Smart Water Systems: Monitoring, Control and Resilience

Marios Polycarpou

KIOS Research and Innovation Centre of Excellence

Professor, Electrical and Computer Engineering, University of Cyprus

Visiting Professor, Imperial College London

Member, Cyprus Academy of Sciences, Letters and Arts

IEEE CSS TC on Smart Cities Tutorial
Rio De Janeiro, Brazil, 12 December 2025

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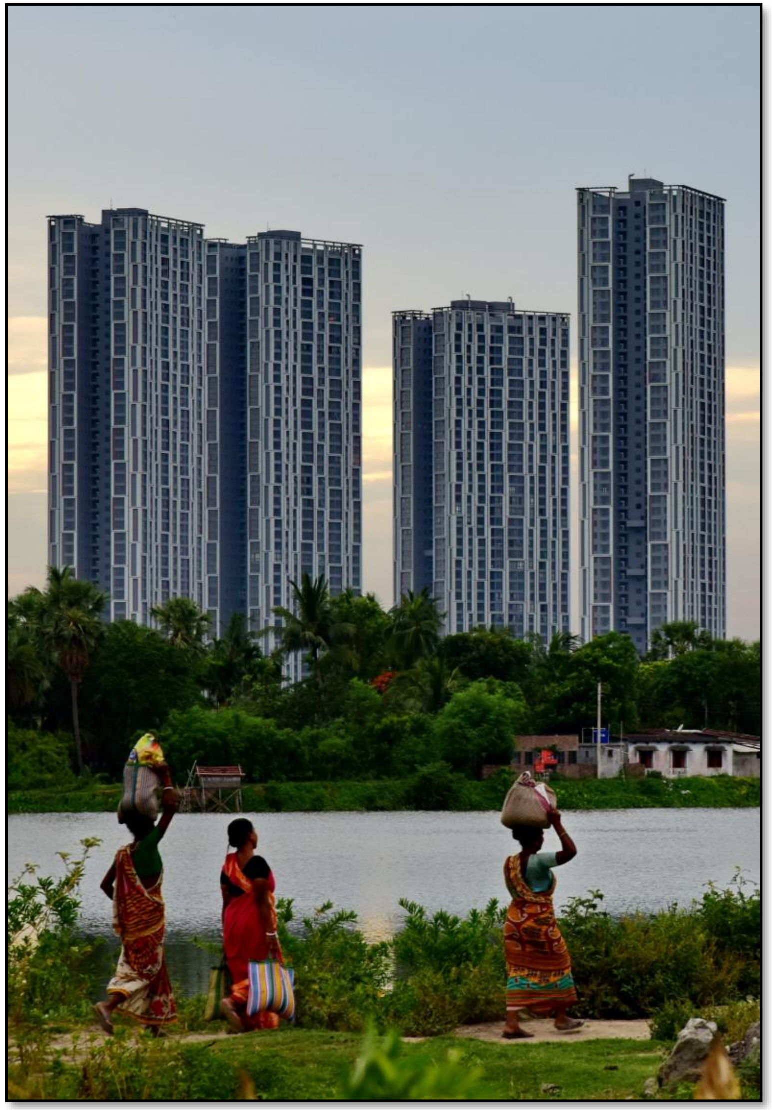
European Research Council
Established by the European Commission

Challenges to our water future

- 80% of the world's population is exposed to high levels of threat to water security due to anthropogenic climate change
- 70% of the world's population is expected to live in urban areas by 2050
- Urbanization and climate change will cause increased water demand
- Urban water distribution systems are complex, large-scale, time-varying, long-lasting networks

→ **Role of systems and control?**



Already limited water resources will become even more precious in the future

Italy's River Po drought: Rome declares a state of emergency in five northern regions COMMENTS

By Euronews • Updated: 05/07/2022 - 18:39

Dry cracked land is visible under a bridge in Boretto on the bed of the Po river, 15 June 2022 - Copyright AP Photo

Italy has declared a state of emergency in five northern regions amid the worst drought in 70 years.

Bolivia: Lake Poopó was once the country's second-largest lake. Excessive use for irrigation and a warming climate undermine its recovery.

Lake Poopó Image: World Economic Forum

Water Distribution Challenges and Risks

Revenue & Water Losses → Water Quality → Energy Consumption → Safety & Security


Water loss: seven things you need to know about an invisible global problem

A staggering 46bn litres of drinking water are lost globally every day. What can consumers, business and governments do?

▲ Iraqis fill drinking water and wash clothes at a broken water pipeline in a Shia district of Sadr City, Baghdad. Photograph: Karim Kadim/AP


China water contamination affects 2.4m after oil leak

12 April 2014

Share

AP

Queuing up to buy bottled water on Friday - shops are now reported to have sold out


Guardian sustainable business

Solutions to the water energy nexus remain elusive

Volkswagen and Coca-Cola among businesses acting on interconnected issues of water and energy, but the voice of power companies and energy producers is largely absent

Giulio Boccaletti

Wed 10 Sep 2014 13.09 BST

49 3

▲ A section of Lake Oroville, California. The drought-stricken state uses around a fifth of its electricity for water-related purposes. Photograph: Justin Sullivan/Getty Images


The New York Times

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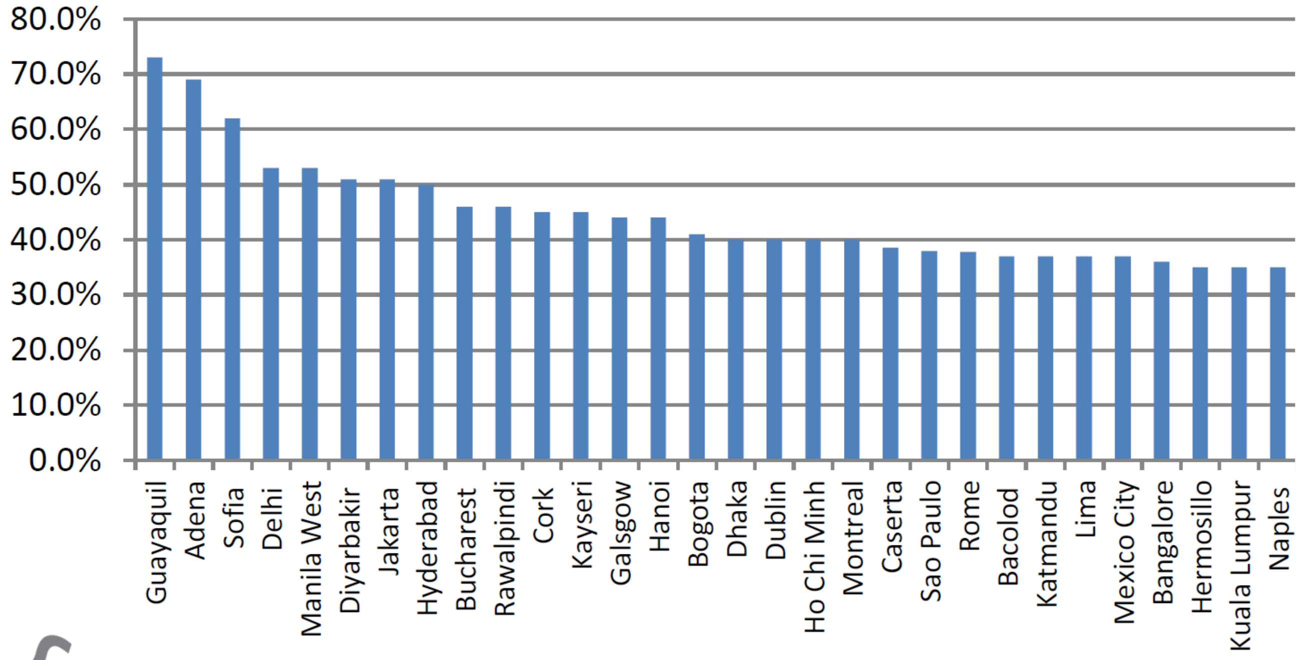
'Dangerous Stuff': Hackers Tried to Poison Water Supply of Florida Town

For years, cybersecurity experts have warned of attacks on small municipal systems. In Oldsmar, Fla., the levels of lye were changed and could have sickened residents.

Give this article

Revenue & Water Losses

% of Non-Revenue Water



Main causes of revenue & water loss:

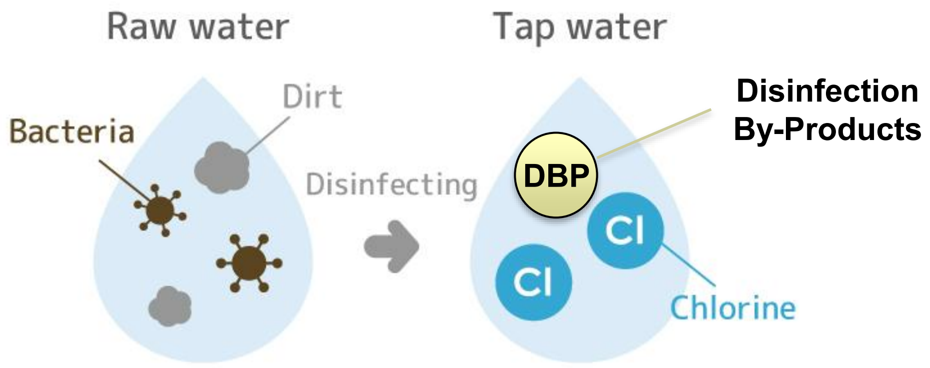
- Ageing infrastructure
- Pipe breaks
- Background leakages
- Tank overflows
- Water theft
- Metering errors

Daily drinking water loss (worldwide) = 46,000 Olympic pools

An Olympic swimming pool is equal to 1 million Litres

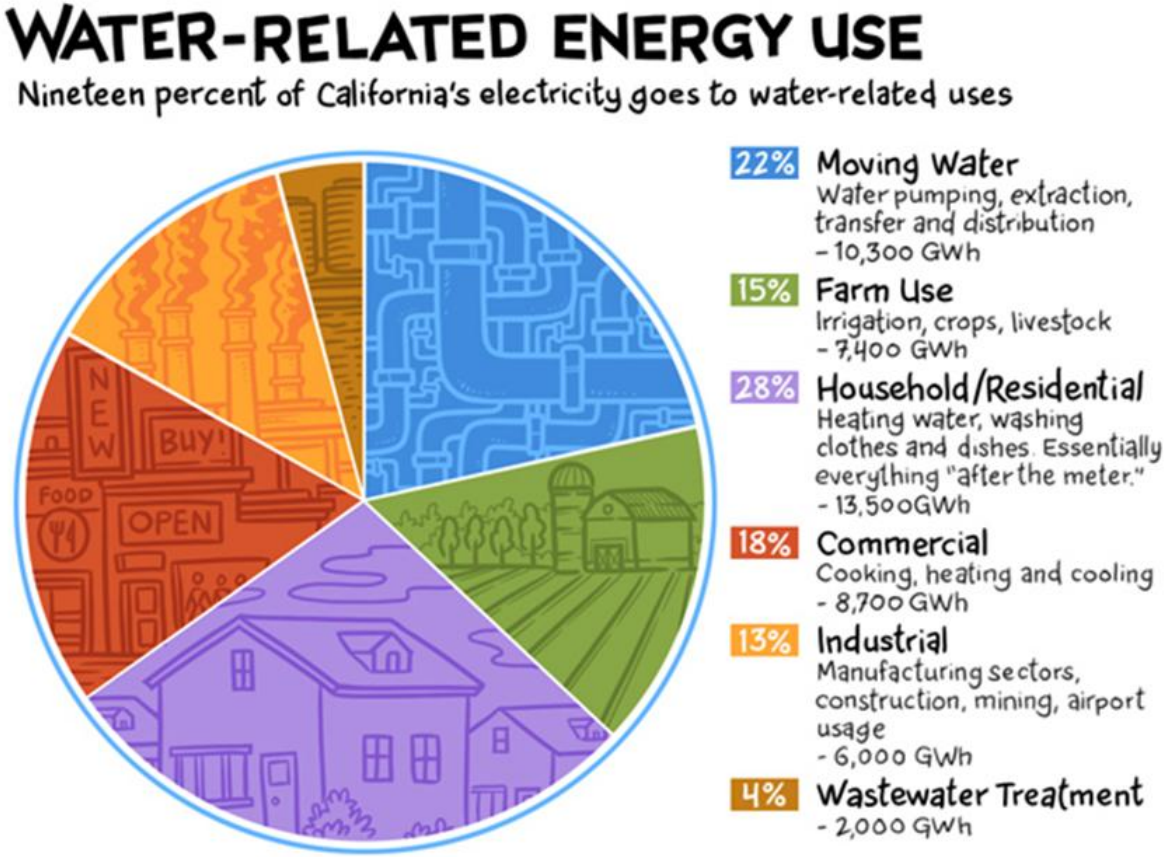
Water Quality Challenges & Risks

- Regulating disinfectants and their by-products
- Early detection of changes in water quality
- Managing natural/accidental contamination events
- Responding to malicious attacks



Energy Consumption

- 4% of EU's electricity is used by the water industry
- Produce 0.5% of greenhouse gas emissions
  - UK: 4M tons CO2-eq
  - US: 45M tons CO2-eq
- Potential for significant savings



Created by KQED.org's Andy Warner.
Data source: California Public Utilities Commision

Safety & Security

- Supervisory Control and Data Acquisition (SCADA) systems are unprotected.
- Internet-enabled devices are susceptible to attacks.
- 2021 attack in Florida water supply. Hacker(s) modified chemical concentration x100


The New York Times

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Feb. 8, 2021

'Dangerous Stuff': Hackers Tried to Poison Water Supply of Florida Town

For years, cybersecurity experts have warned of attacks on small municipal systems. In Oldsmar, Fla., the levels of lye were changed and could have sickened residents.

Give this article

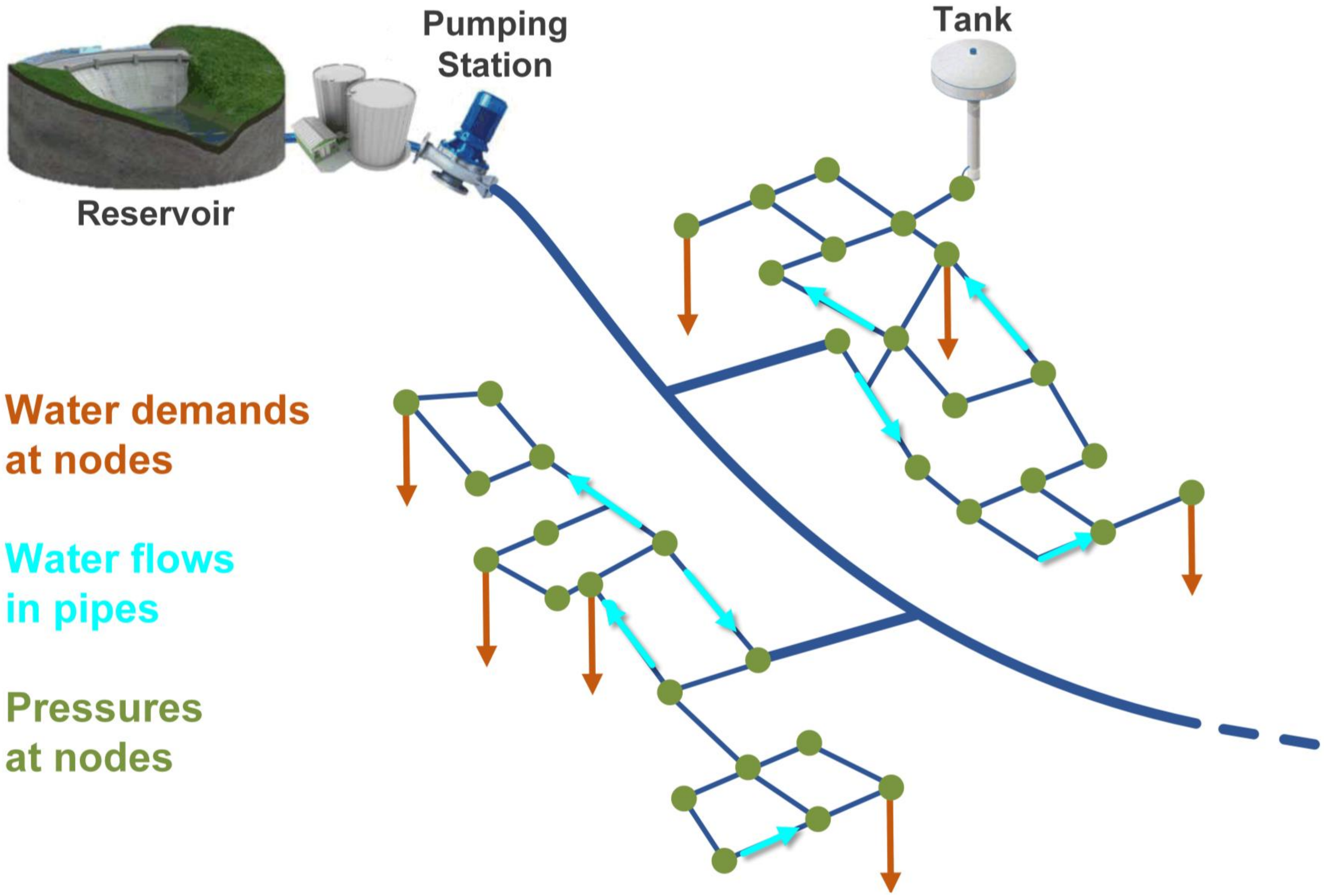
Towards Smart Water Systems

- Integrate smart sensors and actuators in water systems with advanced information & communication technologies and big-data platforms
- Apply intelligent algorithms for short and long-term decision-making using modelling, simulation, optimization, estimation and control tools

Goal:

- Enhance efficiency and improve security, reliability, resilience, quality, and robustness of drinking water distribution systems
- Minimize the impact of unforeseen events.

Water Systems — Hydraulics

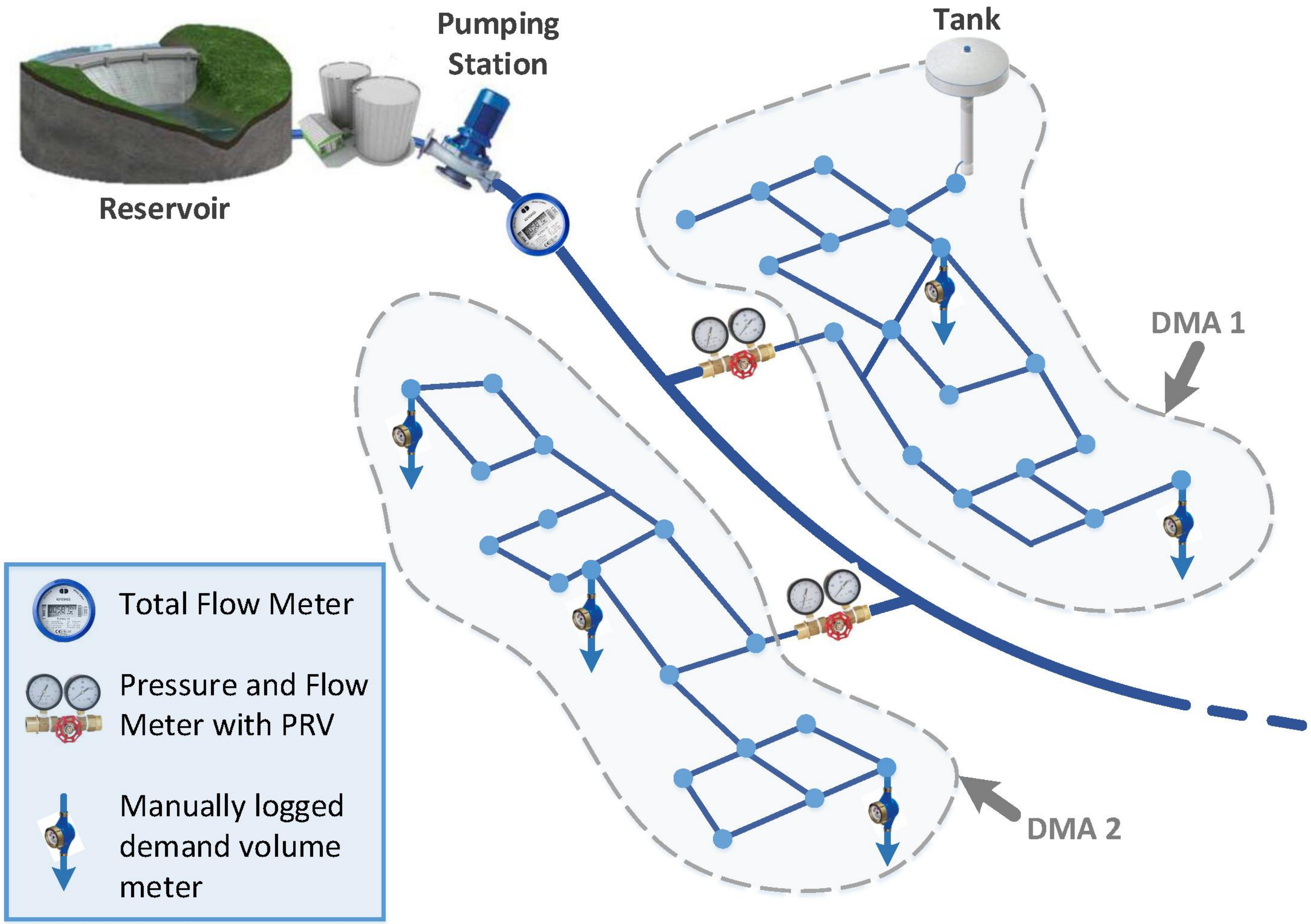


Hydraulic states:
- **Pressures** at nodes
- Tank **levels**
- **Flows** in links

Uncontrolled input:
- Water **demands**

Actuators:
- Valves
- Pumps

Water Systems — Hydraulics (current)



Transport network and district metered areas (DMAs)

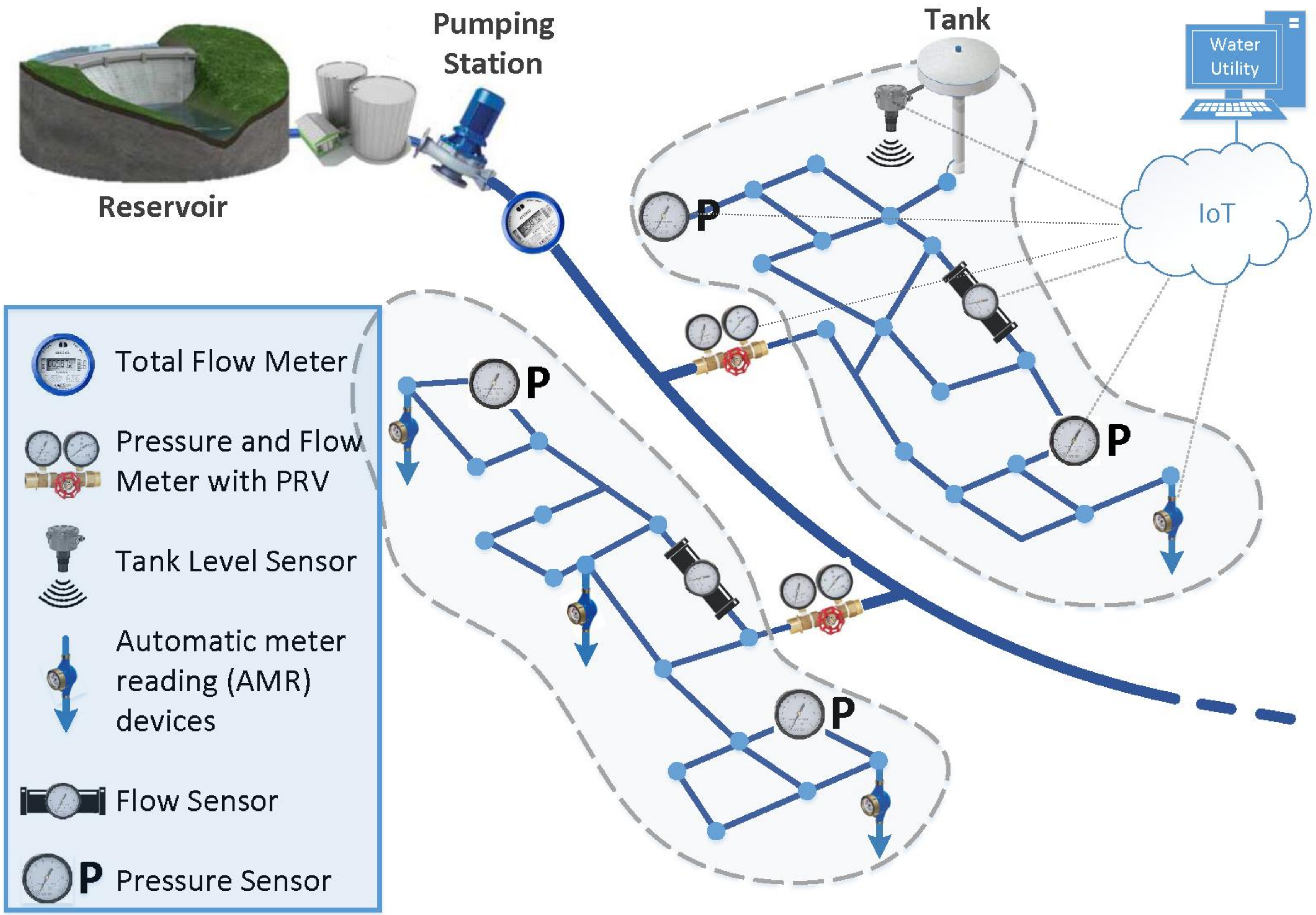
Scarce measurements (unobservable system)

Expert operators monitor SCADA (if they exist)

Periodic maintenance

Consumers report pipe breaks via phone

Water Systems — Hydraulics (envisioned)



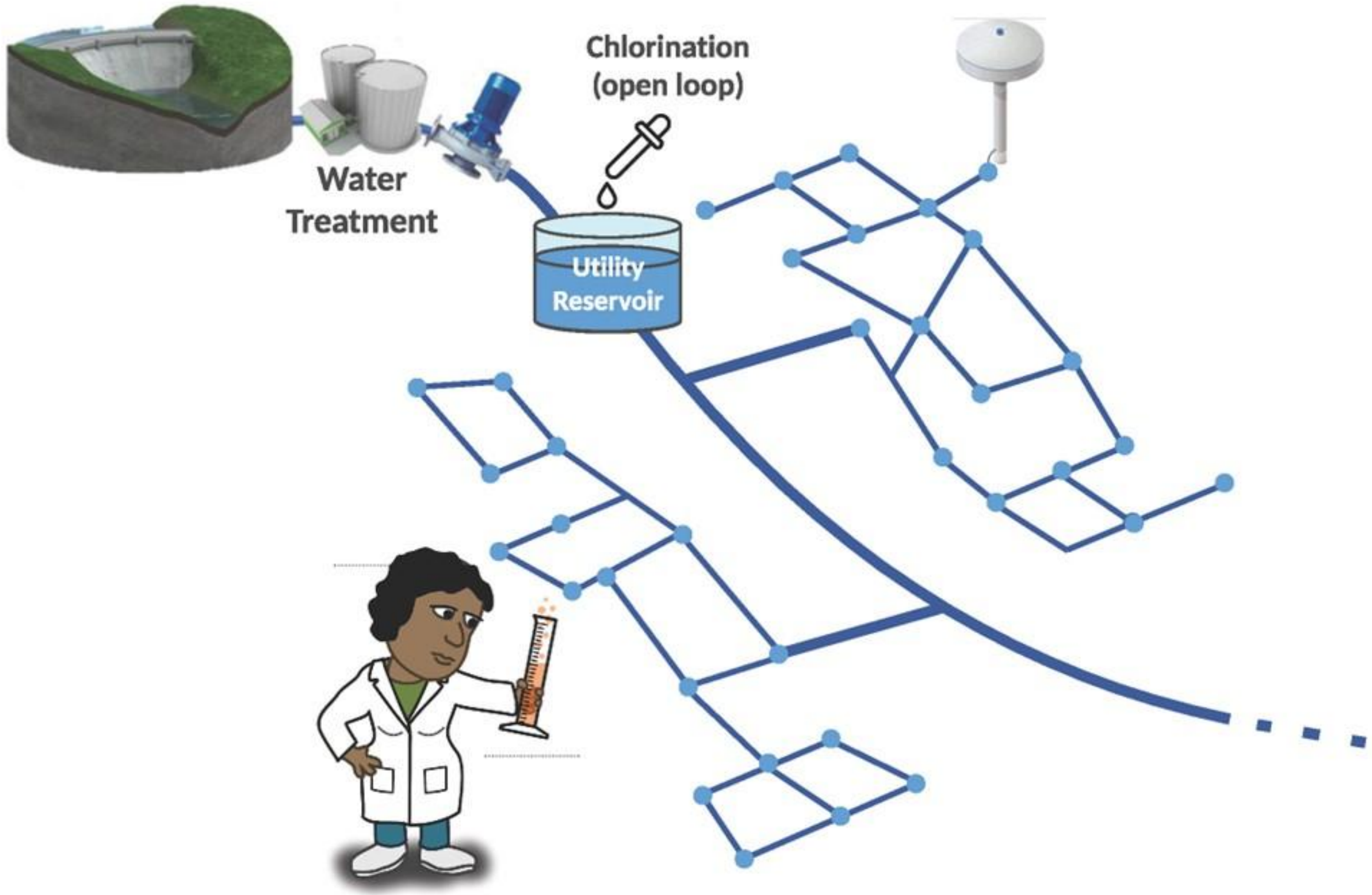
Remote sensing

Real-time state estimation using measurements

Remote actuation: Real-time pressure and flow regulation using valves

Real-time leakage detection

Water Systems — Water Quality (existing)



Water-quality states:

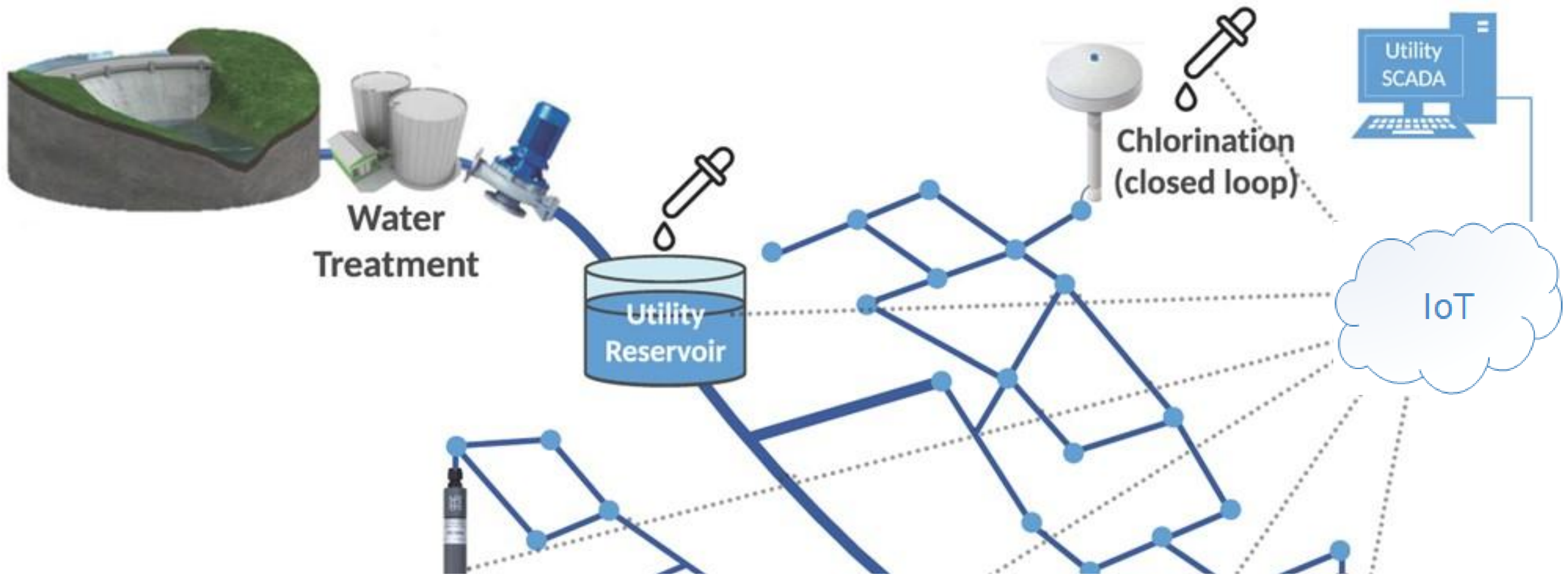
- Disinfectant concentration and
- By-products
- Pathogens
- Contaminants

Chlorination without feedback (open loop)

Contaminant detection using periodic manual sampling

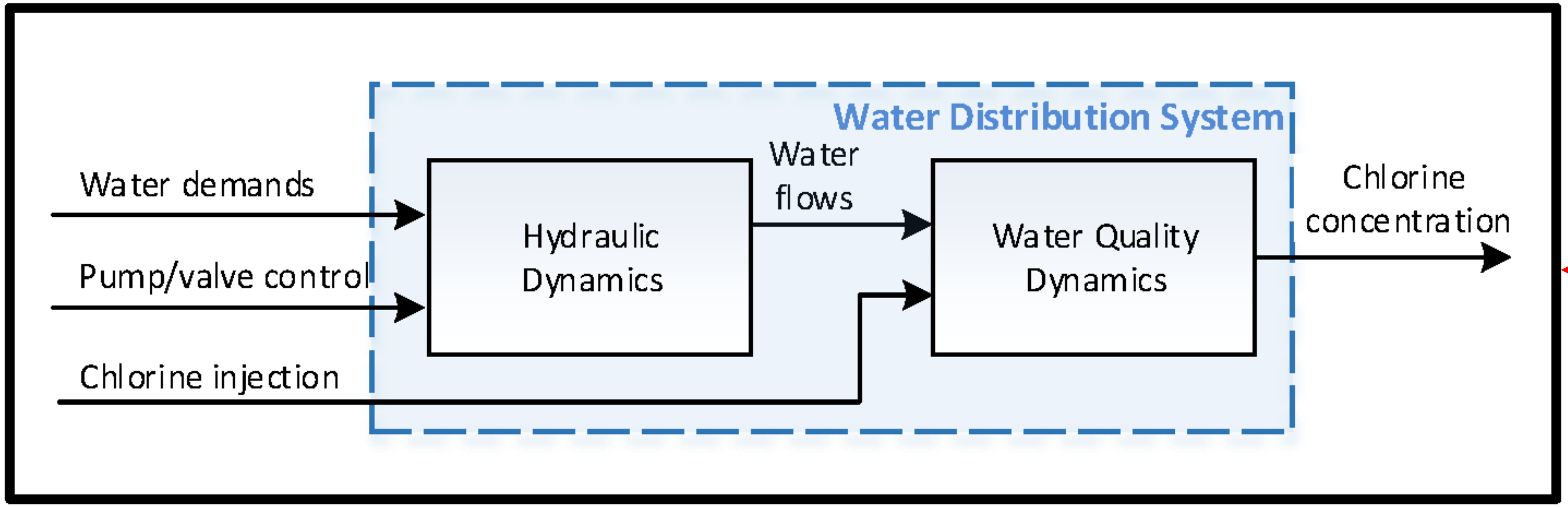
Consumers report problems with quality

Water Systems — Water Quality (envisioned)



Multi-parameter sensors placed for quality monitoring and contaminant detection

Disinfections booster stations for improved regulation



Contaminants react with disinfectants

- chlorine estimation for contaminant detection
- Time-varying model

Hydraulics Research challenges

- Flow/pressure **sensor placement** [1]
- Demand estimates and reduced models to address lack of **observability** [2]
- Real-time hydraulic **state estimation** considering uncertainty [3]
- Statistical/model-based **leakage diagnosis** algorithms
- Dynamic **pressure control** using pressure-reducing valves and network reconfiguration [4]
- **Demand management** / consumers in the loop

[1] M. À. Cugueró-Escofet, V. Puig, and J. Quevedo, “Optimal pressure sensor placement and assessment for leak location using a relaxed isolation index: Application to the Barcelona water network,” *Control Engineering Practice*, vol. 63, pp. 1–12, Jun. 2017.
[2] S. Díaz, J. González, and R. Mínguez, “Observability Analysis in Water Transport Networks: Algebraic Approach,” *ASCE Journal of Water Resources Planning and Management*, vol. 142, no. 4, p. 04015071, 2016.
[3] S. Wang, A. F. Taha, N. Gatsis, L. Sela, and M. H. Giacomoni, “Probabilistic State Estimation in Water Networks,” *IEEE Transactions on Control Systems Technology*, pp. 1–13, 2021.
[4] D. Nerantzis, F. Pecci, and I. Stoianov, “Optimal control of water distribution networks without storage,” European Journal of Operational Research, vol. 284, no. 1, pp. 345–354, Jul. 2020.

Water Quality Research challenges

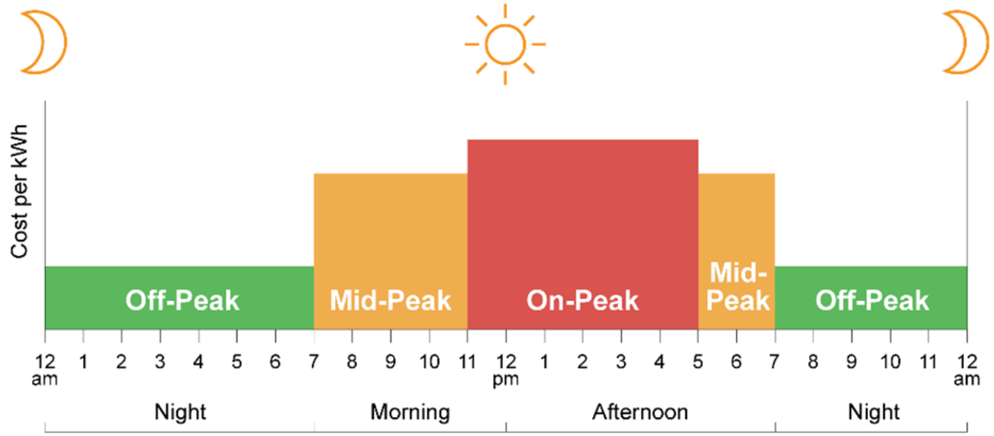
- Water-quality **sensor placement** [1]
- Real-time **quality state estimation** considering uncertain input-output time delays [2]
- Model-based algorithms for contamination **event diagnosis**
- Robust control algorithms for **booster chlorination** [3]
- **Valve control** to mitigate a contamination (fault accommodation)
- Modeling **contamination impact** on society [4]

[1] Q. Zhang, F. Zheng, Z. Kapelan, D. Savic, G. He, and Y. Ma, “Assessing the global resilience of water quality sensor placement strategies within water distribution systems,” *Water Research*, vol. 172, p. 115527, 2020.
[2] S. G. Vrachimis, D. G. Eliades, and M. M. Polycarpou, “Calculating Chlorine Concentration Bounds in Water Distribution Networks: A Backtracking Uncertainty Bounding Approach,” *Water Resources Research*, vol. 57, no. 5, p. e2020WR028684, 2021.
[3] S. Wang, A. F. Taha, and A. A. Abokifa, “How Effective is Model Predictive Control in Real-Time Water Quality Regulation? State-Space Modeling and Scalable Control,” *Water Resources Research*, vol. 57, no. 5, p. e2020WR027771, 2021.
[4] G. R. Abhijith and A. Ostfeld, “Model-based investigation of the formation, transmission, and health risk of perfluorooctanoic acid, a member of PFASs group, in drinking water distribution systems,” *Water Research*, vol. 204, p. 117626, Oct. 2021.

Water and Energy Nexus Challenges

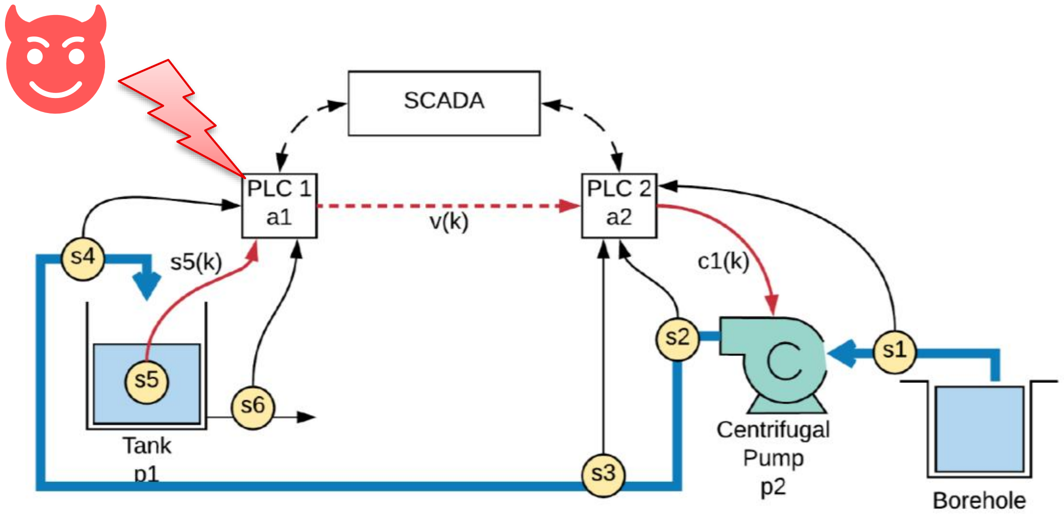
- **Estimate energy usage** in real-time.
- **Optimize water pump control** under uncertainty, considering pump models, energy efficiency and Time-of-Use tariffs.
- System reconfiguration to **reduce energy usage**.
- Optimize water **pump** selection for **load shedding** to reduce the risk of **power system instability** and water shortage.
- **Detect anomalies in pump energy consumption** in real-time.
- Optimize **pump usage depending on renewables** production.
- Investigate **interdependencies between infrastructures.**

Time-of-Use Schedule for Summer (May 1 to October 31)



Cyber-Physical Security Challenges

- Resilient design of ICS architecture [1]
- Early detection of cyber-physical attacks [2]
- Responding to events to minimize their impact
- Privacy in cyber-physical systems [3]

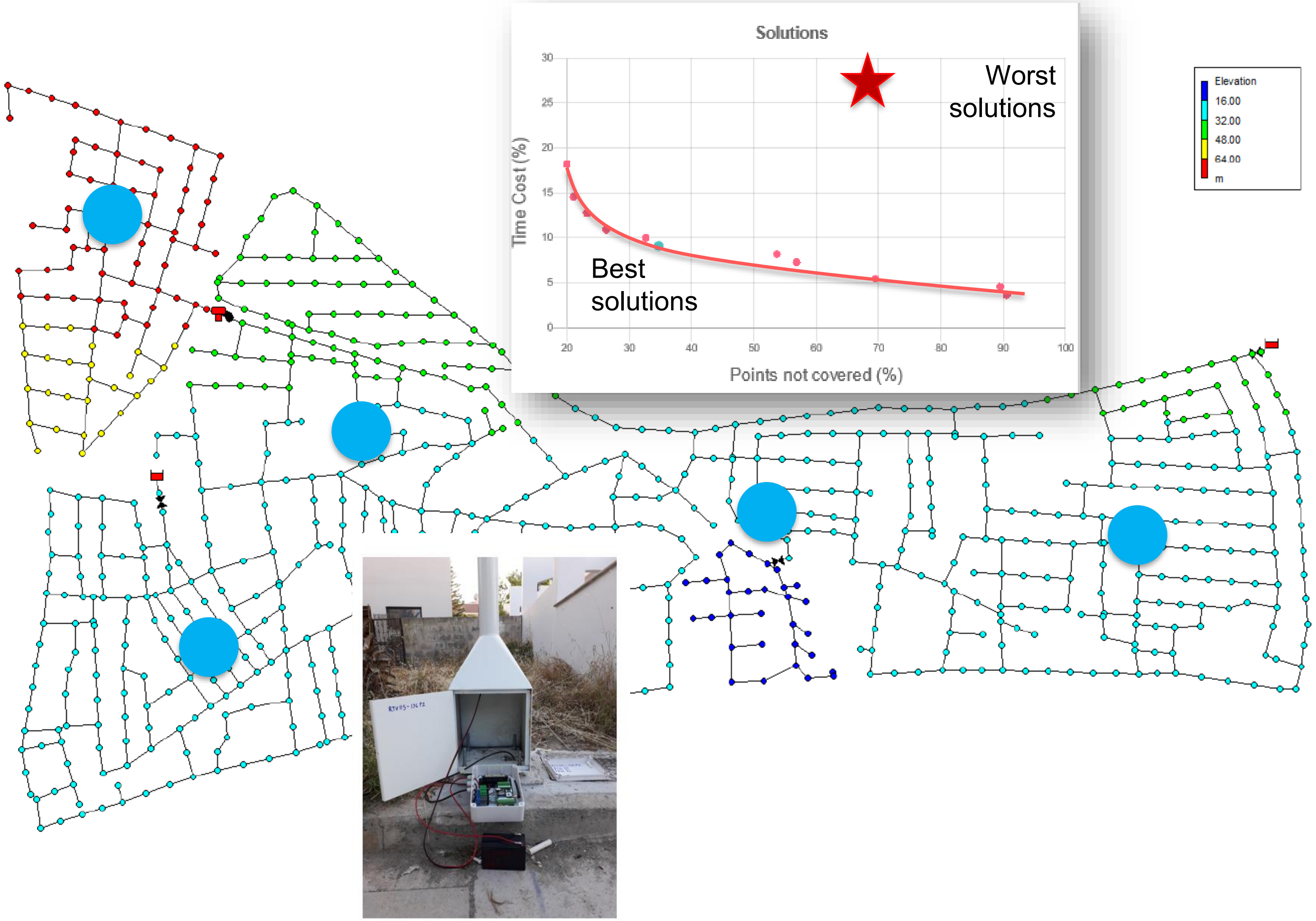


[1] M. Barrère, C. Hankin, N. Nicolaou, D. G. Eliades, and T. Parisini, "Measuring cyber-physical security in industrial control systems via minimum-effort attack strategies," *Journal of Information Security and Applications*, vol. 52, p. 102471, 2020.
[2] Taormina et al., "Battle of the Attack Detection Algorithms: Disclosing Cyber Attacks on Water Distribution Networks," *ASCE Journal of Water Resources Planning and Management*, vol. 144, no. 8, p. 04018048, 2018.
[3] E. Salomons, L. Sela, and M. Housh, "Hedging for Privacy in Smart Water Meters," *Water Resources Research*, vol. 56, no. 9, pp. 1–16, 2020.

Monitoring and Control of Water Systems

- **Modelling**
  - Hydraulics and quality with uncertainties
  - Fault models
  - Social behavior (consumers and operators)
  - Infrastructure inter-dependencies
- **Decision**
  - Design and Planning
  - Placement of sensors and actuators
  - Operational optimization
- **Estimation**
  - Hydraulic states (flow, pressure)
  - Quality states (disinfectants, contaminants)
  - System parameter estimation
- **Control**
  - Regulation of pressure
  - Regulation of chemicals concentration
- **Diagnostics & Security**
  - Leakage detection and localization
  - Contamination detection and mitigation
  - Cyber-physical security and response
- **Research Tools**
  - Simulators & Toolkits
  - Research infrastructures
  - Digital Twins

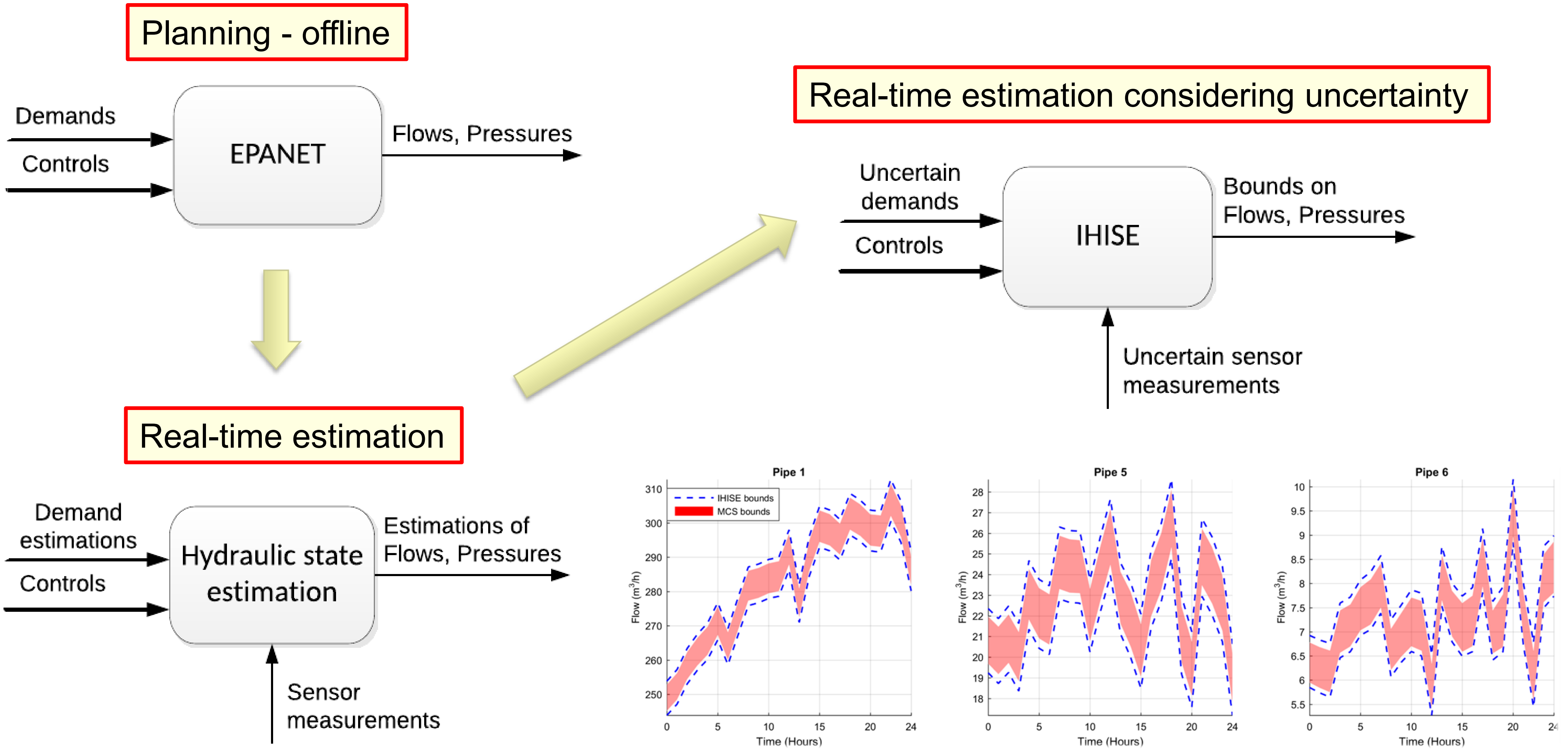
Placing quality sensors for monitoring



- Multi-objective problem:
  - Minimize contamination impact
  - Minimize detection delay
- Risk-based impact metrics
- Challenging problem:
  - For 5 water quality sensors→ 10^{12} solutions

D. G. Eliades and M. M. Polycarpou. "A fault diagnosis and security framework for water systems." *IEEE Transactions on Control Systems Technology* vol. 18, no. 6, pp. 1254-1265, 2009.

Hydraulic state estimation with uncertainty

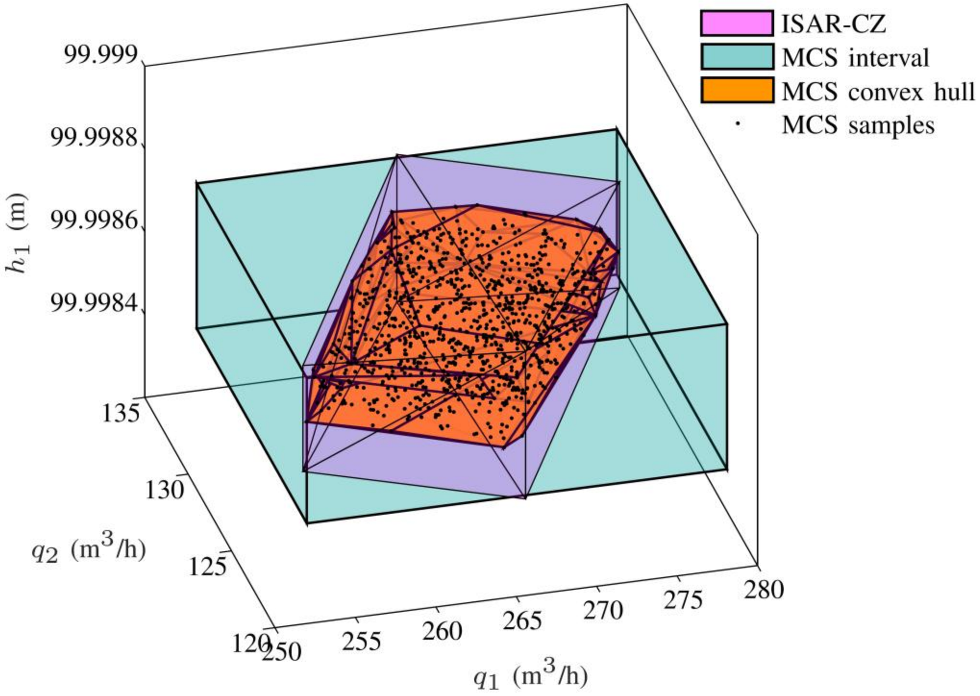


Vrachimis, S. G.; Timotheou, S.; Eliades, D. G. & Polycarpou, M. M., Iterative Hydraulic Interval State Estimation for Water Distribution Networks, *ASCE Journal of Water Resources Planning and Management*, vol. 145, p. 04018087, 2018.

Constrained Zonotopes for uncertain state estimation

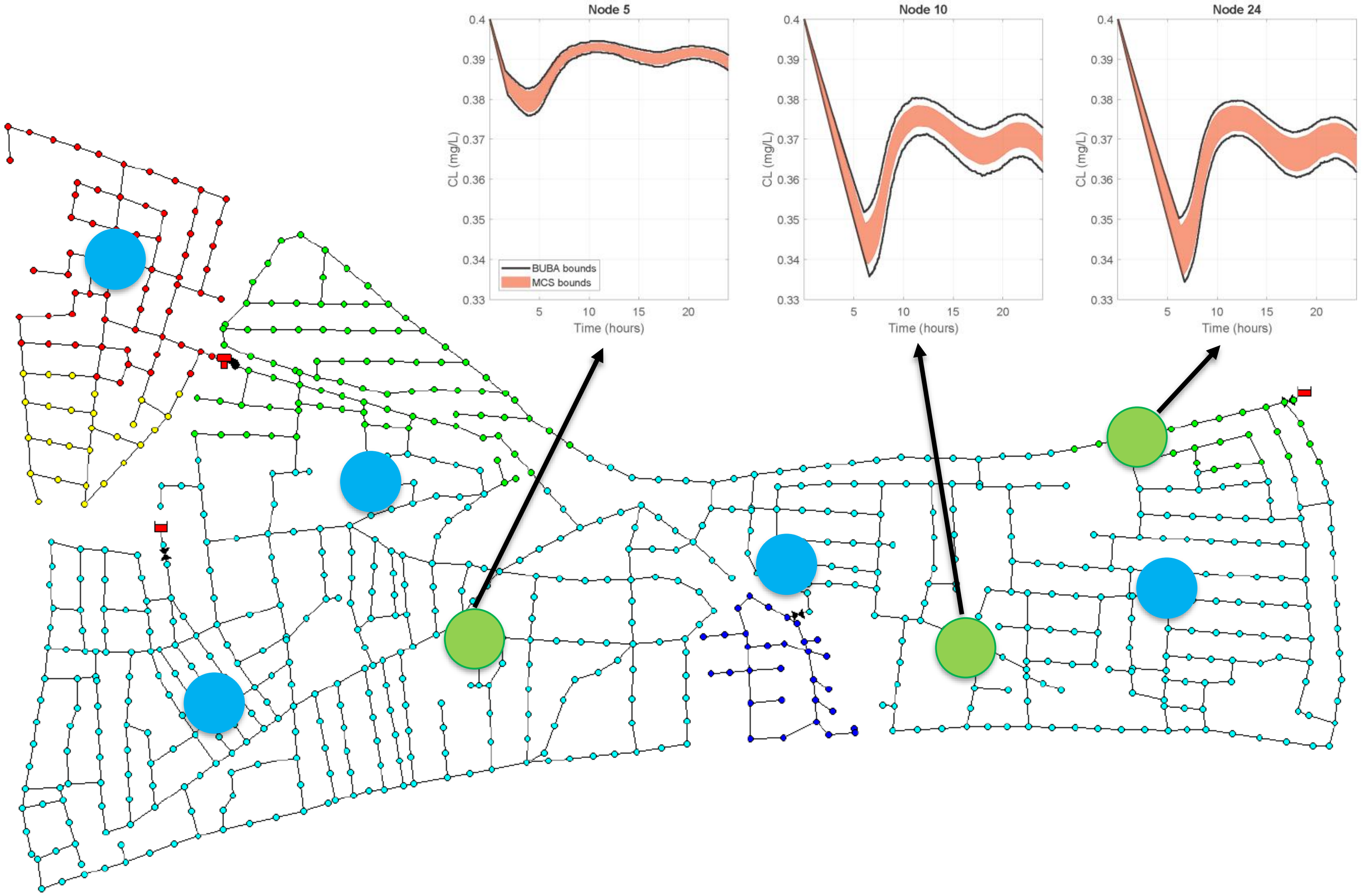
- Intervals do not capture the dependencies between state variables
- Use of constrained zonotopes (CZs) as an additional step to IHISE
- New algorithm capable of capturing the dependencies between hydraulic states
- Results in sets with significantly smaller volumes than intervals
- The benefits of CZs are highlighted when the new enclosures are used for leakage detection, providing higher leakage detection rates

	Average execution times (seconds)	Number of iterations (#)
IHISE	0.0243	2
ISAR	0.0118	3
IHISE-CZ	0.0286	2
ISAR-CZ	0.0167	3



Rego, B. S., Vrachimis, S. G., Polycarpou, M. M., Raffo, G. V., Raimondo, D. M. State Estimation and Leakage Detection in Water Distribution Networks Using Constrained Zonotopes. *IEEE Transactions on Control Systems Technology*, vol. 30, no.5, September 2022.

Estimating water quality in the system

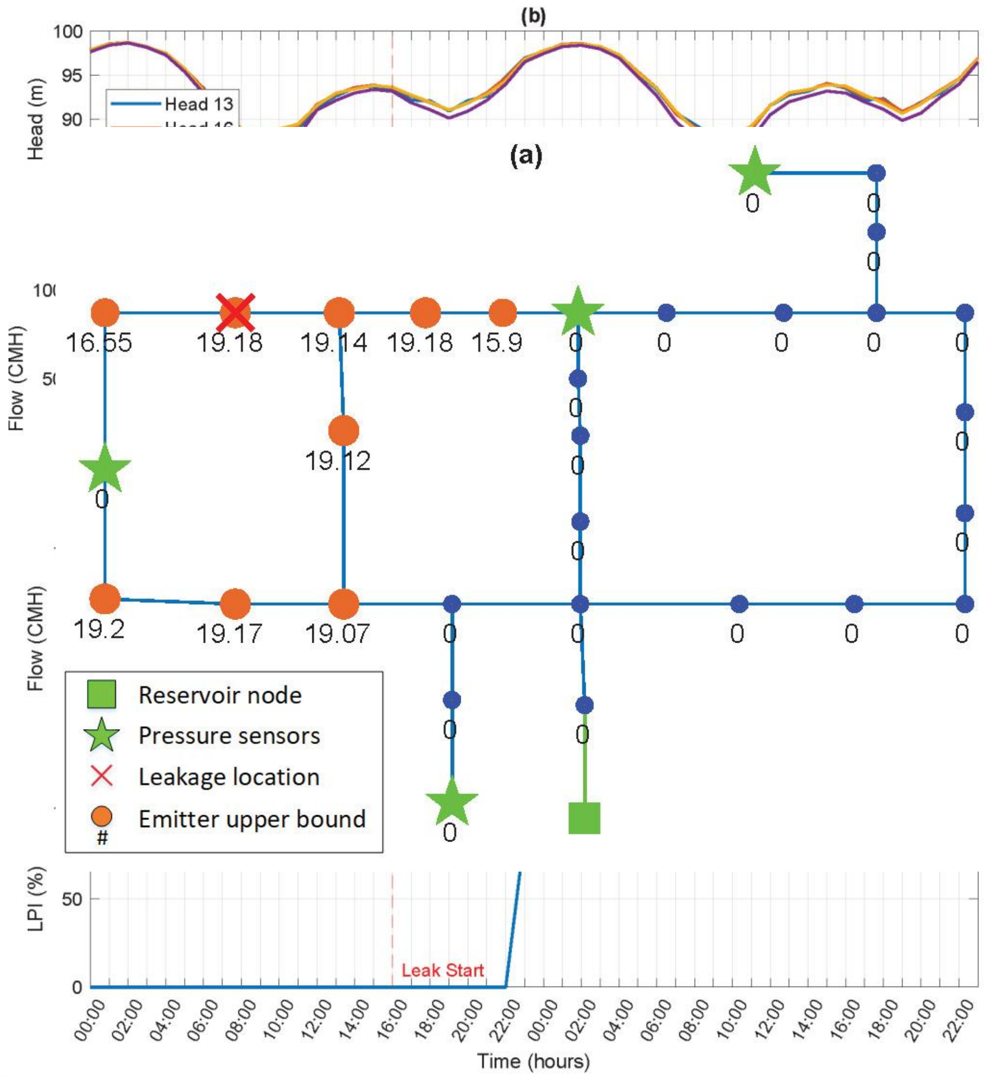


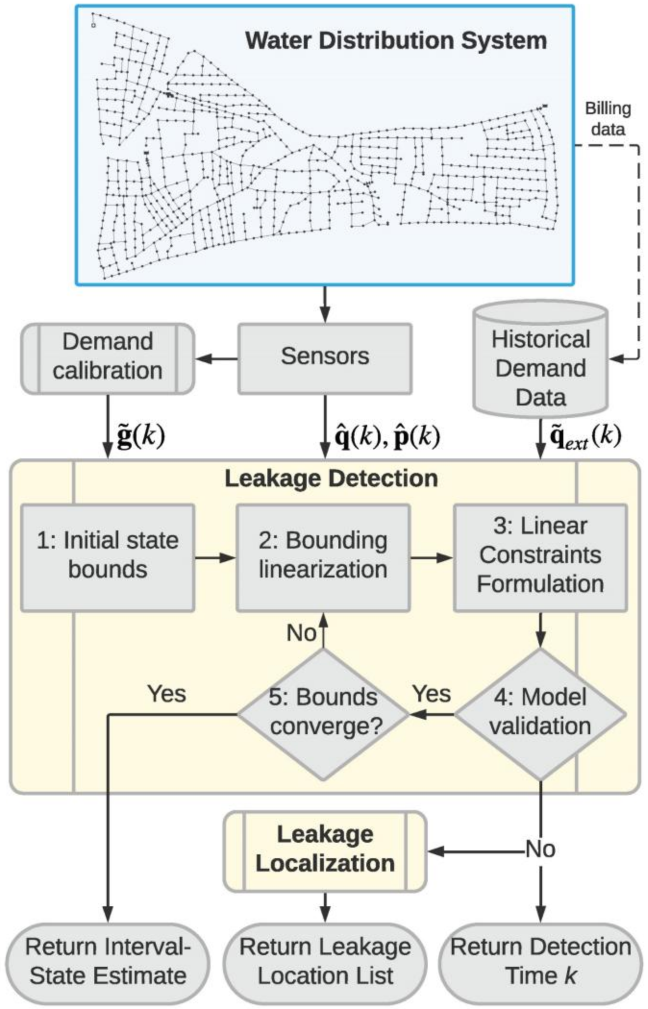
- The Backtracking Uncertainty Bounding Approach
- Compute **bounds** of **disinfectant concentrations** in the network
- Incorporates **sensor measurements**
- Considers **demand** and **reaction rate** *uncertainties*

S. G. Vrachimis, D. G. Eliades, and M. M. Polycarpou, “Calculating Chlorine Concentration Bounds in Water Distribution Networks: A Backtracking Uncertainty-Bounding Approach,” *Water Resources Research*, p. e2020WR028684, Mar. 2021.

Leakage diagnosis - model invalidation

- Set-based model of hydraulics in healthy operation
- Able to detect and localize small leakages
- Possible leak nodes are given in a priority list

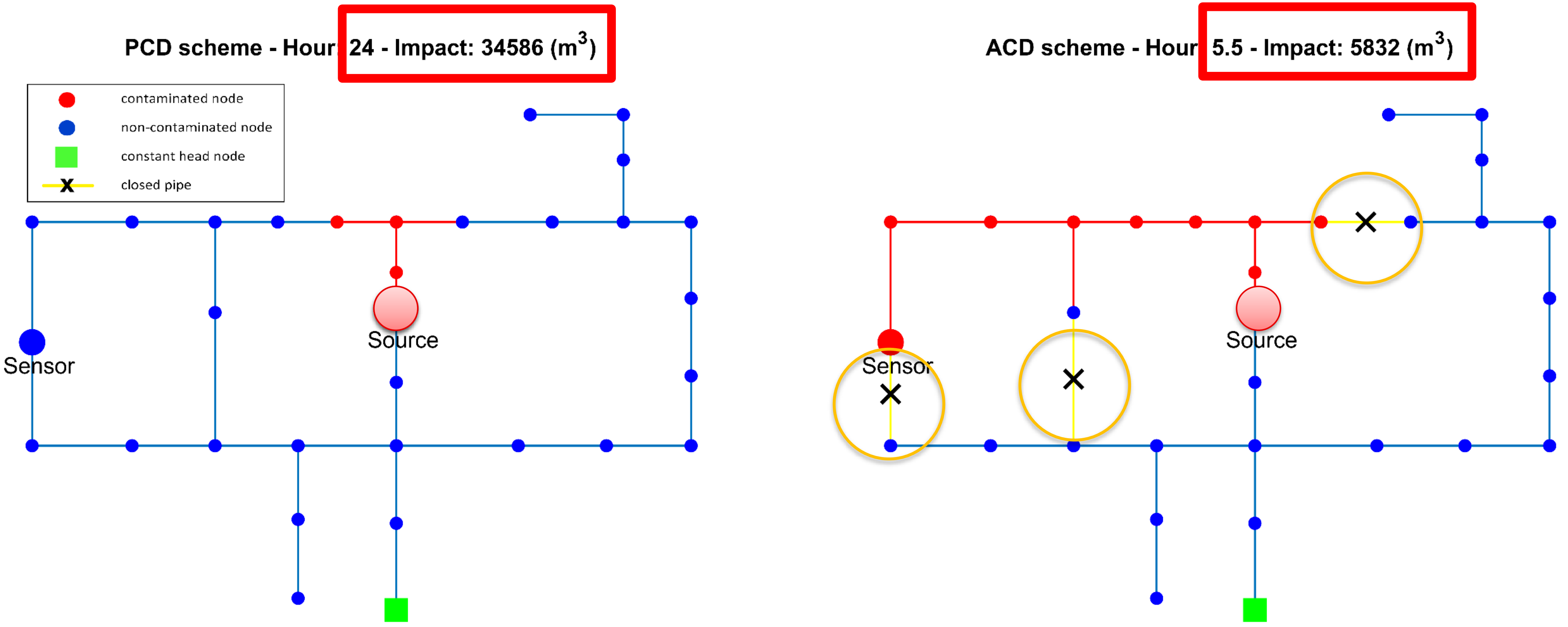




S. G. Vrachimis, S. Timotheou, D. G. Eliades, and M. M. Polycarpou, "Leakage detection and localization in water distribution systems: A model invalidation approach," *Control Engineering Practice*, vol. 110, p. 104755, May 2021.

Active contamination detection

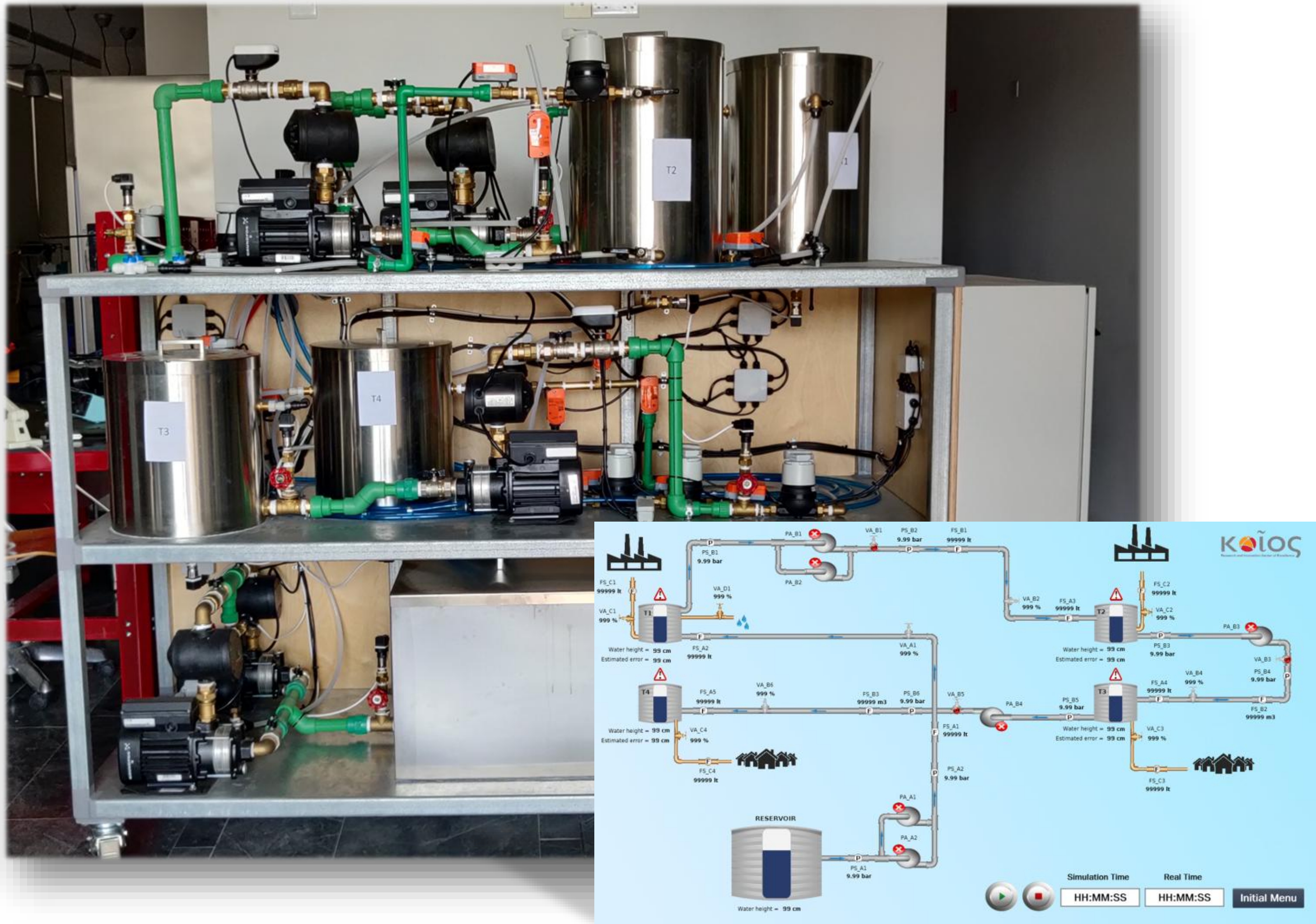
Confirm a contamination by driving the contaminant to a sensor



S. G. Vrachimis, R. Lifshitz, D. G. Eliades, M. M. Polycarpou, and A. Ostfeld, "Active Contamination Detection in Water-Distribution Systems," *ASCE Journal Water Resources, Planning and Management,* vol. 146, no. 4, p. 04020014, Apr. 2020.

RESEARCH TOOLS

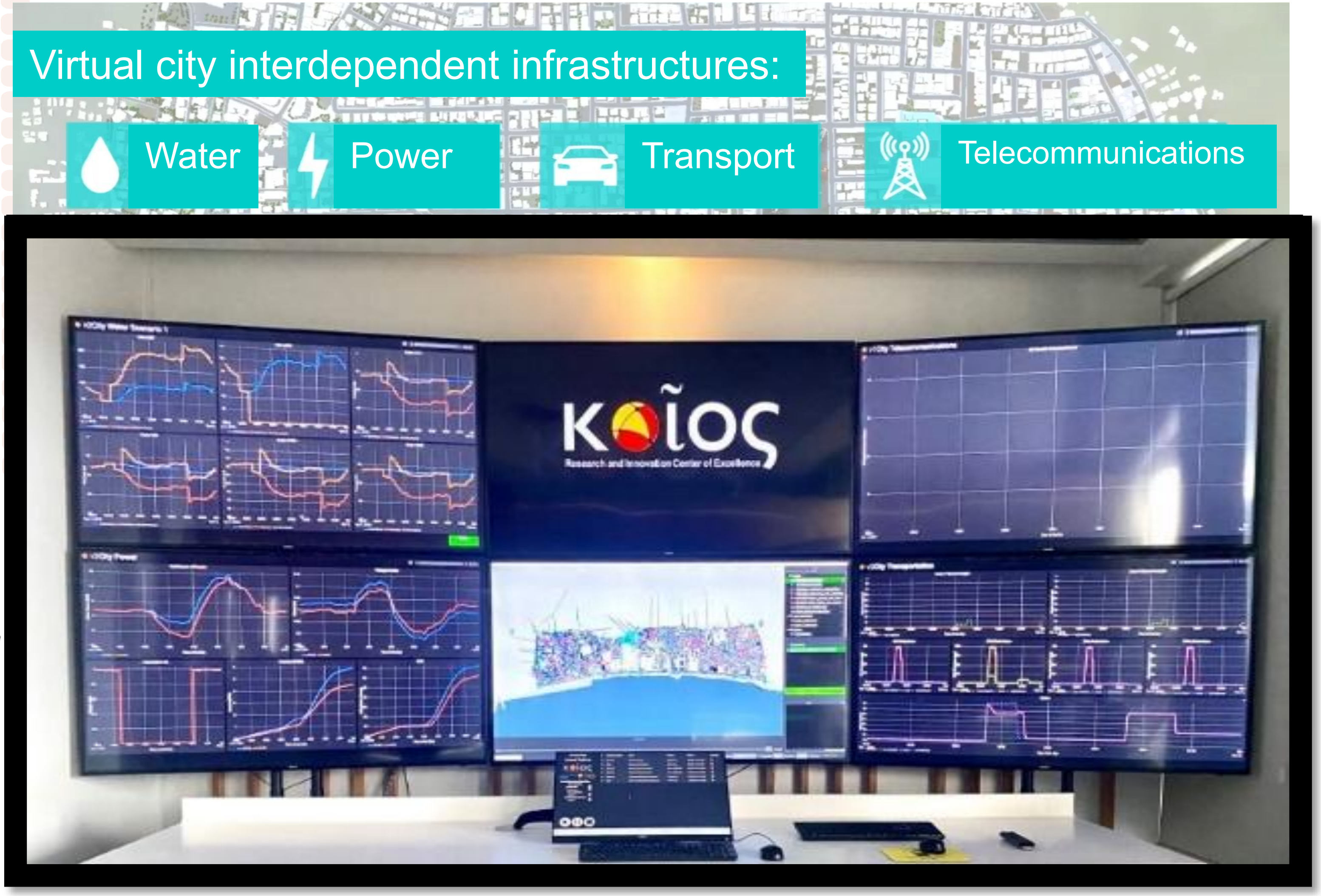
KIOS Water Security Testbed



- Fully observable **physical system** representing transport network
- Simulates realistically events such as attacks on **PLCs**, **sensor and actuator faults**
- Hydraulic model and real datasets available online

S. G. Vrachimis, et al., “WaterSafe: A Water Network Benchmark for Fault Diagnosis Research”, In Proc. of 11th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes, *Proceedings of 2022 IFAC SAFEPROCESS Conference*, June 2022.

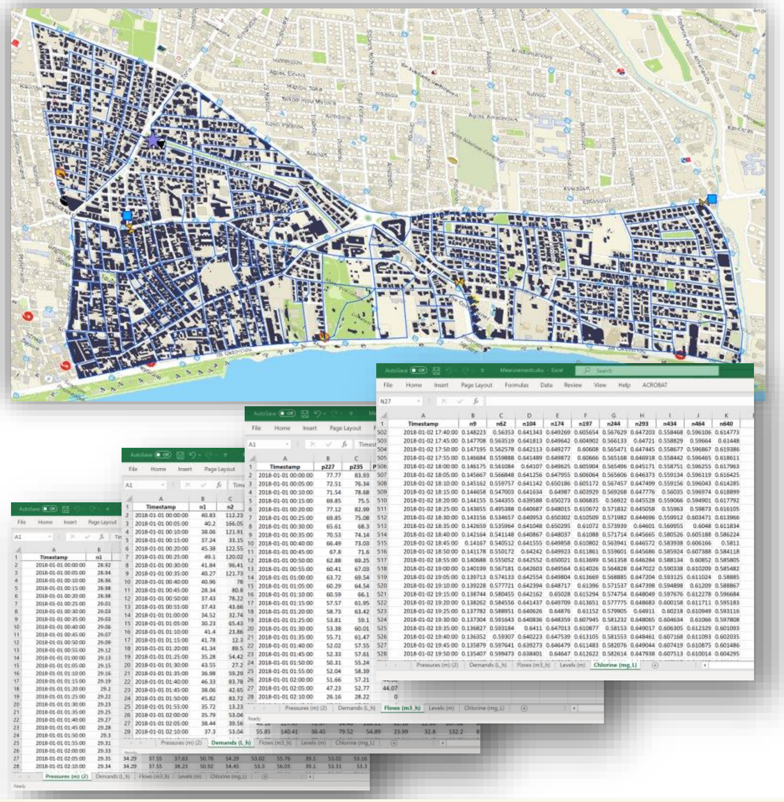
Cyprus Digital Twin (developed at KIOS CoE)



- **Cyprus Digital Twin** based on realistic data (use of Open Data)
- Integrated **realistic simulation platform** of most city infrastructures:
  - Water, power, transport, telecommunications
- **Simulates interdependencies** between systems
- **Simulates events in the city** (natural disasters, malicious attacks, accidents)
- Used for **research** and **operator training**

Benchmarks and Tools for the Control Community

- **BattLeDIM** – Battle of the Leakage Detection and Isolation Methods [1]
  - Realistic 2-year simulated SCADA dataset with leakages
  - **L-TOWN** – a benchmark network based on a real city
- **EPANET-MATLAB toolkit** [2] – Tool for developing algorithms for water systems using MATLAB
- **WaterSafe** [3] – Dataset with actual faults of the KIOS Water Testbed + SIMULINK model
- **LeakDB** [4] – Leakage database for training AI algorithms



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[3] S. G. Vrachimis, et al., "WaterSafe: A Water Network Benchmark for Fault Diagnosis Research", In Proc. of 11th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes, SAFEPROCESS 2022, 2022
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ERC Synergy Grant – Water Futures

- Smart Water Futures: designing the next generation of urban drinking water systems
- Acronym: **Water-Futures**
- Beneficiaries:
  - University of Cyprus (Cyprus) – **M. Polycarpou**
  - Bielefeld University (Germany) – **B. Hammer**
  - Athens University of Economics and Business (Greece) – **P. Koundouri**
  - KWR Water Research Institute (Netherlands) & University of Exeter (UK) – **D. Savic**
- Total budget: € 9,982,320

Project Information

Water-Futures
Grant agreement ID: 951424

Start date 1 August 2021
End date 31 July 2027

Funded under
H2020-EU.1.1.

Overall budget
€ 9 982 320

EU contribution
€ 9 982 320

Hosted by
UNIVERSITY OF CYPRUS
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https://cordis.europa.eu/project/id/951424

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Take Home Messages

- Water is a precious resource, which is becoming even more precious!
- Water distribution systems are going through a digital transformation with new instrumentation for sensing and actuation
- The Internet of Things (IoT) technology will influence the progress of smart water systems
- *Systems and Control can play a key role in developing intelligent algorithms and new tools for making water distribution systems more efficient, more resilient, more secure and more aligned with a green economy.*

Acknowledgements

Funded by the European Research Council (ERC) under the ERC Synergy Grant 'Water-Futures' (Grant agreement No. 951424)

Supported by the European Union Horizon 2020 programme Grant Agreement No. 739551 (KIOS CoE), and the Government of the Republic of Cyprus through the Deputy Ministry of Research, Innovation and Digital Policy.

Strategic partners: **Cyprus Water Development Department** and the **Water Board of Limassol**

University of Cyprus

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Thank you!

Questions?