduction programs.

The work also demonstrates to regulators that water utilities can exploit the latest innovations of modeling technology to manage, detect, control and reduce water leakages and make the best endeavors, with its supply chain partners, to mitigate some of the current concerns being expressed by government agency about the lack of technical progress with leakage reduction. The lessons are valuable to water industry to reduce the revenue losses within distribution pipeline networks around the world.

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