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Augmented Resilience of Water Distribution Systems following Severe Abnormal Events

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ABSTRACT

The detection of faults and the capacity to return quickly to a normal state after failures and interruption of services are essential for water utilities. The ResiWater project aims to improve the following three aspects for better network security and enhanced resilience: prevention, surveillance and response of water distribution systems facing the major threats. In this paper, we present the ResiWater project main results after two years. A focus is made on the resilience framework and the development of high-performance sensors for fast detection of water quality deterioration or system breakdown.

Keywords: Secure sensor networks; Robust simulation models; Resilience assessment.

1 BACKGROUND

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. The ResiWater project [1] aims to improve prevention, surveillance and response regarding realistic case studies of collapse of WDS, water quality deterioration and cascade effects between water, energy and IT infrastructures.

The prevention and level of required preparation include the development of new hydraulic analysis software solutions, and of training and resilience strengthening tools. The surveillance includes the continuous recording of the real system state with a network of high-performance sensors for fast

detection of water quality deterioration or system breakdown. To serve in case of connectivity loss, modelling tools should be more robust for solving numerically difficult problems (or poorly conditioned) than those of the normal state. Knowing the degree of uncertainty of the model results, which depends on the level and on the quality of the instrumentation, the modelling error but also the parameter uncertainty, is a strong request for the operator decision-making.

For the realization of the ResiWater project, five main steps were defined: specification of critical case studies, design of integrated and secure sensor networks, development of a self-learning module for abnormal event detection, development of robust hydraulic and water quality simulation tools for modelling of extreme events, and decision support tools for improving resilience of WDSs.

The French-German cooperative research project integrates end users (BWB Berlin in Germany, EMS Strasbourg in France and Veolia Eau d'Ile de France around Paris), technical and socio-economic research institutions (Fraunhofer IOSB, Fraunhofer IGB, TZW, CEA, Irstea, ENGEES) and industrial partners on French and German sides (Veolia Eau d'Ile de France, 3S Consult). Two simulation software tools are extended for crisis management and preparedness: Porteau for Irstea [2] and SIR 3S for 3S Consult [3]. The three water utilities benefit from the outputs, training and decision support tools.

Among the main results that will be presented to the CCWI 2017 conference:

- Three use cases per water utility were chosen: WDS collapse, water quality deterioration and cyber-attack.
- A resilience framework has been fitted to the ResiWater needs with a ranking method devised for each case studies of the three project end users.
- Two spectroscopic sensors (absorption, fluorescence) have been installed at Berliner Wasserbetriebe (BWB) for testing their functionality under practical conditions at water utilities.

Here below are listed additional main results beneficial for the project:

- A database for the detection potential of a variety of substances by fluorescence as well as absorption sensors was developed.
- A multi-step approach is proposed for monitoring water quality into the distribution network. As a first step, a temporal segmentation has been implemented and validated on a real hydraulic sector at Veolia Eau d'Ile de France [4].
- A first software solution was delivered for alarm generation that is based on Dynamic and Incremental Principal Component Analysis [5].
- 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 equation [6].
- The optimisation framework has been extended to afford for pumps and control devices under abnormal operational conditions [7].
- Spectral Propagation of Parameter Uncertainties in Water Distribution Networks is done by chaos polynomial method to infer the model output uncertainty [8].

Other developments are underway, within this project, for instance, cyber security analysis, EU, French and German Law analysis, crisis costs valuation and resilience cost benefit analysis including vulnerability of natural and human environments.

In the following, the resilience framework and the development of sensor network in the project are described.

2 Results

2.1 Vulnerability and Resilience Framework in ResiWater

In the context of the project, vulnerability is composed of the following four items (cf. Figure 1):

- $V_{physical}$ = Physical vulnerability (initial).
- $V_{functional}$ = Functional vulnerability (initial).
- V_{system} = System vulnerability (time-dependent) .
- $V_{external}$ = External vulnerability (time-dependent).

The three first items describe the internal vulnerability of the system. In contrast, the 4th item, external vulnerability, measures the impacts of the system outside its own boundaries on consumers and human activities but also on the natural environment.

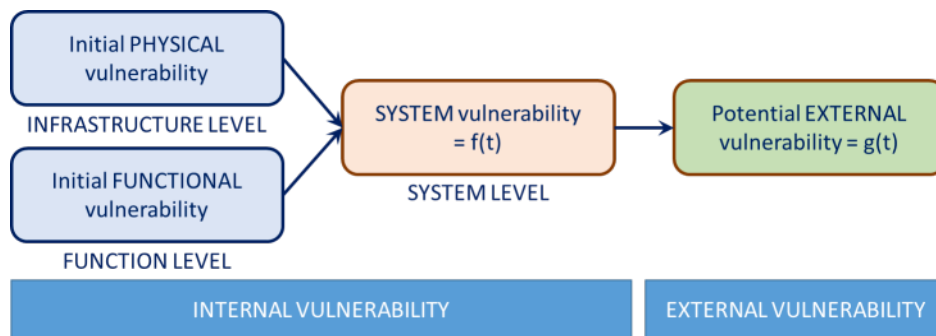


Figure 1. The four vulnerability components in the ResiWater project.

System vulnerability V_{system} describes both the interaction of system functions (for instance the influence of closing a valve on the network topology) and the physical evolution of the system (for instance a sudden pressure drop causing pump cavitation). It is assessed through the loss of performance P (see Fig. 2) of the WDS during the passive phase (before any reaction). V_{system} is defined as the difference of system performance (in case of performance loss) between the pristine system and the residual system measured at a characteristic time. The residual performance (Figure 2) at time t is thus given by $(P_{initial} - V_{system}(t))$, where $P_{initial}$ denotes the initial performance. The performance evolution is computed by the hydraulic and transport models, considering the initial physical and functional vulnerability.

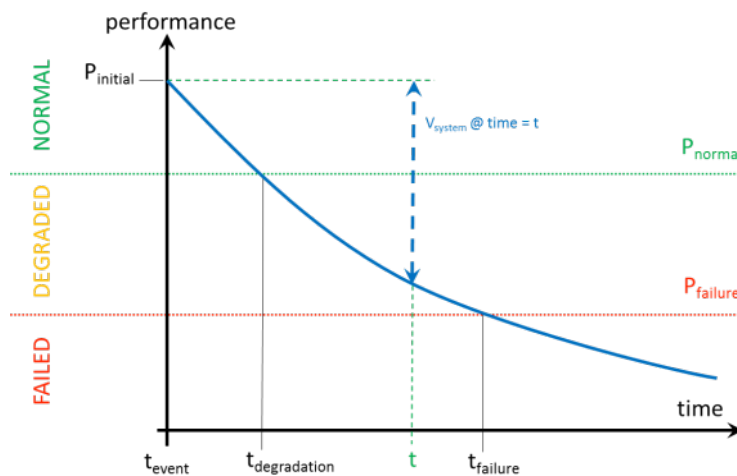


Figure 2. Residual performance at time t .

From the other side, resilience is composed of three capacities: *Absorptive* (linked to vulnerability), *adaptive* and *restorative capacity* (see Fig. 3). It is adapted from [9].

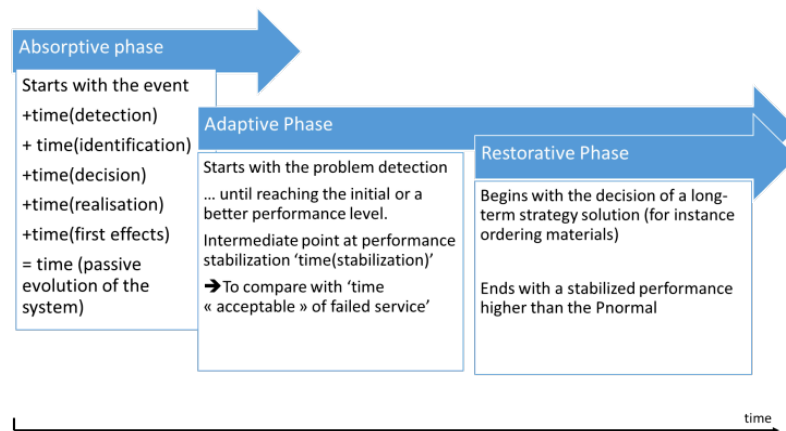


Figure 3. Timeline for the three resilience phases in the ResiWater project.

The *absorptive capacity* is defined as “the degree to which a system can absorb the impacts of system perturbations and minimize consequences with little effort”. It is merely the passive evolution of the system facing a performance loss, whereas adaptive and restorative capacities both involve system reactions. The absorptive capacity includes the robustness and redundancy (both physical and functional) aspects of the Bruneau 4Rs [10].

The *adaptive capacity* is defined as “ability of a system to adjust to undesirable situations by undergoing some changes [...] if absorptive capacity has been exceeded” [9]. It focuses on the emergency responses from the preparedness level up to the implementation of temporary solutions, considering the ability of detection and of decision making by the operator. The adaptive capacity includes preparedness (not explicitly mentioned in the 4Rs approach), resourcefulness (internal resources) and part of rapidity (to overcome the disruption and tend to a stable state).

Finally, the *restorative capacity* focuses on long-term solutions. It is “characterized by rapidity of return on normal or improved operations and system reliability. This capacity should be assessed against a defined set of requirements derived from a desirable level of service or control” [9]. The duration of the restorative phase is usually much larger than the delay to implement emergency solutions. The restorative capacity also includes from the 4Rs resourcefulness (external resources) and part of rapidity (restoring service).

Vulnerability and resilience signatures are also assessed on a simple three-level scale (see Figure 4). Defining the end of the passive evolution of the system ($t_{\text{palliative}}$ value) requires estimating the average time of detection, the delay of decision making and the estimated time for implementing the “emergency” reactions in such cases. Ideally, the operators should react before t_{failure} , which corresponds to the delay before a failure if the system evolves without reaction at all (Figure 4). The internal system vulnerability ranking is a mirror of the absorptive capacity ranking ($R_{\text{absorptive}}$): $V_{\text{system}}(t_{\text{palliative}}) = 4 - R_{\text{absorptive}}$. The vulnerability ranking helps to detail the steps for modelling the passive evolution of the system. Vulnerability assessment at system level requires a hydraulic and transport model (Porteau, SIR 3S), given an initial state of perturbed infrastructures and functions. Resilience can be assessed by using characteristic times and residual levels of performance (analysis of past events), or using simple survey, when no past event is available.

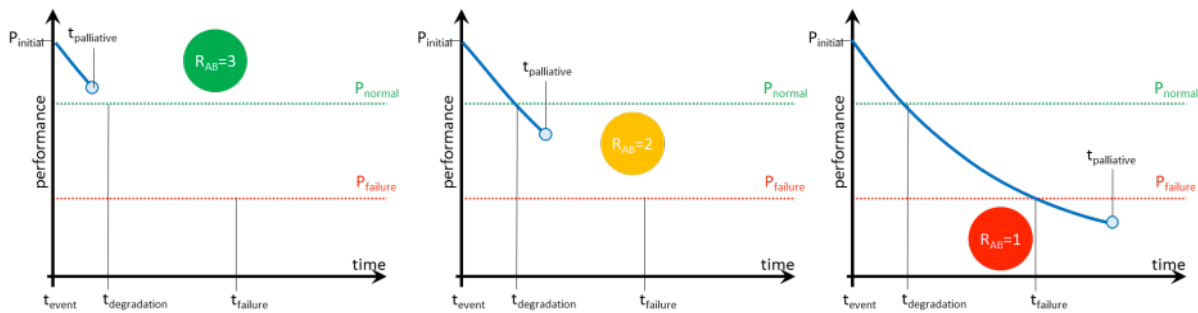


Figure 4. Ranking of the absorptive resilience from green (low system vulnerability) to the worst red case (critical system vulnerability).

For BWB (Berlin) three case studies are defined:

1. Two waterworks are cutting off by a regional power cut;
2. Contamination (by a non-pathogen bacteria) in south east of Berlin;
3. Cyber-attack at control systems (stuxnet).

For EMS (Strasbourg) also three case studies are investigated:

1. Main production unit stopped by major flood event;
2. Water quality degradation by intentional network contamination;
3. IT attack stopped Oberhausbergen power, event masked by false data (replicated data set).

And for Veolia Eau d'Ile de France, four case studies are defined:

1. Fire Hydrants operation in "Street Pooling" situation;
2. Terrorist attack on network in the situation of a major International Event (COP 21);
3. Centennial Flood;
4. Above Centennial Flood – Establishment of the major crisis emergency plan.

The vulnerability and the resilience was assessed for the nine case studies at the beginning of the project. They will be assessed again at the end to evaluate the solutions proposed by the project.

2.2 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 water network is needed, i.e. a higher number of sensors should be installed [11]. 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.

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

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.

[12]. NMR² techniques are in designing phase [13] 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. A decisive higher quality level can be reached by combination of “classical” physicochemical sensors with spectroscopic sensors.

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 5: Prototype of biosensor AquaBioTox.

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 see Figure 5 which has the potential for a fully automated system and hence can be installed even

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.

directly in the water supply network. The sensitivity of the AquaBioTox for a wide spectrum of substances and concentrations has been proved (see also Table 1). During the project, the AquaBioTox prototype shall be fully automated, enabling its installation in the pipe network.

Low-Cost flow rate measurement system.

The most currently monitoring parameter is the flow rate and several devices and technologies are available and the uncertainties well known. 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 pipe, giving the best way to minimize uncertainties on flow.

Sensors, sensor data as well as the communication network of water distribution systems 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 CONCLUSIONS

The project ResiWater aims to 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.

A new vulnerability resilience framework is proposed for ranking the crisis case studies defined by the project end users. A simple three-level scale was chosen and is illustrated in the paper.

New spectroscopic, biological sensors and a low-cost flow rate measurement system are under investigation in the project. They will be part of a broad and secure sensor network for monitoring the systems.

Other solutions were also studied in the project for the prevention and response of critical events. Among the main results, we may put forward the robust modelling for training in presence of large disconnected network parts, the enhanced event detection by PCA and Gaussian mixture model (oscillating data and drifting sensor data) and the economic evaluation by cost benefit analysis.

Once the robust simulation software solutions for severe abnormal situations and the uncertainty quantification tool will be released in the project, they will be used for assessing the resilience of WDN by simulating the scenarios.

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