DeSw Project Results on Development of Soft Sensors in Water Distribution Networks

Fotis N. Koumboulis, Nikolaos D. Kouvakas, Maria P. Tzamtzi, Dimitrios G. Fragkoulis, and Michalis G. Skarpetis

Laboratory of Robotics, Automatic Control and Cyber-Physical Systems, University of Athens

Konstantinos S. Katsiavrias and Klimis K. Katsiavrias

AKATT SA, 251, Agiou Dimitriou str, 173 42, Agios Dimitrios, Athens, Greece

Abstract—Reliable drinking-water operation requires more than periodic compliance sampling; it requires timely knowledge of hydraulic conditions, residual disinfectant, and contaminant-related quality variables throughout the distribution network. This article presents the results of the research project "Development of Soft Sensors in Water Distribution Networks" for real-time estimation and Discrete Event Systems based decision support. The approach combines a coupled hydraulic–water-quality model with a bank of linear state observers that operate as soft sensors. Each observer is designed for a local operating region, while a switching mechanism selects the observer most suitable for the current state of the network. The methodology targets variables whose direct measurement is difficult or spatially sparse. The soft-sensing layer is integrated with supervisory control and fault diagnosis units. The resulting architecture links field instrumentation, edge computing, and cloud-based reasoning through standard SCADA systems. The project demonstrates a scalable, interpretable, and computationally light alternative to dense deployment of physical sensors, while preserving compatibility with regulatory monitoring and human operator oversight.

Keywords—*water distribution networks, water quality, soft sensors, state observers, supervisory controllers, fault diagnosers, SCADA, edge computing*

1. Introduction

Water distribution networks are dynamic cyber-physical systems in which water quality changes while water travels through pipes, tanks, valves, and pumping stations. The final quality delivered to consumers depends on source mixing, residence time, pipe-wall reactions, disinfectant decay, operational actions, and device faults. For this reason, modern drinking-water management increasingly moves from isolated parameter checks toward risk-based supervision of the complete supply chain, as reflected in international and European regulatory frameworks [1]–[2].

Conventional monitoring has two main limitations. Laboratory analysis provides high-quality measurements but is delayed, labor intensive, and typically sparse in time and space. Physical online sensors can improve temporal resolution, but their installation, calibration, and maintenance costs restrict network coverage. Moreover, not every quality species of interest is easily measured online. These limitations motivated the development of a soft-sensor system: a model-based digital layer that converts available hydraulic and quality measurements into estimates at uninstrumented or poorly instrumented locations.

The principal contribution of the project is an integrated framework that links soft sensing with operational decision support [3]-[22]. Instead of relying on purely data-driven black-box prediction, the project adopts state-observer theory, hydraulic simulation, and discrete-event supervisory control. This choice provides interpretability, supports engineering diagnosis, and reduces dependence on large historical training datasets. At the same time, the framework addresses a central difficulty of distribution networks: their behavior is nonlinear and varies with demand patterns, flow direction, pipe velocities, residence times, and actuator states.

2. Methodological Framework

The methodology of DeSw project begins with a coupled representation of hydraulics and quality. The hydraulic layer describes flows, heads, velocities, flow directions, and residence times. These quantities determine how solutes move and mix. The quality layer then represents transport, junction mixing, chemical transformation, disinfectant decay, production or consumption reactions, and pipe-wall interactions. Since the quality dynamics depend strongly on water movement, the hydraulic and quality models are treated as interconnected rather than independent subsystems.

A single linear observer cannot adequately represent the complete operating envelope of a water distribution network. Demand changes, pump scheduling, valve operations, and storage-tank levels may shift the system into substantially different dynamic regimes. The project therefore uses an observer bank [3]-[10], [22]. Each observer is reliable over a defined region, and an intelligent switching logic selects the active observer from real-time measurements and operating-condition indicators. A dense grid of operating regions reduces abrupt transitions and helps preserve estimation quality when the active observer changes.

The soft-sensing digital framework, is enhanced by a set of Discrete Event System supervisors and diagnosers [10]-[17]. The supervisors implement operational rules through discrete-event supervisory control. Their purpose is to prevent commands that could move the network into unsafe or undesirable states. For example, pump, valve, or disinfectant-dosing commands may be restricted when quality limits, hydraulic constraints, device-fault information, or communication status indicate elevated risk. The DES diagnosers identify faults and alarm situations, performing DES model-based fault-diagnosis, where observation of event sequences is compared with expected system behavior to infer abnormal conditions.

All the aforementioned software units are combined in a hybrid field–edge–cloud DSS architecture [3].

4. Results and Discussion

The project proposes a digital solution for increasing the effective measurement density of drinking-water networks without requiring equivalent growth in physical instrumentation. Its main result is not a single sensor device, but a software-based monitoring and decision-support framework. The framework transforms existing measurements into additional estimates of water-quality and hydraulic variables at critical points where physical sensors may be unavailable.

The first result is methodological. The project specifies a way to design switching soft sensors for coupled hydraulic and quality dynamics, with special attention to specific quality variables, such as residual chlorine. The approach explicitly recognizes that water-quality evolution is governed by both chemical processes and network hydraulics. It therefore avoids treating contaminant or disinfectant concentration as a purely local time series. This is important for distributed systems where the same quality measurement may have different meaning depending on residence time, flow reversal, or mixing history.

The second result is operational. By delivering online estimates in a form usable by SCADA-connected software agents, DeSw project converts soft sensing into actionable decision support. Estimates are not isolated numerical outputs; they feed supervisors, diagnosers, alarms, and command-generation logic. This coupling makes the system suitable for early detection of degradation, restriction of unsafe control actions, and prioritization of operator attention.

The third result is architectural. The proposed field–edge–cloud deployment allows the computational workload to be divided according to urgency and scale. Time-critical estimation and local diagnosis can be performed close to the process, while more global reasoning can occur in the cloud. The modular design also supports scaling: additional observers, network zones, quality variables, or diagnostic rules can be integrated without changing the entire system.

Several advantages follow from the model-based design of soft-sensors. The system is interpretable because estimates are linked to hydraulic and quality equations. It is economical because it reuses existing measurements and digital infrastructure. It is computationally suitable for real-time operation because only local linear observers and the switching algorithm need to run online. It is also expandable because the same design workflow can be repeated for networks of different size and complexity.

The framework should be understood as complementary to, not a replacement for, regulatory sampling and calibrated physical sensors. Laboratory measurements remain essential for compliance, calibration, and verification. Physical sensors remain essential at strategically selected locations. The contribution of DeSw is to fill the spatial and temporal gaps between those measurements, giving operators a more continuous picture of network behavior.

5. Conclusions

The DeSw project shows that model-based soft sensing can provide a transparent and computationally efficient layer for drinking-water quality management. By combining coupled hydraulic-quality modeling, banks of locally valid linear observers, intelligent switching, and multi-agent decision support, the framework addresses nonlinear network behavior while supporting real-time operation. Future work should prioritize field validation, uncertainty quantification, optimal placement of remaining physical sensors, cybersecurity of the communication architecture, and extension to additional contaminants and by-products.

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References

[1] World Health Organization, Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda. Geneva, Switzerland: WHO, 2022.

[2] European Parliament and Council of the European Union, "Directive (EU) 2020/2184 of 16 December 2020 on the quality of water intended for human consumption," Official Journal of the European Union, L 435, pp. 1–62, Dec. 2020.

[3] Fotis N. Koumboulis, Maria P. Tzamtzi, Nikolaos D. Kouvakas, Dimitrios G. Fragkoulis, Konstantinos S. Katsiavrias, and Klimis K. Katsiavrias, A Decision Support System Architecture for Quality in Water Distribution Networks, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[4] N.D. Kouvakas, F.N. Koumboulis, M.P. Tzamtzi and D.G. Fragkoulis, Toward the design of chlorine soft sensors via stepwise safe switching observers for a primary water distribution network, in Proc. 2nd Olympiad in Engineering Science (OES 2025), Stavanger, Norway, June 10–14, 2025 (2025)

[5] N.D. Kouvakas, F.N. Koumboulis, M.P. Tzamtzi and D.G. Fragkoulis, Soft sensor design for water distribution networks using unknown input safe switching observers, in Proc. 3rd Springer Int. Conf. on Frontiers of Artificial Intelligence, Ethics and Multidisciplinary Applications, Stavanger, Norway (2025)

[6] F.N. Koumboulis, N.D. Kouvakas, M.P. Tzamtzi, D.G. Fragkoulis, A.N. Menexis, Kl. Katsiavrias, K. Katsiavrias and J. Dimitropoulos, Toward edge implementation of soft sensors for water distribution networks, in 12th Int. Conf. on Control Engineering & Information Technology (CEIT 2026), Istanbul, Turkey (2026)

[7] N.D. Kouvakas, F.N. Koumboulis, M.P. Tzamtzi, D.G. Fragkoulis, Kl. Katsiavrias, K. Katsiavrias and J. Dimitropoulos, On the discrete time stepwise safe switching soft sensor design for water distribution networks, in 12th Int. Conf. on Control Engineering & Information Technology (CEIT 2026), Istanbul, Turkey (2026)

[8] N. D. Kouvakas, F. N. Koumboulis, M. P. Tzamtzi, D. G. Fragkoulis, Kl. Katsiavrias, K. Katsiavrias, "A Circuit Model of WDNs Toward Low Power Chlorine Soft Sensor Implementation", 8o PAhellenic Conference on Electronics and Telecommunications (PACET 2026), Greece, 2026

[9] Nikolaos D. Kouvakas, Fotis N. Koumboulis, Maria P. Tzamtzi and Dimitrios G. Fragkoulis, Discrete Time Soft Sensor Design for Water Distribution Networks via Metaheuristic Parameter Optimization, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[10] Maria P. Tzamtzi, Fotis N. Koumboulis, Nikolaos D. Kouvakas, and Dimitrios G. Fragkoulis, DES Supervisor realization of the Safe Switching Mechanism of Soft-Sensors, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[11] Fragkoulis, D.G., Koumboulis, F.N.: Supervisor Water Level Control for the Tanks in a Modular Water Distribution Network Testbed. In: 29th International Conference on Intelligent Engineering Systems 2025 (INES 2025). IEEE, Palermo (2025)

[12] D.G. Fragkoulis, F.N. Koumboulis, M.P. Tzamtzi and N.D. Kouvakas, Supervisor control of a cyber-physical water distribution network in the presence of actuator and sensor faults, in Proc. 2nd Olympiad in Engineering Science (OES 2025), Stavanger, Norway, June 10–14, 2025 (2025)

[13] D.G. Fragkoulis, F.N. Koumboulis, M.P. Tzamtzi and N.D. Kouvakas, Supervisor control and pump fault diagnosis through flow and pressure sensors in a water transfer network, in 2025 10th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM), Patras, Greece, 1–6 (2025)

[14] D.G. Fragkoulis, F.N. Koumboulis, A.N. Menexis, M.P. Tzamtzi and N.D. Kouvakas, Design and FIWARE implementation of a pump fault modular diagnosis system in water distribution networks, in Proc. 3rd Springer International Conference on Frontiers of Artificial Intelligence, Ethics and Multidisciplinary Applications, Stavanger, Norway (2025)

[15] Fotis N. Koumboulis, Dimitrios G. Fragkoulis, Maria P. Tzamtzi and Nikolaos D. Kouvakas, Supervisor Control of Water Distribution Network Actuators under Partial Observation, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[16] M.P. Tzamtzi, F.N. Koumboulis, D.G. Fragkoulis and N.D. Kouvakas, A generic supervisor control and fault diagnosis scheme for water quality and safe performance of water distribution networks, submitted

[17] Dimitrios G. Fragkoulis, Fotis N. Koumboulis, Maria P. Tzamtzi, Nikolaos D. Kouvakas, Konstantinos S. Katsiavrias, Klimis K. Katsiavrias, Discrete Event Modelling, Supervisor Control and Fault Diagnosis of the Chlorinated Water Station of Delfino based on the Sensor and Actuator Interaction, submitted

[18] N.D. Kouvakas, F.N. Koumboulis, M.P. Tzamtzi, D.G. Fragkoulis, Kl. Katsiavrias, K. Katsiavrias and J. Dimitropoulos, Composite water quality indices for supply networks, in 12th Int. Conf. on Control Engineering & Information Technology (CEIT 2026), Istanbul, Turkey (2026)

[19] M.P. Tzamtzi, F.N. Koumboulis, D.G. Fragkoulis, N.D. Kouvakas, K. Katsiavrias and K. Katsiavrias, Toward the development of an ontology for supervisory control and fault diagnosis in water distribution networks, in 2025 10th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM), Patras, Greece, 1–8 (2025)

[20] Michael Skarpetis, Fotis N. Koumboulis, Nikolaos D. Kouvakas and Maria P. Tzamtzi, An Integrated MATLAB Graphical User Interface for Hydraulic and Water Quality Modelling and Analysis in Water Distribution Networks, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[21] Tatiana Drosou, Nikolaos D. Kouvakas, Fotis N. Koumboulis, Maria P. Tzamtzi, Dimitrios G. Fragkoulis and George, Chamilothoris, Performance Quantitative Assessment of Linear and Discrete Time Approximants for Dynamic Water Distribution Network Models, 1st International Conference on Monitoring and Control of Water Systems (MoCWS 2026), Halkis, Greece, 2026

[22] Nikolaos D. Kouvakas, Fotis N. Koumboulis, Antonios N. Menexis, Dimitrios G. Fragkoulis and Maria P. Tzamtzi, On the Reduced Observer Bank Synthesis and Edge Implementation for Residual Clorine Concentration Soft Sensors in Water Distribution Networks, submitted