Supplementary Material: Smart Water Networks as Cyber-Physical-Socio-Environmental Systems

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Case Study: Pathogen Contamination Emergency Response

To demonstrate how the CPSES modelling framework can be applied in real-world scenarios, we present a case study from a full-scale emergency response exercise, conducted as part of the EU-funded Horizon 2020 project entitled “Pathogen Contamination Emergency Response Technologies” (PathoCERT).

The exercise was organized in Limassol, Cyprus, on September 21, 2023, by the Cyprus Civil Defense in collaboration with the University of Cyprus and the Limassol Water Board, to assess smart technologies for responding to a water contamination emergency caused by a simulated high-intensity earthquake in Yermasogia, Limassol. The exercise involved first responders, water/wastewater authorities, regional government, volunteers, and other experts.[1]

Below, we provide more insights on how the case study aligns with the CPSES framework.

A. Application of the CPSES Framework on PathoCERT

In accordance with the proposed framework, different aspects of the CPSES constituents were investigated, as well as their interdependencies. The first step involved mapping the societal stakeholders through a series of Communities of Practice [1]. This included water operators and managers, policy officers, citizens, first responders, local authorities, and other external stakeholders.

This work was co-funded by the European Research Council (ERC) under the ERC Synergy grant agreement No. 951424 (Water Futures), the European Union’s Horizon 2020 Research and Innovation programme under grant agreement No. 883484 (PathoCERT), and supported by the European Union’s Horizon 2020 Teaming programme under grant agreement No. 739551 (KIOS CoE), and the Government of the Republic of Cyprus through the Deputy Ministry of Research, Innovation, and Digital Policy.

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[1]A video summarizing the case study results is available at: https://www.youtube.com/watch?v=fk_Z-uUdxgU

The stakeholder engagement activities were critical in identifying and mapping the interdependencies between the different stakeholders, as well as their needs concerning data and information, which are essential for their decision-making.

A mapping of the CPSES framework is provided in Fig. 1. The initial event is triggered by an earthquake. This event activates the response of the first responders, who in turn activate the water operators by establishing a joint coordination center. Due to the earthquake, some ICT infrastructure is destroyed, and the first responders, in collaboration with the water operators, establish a temporary ICT infrastructure (based on LoRaWAN) to regain the collection of existing and new sensor measurements from the field.

The simulated earthquake scenario, causes a break in a sewage pipe, which subsequently leads to an overflow into a nearby river. The river feeds an aquifer that supplies a local water utility. Due to the sewage infiltration, pathogens contaminate the water supply, affecting water quality and posing health risks to consumers. Some consumers make complaints, triggering an alert in the early warning system. This is confirmed by sensors in the water supply that measure water quality parameters, which are communicated and processed via the ICT infrastructure.

The water operators initiate an investigation at the pumping station in the aquifer and the water supply. Based on their findings, they use the Pathogen Contamination Investigation (PathoINVEST) Digital Twin, which is linked with the ICT and early warning system, to identify optimal sensor placement locations, determine where to take samples to isolate the contamination source, estimate future risk, and evaluate different mitigation actions.

Based on this analysis, and in coordination with the first responders, the water operators use the SCADA system to control specific actuators, such as valves, to isolate the contaminated area and flush the contaminated water from the system. Meanwhile, the first responders provide relief to affected consumers and give recommendations on water usage, suggesting reduced consumption.

B. Constituent Details

In the following subsections, we provide more insight regarding the different CPSES constituents.

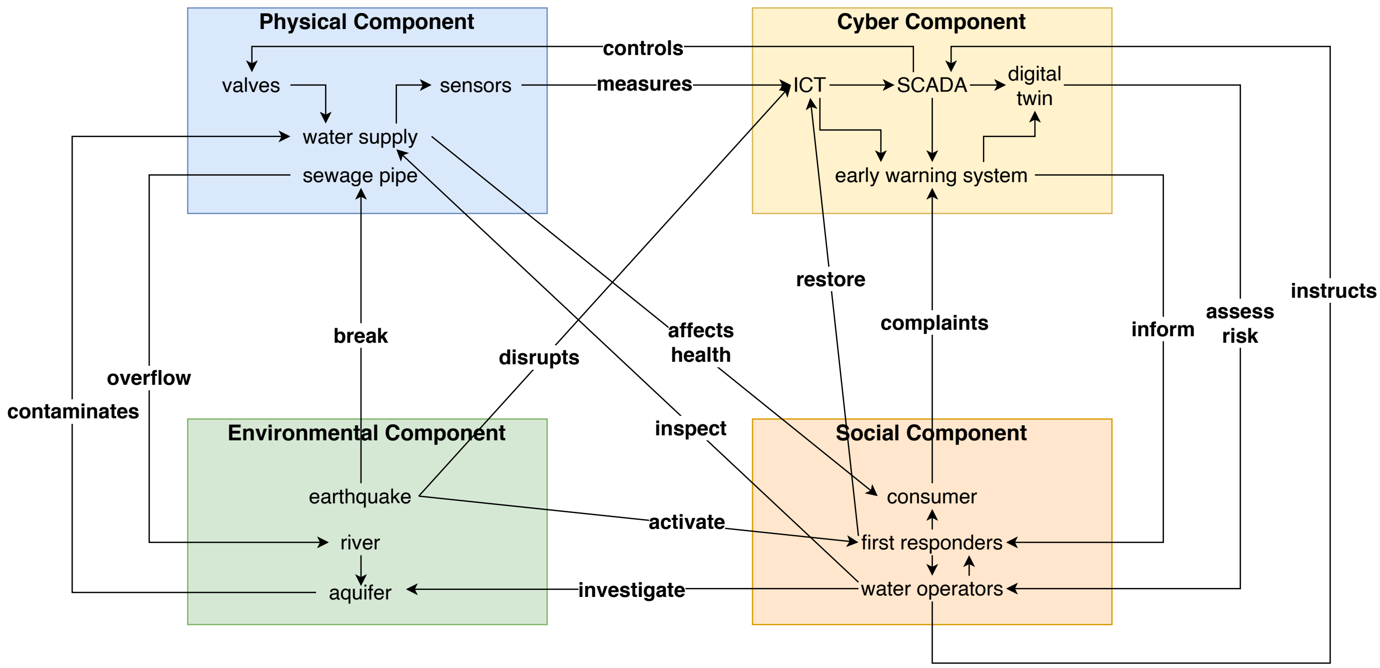

Fig. 1. Overview of the CPSES Framework in PathoCERT.

1) Physical Constituent: The physical location has a separate water collection and storage system, pumping water from the aquifer. The system is equipped with pumps and various sensors for monitoring flows, pressures, and water tank levels, all connected to a central SCADA system. New smart water quality sensors were also installed, along with mobile-based rapid pathogen testing sensors [2].

2) Environmental Constituent: The simulation scenario involved the *contamination* of the Yermasogia reservoir and the Amathos River with wastewater, and subsequently the aquifer, after various cascading *failures* due to the earthquake. According to the scenario, the failure in the physical infrastructure of the sewage system caused an overflow into the river. Dangerous pathogens from the pollution exposed first responders, volunteers, and utility staff working in the field to potential *health* and *safety* risks. Moreover, cross-contamination of the wastewater with the drinking water system elevated the risk of exposing citizens to contaminated water, creating *security* concerns. Finally, cascading failures disrupted the telecommunication service, impacting the Cyber Constituent, which required the activation of alternative *Low-Power Wide Area Networks* (LP-WAN) based on LoRaWAN.

3) Social Constituent: Citizens reported observable events, such as sewage overflow and pollution of the Amathos River, through social media. Other volunteers and professionals communicated via a mobile app to exchange information and create maps highlighting hazards, such as areas where contamination had spread. Additionally, citizens received instructions from authorities to limit their water usage.

Operators analyzed the information from the sensors and mobile apps, and using software tools (Digital Twins) and models, gave instructions to personnel to modify the physical infrastructure topology by closing valves and analyzing water samples with portable sensors. Furthermore, operators issued instructions for citizens to avoid using water.

Managers of different agencies coordinated efforts based on shared information to minimize risk. For decision-making, the managers relied on Cyber tools such as monitoring systems and digital twins, which estimated the impact of events, forecasted their evolution, and suggested mitigation actions.

Policy officers, representing higher levels of government (local administration and ministries), also received critical information and guided the crisis management process in accordance with national crisis protocols.

4) Cyber Constituent: In practice, the CPSES framework is enabled by various software tools and components. This includes a real-time sensor data processing and gateway module, modules for processing social media, satellite, and camera images, a data space for integrating and managing different data sources, a real-time alerting and risk alerting module, a GIS visualization tool for providing situational awareness to Managers and Operators, as well as an Incident Management System for first responders.

C. The Pathogen Contamination Investigation Digital Twin

The *Pathogen Contamination Investigation (PathoINVEST) Digital Twin*, developed in PathoCERT, is aligned with the CPSES framework [3], [4]. The tool is designed to enhance the response capabilities of water utilities during pathogen contamination events in drinking water networks. It offers real-time pathogen contamination modeling, which is crucial for effective emergency response and decision-making during contamination crises.

PathoINVEST integrates advanced computational modeling to forecast the evolution of pathogen contamination, assess

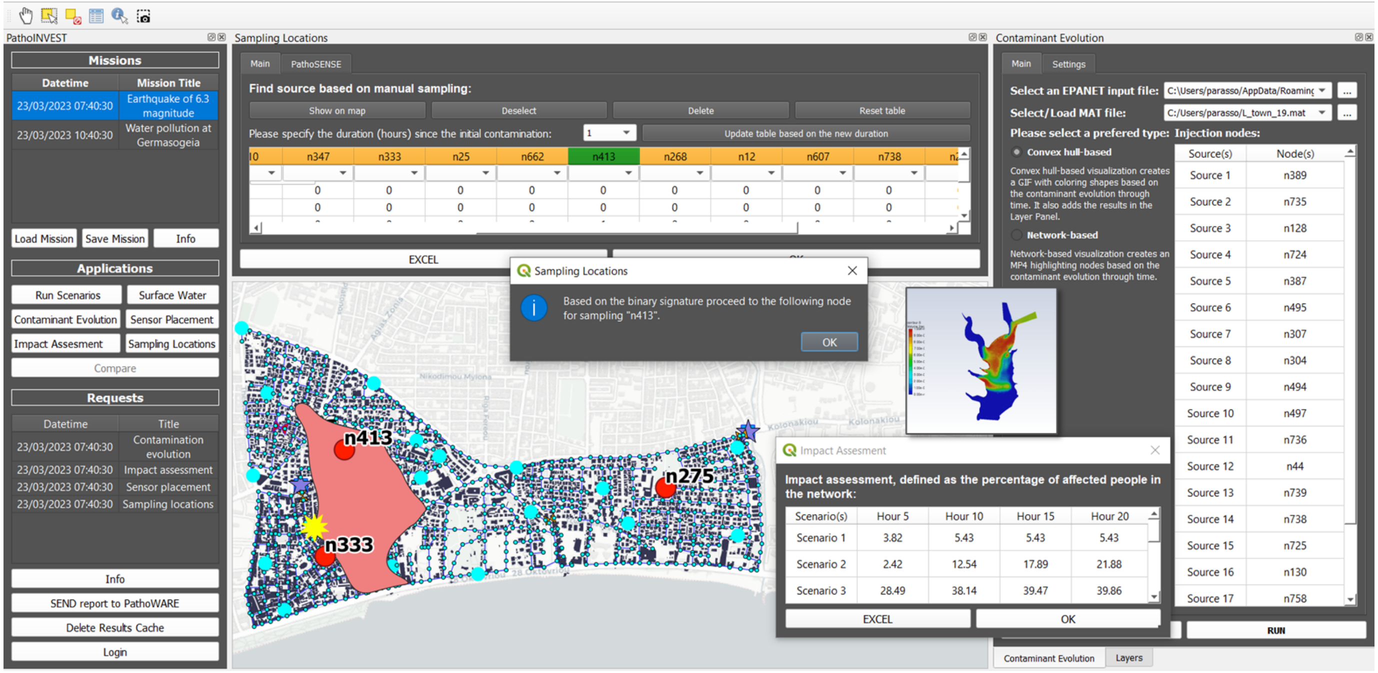

Fig. 2. The graphical interface of PathoINVEST showcases some of its capabilities: contamination evolution within the environment and the physical network, societal impact assessment, and source isolation.

health risks using Quantitative Microbial Risk Assessment, and identify potential sources of contamination through strategic manual sampling. Moreover, it provides actionable mitigation strategies, such as valve manipulation, booster disinfection, and system flushing, to effectively mitigate health risks. It also assists in the optimal placement of water quality sensors within the network.

PathoINVEST can help answer questions that relate to different CPSES constituents, such as:

- How will contamination at a certain location spread in the network? [Environmental, Physical]
- How many people will be affected and possibly infected during the next few hours? [Physical, Social]
- Where should sensors be placed to reduce social risk? [Physical, Social]
- What is the optimal response to minimize contamination spread? [Cyber, Physical]
- How does contamination influence water quality in connected water bodies? [Environmental, Cyber]
- Where is a suitable location to establish a First Aid Station and provide access to safe drinking water? [Environmental, Social]
- What are the possible cascading threats due to the earthquake? [Environmental, Physical, Cyber, Social]
- How will water supply and hydraulics change if water demands are affected? [Physical, Social]

Through the PathoINVEST case study, we demonstrate and emphasize the necessity of leveraging the CPSES constituents to address complex challenges such as contamination risks and public health safety.

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