Real-Time Hydraulic Modelling of a Water Distribution System in Singapore

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Real-Time Hydraulic Modelling of a Water Distribution System in Singapore

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Abstract

This paper describes the implementation of a real-time hydraulic model of a water distribution system in Singapore. This on-line system is based on the Integration of real-time hydraulic data with hydraulic computer simulation models and statistical prediction tools. To facilitate this implementation, a network of wireless sensor nodes continuously sample hydraulic data such as pressure and flow rate, transmitting it to cloud-based servers for processing and archiving. Then, data streams from the sensor nodes are integrated into an online hydraulic modeling subsystem that is responsible for on-line estimation and prediction of the water distribution system's hydraulic state for a rolling planning horizon of 24 hours ahead. This online hydraulic model is one of the components of the WaterWiSe (Wierless Water Sentinel) platform which is an end-to-end integrated hardware and software system for monitoring, analyzing, and modeling urban water distribution systems in real-time.

1. Introduction

The integration of near real-time hydraulic data with computer simulations for on-line operation and control of large-scale urban water distribution systems can be used in a variety of applications ranging from demand prediction, valve operation simulations and impact assessment, water age simulation and real-time optimization of pump and valve settings for efficient power management. Such a system can also be used for the implementation of water security systems and for the prediction of system performance during emergency events (e.g., pollution events, main pipe rupture, or significant fire).

This paper describes the development and application of a real-time hydraulic modelling system as a component of the WaterWiSe platform (Figure 1) which is an end-to-end integrated hardware and software system for monitoring, analyzing, and modeling urban water distribution systems in real-time (Allen et al 2011). Three main goals have been achieved during the ongoing development of this system: 1) a wireless sensor network of 25...
sensing units was applied for high data rate, on-line monitoring of hydraulic and water quality parameters within a large urban water distribution network in Singapore; 2) remote detection of leaks and pipe burst events was enabled with sophisticated data mining algorithms; and 3) 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.

The Wireless Water Sentinel (WaterWiSe) project has provided a unique opportunity to develop an integrated decision support system in collaboration with PUB (Singapore’s national water agency). This has led to an end-to-end system for continuous remote monitoring of a water distribution system, including wireless sensing hardware for hydraulic, acoustic and water quality parameters (Figure 2), a data collection and visualization infrastructure, and a set of hydraulic modeling and analysis tools that will be described in more details in the following sections.

Figure 1. The WaterWiSe system components

Figure 2. The WaterWiSe Sensor network deployment in Singapore
The authors are aware of only one real-life application reported in the literature prior to the WaterWiSe system deployment that has assimilated on-line measurements into hydraulic state estimation models done by DHI Water & Environment. DHI have developed the MIKE NET on-line (2003). This was a software module that integrates SCADA system, GIS and hydraulic modeling package into one combined platform. This tool has several limitations: Firstly, it doesn’t perform automated hydraulic model calibration, it just assimilates SCADA data into hydraulic model; Secondly, it doesn’t include a demand zones identification capability; Thirdly, it can run only with conjunction with SCADA server and it can’t use external data sources like field measurements or information about climatic conditions and public holidays; Fourthly, the software doesn’t include a tool to filter bad measurements or to deal with cases where a sensor is broken and not transmitting data to the server; Fifthly, the software only works on Windows OS; and finally, it is not an extensible platform that can host/integrate other applications.

2. The WaterWiSe Real Time Hydraulic Modeling System

The on-line hydraulic model (Figure 3) starts with identifying virtual demand zones (i.e., clusters of water consumers) within the complex topology of the urban water supply system. The demand zone identification method implements optimization tools and graph algorithms to partition the system into homogenous clusters. Thereafter, an on-line Predictor-Corrector (PC) procedure is employed for forecasting future water demands for each zone (Preis et al 2010).

![Figure 3. Real-time Hydraulic modeling system](image-url)
A time-series algorithm is used to forecast future water demands (for each demand zone) for a rolling planning horizon of 24 hrs ahead taking into account changing weather conditions and day-of-the-week classification (weekday, weekend & public holiday) and an evolutionary optimization technique is used to correct these predictions with near real-time monitoring data provided by the sensor network. The calibration problem is solved using a modified Least Squares (LS) fit method in which the objective function is the minimization of the residuals between predicted and measured pressure and flow rates at several system locations, with the decision variables being the variations in the zones/ clusters water demands.

In the current set-up, the model receives 15 minutes averaged hydraulic data (pressure and/or flow) from 25 multi-parameter sensor nodes, as well as online updates from the water utility’s SCADA system on the boundary conditions of the system (i.e., the service reservoirs’ water elevations and outflows, and the pumping station outflow).

Running the on-line predictor-corrector hydraulic model requires continuous data from all sensor nodes. If data is temporarily unavailable, a data imputation technique is implemented to predict missing data streams.

3. Results

The 25 sensor network monitors a 60km² (23.15 sq mi) area of downtown Singapore that is supplied by a Water Distribution System consisting of three service reservoirs, over 19000 junctions, over 20000 pipes and a pumping station. The average distance between currently deployed sensors is 1km.

The data collected by the sensing system that is used by the on-line model includes the boundary conditions of the system (reservoirs elevations and outflows) and pressure & flow measurements from 25 sensing sites across the distribution system.

The water consumptions in the demand zones are predicted in advance for a 24-hour rolling window. Predictions are shown on a daily summary, with comparison to the actual consumption, as well as at 15-minute intervals, across the whole zone or in specific sub-zones.

Figure 4 shows examples of the different modes of prediction. The prediction model assimilates historical trends as well as calendar and seasonal information (holidays, special events).
In order to gain confidence in the model, and also to identify possible shortcomings, several measures were used to evaluate its performances such as cross-validation with actual pressure and flow-rate measurements. The WaterWiSe system implements a frequently-used measure called Relative Prediction Accuracy (RPA) which is based on the differences between values predicted by a model and the values actually observed. The RPA formula is described below:

$$RPA\% = 100 \left[ 1 - \frac{\sum_{i=1}^{N} |p_i - a_i|}{\sum_{i=1}^{N} a_i} \right]$$

where $p_i$ and $a_i$ are the predicted and actual values of case $i$; and $N$ is the number of cases.

Figures 5 and 6 show typical RPA calculations for flow and pressure measurements where the pressure and flow RPA is recurrently above 90% and 80% respectively.
The real time hydraulic modelling system facilitates the implementation of real-time decision support tools as outlined in the following sections:

**On-demand valve operation simulation**

The operation simulation tool is used to analyze the potential impact on the network hydraulics of an operational event such as valve closures and pipe isolations. The simulation is done in real-time on the on-line hydraulic model and the results are presented, identifying pipes that will have low or reversed flow, areas that will have abnormally low or high pressure, and customers that will be isolated by the operation (Figure 7).

![Figure 7. Example output from an operational simulation. Blue dots show isolated customers, red pipes show reversed flow and green pipes show increase velocity. The pop-up shows the predicted data trace with and without valve closure.](image)

**Water age and water source analysis**

Using the real-time hydraulic model, water age in the system is predicted and compared against the real-time water quality measurements being taken in the system. This helps to identify areas of high water age that may be of concern (Figure 8). The mixing of water in the system from different reservoirs can also be predicted and visualized, showing relative percentages of water sources at any given location over user-defined time periods (Figure 9).

![Figure 8: Water age predictions are visualized and compared to actual water quality data](image)
4. Summary

This paper described the implementation of a real-time hydraulic model of a water distribution system in Singapore. This on-line system is based on the Integration of real-time hydraulic data with hydraulic computer simulation models and statistical prediction tools. To facilitate this implementation, a network of wireless sensor nodes continuously sample hydraulic data such as pressure and flow rate, transmitting it to cloud-based servers for processing and archiving. Then, data streams from the sensor nodes are 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 for a rolling planning horizon of 24 hours ahead. This online hydraulic model is one of the components of the WaterWiSe (Wireless Water Sentinel) platform which is an end-to-end integrated hardware and software system for monitoring, analyzing, and modeling urban water distribution systems in real-time.

Future work will focus on using the real-time hydraulic modelling platform to support pump optimization strategies with the goal of saving energy while maintaining the required standards for hydraulic and water quality parameters.

5. Acknowledgment

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6. References

