SMaRT-OnlineWDN: Online Security Management and Reliability Toolkit for Water Distribution Networks

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ABSTRACT

Water distribution Networks (WDNs) are critical infrastructures that are exposed to deliberate or accidental contamination. Until now, no monitoring system is capable of protecting a WDN in real time. In the immediate future water service utilities that are installing water quantity and quality sensors in their networks will be producing a continuous and huge data stream for treating. The main objective of the project SMaRT-Online^{WDN} is the development of an online security management toolkit for water distribution networks that is based on sensor measurements of water quality as well as water quantity and online simulation. Its field of application ranges from detection of deliberate contamination, including source identification and decision support for effective countermeasures, to improved operation and control of a WDN under normal and abnormal conditions.

Keywords

Water supply networks, contamination, online simulation, transport model

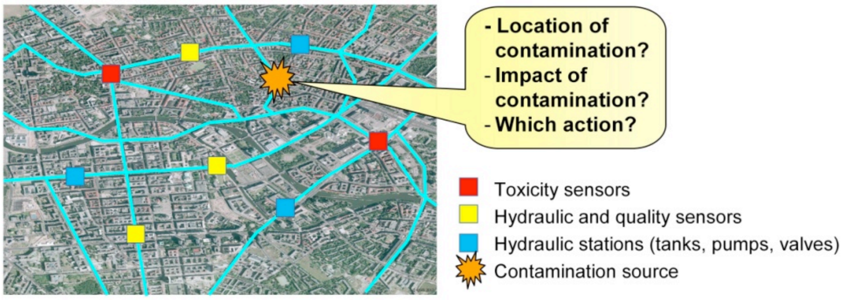
INTRODUCTION

Water Distribution Networks (WDNs) are critical infrastructures that are exposed to deliberate or accidental contamination. In particular, the drinking water supply is at potential risk of being a terrorist target and contamination need to be detected in due time. The resource, the treatment plant or the distribution network may be contaminated with a deliberate injection of chemical, biological or radioactive contaminants. Several papers report deliberate contamination of a water distribution networks in the past as summarized in (Gleik, 2006).

Until now, no monitoring system is capable to protect a WDN in real time. Powerful online sensor systems are currently developed and the prototypes are able to detect a small change in water quality. In the immediate future, water service utilities will install their networks with water quantity and water quality sensors. For taking appropriate decisions and countermeasures, WDN operators will need to dispose of:

1) a fast and reliable detection of abnormal events in the WDNs;
2) reliable online models both for the hydraulics and water quality predictions;
3) methods for contaminant source identification backtracking from the data history.

Actually, in general none of these issues (1) – (3) are available at the water suppliers. Consequently, the main objective of the project SMaRT-Online^{WDN} is the development of an online security management toolkit for water distribution networks (WDN) that is based on sensor measurements of water quality as well as water quantity. Its main innovations are the detection of abnormal events with a binary classifier of high accuracy and the generation of real-time, reliable (i) flow and pressure values, (ii) water quality parameter values of the whole water network. Detailed information regarding contamination sources (localization and intensity) will be explored by means of the online running model, which is automatically calibrated to the measured sensor data.



Its field of application ranges from detection of deliberate contamination including source identification and decision support for effective countermeasures to improve operation and control of a WDN under normal and abnormal conditions (dual benefit).

Figure 1: In case of a toxic contamination of the water distribution network, the water suppliers will be supported by the SMaRT-Online^{WDN} security management toolkit.

In this project, the technical research work is completed with a sociological, economical and management analysis. SMaRT-Online^{WDN} combines applied mathematics, civil and environment engineering, fluid mechanics research and social science and economics in a multidisciplinary approach. The French-German cooperative research project consists of end users (BWB in Germany, CU Strasbourg and Veolia Eau d'Ile de France), technical and socio-economic research institutions (Fraunhofer IOSB, TZW, Irstea, ENGEES) and industrial partners on both French and German sides (Veolia, 3S Consult).

System Concept and Objectives of SMaRT-Online^{WDN}

The overall objective of the project SMaRT-Online^{WDN} is the development of an online security management toolkit for WDNs. The general system concept is sketched in Figure 2. The software solution relies on data treatment and assimilation from a sensor network of water quantity values (pressure, flow rate) and water quality values (e.g. chlorine residue, pH, conductivity, turbidity, temperature,). The core of the online security management toolkit consists of a grid of smart sensors in combination with an online simulation model. The boundary conditions of the network model are regularly updated by measurement data guaranteeing the compliance of the model with the observations. The consistency of the measurements is checked e.g. by use of an Artificial Neural Network. With this information the online security management toolkit is able to reflect the current hydraulic state of the entire system. In addition, monitoring of water quality parameters supports the detection of biochemical contamination of the drinking water.

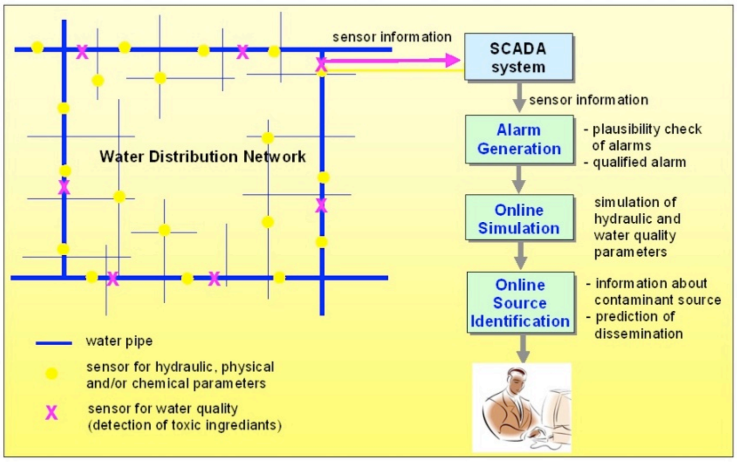


Figure 2: General system concept of SMaRT-Online^{WDN}

The SMaRT-Online^{WDN} modules can be summarized as follows:

1. Event Detection and Alarm Generation: To enable a robust detection of changes in the water quality, a sensor data fusion module will evaluate the data of smart sensors. Online simulation model is used for plausibility check of the event detection.

2. Optimal sensor placement. A concept for the optimal placement of a defined number of quality sensors in a real-world network topology and an existing network of usual sensors (hydraulic state, physical/chemical parameters) will be developed and implemented as a software tool. It enables the user (e.g. WDN operators) to find optimal locations for early warning detection system (Propato and Piller, 2006; Deuerlein et al., 2010) and for parameter estimation (Piller, 1995; Fabrie et al., 2010).

3. Online Simulation: Generation of real-time, reliable (i) flow and pressure values, (ii) water quality parameter values of the whole water network

4. Transport model: A detailed experimental and simulation based study of the transport of conservative

substances in real-world water drinking networks will be performed. A special focus is on the flow and distribution of substances at crosses and T-junctions as in most of the actual available WDN simulation software tools (e.g. EPANET) a complete mixing of the substances is assumed. These phenomena will be investigated by means of detailed 3D computational fluid dynamics (CFD) models. Later on, a simplified 1D model will be implemented due to the need of a short simulation time in the real-time management toolkit software.
5. Online contaminant source identification and mitigation of risks: A backtracking algorithm that uses the data history of the measurements has to be implemented. The merit of off-line methods (e.g.: Propato et al. 2007) and pseudo real-time ones (Preis and Ostfeld, 2011) will be studied compared to the developed online solution method. As a result of water quality sensor alarms, the possible localisations of the intrusion of contaminant can be calculated.
6. Risk analysis and impact assessment: Risk analysis and impact evaluation (real impacts and perceived ones) will be performed for the three aspects of sustainability: environmental, social and economical, combined with technical innovation.
SMaRT-Online^{WDN} will improve the observability of water quality and quantity in the distribution network in near real-time. It acts as an early warning system as well as decision-support system in case of contamination events. Furthermore, it supports a better understanding of the physical and bio-chemical processes in the pipe systems. E.g., it will be possible to use it offline for training of staff by use of simulation.

In the sequel we will focus on the concept and first results of online simulation and transport modelling.

ONLINE SIMULATION

The main difference between online and offline hydraulic simulation is that the boundary conditions (tank water levels, zone inflow, demands, etc.) and operational states of devices (like valve status, pump operations, etc.) of the online model are not predefined by the user, as it is true for the offline case, but derived from (near) real time data originating from the SCADA (**S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition) system of the utility. Therefore these data of the online model are always up to date. The simulation based on online data is able to reflect the actual current state of the system much better than the offline model where the proper choice of the boundary conditions is based on historical data or the experience and the knowledge of the modeller.

However, in practice, not all of the model parameters can be measured and transferred online due to financial and technical limitations. This applies in particular to the time varying demands of the customers. As a result, one major issue of online simulation is the proper estimation of the noisy data “user demands”. Therefore an online calibration tool will be developed that calculates (or estimates) the distribution of actual demands within the particular zones by minimizing a least-squares function of calculated and measured values of all available measurements of the zone such as in Piller *et al.* (2010).

Another challenge of online simulation consists in the strong requirements for calculation time and data transfer. The objective is to run the online simulation cycle at least every five minutes including online calibration, data transfer and monitoring. In order to enhance the overall process a method for simplification of large water distribution system networks has been developed, which is based on topological decomposition of the network graph (Deuerlein *et al.* 2010; Deuerlein, 2008). On the one hand the method shall be used for the enhancement of the solution of the hydraulic calculations by a new method for reordering of the system of equations that has been published recently (Deuerlein and Simpson, 2012). On the other hand, graph decomposition can be used as general tool for adaptive modelling in the context of SMaRT-Online^{WDN}.

In the context of SMaRT-Online^{WDN} the online simulation framework is not used only for the monitoring of the current state of the system but also for the management of mitigation measures in case of an accident. For that purpose the additional simulation modes look-ahead, what-if and reconstruction are required. Look-ahead simulations can be used for predicting the spread of contamination if the location of the source is known. What-If simulations support the fast and efficient development of counter measures like isolation of contaminant and flushing. Reconstruction of system states of the recent past is needed for the solution of the source identification problem in cases where alarms for contamination are released by the sensors but the source of contamination and its location are unknown.

TRANSPORT MODEL

Existing transport model tools are not adapted for online modelling and ignore some important phenomena that may be dominant when looking at the network in greater detail with an observation time of several minutes. These phenomena are addressed in SMaRT-Online^{WDN}. In summary, it is important to consider: 1) Inertia terms to make slow transient predictions of the hydraulic state; 2) The hydrodynamic dispersion and possibly the molecular diffusion to improve the transport along a pipe and at junctions; 3) The imperfect mixing at T- and

Cross junctions depending on velocity inlets; 4) The diameter reduction and the wall roughness (Shen, 2008).

In a first project phase, these phenomena are investigated by means of 2D and 3D Finite Element simulations as well as in experimental studies (see next section). In the sequel, some first results of transport modelling are presented.

Investigation of turbulent flow at T-junctions: When simulating the behaviour of pollutant at the junctions of pipes it is important to consider the effects of turbulence induced. For this, two turbulence models have been compared : 1) a "large eddy simulation" (LES) model that is more accurate but with large computational burden; and 2) a "Reynolds-Averaged Navier-Stokes" (RANS) model that neglects the small perturbations that are significant in the pollutant streamlines in the tubes. Figure 3 shows the differences between the two methods (RANS k-ε and LES Smagorinski Lilly). The inlet is West side and the two outlets are North and East.

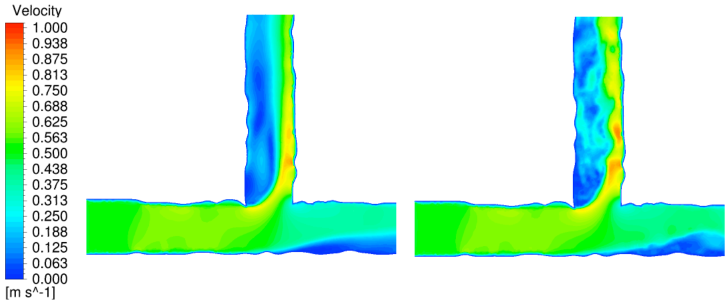


Figure 3: Comparison of turbulence simulation (velocity) using methods RANS (left) and LES (right)

Simulating mass flow distribution at T-junctions: To adapt for 1D model more accurate than those used actually, we simulated many various configurations of T-junctions. The first results are used to define the methodology, to measure the conception and calculation time for one test case. The configuration is with one inlet and two outlets. Figure 4 shows the difference in distribution of the pollutant function of the shared flows of the two outlets. Main is the straight direction, secondary the one that turns 90 degrees. This demonstrates that it is important to simulate imperfect mixing for T-junction configuration.

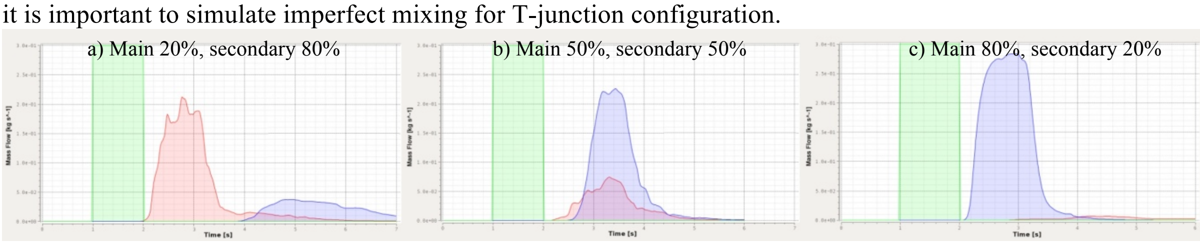


Figure 4: Influence of Mass Flow distribution with three case studies. Green represents the inlet; blue the main outlet and red the secondary outlet. Parameters: v=0.8m/s at the inlet, injection of 306g by constant mass flow.

Influence of curvature T-junctions: In a first study the influence of the curvature at the joint of a T-junction on the flow are analysed. The diameter of the pipes is D=0.1m and velocity at the inlet is set to v=0.02 m/s, so the problem is laminar. Compared are a junction without curvature (Figure 5, left) to a curved junction with the radius of R=0.1m (Figure 5, right). The inlet is East side and the two outlets are North and West.

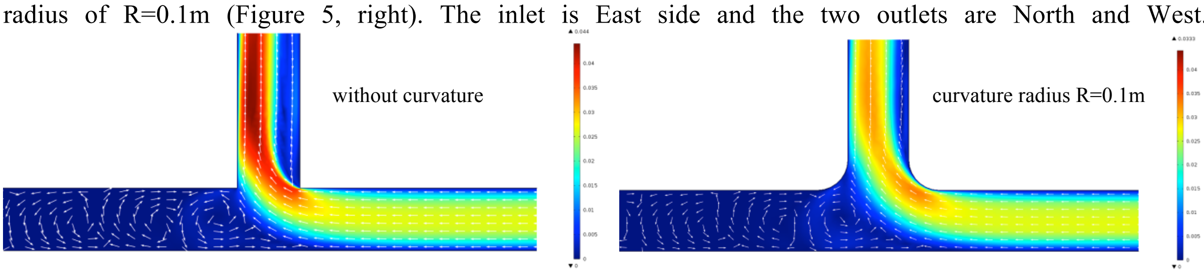


Figure 5: Influence of the curvature radius on the flow at a T-junction

TEST NETWORK FOR EXPERIMENTAL INVESTIGATIONS

During the project SMaRT-Online^{WDN} test networks at project partners TZW (Dresden) and BWB (Berlin) are available. At these test networks the developed SMaRT-Online^{WDN} tools will be investigated and tested under practically relevant conditions. The network of partner TZW has a total length of about 300 m and is made of PVC-clear pipes with a diameter of 100 mm (Figure 6, left).

First investigations at TZW have been performed applying several color tracers with different densities under laminar and turbulent flow conditions (see Figure 6, right). The experiments were conducted in a straight pipe with velocities in a range of 0.004m/s to 0.5 m/s. The main results under laminar flow conditions are: 1) Dispersion is the main process for spreading and mixing, 2) The behavior (moving up or down) of the tracer depends particularly on the density of the injected liquid, 3) An injected liquid with a higher or lower density than the water moves at the pipe wall with a lower velocity than the water body.

Under turbulent flow conditions, total mixing occurs immediately after injection, the position of the injection and the density of the injected liquid are not relevant. Further experiments will be done with a focus on cross- and T-junctions.

Figure 6: Test network for SMaRT-Online^{WDN} (left); Injection experiments with a color tracer (right)

CONCLUSION

The main objective of the project SMaRT-Online^{WDN} is the development of an online security management toolkit for water distribution networks (WDN) that is based on sensor measurements of water quality as well as water quantity. In this paper, the concept and first results have been presented. Actual work is focused on the implementation of the SMaRT-Online^{WDN} modules.

ACKNOWLEDGMENTS

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