OntoAqua: Ontology-based Modelling of Context in Water Safety and Security

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Abstract: Water distribution systems are comprised of a variety of different components that must be monitored in order to combat crises as effectively as possible. In particular, the subsystems that monitor the different components are varied and diverse, and as a result, their produced data are heterogeneous and occupy different modalities. This paper describes the OntoAqua ontology that aims to semantically represent knowledge and data sources in the event of a water-related crisis, including preparatory and follow-up measures. Towards the creation of an ontology that is semantically sound and adopts international standards, existing ontologies and resources were reused. More specifically, the specification and the semantics of the ontology are inspired mainly from the ISO 15975 - Security of drinking water supply. The modelling of sensor data was implemented by reusing the SAREF ontology and its extension for the water domain. For crowdsourcing and social media, the ontology imports classes and properties from the SIOC ontology.

1 INTRODUCTION

Water is vital for all life and therefore ensuring its quality and quantity is of great importance. Unfortunately, both water's quality and quantity are at stake due to natural or man-made disasters. In order to strengthen the protection of drinking water and combat crisis as effectively as possible, several research actions are initialized that involve the combination and integration of several technologies into water distribution systems. Towards this direction, the aqua3S Horizon-2020 project [1] proposes the combination of novel technologies in water safety and security, which involve the use of direct sensing methods based on the use of sensors and indirect sensing methods that involve social media posts.

The use and combination of different components and technologies is a major step towards better monitoring of larger parts of the networks including the water sources and water distribution network and eventually towards ensuring water safety and security. However, these components are diverse and the data that are produced are heterogeneous and occupy different modalities. In order to utilize this information, it is imperative to build a vocabulary that will define their representation in a uniform way and hold the pertinent information regardless its source. Building such a model enables the improved understanding of the meaning of the data (i.e. semantics). Moreover, the combination of semantics from different sources is important, because heterogeneous data cover a greater range of knowledge.

The Semantic Web is the web of data that can be processed directly and indirectly by machines (Berners-Lee et al., 2001) and has multiple technologies for semantic enrichment and representation of data. Ontologies are a powerful means in representing semantic knowledge, and they promote interoperability and semantic reasoning. They are the specification of a vocabulary for semantically representing a shared domain of discourse (Gruber, 1993), which means that an ontology can semantically model domain knowledge via the means of defining a set of classes (i.e. objects, concepts) of the domain and their properties (i.e. interconnections, attributes).

In this work, Semantic Web technologies are used to represent knowledge and data sources in the event of a water-related crisis, including preparatory and

[1]https://aqua3s.eu/

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follow-up measures. Towards the creation of an ontology that is semantically sound and adopts international standards, existing ontologies and resources were adapted and extended. More specifically, the specification and the semantics of the ontology are inspired mainly from the ISO 15975 - Security of drinking water supply. The modelling of sensor data was implemented by reusing the SAREF ontology and its extension for the water domain. For crowdsourcing and social media, the ontology imports classes and properties from the SIOC ontology.

The paper is structured as follows. Section 2 presents the Related Work on ontologies related to crisis, crisis management, sensors and IoT devices. In section 3, the data model is presented, along with the developed ontology. Then, in section 4 an example of the developed ontology is presented. The paper concludes in section 5 presenting the most important parts of the paper and future work.

2 RELATED WORK

Several ontologies have been designed to describe crises and provide improved management, along with enhanced decision support. The beAWARE ontology (Kontopoulos et al., 2018) was designed and used within the context of the Horizon 2020 project beAWARE. It handles heterogeneous data in climate crisis situations (floods, earthquakes, forest fires etc.) in order to provide decision support. The ontology supports data both from sensors and from human agents, along with the implementation of social media input. First responder (FRs) assignment capabilities, operational missions and breakdown of the crisis into incidents lead to more fine-grained crisis management.

The ISyCri ontology (Bénaben et al., 2008) was used on the ISyCri project and provides a general crisis management ontology that is suitable for a wide range of crises (e.g. technical, political, legal, natural, etc.). The focus is on the description of the crisis and the related entities in a somewhat abstract manner, considering mainly the higher-level information about the ontology. In particular, the crisis is characterized by the gravity factors (conditions that may change the severity of the crisis), and the complexity factors (conditions that may change the type of the crisis). Moreover, the ontology introduces risks as an ambient factor of the system that is always present and can cause or exacerbate a crisis. A different approach to crisis management was followed by empathi (Gaur et al., 2019) that supports a broader overview of such situations. The ontology models the core concepts of emergency management and hazard crises planning. It achieves this by capturing and integrating information from sources such as satellite images, local sensors and social media content generated by locals.

The VuWiki ontology (Khazai et al., 2014) was initially developed as an explicit reference system to describe vulnerability assessments. Then, classification and annotation of vulnerability assessment was realized by implementing an ontology in a semantic wiki. The result of this implementation provides a uniform ontology as a reference system and easy, structured access to the knowledge field of vulnerability assessments. The ontology proposed in (Ahmad et al., 2019) also tackles the issue of disaster trail management by initiating rules that search for data in the World Wide Web. These rules are employed for data extraction and reasoning purposes. This results to a semantic web-based disaster trail management ontology, which encompasses a plethora of important aspects of disasters, like disaster type, disaster location, disaster time, misfortunes including the causalities and the infrastructure loss.

The European Committee for Standardization (CEN) approved the ISO 15975 standard (ISO 15975:2013(E), 2013) for the management of drinking water supplies. It focuses on the procedures necessary to ensure the safety of crisis management for risk mitigation. The ISO defines the issues mainly in terms of Crisis and the associated Hazards and Risks for all potential types of crises (natural, technical, malicious etc.). It promotes the definition of procedures that work towards risk mitigation, in all time frames; before, during and after the crisis (preparation, operative and follow-up stages respectively). Overall, the ISO stretches the proactive stance that is necessary, and the clear definition of potential crisis in order for effective mitigation and communication to take place.

Other contextual information, such as sensor measurements and social media observations, can provide useful insights for risk assessment and decision making. SSN (Janowicz et al., 2019) is a joint OWL2 ontology of W3C and OGC that models sensors along with their characteristics, observations, procedures, features of interest, etc., with SOSA being its core model. Additionally, Smart Appliances REFerence (SAREF) (Daniele et al., 2015) is an ontology that was created with the support of European commission to promote IoT in the context of smart appliances and devices. The core ontology models smart appliances and devices along with their functionalities and the transmitted commands. Moreover, sensors are also included as a subcategory of devices, and they perform measurements of relevant features of interest (e.g. water). SAREF4WATR ((ETSI), 2020) is a re-

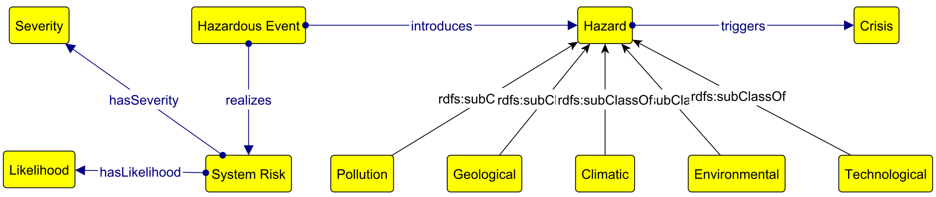

Figure 1: Hazards, Hazardous Events and System Risks.

cent SAREF extension that specializes in the domain of water management. Lastly, the SocIoS (Tserpes et al., 2012) ontology aims to devise a unified Social Network model that is directly mapped to the most prominent social networks APIs (OpenSocial, Facebook, Twitter, FlickR and Youtube). It also provides associations with other notable ontologies (such as FOAF (Brickley and Miller, 2007) and SIOC (Bojars et al., 2010)) in order to promote interoperability.

3 ONTOLOGY CONCEPTUALISATION

The OntoAqua ontology follows the ISO 15975 (ISO 15975:2013(E), 2013), so as to consider the official definitions for related concepts. The ISO studies the risk and crisis management of water supply chain that covers the pre-crisis, post-crisis and during the event phases. The pre-crisis phase (preparatory crisis management) aims to detect the risks and prepare mitigation mechanisms. During the crisis (operative crisis management), the aim is to reduce the negative impacts as soon and effectively as possible. Finally, after the crisis has passed (follow-up crisis management), the objective is to restore the operational order and to debrief the situation in order to improve the mitigation mechanism for future crises. In our work, the modelling focuses on the phase when the crisis is ongoing because it has the highest potential impact.

The definition of relevant entities, concepts and procedures is crucial towards the management of hazardous situations in water supply chains. In particular, points of interest include (a) risk assessment, (b) subdivision of different types of irregularities, (c) causal relationships, (d) involved actors, (e) assets that are liable to damage, (f) data sources and (g) spatial and temporal specification. The points of interest (a) through (e) are modeled based on the ISO 15975 in as high fidelity as possible, resulting in the core ontology about crises in the water domain. The particular data sources (f) that were considered are water sensors and social media. The water sensors provide information mainly about the existence of pathogens in the water, and the social media are mined in order to determine abnormalities in the water supply that are perceptible to the communities. Finally for spatial and temporal specification (g) of particular entities or events, the most prominent resources were utilized that ensure validity and compatibility with external resources.

3.1 Competency Questions

Competency Questions (CQs) are a set of questions that the ontology needs to be able to answer. The CQs are important for the lifecycle of the ontology as they both represent the requirements of the ontology and can be used as means for validation (Bezerra et al., 2013). The following list includes the CQs that guided the development exclusively of the core of the ontology. Moreover, the CQs summarize the motivation behind the development of the core of OntoAqua ontology. **Competency Questions:**

- What is the type of the crisis? (e.g. flood, mechanical failure)
- What is impacted by the crisis?
- What are the identified causes of the crisis? (i.e. hazards)
- What are the identified abnormalities within the crisis? (i.e. incidents)
- What is the location of an incident?
- When was the incident detected?
- What entities does the incident impact?
- How were the incident detected? (i.e. what are the data that detected its existence)
- What analysis task detected the incident?
- If applicable, what sensor measurement detected the incident?
- What operational forces are involved to an incident?
- Who are the first responders that are assigned to an incident?
- What operational force does one first responder agent belong to?

3.2 Core Ontology

Starting with the most important classes that define a crisis, as illustrated in Figure 1, the Crisis entity corresponds to the event or situation that has the potential to affect seriously a drinking water supply chain. A Hazard is a condition or agent in the water with the potential of causing harm. One or more Hazards may trigger a Crisis, if the Hazards are not contained. The Hazards are classified into five main categories (Biological, Geological, Hydrometeorological, Environmental, and Technological) depending on their nature. These five classes represent prominent types of hazards, and they stand to be specialized further. For example, Pollution hazards can be subdivided into chemical and microbiological pollution.

Hazardous Events are events that introduce Hazards (or hazardous situation) to the system, based on existing System Risks. Such risks exist inherently in the system and have the potential to be realized by an event and subsequently introduce a Hazard to the system. System Risks are characterized by their Likelihood (which defines how likely the event is to occur, not necessarily given as a probability) and their Severity (which defines the extent of the expected impact if the Risk comes to pass). For example, the risk of flood in a particular area might be exceptionally low (low likelihood) and the severity of the consequences exceedingly high. Overall, the importance of the risks is the product of the likelihood and the severity. However, the numerical representations of the likelihood and the severity lack the corresponding standards, so their product is not straightforward. Similarly, the ISO 15975 does not define a specific formula that combines the likelihood and severity; thus, we elected to follow the same approach and specialize it according to specific needs in the future.

The crisis management aims to either avoid or ameliorate the negative impact of a crisis on the associated assets. Thus, the inclusion of the components that are liable to be harmed is important in order to provide better understanding of the crisis. Figure 2 depicts the System Components that are potentially impacted by the Crisis or by particular Hazardous Events within the crisis. They are subdivided into four basic categories (Social, Resource, Environmental, and Economic). Finally, a Disaster is classified as a Crisis in case it has already caused widespread losses on some System Components.

In crises, it is often necessary to involve external forces in order to mitigate the losses. Such forces are typically FR from various fields of expertise. In particular, the FR Agent class represents entities that belong to some FR Operational Force, and mainly are either FR Teams, or individual FRs (Figure 3). The FR Operational Force is used to categorize the expertise of the team and to provide better view of the Crisis. One important detail from the perspective of decision support is that the FR Agents are assigned to resolve particular actionable Incidents (including Hazardous Events) within the crisis, and not loosely assigned to the whole crisis. Finally, the core classes of the FR Agents with respect to their structure allows for the definition of teams (potentially with elaborate structure) that include (via the ‘has member’ property) multiple individuals and other sub-teams. Further specialization can be achieved through subclasses of FR, depending on their role.

Moving to a finer granularity of the crisis, the Incidents (Figure 4) are defined as “deviations from normal operating conditions” (ISO 15975:2013(E), 2013). They represent particular happenings that hold some interest for the specification of the crisis. Incidents may also be Hazards that are manifestations of underlying Risks (Hazard is a subclass of Incident).

Within water crisis management systems, it is important to have a connection between the data generators and the crisis. In particular, the objective is to connect the various abnormal sensor measurements and the detections from analysis components with the crisis itself. This is done via the Incident class that denotes an irregularity within the crisis, which also might be a Hazardous Event. Doing so allows for the provenance of the irregularities to be transparent and available for further decision support. Additionally, the impact of the Incident is a secondary way to connect to the crisis, as it shows which System Components are impacted by the Incident.

Figure 4 shows the structure of the incidents that is adopted, and it is based on the beAWARE [2] project. The class Incident is the blanket entity that correlates the abnormalities to the crisis, regardless of their provenance. For the spatial extend of the Incident the GeoSPARQL Geometry class (see Section 3.3.1) is used that allows for a variety of different spatial geometrical shapes. The temporal characteristics of the incident are defined according to the specification of the OWL Time ontology (see Section 3.3.2) . In relation to the analysis components the association is made through the Media Items that they produce. In particular, the Media Items are the results of the analysis Tasks (e.g. object detection analysis and social media analysis) and they justify the existence of the Incident. The Media Item class can be subdivided into particular categories according to the nature of the Media, with the most prominent cases being occurrences of Image and Textual Entity. In regard to

[2]https://beaware-project.eu/

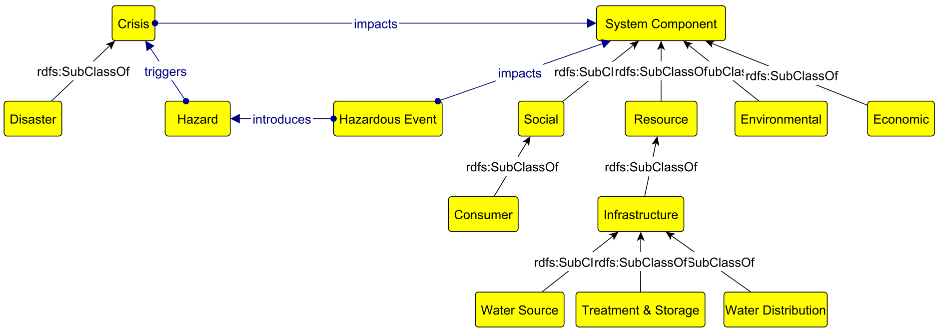

Figure 2: The impacted components of the system.

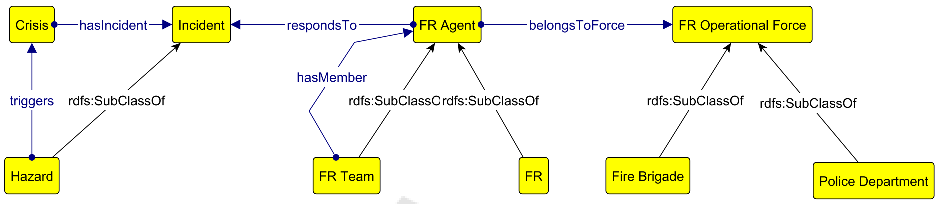

Figure 3: Relationships between First Responders and the crisis.

the sensor measurements, no analysis is realised and thus the association with the incident is done via the sensor measurements. The representation of the sensor measurements is adopted according to the SAREF ontology and its extension SAREF for Water (S4W).

The core ontology covers the basis for representing water distribution crises and the associated hazards, risks, impacts, and participants. The ontology includes 67 concepts (classes), 21 properties, 88 logical axioms and 84 declaration axioms. Overall, the core ontology provides a concise framework for water crises that is designed to promote extensibility as manifested in the following sections.

3.3 Ontology Extensions

The core ontology lays the groundwork for the conceptual representation of information about the crisis. However, water distribution management systems need to combine the high level information with specific and actionable information. In particular, temporal and spatial information is crucial in order to determine and combat irregularities. For example, an incident of high pollutants on a lake might become apparent via the measurements of a sensor with combination of some Twitter posts. In that case, information such as the exact locations and times of the measurements and the type of the sensor might prove crucial in determining the crisis and resolving it. Similarly details about the social media activity is also important in specifying the irregularities.

Thus, we first describe how the core crisis ontology is enriched with temporal and spatial information using existing and well established resources and then we present the extensions for sensor measurements and social media data. The presented extensions are build upon the core ontology but are not strongly coupled with it, meaning that the core can be used in isolation, or with different extensions that are appropriate for a particular use case.

3.3.1 Geospatial Information

Spatial information is modelled using GeoSPARQL (Perry and Herring, 2012), which is an OGC standard. GeoSPARQL consists of a lightweight ontology for representing spatial information and an ontology that defines the SPARQL interface that allows qualitative and quantitative relationships to be expressed via a SPARQL endpoint. The most prominent RDF stores (RDF4J and GraphDB) support natively the GeoSPARQL relationship schema, thus, allowing for complex spatial semantic reasoning. This representation is also used by the SAREF ontology, thus, achieving a uniform spatial representation within the semantic reasoning component.

As the decision support functionalities heavily rely on spatial configurations in various forms, it was necessary for all entities holding geospatial information to be subsumed by the GeoSPARQL class so as to utilize the functionalities of the GeoSPARQL ontology. This Feature class is connected with the GeoSPARQL Geometry class that allows the spatial

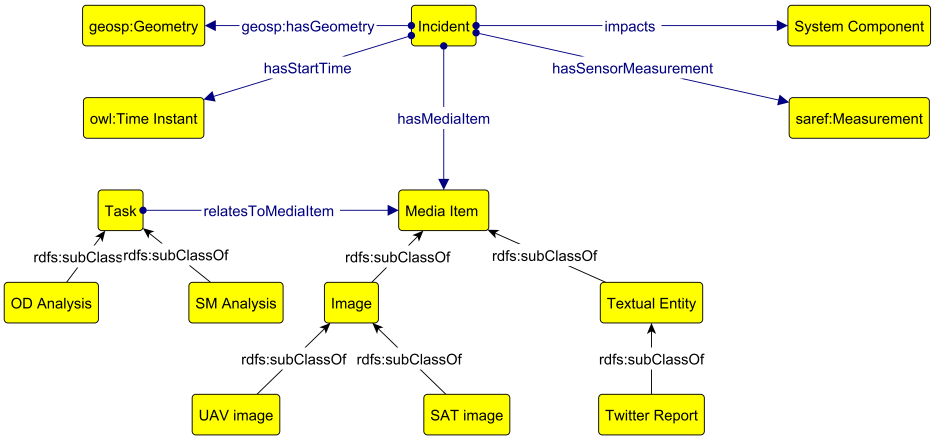

Figure 4: The Incident, Media Item and the Task classes.

specification. The most useful geometries are the Points given the sources as they are used to represent position of various entities (sensors, individuals, tweets etc.), and secondarily the Line Strings which can be used to represent trajectories of entities, e.g. the movement of a First Responder.

3.3.2 Temporal Information

For temporal information, we employ the widely used OWL Time Ontology (Hobbs and Pan, 2006), which is a W3C candidate recommendation It represents time in terms of time Instants and time Intervals. The format that is adapted for Date/Time representation is the ISO 8601 (Houston, 1993). An important set of features that the ontology offers is the relationships between time entities. Such relationships include those used to assert that a given event occurs before or after another, as well as more complex ones such as those used to assert that a given event overlaps with or contains another. Overall, temporal relationships are crucial to the characterization of the crisis, for example, the temporal sequence of hazardous events and incidents affects the crisis in a major way.

3.3.3 Sensors

This extension of the core ontology is on the dimension of sensors that provide raw data to the system. The data produced by the sensors are associated with the high level crisis information via the Incident class. The SAREF and S4W ontologies were used for the representation of sensor information. They provide the framework for storing and processing sensor measurements. Moreover, they include an extensive modeling tools for sensors, devices and more complex systems. In a more abstract level, they define a set of classes (e.g. raw water source, waste water and drinking water) that are central to the system.

The S4W ontology also provides more specific classes for the water domain, including a hierarchy of water properties that are of relevance for water management and security. In particular the top level of this hierarchy divides the properties in microbial, chemical and acceptability properties. Each category determines what kind of irregularity is measured, where microbial properties measure the existence of microbes (e.g. E. coli), the chemical properties measure the existence of chemical substances (e.g. chlorine) and the acceptability properties measure the appearance (e.g. cloudiness), the smell and taste of the water. The hierarchy goes into more specific subcategories that cover most water security applications. Overall, the two sensor ontologies are extensive and complete so there was not need for modifications in order to be integrated with the core crisis ontologies.

3.3.4 Social Media

Social media analysis is an important part of the water distribution management platforms, as it studies the public perception of the water distribution system, and the water services. Especially with the advent of microblogging services (like Twitter), the monitoring of social media can unveil abnormalities on the water distribution system in a timely fashion. Twitter was deemed the most suitable platform for such monitoring, thus, the ontology is focused on it, while providing a scheme that is extensible to other social networks. In order to promote interoperability, the entities used for the representation of social media knowledge were mapped as closely as possible to the SIOC ontology (denoted by the “sioc” prefix). SIOC is widely used (W3C member submission) and aims to represent online users, their activity, and their relationships in the context of communities. In the context of this work, the focus is mainly the textual content of the posts itself and less so the social aspects and interactions between the users.

In particular, the main class is the Tweet that is a subclass of the sioc:Post class, meaning is a more specific category of an online post. The Tweet class represents an online post made by a user in the Twitter microblogging platform. Tweets (or sioc:Posts in general) are created by online users (sioc:User).

The users can also be organized into communities or Usergroups that have individual users as their members. Overall, given that the importance is placed on the posts (tweets) themselves rather than the users that created them or the communities they belong to, we did not expand the classes sioc:User and sioc:Usergroup.

The connection between the Twitter data and the crisis is implemented via the Incident class of the core crisis ontology, which, connects social media posts to abnormal situations. Sometimes, it is useful to analyze the social media posts in mass to determine an event with more confidence. Towards this goal, the ontology is modified to support post aggregations that collectively show a deviation from normal conditions. Moreover, in order for the ontology to be compliant with the SAREF ontologies, the same features of interest and properties were adopted. For example, the feature of interest ”drinking water” that is defined by the SAREF ontology is used associated with the social media analysis as well. Similarly, the water properties (e.g. Acceptability Property) are adopted by the social media analysis data.

4 EXAMPLE

The ontology models the schema and the structure of the stored information, in order to add semantics according to domain knowledge and subsequently enhance the understanding of the situation. So far, the ontology schema was presented in terms of classes, hierarchies, and properties. However, in applications that utilize ontologies, the data are transformed as instances of the ontology in order to adhere to the specification. In detail, instances are the real-world entities that belong to some class, or alternatively, instances are concrete entities that correspond to some abstract entities (the classes). In this subsection an example of the representation of some knowledge that adheres to the ontology schema is shown.

Figure 5 illustrates the instance graph that corresponds to some knowledge regarding a crisis and is modeled according to the ontology. In particular, the crisis instance is of Chemical Pollution subclass and is triggered by a Hazard that defines that the Chlorine concentration is elevated. The hazard itself was realized by a Hazardous event that also has a starting time associated, and a Risk instance. Another aspect of the crisis is the impacted system component, in particular, the lake instance. The particular system component is bounded by a polygon instance of the corresponding GeoSPARQL class. Moreover, the lake has the chlorine instance of the class saref:Property that is measured by a device, and corresponds to the chlorine concentration of chlorine in the lake.

5 CONCLUSIONS

This paper presents the OntoAqua ontology for representing crises, their high-level characteristics, and also it offers a framework for finer granularity of incidents within a crisis. The ontology models the crisis according to the specification of ISO 15975 and while the core ontology offers the basis for representation of crisis of the water domain, it is also at the same time a modular and versatile core ontology for crisis that can be adjusted as needed and cover other domains as well. Additionally, standardized ontologies were adopted and imported for the specification of temporal and spatial information.

Moreover, the ontology was extended in order to cover knowledge originating from sensor measurements and from social media. In particular, for sensor measurements, the adopted structure is mapped as closely as possible to the SAREF ontology and its new extension for water, in order to ensure interoperability. Regarding the social media knowledge representation, the focus was on both individual posts and collections of multiple posts. Collections of posts are expected to be analyzed and produce better insights than individual posts on the public perception. For the social media representation, entities, and relationships from the SIOC ontology were adopted, and new additions were also realised.

As future work, we envisage the expansion of the ontology to accommodate for satellite and drone data and adjust to the maturing analytics components that will produce insightful knowledge. Finally, semantic rules will also be created that will be used for inferring advanced knowledge and thus better support the decision-making process.

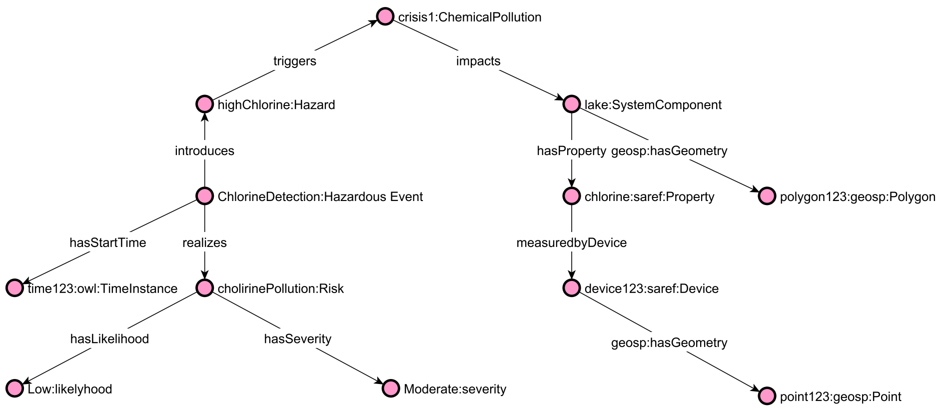

Figure 5: Example of instance graph about a crisis.

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