An Ontology Framework for Water Quality Management

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Abstract. Although Semantic Web builds on well-established foundations and we are witnessing its expansion across multiple domains, the community has to-date been rather keen on building hybrid ontology-based water quality management systems. Our vision is to build a pure Semantic Web framework for effective management of water quality. In line with this, an SSN-based ontology for water quality management has been developed to support water quality classification based on different regulation authorities such as Water Framework Directive. A couple of case studies from surface waters and drinking waters have been used to illustrate the usability of the proposed ontology.

Keywords: ontologies, wireless sensor networks, water quality monitoring, Semantic Web, OWL, SWRL, reasoning, Semantic Sensor Web

1 Introduction

The old-fashioned approach of monitoring water quality by collecting water samples manually and transporting them to a laboratory for analyses is expensive, time-consuming, prone to miss fluctuations of pollutant concentrations such as periodic release of toxins, may be limited by weather conditions, and does not allow for continuous data collection [1, 25].

On the other side, the technological improvements on the sensor and network capabilities for long range data distribution and storage provide a capable platform to utilize low cost, high performance and real-time monitoring Wireless Sensor Networks (WSN) for water quality management (WQM).

Sensor data processing encapsulates processing historical data stored on permanent databases, as well as real-time stream data. Thus, a flexible knowledge management system is required to represent the water domain knowledge. The research community has integrated different representational schemes. Modern approaches are mainly ontology-based [3, 4, 11, 16, 18, 19]. The ontological capability of knowledge reuse and sharing is the main reason why the ontologies are best suited for modeling water quality monitoring domains.

The current state-of-the-art WSNs are employing diverse Semantic Web technologies to not just automate real-time monitoring of water health, but also enrich it with semantics. Different intelligent real-time WQM systems are established and currently in place, be it centrally managed (e.g. [4]) or distributed on sensor nodes (e.g. [19]). Query answering has been leveraged in [4, 20] over water domain ontologies, while in [6, 7, 8] ontologies in pair with rules are used for efficient WSN. Yet in terms of support for WQM of semantic technologies, according to [14], there is to date no WSN for WQM able to address all requirements on water quality standards set up by the Water Framework Directive (WFD) [15] which represents one of the main environmental challenges in EU water policy [29].

The recent emergence of Semantic Sensor Web (SSW) has enabled the interoperability of heterogeneous WSNs. The SSN (Semantic Sensor Network) ontology [3], an OWL2 [24] ontology, offers a unique knowledge management base for WSNs. This way, the WSN community has somehow committed to the Semantic Web platform and its tendency is to build applications which base on recommended models and paradigms. However, when it comes to querying and reasoning over rules in Semantic Web, the sensor networks community has rather omitted to deploy them and instead approached a hybrid solution of combining the ontological knowledge base with frameworks different from Semantic Web, like Complex Event Processing (CEP), Data Stream Management Systems (DSMS), production rules, or association rule mining [2]. As described in [2], the main reason of layering different reasoning approaches over ontology bases is the issue of monotonicity and the closed or open world assumption. Namely, the OWL and SWRL’s support of monotonic inference and open world assumption only is the one to blame for this. Although authors in [6, 7] prove that WSN knowledge might be managed within a pure Semantic Web platform, these implementations suffer from reasoning obstacles, e.g., sensor output modifications are not allowed in monotonic reasoning [2]. Hence, our aim is to tackle these issues and find a suitable solution in order to build an efficient pure Semantic Web framework for WQM. In line with this hypothesis, we have built an ontology for WQM, which will be described in this paper.

The paper is structured as following: Section 2 states our system’s requirements. The ontology model comes in Section 3 by describing its modules. Section 4 presents two case studies for usability testing of our ontology. Section 5 describes current state-of-the-art of WSNs for WQM focusing on ontological layer. In Section 6 the paper concludes with a summary and future works.

2 Requirements

Firstly, we are looking to build an ontology to model a WSN for WQM system. In traditional settings, WSN architecture for WQM is composed of spatially distributed (1) *sensor nodes* (also called *motes*) for capturing water quality values through one or more sensor probes or automatic samplers, (2) *gateway nodes* (also called *sink nodes*), usually one per site, for data gathering and transferring to a (3) *remote monitoring center* which retrieves data, performs some validation rules, stores them in a database, and eventually raises an alarm event if any parameter value is out of its threshold or any other alarming event occurs.

Secondly, the ontology should model the observations made by sensing devices, e.g., by sensor probes or automatic samplers. Observation data must be recorded such as: location (latitude and longitude of the sensor node), time (the sampling and entry system time), and the water quality element (e.g., pH, temperature etc.). Additionally, the ontology needs to model devices. In particular, the ontology shall model data on where the devices are deployed (i.e., in which sensor nodes), what RFID they hold, and the type of devices.

Thirdly, the system should support classification of sensor observations based on different regulation authorities. We are looking to classify the observation with four regulation authorities: the WFD, UNECE standards [26] (statistical classification of surface freshwater quality for the maintenance of aquatic life), Kosovo Environmental Protection Agency (KEPA) [27], and surface water classification in Kosovo based on the standards of former Yugoslavia - past classifications [28].

Finally, the ontology should model pollution sources. Polluter is any facility or entity discharging to the water body.

A typical scenario will consist of the following workflow: an expert rule will get the observation values, it will compare the observed value with the specified regulation threshold and will classify the sensor node to a particular regulations status; if the sensor node provided dangerous values, another rule will check if the polluters nearby the sensor node are possible causes for this; if so, an alarm event consisting of event location, time, and potential polluter(s) should be raised.

3 The Ontology Model

In this section we will describe our developed ontology, which will fulfill the requirements specified in the previous section. For brevity we will refer to our WQM system with INWATERSENSE. According to [4], three types of water quality monitoring knowledge need to be modeled: *observational data items* (e.g., the amount of ammonia in water) collected by sensing devices, *regulations* (e.g., safe drinking water acts) published by authorities, and *water domain knowledge* maintained by scientists (e.g., water-relevant contaminants, bodies of water, etc.). We will extend this model for capturing the knowledge of sources of pollution. Namely, it consists of four ontology modules:

- *The core ontology*[1], consisting of classes and relationships for deploying real-time observational water quality data coming from data sources, i.e., sensors or lab measurements.
- *The regulations ontology*[2], a module which deals with permitted water parameter thresholds regulated by different authorities.
- *The polluters ontology*, a module representing polluters entities and their attributes.
- *Water expert rules*, a module representing if-then water expert rules.

In order to be able to reason over all ontology modules as a whole, and to express the scenario of the previous section in particular, all of these modules are integrated into a single ontology. As depicted in Fig. 1, sensor observation data are consumed in the core ontology. Water expert rules will classify water bodies to appropriate status following the regulations ontology model and core ontology observation data. Additionally, expert rules based on polluting semantics modeled in the polluters ontology will identify the pollution causes.

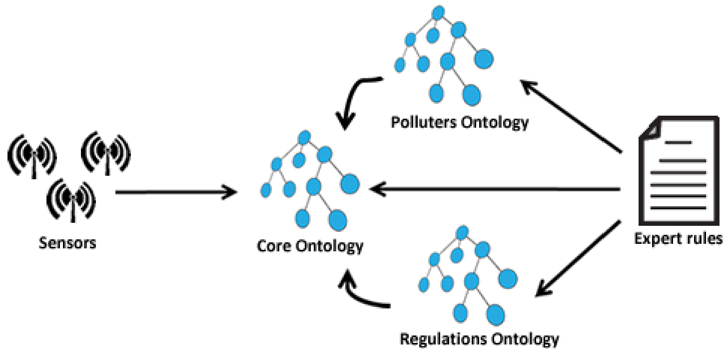

Fig. 1. Ontology framework modules

3.1 The Core Ontology

Following the ontology design pattern used in [4], the core ontology will represent observational water quality data together with the corresponding descriptive metadata, including the type and unit of the data item as well as the provenance metadata such as the locations of sensor nodes, the time when the data item was observed and optionally the test methods and devices used to generate the observation. The SSN ontology has recently emerged as main upper ontology for modeling WSN knowledge bases. It can describe sensors in terms of capabilities, measurement processes, observations and deployments. Thus, this ontology is best suited to be used for our core ontology. It is eventually extended with few additional classes and relationships as specified by the system requirements. For example, for representing time-related

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[1] http://inwatersense.uni-pr.edu/ontologies/inws-core.owl

[2] http://inwatersense.uni-pr.edu/ontologies/inws-regulations.owl

features, the OWL Time[3] ontology is used, while asserting geo location attributes, the longitude and the latitude, is realized through the basic geo location vocabulary[4]. The complete list of ontology namespaces used by the ontology modules is described in Table 1.

Because we are planning to employ SWRL [21] rules in our framework we have used Protégé 3.5 as the main ontology development environment. We have chosen version 3 over 4 because of version 3's SWRL built-ins support. But, the SSN ontology is an OWL2 ontology which cannot be directly imported in version 3. Hence, we imported the desired SSN features extending them with other ontologies and our own concepts.

Table 1. INWATERSENSE ontology namespaces

Prefix	Namespace	Description
	http://www.co-ode.org/ontologies/ont.owl#	INWATERSENSE base ontology
ssn	http://purl.oclc.org/NET/ssnx/ssn#	The SSN ontology
body	http://sweet.jpl.nasa.gov/2.1/realmHydroBody.owl#	Describes water bodies like river, basin etc.
Chem	http://sweet.jpl.nasa.gov/2.1/matr.owl#	Chemical substances ontology
Elem	http://sweet.jpl.nasa.gov/2.1/matrElement.owl#	Chemical elements ontology
Dul	http://www.loa-cnr.it/ontologies/DUL.owl#	DOLCE - a Descriptive Ontology for Linguistic and Cognitive Engineering
Event	http://www.csiro.au/EventOntology#	CSIRO event ontology
Geo	http://www.w3.org/2003/01/geo/wgs84_pos#	Geographical location ontology
Time	http://www.w3.org/2006/time#	OWL Time Ontology
Qu	http://www.purl.oclc.org/NET/ssnx/qu/qu#	Library for Quantity Kinds and Units
Qurec	http://www.purl.oclc.org/NET/ssnx/qu/qu-rec20#	Ontology for Quantity Kinds and Units: units and quantities definitions
Twcc	http://tw2.tw.rpi.edu/zhengj3/owl/epa.owl#	TWC-SWQP core ontology
Twcp	http://escience.rpi.edu/ontology/semanteco/2/0/pollution.owl#	TWC-SWQP pollution ontology

In order to capture different system alerts, the class `event:Alert` of the CSIRO ontology is reused together with its subclasses `event:EmailAlert` and `event:SMSAlert`. To represent different types of device, a class `DeviceType` is added including subclasses for each device type, e.g. `AutoSampler` to model auto sampler devices. A property `hasDevice` is added to indicate anything that is related to a particular device, e.g., a sensor node consisting of a set of devices.

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[3] http://www.w3.org/TR/owl-time/

[4] http://www.w3.org/2003/01/geo/

To model the WSN spatial distribution of sensor nodes, gateway nodes and central monitoring center, the following classes `SensingNode`, `GatewayNode`, and `CentralMonitoringNode` as subclasses of `ssn:Platform` are added. Since one sensor node may have more than one location, we added another class `SensingNodeLocation`, which together with `GatewayNode` and `CentralMonitoringNode` are subclasses of `geo:Point`. In fact, `SensingNodeLocation` is a subclass of `twcc:MeasurementSite`, which in turn is designed to be a subclass of `geo:Point`. Based on the requirements defined in Section 2, the `SensingNode` class may have as location only instances of class `SensingNodeLocation`, may consists of at least one sensor probe and one RFID, and may have at most one auto sampler.

A subclass of `WaterQuality` (which is itself a subclass of `ssn:Property`), namely `RiversWaterQuality`, is introduced to model different categories of quality elements: `Biological`, `Hydromorphological` and `Physico-chemical`.

In the existing `ssn:Sensor` class, several new subclasses are introduced, one for each water quality element that a given sensor measures. For example, the `DissolvedOxygenSensor` class will model sensor devices which measure dissolved oxygen. A sensor measuring more than one element may be instance of more than one `ssn:Sensor` subclasses. In the `ssn:Observation` class, we introduced a new object property, namely `observationResultLocation,` to describe observation location. The axioms `observationResultLocation only geo:Point` and `observationResultLocation min 0` are added to capture the semantics of observation location descriptions.

In the class `ssn:Platform`, the following axiom `dul:attachedSystem owl:hasValue InWaterSense` is assigned to indicate that all `ssn:Platform` instances are attached to our system instance named `InWaterSense`.

A `ssn:FeatureOfInterest` subclass `WaterFeature` is also introduced, which will hold instance `RiversWaterFeature` in our first case study, and `DrinkingWaterFeature` in the second one.

3.2 Regulations Ontology

According to [4], regulations concerning water quality have not been modeled as part of any existing ontology so far. Their attempt anyway produced a basic regulations ontology which follows different authoritative water quality regulations. Led by our system requirements described above, we modeled the following regulation ontologies within `InWaterSense`:

- WFD regulations,
- UNECE standards, statistical classification of surface freshwater quality for the maintenance of aquatic life,
- Kosovo Environmental Protection Agency (KEPA), and,
- Surface water classification in Kosovo based on the standards of former Yugoslavia (past classifications).

The class `Standards` is the central class in this ontology, and holds subclasses which model all the regulations authorities – one subclass per authority. In the next subsection, we will describe the WFD regulations ontology, while other regulations ontologies are subject to ongoing development.

3.2.1 The WFD regulations ontology

The WFD regulations classify water quality parameters into three broad categories: biological, hydro-morphological and physico-chemical [15]. This categorization is illustrated in ontological class-hierarchy representation in Fig. 2.

In WFD, instead of classifying water bodies as polluted or clean as was practiced in [4], water bodies are classified into five statuses and their corresponding colors: high/blue, good/green, moderate/yellow, poor/orange and bad/red. In WFD, a general rule called one-out-all-out applies: the quality element of the lowest (worst) status for a given water body determines the overall ecological status [15] of that water.

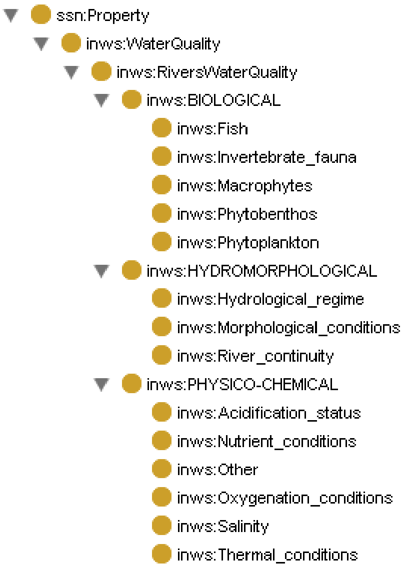

Fig. 2. WFD categorization of water quality elements in Protégé class/hierarchy terms

A class named `WFDSurfaceWaterStatus` is used to capture all five different water statuses of surface water from `Pure`, `Low`, `Moderate`, `Good`, to `High`, each as a subclass of its own. The semantics of equivalent status/color pairs are captured through the built-in `owl:equivalentClass` property, as stated, e.g., in the following axiom `High owl:equivalentClass Blue`. Further, to express which WFD statuses are valid for elements of which `RiversWaterQuality` category, a new class `EcologicalStatus` is introduced. Since the latest class is about WFD regulations, there is an `owl:Restriction` restricting the `hasStandard` property to have values only from the `WFD` class. The class `twcc:WaterMeasurement` is reused as a superclass of all classes representing water quality statuses of elements, e.g. of the class `HighNutrientConditions`. The semantics linking observations with measurement statuses (subclasses of `twcc:WaterMeasurement`) are captured in our framework with the TWC-SWQP regulation ontology property `twcc:hasMeasurement`.

In [4], the regulation status is expressed through OWL property restrictions. Based on SSN ontology design pattern, we are unable to do this at the ontology level. This is due to involvement of more individuals representing a single sensor data stream i.e. every `ssn:Observation` asserted individual is related with one or more individuals from: `ssn:featureOfInterest`, `ssn:Point`, `geo:Point`, `time:Instant`, etc. SWRL's support of free variables is a suitable solution for expressing this rationale. For example, the following WFD rule "*If total ammonia is less than 0.04 (mean), than river belongs to the high status of nutrient conditions*" assuming that we are querying the observations after date 2013-02-13 on 09:11, may be expressed through the following SWRL rule:

```
ssn:Observation(?x) ∧ ssn:observedProperty(?x, Ammonia)
∧ ssn:observationResultTime(?x, ?y) ∧
hasObservationTime(?y, ?z) ∧ temporal:after(?z, "2013-
02-13T09:11:00") ∧ ssn:observationResult(?x, ?r) ∧
ssn:hasValue(?r, ?v) ∧ dul:hasDataValue(?v, ?val) ∧
sqwrl:makeSet(?sv, ?val) ∧ sqwrl:avg(?avg, ?sv) ∧
swrlb:greaterThan(?avg, 0.04) →
HighNutrientConditions(?o)
```

The rule checks each observation data stream (`ssn:Observation(?x)`) observing Ammonia (`ssn:observedProperty(?x, Ammonia)`) recorded after the specified time (`hasObservationTime(?y, ?z) ∧ temporal:after(?z, "2013-02-13T09:11:00")`), binds the observed values to a variable `?r` (`ssn:observationResult(?x, ?r)`) makes a set `?sv` of these values (`sqwrl:makeSet(?sv, ?val)`), finds the average of the values in the set (`sqwrl:avg(?avg, ?sv)`), filters the ones which are greater than 0.04, and finally the observations satisfying all these conditions are instantiated within the class `HighNutrientConditions`.

3.3 Polluter's ontology

The polluter's ontology will model facilities and other entities discharging wastes in water bodies. The semantics modeled in this ontology in cooperation with other ontology modules will help to identify the possible cause of the pollution.

4 Use Cases

In order to illustrate the usability of our InWaterSense ontology in the domain of water quality management, two use cases from that domain are next provided:

- A stream data scenario from the domain of surface water quality management.
- A static data scenario from the domain of drinking water quality management.

4.1.1 Use Case 1: Surface Water Quality Management

In absence of real sensor observation data, we investigated the InWaterSense ontology in the domain of surface waters with simulated SQL data. Testing with real sensor data are planned in the very near future. An SQL stream data generator was employed to produce simulated water quality data. The generated data are then converted into RDF data through D2RQ[5] mapping tool. Populating the InWaterSense ontology with the D2RQ generated data in Protégé incurred difficulties when trying to render object property instances. Namely, instead of rdf:Description statements, Protégé 3.5[6] expects abbreviated syntax for object property instances. The following D2RQ generated code snippet describes an object property linking the sensor node instance `sn3` with a sensor node location instance `sl3`:

```
<rdf:Description rdf:about="sn3">
    <dul:hasLocation rdf:resource="sl3"/>
    <rdf:type rdf:resource="&ont;SensingNode"/>
</rdf:Description>
```

The same assertion in the abbreviated RDF/XML syntax as expected in Protégé is:

```
<SensingNode rdf:about="sn3">
    <dul:hasLocation rdf:resource="sl3"/>
</ont:SensingNode>
```

In order to enable this translation, SWOOP [21] was used to load the D2RQ generated RDF data and produce the abbreviated syntax for object property instances. The ontology gained at the output of SWOOP is then imported in Protégé 3.5 to populate the corresponding class and property assertions of the core ontology.

To reflect our case study, the following initial axiom assumptions were asserted into the core ontology:

- `ssn:featureOfInterest owl:hasValue RiversWaterFeature` to indicate that the sole feature of interest in all observations is the river water quality.
- `ssn:sensingMethodUsed owl:hasValue SimulatedData.`
- `ssn:includesEvent owl:hasValue ScheduledObservation.`

As for the instance data (ABox), we have used an example of observation stream datanamely the observation instance `oo11724` depicted in Fig. 3. That instance represents a water temperature measurement, which is in turn a river feature

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[5] D2RQ Accessing Relational Databases as Virtual RDF Graphs, http://d2rq.org/

[6] Protégé ontology editor, http://protege.stanford.edu/

(`oo11724 ssn:observedProperty Temperature`, `Temperature ssn:isPropertyOf RiversWaterFeature`); it is produced by a device named `d1` (`oo11724 ssn:observedBy d1`); it is sampled on 2013-02-13 at 09:32:22, which is same as the entry system time since there is no latencies, i.e., data are already in machine (`oo11724 ssn:observationSamplingTime v11724`, `oo11724 hasObservationTime "2013-02-13T09:32:22.133"^^<xsd: date>`); it's measured value is 15.58 (`oo11724 ssn:observationResult so11724`, `so11724 ssn:hasValue ov11724`, `ov11724 dul:hasDataValue "15.58"^^<xsd:double>`); it is measured by the s2 sensing node (`hasSensingNode sn2`), at the sample position of 21.0E0 for longitude, and 42.0E0 for latitude (`oo11724 observationResultLocation l11724`, `l11724 geo:lat "42.0E0"^^<xsd:double>`, `l11724 geo:long "21.0E0"^^<xsd:double>`).

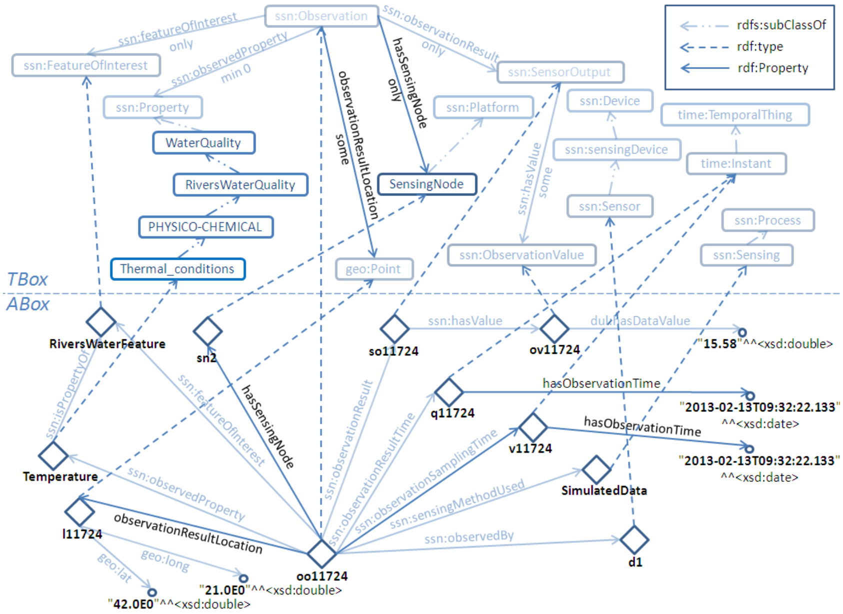


Fig. 3. TBox and ABox statements for the surface waters case study

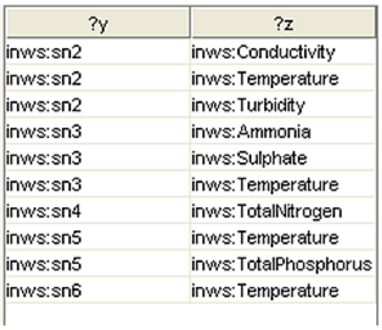
To query about each sensor node and the water quality elements it observes, the following SQWRL [23] query may be posed to our ontology:

```
ssn:Observation(?x) ∧ inws:hasSensingNode(?x, ?y) ∧
ssn:observedProperty(?x, ?z) ∧ sqwrl:makeSet(?sx, ?x) ∧
sqwrl:groupBy(?sx, ?z) → sqwrl:select(?y, ?z)
```

In case of our simulated data, this query produces the output as depicted in Fig. 4.

4.1.2 Use Case 2: Drinking Water Quality Management

Drinking waters represent another water quality management domain. InWaterSense ontology supports its population with data from this domain as well. We have used CSV data available from [13] converted to RDF to populate our ontology. Data are taken from measurements made in 15 measurement points in the city of Tetova (Macedonia) during three summer months of 2012: June, July and August. This case study will show how the rule layer of InWaterSense system performs over static, instead of stream data.



?y	?z
inws:sn2	inws:Conductivity
inws:sn2	inws:Temperature
inws:sn2	inws:Turbidity
inws:sn3	inws:Ammonia
inws:sn3	inws:Sulphate
inws:sn3	inws:Temperature
inws:sn4	inws:TotalNitrogen
inws:sn5	inws:Temperature
inws:sn5	inws:TotalPhosphorus
inws:sn6	inws:Temperature

Fig. 4. A sample rule output

The axiom `ssn:featureOfInterest owl:hasValue DrinkingWaterMeasurement` is added to indicate that the observation's sole feature of interest is the drinking water quality. Fig. 5 illustrates an observation instance `AugObserveChloridesT9` representing measured values of Chlorides (`AugObserveChloridesT9 ssn:observedProperty DrinkingWaterChlorides, DrinkingWaterChlorides ssn:isPropertyOf DrinkingWaterFeature`) during August 2012 (`AugObserveChloridesT9 ssn:observationResultTime August2012, August2012 ssn:startTime ObservationAugustStart, ObservationAugustStart time:inXSDDateTime "2012-08-01"^^<xsd:date>, August2012 ssn:endTime ObservationAugustEnd, ObservationAugustStart time:inXSDDateTime "2012-08-31"^^<xsd:date>`) on measurement point `T9` (`AugObserveChloridesT9 ssn:observationResultLocation T9`) with measured Chloride value 8.3 (`AugObserveChloridesT9 ssn:observationResult AugOutputChloridesT9, AugOutputChloridesT9 ssn:hasValue AugValueChloridesT9, AugValueChloridesT9 dul:hasDataValue "8.3"^^<xsd:decimal>`).

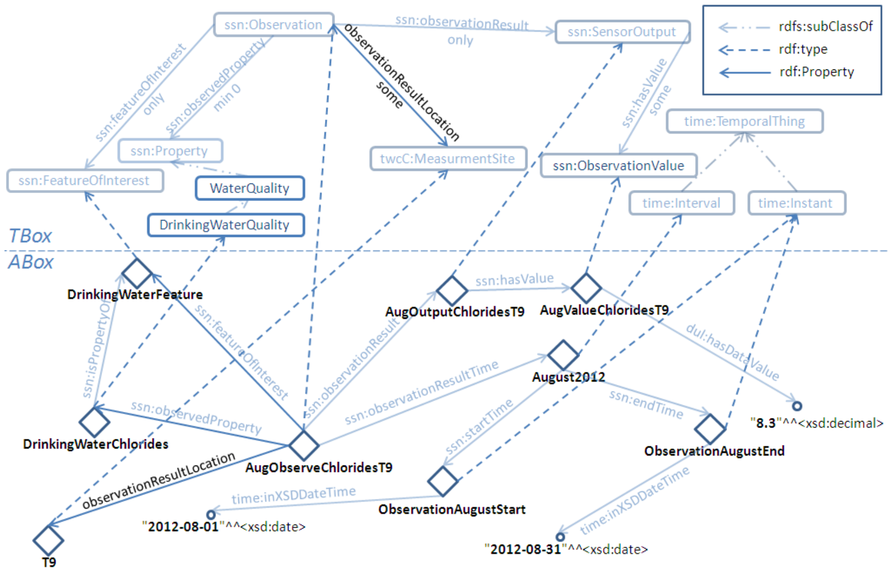


Fig. 5. TBox and ABox statements for the drinking waters case study

If one is interested to calculate the median of June temperature observations, the following is the SQWRL rule which produces the same result as obtained in [13] through Excel formulas:

```
ssn:Observation(?x) ∧ ssn:observedProperty(?x,
DrinkingWaterTemperature) ∧ ssn:observationResult(?x,
?r) ∧ssn:hasValue(?r, ?v) ∧dul:hasDataValue(?v, ?val)
∧ sqwrl:makeSet(?sv, ?val) ∧ sqwrl:median(?m, ?sv) →
sqwrl:select(?m)
```

5 Related Work

A large number of WQM systems have been developed in the last decades. One of the first WQM systems that has benefited from the ontological knowledge representation is OntoWEDDS [16]. The inclusion of ontological reasoning alongside case-based and rule-based reasoning has resulted with significant improvement. In the rest of this section, we will identify some of the current WQM systems as compared to our approach.

In order to provide a portal for WQM, Tetherless World Constellation (TWC)[7] has developed Semantic Water Quality Portal[8] (TWC-SWQP) described in [4]. They are pioneers for including regulations ontology. However, their approach is very basic

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[7] TWC, http://tw.rpi.edu/web/TWC

[8] TWC-SWQP, http://aquarius.tw.rpi.edu/projects/semantaqua/

since it only finds the excessive threshold measurements and classifies the polluted data sources. We have reused and eventually extended this ontology for supporting regulations standards we are interested in. WFD regulations for example are more specific by specifying different quality statuses (high, good, moderate, poor or bad) based on the category of the water quality element (biological, physic-chemical, hydro morphological). Another issue is the core ontology. TWC-SWQP core ontology is not completely suitable for our purpose. For example, it does not model sensors. However, we have reused some of TWC-SWQP core ontology concepts e.g. `MeasurementSite` and `WaterMeasurement` while from the regulations ontology the concepts like `PollutedFacility` and `PollutedSite`. Another distinction from our approach is the OWL2 classification inference used in TWC-SWQP. Instead, we will use SWRL rules in conjunction with OWL restrictions to support regulations features.

An ontology which models sensors is the SSN ontology. This ontology is the main building block of our core ontology. We have extended it with some other ontologies to fulfill our system requirements. An earlier version of this ontology has been used by Taylor and Ledinger in [11] for designing an ontology-based complex event processing system in the field of heterogeneous sensor networks. Complex Event Processing (CEP) represents an area dealing with timely detection of events inferred from complex correlations of stream values. In [11] authors translate the event ontology into CEP statements for processing of events. Another CEP approach has been taken by Anicic et al. [12] who combine the reasoning power of Semantic Web with real-time detection of events affinity of CEP. Opposed to CEP approaches our tendency is to build a pure Semantic Web approach by relying on Semantic Web standards and recommendations such as OWL and SWRL. In our previous work [2] we have stated our aware of the challenges appearing from the likes of open world and monotonicity semantics. CEP systems described in [11, 12] are implemented in Prolog, which is a Logic Programming language. This implies that CEP adopts the closed world assumption and nonmonotonic reasoning. But the question is, are we confident on preferring one over the other i.e. open over closed world assumption or monotonic over nonmonotonic reasoning or we should support both opposite "worlds". For example, if none of the observed quality elements has passed a threshold in closed world we would end up with a conclusion that the water body is healthy but in terms of open world we cannot infer this. There may still be any other condition which will probably classify the water body as polluted.

Approaches [6, 7, 8] prove that rule-based reasoning in pair with ontologies can be performed over the sensor observation and measurement data and linked data to derive additional or approximate knowledge. For example, in [6] SWRL rules recommend personalized surf spots based on user location and preferences, while in [7] SWRL rules are used for inferring approximate temperature for nearby cities based on known ones. In [8] Jena rules are employed in SSW platform to determine blizzard events based on wind speed, visibility and precipitation. These approaches demonstrate fact assertion into the knowledge base, but they do not consider modification and retraction and thus the monotonicity issues.

6 Conclusion

Integrating ontologies into sensor networks is becoming a natural step. With the vision of building a complete Semantic Web framework for WSNs in WQM domain, we developed INWATERSENSE, an SSN-based ontology framework for WSNs in WQM to enable that vision. It has further been shown how our ontology can be paired with SWRL rules to infer new knowledge. Additionally, we demonstrated how the WFD regulations ontology coupled with SWRL rules may be employed to classify water bodies. Adding ontologies of other regulation authorities is subject of our ongoing work, as is a polluter's ontology aimed to support representation of potential sources of pollution (i.e., polluters) in water.

As a platform for reasoning over WQM knowledge, the community has rather considered a hybrid approach, while we pretend to rely on Semantic Web standards. The INWATERSENSE ontology is a building block of a system which we aim to provide including efficient rule-based reasoning over sensor data. In support of that, in the future we plan to address more explicitly the problem of open world assumption and monotonicity, and herewith enable reasoning as required for the waters domain.

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