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ResiWater: A Franco-German Project for Augmented Resilience of Water Distribution Systems following Severe Abnormal Events

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Abstract. Water Distribution Systems (WDSs) are constantly exposed to deliberate or accidental contaminations or may undergo a partially or full system collapse. In this paper we present the goals and preliminary results of the French-German project ResiWater (2016). The project ResiWater aims to develop tools to prepare water utilities for crisis management and enhance their resilience with regards to three specific case studies: collapse of WDS, water quality deterioration and cascade effects between water, energy and IT infrastructures.

1 Introduction

Water Distribution Systems (WDSs) are critical infrastructures that may fail to distribute drinking water of adequate quantity and quality. Given their distributed topology and interconnectivity with other infrastructure systems, such as power supply and telecommunication, WDSs are exposed to a variety of risks including terrorist attacks, natural hazards and widespread technical failures that may be caused by cascade effects. ResiWater aims to develop tools to prepare water utilities for crisis management and enhance their resilience with regards to three realistic case studies: collapse of WDS, water quality deterioration and cascade effects between water, energy and IT infrastructures. For its realization, four main objectives have been defined:

1.1 Innovative water quality and flow sensors and secure sensor networks

Possible improvements will be studied by the extended usage of low cost flow and water quality sensors. Innovative and more sophisticated sensor systems will be also investigated in terms of their potential to increase the resilience of WDS.

1.2 Enhanced self-learning Monitoring and Event Detection Methods

Enhanced self-learning monitoring and event detection methods, which can be applied to a large number of sensors in the network, will be developed. The module will be able to recognize and adapt to changing operation modes (short-term and long-term) of the WDS.

1.3 Robust hydraulic simulation methods and training simulator

Dealing with extreme situations and their impact on technical infrastructure requires the use of simulation and planning software solutions that are much more robust and reliable than available hydraulic modelling packages. Existing hydraulic simulation models often fail to give realistic solutions and model uncertainty is not considered. Therefore, one main objective of the project is the improvement of existing simulation models that focuses on robust calculation of systems under abnormal, extreme operational conditions.

1.4 Tools for Assessing WDS Vulnerability, Resilience and Robustness and Decision Support for Design

Tools for the assessment of global vulnerability and resilience will be developed. The new developments will be investigated and evaluated by means of real-world use cases. The use cases are structured with respect to (1) partial system collapse, (2) water quality deterioration and (3) cascade effects by manipulation and accidental failures of IT and/or power supply. The specific threats are defined by the partner water utilities *Berliner Wasserbetriebe* (Germany), *EMS* (Strasbourg, France) and *Veolia Eau d'Ile de France* (around Paris, France). Additionally, experiments will be conducted at *TZW* (Dresden, Germany) with test platform facilities and also on the private water network at *CEA/DAM* (Gramat, France). The R&D work is accompanied by socio-economic studies ensuring, amongst others, that the privacy and the freedom of the citizens are not compromised.

In the following, we develop further each of the four work packages that were defined in the project and the relevance for reaching the increased resilience for the project case studies.

2 Water quality sensors and flow measurements

For a better management of networks for the routine status as well as for accidents or CBRN attacks, online information of water quantity and quality of the whole WDS is needed, i.e. a higher number of sensors has to be installed (Aisopou et al., 2012). To overcome the limitation of sensor placement through monetary restrictions low cost products are available. However, the performance of such low cost products for an online and long term running is unknown. In this project, non-specific multi-probe sensors are used together with spectroscopic sensors, biosensors and accurate flow metering systems.

2.1 Spectroscopic sensors

Spectroscopic sensors become more relevant due to their ability to detect a broad range of contaminants (see Table 1). Routine and test equipment is available for UV-VIS¹ absorption and fluorescence, the mid and near infrared including Raman-spectroscopy as well as flow cytometry (Wagner, 2014). NMR² techniques are in designing phase (Maiwald, 2011). These spectrometers are small, robust and produce colossal data sets (in frequency spectrum). However, the assessment and interpretation of this spectrum data is a challenge up to now. With the appropriate interpretation, chemical-structural knowledge can be obtained, see e.g. the detection of single compounds as pesticides and pharmaceuticals as well as algal-like toxins (Weingartner et al., 2010). A decisive higher quality level can be reached by combination of “classical” physicochemical sensors with spectroscopic sensors (Whittle et al., 2013).

¹ Ultraviolet–visible spectroscopy or ultraviolet-visible spectrophotometry (UV-Vis or UV/Vis) refers to absorption spectroscopy or reflectance spectroscopy in the ultraviolet-visible spectral region.

² Nuclear magnetic resonance spectroscopy, most commonly known as NMR spectroscopy, is a research technique that exploits the magnetic properties of certain atomic nuclei. This type of spectroscopy determines the physical and chemical properties of atoms or the molecules in which they are contained.

2.2 Biological Sensors

Biological Sensors (biosensors) use organisms (e.g. bacteria, daphnia) and evaluate characteristic properties of the organisms (e.g. fluorescence or motion pattern). Changes of these properties indicate a change in water quality. The benefit of biosensors is that they detect a broad range of hazardous changes in the water quality in a very short time (some systems within a few minutes). Currently, there are worldwide only a few biological sensors available that are capable to measure a broad spectrum of toxic components in drinking water online (e.g. DaphToxII of bbe moldaenke, MicroTox CTM of ModernWater, iToxControl of microLAN). All these systems have the drawback that the maintenance effort is very high and consequently, the systems are not well suited for an operation in the drinking water network.

The partners Fraunhofer IOSB and IGB have developed a prototype of a biological sensor system (Bernard et al., 2012), see Figure 1, which has the potential for a fully automated system and hence can be installed even directly in the water supply network. The sensitivity of the AquaBioTox for a wide spectrum of substances and concentrations has been proved (Bernard et al., 2011, see also Table 1). During the project, the AquaBioTox prototype shall be fully automated, enabling its installation in the pipe network.

Table 1: Capability of different sensors for the detection of different classes of substances in drinking water

Target of Identification	can be detected by ...	can be detected by ...	can be detected by ...
	Physical/chemical Sensors (pH; turbidity; conductivity; chlorine)	Spectroscopic Sensor configuration (Measurement Principle)	Biosensor AquaBioTox
inorganic components	yes		yes
natural organic matter (NOM-fingerprints)		yes (Fluorescence)	yes
anthropogenic organic matter (single compounds)		yes (IR; Raman)	yes
inorganic/organic matter	yes	yes (UV-VIS)	yes
natural organic/ anthropogenic org. matter (fingerprints)		yes (Fluorescence; IR)	yes
DNP-formation		yes (Fluorescence; Raman)	possible
enhanced characterization of natural organic/ anthropogenic organic matter		yes (Fluorescence /UV-VIS / IR / Raman)	possible
inorganic components / enhanced characterization of natural organic -/ anthropogenic organic matter	yes	yes (Fluorescence /UV-VIS / IR / Raman)	possible
inorganic / enhanced characterization of natural organic/ anthropogenic organic matter / DNP	yes	yes (Fluorescence /UV-VIS / IR / Raman)	possible



Figure 1: Prototype of biosensor AquaBioTox.

2.3 Flow Measurement

The most currently monitoring parameter is the flow rate and several devices and technologies are available and the uncertainties well known (Furuichi, 2013). For economic reasons, mostly simple devices are installed, e.g. electromagnetic insertion flow meters. The accuracy depends on the precise knowledge of the pipe diameter, which is needed for calculation of the volume flow. However, the inner pipe diameter is very often not precisely known. Currently, no method exists to obtain the wet section from the inside of the flow, giving the best way to minimize uncertainties on flow.

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Sensors, sensor data as well as the communication network of WDS have become an increased target from the cyber space in recent years. Thus, the project investigates the impact and the risk of cyber incidences and develops new concepts for security and authentication of sensor networks in water supply.

3 Monitoring and event detection in WDSs

Monitoring of the dynamic state of WDSs is mainly based on sensor data of the hydraulic state (pressure and flow velocity). In contrary, water quality is mainly monitored at the waterworks. This is done by enhanced online sensors (e.g. Fish toximeter, spectroscopic sensors) as well as by a set of physicochemical sensors. Due to the availability of new low cost sensors, actually more and more water quality sensors are installed in WDSs. However, up to now at the water utilities, alarms are generated mostly based on simple threshold algorithms.

Since several years, data-driven approaches are available for the alarm generation based on physicochemical water quality sensors. However, these approaches are focused on the evaluation of sensors at single stations in the WDS: e.g. Murray et al. (2010) proposed the event detection software CANARY. Other academic approaches exist (e.g. Arad et al., 2012, Olikier and Ostfeld, 2012). Still, all proposed approaches have not been widely applied in water distribution networks. This is mainly caused by the fact that the parameterization and launch of these tools is very complex and time consuming. Therefore, within the project SMaRT-Online^{W_{DN}} (Bernard et al., 2013) the partner IOSB has developed a new, easy-to-parameterize event detection module (Kühnert et al., 2014).

Another issue, which is not addressed sufficiently in existing event detection tools (but is addressed in the project), is the adaptation to changing operation modes of WDSs. Both, short-term changes due to operational measures and long-term changes and drifts occur in WDSs. Obviously, for a self-learning approach, it is necessary to cope with these short-term and long-term changes. The paper proposed by Rafika et al. (2016) is a practical methodology designed as a preprocessing step for early warning systems. This approach aims automatically to extract operational profiles revealing distinct states of a hydraulic behavior into a WDN. Experimental results are provided by Veolia Eau d'Ile de France. Alternative machine-learning algorithms are available from academic research to address this issue (e.g. Banko et al., 2011, Vieira and Nehmzow, 2005).

4. Robust hydraulic simulation models and training simulator

Robustness of hydraulic simulation models includes stable convergence of the iterative solution for all kind of loading and operational conditions. Existing software is developed for simulation of "normal" operational conditions resulting in a well-posed system of nonlinear equations. However, failure of one or more important components of the supply system may result in decomposition of the network and ill-posedness of the system of equations leading to non-convergence of the iterative calculation. Examples are reported in literature (e.g. Deuerlein et al., 2012) and can be easily reviewed by using the open source software EPANET. Especially, pressure deficient conditions and the consideration of pumps and control devices such as flow and pressure controlling valves still cause solvers to fail to converge (Braun et al., 2016a). Although there are promising approaches for tackling that problem (Deuerlein et al., 2009; Piller and van Zyl, 2014), when the system differs greatly from the normal operational state, existing software packages are not applicable. In this project, an optimisation framework was developed that enables the fast and robust solving of a range of algorithms for the pressure-driven modelling (PDM) system of equations (see: Elhay et al., 2015). It is being extended for incorporation of control valves.

Network parameters that are used in hydraulic and transport models are often rough estimates because there is a significant uncertainty in nodal demand, leakage, pipe roughness, valve statuses and diameter input parameters. The measurement values (pressure, flow, tank level, concentration, conductivity, etc.) may be used to calibrate the parameters of both the

hydraulic and the transport models, and to estimate the unknown state of the network (Piller et al., 2016). The proper choice of the sensor system must ensure observability of the network but also prevent small errors in measurement resulting in incorrect estimations of the parameters (Piller et al., 1999). There exist methods to calibrate the parameters, but no tool exists that gives as an output the uncertainty of prediction. The model uncertainty issue has been addressed in the project (Braun et al., 2016b; Piller et al., 2016) by use of polynomial chaos and sensitivities.

5 Vulnerability and resilience analysis of WDS

5.1 Vulnerability

Vulnerability analysis permits assessing the criticality of a system to a potential threat. Action can concern prevention (reduction of the probability of occurrence) or the protection (reduction of the seriousness or impact). The definition of hydraulic reliability may be found in Bao and Mays (1990), or early-warning detection vulnerability indexes are given in Ostfeld et al. (2008). New vulnerability indices, which are more robust and allow evaluation of contamination mitigation, have been proposed in SecurEau (2016) and SMaRT-Online^{W_{DN}} (2016), such as the average number of contaminated connections and the contaminated inner surface of pipes following a targeted contamination event set. Partner CEA/DAM is involved in global vulnerability assessment methodologies through various projects (FR ANR DEMOCRITE, EU FP7 CIPRNet and PRECDICT), including the description of network vulnerability depending on the definition of network loss-of-functions and vulnerability of interdependent critical infrastructures. These tools are designed to be used with GIS (Geographic Information System) data, such as population density or network service areas.

External vulnerability on consumers but also on the natural environment and human activities are also taken into account and will be implemented within a cost benefit analysis on resilience scenarios, using accountancy and economic approaches.

5.2 Resilience

Infrastructure Resilience is the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin (Lansley, 2012). Mechanical or pipe failures, power outage, catastrophic natural events are examples of abnormal disturbances of a WDS. In literature, system functionality was mainly addressed in term of hydraulic capability (supplying a given desired flow rate). Water quality resilience still has to be developed. Resilience may also be perceived as a more general concept that includes Robustness, Redundancy, Resourcefulness and Rapidity (the four R's of resilience and multi-hazard engineering, Bruneau et al. 2003). Moreover, this is a multi-disciplinary approach and comprises technical, organizational, social and economic aspects.

In the project and for vulnerability, four components have been defined (*physical, functional, system and external*) and the approach is bottom-up and scenario-focused. Resilience relies on three distinct capacities: *absorptive, adaptive and restorative* as in Francis and Bekera (2013). Sensors, sensor data as well as the communication network of WDS have become an increased target from the cyber space in recent years. Thus, the project investigates the impact and the risk of cyber incidences for security and authentication of sensor networks in water supply.

Conclusion

The project ResiWater will increase the resilience of water infrastructures by means of enhanced sensors and secure sensor networks, self-learning monitoring tools, robust simulation models and training simulator, vulnerability and resilience assessment tools. This includes the interdependencies between energy and communication infrastructure and the WDS. Thus the proposal takes into account:

- ✓ New risks and solutions for increasing the resilience of water supply with a special focus on interoperability of smart networks in Germany and France;
- ✓ Solutions for the protection of water infrastructures, decentralized or remote sites for the production and distribution of water;
- ✓ Concepts and solutions for crisis management, taking into account societal, technical and organisational aspects, including enhanced preparedness and operational procedures, recovery from the outage and resulting cascading effects.

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