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Water Distribution Network performance and device placement location schemes assessment under multiple hydraulic transient generative scenarios

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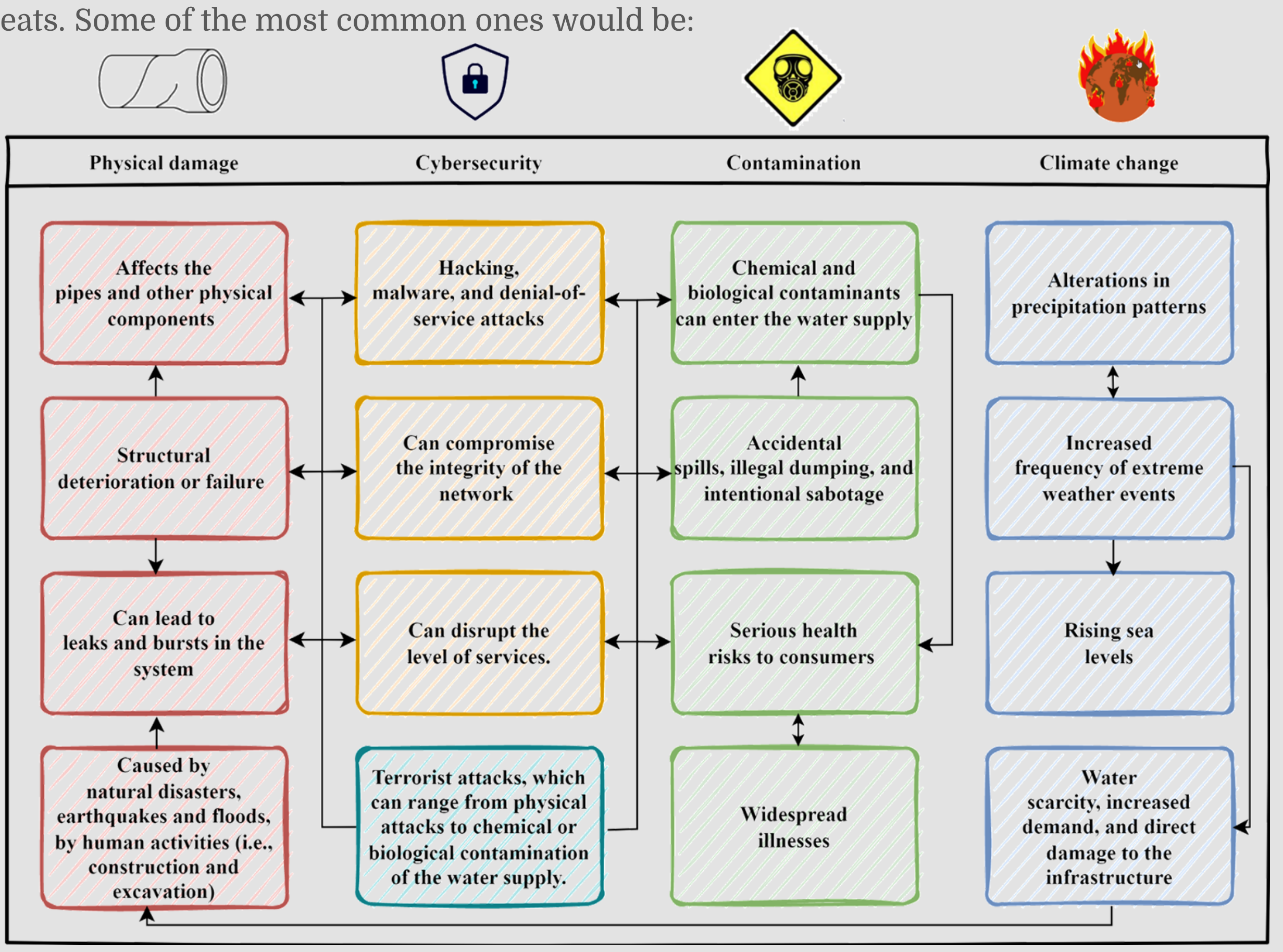
Abstract

- Water Distribution Networks (WDNs) have been thoroughly investigated in terms of uncertainty in the demand at the household level. Meanwhile, novel frameworks exploring the **resilience** of such systems **under contemporary threats (such as cyber-physical attacks)** have also significantly contributed to the enhanced security, reliability, and efficiency in the process of their design and operation. On the contrary, other network effects such as **hydraulic transients -also known as pressure surges or water hammers-** are often overlooked, despite the significant disturbance they could induce to the steady-state flow conditions of the WDN due to the added pressure variability and the heavily increased internal pressure forces exerted on pipelines. Pressure forces and pressure variability are dependent on highly variable phenomena, such as pipe failures and/or operational decisions (i.e., valve closing schedules, pump operations).
- Evidently, predicting the behavior of transients under an ensemble of scenarios is not limited only to **the network design and operational scopes**, but extends to applications such as **optimal sensor and protection device placement**, dimensioning or placement of pressure neutralizers (e.g., surge tanks/chambers), establishment of appropriate pump shutdown schedules. Avowedly, commercial software for transient simulation in WDNs is available, yet open-source packages suitable for research applications, such as TSNet, have only recently become publicly available and, hence, provide a flexible framework for coupling with other applications.
- In this work, the python **packages WNTR** and **TSNet** are integrated to present a framework for evaluating hydraulic transient conditions via EPANET simulation of multiple scenarios of pipe bursts and valve closures according to control schemes. The results can be utilized to assess the WDN's performance and monitoring **sensors placement location schemes** in the light of protection under transient flow occurrence.

Introduction

Water Distribution Networks (WDNs) are critical infrastructure characterized of high complexity and embodying a wide plethora of interconnected assets (i.e., pipes, reservoirs. Pumps, valves, flowmeters) and technologies (PRVs, SCADA units, sensors) (Nikolopoulos & Makropoulos, 2023). Potential disruption makes them vulnerable to a wide spectrum of threats. Some of the most common ones would be:



Physical damage	Cybersecurity	Contamination	Climate change
Affects the pipes and other physical components	Hacking, malware, and denial-of-service attacks	Chemical and biological contaminants can enter the water supply	Alterations in precipitation patterns
Structural deterioration or failure	Can compromise the integrity of the network	Accidental spills, illegal dumping, and intentional sabotage	Increased frequency of extreme weather events
Can lead to leaks and bursts in the system	Can disrupt the level of services.	Serious health risks to consumers	Rising sea levels
Caused by natural disasters, earthquakes and floods, by human activities (i.e., construction and excavation)	Terrorist attacks, which can range from physical attacks to chemical or biological contamination of the water supply.	Widespread illnesses	Water scarcity, increased demand, and direct damage to the infrastructure

On top of the latter, **transient phenomena (water hammers)** are adding to the vulnerability of the overall system, while they are simultaneously demanding in terms of understanding the fundamental equations and performing numerical simulations. By modeling different generative scenarios through the utilization of TSNet (Xing & Sela, 2020), we assess different quality sensor placement location schemes under the prism of being compatible for installing a pressure surge protection structure (i.e., surge tank or air chamber).

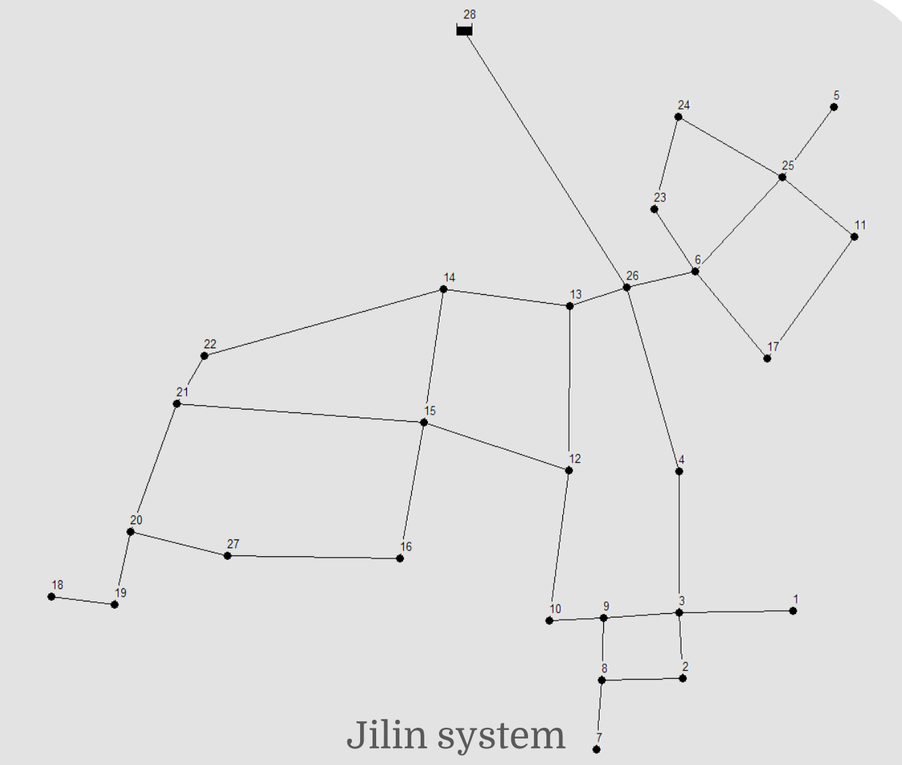
Materials

The proposed framework is tested in two case studies:

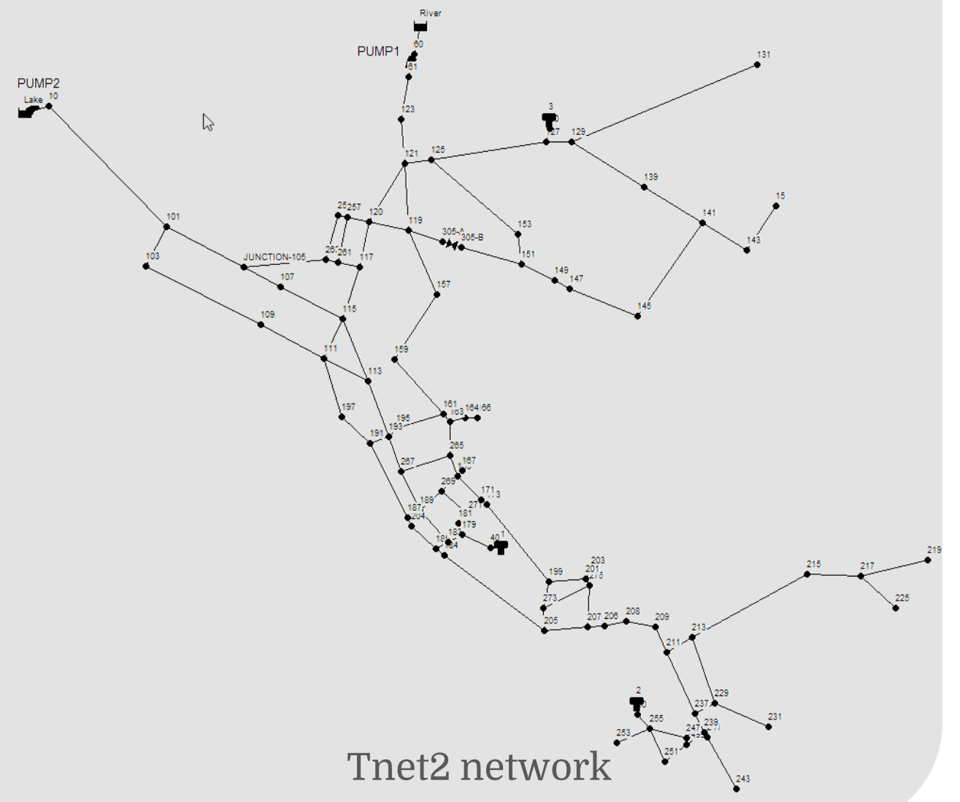
- **The Jilin system:** a synthetic system originally developed by Bi & Dandy in 2014 as part of a study on online retrained metamodels. The system has a total demand of 112,000 CMD, one reservoir, and 29 km of pipe. It is classified as distribution dense-grid by Hwang & Lansey (2017) and gridded by Hoagland et al. (2015).
- **Tnet2:** comprises 113 pipes, 91 junctions, 2 pumps, 2 reservoir, 3 tanks, and one valve located in the middle of the network (Xing & Sela, 2020).

The tools used in the present study are the following:

- The package used to **simulate the water hammer phenomena** is TSNet, a Python package designed to perform transient simulation in water distribution network using Method of Characteristics (MOC) (Xing & Sela, 2020).
- The **quality sensor placement strategy framework** applied is the one proposed in the work of Nikolopoulos & Makropoulos (2023). They suggest a methodology that maximizes the resilience of a given water quality sensor layout in WDNs against failures, and specifically in the case of cyber-physical attacks.



Jilin system

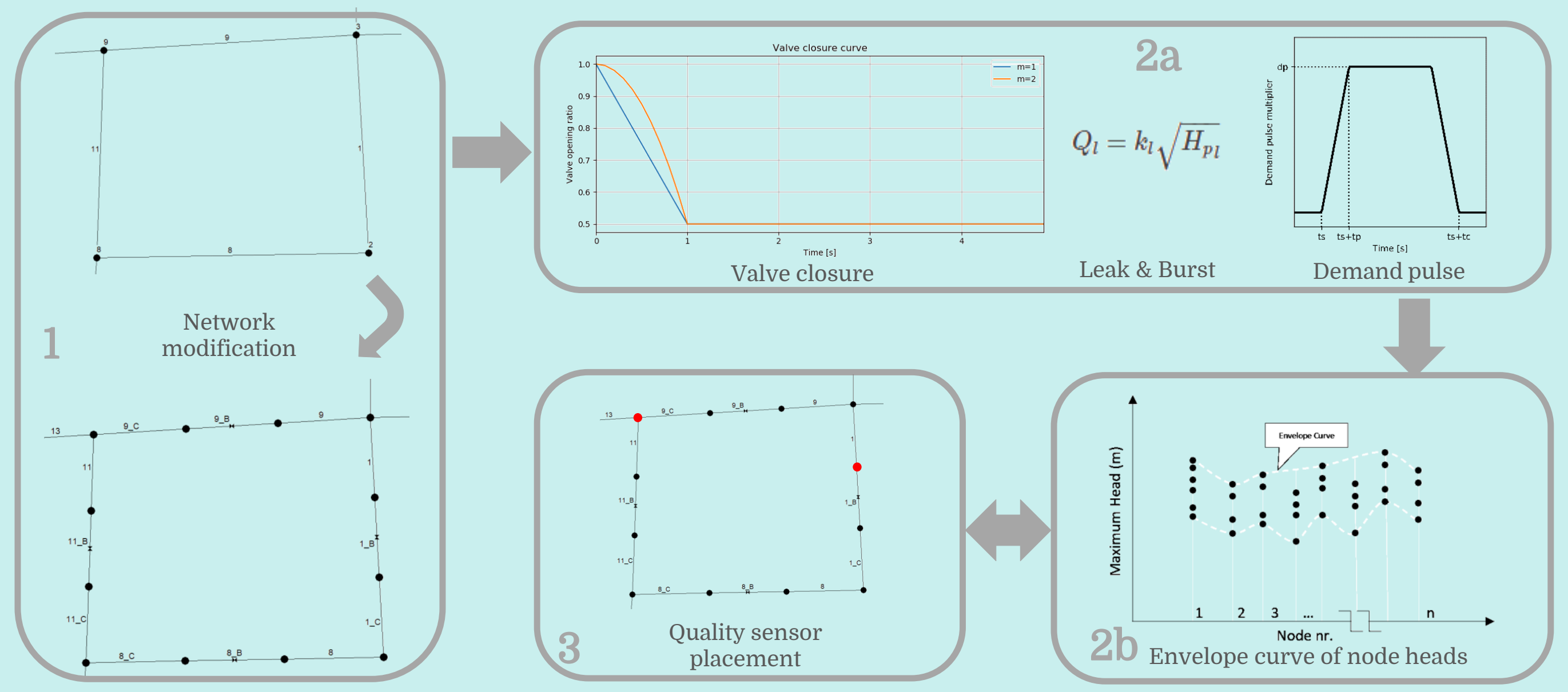


Tnet2 network

Methodology

The overall methodology comprises of three parts:

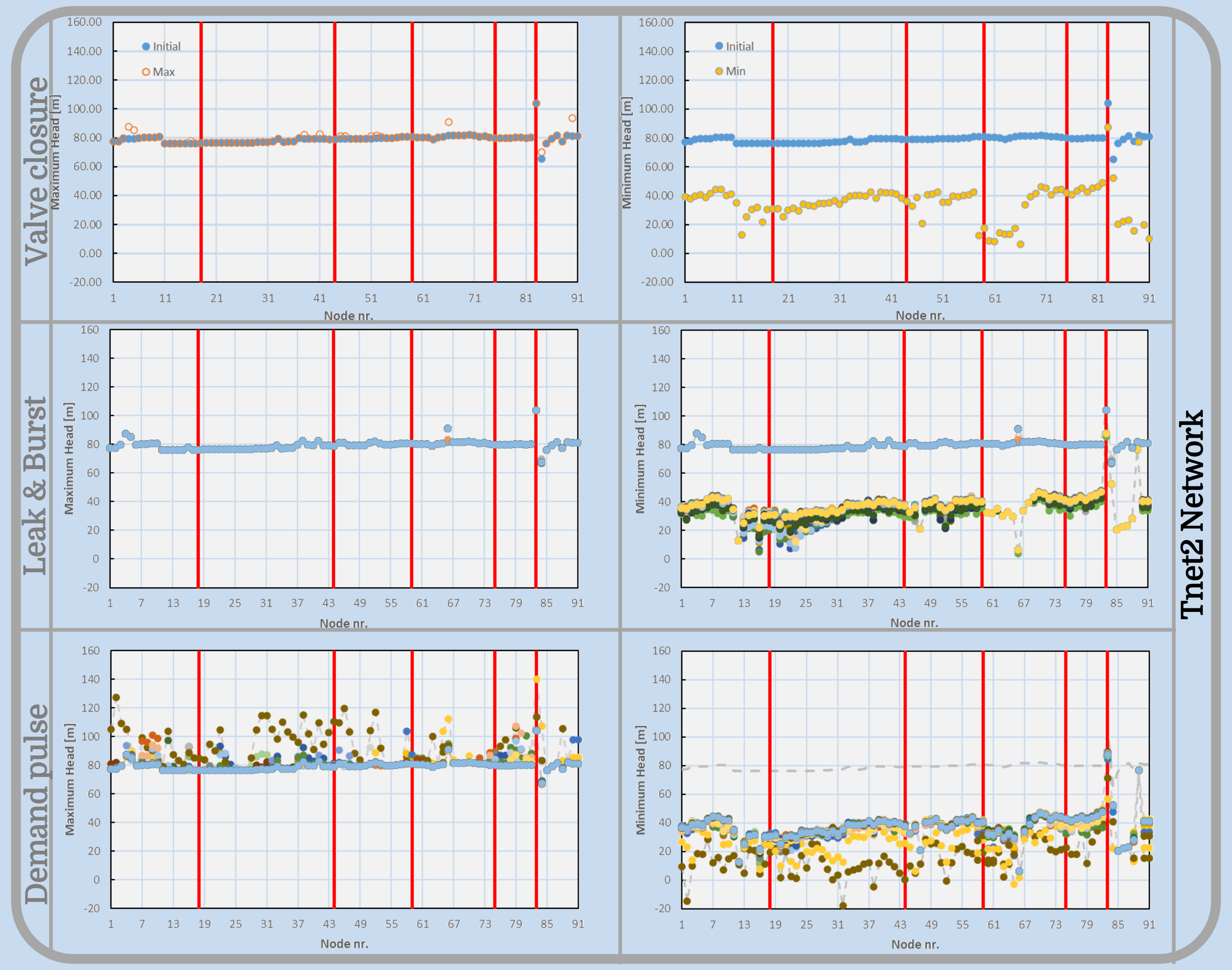
1. **Employing WNTR package** in Python (Klise et al., 2017), each pipe of the network is divided in three pipes of equal length. The leftmost and the rightmost ones are having the same diameter and the half length of their parent pipe, while the middle one is replaced by an open PRV.
2. **Using TSNnet package** three families of scenarios are simulated: (i) valve closure in 0.5 seconds for each valve of the system, (ii) burst and leak by introducing an emitter (a device that simulates flow that discharges to the atmosphere) the flowrate of which depends on the pipe cross sectional area, and (iii) a demand pulse transient generated by allowing the demand coefficient to change with time (following a symmetrical trapezoidal time-domain function).
3. **Applying the quality sensor placement strategy framework** using the mean population affected from all cyber-physical attack scenarios as the objective function, as explained in the publication of Nikolopoulos & Makropoulos (2023).



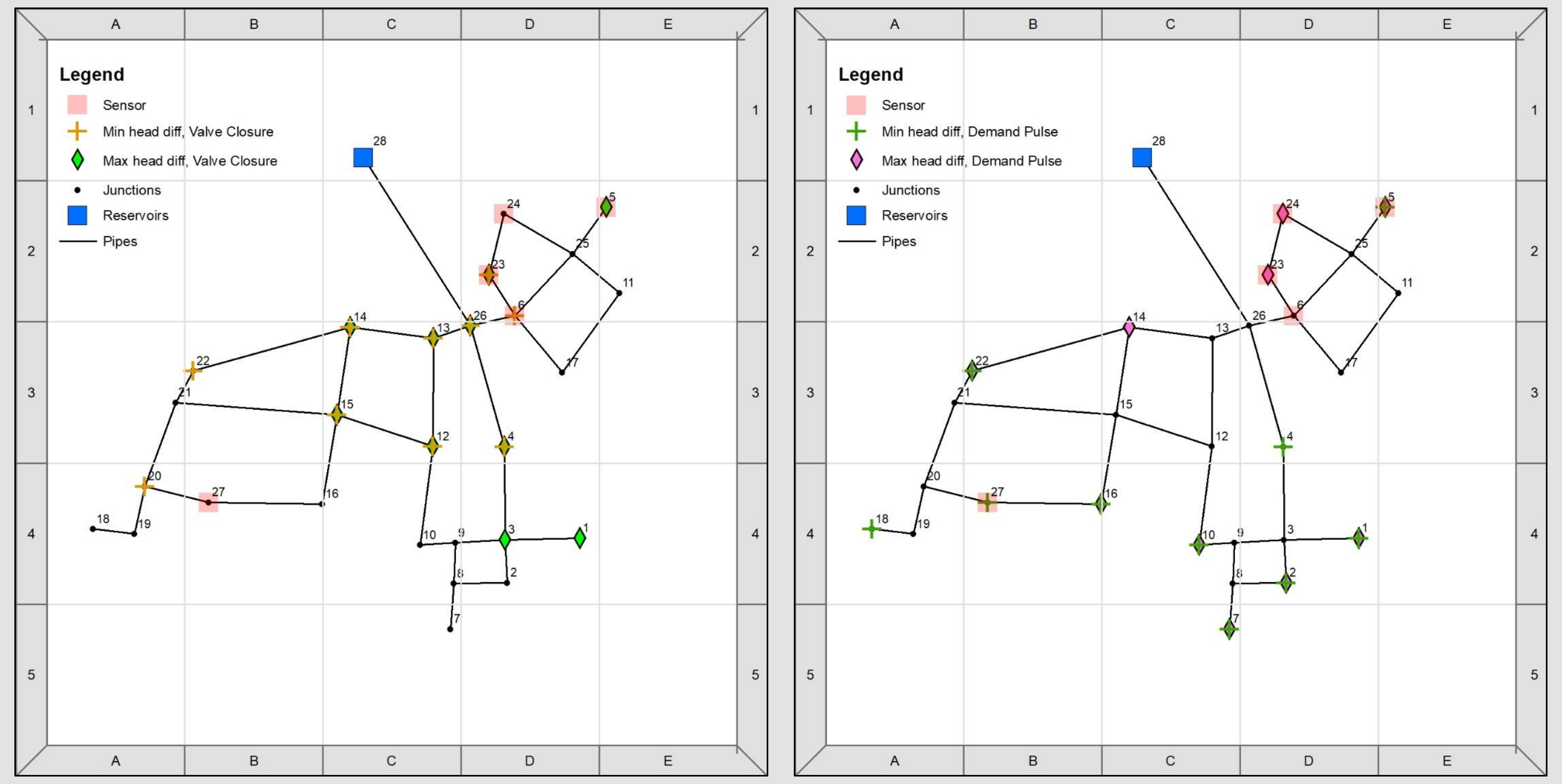
$$Q_l = k_l\sqrt{H_{pl}}$$

Results

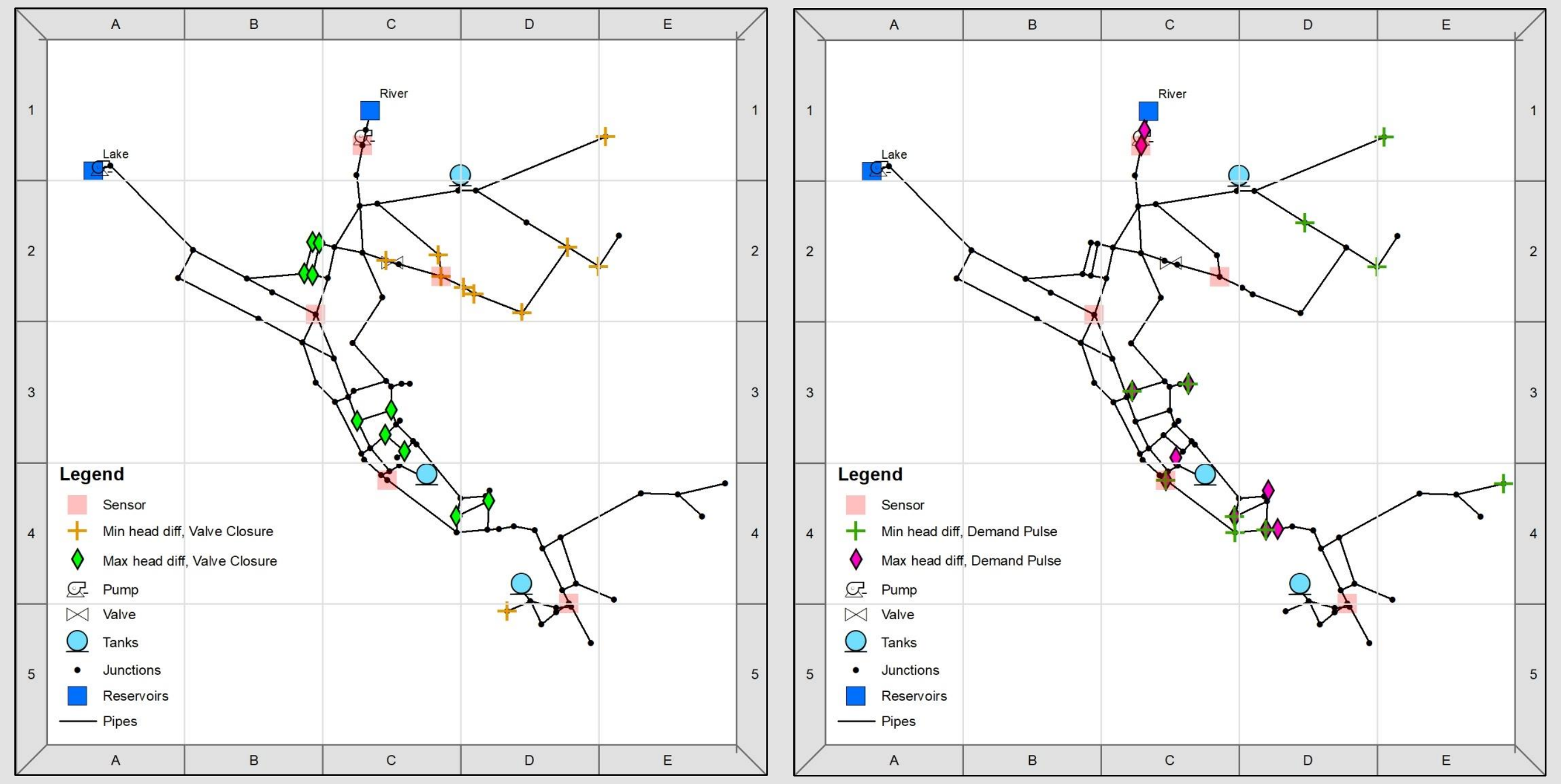
- Envelope curves of node heads for different hydraulic transient generative scenarios.
- The red lines indicate the optimal nodes identified by the quality sensor placement framework.



Interpretation of Results



Jilin System



Tnet2 Network

Conclusions

- The proposed framework offers **a consistent and intuitive methodology** of identifying specific nodes of the system that are suitable for installing both a water quality sensor and a hydraulic transient protection device.
- The model performs satisfactorily in the two case studies. In the case of **Jilin all 5 sensor positions** are also critical in terms of transient phenomena. In **Tnet2, 3 out of the 5 sensors** overlap with nodes where maximum (pressure surges) and minimum (drops) head differences appear.

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