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

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Olivier PILLER[1], Denis GILBERT[1], Fereshte SEDEHIZADE[2], Cyrille LEMOINE[3], Anne-Claire SANDRAZ[4], Caty WEREY[5], Jean-Marc WEBER[6], Jochen DEUERLEIN[7], Andreas KORTH[8], Thomas BERNARD[9]

[1] IRSTEA, groupement de Bordeaux, UR REBX, 50 avenue de Verdun, F-33612 CESTAS Cedex, France

[2] Berliner Wasserbetriebe, Neue Jüdenstraße 1, D-10179 Berlin, Germany

[3] Veolia Environnement, Chemin de la digue BP76, F-78603 Maisons-Laffitte, France

[4] Veolia Eau d'Ile de France, 6, Esplanade Charles de Gaulle, F- 92751 Nanterre, France

[5] Engees, 1, quai Koch, BP 61039, F-67070 Strasbourg, France

[6] Service de l'eau de la Communauté Urbaine de Strasbourg, 1 Parc de l'Etoile, F-67076 Strasbourg, France

[7] 3S Consult GmbH, Albtalstraße 13, D-76137 Karlsruhe, Germany

[8] DVGW-Technologiezentrum Wasser, Wasserwerkstraße 2, D-01326 Dresden, Germany

[9] Fraunhofer Institute IOSB, Fraunhoferstraße 1, D-76131 Karlsruhe, Germany

olivier.piller@irstea.fr, denis.gilbert@irstea.fr, fereshte.sedehizade@bwb.de, cyrille.lemoine@veolia.com, anne-claire.sandraz@veoliaeau.fr, caty.werey@engees.unistra.fr, jean-marc.weber@strasbourg.eu, deuerlein@3sconsult.de, andreas.korth@tzw.de, thomas.bernard@iosb.fraunhofer.de

Résumé – Les réseaux d'Alimentation en Eau Potable (AEP) sont des infrastructures à risques exposées à la contamination délibérée ou accidentelle. Jusqu'à présent, aucun système de surveillance n'est capable de protéger un réseau avec une rapidité suffisante. Dans un avenir proche, les services publics d'eau vont installer sur leurs réseaux des capteurs de la qualité de l'eau produisant un flux continu et considérable de données à traiter. L'objectif principal du projet de consortium SMaRT-Online^{WDN} est le développement d'une boîte à outils de gestion de la sécurité en temps réel pour les réseaux de distribution d'eau qui soit fondée sur des mesures tant de la qualité de l'eau que de la quantité. Pour prendre les décisions appropriées et des contre-mesures, les opérateurs auront besoin de disposer : 1) de modèles fiables temps réel pour prédire à la fois l'hydraulique et la qualité de l'eau ; 2) de méthodes d'identification des sources de contamination se fondant sur l'historique des données. L'acquisition de cet énorme flux de données et son traitement sont de réels challenges. Ce projet est un projet de recherche industriel CSOSG sélectionné par l'ANR et le BMBF pour une coopération franco-allemande sur la sécurité des réseaux. D'une durée de trois ans, il a commencé en avril 2012.

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 proposed 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. 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 (dual benefit). This French-German cooperative research project was selected by ANR and BMBF to start in April 2012 for 3 years under the call CSOSG 2012.

1. Introduction

Water Distribution Networks (WDNs) are critical infrastructures that are exposed to deliberate or accidental contamination. 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 capable 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 producing a continuous and huge data stream to treat.

For taking appropriate decisions and countermeasures, WDN operators will need to dispose of: 1) reliable online models both for the hydraulics and water quality predictions and of 2) methods for contaminant source identification backtracking from the data history.

Acquisition of such a huge data stream and assimilation raise challenging problems.

The main objective of 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 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). Detailed information regarding contamination sources (localization and intensity) is explored by means of an online running model, which is automatically calibrated to the measured sensor data.

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.

To this extent, four main research objectives are defined as 1) Online Simulation Model considering hydraulic state and water quality, 2) Optimal Location of Sensors based on the online simulation model, 3) Online Source Identification of Contaminants and 4) Risk analysis, identification and evaluation of impacts (real impacts and perceived ones).

The French-German cooperative research project consists of end users (BWB in Germany, CUS 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). It ideally combines top-level research with the practical needs of water supply utilities. Among the main expected results, two simulation software tools are planned to be extended for online use: those of partners Irstea and 3S Consults. The three WDN operators will benefit from the outputs and data traceability technology.

2. Originality and novelty of the project

The main objective of the proposed project SMaRT-Online^{WDN} is the development of an online security management toolkit for WDNs. The software solution relies on data treatment and assimilation from a sensor network of water quantity values (pressure, flowrate) and usual water quality values (chlorine residue, pH, conductivity, turbidity, UV). To this extent, four main research aims are defined as: 1) Online Simulation Model considering hydraulic state and water quality, 2) Optimal Location of Sensors based on the online simulation model, 3) Online Source Identification of Contaminants and 4) Risk analysis, identification and evaluation of impacts (real impacts and perceived ones).

The core of the online security management toolkit consists of a grid of smart sensors in combination with a 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, for example 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 water quality parameters support the detection of biochemical contamination of the drinking water.

Innovations of the proposed approach are:

- Detection of abnormal events with a binary classifier of high accuracy. How to differentiate from non-reported but normal change in the system?
- Generation of real-time, reliable (i) flow and pressure values, (ii) water quality parameter values of the whole water network. Which physical phenomena are to consider?
- Consideration of water quality measurement for online calibration of the hydraulic model;
- Semi-automatic aggregation of complex networks;
- Semi-automatic update and online-calibration of the model ;
- Taking into account nature of consumers and impacts evaluation through risk analysis methods.

Over the last decade a significant number of research papers have focused on the problem of finding an optimal sensor network design for early warning detection of deliberate contamination in water distribution systems (e.g. [1, 2]). The sensor placement problem is usually formulated as a multi-objective optimisation problem. The result is the trade-off between different, conflicting design criteria (e.g. maximising the area observed and minimising the time to detection). For large-size networks, a sampling method for critical contamination events is crucial for assessing accurately the impact costs [3]. Moreover, for online calibration of the transport model the offline calibration framework from [4] will be developed. It will be required to solve the associated sensitivity equations [5, 6]. As a second innovation the sensor network placement is understood as a multi-stage problem with successive improvements by expanding an existing sensor network (not a green field planning). This approach better reflects the real circumstances of water supply utilities as usually a sensor network (at least for hydraulic data) already exists. The general concept is illustrated in figure 1 below.

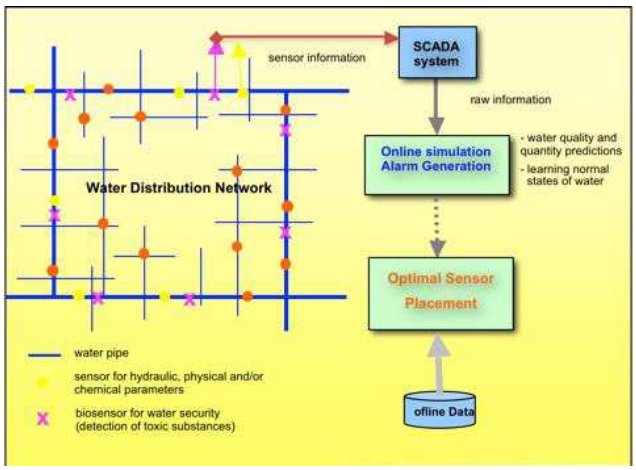

FIG. 1: Optimal sensor placement concept for both early warning detection and online calibration.

The third main objective concerns contaminant source identification. Deterministic and probabilistic solution methods [7, 8] that were developed for offline models will be extended within the framework of real-time modelling. An essential prerequisite is a transport model that yields hydraulic results in accordance with the quasi-real time measurements (e.g., every 5 minutes). A backtracking algorithm that uses data history for the last hours will be implemented. Then, once an alarm is raised (and validated) the pre-localisation of contaminant sources can be worked out (cf. figure 2).

Finally, risk analysis is proposed in this project up to impact assessment considering for the three aspects of sustainability: environmental, social and economical, combined with technical innovation provided in the other project work packages.

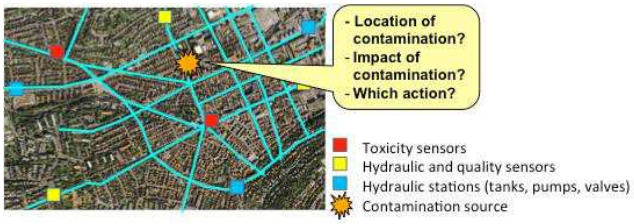

FIG. 2: Source identification and contaminant plume simulation from online modelling and sensor responses.

The online security management solutions are shown in a diagram in figure 3.

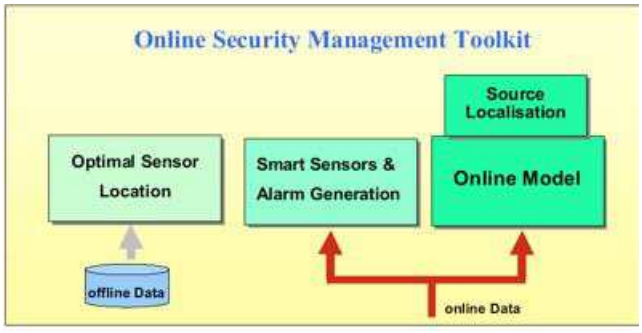

FIG. 3: The software solutions of the SMaRT-Online^{WDN} project.

3. Scientific and technical program

For the realization of the four main research aims (§2), the work has been split into 8 Work Packages (or WPs) or tasks. They are shown in figure 4 with the partners involved (the WP leader is underlined). We describe below the definition of each WP in detail:

- WP1: Specification of the online security management toolkit. The features, architecture, software modules and interfaces of the Online Security Management Toolkit have to be specified in detail. Typology of failures and dysfunctions (e.g. chemical water contamination, biological water contamination, physical degradation of a part of the infrastructure making a break in water delivery) has to be specified. All partners are involved.
- WP2: Smart sensors and alarm generation. The objective of this WP is the development of a robust and reliable online system, capable of monitoring locally distributed smart sensor systems. To enable a robust detection of changes in the water quality, a sensor data fusion module will evaluate the data of the smart sensors.
- WP3: 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) has to be developed. The concept has to be implemented as a software tool which enables the user (e.g. WDN operators) to find optimal locations for the sensors. This work package should also solve additional sensor placement to supplement an existing sensor network.
- WP4: Transport model. We look for water quantity and water quality slow transient models that fit the data with a scale of few minutes. Laboratory tests have started especially to study hydrodynamic dispersion in pipes, effect on diameter reduction and mixing at tee and cross-junctions. Also, it was found that it is important to consider the diameter reduction and the wall roughness. Two and three-dimensional Computational fluid dynamics CFD will be conducted to match the experiments. A simplified 1D model will be implemented due to the need of a short simulation time in the real-time management toolkit software.
- WP5: Online simulation. This task is central and concerns the design of the online models with the software solutions.
- WP6: Online contaminant source identification and mitigation of risks. The dependency with WP5 is strong. Counter-measures will be proposed.
- WP7: Risk analysis and impact assessment. The methodology will be conducted with ENGEES

partners (UMR GESTE and UMR IMFS) with the three water operators involved in the project.

- WP8: Application tests at technical scale and real world. The aim of this WP is the evaluation of the models by the verification of the functionality of the software modules developed in WP2 – WP6 regarding the alarm generation; the optimal sensor location; the transport model; the online simulation model; the online source identification. The application tests will be conducted by the three operators (Veolia Eau d'Ile de France and CUS for France and the Berlin network for Germany, BWB) and the technical centre for water TZW in Germany.

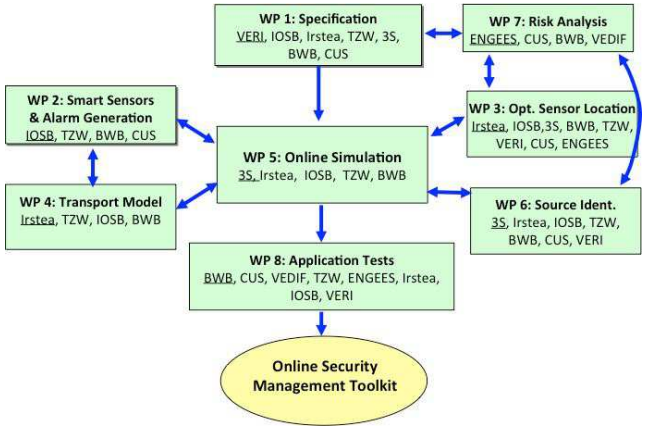

FIG. 4: Technical flowchart of the SMaRT-Online^{WDN} project.

4. Dissemination and exploitation of results

4.1 Scientific utilization

From a scientific point of view the development of SMaRT-Online^{WDN} is very challenging. Online-simulation of water supply systems is not really used in practice yet. However, software tools are available that can be extended for online use. With Irstea and 3S Consult, two of the leading providers of simulation tools are part of the project.

The research described in this proposal ideally continues with the results from current research projects. The risk analysis and first implementation of pilot online-simulation tool within the German BMBF funded project STATuS are extended for the development of a general water network security tool. The research of this project focuses on additional issues that are not included in STATuS like sensor placement, online-calibration and online-source-identification. Also, this will complement research lead in the FP7 SecurEau project that is not focused on online modelling, data acquisition and assimilation.

The results of SMaRT-Online^{WDN} can be further extended by applications for more efficient operation of water distribution networks. Energy savings and decreased CO_2-emissions are of high priority task for the future generations. The optimisation of pump operations in real time can be realised by application of online-simulation techniques as well.

For SMaRT-Online^{WDN}, the consideration of social economic dimensions linked with risk analysis will permit to complete the technical criteria.

Irstea and ENGEES plan to lead PhD and post doctorate studies, funded by the project. Three publications in ASCE and Applied Mathematics journals and yearly participations to international conference are forecast.

4.2 Technical utilisation

The usefulness of SMaRT-Online^{WDN} for a water supply is clear. It improves 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. It can be used offline for training of staff by use of simulation. Three water supply operators will benefit from the outputs and data traceability technology, CUS and Veolia Eau d'Ile de France in France and BWB in Germany.

4.3 Economic utilisation

The implementation of such large sensors network enables to allow water traceability. This is a huge investment for operators and municipalities. Even if online sensors fully wireless are now available, various strategic questions still remained to answer especially: How many probes should be installed to reach water traceability from the drinking water plant to the consumer? Where are the best locations? Could we operate such a system in real time for event detection? This project will provide answers on these topics and will contribute to develop such concepts and create new services around water quality sensors network and water traceability.

Last but not least, there exists a strong dual benefit from this project. The tool developed for the online security management toolkit can be generalised for more efficient network control and operations of water supply systems besides the security against deliberate contamination of drinking water.

References

[1] M. Propato, and O. Piller. *Battle of the Water Sensor Networks*. 8th annual Water Distribution System Analysis Symposium, University of Cincinnatti, Cincinnati, Ohio USA, August 27-30 2006, printed by ASCE, 8, 2006.

[2] J. Deuerlein, A. Wolters, L. Meyer-Harries and A. R. Simpson. *Graph Decomposition in Risk Analysis and Sensor Placement for Water Distribution Network*

Security. Water Distribution Systems Analysis 2010, ASCE, Tucson, 394-411, Decembre 2011.

[3] L. Perelman, and A. Ostfeld. *Extreme Impact Contamination Events Sampling for Water Distribution Systems Security*. Journal of Water Resources Planning and Management, 136(1), 80-87, 2010.

[4] O. Piller. *Modeling the behavior of a network - Hydraulic analysis and sampling procedures for parameter estimation*. Applied Mathematics thesis from the University of Bordeaux (PRES), 288 pages, Talence, France, defended on the 3rd February 1995.

[5] P. Fabrie, G. Gancel, I. Mortazavi, and O. Piller. *Quality Modeling of Water Distribution Systems using Sensitivity Equations.* Journal of Hydraulic Engineering, 136(1), 34-44, 2010.

[6] O. Piller, D. Gilbert and J. E. Van Zyl. *Dual Calibration for Coupled Flow and Transport Models of Water Distribution Systems*. Water Distribution Systems Analysis 2010, ASCE, Tucson, 722-731, Decembre 2011.

[7] M. Propato, M. E. Tryby and O. Piller. *Linear algebra analysis for contaminant source identification in water distribution systems*. World Environmental and Water Resources Congress 2007, Tampa, Florida, USA, 15-19 May 2007, 10, 2007.

[8] A. Preis and A. Ostfeld. *Hydraulic uncertainty inclusion in water distribution systems contamination source identification*. Urban Water Journal, 8(5), 267-277, 2011.