ICA2025OSLO
14th IWA Specialised Conference on
Instrumentation, Control and Automation

# An ontology-driven multi-agent system for decision support in decentralized water management

Athanasios Latinis*,**,***, Elena Torfs***, Ingmar Nopens*, **, Saba Daneshgar*,**,****
*BIOMATH, Department of Data Analysis and Mathematical Modelling, Ghent University, Coupure links 653, 9000 Ghent, Belgium
**Centre for Advanced Process Technology for Urban Resource Recovery (CAPTURE), Frieda Saeysstraat 1, 9000 Gent, Belgium
***Université Laval, 1065 avenue de la Médecine, Québec G1V 0A6, QC, Canada
****VITO, Water and Energy Transition Unit, Boeretang 200, 2400, Mol, Belgium
Athanasios.Latinis@UGent.be, Saba.Daneshgar@UGent.be

**Abstract:** This work presents a Python-based framework for decentralized water management that leverages an ontology-driven knowledge graph and a multi-agent system. In contrast to traditional, linear methods, this framework supports closed water cycles at the household level and scales to neighbourhoods. A custom ontology provides a semantic backbone for integrating heterogeneous data sources and dynamically managing knowledge. Through this ontology, agents autonomously query, compute, and update information, ensuring timely simulations and decision support. Interoperability is demonstrated by integrating external treatment process models and enabling efficient data exchange. By connecting disparate data and simulation models through a flexible, ontology-driven architecture, this framework offers a scalable solution to enhance water resilience at both the household and community levels.
**Keywords**: Decentralized Water Management; Knowledge Graphs; Autonomous Agents; Ontology; Interoperability

## Introduction

Water scarcity, heightened by climate change and rising demand, poses critical challenges for many regions [1,2]. Transitioning to a circular water and resource economy can address these issues by bridging siloed sectors (e.g., drinking water, wastewater, agriculture, industry). As Olsson [3] highlights, addressing global challenges such as water scarcity and climate resilience requires moving beyond traditional 'component views' to adopt a systemic perspective that recognizes the interconnections between water, energy, food, and other sectors. To develop a more systemic and resilient approach to water management, interoperability is a key challenge which requires integrating diverse data and enabling adaptive optimization [4].

Semantic web technologies—ontologies, knowledge graphs (KG), and data standards—offer interoperability and efficient data integration [5-7]. An ontology is a graph-based representation of domain knowledge, enabling data mapping and retrieval. Moving from stand-alone models to ontology-based frameworks boosts knowledge exchange and informed decision-making. This work focuses on closed water cycles at household and neighbourhood levels. A new ontology and knowledge graph enable a multi-agent system that unifies external models, real-time data, and optimization. Scaling from households to neighbourhoods demonstrates adaptability and bolsters water resilience while promoting standardization, modularity, and alignment with global sustainability goals.

## Novel ontology framework development

The ontology framework harmonizes diverse water data—treatment configurations, storage, flows—using semantic modelling to ensure consistent interpretation. Mapping data onto the ontology creates a queryable knowledge graph [8]. Intelligent agents then perform computations for system scaling.

***Ontology:*** The domain-specific ontology provides a semantic backbone for modelling decentralized water systems. It includes classes for water sources, usage points, treatment processes, and storage units, represented in RDF, a directed graph of triple data. Relationships like "flowsTo" connect entities, enabling integration of static and dynamic data. A simplified graphical representation of the ontology is shown in Figure 1a, and its application to a household-scale water

cycle in Figure 1b. Additionally, it links to top-level ontologies for domain-agnostic concepts (e.g., units of measurements). Further coupling to existing ontologies in the water or related domains allows easy scale-up and extension.

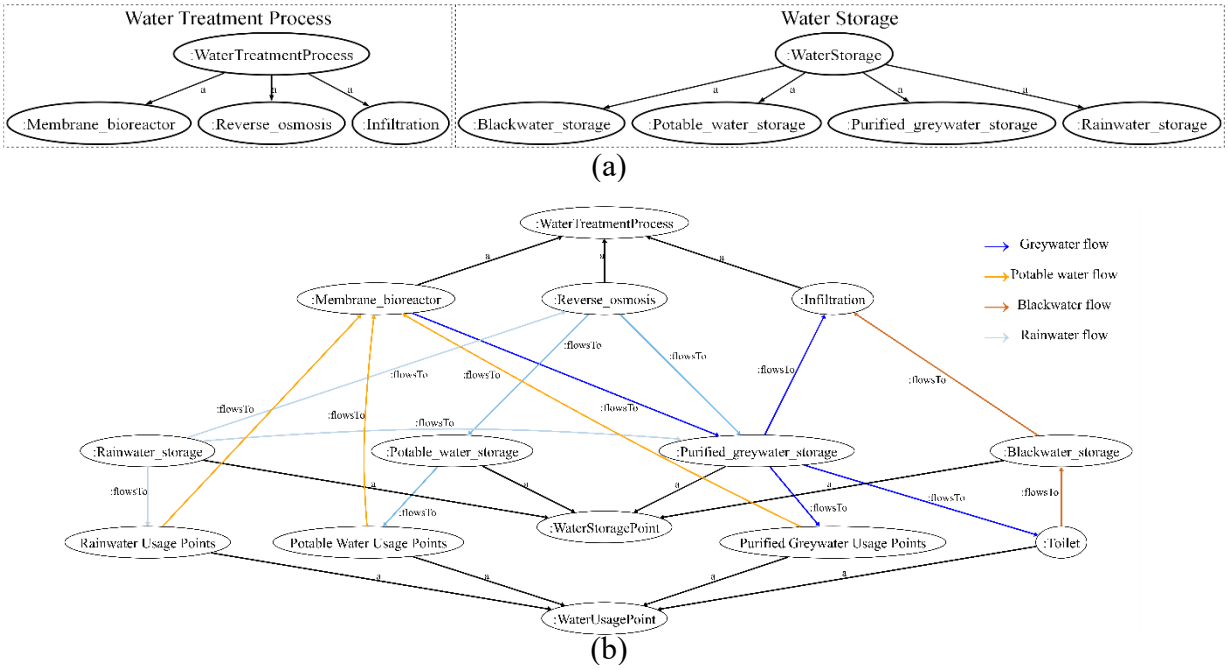


**Figure 1.** (a) RDF triple-based ontology showing key entities (e.g., water treatment processes, storage types) and their relationships within decentralized water systems. (b) Application of the ontology to a household-scale water cycle, illustrating flows between treatment processes (e.g., membrane bioreactor, reverse osmosis), storage units (e.g., potable and rainwater storage), and usage points (e.g., kitchen, shower, toilets and other water usage points).

***Data Mapping:*** Using YARRRML [9] mappings, system data (e.g., tank capacities, current levels) is tied to ontology concepts. Updated data is stored as RDF triples, maintaining consistency between real-world sources and the ontology.

***Agent-Based Computation:*** The following agents have currently been developed to interact with the knowledge graph and aid in decision support:

- **Query Agent:** Executes SPARQL queries, identifies missing data, and triggers computations as needed.
- **Mass Balance Agent:** Simulates tank levels and flow rates using known configurations and real-time inputs, based on mass balance principles [10].
- **RO Agent (Reverse Osmosis):** Steady-state model for RO unit's simulation [11].

***External Data Integration:*** Weather data from the Open-Meteo API [12], combined with geospatial metadata [13], provides localized inputs like temperature and rainfall. Integrating this information into the ontology and KG supports interoperability and adaptive decision-making.

**Results and Discussion**

The developed framework (Figure 2) enhances decentralized water management by integrating ontologies, KGs, and agents to handle both static and dynamic queries.

Static queries (e.g., tank capacities) are returned if the KG has already the data; otherwise, missing data prompts new mappings. Dynamic queries (e.g., current tank levels) require additional steps: if data are not present, the Mass Balance Agent computes them, the database is updated, and the KG refreshed.

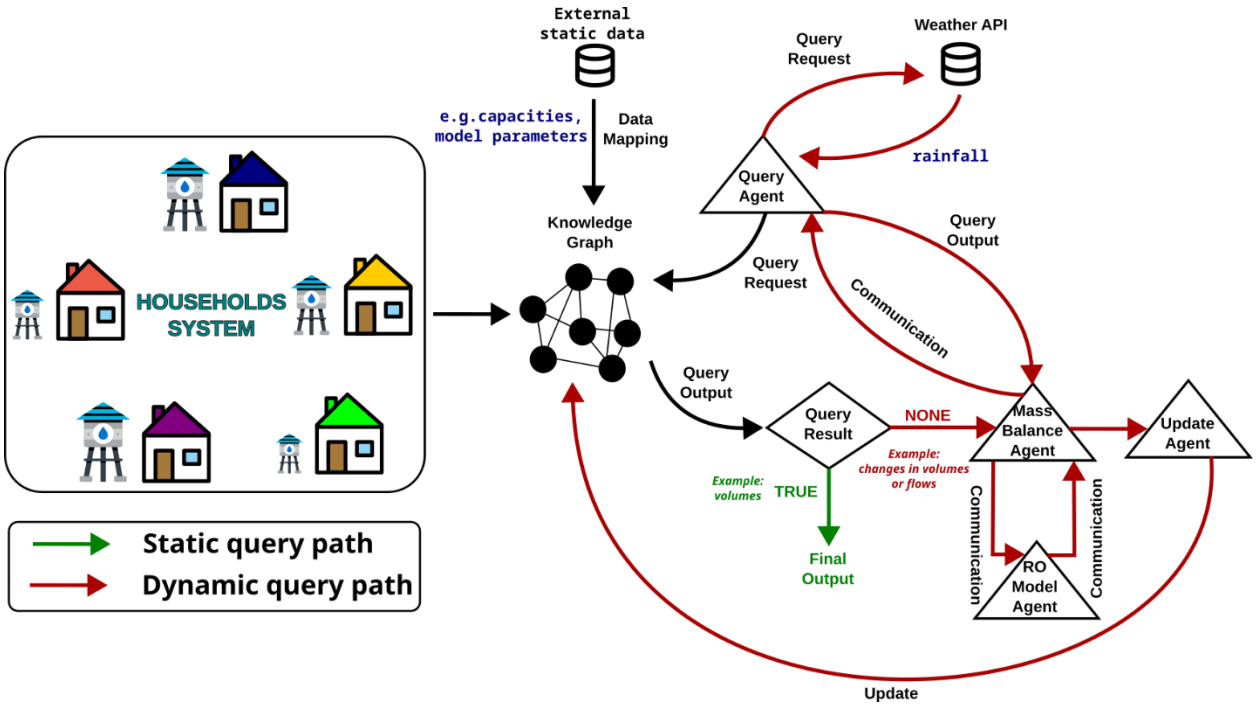


**Figure 2.** The multi-agent, ontology-driven framework for decentralized water management. Household-level data (left) feed into the knowledge graph (center), enabling queries through the Query Agent from external data sources (e.g., weather APIs). When data are missing or outdated, the Mass Balance Agent, RO Model Agent, and Update Agent coordinate to refresh the ontology and re-run queries, ensuring real-time responsiveness.

Figure 3 shows rainwater tank levels for five households simulated alongside daily rainfall. Each household has distinct roof surface area and tank capacity, affecting collection and usage patterns. HH1, lacking rainwater collection, depends on potable water refills and experiences frequent depletion. HH3, 4, and 5 progressively increase resilience with larger tanks and roof areas. HH4 and HH5 avoid refills entirely, highlighting the influence of storage capacity on reliability.
This modular approach remains scalable across various queries, from single households to entire neighbourhoods, incorporating real-time weather and external models. Separating static and dynamic query handling achieves both computational efficiency and responsiveness.

**Future Work**

1. **Ontology Expansion:** Extend the ontology to include more concepts like other sources of water (e.g., effluent wastewater, groundwater, ...) and other reuse purposes (e.g., industrial use) to allow for more complex water management scenario analysis.
2. **Agent Layer Enhancement:** Introduce additional computational agents and predictive models (e.g. for MBR and centralized WWTP) to simulate diverse scenarios, improving adaptability and decision-making accuracy.
3. **Optimization Agent:** Develop an intelligent optimization agent leveraging results from multiple computational agents to balance efficiency, costs, and sustainability for multi-criteria decision-making.

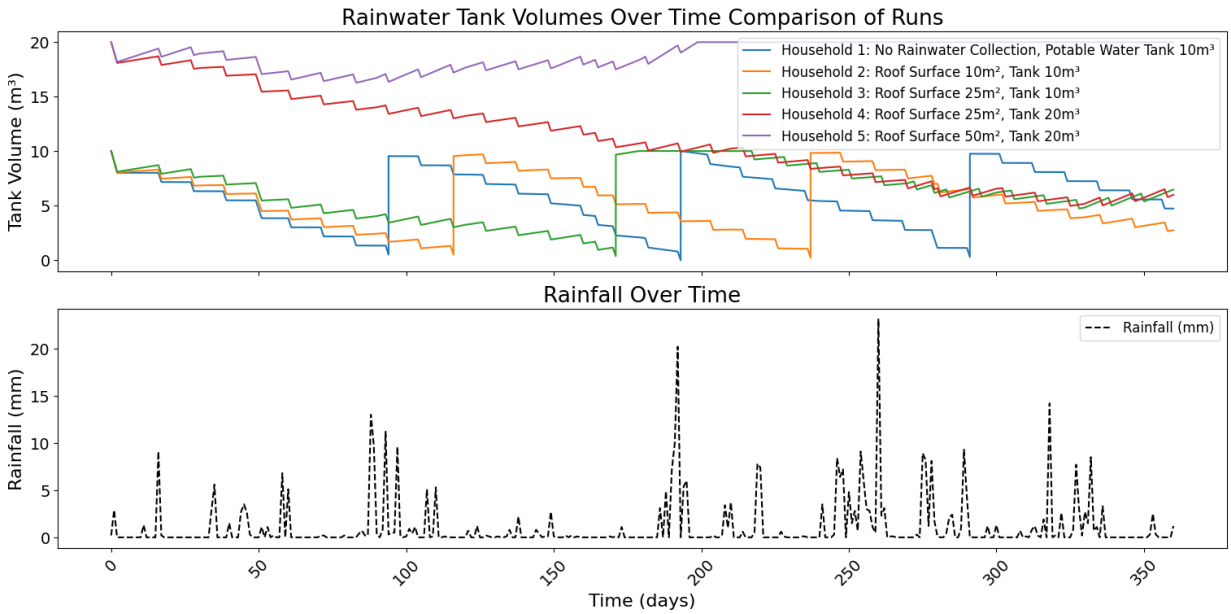


**Figure 3.** Simulated rainwater tank levels of the 5 households as a result of the dynamic query over the KG.

## ACKNOWLEDGEMENT

This work has been carried out within the FWO-SBO WaterFRAME project (S001124N).

## REFERENCES

1. WRI 2021 Water Stress by Country. World Resources Institute. Available at: https://www.wri.org/data/water-stress-country
2. Flato, G. et al. 2013 IPCC Fifth Assessment Report: Climate Change 2013 – The Physical Science Basis. Cambridge University Press, Cambridge, UK.
3. Olsson, G. 2022 Water Interactions – A Systemic View: Why we Need to Comprehend the Water-Climate-Energy-Food-Economics-Lifestyle Connections. IWA Publishing, London.
4. Yuan, Z., Olsson, G., Cardell-Oliver, R., van Schagen, K., Marchi, A., Deletic, A., Urich, C., Rauch, W., Liu, Y., Jiang, G. 2019 Sweating the assets - The role of instrumentation, control and automation in urban water systems. Water Res. 155, 381–402.
5. Hofmeister, M., Bai, J., Brownbridge, G., Mosbach, S., Lee, K.F., Farazi, F., Hillman, M., Agarwal, M., Ganguly, S., Akroyd, J., & Kraft, M. 2024 Semantic agent framework for automated flood assessment using dynamic knowledge graphs. Data-Centric Engineering, 5, e14.
6. Elag, M. & Goodall, J.L. 2013 An ontology for component-based models of water resource systems. Water Resour. Res. 49, 5077–5091.
7. Ceccaroni, L. 2001 OntoWEDSS—An ontology-based environmental decision-support system for the management of wastewater treatment plants. Doctoral Thesis. Universitat Politècnica de Catalunya, Barcelona, Spain.
8. Zhou, X. et al. 2019 An agent composition framework for the J-Park Simulator – A knowledge graph for the process industry. Comput. Chem. Eng. 130, 106577.
9. YARRRML Specification. rml.io. Available at: https://rml.io/yarrrml/
10. Van de Walle, A. et al. 2022 In silico assessment of household level closed water cycles: Towards extreme decentralization. Environ. Sci. Ecotechnol. 10, 100148.
11. Gaublomme, D., Strubbe, L., Vanoppen, M., Torfs, E., Mortier, S., Cornelissen, E., … Nopens, I. (2020). A generic reverse osmosis model for full-scale operation. DESALINATION, 490. https://doi.org/10.1016/j.desal.2020.114509
12. Open-Meteo API. Available at: https://open-meteo.com/en/docs
13. OGC 2015 OGC Standards and Specifications. Open Geospatial Consortium. Available at: https://www.ogc.org/