

Water distribution infrastructure worldwide is aging, resulting in increasing failures and underscoring the need for real-time monitoring to avoid interruption of an essential service. In this research an end-to-end integrated hardware and software system was developed for monitoring, analyzing, and modeling large urban water distribution systems in real time. During the ongoing development of this system, three main goals were achieved. First, a low-cost wireless sensor network was applied for high-data-rate, on-line monitoring of hydraulic and water quality parameters within a large urban water distribution network. Second, remote detection of leaks and pipe bursts was enabled with sophisticated data-mining algorithms. Third, real-time pressure and flow measurements from the sensor network were assimilated into hydraulic models that were used to improve state estimation for the network. In the two years since it was launched, the Wireless Water Sentinel project in Singapore has demonstrated great potential to improve the operational efficiency of the water supply system.



During leak-off experiments artificial bursts and leaks were generated by rapidly opening solenoid valves connected to fire hydrants.

Real-time in-network distribution system monitoring to improve operational efficiency

In cities around the globe, the drinking water distribution infrastructure is aging rapidly and encountering failures with increasing frequency. The result has been significant water losses (imbalances between water entering and leaving the system), inefficiencies in system operation, and concerns about the quality of drinking water that is provided to the consumer.

Recently two US cities faced major failures in their water system operations. During the summer of 2009, Los Angeles, Calif., experienced a series of pipe breaks and leaks that caused significant disruption (Kim, 2009). A report presented to the city after an expert review attributed the pipe breaks to pressure drops associated with a regimen of water rationing introduced in Los Angeles (Bardet et al, 2010). In light of the absence of direct pressure monitoring data, however, this finding remains largely speculative.

In May 2010, a huge main rupture in Boston, Mass., caused two million residents of the greater Boston area to lose clean drinking water, prompting a state of emergency (Finucane et al, 2010). The backup water supply did not meet US Environmental Protection Agency (USEPA) standards, and the public was without usable drinking water for several days. The lack of a real-time monitoring regimen for water quality caused a delay because data had to be collected and analyzed before authorities could assure residents in

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Boston and dozens of surrounding communities that the water was again safe for consumption.

These two recent examples illustrate typical operations in which many water utilities have only limited on-line monitoring and analyzing capabilities within their systems and usually only at the demand metered area level (a subsystem of few thousand consumers). Hydraulic parameters such as pressure and flow as well as water quality parameters such as chlorine, pH, and oxidation reduction potential (ORP) typically are only collected continuously at inlets and outlets of the distribution system. At this level, it is hard to determine the area within the subsystem where specific problem areas related to leakage, water age, and quality may be found.

Water distribution systems are essential civil infrastructures that must be adequately managed and maintained in order to provide expected levels of service to consumers. As such, they have a need for on-line decision-support systems based on continuous monitoring of hydraulic and water quality parameters within the system, at a fine temporal and spatial granularity. An accurate, continuously updated view of the state of the water distribution system (i.e., pipes within the system) allows a water utility to improve optimization of system operation, manage leakage control more effectively, and reduce the duration and disruption of repairs and maintenance.



The WaterWiSe@SG sensor node processing unit features water-resistant packaging to allow use inside an access point if required. The 2009 version (left) is 120 x 260 mm in size, whereas the 2010 version (right) is 90 x 200 mm in size.

Water distribution systems are essential civil infrastructures that must be adequately managed and maintained in order to provide expected levels of service to consumers.

The Wireless Water Sentinel project in Singapore (WaterWiSe@SG) has provided a unique opportunity to develop an integrated decision-support system in collaboration with a water utility. It has led to a proof-of-concept, end-to-end system for continuous remote monitoring of a water distribution system, including wireless sensing hardware (for hydraulic, acoustic, and

water quality parameters), a data-collection and visualization infrastructure, and a set of modeling and analysis tools.

This article describes several aspects of WaterWiSe@SG including system architecture, deployment, and exploratory

data collection for anomaly detection and localization analysis. WaterWiSe@SG forms a wireless sensor network (WSN)-based hydraulic test bed in a section of downtown Singapore; to the authors' knowledge, this is the first permanent hydraulic test bed used in an actual water distribution system. A network of wireless sensor nodes continuously samples hydraulic and water quality data, transmitting it to lab-based servers for processing and archiving. Data streams from the sensor nodes have been integrated into an on-line hydraulic modeling subsystem that is responsible for on-line estimation and prediction of the water distribution system's hydraulic state. Several controlled leak-off experiments have been performed using the WaterWiSe@SG test bed; results of these experiments have been used to inform leak and burst detection and localization algorithms. In addition, the system has indicated several significant operational occurrences within the distribution system, as well as real bursts and leaks.

RELATED WORK

PipeNet. WaterWiSe@SG is most closely related to PipeNet (Stoianov et al, 2007, 2006), a low-power WSN for monitoring large-diameter bulk-water transmission pipelines. In many respects, WaterWiSe@SG represents a significant advancement beyond the accomplishments of PipeNet. Although PipeNet included the field deployment of a small network for 22 months, much analysis and experimentation associated with PipeNet was carried out off line and in laboratory environments. WaterWiSe@SG has gone a step farther than PipeNet by facilitating in situ experimentation. To the authors' knowledge, this is the first time a system has been used in a water distribution network for continuous monitoring and in situ experimentation. The PipeNet authors chose a relatively limited sensing platform¹ to optimize for power consumption, and this affected their sampling policy (100 Hz for five seconds at five-minute intervals). For the WaterWiSe@SG project, the authors deliberately decided against platform optimiza-

tion in the first instance to allow the exploratory value of the collected data to be maximized.

Pilot water security initiative in Cincinnati, Ohio.

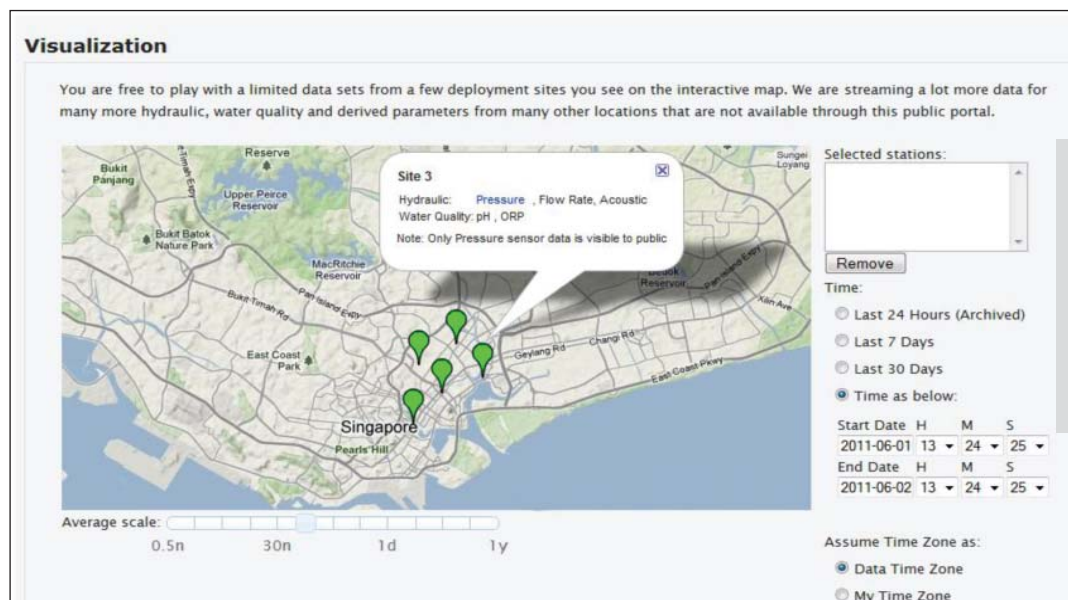
Between 2005 and 2010 the USEPA, in partnership with the city of Cincinnati, instituted a contamination warning system pilot at the Greater Cincinnati Water Works. Planning and predesign activities for the pilot began in December 2005 and were substantially completed in June 2009; data collection concluded in June 2010. According to the project report summarizing the pilot results (USEPA, 2008), 17 water quality monitoring stations with capability to measure a variety of water quality parameters (pH, turbidity, conductivity, free chlorine, temperature, total organic carbon, and ORP) were installed primarily in storage tanks and pump stations. In addition, a dedicated communication network and supervisory control and data acquisition (SCADA) system was installed, and two water quality anomaly detection systems were set up.

WaterWiSe@SG distinguishes itself from the Cincinnati pilot project in several areas, such as functionality, deployment constraints, and system cost. First, WaterWiSe@SG is an integrated system to monitor both hydraulic and water quality parameters and complements existing SCADA monitoring performed by a utility. Second, WaterWiSe@SG takes insertion-based measurements for both water quality and hydraulic parameters. This allows readings to be taken directly in the pipe flow at arbitrary locations in the water distribution system, rather than having to rely on sites that provide flow-through and permanent alternating current power (pumping stations or storage tanks as described in the USEPA report). A consequence of this approach is that the WaterWiSe@SG deployment has focused initially on robust measurements of a small number of water quality parameters (currently pH and

ORP). Third, the WaterWiSe@SG software infrastructure enables integrated and real-time sensing, anomaly detection, and hydraulic modeling. Each component of this system is dynamically configurable and designed to withstand and compensate anomalies at different levels such as power and communication network outages in the field and missing data points at the back end. Fourth, use of WSN technology compensates for the fact that current general packet radio services (GPRS) third-generation (3G) networks are not well optimized for traditional SCADA systems from a data yield perspective. WaterWiSe@SG provides the capability to dynamically adapt or retrofit the functions of a sensor node based on the status of the communications network, while still meeting quality-of-service requirements. Finally, the overall cost of the Cincinnati water quality monitoring system was \$4 million for 17 stations, an amount almost 10 times the expenditure of about \$500,000 for a 25-node WaterWiSe@SG system.

SYSTEM DESIGN AND IMPLEMENTATION

WaterWiSe@SG is an integrated, end-to-end system dealing with node-level acquisition and transmission of data as well as server-based archiving, processing, and visualization of data. Sensor nodes deployed across the water distribution system acquire and transmit data via the Internet to the WaterWiSe@SG archive server, which is responsible for long-term storage and access to the raw data. A processing server facilitates hydraulic modeling based on the archived data, and a web server hosts the web portal that is the interface between the WaterWiSe@SG system and its users, facilitating visualization of data streams in near real time. The following section describes the design and architecture of the WaterWiSe@SG system, as well as its deployment within the water distribution system in Singapore.



This screenshot of the WaterWiSe@SG public portal shows sensor locations on a map and some of the interactive parameters that are available.

Sensor node hardware. The lowest tier of the WaterWiSe@SG system is the sensing hardware used in the water distribution network. Two iterations of a custom sensor node have been designed and developed, enabling continuous collection of data at high rates (kHz) and transmission in real time to the WaterWiSe@SG data archive server. This allows nodes in the field to provide full data sets suitable for centralized on-line and off-line analysis. Additionally, the platform is capable of performing data processing locally when required.

As shown in the photo on page 64, two sizes of sensor node were developed: a 2009 version 120 × 260 mm in size and a 2010 version 90 × 200 mm in size. Both versions are packaged in a clear plastic acrylic tube, with polyvinyl chloride caps at each end. These end caps house waterproof debugging ports, sensor ports, and attention buttons. The water-resistant packaging enables the sensors to be used inside an accesshole if required.

The sensor node is a combination of off-the-shelf hardware (an embedded single-board computer²) and a custom-designed sensing board. The first version of the sensor node supported the simultaneous attachment of three sensor types: a pressure transducer, a hydrophone, and a flowmeter. Both the pressure sensor and hydrophone are sampled at a frequency of 2 kHz (2,000 samples per second), whereas flowmeter data are sampled with a frequency of 1 Hz.

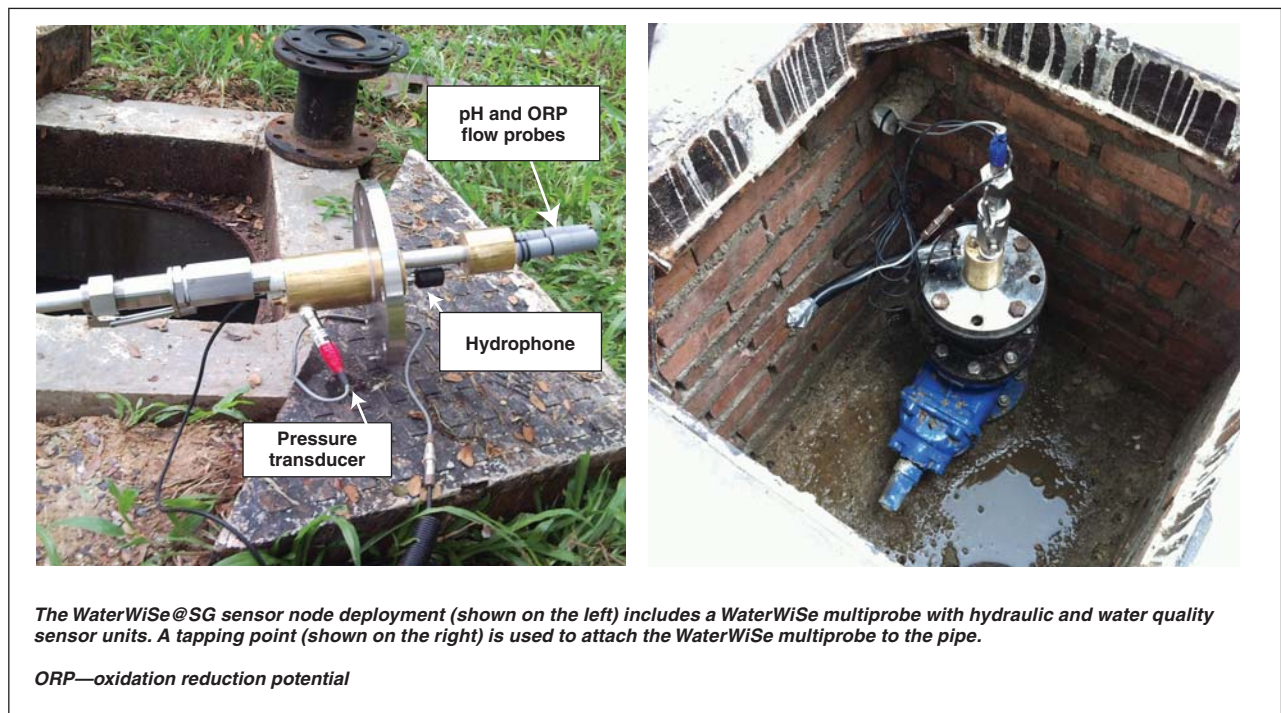
The second revision of the sensor node extended its capabilities by providing water quality sensors (pH and ORP) that are sampled with a frequency of 0.033 Hz. For temporary storage of data, the node has a 2-gigabyte micro secure digital memory card that provides enough

space to buffer sensor data for several days in the event of disruptions in the wireless communication system.

Continuous wireless transmission of sensor data is enabled by a USB 3G modem, providing an Internet connection with an average upload rate of 4 to 8 KB/s. Each node is also equipped with a pulse-per-second-capable global positioning system (GPS) unit with a maximum accuracy of ±50 μS. The GPS unit is used to synchronize the clock of the sensor node to coordinated universal time, providing a global time base for all data gathered across sensor nodes. The high accuracy of time synchronization (standard operation is well within ±1.5 ms) is suitable for burst location schemes based on the relative arrival times of the transient pressure wave front at different points in the network (Sriranarajan et al, 2010).

Physical deployment of sensor nodes. WaterWiSe@SG currently monitors a 60-km² (23.15-sq-mi) area of downtown Singapore that is supplied by a gravity-fed water distribution system consisting of two service reservoirs, more than 19,000 junctions, and more than 20,000 pipes. The average distance between sensors is 1 km (0.62 mi). The initial node locations were chosen with advice from the engineers of Singapore’s Public Utilities Board. For security purposes, the exact sensor node locations with respect to the system layout are not provided.

Each of the sensor nodes in the distribution system is connected to a water main (via an access point) through a custom-built tapping point that can house several off-the-shelf sensors, as shown in the photographs on this page. A pressure transducer and acoustic hydrophone are attached at the side wall of the pipe; flow and water



quality measurements are taken from inside the pipe via an insertion port.

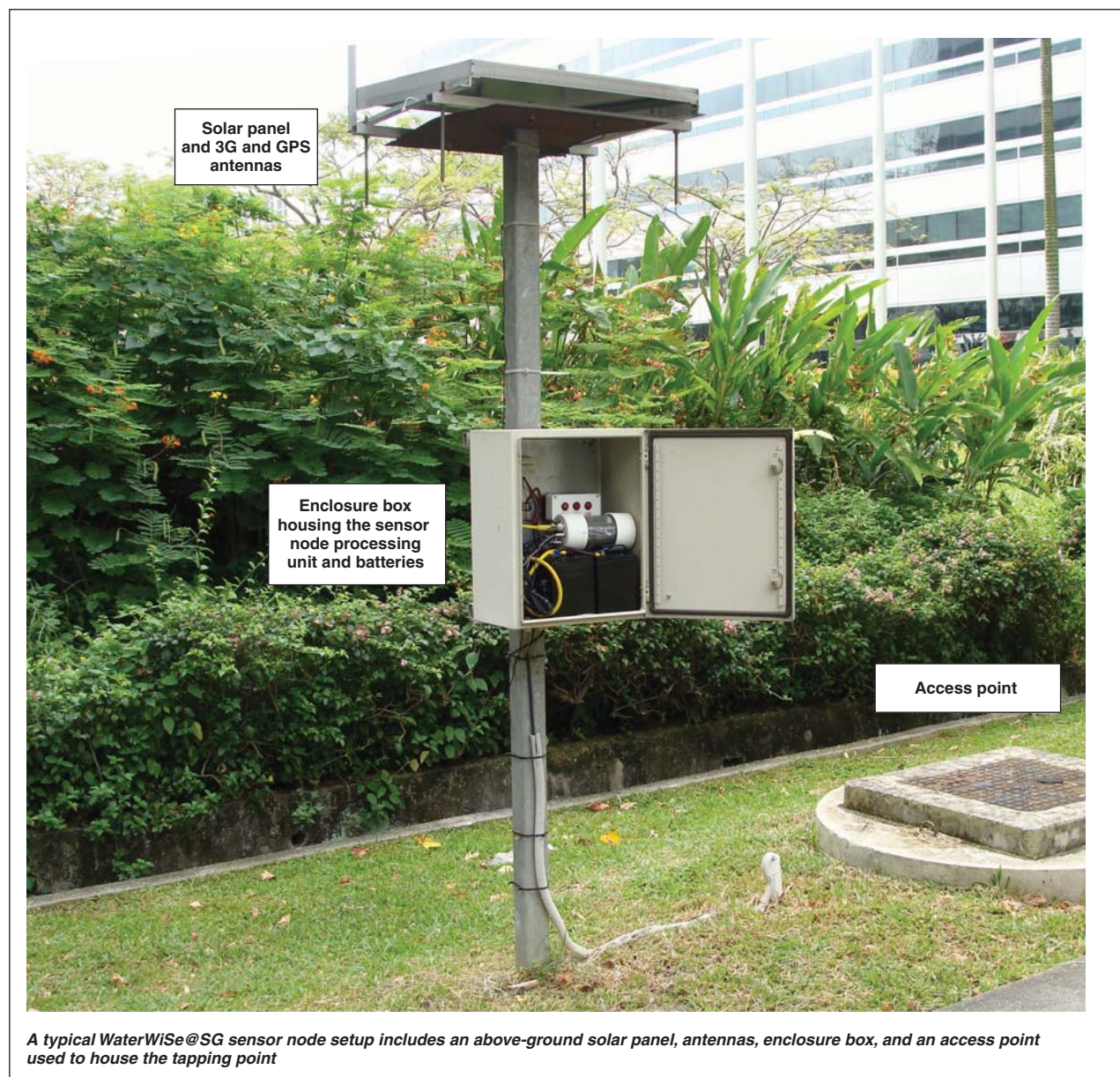
The sensor node is housed aboveground within an electrical enclosure attached to a pole, as shown in the photograph on this page. Each node is powered by batteries that are recharged during the day via a solar panel mounted on top of the pole.

By October 2010, eight sensor nodes had been deployed, and the network was being extended to a total of 25 hydraulic and water quality nodes. The new sensor node locations were optimized for water quality monitoring and were determined using the Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Toolkit (TEVA-SPOT) software developed by USEPA (2009). TEVA-SPOT implements an automated optimization method to find a layout that minimizes contamination risks to water consumers, given a suitably

calibrated hydraulic model of the distribution system. The hydraulic data collected by the initial eight sensor nodes were used as the basis for the hydraulic calibration of the water distribution system.

System architecture and data flow. Figure 1 shows the flow of data between key components in the system. Raw data acquisition, reduction, and transmission are performed at each sensor node, using custom-built integration software. Streams of data are windowed into discrete 30-s files that are compressed before transmission to the archive server.

Each file received by the server is archived to disk, and summary statistics (mean, minimum, maximum, and standard deviation) are computed; the resulting values are calibrated (i.e., converted from raw voltages to the units of the condition being measured) and stored in a database for visualization.



After archiving, data are available to any of the system services. WaterWiSe@SG currently has three active services: visualization (hydraulic and water quality data), on-line anomaly detection (hydraulic data), and an on-line hydraulic model of the system. The on-line hydraulic model expects input data to be provided at hourly intervals, and if data are not available, then these input values are predicted using a data imputation service based on Gaussian process regression (Goldsmith et al, 2010). The detection component operates directly on the archived pressure data files.

A vital component of the system is interactive data display and retrieval, which is provided through a web-based control panel. Sensor locations are shown on a map (see the screen capture on page 65). When a node is selected, a control panel gives an on-line graphical interface to the data sent by the nodes, allowing the visualization of real-time sensor data for the distribution system engineer or researcher.

Near real-time graphs and historical data from previous days or months can be viewed on the web portal. Figure 2, parts A, B, and C, show screenshots from the portal of pressure, flow, and pH data, respectively, from three sensor nodes. Data displayed on the WaterWiSe@SG portal are primarily drawn from the summary statistics stored in the database, which facilitates observation of trends on the order of minutes to months. To allow users to process data locally using their preferred applications, the summary data shown in graphs are also available for download in the ASCII (American standard code for information interchange) format.

A fundamental goal of the WaterWiSe@SG test bed was to ensure that nodes transmit data to the server in a timely and reliable manner, i.e., that a high percentage of the data be collected from the network; the percentage often quoted in the literature is 99.99% (Doherty & Teasdale, 2006). To quantify the reliability of WaterWiSe@SG, the authors examined the data yield of the network between April

2009 and June 2010 as well as the average latency of data transmissions over a period of several weeks. (Each node generates around 332 megabytes of raw data per day.) Between April 10, 2009, and June 10, 2010, a total of 2,726 node-days of data theoretically could have been generated by nodes and archived at the server; server records indicated that only 2,337 days of data were collected, for a data yield of 86% across the eight nodes. The causes of data loss were classified into three categories:

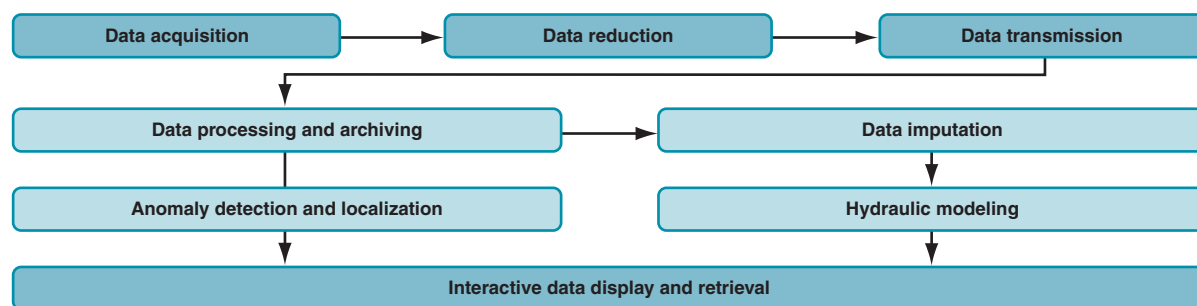
- Long continuous outages caused by maintenance, drained batteries, or software bugs. These outages usually were longer than 10 minutes.
- Short outages caused by the loss of a file between node and server (an application-level protocol error) or radio malfunction (causing node restart). These outages usually were less than 10 minutes.
- Corrupt or incorrectly sized data caused by an error somewhere between sampling at the node and archiving at the server that corrupted a particular 30-s file. This caused a loss of 30 s of data for each damaged file.

Long continuous outages made up about 92% of the total amount of data lost, whereas the other two factors combined accounted for slightly more than 8%. These continuous outages represented issues with ongoing node maintenance and time taken to replace a battery after failure. When these are factored out, the overall data yield is 98.84%. Although not 99.99%, the authors considered this high enough to declare the system reliable under normal operation.

APPLICATIONS

The research and development of WaterWiSe@SG had three primary goals: to demonstrate the application and control of a low-cost WSN for high-data-rate, on-line monitoring of hydraulic parameters within a large urban water distribution system; to develop systems that enable remote detection and localization of leaks and prediction of pipe bursts; and to integrate monitoring

FIGURE 1 Schematic showing WaterWiSe@SG system data flow

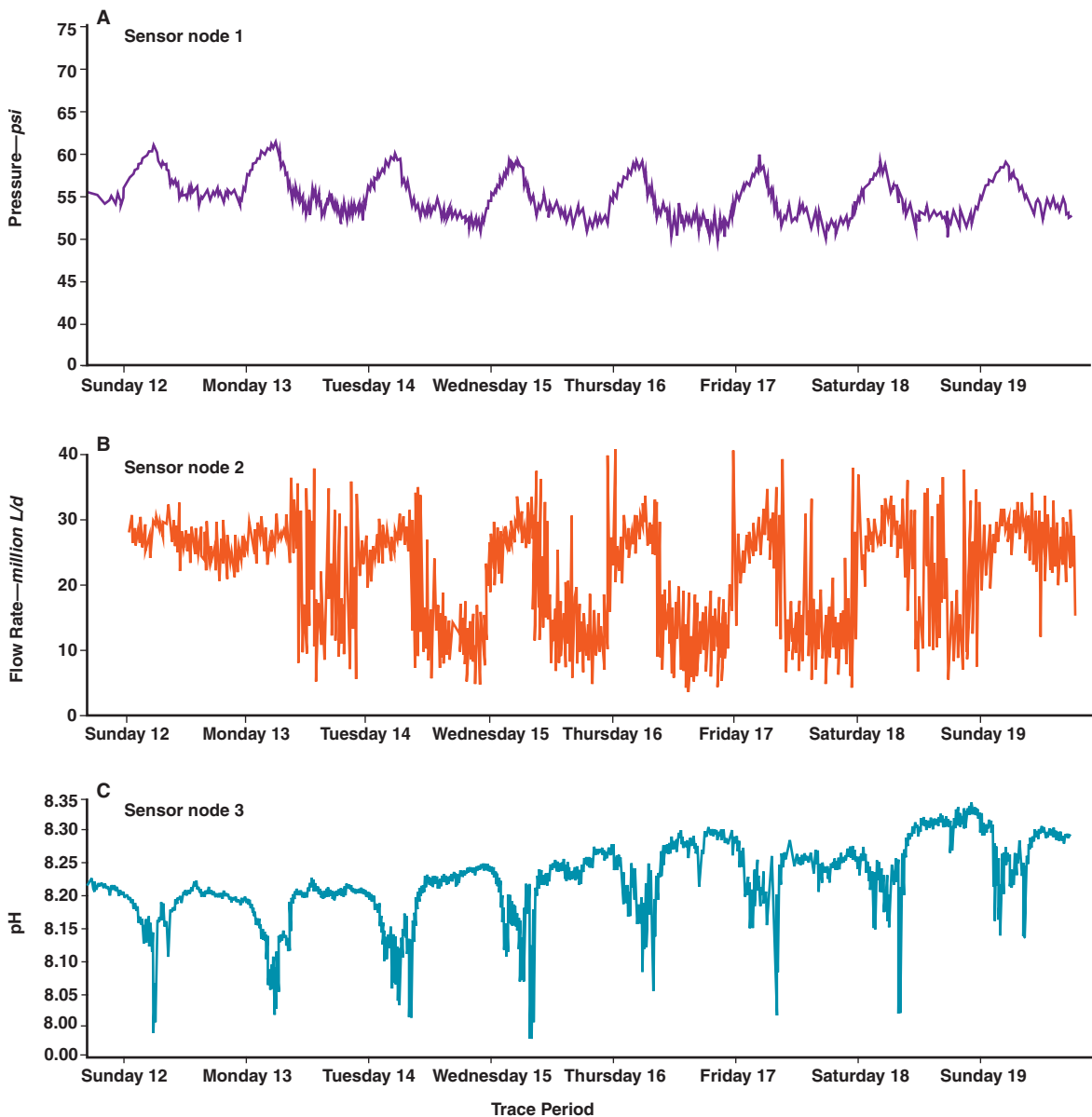


of hydraulic and water quality parameters. This final goal included evaluation of the long-term performance and robustness of nonspecific water quality sensors, the use and development of multiparameter measurement technologies, and the application of cross-correlation techniques to interpret water quality signatures locally within the network (i.e., through local signal processing at the node level). The following sections describe applications that have been enabled by the WaterWiSe@SG

system: burst detection and localization, operational analysis, and hydraulic modeling.

Detection and localization of pipe bursts and leaks. Sudden pipe bursts can occur in high-pressure water transmission mains and distribution pipelines. Such occurrences can be expensive because of the outage time for repair of the burst pipe, the cost of the repair, and the damage to surrounding property and infrastructure. Therefore, utilities find it advantageous to minimize the

FIGURE 2 WaterWiSe@SG portal examples of a one-week pressure trace (A), a flow rate trace (B), and a pH trace (C)



Data resolution equals five minutes.

detection and localization time after the burst occurs. The advances in sensor network technology that were implemented in the WaterWiSe@SG project have enabled continuous monitoring of physical environments for long periods (days, months, or even years) and detection of bursts and breaks in environments that are difficult to access.

In Singapore water losses attributable to leaks or pipe bursts are small, i.e., less than 5% (Tortajada, 2006). Still leaks and/or pipe breaks occasionally occur. Figure 3, parts A and B, shows typical pressure drops that were measured during two actual pipe breaks that took place near one of the WaterWiSe@SG sensor nodes.

Although techniques for burst or leak localization have been presented in the relevant literature, few techniques have been proposed in the context of large networks (Silva et al, 1996). Furthermore, most of these have been validated using simulated data (Misiunas et al, 2003), in controlled laboratory environments (Misiunas et al, 2005; Stoianov et al, 2001) or in transmission pipelines that are immune from pressure variations attributable to demand fluctuations (Misiunas et al, 2005). The WaterWiSe@SG burst detection and localization algorithms have been validated on an actual large-size, urban water distribution system.

The approach the authors used to detect transients in pressure traces was wavelet analysis, which has been applied previously to detect transients in pressure signals for leak detection and location in water pipelines (Stoianov et al, 2002, 2001). In wavelet analysis, a one-dimensional signal is mapped into a time-scale representation using a bank of band-pass filters. The authors' wavelet detection algorithm determines the approximate time of the pressure front arrival by analyzing the different decomposition levels of a wavelet-transformed signal. Figure 4 shows an example multi-scale wavelet decomposition of a controlled pressure transient, in which the pressure signal is decomposed into several levels of detail coefficients. The onset of the transient is determined

by analyzing the coefficients over the different levels of detail and picking the most consistent signal. These pressure-front, arrival-time estimates are used as input to a burst localization algorithm that can be used to determine the location of pipe bursts (Misiunas et al, 2005). The localization algorithm uses a graph-based search procedure to determine the physical location that best matches the relative time difference of arrivals of the pressure front between sensor nodes.

To better understand the characteristics of pressure transients and their relation to pipe bursts, the authors used WaterWiSe@SG as a live test bed, conducting several controlled leak-off experiments to simulate pipe breaks. The data generated during these experiments have helped to further develop the leak detection and localization algorithms.

To date, leak-off experiments have been performed using a solenoid-controlled valve connected to the pipeline via an air valve or a fire hydrant (see the photograph on page 63). The solenoid-controlled valve is triggered to create transients emulating instantaneous pipe ruptures. The rapid opening of the solenoid (0.1 s) creates a sudden pressure transient whose front can travel considerable distances around the network before it is fully damped. Because the sensor nodes are gathering high-rate data continuously, they capture both the pressure front and subsequent reflections. To date, four leak-off tests have been carried out at different system locations across the monitoring area. Figure 5 shows the distances involved in a typical experimental setup and examples of the pressure transients recorded over short time scales (order of seconds) by sensor nodes.

A series of multiple experiments with burst rates of 4 to 9 L/s (~1 to 2.3 gps) at different settings and locations across the water network have validated the algo-

Future plans related to leak detection involve creating more complex and realistic pipe bursts (from within gravel packs rather than air, for example) to further test and train anomaly detection and localization capabilities.

FIGURE 3 Pressure traces during two water main breaks

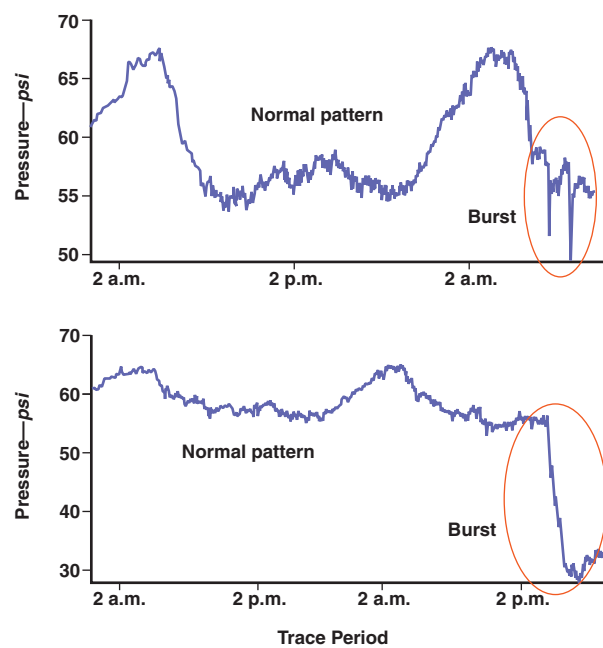
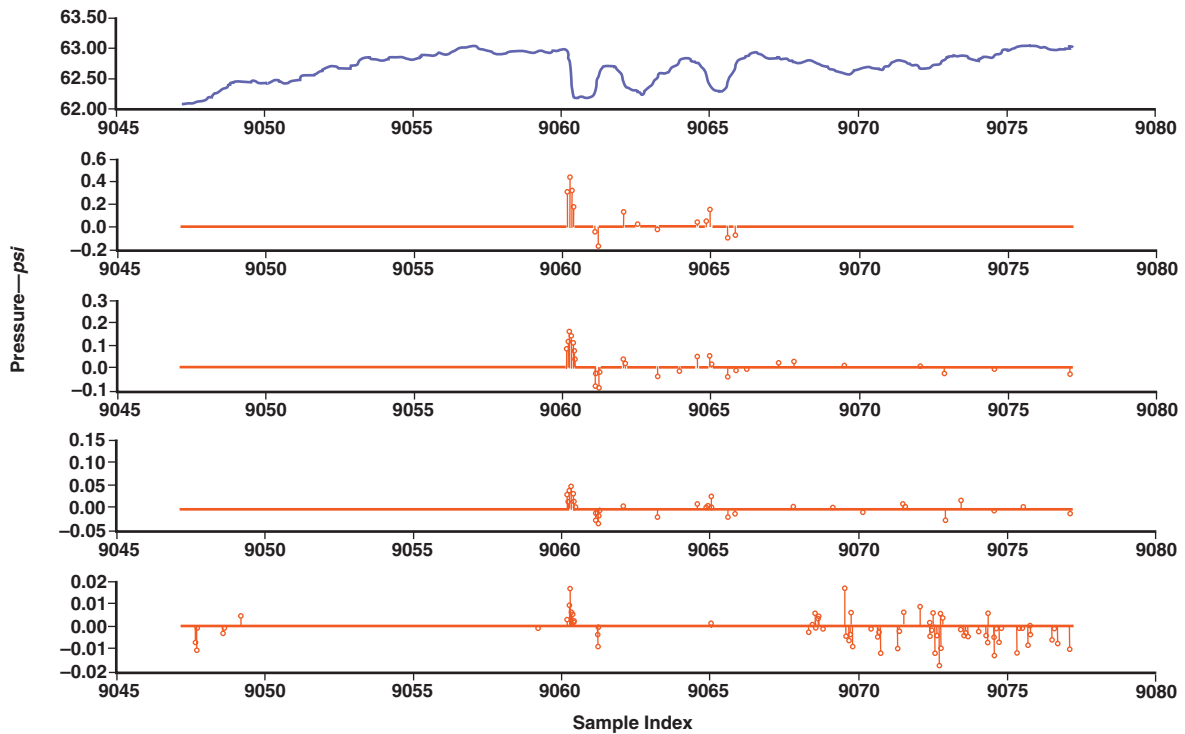
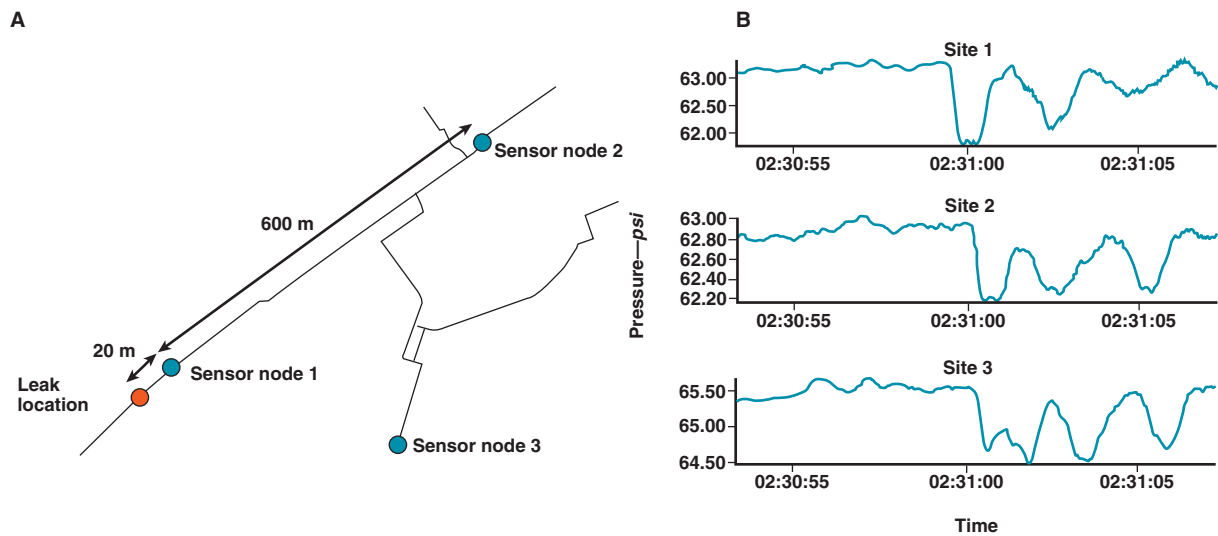


FIGURE 4 Wavelet decomposition of a controlled pressure transient into four levels of detail coefficient



The transient is consistent across the four levels, making it easy to classify against noise.

FIGURE 5 A typical leak-off test setup (A) and associated pressure records taken during the test (B) presented over a 15-s window



rithm's ability to localize bursts in an average localization error of 45 m (147 ft; Srirangarajan et al, 2010). Although this is not accurate enough to determine the exact location of the burst, it can help identify the section of the pipe that must be isolated, reducing the time required to isolate a leak. A pipe section of this length can be inspected in detail, using acoustic correlation or similar techniques to determine the precise burst location.

WaterWiSe@SG sensor nodes can also gather hydrophone data, potentially enabling acoustic leak detection. In the experiment described in Figure 5, a hydrophone located at sensor node 1 was used to record the acoustic profile generated during the solenoid opening. Figure 6 shows a spectrogram of three discrete periods: when the solenoid was closed, when the solenoid was open, and when the leak was slowly turned off through a globe valve before closing of the solenoid valve. The characteristics of the artificially created leak are evident. When the solenoid was closed, the only energy present was in low-frequency bands (< 50 Hz); when it was opened, a significant energy increase was observed, up to 500 Hz (with a dominant frequency around 300 Hz). As the valve was slowly closed over the span of one minute, the acoustic energy was reduced significantly until finally the solenoid switched off.

Future plans related to leak detection involve creating more complex and realistic pipe bursts (from within gravel packs rather than air, for example) to further test and train anomaly detection and localization capabilities. The authors also plan to augment the pressure traces with the hydrophone data to understand their relative sensitivity with respect to leak size and opening time as well as the benefits of using multiple parameters in estimating leak and burst locations.

On-line hydraulic modeling of a water distribution system.

Integration of near real-time hydraulic data with hydraulic computer simulation models allows utility engineers to operate and control their large-scale, urban water distribution systems in real time. In conventional practice, hydraulic models are calibrated off line (USEPA, 2005), typically

using a one-week sample of flow rate and pressure measurements within the network. Thereafter, uncertain system parameters (e.g., water demands and pipe roughness) are adjusted until an acceptable match is achieved between the model outputs and physical observations.

The main limitation of all off-line calibration procedures is that they approximate the unknown parameters using a short-term sample of hydraulic data. The cali-

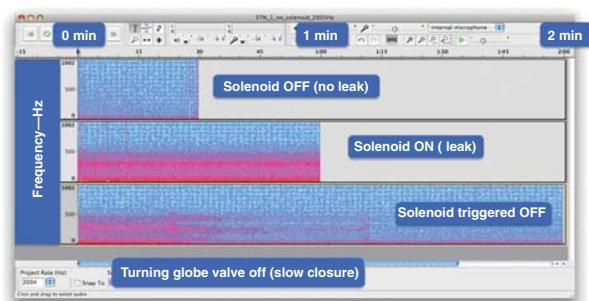
Integration of near real-time hydraulic data with hydraulic computer simulation models allows utility engineers to operate and control their large-scale, urban water distribution systems in real time.

bration results may represent the system hydraulics during the short period of the sampling procedure, but they cannot be expected to accurately represent the system conditions for the full range of operational conditions that can occur. In principle, much more realistic predictions can be achieved by updating the hydraulic state estimation using continuous on-line hydraulic measurements provided by a sensor network installed within the distribution system.

Several studies have proposed methods for assimilating on-line measurements into hydraulic state estimation models. Davidson and Bouchart (2006) proposed proportional and target demand methods. These are two techniques for adjusting estimated demands in hydraulic models of water distribution networks to produce solutions that are consistent with available SCADA data. Shang and colleagues (2006) presented a predictor-corrector method, implemented in an extended Kalman filter to estimate water demands within distribution systems in real time. A time-series autoregressive moving average model was used to predict water demands based on the estimated demands at previous steps; the forecasts were corrected using measured nodal water heads or pipe flow rates. Although these studies were not tested against real-world cases of complicated urban water systems monitored with on-line sensors, they provided a modeling framework and the mathematical tools to enable larger applications to be used for more complex systems.

The development of the on-line hydraulic model for the urban water distribution system monitored by the WaterWiSe@SG WSN is described elsewhere (Preis et al, 2010, 2009). The current implementation of the on-line hydraulic model has been operational since January 2010. The hydraulic model is an all-pipe model comprising more than 19,000 junctions and 20,000 pipes with

FIGURE 6 Acoustic measurement by a hydrophone during a leak-off experiment



diameters ranging from 2 to 54 in.; the water system pipes and junctions are spread over an area of 60 km², and the distance between any two neighboring sensor nodes ranges from 0.5 to 1.5 km.

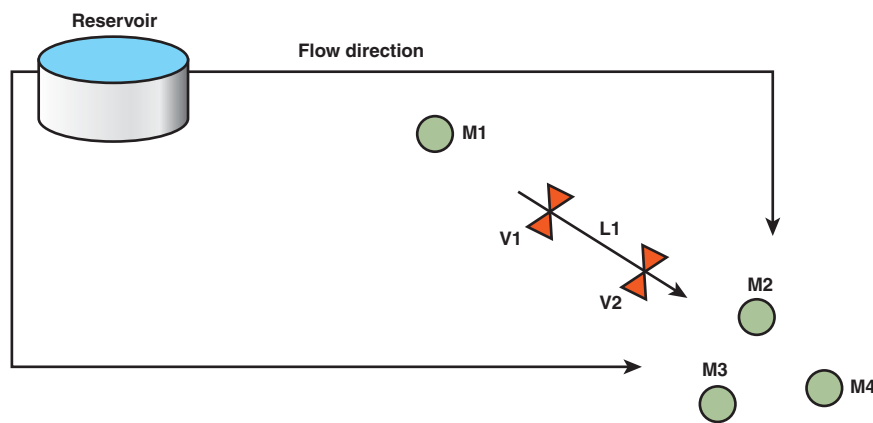
The model receives hourly averaged pressure data from the eight sensor nodes, as well as on-line updates from the water utility's SCADA system on the boundary conditions of the system (i.e., water elevations and outflows of the service reservoirs). Running the on-line predictor-corrector hydraulic model requires continuous data from all sensor nodes. If data are temporarily unavailable, a data imputation technique is implemented in which data trends in each node's data stream are tracked and data are predicted using a technique based on Gaussian process regression (Goldsmith et al, 2010).

In order to gain confidence in the model and identify possible shortcomings, the authors used several measures to evaluate its performance, such as cross-validation with supplementary independent measurements

(three for pressure and one for flow rate) in different locations across the water distribution system. Results for the supplementary pressure sensors showed a mean absolute error of ~1.5 psi; for the supplementary flowmeter, the mean absolute error was 23 m³/h (~100 gpm), which was less than 5% of the mean flow in the pipe.

Preliminary assessment of the model performance at the end of phase 1 of the WaterWiSe@SG project showed promising results (Preis et al, 2010), taking into consideration the limited number of sensor nodes that may not provide complete coverage of the water distribution network. That analysis of the model's performance created a framework for a much more comprehensive and elaborate on-line hydraulic model implementation during phase 2 of the WaterWiSe@SG project (in progress as of March 2011); during this phase the size of the sensor network will increase to 25 sensor nodes, and much better coverage of the water system will be available.

FIGURE 7 Schematic of a maintenance operation in the monitored water system



L1—isolated pipe; M1, M2, M3, M4—sensor nodes; V1, V2— isolation valves

FIGURE 8 Pressure data in relevant sensor nodes during a maintenance operation (pipe shutdown) in the monitored water system

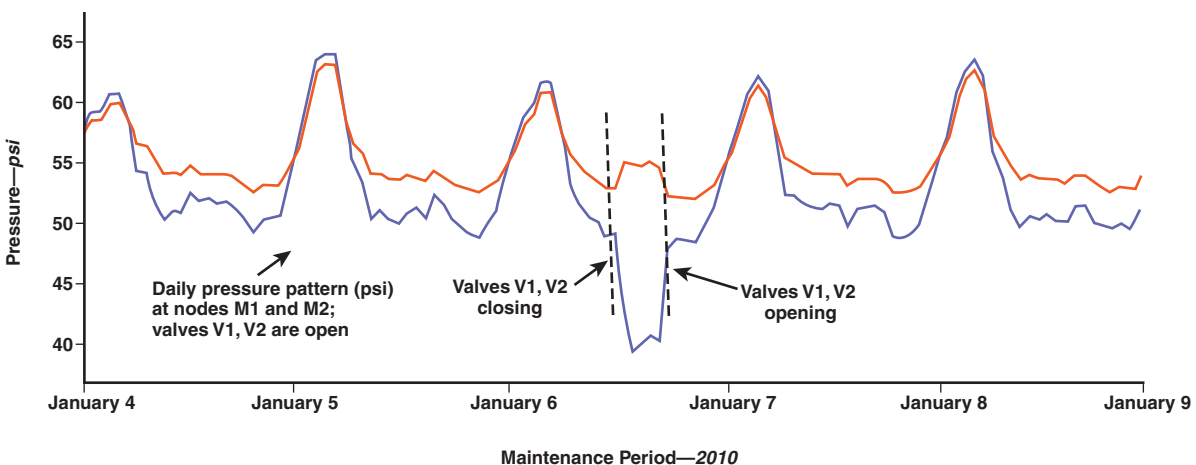
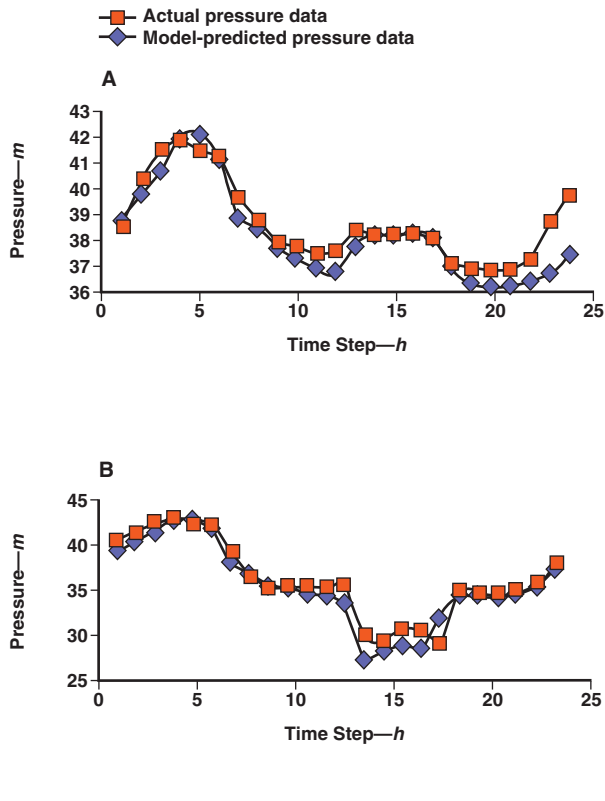


FIGURE 9 Comparison of actual and predicted pressure data in sensor nodes M1 (A) and M2 (B) during a maintenance operation (pipe shutdown) in the monitored area of the water system



The on-line hydraulic model was found to be useful in modeling the system response to various maintenance operations that took place in the distribution system. In the following example, a water main was isolated for maintenance operations by the water utility. Closing several valves within the system isolated the pipe. Figure 7 provides a schematic depiction of this operation in which link L1 was isolated by closing valves V1 and V2; pressure sensor node M1 was located upstream of the isolated link, and sensor nodes M2, M3, and M4 were located downstream of the closed pipe.

During the five-hour operation, the pressure at a sensor node that was located upstream of the isolated pipe increased whereas pressure records at sensor nodes that were located downstream of the isolated section decreased. At the end of the maintenance operation, when the isolation valves were opened again, pressure in all sensors nodes returned to normal. Figure 8 shows the pressure data at sensor nodes M1 and M2.

The on-line hydraulic model was used to predict the system response to this anomaly by updating the valve settings for V1 and V2 in the system's on-line calibrated

EPANET model (USEPA, 2002) from open to closed status during the expected maintenance operation period. Figure 9 shows the predicted pressure values for sensor nodes M1 and M2 alongside the observed pressure values at these same sensor nodes.

This example shows how useful an on-line calibrated hydraulic model can be in predicting the system response to hydraulic anomalies within the water utility. With this hydraulic state information, the water utility operator is able to facilitate the forecasting of minimum and maximum pressures that would be experienced in the system during proposed maintenance operations.

SUMMARY

Phase 1 of the WaterWiSe@SG saw the deployment of a WSN to enable real-time monitoring of the water distribution network in Singapore. The overall project has been directed toward three main goals: application of a low-cost WSN for high-data-rate, on-line monitoring of hydraulic parameters within a large urban water distribution system; development of systems to enable remote detection of leaks and prediction of pipe bursts; and integrated monitoring of hydraulic and water quality parameters. To the best of the authors' knowledge, WaterWiSe@SG is the first in situ hydraulic test bed that is being used to gather and process data continuously on an actual water distribution system.

Future research plans include

- refining the sensor node design to achieve greater efficiencies in power consumption,
- evaluating the performance of nonspecific water quality sensors for in-line monitoring (current plans are to focus on pH and ORP sensors),
- completing the next phase deployment of 20–25 nodes (with locations optimized using the calibrated hydraulic model of the water network),
- implementing a software system for managing the data streams, including a data query system based on the WaveScope project at the Massachusetts Institute of Technology in Cambridge (Girod et al, 2007), and
- implementing and evaluating local algorithms for leak detection and localization on the sensor nodes.

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FOOTNOTES

¹Imote2, Intel Corp. Research, Santa Clara, Calif.

²Gumstix, Portola Valley, Calif.

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