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An Ontology-Underpinned Emergency Response System for Water Pollution Accidents

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Received: 23 January 2018; Accepted: 17 February 2018; Published: 20 February 2018

Abstract: With the unceasing development and maturation of environment geographic information system, the response to water pollution accidents has been digitalized through the combination of monitoring sensors, management servers, and application software. However, most of these systems only achieve the basic and general geospatial data management and functional process tasks by adopting mechanistic water-quality models. To satisfy the sustainable monitoring and real-time emergency response application demand of the government and public users, it is a hotspot to study how to make the water pollution information being semantic and make the referred applications intelligent. Thus, the architecture of the ontology-underpinned emergency response system for water pollution accidents is proposed in this paper. This paper also makes a case study for usability testing of the water ontology models, and emergency response rules through an online water pollution emergency response system. The system contributes scientifically to the safety and sustainability of drinking water by providing emergency response and decision-making to the government and public in a timely manner.

Keywords: ontology; emergency response system; water pollution accident; reasoning; models

1. Introduction

Water pollution accidents become risks of degradation of human health and ecosystem [1]. The rapid development of the Chinese economy in the last 30 years posed great challenges on water quality, especially on drinking water safety and security. One specific example is the city of Wuhan, the largest metropolis in central China, where 55% of its 108 lakes have been polluted in varying degrees according to Wuhan Municipal Water Authority (http://news.cnhubei.com/xw/wuhan/201503/t3213673.shtml). This puts water quality and sustainability to the forefront of the city's economic agenda and calls for fundamental efforts on the precise and real time determinations of pollution sources and accurate estimations and predictions of pollution events and loads. Taking another pollution accident as example, on 23 April 2014, two major water suppliers (Baihezui and Yushidun water plants) in Wuhan city had halted production at around 4 p.m. and 7 p.m. The result showed that the water in Wuhan section of Han River contained excessive amount of ammonia and nitrogen which had exceeded the national standard. The suspension of water supply caused a water shortage and affected 300,000 people (http://www.chinadaily.com.cn/china/2014-04/24/content_17460393.htm). The production of Yushidun Water plants restored at 8 a.m. on 24th April, however, it was suspended at 9:40 a.m. again. When it was get back to normal around 4 p.m. on 24th April the citizens worried about the safety of drinking water and another suspending. This kind of serious accidents alerted governments that it is necessary to have an emergency response system for polluter identification, pollutant tracing, early warning, decision support and public awareness for water pollution accidents.

Quantitative description of pollution sources relies on vast multi-type sensors which are able to measure different parameters of water. Mostly, two kinds of technologies are mainly involved in modern water quality monitoring system: the first is ground sensor network that are built of "nodes" with chemical, biological and physical sensors; the second is remote sensing with multispectral or hyperspectral imaging sensors on airborne or spaceborne platform [2,3]. The spatio-temporal variations of water quality are generally analyzed by multivariate statistical methods and multiple regression analysis (MRA) [4–8]. It is also necessary for pollutant source identification in the study of water quality monitoring. Accurate and rapid pollutant source identification, such as information about the release time, strength, and location, is vital for contaminant remediation and risk assessment. Atmadja et al. [9] presented a review about mathematical methods for water pollution source tracing and identification for ground water. Especially for surface water, the geostatistical method and the simulation-optimization method are conducted for pollution source identification [10,11]. Governing equations of the backward probability density are the core of the above method, simulating contamination status by using a presumed contamination source. In summary, pollution source identification of surface waters relies heavily on a large amount of combined spatial and temporal water quality measurements that requires high-precision geographical information. Fine-grained water quality data is needed to enable accurate modeling through hydrodynamics equations and a variety of physical quantities.

Since the spatial distribution is very important for water quality monitoring, the multivariate methods and Geographic Information System (GIS) have been applied in environment monitoring network and data analysis. There were numerous GIS-based real-time water quality monitoring projects all over the world with sensor networks. In Korea, the automatic water system was completed in 2006 by the waterworks of the Seoul metropolitan government. Its objective was to monitor water quality from companies to publics to maintain the security of water quality, while the real-time monitoring data was available on the Internet [12]. USGS from USA also built up national water quality monitoring systems, and integrate the monitoring data with geographic information, land use, and other landscape features to study the change of water quality and its relationship with human society [13]. In China, GIS-based emergency response systems were developed for improving optimization of water system operation, usually named Smart Water projects [14,15]. Recently, some experts had also developed a water alert system just through inputting requirements and essential conditions from the web, without the needs to build extra data servers and models [16].

Coping with the above issue, we turn to smart system combined with the real-time sensor data of various water quality monitoring methods instead of developing a sophisticated, complicated and labor-consuming and time-costing inversion method based on physical mechanism. It is expected to obtain both qualitative rules and quantitative equations which illustrate and describe details about contamination sources. We use smart and semantic interchangeable. There are a lot of popular semantic-rich (smart) applications in the areas of semantic search engines, semantic browsers, open government, marketing and advertising, healthcare, legislation semantics, P2P Networks, etc. It is useful to define the ontologies which support the sharing and reuse of formally represented knowledge among smart applications [17]. The ontologies contribute to the building of better GIS [18], since the use of them in spatial studies was been introduced in the 1990s. The semantic measures in the field of informatics have been extended and reused to retrieve geographic information [19]. In recent years, ontology technology has also been introduced into the field of water management to develop decision-support systems [20]. An ontology-based system was presented to simulate human expertise for water quality modeling and management [21]. The InWaterSense [22] was proposed as a SSN (Semantic Sensor Network)-based ontology framework, with W3C OWL2 description in the field of semantic sensor web [23], and expert system for water quality monitoring. Although the effort of developing ontologies and integrating knowledge bases distributed across the Internet costs much time, the richness of the ontologies and the capabilities of large reasoning offer much promise in revealing the value of water information.

This study proposes a real-time knowledge-based system which obtains both qualitative ontology model and quantitative mechanistic model, in order to illustrate and describe details about polluter identification and tracing, early warning, decision support and public awareness for emergency response for water pollution accidents. We use the ontological capability of knowledge reuse and sharing for modeling water quality monitoring domains. We develop the system under both the OGC Sensor Web Enablement (SWE) framework [24] with its simple time, space and thematic constructs, and Semantic Web framework with its rich expressivity and reasoning capabilities for sophisticated time, space, and thematic (water quality) knowledge. The system contributes scientifically to the safety and sustainable development of drinking water in urban areas by providing emergency response and decision-making to the government in a timely manner. The system also could disseminate information with XML-based or script-based formats to the public through SMS (cellphone messages) and WeChat. For the remainder of this paper, Section 2 states the materials and methods of the system. Section 3 presents the implementation and case study. In addition, finally, this study is concluded in Section 4.

2. Materials and Methods

2.1. Study Area

Han River (Hanjiang) is proposed as the study area (see Figure 1) in our system. This river is the largest tributary of the Yangtze River (Changjiang) in China, and it has 1577 km in length, out of which 657 km long in Shanxi Province and 920 km in Hubei Province. There are 20 boundary stations along the Han River in Hubei Province, providing continuous flow of the hydrology and water quality data. The real-time stream data can be read through the existing Online Water Quality Monitoring Platform (http://www.hbemc.com.cn/) developed by Hubei Environmental Monitoring Central Station.

Figure 1. Study area.

2.2. Architecture and Data

Figure 2 illustrates the rationale and the possible outcomes the emergency response system can reveal. The hydrology, polluter and water quality data are automatically retrieved from existing monitoring systems, or manually imported. The ontology model and the mechanistic model are the key of using the data to realize polluter tracing and early warning. The outcomes of the system with responses include three aspects as follows:

- Alert: The emergency response system has the web service interfaces to get water quality data and hydrology data for pollution discovery. The qualitative ontology model and quantitative mechanistic model work together to assess the water quality risk. The system can present the calculating steps and the predication information for early warning the residential area.
- Source (reason): The monitoring agency needs to confirm the pollution source and reason responsibility. The rules of risk identification, assessment and analysis are formalized by using standard semantic rule language. The polluter database is mapped to polluter ontology for polluter tracing through logical reasoning.
- Regulation (decision): The system also stores the established regulations by using the rule format, since the regulations are applied to achieve reasoning. The regulation files are about counterplan measure, risk prevent and reduction, risk source classification, hydrology adjustment, water control, subsequent pollution responsibility identification, related administrative, economical, and legal punishment, etc.

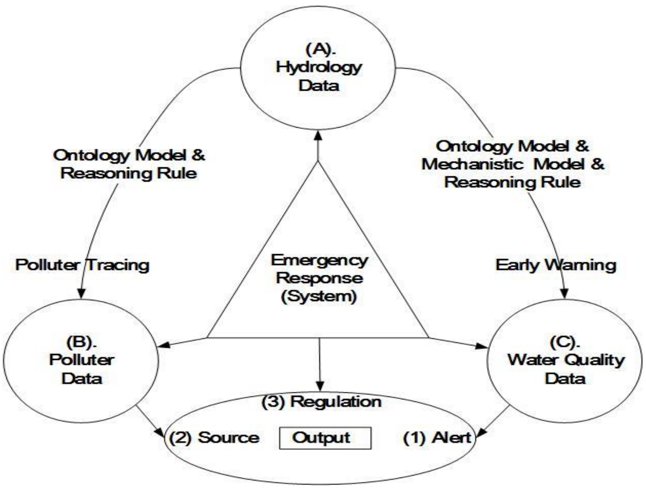

Figure 2. Design architecture of water pollution emergency response.

The specifications of data categories and sources in the system are shown in Table 1. The letters (A), (B), (C) in Table 1 recall the data categories in Figure 2. Some data type has the vector characteristic, which is only summarized as point or non-point. The "Source" column clarifies who provide the data. The water quality parameters, which the boundary stations in Han River can monitor, are listed at the water quality category part in the table. The concentrations of ammonia nitrogen (NH_3-N), COD_{Mn}, and total phosphorus are the focus of the monitoring.

In order to validate the data from many different data sources, we have developed the software tools to help with importing data from other systems through the web services which specify the standardized data input formats. The web services also help with the automatic synchronization by setting the time series. However, some data (e.g., hydrology data) are also need to be imported by transmitting excel files or manual, since there are some barriers between our system and the sources.

Except the sensors at boundary stations, the government has also deployed many sensors at some big polluting plants to monitor the spill of pollutants. Besides that, the government asks the main polluters to submit their measurements of the pollutant concentrations every day, and to publish them to the public Internet. We have already used those data for tracing back the source of the spill accident. They are summarized as the point sources tracing which is shown in Section 3.1.

Table 1. Data categories and sources.

Data Category	Type	Vector Characteristic	e.g.,	Source	Comment
(A). Hydrology and water resources	Lakes and reservoir	Non-point	Dam	(1) layers described information of lakes and reservoir elaborated by Wuhan University; (2) data provided by water resources bureau	Off-line data are input by manual entry or excel import. Especially, the main hydrologic data are from another system which monitors the hydrologic of Yangtze River and Han River technically. We imported the data (excel format) to our system once a while when we need.
	Watershed and runoff	Non-point	Hanjiang river	In situ measurement	
	Profiles of rivers	—	Length, width, flow velocity and information of bed	(1) In situ measurement; (2) historic data; (3) estimated data.	
(B). Polluter Data: Plant Effluent	Stationary source	Point	Industrial plant, sewage treatment plant	(1) data from on-line real time monitoring of pollutant source (collected by governments); (2) data measured by plants themselves and submitted to governments; (3) data published on internet by plants themselves.	(1) On-line measurements are automatically acquired by Web services; (2) Off-line data are input by manual entry or through excel; (3) pollutant source data are also from special monitoring data; (4) when measurements are unavailable, data rely on estimation or deduction of experts; (5) unofficial data should be used unless being approved.
	Agricultural non-point source	Non-point	Farmland	Environmental statistics and dedicated investigation (update annually)	
	Mobile source	Point	Vehicles, transport ships	Reported by citizens	
(C). Water quality	Monitoring site	Point	Boundary station	Automatic on-line real time measurement	(1) on-line measurements are automatically acquired by Web services; (2) Off-line data are input by manual entry or through excel; (3) water quality data are also from special monitoring data; (4) the monitoring water quality parameters include temperature, pH, conductivity, dissolved oxygen (DO), manganese, biochemical oxygen demand (BOD5), ammonia nitrogen (NH3-N), petroleum hydrocarbons, phenol, total mercury, total lead, chemical oxygen demand (COD), total nitrogen, total phosphorus, total copper, total zinc, fluorides, selenium, arsenic, total cadmium, chromium, cyanide, anionic active surfactants, sulphide, and fecal coliforms.
	Monitoring campaign	Point	Routine measurement	(1) regular and special campaign for water quality measurement; (2) historic data and its statistics.	
	Consumer and producer of water	Point	Water quality test	On-line real time monitoring from water works	
Expertise knowledge rule	File	—	GB3838	Literatures; survey.	Summary of Representative case, Analogies, Professional deduction, Relevant regulations and technique, Manual about warning and treatment of water environment risk
	Logical inference rules	—	InWaterSense base	Expertise knowledge base	
Infrastructure data	Geography data	Point & Non-point	Residential area	Provided by Wuhan University	Residential areas include school, downtown, hospital etc.
	Economic data	—	Population	Government reports	
	Base map	—	Road	Tianditu API	
System data	Role users, and configurations of models	—	Administrator	Information provided by water resources bureau	Manual entry
Remote sensing data	Hyper spectral images	—	Retrieved attributes of target	(1) UAV-based spectrograph, wavelength range spans 400–900 nm; (2) Hyperion of EO1, spatial resolution is 30 m.	

—: This is not vector data.

This system adopts B/S architecture and conforms to service specification of OGC Web Map Services (WMS), Web Feature Services (WFS) and Sensor Observation Service (SOS). This system is programed in java, and is based on Tomcat 7.0 for the web server. The GIS Server is an open source project called GeoServer, with the popular and reliable web open source application framework SSH (Struts, Spring, Hibernate) of environment to build. Using open-source PostGIS as spatial database, and the client browser using Openlayers package to design and implement. Figure 3 and Table 2 illustrate the overview of the system architecture and referred open-source development tools.

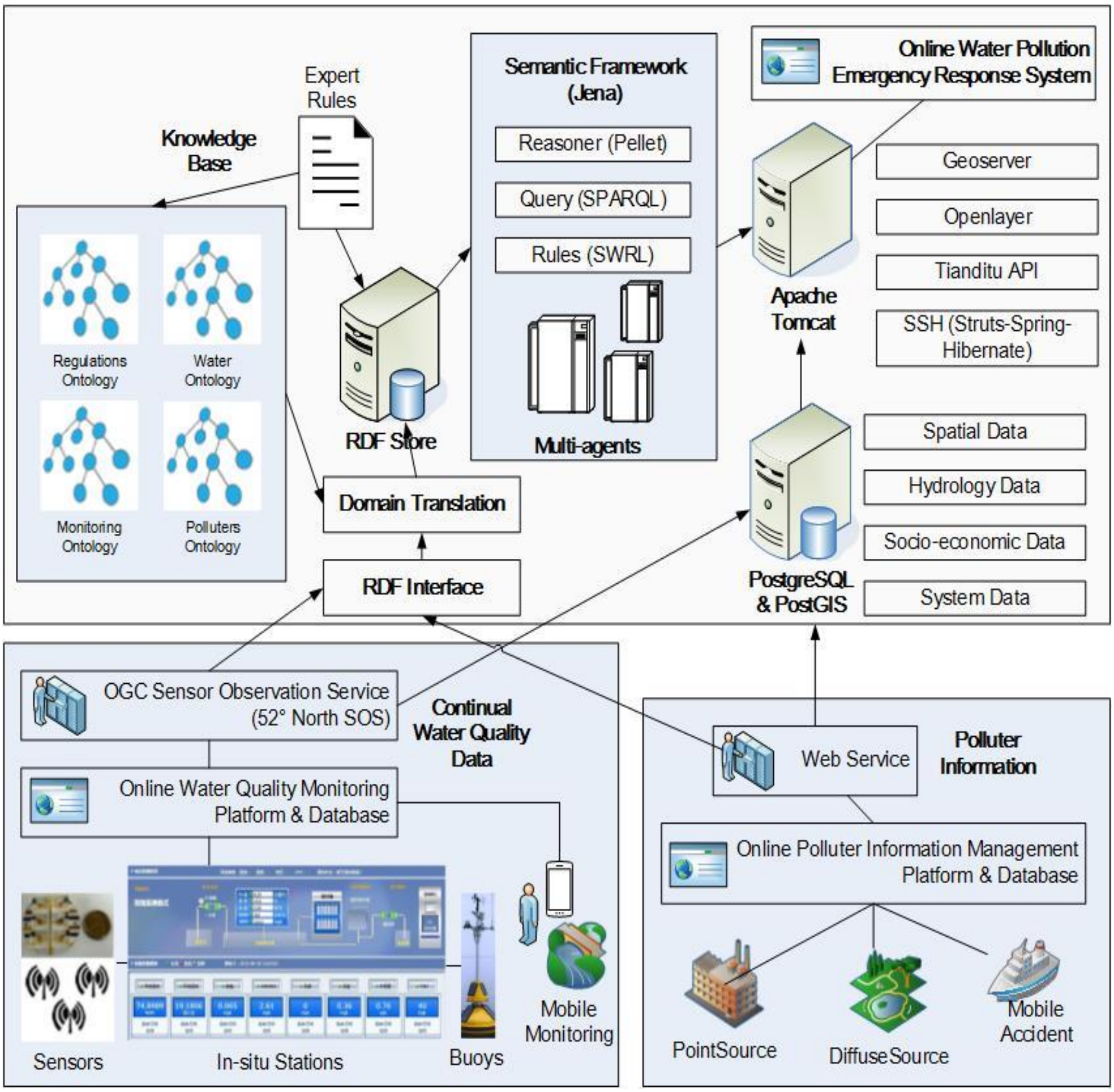

Figure 3. Overall system architecture.

In order to ensure a clear system structure and reduce development difficulty, this system uses a hierarchical design method and an idea of oriented programming interface. The whole system is divided into classical three layers which are respectively the data, service and application layers. This structure can be easy to encapsulate the various levels of function, reduce the degree of coupling between the layers, and is easy to modify and maintain in an iterative development process.

The data of hydrology, water quality and polluter can be achieved automatically through web services. Various sensors are deployed in the water monitoring stations to detect the water quality and hydrology. For the purpose of sharing the observation data from heterogeneous sensor nodes, the OGC

SWE, which is a standards-based Service Oriented Architecture (SOA) approach, is involved as the solution for both in situ stations and mobile monitoring devices. This is the intermediary between the emergency response system and the online water quality monitoring platform. Each data source is exposed to the system using the Resource Description Framework (RDF, an ontology language) interface. This interface generates RDF from the data contained in the data source. Each RDF interface generates ontologically described RDF. This component performs any ontology translation required to get the data into the knowledge models, including the water, polluter and regulation ontology models. Once the data is in RDF and described according to the appropriate ontology, it is stored in the RDF store which is a knowledge base, and is accessible to the system interface.

Table 2. Development environment and open sources for the implementation.

Development Tool	Open Source
Integrated Development Environment (IDE)	Eclipse 3.6
Development framework	SSH (Struts + Spring + Hibernate)
Web server	Apache Httpd, Tomcat 7.0
GIS web container	Geoserver 2.7
Database	PostgreSQL, PostGIS
Testing client browser	FireFox, IE, etc.
Client data container	OpenLayers
Programming language	JAVA (JAVA JDK 1.6)
Semantic framework	JENA
Reasoner	Pellet 1.5.2
Query	Sparql
Rules	SWRL
Sensor observation service	52 north
Ontology editor	Protégé
Base map	Tianditu API

2.3. The Ontology Model

We respectively model three main kinds of referred knowledge, which are (a) water items and their observation and measurement (see Section 2.3.1), (b) polluter entities and related attributes (see Section 2.3.2), and (c) local regulations and references (see Section 2.3.3). The ontology modules are integrated into a single ontology with a water expert rule module which represents if-then reasoning rules (see Section 3.1).

2.3.1. The Water Ontology

To develop the water domain ontology (see Figure 4), a module which consist the water domain knowledge and monitoring knowledge, we have identified the general water terms, and specific terms. The general ones include WaterBody (water body), WaterTime (the time when water is not dry up), Basin, WaterPollute (the main pollutant in the water), etc. The special WaterQuality (water quality) item is modeled as the subclass to presents different pollutant elements (e.g., NH_3-N). The Water Ontology also contains two hydrological terms, HydrologicParticular (hydrologic particularity) and HydrographicNet (hydrographic net), since they are important for the analysis and control of water pollution. This Water Ontology can be extended with new terms to be adapted for external expert systems, multi-agent systems and other kinds of smart water systems.

One of the key aspects in Water Ontology is the knowledge of water monitoring which is represented as WaterMonitoring Ontology in Figure 5. This WaterMonitoring item always works with the Observation to describe the metadata of water quality monitoring data including not only observation and measurement data from sensors, but also the attributes of sensors (e.g., locations, time, manufacturer etc.) We emerges the W3C SSN ontology as the basic model of Observation item, since it defines the general protocols of sensors and sensor networks. It is suitable for the status of heterogeneous deployment of sensors, and can be easily extended with W3C OWL Time ontology which reveals time-related features, and W3C geo location vocabulary which describes the location of the sensor sites. For example, as a subclass of Observation, the ssn:Sensor will demonstrate each one for observation term with a standard sensor measures and extended geo:Point and xs:date-time descriptions. Table 3 lists the reference URLs of the W3C ontologies and the InWaterSense base ontology which has the similar structure.

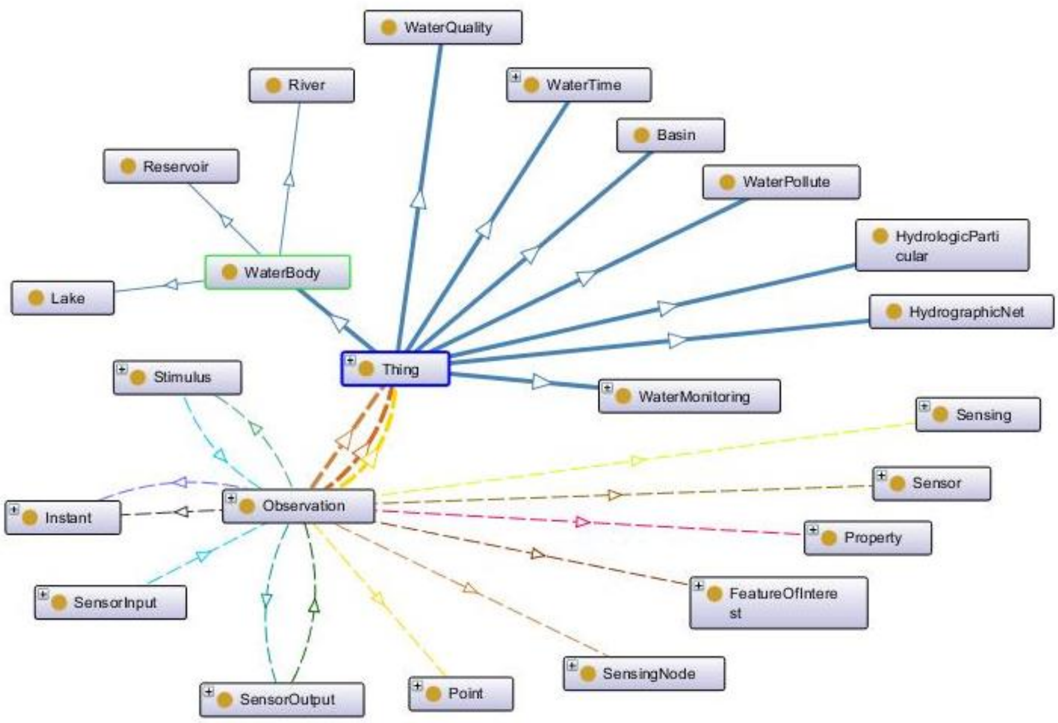

Figure 4. Water Ontology.

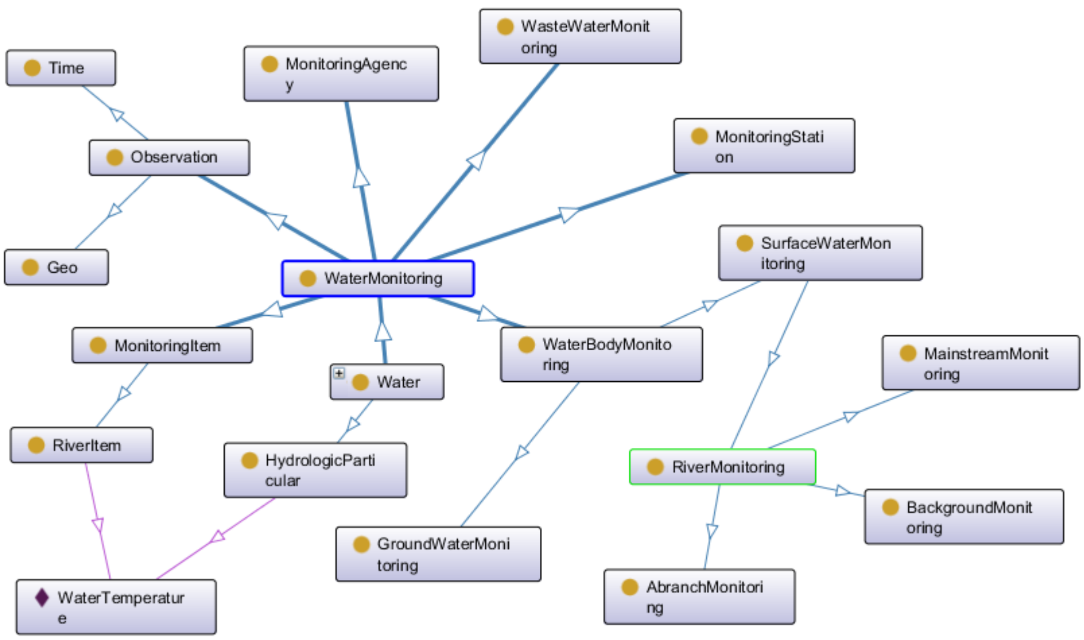

Figure 5. WaterMonitoring Ontology.

Table 3. Ontology references.

Ontology	Reference
W3C SSN ontology	http://www.w3.org/2005/Incubator/ssn/
W3C OWL Time ontology	http://www.w3.org/TR/owl-time
W3C geo location vocabulary	http://www.w3.org/2003/01/geo/wgs84_pos#
INWATERSENSE base ontology	http://inwatersense.uni-pr.edu

Except the relation with Observation, the WaterMonitoring also has the following subclasses: MonitoringAgency (monitoring agency), MonitoringStation (station site) and MonitoringItem (monitoring parameter). The monitoring parameter could also be the hydrologic particularity (e.g., water temperature). This study mainly considers the RiverMonitoring (river monitoring) as the WaterBodyMonitoring (monitoring body).

2.3.2. The Polluters Ontology

The subclasses of Polluters Ontology (see Figure 6) can be partitioned to three categories: (a) point sources attributed to discrete discharge from a stationary factory or sewage outfall, (b) diffuse sources which contain agricultural runoff, urban stormwater runoff and other area wide sources, and (c) mobile sources from dynamic accident such as ships that are clearly discharging pollutants into water sources. The three subclasses are DiffuseSource (alias NonPointSource), MobileSource and PointSource. Some entity could belong to different types, e.g., Mining could be either point or diffuse area. This polluter ontology knowledge helps with the reasoning rules (see Section 3.1) to trace pollution source, identify the polluter, and risk assessment and analysis.

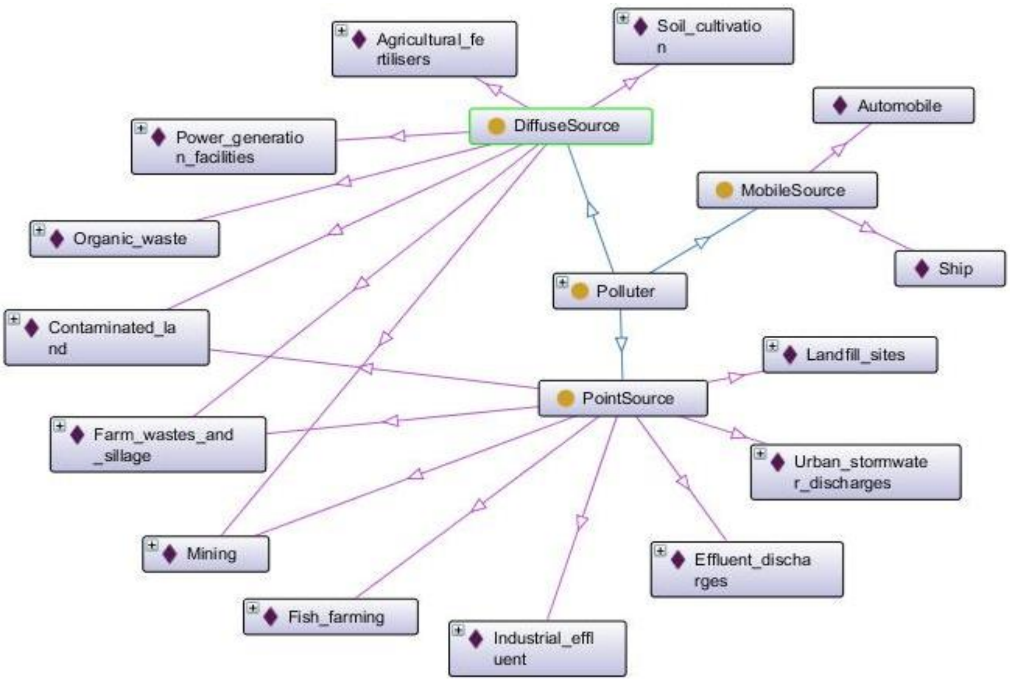

Figure 6. Polluters Ontology.

2.3.3. The Regulations Ontology

Different authoritative water quality regulations could be modeled as part of some existing ontologies. We modeled the Chinese GB3838 regulation ontology within the system. As the comparable references, two other existing ontologies, EU WFD regulations and US EPA standards, are integrated in our model. They could also be found in InWaterSense Ontology listed in Table 3.

In GB3838, water bodies are classified into five categories: Category1 (I) to Category5 (V), which are equivalent as high to bad quality, by the function of the water. The WaterCategory in Figure 7 which is a subclass of GB3838 item illustrates the above five categories. The Regulations Ontology works with WaterQualityModel to realize the mechanistic process (see Section 3.3) of the system. The WaterQualityModel contains the common model specifications.

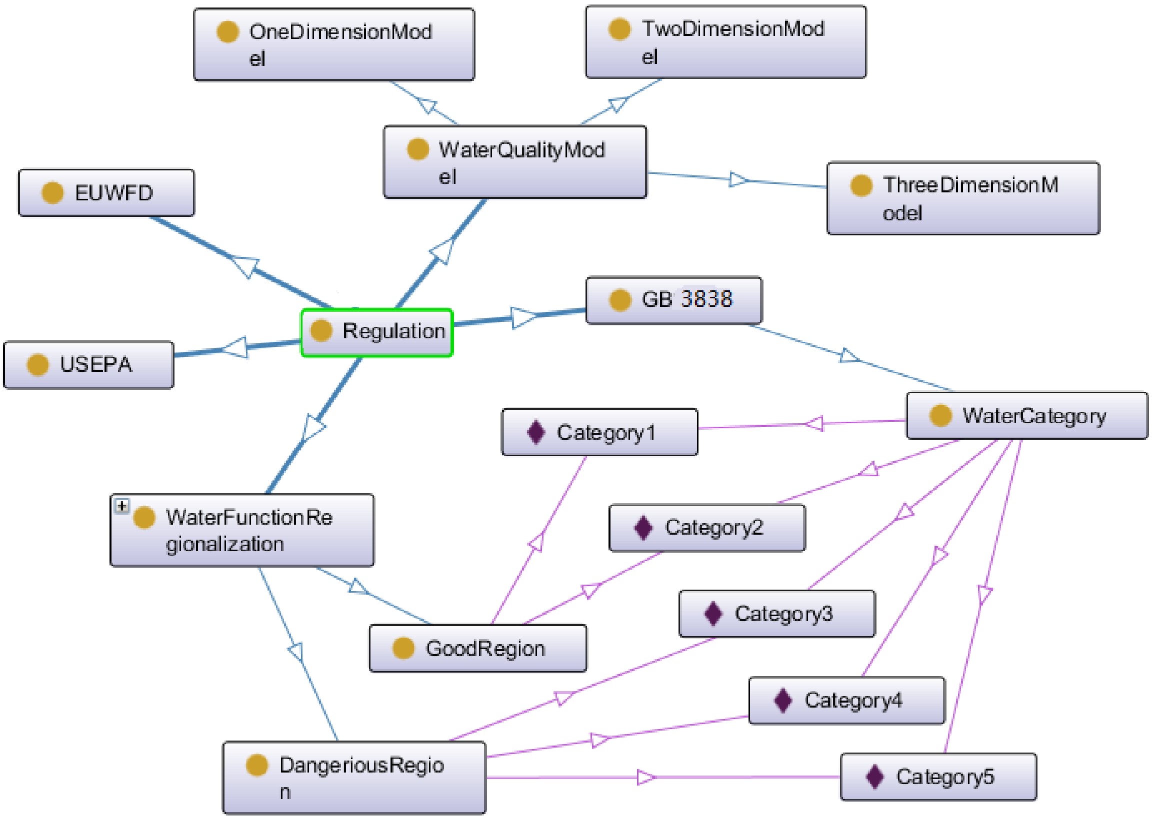

Figure 7. Regulations Ontology.

2.4. The Mechanistic Model

Being useful tools for water resources management, evaluation of environment impact, quality prediction, pollution control and use of water resources, mechanistic water quality models play extremely important roles in water research and applications, and are applied more and more widely. Surface water environment impact prediction includes impact prediction of river, estuaries, big and small lake and gulf water environment, its prediction model has zero-dimension, one-dimension , two-dimensional and three dimensional water quality model. The following mathematic equations represent the mechanistic model in our system.

Regarding a river or river section as a completely mixed reactor, calculate river outflow pollutant concentration according to upper reach river inflow, upper reach pollutant concentration, waste water emissions from draining exit and effluent concentration of pollutant.

The three-dimensional equations are described as follows.

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x}(v_x \cdot c) - \frac{\partial}{\partial y}(v_y \cdot c) - \frac{\partial}{\partial z}(v_z \cdot c) + \frac{\partial}{\partial x}(D_x \cdot \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(D_y \cdot \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(D_z \cdot \frac{\partial c}{\partial z}) + S(x, y, z, c, t) \quad (1)$$

where c (mg/L) is the concentration of pollutants, t (s) is the running time, v_x (m/s) is the velocity in the x-direction, v_y (m/s) is the velocity in the y-direction, v_z (m/s) is the velocity in the z-direction, D_x is the diffusion coefficient of pollutants in x-direction, D_y is the diffusion coefficient of pollutants in y-direction, D_z is the diffusion coefficient of pollutants in z-direction, and *S(x,y,z,c,t)* is the decay of pollutants which are caused by sedimentation and adsorption.

In daily water quality prediction and planning works, it only considers the change of pollutant concentration in the direction of the water flow, which can be obtained from the motion equations of the three-dimensional water flow and the steady-state conditions which includes:

$\frac{\partial}{\partial x}(v_x \cdot c) = v_x \cdot \frac{\partial c}{\partial x}$, v_x is invariant;
$\rightarrow \frac{\partial}{\partial x}(D_x \cdot \frac{\partial c}{\partial x}) = D_x \cdot \frac{\partial^2 c}{\partial x^2}$, D_X is constant;

The first-order decay $\rightarrow S = -k_1 c$, k_1 is the decay coefficient of pollutants.

The concentration of pollutants at a certain spatial location does not change over time in a fully mixed phase of pollutants $\rightarrow \frac{\partial c}{\partial x} = 0$.

The transformed one-dimensional water quality model can be drawn:

$$D_x \cdot \frac{\partial^2 c}{\partial x^2} - v_x \cdot \frac{\partial c}{\partial x} - k_1 c = 0 \quad (2)$$

The second-order partial differential equation at Boundary Conditions (Combining Initial Conditions):
$x = 0 \rightarrow c = c_0$
$x \rightarrow \infty, c = 0$
The solution of the above equation is:

$$c_x = c_0 \cdot \exp[\frac{x \cdot v_x}{2D_x}(1 - \sqrt{1 + \frac{4k_1 \cdot D_x}{{v_x}^2}})] \quad (3)$$

where,

exp = exponent (exponential function).

C_0 can be calculated as $c_0 = \frac{Q \cdot c_1 + q \cdot c_2}{Q + q}$,

C represents pollutant concentration of lower reach (mg/L); Q is upper reach river inflow (m^3/s); C_1 presents upper reach water quality concentration (mg/L); q is waste water emissions from draining exit (m^3/s); C_2 presents effluent concentration of pollutant from draining exit.

Ignoring diffusion effect: $D_x = 0$, there is:

$$c_x = \frac{Q \cdot c_1 + q \cdot c_2}{Q + q} \exp(-\frac{k_1 \cdot x}{v_x}) \quad (4)$$

Or,

$$c_x = \frac{Q \cdot c_1 + q \cdot c_2}{Q + q} \exp(-k_1(t - t_0)) \quad (5)$$

K_1 represents pollutant degradation coefficient, and it is a constant. The Equation (3) applies to the ordinary case that there is no branch or draining exit along the river. The Equations (4) and (5) consider the confluence where two rivers joint.

3. Implementation

3.1. The Reasoning Rules

The integration of ontology models and mechanism models is reflected in the water quality prediction module which uses the reasoning rules as the core of processing. The rules are expressed by the Semantic Web Rule Language (SWRL). In this section, we take one GB3838 standard "The ammonia-nitrogen in the Category III functional water is limited to 1.0 mg/L", as the case study, to verify the usability of ontology models on reasoning. Assuming that we are querying the observations continually from the monitoring sites which have various sensor or sensor networks for observing and measuring the water quality elements, the ontology models in Section 2.3 can be utilized in the following query for real time reasoning (See Rule 1 to Rule 6).

The Rule 1 queries every monitoring data stream through the item ssn:Observation(?x) in Water Ontology (see Section 2.3.1). Some other items of the ontology used in the rule are described as following,

(a) ssn:observedProperty(?x, Element): observing element;
(b) ssn:observationResultTime: recorded at the continuous specified time;
(c) MonitoringStation(?o, ?m): water boundary monitoring sites;
(d) WaterCategory(?m, Category): water's functional category;
(e) ssn:observationResult(?x, ?r): the observed values bound to the observation and measurement result;
(f) sqwrl:makeSet(?sv, ?val): a set of value;
(g) PollutionAlert(?m, Element): alert of the water pollution.

The limit value of NH_3-N element in GB3838 is shown in Table 4. Once the concentration of NH_3-N is above 1.0 mg/L, which is substituted to the StandardValue in the Rule 1, it will trigger the alarm. In addition, as the result, the system server will send the alert to the clients.

Rule 1 Pollution Alert

ssn:Observation(?o)∧MonitoringStation(?o,?m)∧WaterCategory(?m,Category)∧ssn:observedProperty
(?o,Element)∧ssn:observationResultTime(?o,?t)∧ssn:observationResult(?o,?r)∧ssn:hasValue(?r,?v)
∧dul:hasDataValue(?v,?val)∧sqwrl:makeSet(?sv,?val)∧sqwrl:groupBy(?sv,?t)∧swrlb:greaterThan
(?val,StandardValue) ⇒ sqwrl:select(?m,?val,?t,Element)∧PollutionAlert(?m, Element)
e.g.,
ssn:Observation(?o)∧MonitoringStation(?o,?m)∧WaterCategory(?m,Category3)∧ssn:observedProperty
(?o,NH3N)∧ssn:observationResultTime(?o,?t)∧ssn:observationResult(?o,?r)∧ssn:hasValue(?r,?v)
∧dul:hasDataValue(?v,?val)∧sqwrl:makeSet(?sv,?val)∧sqwrl:groupBy(?sv,?t)∧swrlb:greaterThan(?val,1.0)
⇒ sqwrl:select(?m,?val,?t,NH3N)∧PollutionAlert(?m, NH3N)

Table 4. The NH_3-N's limit value in GB3838.

Element	Category I	Category II	Category III	Category IV	Category V
NH_3-N (mg/L)	0.015	0.5	1.0	1.5	2.0

The following Rule 2, Rule 3 and Rule 4 present the pollutant source tracing rules, which are point sources tracing, mobile sources tracing and nonpoint sources tracing respectively. The example points of MonitoringStation, DrainingExit, WaterIntake in the rules are illustrated in Figure 8. The purple points in Figure 8 are monitoring sites, the blue points are draining exits, and the red points are water intakes. Some branch rivers are also considered in the system. For example, the Man River, which is grey highlight in Figure 8, is the branch of Han River. In addition, there are some companies, which could be the polluters, along the branch. The three rules work with the Polluters Ontology (see Section 2.3.2) to identify the polluter of the water pollution. In addition, the results will be shown as a set of suspicious points or areas. For example, the blue point in Figure 8 is the suspicious polluter source which is traced back, and that polluter was the registered one which provided the pollution data periodically.

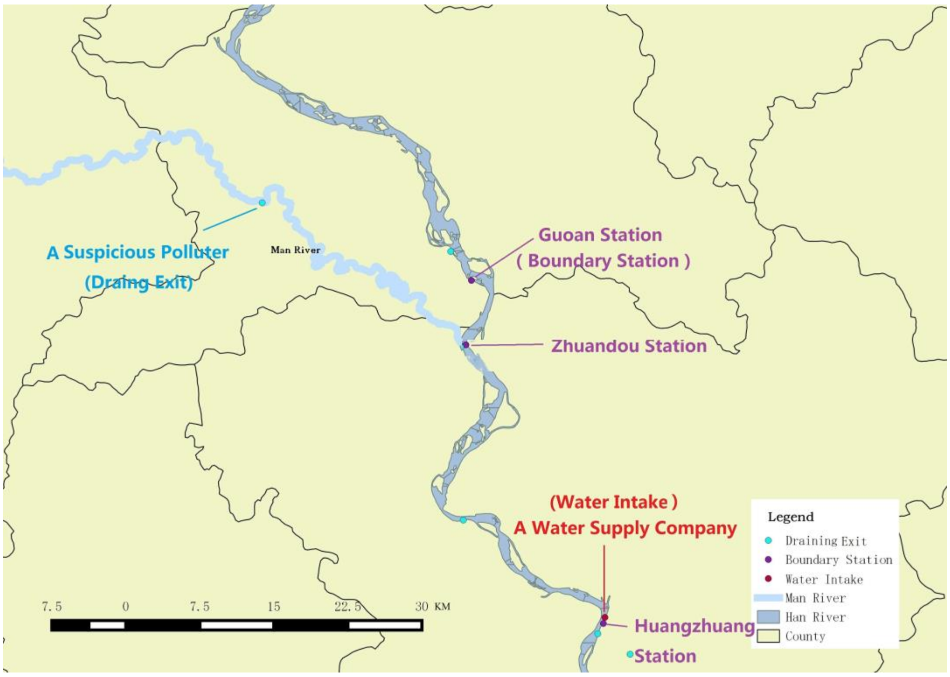

Figure 8. Example.

Rule 2 Point Sources Tracing

PollutionAlert(?m,Element)∧DrainingExit(?m,?d)∧PointSource(?d,?s)∧HasPollutant(?s,Element)
∧sqwrl:makeSet(?sv,?s)∧sqwrl:groupBy(?sv,?m) ⇒ sqwrl:select(?m,?s,Element))∧HasPointSource(?m,?s)
e.g.,
PollutionAlert(?m,NH3N)∧DrainingExit(?m,?d)∧PointSource(?d,?s)∧HasPollutant(?s,NH3N
∧sqwrl:makeSet(?sv,?s)∧sqwrl:groupBy(?sv,?m) ⇒ sqwrl:select(?m,?s,NH3N)∧HasPointSource(?m,?s)

Rule 3 Mobile Sources Tracing

PollutionAlert(?m,Element)∧MobileSource(?m,?s)∧HasPollutant(?s,Element)
∧MobileLocation(?s,?c)∧ssn:observationResultTime(?x,?t)∧sqwrl:makeSet(?sv,?s)∧sqwrl:groupBy(?sv,?m)
⇒ sqwrl:select(?m,?s,?c,?t,Element)∧HasMobileSource(?m,?c)
e.g.,
PollutionAlert(?m, NH3N)∧MobileSource(?m,?s)∧HasPollutant(?s,NH3N)
∧MobileLocation(?s,?c)∧ssn:observationResultTime(?x,?t)∧sqwrl:makeSet(?sv,?s)∧sqwrl:groupBy(?sv,?m)
⇒ sqwrl:select(?m,?s,?c,?t,NH3N)∧HasMobileSource(?m,?c)

Rule 4 Nonpoint Sources Tracing

PollutionAlert(?m,Element)∧NonPointSource(?m,?s)∧HasPollutant(?s,Element)∧sqwrl:makeSet(?sv,?s)
∧sqwrl:groupBy(?sv,?m) ⇒ sqwrl:select(?m,?s,Element)
e.g.,
PollutionAlert(?m, NH3N)∧NonPointSource(?m,?s)∧HasPollutant(?s,NH3N)∧sqwrl:makeSet(?sv,?s)
∧sqwrl:groupBy(?sv,?m) ⇒ sqwrl:select(?m,?s,NH3N)

The Rule 5 and Rule 6 show the pollution early warning and emergency response rules. The Regulations Ontology (see Section 2.3.3) poses to these two rules to give the principles of emergency response. Since the mechanistic model is one type of regulations, the mathematic result OneDimEquationOutput is transferred as one component of the rule. The two rules also work with the alert results from Rule 1 and polluter results from Rule 2, Rule 3 and Rule 4 to obtain the inferences which will be given to the government and public.

Rule 5 Pollution Early Warning

PollutionAlert(?m,Element)∧hasLowerSite(?m,?l)∧OneDimEquationOutput(?l,?val)∧hasPredictTime (?t,?pt)∧dul:hasDataValue(?v,?val)∧sqwrl:makeSet(?sv,?val)∧sqwrl:groupBy(?sv,?m)∧swrlb:greaterThan (?val,StandardValue) ⇒ sqwrl:select(?l,?val,?pt,Element)∧PollutionWarning (?l,Element)
e.g.,
PollutionAlert(?m,NH3N)∧hasLowerSite(?m,?l)∧OneDimEquationOutput(?l,?val)∧hasPredictTime(?t,?pt) ∧dul:hasDataValue(?v,?val)∧sqwrl:makeSet(?sv,?val)∧sqwrl:groupBy(?sv,?m)∧swrlb:greaterThan(?val,1.0) ⇒ sqwrl:select(?l,?val,?pt,NH3N)∧PollutionWarning (?l,NH3N)

Rule 6 Emergency Response

PollutionAlert(?m,Element)∧hasWaterIntake(?m,?i) ⇒ EmergencyResponse(?i,?er)
PollutionWarning(?l,Element)∧hasWaterIntake(?l,?i) ⇒ EmergencyResponse(?i,?er)

3.2. The Software System

The online ontology-underpinned emergency response system for water pollution accidents was designed and developed, namely the Hubei Key Transboundary Water Quality Risk Assessment and Warning GIS Platform which is shown in Figure 9. The Map Layers at right-top and Data Management Functions at left are general GIS functions. The pollution alert processing function is mainly used to help the quick display of the water pollution and related emergency response in Han River in Hubei Province, China.

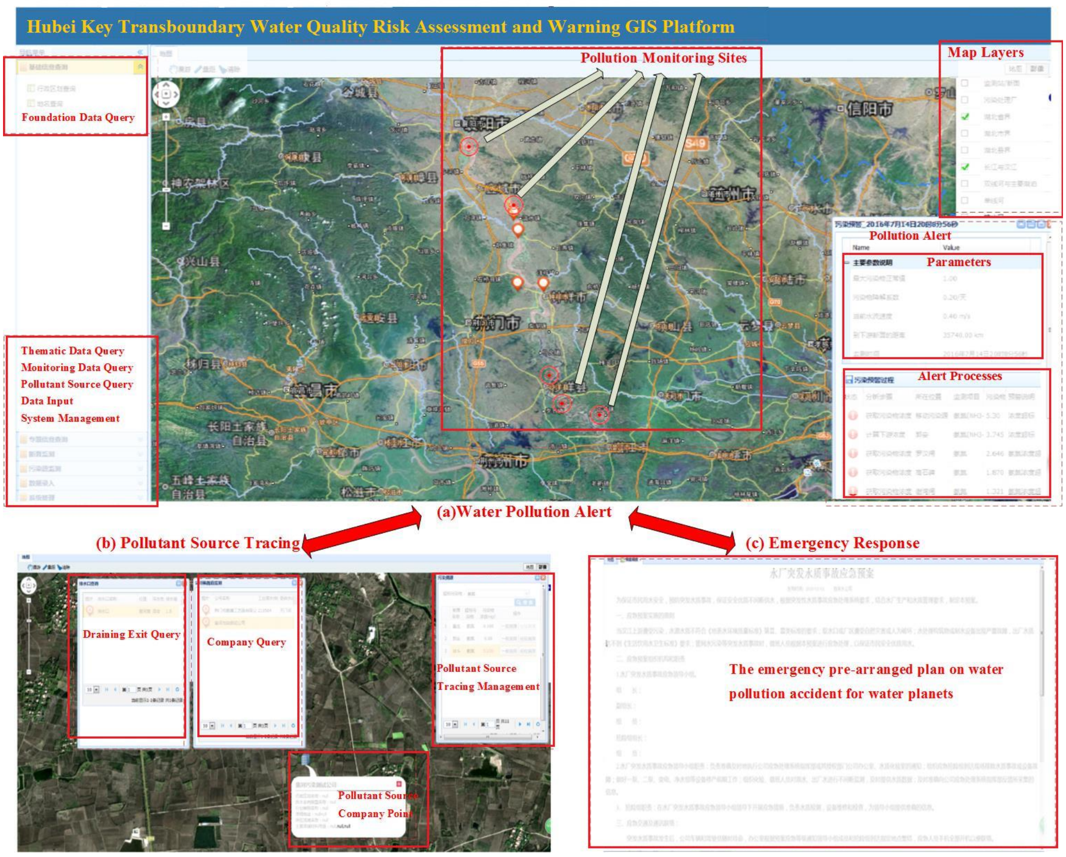

Figure 9. User interface of the software system.

Figure 9 shows the collaborative graph of warning service of the prototype system. The pollution alert in Figure 9a is realized by Rule 1 in Section 3.1. Once the sensors in monitoring sites (see red points in Figure 9) found there was some pollutant concentration exceeding the limitation value, the system will automatically alert with the experiential and mechanistic processing. The detail of demonstration will be presented in Section 3.3.

Pollutant source tracing example is shown in Figure 9b to realize and verify the experiential processing. It could obtain the suspicious companies which make the pollution through the nearest upstream drain exists. There are three different types of pollutant source, and the tracing processes are respectively described in Rule 2, Rule 3 and Rule 4. Specially, users can add the mobile polluters into the system manually. Some of the polluters are reported by public individuals through a cellphone App. All polluters' data will be mapped to Polluters Ontology when executing the reasoning on pollutant source tracing.

The system provides the mechanistic processing function (see Section 2.4), which appears externally as the result of water pollutant impact. After internal functional processing with the control of Rule 5 and Rule 6, the list of the water pollutant impact area will be presented with the emergency pre-arranged plan as the output. One example plan for water planets is shown in Figure 9c. This kind of emergency response information could also be sent to related government officers and public citizens through SMS (cellphone messages) and WeChat, because of its simple and light XML-based or script-based formats.

3.3. The Application Demonstration

In this section, we demonstrate the "Alert" response, which is explained in Section 2.2, through monitoring the concentration of ammonia-nitrogen in the area shown in Figure 8 as the example. There are three boundary stations, which names Guoan, Zhuandou and Huangzhuang, along the Han River (see purple color points in Figure 8). Guoan and Huangzhuang stations monitor the water quality of Han River, but Zhuandou station monitor the water quality of its branch (Man River).

Firstly, the system uses the web service interface to get monitoring data from boundary stations for pollution discovery every an hour. If any concentration is above the limitation value, which is always 1.0 mg/L for Han River, the system will show the alarm. All this kinds of regulations are classified in the Regulations Ontology for querying.

Secondly, the qualitative ontology model and quantitative mechanistic model work together to assess the water quality risk. The real time monitoring data are packaged as the Monitoring Object (see Figure 10) which contains the name, time, position and value of the monitoring parameter. The ontology models in A-BOX work as the classes for representing the continuous monitoring objects at intervals from B-BOX. Once the monitoring value of ammonia-nitrogen concentration is above 1.0, it means there is pollution at that place. The Rule 1 reasoner, which is a software agent (see multi-agents in Figure 3), works with the A-BOX ontology models. The reasoner agent returns the result which is a set of polluted positions, through querying "⇒ sqwrl:select(?m,?val,?t,NH3N)∧PollutionAlert(?m, NH3N)". The positions can include boundary stations, water intakes, water planets, and connected residential areas. The system will send the alarm to highlight the polluted positions, and run the mechanistic model automatically to analyze the pollution possibility downstream.

If there is no branch or draining exit downstream, we can directly use the Equation (3) to get the expected concentrations. However, there are some branches along the Han River actually. We need to consider about the confluence where the two rivers join. For example, assume c_1 at upstream Guoan station equals 0.5 mg/L at a time, and c_2 at Zhuandou station which is not from Guoan downstream equals 1.98 mg/L. The software system uses the Equation (4) to predict the ammonia-nitrogen concentration c_4 at the location of a water supply company downstream. According to the hydrology information, the inflow of Han River is double that of Man River. Ignoring diffusion effect: $D_x = 0$, there is:

$$c_4 = (c_1 \times 1/3 + c_2 \times 2/3) \times e^{-K \cdot \frac{x}{v_x}} \tag{6}$$

The coefficient of ammonia nitrogen pollutant K is 0.2, the distance x between Zhuandou and the water intake is 50 km, and the v_x is 0.6 m/s. Therefore, we can get the result c_4 = 0.819 which is below the limitation value. We could also retrieve the monitoring data from Huanzhuang station to validate the model prediction. If the real-time monitoring concentration c_3 at Huangzhuang station exceeds the prediction value much, the governor will send the people to the sites to analysis the water quality manually, update the observation data in real time, and correct the prediction information. The updated observation data at Guoan site and Zhuandou site will be used to do mechanistic model calculation again to verify the manually tested pollutant concentration at Huangzhuang site.

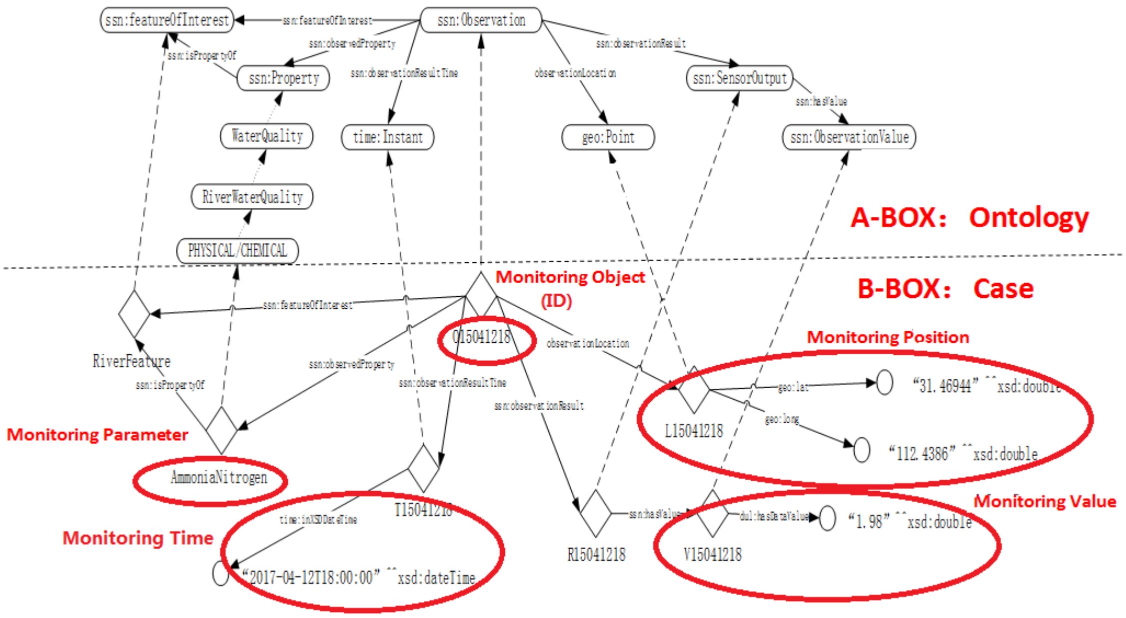

Figure 10. An alert case with Water Ontology.

Finally, the user interface of the "early warning" will be shown in Figure 11. The system can show the calculating steps and the predication information for the interest points. The schools, hospitals and residential areas are connected to the water intake which may suffer the water pollution accident. The alarms are highlighted on the user interface of the system, and the governor can find the pollution position easily and start the emergency response immediately. The total response time of the system is set to be 8 hours for ammonia nitrogen pollution accident.

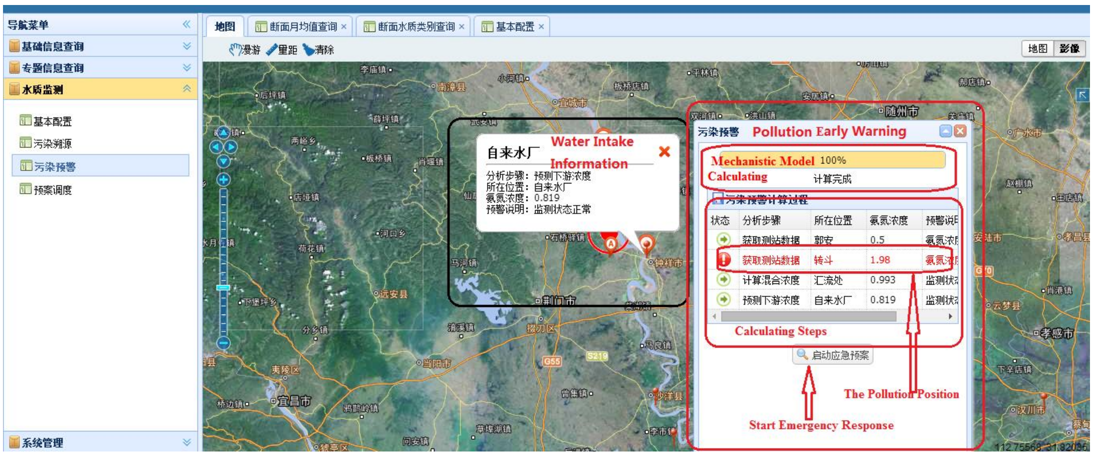

Figure 11. User interface of early warning.

4. Conclusions

This paper makes a study of the theoretical and technical issues of an ontology-underpinned emergency response system for water pollution accidents. We have realized the semantic ontology driven model of the water monitoring area, and the development of the rule-based automatic system. This paper has achieved some scientific findings and mainly made the following contributions.

It proposes and designs ontology-based architecture viewed from the characteristics of the ontology-underpinned system. Specifically, it studies the basic theory of ontology, analyzes the execution of semantic web, and designs rules for water pollution accidents. It proposes to adopt the mechanistic model to extend above innovative semantic architecture, to develop the Hubei Key Transboundary Water Quality Risk Assessment and Warning GIS Platform in China. This system mainly makes use of specifications for the data form Hubei Environment Monitoring Center, in order to illustrate and describe details about polluter identification, pollutant tracing, early warning, decision support and public awareness along Han River. According to the goal of sustainable development, the proposed ontology model and reasoning multi-agents allow the integration among geographic information systems on land use, resource management, ecologic protection, public health, and other topics of earth and health sciences, in order to study the change in water quality and its relationship with ecological public health.

Although this paper has made some research findings, the studies on the perfect automatic system for water pollution accidents cannot be achieved and improved in a short time, especially, the study on the semantic-driven-based auto-combination of the service chain is just in the initial stage. The following problems shall be further studies and settled: (a) the system shall be updated in further perfecting multi-dimensional mechanistic models; (b) the system needs to do reasoning from external semantic web services; (c) we shall analyze and compare the efficiency of the internal data/service and external big data/service in the condition of the existing distributed and heterogeneous sensors deployment.

Acknowledgments: The work is partially funded by NSFC 41501441, the National Key Research and Development Project of China 2017YFB0503600, the Hubei Provincial Natural Science Foundation ZRMS2017000737, the Hubei Provincial Environment Protection Project 2014HB04, the Hebei Provincial Natural Science Foundation D2015402134, and Wuhan University Grant 2042017kf0212. The author is very grateful to the Large Scale Environment Remote Sensing Platform (Facility No. 16000009, 16000011, 16000012) provided by Wuhan University. Appreciation is extended to Guoqiang Song at Hubei Environmental Monitoring Center, Wuhan, Hubei, China for providing the data and access permission to the Hubei Key Transboundary Water Quality Risk Assessment and Warning GIS Platform. Special thanks to editors and reviewers for providing valuable insight into this article.

Author Contributions: Xiaoliang Meng designed the system; Hao Chang developed the system; Xinxia Liu and Junming Bai analyzed the data; Wenhan Zheng and Zhuo Chen contributed some materials and tools for the experiment; Xiaoliang Meng, Chao Xu and Xinxia Liu wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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