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Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: A case study

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Abstract

Water leakage in drinking water distribution systems is a serious problem for many cities and a huge challenge for water utilities. An integrated system for the detection, early warning, and control of pipeline leakage has been developed and successfully used to manage the pipeline networks in selected areas of Beijing. A method based on the geographic information system has been proposed to quickly and automatically optimize the layout of the instruments which detect leaks. Methods are also proposed to estimate the probability of each pipe segment leaking (on the basis of historic leakage data), and to assist in locating the leakage points (based on leakage signals). The district metering area (DMA) strategy is used. Guidelines and a flowchart for establishing a DMA to manage the large-scale looped networks in Beijing are proposed. These different functions have been implemented into a central software system to simplify the day-to-day use of the system. In 2007 the system detected 102 non-obvious leakages (i.e., 14.2% of the total detected in Beijing) in the selected areas, which was estimated to save a total volume of 2,385,000 m^3 of water. These results indicate the feasibility, efficiency and wider applicability of this system.

Key words: drinking water; pipeline leakage; leakage detection and forecast; discrete metering area; geographic information system

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Introduction

Water leakage in drinking water distribution systems is an important issue that is increasingly attracting attention from water industries, governments, and research institutes (Kleiner and Rajani, 2001; Poulakis et al., 2003). As reported by the International Water Association the average leakage ratio worldwide reached as high as 17% in 1997. In China, the average leakage ratio was relatively high for the majority of large and medium-sized cities, which resulted in an expected total loss of 5×10^6 m^3 of water per year (Chen et al., 2008). The rate in China is clearly higher than that in developed countries with respect to the leakage per length of pipeline. On the other hand, the distribution systems in most cities have been rapidly developing and expanding in recent years. For example, the pipelines in Beijing are increasing at a ratio of 200 km per year, and the total length is 8,118.32 km, which serviced an area of 665.95 km^2 in 2010. The rapid expansion brings more challenges to the safe operation of this system. Control of these water leakages is a major objective for the water companies in Beijing. Water leakage not only results in the waste of good quality water resources, but also leads to a higher risk of drinking water pollution (which means a health threat to water consumers). Furthermore, bursts in main pipelines severely disturb the public order. Therefore, the development of technologies and strategies for detecting, providing, advance warning, and controlling water pipeline leakage is of crucial for both the water supply companies and the public (Kishawy and Gabbar, 2010).

Unfortunately, systematic technologies for effective detection, advance warning, and control of water pipeline leakage are still lacking. Traditional technologies for passive detection of leakage are labor-intensive, time-consuming, and of low reliabilities, thus they can not meet the needs of large-scale distribution systems (Shu et al., 2008). In addition, there are no active means (e.g., by adjusting water velocity and water pressure) for flexible and effective control of leaks. Recently, several companies have successfully developed an automatic leakage logger which monitors the continuous acoustic signals from leaking pipes in the middle of the night, when the

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water usage and background noise are at their lowest. This logger can distinguish between the intensity, bandwidth, and frequency of these signals and wirelessly transmit this data to a collection unit for subsequent processing. The logger effectively monitors the leakage from pipelines and help to assess the volume and location of these leaks. The distances over which each logger can detect leaks depend on factors such as the material, and diameter of the pipe, and optimization of the layout of the loggers is also crucial to maximize the benefits and minimize the costs. However, the method to optimize the layout of these loggers has so far not been reported for large-scale implementation of this technology.

Moreover, the evaluation of leakage probability is important to facilitate the inspection and maintenance decisions. A rigorous estimate of the probability of leakages assists local water utilities to establish efficient inspection regimes to optimize their investment in the manual detection, rehabilitation, and maintenance of pipeline systems. Several traditional techniques, such as statistical, deterministic and probabilistic models have been developed to estimate pipe failure (Gat and Eisenbeis, 2000; Kleiner and Rajani, 2001; Poulakis et al., 2003; Shamir and Howard, 1979; Davis et al., 2007; Yamijala et al., 2009). Recently, approaches based on the GIS have been proposed to improve the accuracy of the estimates. Jafar et al. (2010) applied artificial neural networks and Ho et al. (2010) have used a GIS-based hybrid artificial neural network to evaluate pipe failure. Genetic algorithm techniques have also been used for certain aspects of the design and rehabilitation of pipe networks (Murphy et al., 1993; Simpson et al., 1994; Dandy et al., 1996). These studies were mainly based on the historical statistics and cost information. The large-scale implementation of the leakage loggers will generate a large quantity of signals. However, only a few studies have investigated the use of these signals to evaluate and manage the pipe distribution systems.

This study focused on the scientific operation and maintenance of water pipe networks, and the reduction of drinking water loss. It aimed to develop key technologies and strategies for timely detection, advance warning, effective control of pipeline leakage, management of leakage-detecting instruments, network classification and management of water distribution systems. It also considered a pilot scheme to apply these technologies and strategies in the core areas of Beijing.

1 Development of the system for the detection, advance warning, and control of pipeline leakage

1.1 Brief description of the system

There are several key issues to be resolved in the control of leakages from pipelines: (1) the effective and timely detection of leaks; (2) the prediction and assessment of the probability of leaks in different pipelines and areas, and the development of appropriate techniques based on the probability analysis; (3) the classification and management of the sub-areas within the whole distribution system; (4) the management of the large-scale detection instruments and signals, and the processing and utilizing their data to optimize the operation of the distribution system. Based on these requirements, this study has successfully developed a system to detect, forecast, provide advance warning, and control of pipeline leakage.

1.2 Pipe leakage detecting system

1.2.1 Structure and functions

Considering the complexity of urban drinking pipe distribution, a large number of leakage monitoring meters are required. Thus, firstly it is very important to design the scheme for the least number of leakage monitoring meters with the maximum capacity to cover the given pipe network. For this purpose, a system module on automatically arranging urban water pipe leakage monitoring meters based on GIS was developed. Using this module, with any pipe network, the most optimal settings of pipe leakage monitoring meters can be fast completed. Then, the related information management system for data collection, transmission and management was developed. Applying this system, the real-time leakage information from widely distributed meters can be orderly managed and rapidly direct the workers to carry out efficient actions. Additionally, this system can support the managers in monitoring and managing pipe leakages at divisional level, which is necessary for a large area of pipes.

1.2.2 Application methods

The accessibility analysis was applied to arrange the optimized leakage monitoring meters. The accessibility is generally defined as the ability to transport within the network, which expresses the extent to which spatial separation can be overcome (Kotavaara et al., 2011). Now the operating principle of most widely used leakage monitoring meters is the acoustic leak noise detection. The leakage status can be detected through discerning the acoustic signature of leaks from background noise by setting leakage monitoring meters on pipes. Due to the acoustic transfer behavior and different pipe segments' characteristics such as material and diameter, the effective detecting range of each monitoring meters are limited and varied. Thus, the most optimized leakage monitoring scheme is the maximum extent can be detected with the minimum number of leakage meters. The module on the optimized pipe leakage monitoring arrangement through accessibility analysis was developed under Arcgis platform (Fig. 1).

In addition, a GIS information management system to manage pipe network and their related facilities (valve, well, fire hydrant et al.) and leakage monitoring information was developed by coupling Oracle database.

1.2.3 Illustrative application

Beijing is one of the world's mega-cities and has a long history. The drinking pipe distribution in Beijing is very complex with an interlaced ring-shaped pattern.

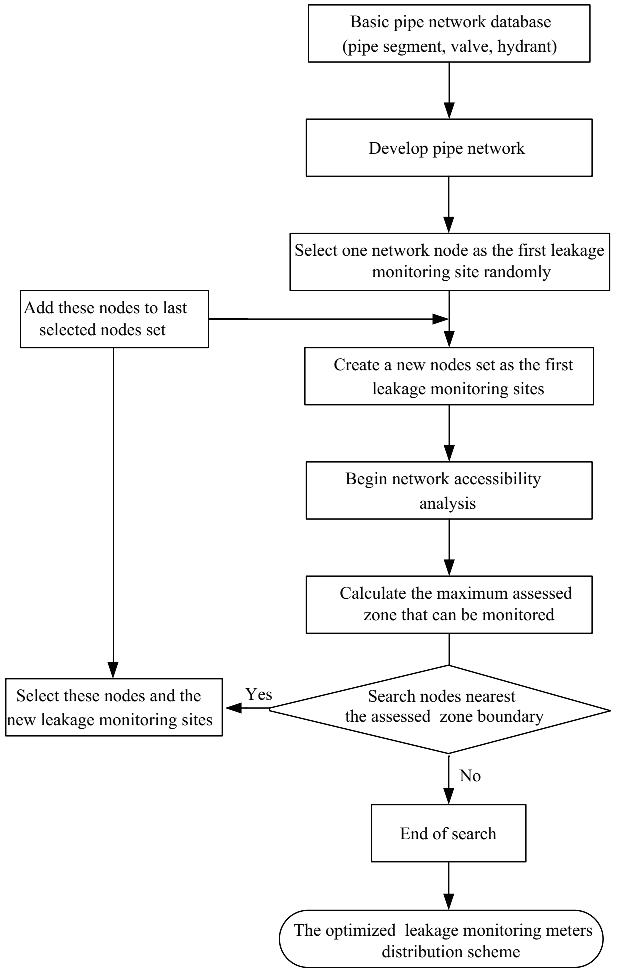

Fig. 1 Methodology of establishing the optimized leakage monitoring meters distribution scheme

Pipe leakage is a serious problem. How to take efficient measures to manage the number of pipe leakage accidents and carry out timely pipe maintenance is a big challenge and the primary task for local government. As an example, the scheme was demonstrated within the 2nd ring belt of Beijing. In total, 2644 locations were identified as the optimal sites for the leakage monitoring meters (Fig. 2).

1.3 Pipe leakage forecast and advanced warning system

1.3.1 Structure and functions

Although the reasons for leakages from pipes are very complex and uncertain, there are still some main factors that could be explored for a specific area. In Beijing, the age of the pipe and its diameter are the main factors which cause leaks. Thus, it is necessary to develop a pipe leakage forecast and warning system to improve the management of leaks. The forecasting system should fulfill three main functions. The first one is to develop a forecasting model to predict the possible future leaks based on the historic information. Using the model, the potential pipe leakage risk could be assessed to direct efficient monitoring work. The second function is to develop a warning model to clearly determine whether the alarm signals are true or false. The last function is to develop the model to determine the exact location of leaks, which helps to improve the efficiency of practical pipe leakage examination work.

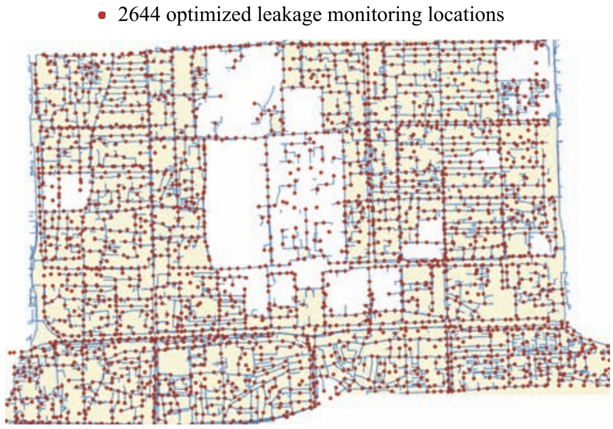

Fig. 2 Optimized leakage meters distribution plan within the 2nd ring belt of Beijing.

1.3.2 Pipe failure forecasting model

Due to the complex causes of pipe aging and failure, it is difficult to develop a physically based model to simulate possibility of pipe leakage. Mathematical statistics models, such as Bayesian analysis, statistical regression analysis and neural network analysis are suited to the task. In this study, data mining techniques, Genetic programming (GP), were used to develop the pipe failure forecasting model. GP is an evolutionary algorithm-based approach. In a GP, populations are symbolic formulae presented in the form of a tree. A certain number of formulae are generated randomly at the first generation, evaluated and sorted by the degree of fitting the data. The best ones are then selected to implement the genetic operation such as crossover and mutation. The worst fitted formulae will be replaced by the children of the best ones. Till now, a new generation is obtained. After certain iterative steps, a formula that best fitted the data will come forth in one generation (Xu et al., 2010).

In this project, the water distribution system of Beijing is selected. The main pipe network features (pipe material, age, diameter and length) and historic leakage information (leakage time, and location) from 1987 to 2005 were used to develop the pipe failure forecasting model.

1.3.3 Leakage signal judgment model

Many alarm signals were collected from the widely distributed leakage monitoring meters at fixed intervals. The theoretical basis of the meters was the laws governing the propagation of acoustic waves through pipes. Thus, many factors other than damage due to water leaks would impact the propagation of the sound waves, resulting in many "false" alarm signals. Therefore, the pipe leakage warning model was developed to identify the "true" alarm signals.

Regression tree and GP are integrated to judge whether or not the detected leakage signals are true. Regression Tree is a nonparametric technique that can select from a large number of variables and their interactions to determine the outcome can be explained. Herein, the signal intensity, signal bandwidth, leakage detected by monitoring meters, pipe diameter, pipe material and pipe age are selected as the variables to determine the real leakage situation. By applying the Regression Tree analysis, the real leakage situation, true or false, can be determined. To further quantify the possibility of leakage, GP is applied based on the Regression Tree results. According to the large amount of leakage signals collected, the possibility of leakage in Beijing was modeled (Eq. (1)).

$$P = \begin{cases} \dfrac{0.83}{\ln(\mathrm{Lv}) + 1.87} & \mathrm{SP} \geqslant 22 \\ \\ \dfrac{\ln(\mathrm{Lv})}{\ln(\mathrm{Lv}) + 3.68} & \mathrm{Else} \end{cases} \tag{1}$$

where, P is the possibility of the truth of the leakage signal, Lv is the signal intensity and SP is the spread threshold. When the $P \geqslant 0.5$, this signal (Lv) of leakage alarm can be considered to be true.

1.3.4 Precise leakage site positioning model

The leakage monitoring meters may survey the near-by pipe segments over a limited distance. Thus, it is difficult to determine the precise leakage location from the leakage alarm signals surveyed by nearby monitoring meters. Therefore, a mathematic model to identify the exact location of pipe leakage was developed following the acoustic propagation laws, which explore the relations of the intensity of sound source, leakage site and the acoustic attenuation features along pipe segments. Based on large number of *in situ* man-made leakage experiments on different pipe types, the model to determine the accurate leakage location was developed (Eq. 2).

$$x = \frac{L_{AB} - 34.4 \times (\ln(y_A - b) - \ln(y_B - b))}{2} \tag{2}$$

where, x is the distance from the leakage monitoring site A to the proposed pipe leakage location; L_{AB} is the distance between leakage monitoring site A and B; y_A is the alarm signal from leakage monitoring site A; y_B is the alarm signal from leakage monitoring site B; b is the background sound signal.

1.3.5 Illustrative application

Through model verification, it proved that the GP pipe failure model is satisfactory with the average coefficient of determination of 0.98. Using this model, the possibility of leaks in every pipe segment in 2008 in Beijing was calculated (Fig. 3). This simulated result could then help the local managers to take practical measures to monitor

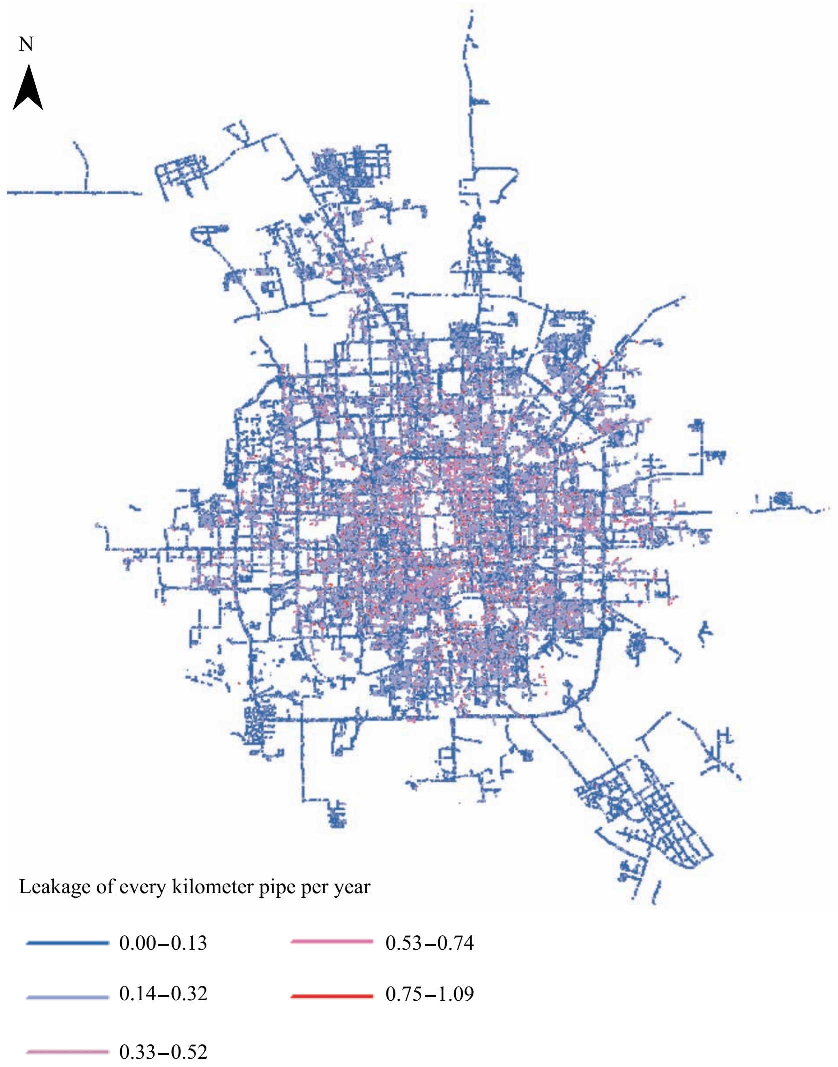

Fig. 3 Simulated possibility of pipe leakage of Beijing in 2008.

and defend the water supply system.

1.4 DMA establishment to control leakage

1.4.1 Procedure of DMA establishment

The DMA is the area of a distribution network which is specifically defined (usually by the closure of valves) and in which the quantities of water entering and leaving the area are metered (Brothers, 2003). The flow is analyzed to determine the level of leakage within the area to enable the engineers to determine the locations where it is most beneficial to search for leaks. The concept of DMA was first introduced to the UK water industry in the early 1980s (Farley and Trow, 2003). Active leakage control based on the use of DMA is known as DMA management. DMA management has been one of the most effective approaches to control water losses from supply systems. So far, DMA has been practiced in UK and North America, and many experiences of using DMA to control leaks have been reported. There are certain differences between the water supply networks in Chinese cities and UK cities, however. In this study, the Beijing water supply network is used as an example. First, the water supply network in Beijing is the combination of grid and tree networks, which means that the design of DMA boundaries tends to be more complex. Second, all residential consumers in Beijing are metered, thus reducing the leakage in the customer section of service pipes is not important. These two characteristics appear similar to those of North American water supply networks. The population density of Beijing is much higher than that of UK cities, with more properties and higher water consumption per unit area.

Taking the major characteristics of the loop lines and foreign DMA experiences into account, design principles for DMA were considered in this study. The water distribution network within the 4th ring of Beijing City was divided into many separate DMAs. The appropriate size of the DMA needs be determined. Since the DMA is mainly used to monitor the leakage of water supply pipes, the length of distribution mains was taken as an appropriate determinant of the size of DMA in Beijing. The integrity of the original pipe network must be conserved, it is cannot be destroyed. Protecting the integrity of main networks also facilitates the application of the DMA. Thus, the DMA layout needs to minimize any modifications to the pipes and to conserve the original structure of the networks. Some areas of Beijing are not suitable for DMA management, especially some old districts where pipes are of parallel structure. DMA management of these old districts would destroy the integrity of their pipes, leading to an unsafe water supply. Additionally, the large-scale modification of these parallel pipes would raise the cost of establishment the DMA. Third, the large main pipes are excluded from DMAs. The water supply network in the 4th ring of Beijing is the combination of grid and tree networks, while the network is a grid system in the 2nd ring of Beijing. The large main pipes within the 4th ring of Beijing are of grid structure, and these pipes were excluded from DMAs. The integrity of large grid pipes were conserved to guarantee the safety of the water supply and to avoid the closure of large boundary valves. Finally, the scattered users who are supplied from the main pipes are excluded from DMAs. The large main pipes are located at side pavements and seeded strips, and many users are supplied from the main pipes. These users are dispersed, so taking the economic benefits into consideration; they are not suitable for inclusion in the DMA. Further, two pilot-scale DMAs were established and their water quality and pressures were monitored to determine whether or not the layout of the DMA was reasonable. It was found that water quality and pressure problems can be solved by a reasonable DMA layout.

1.4.2 Illustrative application

After planning the DMA based on the GIS of an urban water supply network, a pilot scheme was carried out in three demonstration zones. The appropriate approaches for establishment DMAs, which could act as guidance to all water supply networks of large and medium-size cities in China, were determined by summarizing the experience

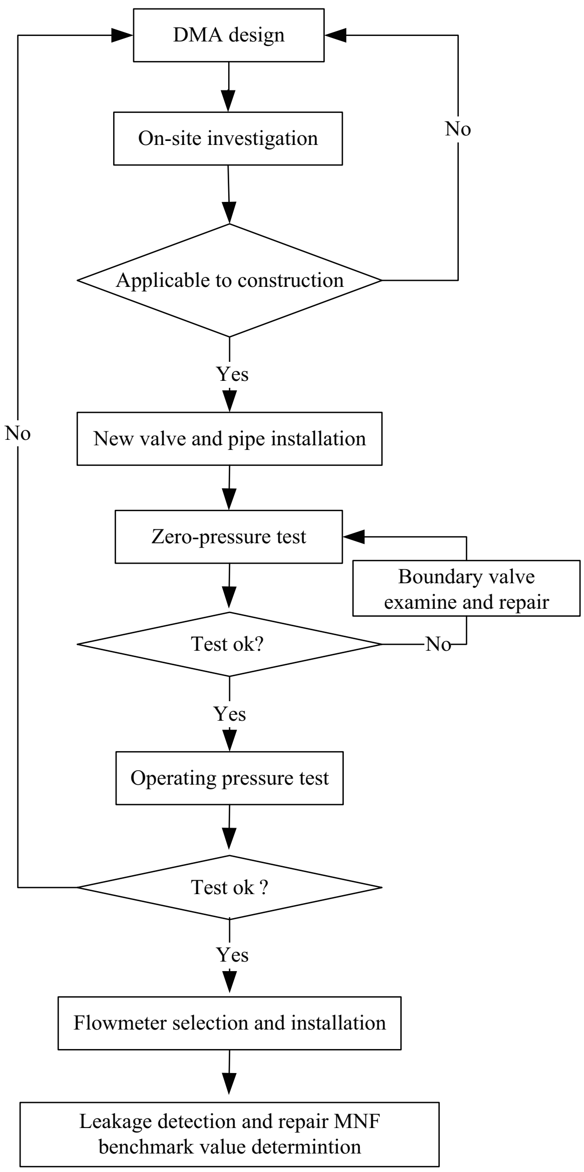

Fig. 4 Flowchart for DMA establishment.

and lessons learned from the pilot schemes (Fig. 4). These approaches normally consist of a series of sequential steps such as: on-site investigation, new valve and pipe installation, zero-pressure test, operating pressure test, flow-meter selection and installation, leakage detection and reparation, and the determination of a benchmark value for the minimum night (Xu et al., 2008).

2 System for pipe leakage detection-forecast-control

Based on the above-developed modes that focused on different functions, an integrated pipe leakage monitoring-forecast-control system was developed. This system could comprehensively couple different modes which have a compatible pattern. This system was developed based on Client/Server (C/S) techniques under the GIS platform and generally included three parts. By operating this system, the entire process from management and optimization of the leakage monitoring instrument, identifying the precise leakage sites, carrying out pipe maintenance to pipe leakage forecasting could be fast automatically controlled and completed. It would greatly improve the efficiency of the local pipe leakage management.

Basically, a detailed information database is required, which contains information about the pipes (pipe age, diameter, material etc.) and related information (time leak occurred, type of leak, and intensity of leak). Based on this information database, the lumped system is composed of six sub-systems: the management system for the pipe leakage monitoring instruments, the automatic optimization system for the distribution of the pipe leakage monitoring meters, the pipe leakage forecasting system, the pipe leakage monitoring system, the management system for the pipe leakage monitoring sites, and the DMA management.

3 Pilot scheme

This system for a water supply network can be used when basic information and data on the water distribution system are available. The necessities required to establish the system include: (1) integrated GIS of the water distribution system, (2) sufficient leakage detection equipment (i.e., flow meters, pressure gauges, and acoustic detectors and analyzers), and (3) a special team of engineers for leakage detection and control set up by the water company.

This pilot scheme started in the central district of Beijing in 2007. In 2007–2009, there were a total of 11,243 noise loggers and collected 66,988 signals including 2184 alarms. Subsequent examination, found 728 leaks (161 non-obvious leaks and 567 obvious leakages in affiliated facilities such as strobes, hydrant). The scheme was estimated to have saved more than 4×10^6 m^3 of drinking water.

The application of this system also increased the detection of non-obvious leaks in the distribution system. In 2006, the total number of detected broken-pipelines (for the pipes with diameters of above DN75 mm) was 1381, which increased to 1563, 1612, and 1467 in 2007, 2008, and 2009, respectively. Among these broken-pipelines, the number of non-obvious leakages increased respectively, to 718, 856, and 857 in 2007, 2008, 2009, whereas the obvious leakages decreased to 845, 756, and 610 respectively. The pilot scheme detected 102 non-obvious leakages (i.e. 14.2% of the total detected in Beijing) from February 2007 to the end of 2007, which was estimate to have saved a total volume of 2,385,000 m^3 of water.

In sum the number of concealed leaks that are detected is increasing, and the number of apparent leaks is decreasing since the system began operating. Thus losses caused by unreported leaks were significantly reduced, which brings important economic benefits to water companies.

4 Conclusions and perspectives

This study focused on the characteristics of the looped networks and on the demand for safe and efficient operation in Beijing. The integrated systems for timely detection, advance warning, and control of leakages in the distribution system using noise loggers was developed. This strategy has been applied in the core area of Beijing to operate and manage the distribution system. Additionally, the pilot demonstration of this system gathered valuable practical experiences, which is important for the large-scale use of this system throughout the Beijing distribution system. However, since water leakage detection and control are very complex issues some problems will need to be addressed on the basis of more practical experiences as it becomes available. For example, the detection distance of the logger on different types of pipe needs to be further optimized. The cycles for leakage data collection should also be optimized according to the leakage situation of the specific pipe distribution system. At present, the pipe material, diameter and age are considered to be the main factors causing the breakages. In future, parameters such as the pressure of vehicle tires on the road surface and soil type need be considered. In summary, the results of the pilot provide valuable experience which should help water companies to standardize, and professionalize the active control of leakages from their pipelines.

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