Smart Water System Interoperability: Integrating Data and Analytics for Demand Optimized Management through Semantics

Shaun K. Howell[1], Yacine Rezgui[2], Tom Beach[3], Wanqing Zhao[4], Julia Terlet[5], and Haijiang Li[6]

1) Ph.D. Candidate, School of Civil Engineering, Cardiff University, Cardiff, UK. Email: HowellSK5@cardiff.ac.uk
2) Professor, School of Civil Engineering, Cardiff University, Cardiff, UK. Email: RezguiY@cardiff.ac.uk
3) Ph.D., School of Civil Engineering, Cardiff University, Cardiff, UK. Email: BeachTH@cf.ac.uk
4) Ph.D., School of Civil Engineering, Cardiff University, Cardiff, UK. Email: ZhaoW9@cardiff.ac.uk
5) Ph.D. Candidate, School of Civil Engineering, Cardiff University, Cardiff, UK. Email: TerletJJ@cardiff.ac.uk
6) Ph.D., School of Civil Engineering, Cardiff University, Cardiff, UK. Email: LiH@cardiff.ac.uk

Abstract:

Efficient urban water management is an increasingly pressing challenge due to growing population density, and competing pressures towards business objectives and sustainability, both in terms of water conservation and energy expenditure. Even in locations of water abundance, the energy consumption of clean and foul water systems mandates efficient management and wastage minimization. Beyond improved system components and localised optimisations, research is approaching this task through methods of 'smart' water management, which utilizes the 'whole-system intelligence' paradigm popularised through the 'smart grid' and 'smart city' phrases. These aim to improve system operation through intelligent sensing, integration of system components, ICT penetration, active users and data-driven management through advanced analytics. This paper therefore presents a novel cloud platform which unifies clean and waste systems to deliver demand responsive water management within a service oriented architecture; integrating state of the art sensing and analytic components through a semantic knowledge base. This knowledge base reuses GIS data alongside dynamic sensor data, social concepts and inference rules. This integrates previously isolated systems as well as supply and demand side optimizations and interventions to improve system performance across various indicators. Further, this paper outlines the key systemic interventions which the overall project addresses and initial results regarding the performance of the various business services offered, within two pilot sites, and discusses the impact of the work alongside similar projects. The findings suggest the value of utilizing a 'smart' and integrated approach within water systems, towards benefits across stakeholders and sustainability objectives.

Keywords: big data, service oriented architecture, water, water management, waste, waste management, semantics, interoperability, demand optimised management, intelligent sensing, smart cities, data analytics

1. INTRODUCTION

The application of ICT to water management holds the potential to improve network efficacy, longevity and efficiency, similar to other fields where ICT is being applied, such as smart electricity grids and smart cities. This has been increasingly recognized across stakeholders over the past 5 years as a means to deliver water loss reduction, energy savings, water quality assurance, improved customer experience and operations optimization, amongst other KPI benefits (Kenny 2013; Peleg 2014; Miller and Leinmiller 2014; Williamson et al. 2014). This is achieved through the use of advanced analytics to provide insight into complex systems through abundant data and an integrated approach. However, as with smart grids and smart cities, the application of ICT in the water value chain is restricted due to an inability to share data and knowledge, and hence interoperate, across the people and software components involved. In smart grids, this has been stated by authoritative bodies to occur due to three main issues: lack of machine communication protocols, lack of common data formats and lack of common meaning of exchanged content (IEEE Standards Committee et al. 2011). In the smart grid and smart city domains, this is being addressed in part through the development of shared data models to facilitate data exchange, integration of legacy systems, and to enable system security and performance (IEEE Standards Committee et al. 2011; BSI 2014). In the 'smart water' domain, the same core issues have restricted the utility and hence prevalence of ICT and analytics penetration. Therefore, the same key functions of shared data models are required in the water domain, and so recognition of the value of a similar approach in this field is growing (ICT4Water 2015). This paper presents a cloud based platform which integrates data from across the water value chain and provides monitoring and decision support, with a focus on the semantic model and associated web service which integrates the heterogeneous data sources and advanced analytics developed within the WISDOM EC FP7 project. Further, as well as presenting a use case which emphasizes the value of the semantic approach, this paper presents the validation of the models developed through ontology validation and software testing.

The following section gives a brief introduction to semantic modeling and reviews relevant previous efforts in the domain, to highlight the gap addressed, then the cloud platform itself and the ontology service are presented before the detailed semantic model is shown. An application scenario of the web platform which highlights the role of the ontology service is presented before the validation of the ontology and associated web service, and finally a discussion and conclusion regarding the relevance of the work and the future work to be conducted.

2. SEMANTIC MODELLING IN WATER MANAGEMENT

Semantic models address the issue of interoperability by creating a shared data format and understanding for the domain. These benefits have been acknowledged in the field of semantic web technologies through the World Wide Web Consortium (W3C) 'semantic web stack', which shows ontologies playing a critical role (W3C 2015). An ontology is a shared and formal conceptualisation of a domain, and has been adopted as a means of integrating data, knowledge and meaning between people and software components. To this end, an ontology formalises a description of the concepts, relationships, data properties and restrictions within a domain, and is instantiated to be applicable to a specific example of the domain. For a full discussion of the semantic web and the role of ontologies, the reader is advised to consult the W3C semantic web stack literature (W3C 2015).

A deployed ontology may be accessed directly by an interface exposed to users, but it commonly forms the backend of an application, or several applications, in order to provide a data store which captures meaning, contextualises data, standardises terminology, facilitates rule application and produces new knowledge beyond that which is inputted. This therefore assists software developers in producing applications which can more easily utilise in-depth knowledge, and data sets from heterogeneous sources, and can more easily integrate with other software components, to deliver more powerful analytics to users.

As a relatively recent concept in this domain, examples of ontological models in the smart water field are sparse. Whilst several mature ontologies were observed in the earth science field, such as the works of CUAHSI (CUAHSI 2015), SWEET (SWEET 2015) and HydrOntology (Vilches-Blázquez et al. 2009), these were not suitable for the application of ICT to the water value chain, and the only relevant ontology observed was the WatERP "generic ontology for water supply distribution chain" (WatERP 2013a; WatERP 2013b), although the Waternomics 'linked data model' ("Waternomics" 2015) contained some useful concepts. The WatERP ontology is intended to be applied differently to the WISDOM ontology, so contains only 25 classes and few details of the physical processes and components involved in water management, and it doesn't describe relationships between features of interest or actors. The WatERP ontology is split conceptually into a 'supply and demand ontology', 'observation and measurement ontology' and an 'alerts and actions' ontology. Further, the WatERP ontology only captures high level concepts such as physical element types, and a few types of actors. Further depth is therefore required in the semantic modelling of this domain across physical, social and sensory concepts across the supply and demand parts of the value chain, towards demand optimized management.

2. CLOUD PLATFORM

2.1 Smart Business Services for Water Management

The system is conceptually arranged into 4 architectural layers: sensing infrastructure, data acquisition and actuation, core services and business services, as shown in Figure 1. The core services layer contains the system's semantic integration service, optimization and analytics services, event bus and governance module. These core components utilize data communicated from the sensing infrastructure to the event bus via the data acquisition layer, and are delivered to users through the GUIs and edge analytics which form the business service layer. The intended users of the system would primarily be operational staff of the water or waste service provider, although consumers may have access to a restricted set of services. The key innovation presented herein is the use of the core services to integrate analytics across heterogeneous data sources by standardizing data syntax and meaning. This service is now discussed in more detail before presenting the enabling ontology.

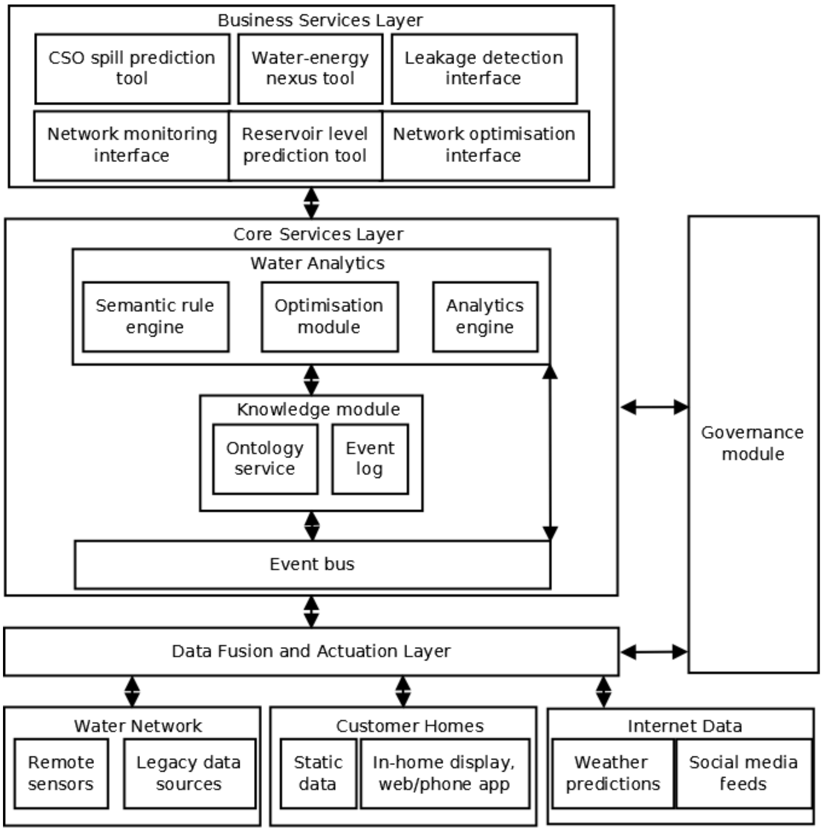

Figure 1: Functional architecture of the proposed ICT solution

2.2 Knowledge Base Integration of Services

The ontology service consists of a water value chain domain ontology common across pilot sites and instantiations of this ontology to create a separate knowledge base for each pilot site. The resulting knowledge bases are stored as persistent RDF triples on a dedicated virtual machine within a cloud computing framework. A RESTful web service, with an API which provides GET, PUT, POST and DELETE functionality via SPARQL queries, as well as convenience GET functions for most common tasks, is also deployed on this virtual machine.

The RESTful web service was developed and deployed in order to provide an interface to the WISDOM ontology. Apache Jena ("Apache Jena - Jena Ontology API" 2015) was chosen to implement this service, which mandated an RDF-centric approach written in Java. The Jena ontology API and TDB API allowed rapid deployment of a persistent OWL DL ontology. Within this deployment, Jena stores ontologies using the ontology model class (OntModel), an extension of the generic RDF model class (Model), and hence views ontologies as more descriptive versions of RDF models. The model is loaded to memory on the startup of the ontology service and currently uses the built-in Jena reasoner to infer new knowledge based on the existing knowledge, and hence creates further RDF triples. Persistence of the ontology is provided by the Jena TDB layer, meaning that the ontology is stored on hard disk and thus data is not lost if the service is terminated or crashes. Within our implementation, SPARQL queries are passed to the Jena model via the Jena ARQ package.

Apache Jena provides a web server implementation of ARQ named Fuseki, which allows the storage and querying of ontologies via SPARQL queries, but Fuseki is designed as a standalone service and was discovered to be time consuming to extend and integrate with the other WISDOM components. For this reason, the Jena implementation of the ontology was wrapped in a RESTful web service and a custom API was developed to allow for querying and updating. This implementation of the ontology service is presented in Figure 2.

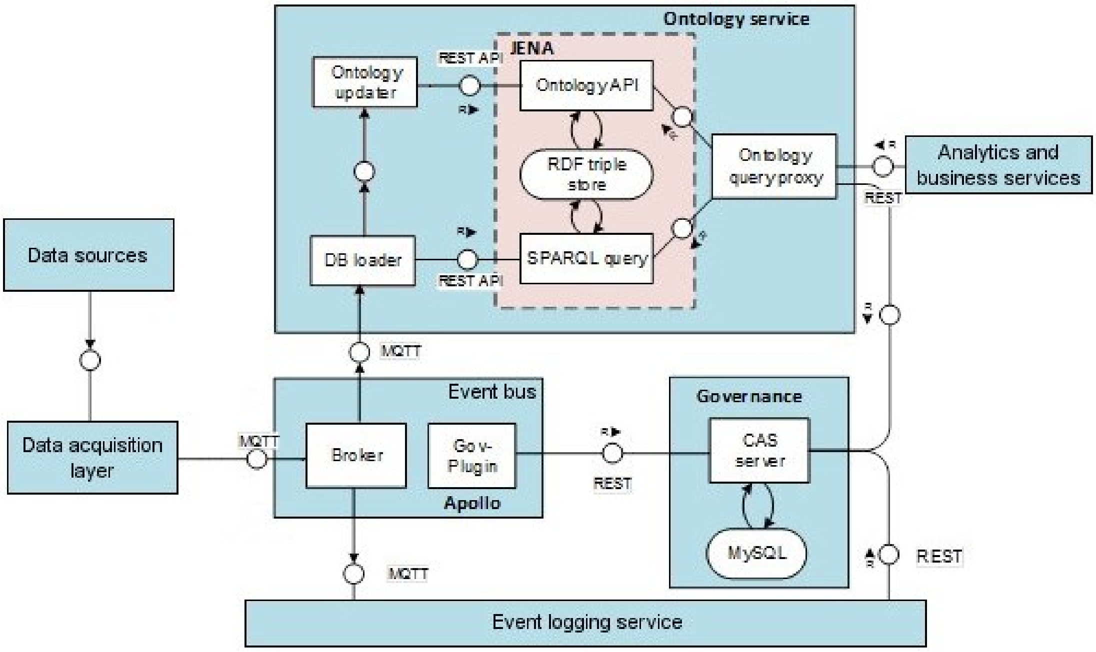

Figure 2: System components of the proposed middleware, showing its role between data sources and analytics

The main use cases of the ontology service are requests for information from other WISDOM system components and updates to the knowledge bases following sensor events. The RESTful GET method which executes a SPARQL SELECT query accepts a URL-encoded SPARQL request and executes this using the Jena ARQ package. The query's result is returned as a JSON object using standard JSON notation for SPARQL results (W3C, 2013).

The deployment of the ontology as a web service supports the benefits of a service-oriented architecture (IEEE Standards Committee et al. 2011) and hence allows plug-and play capability with other software components of the WISDOM architecture, and potentially beyond. The software was developed and tested on a local machine and has since been deployed on the secure cloud environment provided by Imperial College London. This software is now at a mature stage where it is able to handle real-time SPARQL requests as well as custom functions for the most common foreseen uses of the ontology service, evidence towards this is presented in section 5.

3. WATER VALUE CHAIN SEMANTIC MODEL

3.1 Domain Ontology

Developing the domain ontology which underpins the semantic knowledge base service and hence the interoperability innovation of the proposed system used an iterative process. This involved a scoping, development and validation methodology with close domain expert involvement, following the recommendations of the NeOn methodology ("NeOn Wiki" 2015). After knowledge acquisition and a clear requirement specification was completed, a meta-model was developed through reuse of the W3C semantic senor network (SSN) ontology (Compton et al. 2012) and the socio-technical system (STS) ontology of van Dam (Dam 2009). The resulting socio-technical-sensory meta-model of the ontology is presented in Figure 3 below, and its extension to the water domain is subsequently described.

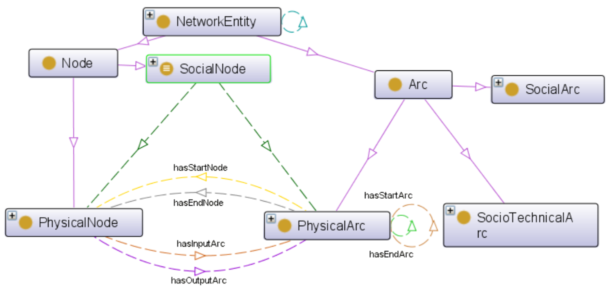

Figure 3: Main concepts and relationships of the ontology meta model

The meta model shown in Figure 3 was extended to fully model both the supply and domestic water value chain by representing the system as 3 interlinked networks: social, physical and sensory, of which the social and physical networks were modelled at the network and node levels of detail. This resulted in an ontology of 384 classes, including detailed hierarchies of asset types, sensor types, hydraulic variables, contract types, and stakeholders in the domain. Some of the key classes involved in managing real time data from sensors attached to the physical water network and their relationships are shown in Figure 4. The sensory concepts shown in Figure 4 are aligned with the W3C SSN ontology, and the entire water model is aligned with the meta model shown previously, to allow broad linkage of data within and external to the domain.

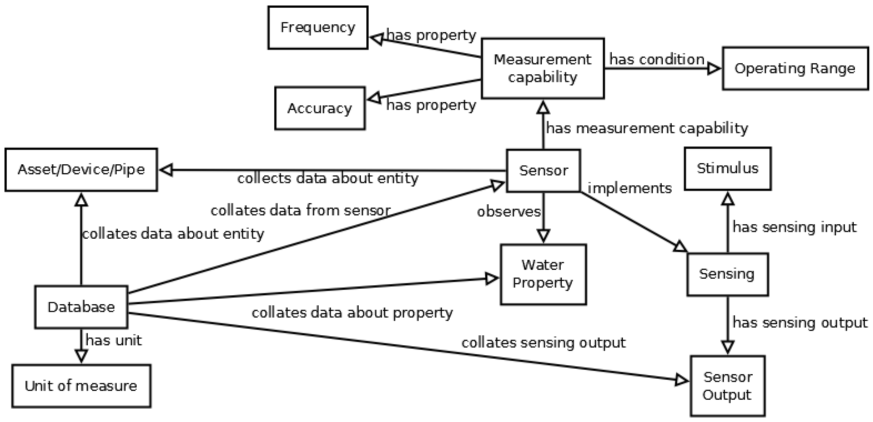

Figure 4: Main concepts and relationships (inverses not shown) for sensory and physical knowledge integration

3.2 Ontology Instantiation and Legacy System Integration

The domain ontology constitutes a vocabulary with which to describe water value chains, and this was utilised to create semantic models for each of the 4 pilot sites. Each of these separate models contains static information regarding the water value chain's physical and social network, such as pipe dimensions, asset information, sensor locations and inhabitant information for residences. They also contain real-time data regarding the current state of the water network, such as the latest pressure reading for a pipe, or the recent consumption of a DMA. The instantiation of the domain ontology for each pilot site was conducted through both automatic federation of existing data sources, and manual elicitation and formalization of expert knowledge.

The cloud platform developed intends to integrate with existing ICT systems within the international water industry to constitute a step change towards smart water, so the ability to integrate with legacy systems was seen as a key requirement. The ontology therefore reuses knowledge available in private GIS systems and sensor databases at each pilot site by federating this into rdf triples, aligned with the domain ontology presented previously. This was achieved for the GIS system in an automated offline manner through a python script. Updating the representation of the water network with real time sensor data from the existing SCADA systems is performed automatically through subscription to the message broker component of the event bus shown previously in Figure 1. Updating the physical infrastructure following maintenance would require an UPDATE SPARQL query to be requested by a system admin, although future work will aim to mask the SPARQL complexity of this task.

4. PLATFORM APPLICATION: OPTIMIZING THE OPERATION OF WATER NETWORKS

One of the key analytics services provided by the WISDOM platform is the optimization of the daily operation of water networks. This uses a range of metaheuristic optimization techniques to minimize the energy and water consumption of the network by providing online near-optimal suggestions for pump and valve control. Meanwhile, a set of constraints such as tank and reservoir operational level ranges and minimum pressure head requirements are intrinsically satisfied as a result of the optimization. Upon receiving a request from the business services layer, the optimization module is initialized by requesting the current state of the water network from the ontology service. This then populates the optimization model with data such as network topology, pipe dimensions, pump descriptions and current consumption behaviors in the network. The optimization service then uses this knowledge within a hydraulic model and a range of candidate optimization methods such as simulated annealing, genetic algorithms and differential evolution. This overall process is shown in Figure 5 below, and ultimately outputs optimal set points for various key actuators in the network, so as to provide decision support to the staff of the water service provider.

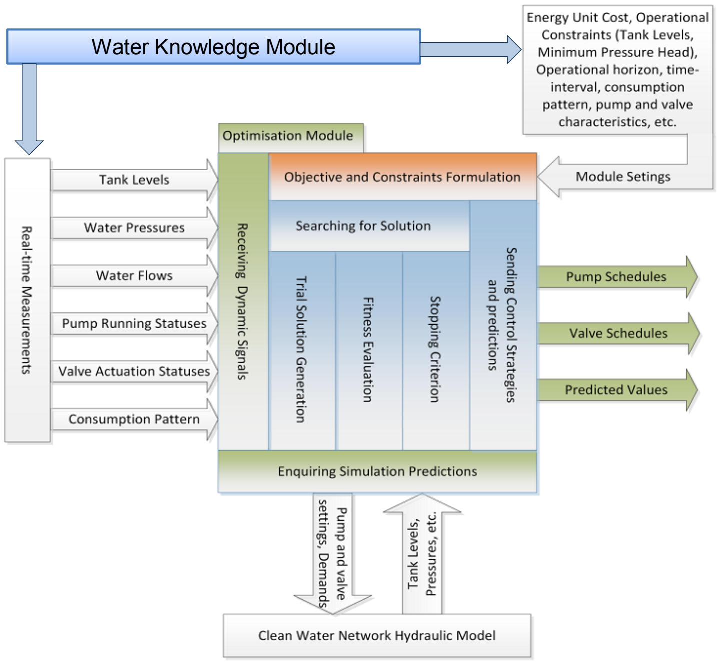

Figure 5: Methodology for water network operational optimization

The ontology service plays a key role in facilitating this optimization of the water network, by integrating data across domains and scales for use by the optimization module. An example of this integration is shown in Figure 6, which also demonstrates the key approach of ensuring data privacy; whilst the use of domestic knowledge is useful for analytics, and network knowledge may be helpful to consumers, it is critical to respect the privacy of data owners. The system therefore balances the benefit of integrating data with the requirement for data security and privacy by facilitating private and shared objects.

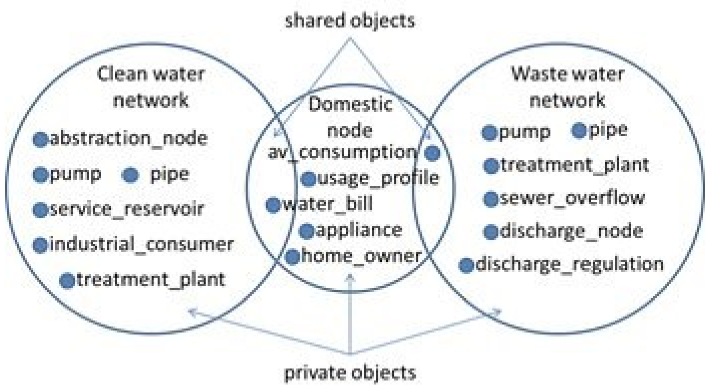

Figure 6: Integration of object knowledge across the water value chain to highlight the capability for data privacy

5. RESULTS

The validation of the process adopted and the interoperability artefacts produced was conducted through 2 stages: firstly the validation of the domain model as an accurate, sufficient and shared conceptualization of the domain. Secondly, the validation of the ontology instantiation and deployment as a web service, through software testing, was conducted.

5.1. Ontology Validation

The validation of the domain ontology was conducted in an iterative manner, starting with simple automated consistency checking to ensure correct syntax usage, leading onto the competency question 'litmus test', and the validation of the ontology by domain experts within the project. Finally, the ontology was validated by a range of experts from across the domain and independent to the project. The results of this process are now briefly outlined.

Preliminary consistency checks were conducted on the ontology within the Protégé ontology development application, which concluded that the ontology was consistent and valid. This shows that the ontology is a valid use of OWL syntax, serialized in XML notation; that the process had in fact produced a semantic model. The second validation stage was to test whether the semantic model produced met the criteria it was intended to meet; the competency questions prescribed in the initial scoping stages. These covered the breadth and depth of the domain deemed necessary to be modelled, resulting in 40 questions which the ontology should be able to answer, to pass this stage of validation. These questions included the following examples, which could all be answered through the concepts and relationships modelled when formalized as SPARQL queries.

- "What is the current water pressure in pipe X?"
- "How much water is currently in reservoir X?"
- "Which pipes feed into sewer X?"
- "How much water does appliance X consume on average?"

Following preliminary validation, the ontology was tested as an accurate, sufficient and shared conceptualization of the domain. This was conducted initially within the project, through the industrial partners in Wales and Italy: the high level approach adopted was agreed as suitable, and the majority of the detailed modelling was also agreed. Some changes were advised and suitable changes were made, including the addition of actuator concepts in parallel to the existing sensor concepts. Finally, the revised ontology was validated by these industrial partners, and the same process was then conducted with representatives from 8 external companies with varied involvements across the water industry, from across Europe. Again, the model was broadly validated and a handful of minor additions were suggested and incorporated.

5.2 Software Testing

Following the validation of the domain ontology, this was instantiated for a Welsh pilot site by reusing GIS data and data from sensor, social and asset databases, as well as heuristic knowledge, operating manuals and product specification sheets. This pilot site knowledge base was then deployed in the cloud based system described previously; with live data updating the instantiation every 15 minutes, as discussed briefly in the next section. Testing was conducted as to the performance of the ontology service within the cloud platform for both retrieval and updating of data, through the RESTful GET and PUT methods.

The service was deployed on a personal laptop (i5-3317U CPU@1.7GHz, 8GB memory, Windows 7 64-bit) so as to test the service's performance, rather than including latency by testing the service in a cloud environment. The semantic model tested was an instantiation of the water value chain domain model, consisting of 1722 named individuals. 11 identical GET requests were issued to the service to retrieve the current sensor reading at an arbitrary sensor in the network, and this test was repeated 5 times, with the service restarted between each test to reset any caching which had occurred. A similar testing protocol was conducted for PUT requests to update the sensor reading, and more realistic testing was conducted by varying the GET request issued, varying the PUT request issued, and finally alternating between GET and PUT requests. The results of the GET request testing are shown in Figure 7 below, which clearly shows caching, and that the typical response time which could be expected would be circa 550ms. The PUT testing indicated a very similar trend, but with approximately an additional 100ms response time across the requests. Changing the request between subsequent requests didn't result in any significant difference in the response time to the results described previously.

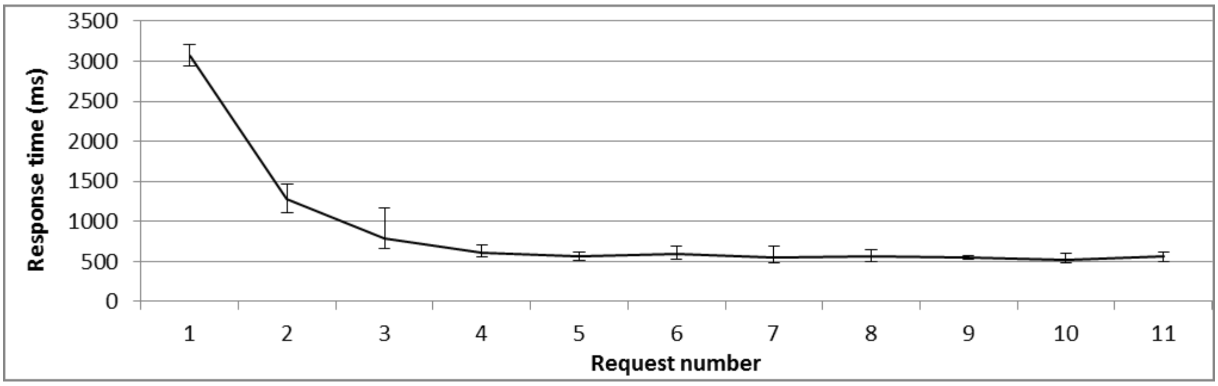

Figure 7: Average response time of the ontology web service across several SELECT queries

6. DISCUSSION

The proposed platform, developed through the WISDOM project, aims to deliver intelligent water sensing and analytics towards demand optimized management. A key innovation of the proposed solution, and the focus of this paper, is the integration of heterogeneous data sources and varied analytics and visualization components, through a domain ontology, which has been instantiated and deployed within a dedicated web service. The utility of such an approach has been highlighted within the network optimization service, as the ontology web service allows this to utilize data from across the water value chain at runtime. The results presented show that the ontology and its software deployment are sufficient as a conceptualization of the water domain for use within a near real-time decision support system. The validation of the domain ontology displays that it is agreeable amongst a wide range of stakeholders within the industry, and that it could contribute significantly to the international standards identified by (ICT4Water 2015, 4) as critical towards the penetration of ICT within the water domain. The software testing conducted indicates that the performance of the ontology service and SPARQL endpoint, which represents an extension of the Apache Jena APIs, was sufficient for the velocity and volume of requests and updates deemed typical within the target software platform's use cases. A request frequency of 15 minutes was chosen for the software testing as this represents a relatively high frequency from real-world wireless sensors in order to conserve battery power. A higher frequency could be tested to replicate the use of the ontology in a domestic setting where real-time data must be processed and all sensors are mains-powered.

The key novelty presented lies in the semantic representation of the water value chain as a detailed manifestation of a socio-technical-sensory system. This goes beyond the ontological modelling conducted elsewhere to offer greater depth and breadth. Specifically, the 'observation and measurement ontology' of the WatERP ontology is similar to the WISDOM sensor ontology, due to their shared roots in the W3C SSN ontology (Compton et al. 2012), although the WatERP ontology's alignment with the SSN ontology is shallow; only reusing a few high level concepts. However, the WISDOM sensor ontology thoroughly reuses the SSN ontology, and extends it directly in order to be relevant to the water domain. The WatERP 'supply and demand ontology' contains concepts from across the rest of the WISDOM ontology, but again only captures high level concepts such as physical element types (storage, transfer, etc.) and a few types of actors (bulk water suppliers, consumers, regulators and water utilities). Hence, the WISDOM ontology is suited to a different purpose to that which the WatERP ontology achieves. Further, the WISDOM ontology captures domestic knowledge, so as to allow the integration of consumers within the water value data chain and hence contextualize smart meter and behavioral readings. The remaining work on the ontology is to develop a custom semantic inference engine to allow the ontology service to directly contribute to the analytics functionality of the system through SWRL rules.

Smart water systems are emerging as a method of leveraging ICT and artificial intelligence to improve the key performance indicators of water networks by utilizing existing sensor networks where available, deploying new sensors, integrating data silos within and across organizations, and applying artificial intelligence techniques matured in other domains. This aims to improve the efficiency and longevity of water networks as well as reducing energy consumption, water losses and costs whilst improving consumer perception of the network. Whilst smart water networks are still an emerging trend, their benefits appear promising, and despite most water networks not utilizing sensor networks sufficiently to currently be considered 'smart', early adopters of the approach are paving the way, and the likely future scenario of water networks enriched with may smart devices will require a robust, flexible and scalable interoperability solution.

7. CONCLUSIONS

The application of ICT and artificial intelligence to water management hold similar potential benefits to those observed in smart grids and smart cities. However, semantic modeling has been identified as a critical obstacle towards realizing this (ICT4Water 2015), and is widely acknowledged as such in the mentioned neighboring fields. Whilst other ontologies take fundamental steps towards overcoming this obstacle, they are either not intended for this domain, or are only suitable for capturing generic knowledge about a water network and relating observations to features of interest and alerts. For these reasons, the proposed ontology offers a significant advancement in the field by capturing in-depth knowledge regarding the technological, network, social, sensory and ICT artefacts involved in water management decisions in a water value chain. This ontology has been deployed as a web service within a cloud based platform to integrate several varied data sources with advanced analytics and visualization components, towards systemic applications in a number of scenarios. An example scenario was presented of optimizing pump and reservoir management schemes in near-real time, to highlight the value of integrating data from across the network at runtime. The validations of the ontology and web service were then presented to demonstrate the approach's efficacy. Finally the primary contribution; the novel underpinning semantic approach and model, was discussed. Significant progress is being made towards achieving and leveraging smart water networks, but interoperability is increasingly recognized as an emerging roadblock, which the presented approach and artefacts take a step towards overcoming.

ACKNOWLEDGMENTS
The authors would like to acknowledge the financial support of the European Commission under the FP7 WISDOM (grant number 619795) project.

REFERENCES

"Apache Jena - Jena Ontology API." 2015. Accessed February 24. https://jena.apache.org/documentation/ontology/.

Apereo CAS. 2015. "Enterprise Single Sign-On." http://jasig.github.io/cas/4.1.x/index.html.

BSI. 2014. "Smart City Concept Model- Guide to Establishing a Model for Data Interoperability."

Compton, Michael, Payam Barnaghi, Luis Bermudez, Raúl García-Castro, Oscar Corcho, Simon Cox, John Graybeal, 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* 17 (December): 25–32. doi:10.1016/j.websem.2012.05.003.

CUAHSI. 2015. "CUAHSI Hydrologic Information System - Hydrologic Ontology for Discovery." Accessed October 23. http://his.cuahsi.org/ontologyfiles.html.

Dam, Koen Haziël van. 2009. *Capturing Socio-Technical Systems with Agent-Based Modelling.* Delft: Next Generation Infrastructures Foundation.

ICT4Water. 2015. "ICT4Water Standards Report."

IEEE Standards Committee, Photovoltaics Dispersed Generation and Energy Storage IEEE Standards Coordinating Committee 21 on Fuel Cells, Institute of Electrical and Electronics Engineers, and IEEE-SA Standards Board. 2011. *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications and Loads*. New York, N.Y.: Institute of Electrical and Electronics Engineers. http://ieeexplore.ieee.org/servlet/opac?punumber=6018237.

Kenny, D. 2013. *Smart Water Network Monitoring Smart Water Network Monitoring SBWWI SBWWI – Intelligent Networks.* TaKaDu.

Miller, J. M., and Leinmiller, M. 2014. *Why Smart Water Networks Boost Efficiency.* Schneider Electric.

"NeOn Wiki." 2015. Accessed April 10. http://neon-toolkit.org/wiki/Main_Page.

Peleg, A. 2014. *Investment in smart water networks on the rise.* Grand View Media Group: Water Technology magazine.

SWEET. 2015. "SWEET Overview." Accessed October 23. https://sweet.jpl.nasa.gov/.

Vilches-Blázquez, L. M., Ramos, J. A., López-Pellicer, F. J., Corcho, O., and Nogueras-Iso, J. 2009. "hydrOntology: A Global Ontology of the Hydrographical Domain." http://mayor2.dia.fi.upm.es/oeg-upm/index.php/en/ontologies/107-hydrontology.

W3C. 2015. "Semantic Web." Accessed December 14. http://www.w3.org/standards/semanticweb/.

"Waternomics." 2015. Accessed February 25. http://waternomics.eu/.

WatERP. 2013a. "D1.1 Generic Taxonomy for Water Supply Distribution Chain."

———. 2013b. "D1.3 Generic Ontology for Water Supply Distribution Chain."

Williamson, F., van den Broeke, J., Koster, T., Koerkamp, M. K., Verhoef, W., Hoogterp, J., Trietsch, E., and de Graaf, B. R. 2014. *Online water quality monitoring in the distribution network.* IWA: Water Practice & Technology Vol 9 No 4.