# AN ONTOLOGY FRAMEWORK FOR DECENTRALISED WATER MANAGEMENT AND ANALYTICS USING WIRELESS SENSOR NETWORKS

**KATSIRI E.**[1] **and MAKROPOULOS C.**[2]

[1]Department of Electrical and Computer Engineering, Democritus University of Thrace, Polytechnioypoli, Kimmeria, 67100, Xanthi, Greece, [2]National Technical University of Athens, 9, Iroon Polytechniou Zografou, 15780, Athens, Greece
E-mail: ekatsiri@gmail.com

## ABSTRACT

Decentralized Water Management (DWM) technologies such as grey water recycling, rainwater harvesting, sustainable urban drainage systems, and their combined application, offer feasible ways of rationalizing existing regimes of water usage (tap water, grey water, rain water) through the use of appropriate technologies, which scale down and localize the management of water. However, the implementation of DWM systems as a mainstream practice is impeded by the knowledge gaps on their actual performance in a range of development types and settings. As the widespread uptake of these approaches in modern cities is relatively new compared to centralised approaches, there is limited information available on their planning, design, implementation, reliability and robustness.

Wireless Sensor Networks (WSN) provide a capable platform for low cost, high performance and real-time monitoring. By bringing together the strengths of WSN technology and distributed, reactive, knowledge management and representation, implemented as a dual-layer ontology framework, this work provides a holistic approach to the management of DWM systems. Real-time data on water consumption, water quality, soil quality, unusual events or infrastructure outages is exploited in order to: control the grey water reuse process, detect and react to any failures and unusual events (e.g., floods, bursts, pump failures), analyze and improve the efficiency of water reuse, and predict the optimal time for maintenance thus improving system availability.

**Keywords:** sensor networks; grey water; smart sustainable home; pilot; water reuse; real-time analytics; ontology; knowledge management, rule-based reasoning

## 1. Introduction

The current context for Decentralized Water Management (DWM) technologies such as grey water recycling, rainwater harvesting, sustainable urban drainage systems, and their combined application have the potential to provide a viable option for long term sustainable management of household wastewater. Yet, at present, such systems hold an uncertain status and are frequently omitted from consideration. Their potential can only be realised with improved approaches to their management, and improved methods to decision-making in planning of DWM systems.

Over the past decade, advances in the semiconductor industry, wireless communication, sensor design, and energy storage technologies have helped realise the concept of a truly pervasive Wireless Sensor Network (WSN) (Bulusu, 2005). Integrated microsensors no more than a few millimeters in size, with onboard processing and wireless data transfer capability are the basic components of WSN. The ICT community has developed several Smart Home and Smart Cities WSN systems and tools that can be built into useful solutions for DWM-enabled smart sustainable homes (Katsiri, 2015). What is still missing is a reactive, distributed knowledge management and reasoning framework for DWM operations. This must be addressed in a systematic way taking advantage of current ICT knowledge.

The smart, sustainable home is event-driven; data is communicated in the form of events that can be low-level e.g., soil.temperature>30C, soil.moisture=0, or abstract (Katsiri, 2007) e.g., garden_needs_irrigation. Events trigger linked actions e.g., open_tank_valve in order to top up processed gray water with potable water, or start_irrigation. The system also raises alerts about insufficient water quality or quantity, about upcoming need for equipment maintenance, or if a fault (pump failure, blackout, leak) occurs. Furthermore, real-time analytics (Jagadish, 2012) such as the calculation of a real-time water balance are continually triggered by event streams.

The ICT community has developed several knowledge management formalisms, e.g. UML, Hoare logic (Hoare, 1969), etc. The most widely adopted is that of an ontology, i.e. a set of representational primitives, typically classes (or sets), attributes (or properties), and relationships (or relations among class members), with which to model a domain of knowledge or discourse (Gruber, 2009). The recent emergence of Semantic Sensor Web (SSW) has produced the SSN (Semantic Sensor Network) ontology (Compton, 2012) as a standard for describing the Stimulus-Sensor-Observation pattern in WSNs. However, SSN lacks both DWM vocabulary as well as abstractions for event-based interaction.

Our approach, DiHydro, firstly, extends the SSN ontology with primitives from the DWM domain (grey water, MBR, CBR, factsheets, actuator observations, alerts, suggested actions). Secondly, by extending DiHydro with Hoare logic rules we a) allow applications to register inference rules that generate abstract knowledge (e.g., garden_needs_irrigation) from low-level, sensor-derived knowledge (e.g., soil.moisture and soil.temperature readings), b) calculate analytics (e.g., real_time_water_balance) from low-level data (e.g., grey water.flow, tank.level) and c) link high level knowledge with actions (e.g., open_tank_valve). Thirdly, by extending DiHydro with event-based abstractions (input, output, topic, publisher, subscriber) we allow users to define distributed WSN topologies.

The presence of DiHydro on the Web provides a centralized machine-readable knowledge repository for DWM-enabled smart sustainable homes that can be used in a variety of ways. First, it acts as a simulation reasoning tool; when linked with real-time data, it can produce as output, alerts (e.g. leak), suggested actions and real-time analytics. Second, it be used as a tool for driving publish-subscribe (Eugster, 2003) communication; by linking at the ontology level the output of a water quality sensing node (publisher) with the input of the Arduino actuator node that controls the tank electro-valve (subscriber), the suggested action open_tank_valve (topic) should be the topic of a WSN message that is physically sent from publisher to subscriber. Third, it implements the business logic of DWM management at WSN node level. The integration of DiHydro with Java code running on each WSN node, is realized by means of the OwlAPI.

## 2. Model description

An event (Mansouri-Samani, 1997) is a happening of interest that occurs instantaneously at a specific time. (Katsiri, 2007) introduced the notion of an abstract event as a change in a logic predicate's state from TRUE to FALSE or vice versa (e.g., leak, garden_needs_irrigation). Abstract event detectors are described by Hoare logic rules and detected by Rete networks (Forgy, 1982). An extension of the publish-subscribe protocol (Eugster, 2003) was proposed that uses abstract events.

We define a Core Ontology Layer (COL) that maintains a low-level but precise view of the current logical state of the smart sustainable home, as produced by sensors that are distributed throughout the environment and continually updated through events. Equally, we define a Deductive Ontology Layer (DOL) maintains an abstract view of the current logical state of the smart sustainable home, which can easily be inferred from the knowledge stored in the COL using Hoare rules. For example, a Hoare logic expression for defining the abstract event garden_needs_irrigation using the soil temperature and moisture values is:

$$\text{soil.moisture}(x)=0 \wedge \text{soil.temperature}(y)>30C \rightarrow \text{garden\_needs\_irrigation}(x,y)$$

The COL contains N individual values (instances) that represent nodes (Arduino), some of which are equipped with sensors and some with actuators. There are also M sensors, K actuators, L

DWM components and one gateway server. All the above systems are devices (Figure 2). Arduino nodes can be either information producers, consumers, or prosumers of certain information topics. Sensors can be of type water quality, water level, flow, leak or current. They are defined by a sensing function and a proxy and each have one input (stimulus) and one output (observation). The observed real-world phenomenon (e.g. “Heraclion, GR” as described by (DBpedia)) is captured using the entity feature of interest and observation value is used to describe the measured value of a given property (e.g., water conductivity). Each observation, has apart from value, a timestamp and a quality estimate (Figure 1). Sensors also have measurement capabilities (accuracy, sensitivity, precision, response time, frequency, drift), measurement properties (measurement range) and energy restrictions (battery lifetime, operating range). Actuators are of type electro-valve, generic actuator, air-pump.

The DOL contains abstract event detectors, i.e., logic rules for generating abstract events, as well as rules for linking abstract events to invoked actions. For example, the abstract event detector grey water tank needs adding potable water is implemented with the following rules that define the output of the sensor node that is attached to the grey water tank to cause the raising of an alert when the value of water conductivity observation is lower than 400μS. When the alert is received by the actuator node (Figure 3) it causes the creation of the suggested action of opening of the tank valve in order to add potable water thus improving water quality.

water conductivity observation value(x)<400
→ grey water tank needs adding potable water (x) ∧ alert(x) ∧ sensor node output (x)
grey water tank needs adding potable water (x) ∧ actuator node input (x)
⟶ suggested action (x) ∧ open tank valve (x)

The DOL also contains rules for estimating the date of due maintenance of a DMW, based on the installation date, its maintenance specification (factsheet) and the current time. Reactive rules also define the optimal sampling rates whenever a situation of interest has been detected.

### 3. Implementation

DiHydro is written in OWL (OWL, 2009), the standard language for expressing Web-accessible ontologies, as approved by the World Wide Web Consortium (W3C). DiHydro is implemented in Protégé (Protégé, 2004), with SWRL support for rules (SWRL, 2004).

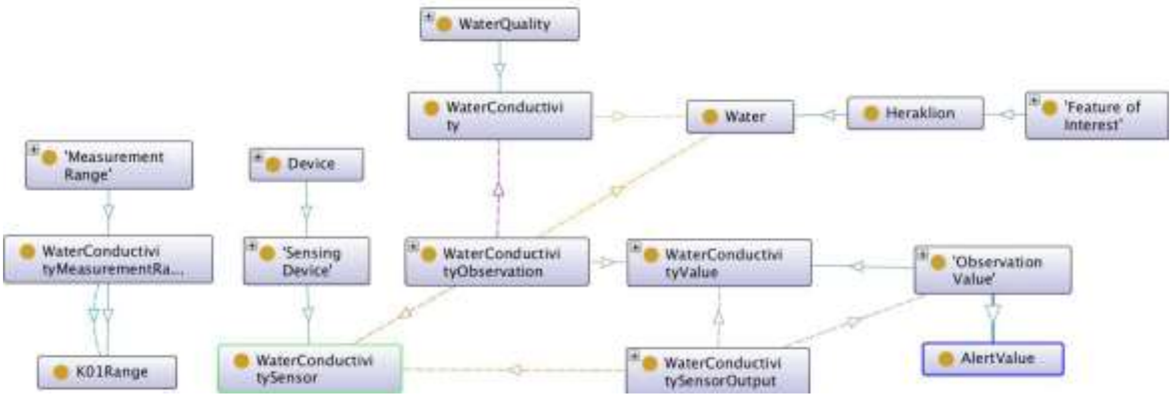


**Figure 1:** Water Conductivity Observation

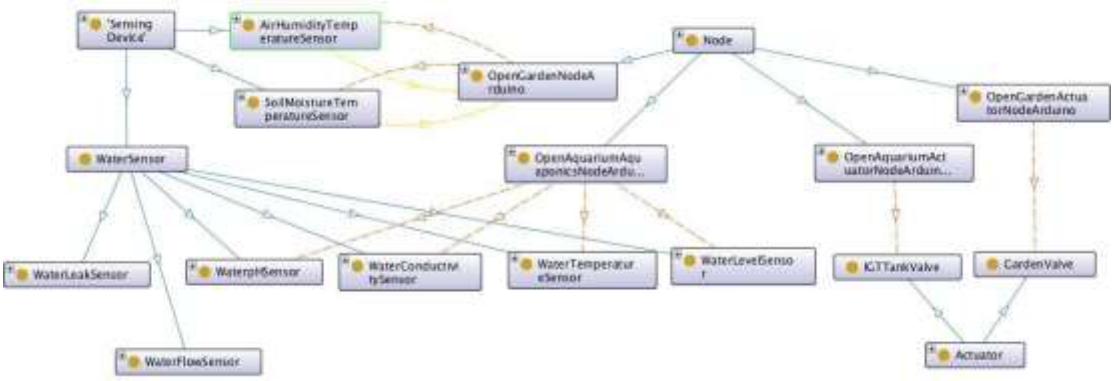


**Figure 2:** System Devices View

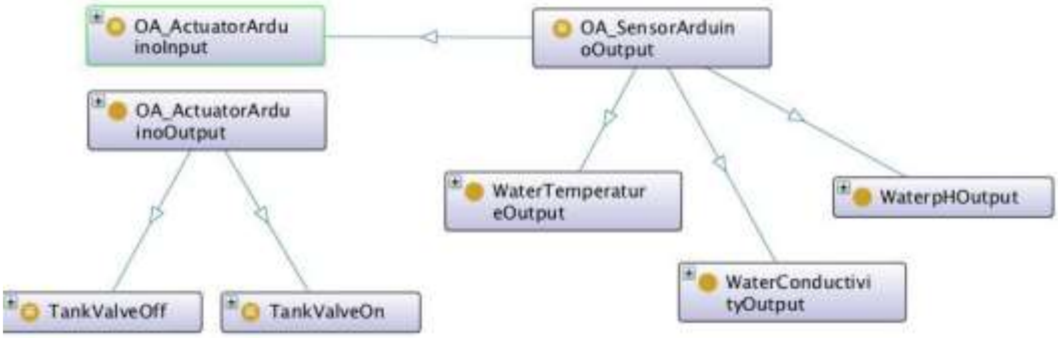


**Figure 3:** The publish/subscribe protocol between sensor and actuator nodes

## 4. Conclusions

Concluding, this paper presents DiHydro, a novel ontological framework that provides the base and standard for the rapid deployment and reliable management of DWM technologies.


## ACKNOWLEDGMENTS

This paper is part of the research program Hydropolis: Urban development and water infrastructure – Towards innovative decentralized urban water management. The programme is co – financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF). Research Funding Program: THALES. Investing in knowledge society through the European Social Fund». The work presented is part of Action 7: “Distributed, cooperative infrastructure management”.


## REFERENCES


1. Arduino. Open-source electronic prototyping platform allowing to create interactive electronic objects. http://www.arduino.cc
2. Bulusu, N.; Jha, S. (2005), Wireless sensor network systems: a systems perspective. Artech House Publishers
3. Compton, M.; et al. (2012), The SSN Ontology of the W3C Semantic Sensor Network Incubator Group, Web Semantics: Science, Services and Agents on the World Wide Web
4. DBpedia http://www.dbpedia.org
5. Eugster, P.T.; Felber, P.A.; Guerraoui, P.; Kermarrec, A.-M. (2003), The many faces of publish-subscribe. ACM Computing Surveys 35(2), 114-131

6. Forgy, C.L. (1990), Rete A fast algorithm for the many pattern/many object pattern match problem. Expert Systems, 324-341
7. Gruber, T. (2009), Ontology. Encyclopedia of Database Systems, Springer-Verlag
8. Hoare, C. A. R. (1969), An axiomatic basis for computer programming. Communications of the ACM 12(10), 576-580
9. Jagadish, H. V. (2012), Big Data. It's not just the analytics. http://wp.sigmod.org/?p=430
10. Katsiri, E.; Bacon, J.; Mycroft, A. (2007), SCAFOS: Linking sensor data to context-aware applications using abstract events. Int. Journal of Pervasive Computing and Communications, 3(4), 347-377
11. Katsiri, E.; Makropoulos, C. (2015), Decentralised water management and analytics using wireless sensor networks, IWA Balkan Young Water Professionals, May, Greece
12. Makropoulos, C. K. and Butler, D. (2010), Distributed Water Infrastructure for Sustainable Communities. Water Resources Management 24(11): 2795-2816
13. Mansouri-Samani, M.; Sloman, M. (1997), Gem: A Generalised Event Monitoring Language for Distributed Systems. Distributed Systems Engineering Journal, 4(2), 96-108
14. Hitzler, P.; Krotzsch M.; Parsia B.; Patel-Schneider P. F. and Rudolph S. (2009), Web Ontology Language: Primer, W3C Recommendation, http://www.w3.org/TR/owl2-primer/
15. Knublauch, H.; Fergerson, W.R.; Noy F.N.; Musen A.M. (2004), The Protégé OWL plugin: An open development environment for semantic web applications, Springer, 229--243
16. Sharma AK; Tjandraatmadja G; Cook S; Gardner T; (2013), Decentralised systems definition and drivers in the current context. Water Sci Technol.;67(9):2091-101.
17. Horrocks, I; Patel-Schneider, P.F.; Boley H.; Tabet, S.; Grosof, B.; Dean, M. (2004), SWRL: A Semantic Web Rule Language Combining OWL and RuleML. W3C Member Submission, May 2004. http://www.w3.org/Submission/SWRL/