Semantic model for flood management

Julián Garrido, Ignacio Requena and Stefano Mambretti

ABSTRACT

Risk assessment involves the study of vulnerability and hazards. When focused on flood events, such an analysis should evidently include the theoretical and practical study of floods and their behavior. Nevertheless, risk assessment is not useful if the results are not subsequently used for more effective management and planning by local authorities and qualified personnel. The risk evaluation process is composed of a set of actions, each of which requires different inputs. In fact, the results of one action are used as the input for another. This paper describes a semantic model for the study and management of floods with a view to elaborating a conceptual framework and designing a knowledge base. The model is based on the environmental assessment ontology and demonstrates how a brief ontology can be generated.

Key words | floods, hazards, knowledge representation, ontology, OWL (Web Ontology Language)

Julián Garrido (corresponding author)
Ignacio Requena
Department of Computer Science and Artificial Intelligence,
University of Granada,
C/ Daniel Saucedo Aranda,
18071 Granada,
Spain
E-mail: *jgarrido@decsai.ugr.es*

Stefano Mambretti
Wessex Institute of Technology,
(Ashurst) Southampton,
UK

INTRODUCTION

The hydrologic cycle describes the continuous movement of water and its many processes. Water evaporates from the oceans and the land surface to become part of the atmosphere by the action of the sun. Water vapor is transported and lifted in the atmosphere by the rising air currents until cooler temperatures cause it to condense into clouds. Then, it precipitates on the land or the oceans as rain, snow or hail (most water falls back as rain). Precipitated water may be intercepted by vegetation, become overland flow over the ground surface, accumulate as ice caps and glaciers, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams as surface runoff. Despite the water that is intercepted or flows as superficial water, much of it returns to the atmosphere through evaporation. The infiltrated water may percolate to recharge groundwater, later emerging in springs or seeping into streams to form surface runoff, and finally flowing out to the sea or evaporating into the atmosphere as the hydrologic cycle continues (Chow *et al.* 1988).

Although the hydrologic cycle seems simple, the phenomenon is enormously complex because of the many interrelated processes. In general, the processes associated with the water cycle are precipitation, canopy interception, snowmelt, runoff, infiltration, groundwater flow, evaporation, sublimation, advection, condensation, and transpiration. However, for flow wave characteristics (and potential flood assessment), such phenomena have to be analyzed on a catchment scale and with relatively short durations (ranging from a few hours to a few days) (Chow *et al.* 1988).

The hydrologic cycle is affected by the weather patterns and physical factors, but also by human progress and activities that alter the equilibrium of the hydrologic cycle, and that start new processes and events. The water cycle affects human development in many ways. It is an essential resource but it also may endanger infrastructures or human activities. Climate change is related to a change in rainfall patterns, and rainfall (as well as other factors) is generally the cause of streamflow. If water flow exceeds normal parameters or if there is some other kind of anomalous event, a flood may occur (Mascarenhas 2005).

Floods have undesirable consequences, and risk assessment seeks to prevent them by studying hazard risk and potential vulnerability to such events. Furthermore, the results of risk assessment are used in management procedures and decision-making. The main goal is always to

doi: 10.2166/hydro.2012.064

prevent damage or reduce the impact of the event to the greatest extent possible. Therefore, actions are classified as preventive, mitigating, or recovery actions, depending on whether they are performed before, during or after the flood. For instance, early warning and evacuation are two common procedures that may save lives (Zschau & Kuppers 2002). However, less immediate aspects also have to be considered. For example, city governments must deal with psychological disorders in the affected population long after the event has occurred, and insurance companies also require information to calculate the costs of insurance premiums and settlements (Lamond & Proverbs 2008; Rose *et al.* 2010).

People with widely differing roles, backgrounds, and profiles are in charge of each phase of these procedures. Not surprisingly, communication problems often arise because different names are often used to refer to the same concepts. Moreover, relevant information can vary, depending on the user. Effective communication is essential since the results produced by a person in a certain phase of the process can be the input that another person needs in the next phase, i.e. raw data versus elaborated data, forecasting versus impact evaluation, level of detail, hazard assessment, vulnerability assessment, economic evaluation, environmental assessment, etc.

Ontologies are a tool that can be used to solve such problems because they specify a conceptual framework or terminology. They also provide explicit definitions and restrictions for concepts, i.e. knowledge representation. They can be used to describe a context or the domain of a context (Dey & Abowd 2000). Ontologies have frequently been used as the basis for knowledge-based systems (Staab & Studer 2004). Examples include the development of an ontology-based system for assisting engineers in the management of knowledge about water flow and quality (Chau 2007) and the SOLERES project (Padilla *et al.* 2008), which is based on a knowledge representation module for the management and automatic generation of ecological maps. The environmental assessment ontology (Garrido & Requena 2011) provides a valid conceptual framework for modeling flood-related knowledge. This ontology not only models environmental knowledge related to floods, but also to other natural events and human actions. This is a great advantage because flood events interact with other natural events as well as with human activities.

This paper proposes the inclusion of a semantic model for flood management in the Environmental Impact Assessment (EIA) ontology and the final generation of a brief ontology in order to simplify and optimize the use of the ontology for flood information. It describes the semantic modeling of floods and flood-related concepts.

The organization of the paper is as follows. The first section briefly outlines the environmental assessment ontology in which the flood model was included. The next section discusses the flood model and its concepts. It then outlines the procedure used to build a separate brief ontology for floods, and discusses its potential application. The final sections include a glossary, the conclusions of this study, and the references cited.

ENVIRONMENTAL IMPACT ASSESSMENT ONTOLOGY

Although there are a wide variety of definitions of ontology, many of them are too focused on a specific application or require a background in logic. However, according to Gómez *et al.* (2004), 'a body of formally represented knowledge is based on a conceptualization: the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them'. These authors go on to define ontology as an explicit representation of a conceptualization (Gruber 1995). This definition was considered sufficient for the purposes of our study.

Following the W3C (World Wide Web Consortium) recommendations, ontologies are built using OWL, which stands for Web Ontology Language (McGuiness & Harmelen 2004). According to the W3C, OWL is a language for content processing of information, which facilitates machine interpretability. This language is used in knowledge representation, and it is characterized by its formal semantics.

OWL-DL is a sublanguage of OWL whose expressiveness corresponds to Description Logics (DL), a subset of first-order logic where computational completeness is guaranteed. This characteristic is required by reasoners in order to make inferences (Sirin *et al.* 2007). Otherwise, computations might not finish in finite time. For this reason, the EIA ontology was built with OWL-DL.

The main objective of the EIA ontology (Garrido & Requena 2011) is to provide a common terminology and a conceptual framework for EIA. This evidently facilitates the structuring and development of the methodology used. As is common in ontologies, knowledge representation has more semantic richness when concepts are linked by other relations apart from the hierarchical ISA relation.

Concepts can be formally defined with expressions of descriptive logic using OWL syntax. For instance, a concept can be described as the union of other concepts, or existential restrictions can be used. There are two types of definition (Baader *et al.* 2003). The first type is *defined concepts* that have complete definitions. All entities that may be generalized by the concept definition will be inferred as subclasses (sub-concepts) or individuals of the concept. These definitions are frequently referred to as necessary and sufficient restrictions, and designated by the symbol $\equiv$ because the definition is equivalent to the concept.

The second type is *primitive concepts* that have incomplete definitions. All the concepts or individuals that are considered subclasses or individuals of a primitive concept must necessarily fulfill the restrictions of its definition. These definitions are frequently referred to as necessary restrictions and designated by the symbol $\subseteq$ because the definition is a generalization of the concept.

As part of the concept definitions, properties (roles) are used in ontologies to express relationships between concepts. These properties allow the expression of the existential, universal, or cardinality restrictions on a concept. For instance, an existential restriction in the definition of a concept A with property R on concept D means that an individual of concept A should have at least an explicit relationship with an individual of concept D using property R. However, it may be related to more than one individual or even be related to individuals of a different concept using the same property.

In contrast, a universal restriction in the definition of concept A with property R on concept D means that if an individual of A makes explicit its relationship with another individual using property R, then this individual must be an individual of class D. However, it does not require an explicit relationship. In fact, there may not be any relationship between individuals of A and individuals of D using property R.

Cardinality restrictions only express the number of times that an individual of A and an individual of D are related using property R. This type of restriction is generally used in conjunction with the other two.

The EIA ontology includes a large taxonomy of the concepts involved in EIA, and it models the essential relationships between these concepts. These include IndustrialActivity, ImpactingAction, PreventiveAction, Impact, PollutantElement, IndicatorAndMeasureUnit, ImpactAssessment, and ImpactedElement.

As its name indicates, the concept IndustrialActivity is the root of the taxonomy of industrial activities that are included in the European Directive concerning integrated pollution prevention and control (IPPC). ImpactingAction may also refer to industrial activities, but in general, it corresponds to human actions that are not included in the IPPC Directive. This taxonomy is divided into two groups: human actions and natural processes. Natural processes and natural events are regarded as impacting actions if they interact with human activities.

PreventiveAction refers to the actions to be taken in order to prevent or reduce the effects of a possible environmental impact as a consequence of human actions and their interactions with natural processes. The concept Impact designates the direct or indirect consequences of human activities and actions, such as industrial activities, landfills, etc. The impact is direct if it is produced as a result of the normal performance of the activity. It is indirect if it is produced, for example, as a result of a service or its products. Impacts can also be categorized, depending on the environmental factors affected.

PollutantElements are chemical substances that have been deliberately dumped or accidentally spilled in the performance of the activity. They may also be contained in gas emissions. The concept IndicatorsAndMeasureUnit refers to simple indicators that provide information about the state of a system from ecological to socio-economic aspects (e.g. the affected area or the depth levels of the river discharge). Complex indicators are represented as Model or Statistical Analysis. The concept ImpactAssessment represents the effect produced by an impact. In this regard, an impact may be considered positive, synergic, permanent, accumulative, etc. And the concept ImpactedElement refers to the environmental and socio-economic factors that may suffer the impacts of human actions and natural processes. It also includes the classification of natural habitats whose conservation requires the designation of special areas of conservation (Nature 2000, 2012), as specified in European Directive 2006/105/EC.

The most noteworthy relations between these concepts are the following:

hasPreventiveAction: An industrial activity or an impacting action may be linked to preventive actions, which are associated with it.

produceImpact: An industrial activity or an impacting action can be linked to the impacts that it produces. It is thus possible to model the fact that a particular activity or action tends to imply a set of impacts. The real impacts of a given activity can also be modeled.

hasIndicatorAndMeasureUnit: An impact is linked to indicators and measuring units. In this respect, a particular set of indicators can be used to measure the impact.

hasImpactAssessment: The impact is linked to environmental assessment, and thus may be characterized by its type of effect.

impactIn: The impact is linked to the impacted elements, which are the set of environmental and socio-economic factors thus affected.

EIA and Environmental Risk Assessment (ERA) are closely related. Traditionally, EIA analyzes the effect of a project before it is implemented whereas ERA analyzes the likelihood that a project will affect the environment or that it will interact with natural events. Although both the EIA and the ERA work with the same concepts, they are carried out at different times. However, the time of analysis does not affect the environmental relationships defined in the ontology. Therefore, concepts in the EIA ontology can be used to deal with ERA-related problems because they are basically the same.

For further details, an in-depth description of the EIA ontology is provided in Garrido & Requena (2011). Suggestions concerning the ontology can be proposed on the following website: http://arai.ugr.es/eiadifusa/index.php.

MODELING FLOODS

An ontology can be used to model floods because of the close interrelation between the elements involved. Other approaches, such as databases, are not satisfactory since they only store data. However, our objective was to provide the representation of an entire system. This necessarily includes a specification of the connections between its components so that the model can perform reasoning tasks.

Although there is no standard for ontology development, there are principles and recommendations that can be followed. One of the most well-known set of guidelines is Methontology (Fernández *et al.* 1999), which recommends reusing ontologies to the greatest extent possible. Besides saving time and resources, this makes integration between applications considerably easier. In particular, the EIA ontology was chosen as a starting point for flood modeling because many of the concepts needed for such a representation are already in the EIA ontology. Some are directly included, whereas others are generalized in the representations of other concepts. In such cases, the concept can be included by adding more details to the existing taxonomy or by establishing new relationships to describe flood-related knowledge. Alternately, new concepts can be added to the first level of the hierarchy.

The following subsections describe how elements in the EIA ontology are represented. The modeling follows the logical sequence of a flood event: rainfall, water discharge, flood, and management. Short descriptions for some of the concepts can be found in the glossary at the end of the paper.

Rainfall

Rainfall is the total amount of rain that falls in a particular area during a given time interval. It is a phenomenon that is closely related to floods either directly or indirectly. Although rainfall increases the probability of floods, it is not the only potential cause since floods can be the result of a conjunction of circumstances i.e. lack of riverbank maintenance, misregulated canals, ineffective town planning, and so on.

Figure 1 depicts the knowledge model used to describe the concept Rainfall. The rectangular boxes may be Concepts or individuals of concepts. Beveled rectangles represent concepts from the original EIA ontology. They are the nodes at which new flood-related knowledge (square rectangles) can be added. The ISA arrows connecting two boxes mean that one concept is a subclass of the other concept. If the arrow is labeled 'individualOf', this means that one concept is an individual of the other concept. The other arrows represent the relation between two concepts by means of the property specified in their respective labels. That relationship may be represented in the ontology in two ways. Firstly, the relationship may be explicit if the property's domain and range are defined. Secondly, a concept definition may include an existential or universal restriction that links this concept to another one. For simplicity's sake, this difference in origin is not depicted in the schema. For the same reason, if a group of concepts have the same connection to a concept, the entire group is enclosed by a rectangle, and the arrow is connected to the rectangle instead of having separate arrows going from the concept to each of the concepts in the rectangle.

On the other hand, if a property has an inverse property defined in the ontology, it can be represented as a small arrow close to the main one though pointing in the opposite direction. However, these inverse relationships are not always represented in order to make the schema more readable.

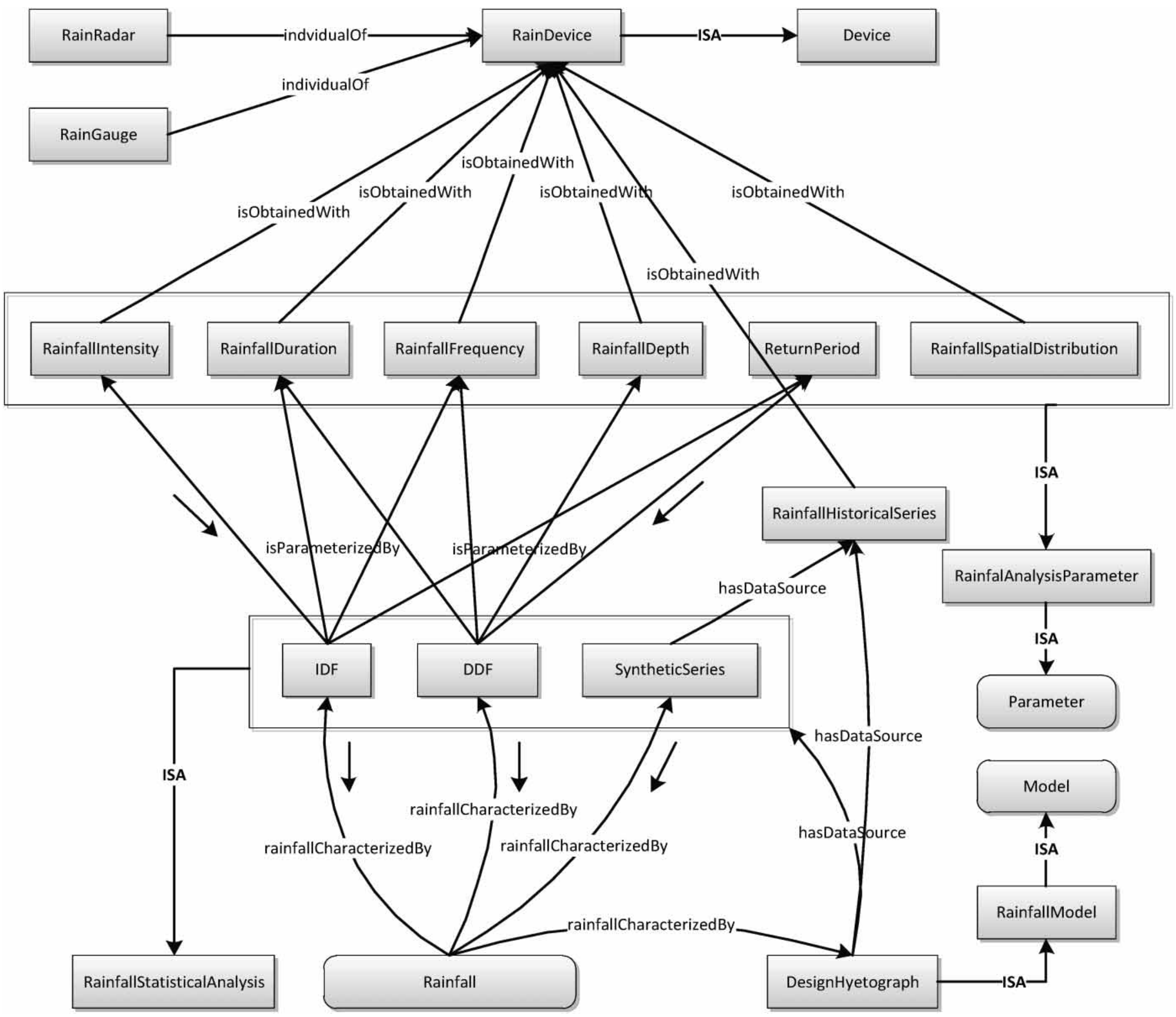

Figure 1 | Conceptual schematic of rainfall.

Modeling the rainfall concept requires identifying the elements that characterize it, its parameters, and its interactions with other elements. From a simplified perspective, rainfalls are characterized by intensity, duration, and spatial distribution. First of all, Rainfall is defined in the EIA ontology as a subclass of AtmosphericHazard, which in turn is a subclass of the concept NaturalProcess, which is an impacting action. Although rainfall intensity values are random during an event, their mean values are related to the duration, frequency, and return period of the rainfall. For instance, the higher the return period, the higher the mean intensity. Rainfall intensity is generally defined with a formula similar to the following expression (Chow *et al.* 1988):

$$i = \frac{A(T)}{(B(T) + \vartheta)^{C(T)}} \tag{1}$$

In this expression, i is the rainfall intensity (in mm h^{-1}); ϑ is the duration (in hours); and A, B, and C are coefficients, depending on the return period T (in years), which are computed statistically from the recorded rains. These IDF/DDF (Intensity Duration Frequency/Depth Duration Frequency) curves are statistically calculated on the basis of historical data records for rainfall and may be also used for the generation of synthetic hyetographs (rainfall models).

Certain concepts can be identified from this brief description. Rainfall is characterized by rainfall models (concept RainfallModel) or by statistical analysis (concept RainfallStatisticalAnalysis). In particular, the concept Rainfall is linked to three different sub-concepts of rainfall statistical analysis: IDF, DDF, and SyntheticSeries. Moreover, it is also linked to the concept DesignHyetrograph which is a subclass of the concept RainfallModel. All of these concepts are connected to Rainfall by an existential restriction on the property rainfallCharacterizedBy (specialization of the property isCharacterizedBy), which means that the rainfall is characterized by IDF, DDF, synthetic series, or a design hyetograph. Although it may be characterized by more than one of these elements, it has to be related at least to one.

This existential restriction belongs to the definition of rainfall, and is represented in Figure 1 in which the concept Rainfall is connected to the concepts IDF, DDF, etc. These connections are labeled in the figure by using the property rainfallCharacterizedBy because it is a restriction on this property. This is represented as follows:

∃ rainfallCharacterizedBy (SyntethicHistoricalRainfallSeries or DesignHyetographs or DDF or IDF)

Because the design hyetograph is a model, it requires data sources. This requirement is also modeled as an existential restriction on the property hasDataSource, based on the different rainfall statistical analyses (IDF/DDF and synthetic series) and the rainfall historical data series. Furthermore, although it is not depicted in Figure 1, the design hyetograph has also defined an existential restriction on the property characterizeRainfall (inverse of rainfallCharacterizedBy).

Statistical models are parameterized by intensity, duration, frequency, depth, return period, and spatial distribution. All of these are subclasses of the concept RainfallAnalysisParameter. However, at the same time, they are environmental indicators (concept defined in the EIA ontology). Moreover, the property isParameterOf (inverse of isParameterizedBy) evidently infers a rainfall analysis parameter since all the individuals are a parameter of some part of the rainfall statistical analysis.

Finally, in the same way as most of the environmental indicators, these parameters are obtained by using a device, namely, a rainfall device, such as a rainfall radar or rain gauge. This fact is made explicit with a restriction on the property isObtainedWith for each sub-concept of the RainfallAnalysisParameter.

Water discharge

Water discharge is defined as the volume of water flow transported through a given cross-section in a certain time interval (the volumetric flow rate). This discharge is also closely related to the catchment, which is the surface area of land draining toward the river. Furthermore, the rain falls on a catchment where part of the water reaches the outlet by flowing over the surface (a fast process) and part reaches it as groundwater by infiltration (a slower process). Melting snow and ice also converge to the outlet which is the point where the water is channeled by the catchment. This point acts as a funnel which collects all the water within the area covered by the basin.

The annual water balance (i.e. the ratio between the volume of water flowing from the outlet and the volume of rainfall) is equal to 1.0. More specifically, for the time scale that applies to floods and because of the large volumes of water involved, only Precipitation, Infiltration, and Runoff are considered. Evidently, during larger events, Evapotranspiration and other phenomena related to water volumes, are negligible when compared to the total rainfall volume and runoff (Maidment 1993).

The amount of water (peak discharge) that reaches the outlet depends not only on the area of the catchment and its geological characteristics, but also on other factors such as land use and its morphology. Another parameter related to catchment is the time of concentration, defined as the time needed by a raindrop to reach the outlet from the farthest position of the catchment (Haan *et al*. 1994). Although different models use different parameters (e.g. a linear reservoir uses a time lag constant), all must consider the time delay between the raindrop and the outflowing discharge.

In general, the discharge ($\bar{Q}$) is proportional to rainfall intensity ($\bar{i}$), the total catchment area (A), and the runoff coefficient (φ), as shown in the following expression:

$$\bar{Q} \propto \bar{i} \times A \times \varphi \tag{2}$$

The outflowing discharge is in fact given by the surface runoff and the subsurface flow. When analyzing the event on a smaller temporal scale (event time scale), not all the rainfall volume is recorded at the outlet because the subsurface flow is much slower than superficial runoff and the peak of the subsurface flow often can hardly be recognized. This is the reason why the runoff coefficient is less than one if it is computed during a single event. This coefficient depends on the soil use, as well as the imperviousness ratio.

The longer the time of concentration, the smoother and longer the wave. The catchment acts as a sort of hydraulic flywheel. This is the reason why the peak discharge is not linearly proportional to the area of the catchment when the rainfall and soil use are the same. Larger catchments not only bring (proportionally) larger volumes to the outlet but also have a larger flywheel effect. Therefore, the peak discharge is (relatively) lower (see Figure 2).

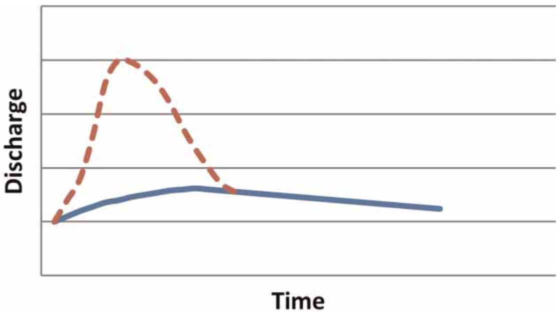

Figure 2 | Wave representation for superficial runoff and subsurface flow.

The final discharge is produced as the result of the composition of the rainfall in the catchment, river, artificial canals, and/or stream modifications to regulate the flow. These modifications include dams, embankments or bypasses. For instance, a high discharge value may be caused by poorly regulated dams or artificial canals.

Figure 3 shows a schema whose nodes represent the previously mentioned concepts and their relations. In this figure, rectangles and beveled rectangles represent concepts. However, the beveled rectangles are concepts that were originally defined in the EIA ontology. Generally speaking, this previous knowledge is suitable for our purpose though some of the definitions need to be specialized. This involves the creation of new subclasses and properties as well as new connections between concepts. It even involves the specification of new connections between pairs of concepts that were previously defined in the EIA ontology.

As shown in Figure 3, water discharge is a sub-concept of HydrologicalHazard, which is regarded as a natural process, and thus an impacting action. The concept WaterDischarge has been defined as the union of SuperficialWaterDischargeFlow and GroundwaterDischargeFlow. However, only the first of these concepts is discussed in this paper since it is related to floods.

The catchment area was modeled as a subclass of LandSurface, which is regarded as an environmental factor. The connection between this concept and water discharge is modeled with an existential restriction on the property dischargeAffectedBy. Moreover, the relation between the discharge and catchment area depends on several factors related to the catchment. These factors are land slope, imperviousness, concentration time (or any time related to

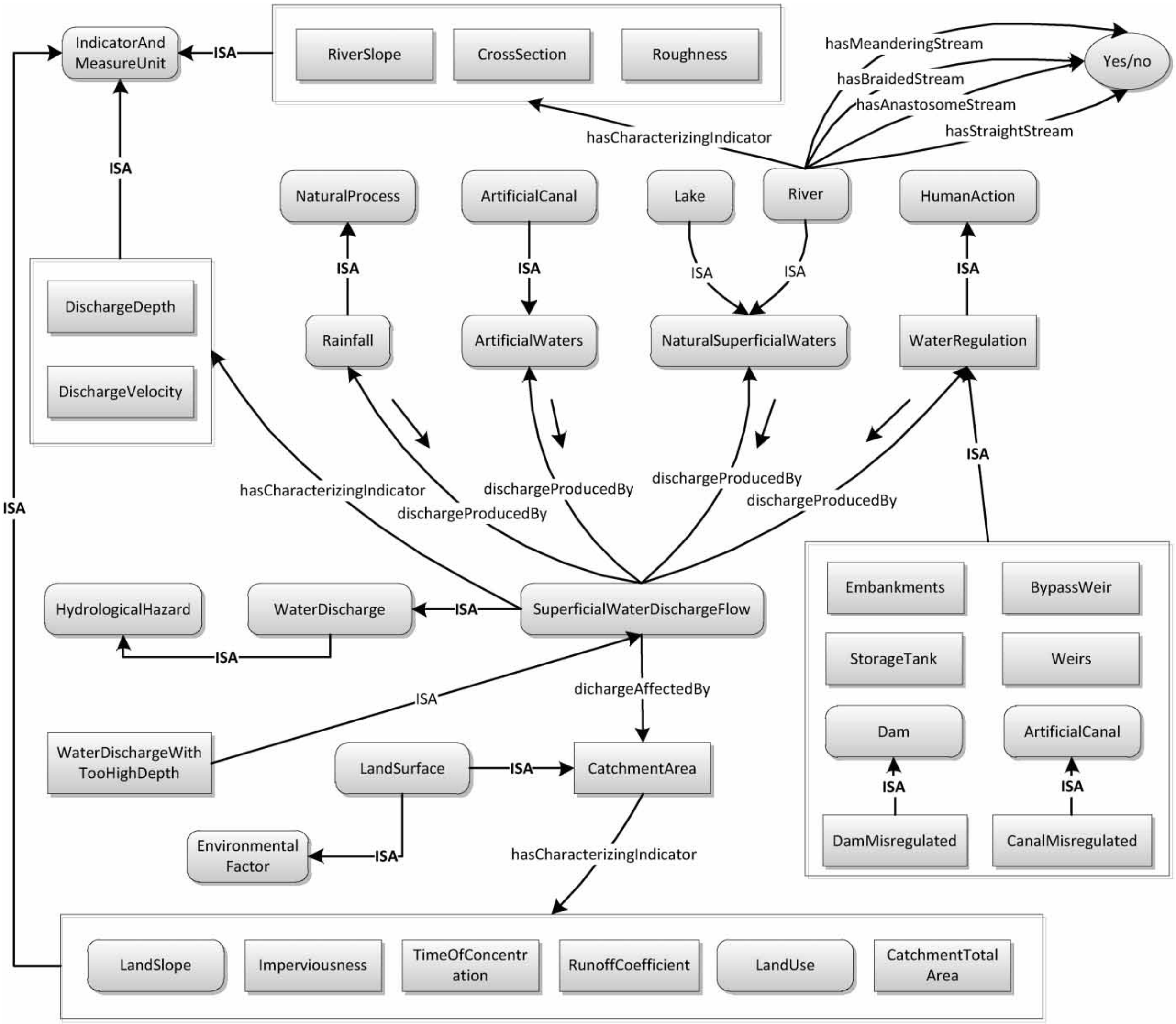

Figure 3 | Conceptual schematization of superficial water discharge.

the delay caused by the catchment), runoff coefficient, land use, and total catchment area. They are modeled as environmental indicators, which are linked to the catchment by several existential restrictions on the property hasCharacterizingIndicator. This means that a complete definition of catchment would have to include all of these elements.

The property hasCharacterizingIndicator is similar to the property hasIndicatorAndMeasureUnit of the EIA ontology. Although both are used to describe relations with indicators and measuring units, they differ in their domains. The latter is used to connect environmental impacts to indicators, whereas the former has a generic domain, and states that a concept has one or more indicators associated with it.

The definition of superficial water discharge also includes restrictions for connecting it to environmental indicators (i.e. depth and velocity of the discharge). For instance, the individual HighLevelOfDischarge belongs to the concept DischargeDepth, which permits the definition of the concept WaterDischargeWithTooHighDepth in the same way as all the elements that are subordinates of the concept SuperficialDischargeFlow, and which have an explicit connection to the individual HighLevelOfDischarge by means of the property hasCharacterizingIndicator.

According to Figure 3, the superficial water discharge is connected to other concepts through the properties hasCharacterizingIndicator, dischargeProducedBy, and dischargeAffectedBy. Moreover, dischargeProducedBy and dischargeAffectedBy are specializations of the properties isProducedBy and isAffectedBy, respectively, both of which also have inverse properties. Although these properties are semantically similar, the former involves a cause–effect relation, whereas the latter is used to identify elements that affect water discharge in some way without being the cause.

The definition of water discharge includes an existential restriction on the property dischargeProducedBy pertaining to the union of the concepts rainfall, artificial waters, non-artificial waters and water regulation. This means that the discharge is caused by at least one of these elements, but not necessarily all at the same time. This connection with the concept rainfall does not appear in Figure 1 because the schemas in the figures do not represent the complete definitions of the concepts, but rather only those relationships that are considered relevant in a particular moment. In fact, except for certain taxonomic relationships (ISA), the figures do not show the connections related to previous definitions (those belonging to the original EIA ontology).

The concepts artificial canal (artificial waters), lake, and river (natural superficial waters) are sub-concepts of superficial waters, a sub-concept of water, which is classified as an environmental factor. Water regulation, however, is regarded as a human action, and is thus an impacting action.

The concept water regulation refers to the actions that interfere in the normal flow of water or in waterways where there are high water discharges in order to prevent floods or reduce potential damage caused by them. Water regulation is defined as the union of the following concepts: embankments, bypass weir, storage tank, weir, dam, and artificial canal. It should be highlighted that artificial canal is not only regarded as a type of water regulation but also as a type of artificial waters. This same pattern, which is found in other concepts, is usually the result of inference mechanisms.

Finally, several indicators (river slope, cross-section, and roughness coefficient) are related to river by means of the property hasCharacterizingIndicator. Nonetheless, Figure 3 also shows four connections to a node with the label *yes/no*. These links allow individuals of the concept river to be connected to Boolean values. For instance, an individual designating the Amazon River (which has meanders) would make this explicit in its description by connecting the property hasMeanderingStream to the value *true*.

Flood

Flood is defined in the European Directive on assessment and management of flood risks as the temporary covering by water of land not normally covered by water. This general definition refers to all types of floods: river floods, flash floods, urban floods, and floods from the sea in coastal areas. Although all of these flood types share certain characteristics, this paper focuses on freshwater floods and particularly on river floods. For this reason, we have defined *flood* as a body of water that overflows its usual boundaries onto a land area with other land uses. This produces negative impacts caused by water velocity, depth, persistence, or any combination of the three.

Socio-economic development in floodplains and the reduction of natural water retention because of land use increase the adverse consequences of floods. For this reason, the European Directive encourages the management of flood risk to reduce the potential adverse consequences for human health, environment, cultural heritage, and economic activity. Although management requires risk assessment in order to identify areas with higher vulnerability, generally speaking, it involves flood prevention, protection, and mitigation (De Wrachien *et al.* 2011). Actions can range from the construction of embankments and other mechanisms of water regulation (structural actions) to town planning (non-structural actions).

Figure 4 shows a diagram of the flood ontology model, which includes most of the previously described concepts. The central concept is freshwater flood, which is represented in the EIA ontology as a sibling concept of coastal flood. Both concepts are subclasses of the concept Flood, which in turn is a subordinate concept of HydrologicalHazard. Accordingly, HydrologicalHazard is modeled as a Natural process, and thus regarded as an impacting action.

Flood causes are modeled with the property floodProducedBy. The semantics of this restriction is that the flood may be produced by at least one of the following: a water discharge, bridge occlusion, or embankment break. In this initial phase, only river-related incidents and river floods have been modeled, but in the future, other causes will

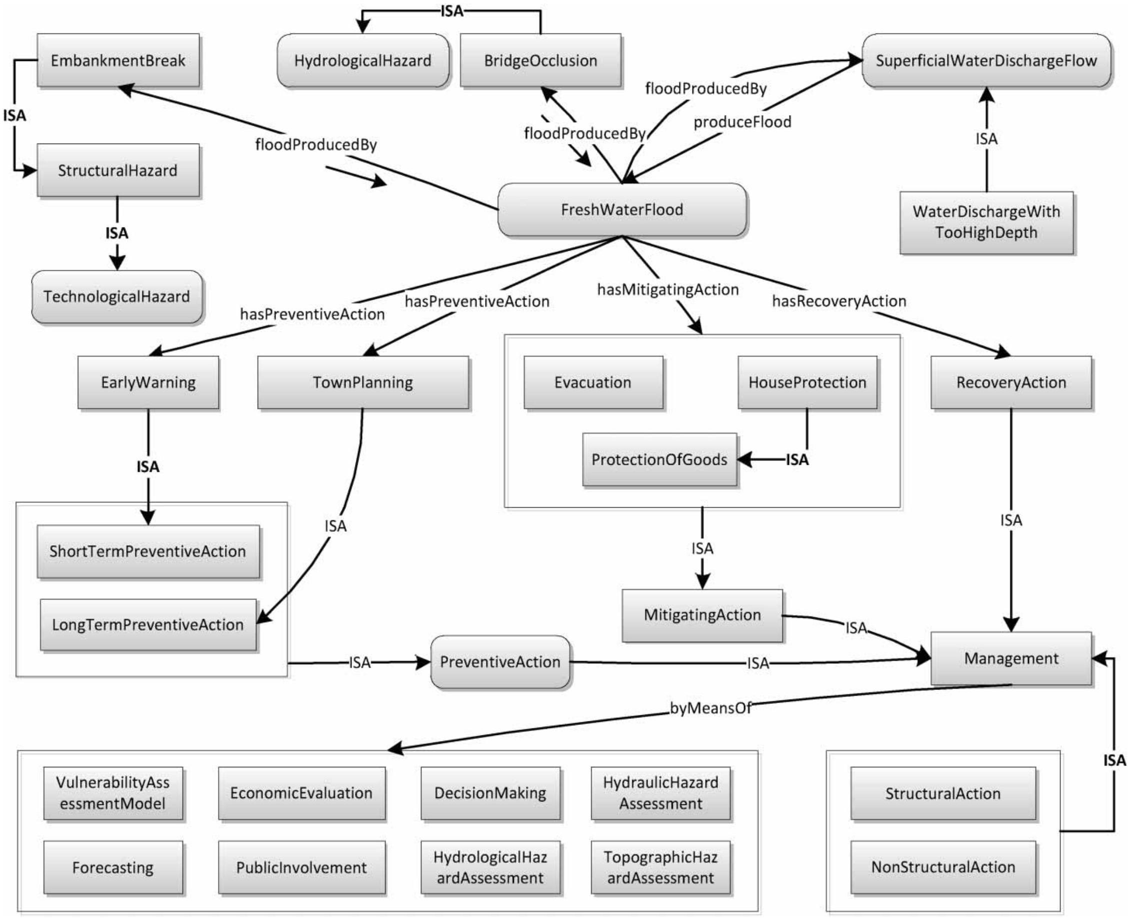

Figure 4 | Conceptual schematic of Flood.

also be taken into account. Bridge occlusion is modeled as a hydrological hazard whereas embankment break is considered a structural hazard, which is also a technological hazard. Therefore, they are all subclasses of the concept ImpactingAction.

The concept Flood also includes existential restrictions to describe its preventive actions (concept PreventiveAction) to avoid or reduce the consequences (before the flood), its mitigating actions (concept MitigatingAction) to reduce the severity of consequences during the flood, and the recovery actions (concept RecoveryAction) to repair the damage or compensate for the loss of resources. In fact, the definition of the concept Management is conceived as the union of these three concepts.

Preventive actions are divided into two concepts: (i) actions with a short-term effect; (ii) actions with a long-term effect. For example, early warning is considered to be an action with a short-term effect whereas town planning is an action with a long-term effect. Both are modeled as preventive actions of freshwater floods with an existential restriction on the property hasPreventiveAction.

Concerning mitigating actions, evacuation and house protection are regarded as actions to be carried out when a flood occurs. A restriction on the property hasMitigating Action for the definition of flood is that any flood event requires at least one mitigation action. Analogously, it also includes a restriction on the property hasRecoveryAction. Even though mitigating and recovery actions might entail not taking any action at all, a decision must at least be made. However, the decision to do nothing generally is made when the land affected by the flood is of little or no value.

These three types of management action can be further categorized as structural or non-structural actions. Town planning is an example of a non-structural action whereas the reinforcement of an embankment is a structural action (Kundzewicza & Takeuchi 1999). This is reflected in the following two subclasses of Management: StructuralAction and NonStructuralAction.

However, management is also characterized by assessment reports or procedures that are required to accomplish the task. In particular, these elements are a vulnerability assessment model, economic evaluation, hydraulic hazard assessment, topographic hazard assessment, hydrological hazard assessment, forecasting, decision-making, and public involvement. All of these elements are linked to management by an existential restriction on the property ByMeansOf. This means that management requires the performance of at least one of these elements.

Management roles

When dealing with complex and delicate matters such as floods, it is evident that responsibility increases with the size of the social group. Individuals must decide on their personal wellbeing and the wellbeing of family members. Similarly, institutions must think about the interest of the community as a whole. In other words, the wide variety of decision makers (with their information needs, responsibilities, and responses to risk) suggests that attempts to provide a single best description of the problem do not necessarily meet the needs of all stakeholders. In order to analyze and design the optimal approach to decision making, a specific point of view must be adopted. This means that formulations of the same problem are required for different stakeholder perspectives. In what follows, the perspective taken is that of the local floodplain manager.

In order to identify the players involved in management, the actions defined in the previous subsection must be analyzed. Early warning is mainly related to the long-term planning phase. When a hydraulic engineer designs an effective early warning system, a basic requirement is hydrologic and hydraulic information to produce a flood wave (De Wrachien *et al.* 2010). This information, produced by the hydraulic engineer, is later used by the Civil Protection Agency because the hydraulic engineer does not know, for instance, how long the evacuation would take. The protection agency must thus develop a plan for actions based on these inputs.

In the case of town planning, the hydraulic engineer again needs hydrologic and hydraulic information in order to design a hazard map. Based on this map, the municipality then enacts and establishes rules for land use.

The Civil Protection Agency, which is also in charge of evacuation, must make decisions based on previous studies (see EarlyWarning). Local authorities need to have instruments capable of monitoring river conditions in real time. When thresholds are exceeded, they must act in consonance with established rules and guidelines.

With regard to recovery actions, immediately after the event, the role and responsibility is again taken by the Civil Protection Agency, which performs a set of actions to restore the status quo before the flood event. After these civil protection actions, rebuilding and recovery work is often carried out by private companies and the cost is often funded by the government when the event is exceptionally severe.

Figure 5 shows the representation of these concepts and relationships. As previously mentioned, there are three kinds of management action: preventive, mitigating, and recovery actions. These actions are managed by a player or government entity that is a subclass of the concept Agent. This relation is represented by an existential restriction on the property managedBy. In particular, the TownPlanning concept is linked to the concept Municipality, whereas EarlyWarning, Evacuation, and RecoveryAction are linked to CivilProtection.

There are two types of agent: (i) agents that manage actions (mainly municipality and civil protection); (ii) agents that produce models and information to be used by other agents (e.g. hydraulic engineer). Therefore, the concept HydraulicEngineer includes an existential restriction on the property '*produce*' over the union of the concepts HazardMap and FloodWave. This describes that the hydraulic engineer designs the hazard map and flood wave. The definitions of players also include an existential restriction on the property use&Need. In particular, HydraulicEngineer is linked to Hydrologic&HydraulicInformation, which represents all the information needed by the engineer to design the hazard map and flood wave. In contrast,

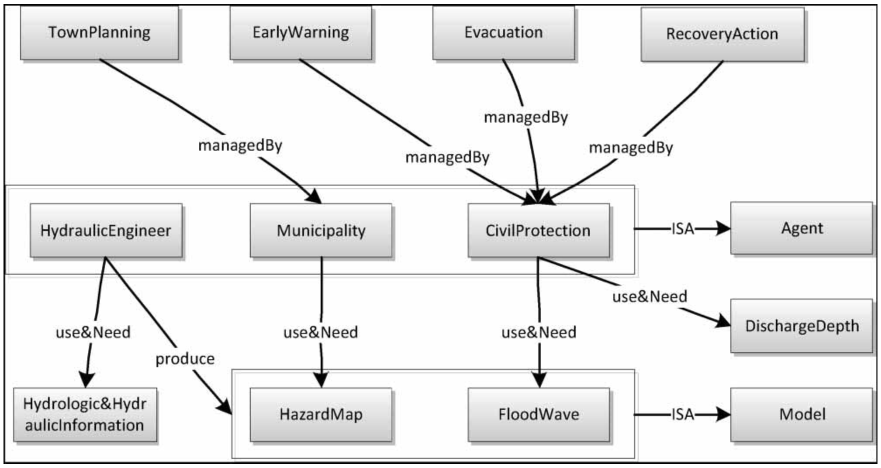

Figure 5 | Conceptual schematic of management roles.

Municipality is linked to HazardMap and CivilProtection to FloodWave by means of this property.

BRIEF ONTOLOGY

Many attempts have been made to summarize monolithic semantic networks and ontologies: (i) partitioning (Gu *et al.* 1999); (ii) modularization involving the minimization of semantic relations between modules (Stuckenschmidt & Schlicht 2009); (iii) pruning (Kim *et al.* 2007); (iv) extraction of views (Noy & Musen 2009). However, the concept of brief ontology was first introduced by Delgado *et al.* (2005) to provide access to the most relevant information in databases for a web service-based, multi-agent architecture.

The concept of brief ontology is formally defined in Garrido & Requena (2012), who describe an extraction algorithm and tool. In essence, it is a reduced version of the ontology in which only the most relevant knowledge is represented. The construction of a brief ontology is automatically carried out with a traversal algorithm. However, the process is parameterized in order to extract only the most relevant knowledge. In particular, the traversal algorithm moves through concepts and individuals (candidates) of the ontology to decide if they will be included in the brief ontology.

Not all concepts and individuals of the ontology are considered to be good candidates. This requires the specification of a selection strategy. Once a concept is selected to be in the brief ontology, its definition is processed, and all the concepts and individuals involved are regarded as candidates. For this reason, one of the parameters required by the algorithm is the set of concepts that would be initially included in the brief ontology (starting point of the traversal algorithm).

The decision of which candidates to include in the brief ontology also involves analyzing the definition of the candidate. As previously described, definitions may range from simple to complex expressions. For this reason, the second parameter needed by the algorithm is a set of properties that filters the candidates. The candidates are included in the brief ontology unless the expression relates them to a property that is not included in this set of properties. This means that the algorithm spreads across the ontology and explores the connections and relations between individuals and concepts. Only the concepts connected to our set of relevant properties are included in the brief ontology.

In order to build the brief ontology for floods, it is necessary to select the starting point as well as the set of relevant properties from the EIA ontology. This requires the study and analysis of the properties that are used in concept definitions and the way in which the concepts are related by these properties. As the main concept in the flood ontology, flood is evidently a good candidate for the starting point. In this more specific case, however, the starting point is the concept FreshwaterFlood. Initially, the brief ontology contains the concept FreshwaterFlood. By selecting the set of relevant properties, we thus limit the concepts that are linked to the concept in the brief ontology. Nonetheless, this also implies that some parts of the definition must be removed or generalized.

Figure 4 shows that FreshwaterFlood has the following four restrictions: (i) a restriction on the property floodProducedBy over the concepts superficial water discharge, bridge occlusion, and embankment; (ii) a restriction on the property hasMitigatingAction over the concepts evacuation and house protection; (iii) a restriction on the property hasPreventiveAction over the concepts town planning and early warning; (iv) a restriction on the property hasRecovery Action over the concept RecoveryAction. If all these properties are included in the set of relevant properties, then all of the previously mentioned concepts are added to the brief ontology. However, if the property floodProducedBy was not included, then superficial water discharge, bridge occlusion, and embankment would be rejected in the ontology building process, and the existential restriction would be removed from the flood definition.

The concept flood belongs to the hierarchy of impacting actions. Since it is a concept defined in the EIA ontology, the property produceImpact is also associated with it. This property connects impacting actions to impacts. Impacts are in turn linked to environmental factors, indicators, and environmental assessments by means of the properties impactIn, hasIndicatorAndMeasureUnit, and hasImpactAssessment, respectively. The property produceImpact is not included in the set of relevant properties because there is no interest in impacts and impact-related concepts. This is a type of pruning process, which rejects the impact taxonomy and its neighborhood (indicators, environmental factors, and impact assessment).

However, the fact that a concept has been rejected does not mean that it will not be included in the brief ontology since concepts may be connected to others by means of different properties. If one of these properties is in the set of relevant properties, then the concept may be reached through a valid path with relevant properties. This is the case of the indicators and measure units. There is a path that connects flood to indicators through the properties impactIn and hasIndicatorAndMeasureUnit, which are not considered to be relevant properties. Nonetheless, the property hasCharacterizingIndicator connects other concepts (e.g. CatchmentArea, River, etc.) to the indicators. Indicators are thus added to the brief ontology because these concepts (e.g. CatchmentArea) are in the brief ontology and are related by means of a relevant property.

Relevant concepts and relations for our flood ontology are all those that have been described in the modeling section. These concepts and relations are used to model floods. (Table 1 includes the list of properties whose semantics is considered relevant.) The final result is a brief ontology in which the number of named classes has been reduced from 2054 to 91 since only the most relevant knowledge is included. The knowledge in the brief ontology matches the knowledge described in the modeling section, and the rest of the knowledge is excluded as irrelevant in this case.

The concepts in Figures 1, 3, 4, and 5 are especially prominent in the brief ontology because they are connected by using properties that belong to the set of relevant properties (see Table 1). Nevertheless, the brief ontology includes some additional concepts that are, in fact, superclasses of the concepts described because they belong to the upper levels of the taxonomy. In particular, the first level of concepts consists of the following: Agent, Assessment ReportOrProcedure, DataSource, Device, EnvironmentalFactor, Management, Model, ImpactingAction, Indicator AndMeasureUnit, Parameter, PublicInvolvement, and StatisticalAnalysis.

These concepts have been aligned with the DOLCE ontology (http://www.loa.istc.cnr.it/DOLCE.html) in order to allow semantic interoperability between the ontologies that use the upper ontology. The conceptual representations in the figures could be grouped into a single representation because they all have shared concepts. For example, Figures 1 and 3 share the concept Rainfall; Figures 3 and 4 share SuperficialWaterDischarge Flow; and Figures 4 and 5 share TownPlanning, EarlyWarning, Evacuation, and RecoveryAction. For this reason, they are all included in the conceptual schema of the brief ontology.

An intuitive way of seeing how the concepts are configured in the brief ontology is by tracing the path between the concept FreshWaterFlood in Figure 4 to concepts in Figures 1, 3, 4 and 5 by using the properties listed in Table 1 and the structural relationships (ISA, individualOf).

Table 1 | Set of relevant properties

Property	Description	Domain/Range
OBJECT PROPERTIES		
byMeansOf	Generic property to refer that the domain is done or implemented by using the range.	owl:Thing/owlThing
characterizeRainfall	Something (model or statistical analysis) is used to characterize the rainfall.	owl:Thing/Rainfall
dischargeAffectedBy	Water discharge is affected but not produced by something.	WaterDischarge/owl:Thing
dischargeProducedBy	Water discharge is produced (causal connection) by natural/human impacting actions.	WaterDischarge/ ImpactingAction
floodProducedBy	Flood is produced (causal relationship) by natural impacting actions.	Flood/ImpactingAction
hasCharacterizingIndicator	Something is characterized by and indicator or measure unit.	owl:thing/ Indicator&MeasureUnit
hasDataSource	Something (statistical analysis or model) has a data source with structured information or information that requires processing.	owl:Thing/DataSource
hasMitigatingAction	If an impacting action is happening, its effect is reduced with mitigating actions.	ImpactingAction/ MitigationAction
hasPreventiveAction	The effect of impacting actions is avoided or reduced with preventive actions.	ImpactingAction/ PreventiveAction
hasRecoveryAction	After an impacting action happens, its effect is reduced or removed with recovery actions.	ImpactingAction/ RecoveryAction
isCharacterizingIndicatorOf	An indicator or measure unit is used to characterize something (e.g. rainfall).	Indicator&MeasureUnit/owl: Thing
isDataSourceOf	A data source is used in something (e.g. statistical analysis or model).	DataSource/owl:Thing
isObtainedWith	An indicator or measure is taken using a particular device.	Indicator&MeasureUnit/ Device
isParameterOf	Something is parameter of something (e.g. an element that needs processing data).	Parameter/owl:Thing
isParametrizedBy	Something depends on a particular parameter.	owl:Thing/Parameter
managedBy	A task or action is managed by an agent in charge.	Management/Agent
produce	General property to express causal relationships.	owl:Thing/owl:Thing
produceDischarge	A natural or human impacting action is cause of the water discharge.	ImpactingAction/ WaterDischarge
produceFlood	An impacting action is cause of flood.	ImpactingAction/Flood
rainfallCharacterizedBy	Rainfall is characterized by elements like models and statistical analysis.	Rainfall/owl:Thing
use&Need	Generic property to describe that an agent needs or use something.	Agent/owl:Thing
DATATYPE PROPERTIES		
hasAnastosomeStream	Boolean property to describe if the river has an anastosome stream.	River/boolean
hasBraidedStream	Boolean property to describe if the river has a braided stream.	River/boolean
hasMeanderingStream	Boolean property to describe if the river has a meandering stream.	River/boolean
hasStraightStream	Boolean property to describe if the river has a straight stream.	River/boolean

For instance, Figure 6 represents the path connecting the main concept FreshWaterFlood to the concept Device and to the individuals RainGauge and RainRadar. The concept RainDevice is reached through the connections represented with the relevant properties of the figure. In contrast, Device, RainGauge, and RainRadar are reached through the structural properties, ISA and individualOf. The concept Device is reached from RainDevice, following

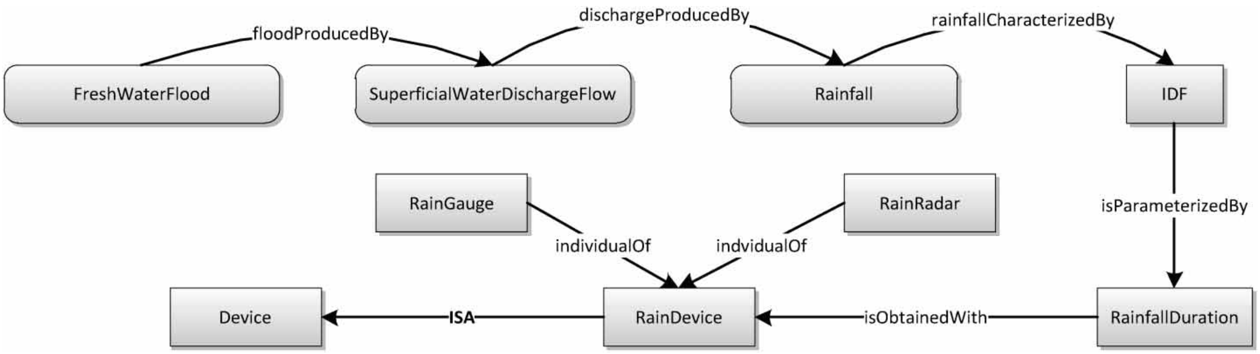

Figure 6 | Path to connect the concept FreshWaterFlood to the concept Device and the individuals RainGauge and RainRadar.

the direction of the arrow, whereas the individuals connected to it with arrows are reached by going in the opposite direction. Two elements connected by structural relationships may sometimes be reachable even if it is necessary to follow an arrow pointing in the opposite direction. This depends on the concept definition. For instance, the individual RainGauge is reachable from the concept RainDevice when RainDevice is defined as an enumeration of its individuals. However, when this is not the case, RainGauge is not reachable.

In particular, it should be emphasized that one concept cannot be reached by following a directional path. Even though the concept HazardMap can be reached from the concept HydraulicEngineer in Figure 5, HydraulicEngineer is not reachable from any other concept. This concept is thus not included in the brief ontology. If we wish to force its inclusion in the brief ontology, there are two alternatives. The first entails including the concept as a starting point for the algorithm. The algorithm will iterate twice in order to spread through the ontology from two different concepts. The second entails creating a connection to another concept included in the brief ontology. For instance, if the concept Agent is defined as the union of CivilProtection, Municipality, and HydraulicEngineer, then HydraulicEngineer will also be added to the brief ontology.

Knowledge-based application

The sheer quantity of information currently available in today's society makes it necessary to build applications able to deal with huge amounts of data. In contrast, other applications focus more on knowledge management rather than data storage. This requires the formal representation of knowledge, and ontologies can be used for this purpose because they are based on DL.

An ontology is useful if it contains relevant knowledge for a given application. In this respect, the EIA ontology and particularly the brief flood ontology model contain knowledge related to flood events. For this reason, it can be used in a knowledge-based system for the management and planning of flood events. The knowledge for the management and planning application is divided into context knowledge and domain knowledge. Context-related knowledge is needed to describe the situation and event. In contrast, domain-related knowledge is used during the decision-making process as well as in the management of a given context or situation.

In this case, the context consists of a flood event and/or flood-related events, such as embankment break, bridge occlusion, level of water discharge, and poor water regulation. The time of the event is also part of the context. There are significant differences when designing a plan and managing an event that will happen in the distant, near, or immediate future. Nor is it the same thing to design a plan whose purpose is to deal with the effects of a past event. The standard operating procedure is different, depending on the time that elapses before the event occurs.

Planning and management (domain-related knowledge) consist of specifying the set of actions to be performed, identifying the agent in charge of them, and the elements or information needed by the agent to carry out these tasks. Each situation or event may require different actions. Furthermore, the set of actions depends also on whether the planning and management is for a past or future event.

For this reason, there are four types of plan, each with a different set of actions: long-term actions whose application requires a long period of time – these are preventive actions which are generalized by the concept LongTermPreventiveAction; short-term actions whose application requires a short period of time – these are preventive actions which are generalized by the concept ShortTermPreventiveAction; mitigating actions that are performed immediately previous to the event in order to reduce its effects – these actions are generalized by the concept MitigatingAction; recovery actions that include the set of actions that should be performed after the event in order to restore the affected area to its previous state – these actions are generalized by the concept RecoveryAction.

This knowledge is represented in the brief ontology by using the properties hasPreventiveAction, hasMitigatingAction, and hasRecoveryAction. Similarly, the properties manageBy and use&Need represent the agent in charge of any action and the elements required during the decision-making process or its subsequent implementation.

Table 2 shows an example that includes the long-term preventive actions for general freshwater flood, river overflow, and heavy rainfall events. Both river overflow and heavy rainfall events are regarded as direct causes of fresh water floods in our model. In Table 2, the four agents considered are municipality, river authority, civil protection, and house owner.

As previously mentioned, a planning and management application requires a context. In this example, the context could be that the municipality wishes to know the long-term preventive actions that should be considered in the case of a flood. Therefore, different types of information will be displayed, depending on the type of action (long-term preventive action), the agent (Municipality), and the event.

Ontologies are useful because they represent the most meaningful knowledge associated with a problem. Nevertheless, they are also useful because they permit reasoning and inference processes. Inference mechanisms make recommendation procedures possible. For instance, preventive actions related to a more specific or general

Table 2 | Long-term preventive actions for river overflow and heavy rainfall

Preventive action	Agent in charge	Needs
FRESHWATERFLOOD		
TownPlanning	Municipality	HazardMap
		TopographicMap
RIVEROVERFLOW		
AlternativePathway	Municipality	HazardMap
TownPlanning		TopographicMap
StorageBasin	RiverAuthority	
Enbankment		TopographicMap
BypassWeir		DesignHyetograph
Weir		
HEAVYRAINFALL		
StorageTank	Municipality	
SignalingPanelSystem		DesignHyetograph
EducationPolicies		HydraulicHazardAssessment
ResizingSewerSystem		HazardMap
Reforestation		
StreetGullyCleaning		
DrainagePumpAcquisition	CivilProtection	Warehouse
BalconyGullyCleaning	HouseOwner	

event may be suggested. Particularly, if planning for fresh water floods is selected, preventive actions for river overflow or heavy rainfall are evidently advisable because both are direct causes of flood.

The ontology represents the knowledge related to each separate event. Nonetheless, it is rare for these types of event to happen independently. Because of a cause–effect relation, for example, one event can trigger another. This problem is also resolved by using inference mechanisms that allow the possibility of dealing with new knowledge dynamically.

For example, local authorities may need to know long-term preventive actions for the municipality when river overflow and heavy raining simultaneously occur. According to Table 2, such preventive actions would be the construction of alternative pathways, town planning for the regulation of land use with high flood risk, storage tanks for storm runoff, the creation of a signaling panel system for early warnings, education policies that make people aware of careless behavior, resizing of the sewer system so that it can withstand higher water discharges, reforestation to control water infiltration, and street drain cleaning.

CONCLUSIONS

This paper has presented a semantic representation or ontology of floods and flood-related concepts. This ontology was built because experience has shown that more sophisticated techniques are needed to structure a conceptual model of flood-related elements as well as of flood management and planning. We have presented a simplified description of a flood event that includes only the most relevant concepts though in future work, other characteristics will be included.

The semantic flood model is based on the EIA ontology. Because of its conceptual similarities, this concept is represented in the ontology as well as others closely related to it. The concepts needed for environmental assessment, depending on the evaluated activity or impacting actions, were modeled in the EIA ontology. In fact, natural events were regarded as impacting actions if they interacted with human actions and thus produced greater damage. Floods are included in this group.

The usual procedure for elaborating this type of knowledge representation consists of creating new ontologies by importing others, such as the EIA ontology. If this is done in different cases with the same imported ontology, this results in different knowledge specifications in which there are few shared concepts because the resources were modeled separately. The paradigm used in our study consists of enriching the original ontology with the new knowledge of each case and building brief ontologies with the relevant knowledge for each particular context of use. Accordingly, the knowledge specification is more detailed, and the knowledge representation is thus more complete.

Although the EIA ontology has been enhanced with this new knowledge, it is slower and more difficult to deal with the whole ontology because it includes a great deal of knowledge that is not related directly to floods. To avoid this problem, a brief ontology was created, which only includes the most relevant information. This makes queries and reasoning much faster.

The brief ontology for flood management matches the model described in the modeling section because of the selection of relevant properties during its creation. If at some point the EIA ontology is enriched with new knowledge (not necessarily by us) and part of this knowledge is relevant for our purposes, then a new brief ontology might be automatically created in order to include this new knowledge. Additionally, the benefits of using the brief ontology have been described for the planning and management of flood events.

GLOSSARY

IDF and DDF: Intensity-Duration-Frequency (IDF) and Depth-Duration-Frequency (DDF) are synthetic methods for the description of the pluviometry of an area. They are used to compute DesignHyetographs.

SyntheticSeries: In some cases, the design or simulation of a hydraulic structure is misleading if it is based on a single event, therefore, it has to be based on a data series, which can be recorded (RainfallHistoricalSeries) or computed (SyntheticSeries).

RainfallStatisticalAnalysis: In the design of hydraulic structures, the main characteristics of rainfall are usually determined by statistical analysis.

DesignHyetograph: Although the design of hydraulic structures is mainly based on rainfall, historical data records are often unavailable, and, if they are available, they do not represent the average rainfall characteristics of the area. Therefore, a synthetic or design hyetograph represents these average characteristics in only one event, which is then used to design structures.

RainfallHistoricalSeries: Rainfall data are recorded in order to be statistically analyzed or used directly in simulation models.

RainfallFrequency: Certain characteristics of rainfall are observed with a given frequency (depending on the pluviometry of the area).

ReturnPeriod: The return period is the time during which certain rainfall characteristics are equaled or exceeded only once.

RainfallSpatialDistribution: In a given area, during a real event, rainfall characteristics are different from one point to another.

RainDevice: rain devices are specially designed instruments to measure rainfall, and gather the pluviometry characteristics of a certain area.

RainRadar: This radar is used to study rainfall, especially in terms of its spatial distribution.

RainGauge: A rain gauge is a device that records the mean intensity of rainfall in a given time period. It provides very detailed descriptions of rainfall characteristics, but only at the position where the device is installed.

Roughness: When water flows in a channel, it faces a resistance which is mainly produced by the friction between the water itself and the channel. The level of resistance depends on the characteristics of the material of the channel. This is known as roughness and is expressed by means of a set of formulas in which the characteristics of the material are related by means of a numerical parameter.

TimeOfConcentration: Strictly speaking, this is the time needed for water to flow from the most remote point in a watershed to the watershed outlet. However, in hydrology, this concept measures the response of a watershed to a rain event.

RunoffCoefficient: This is the percentage of the rainfall that can be seen as runoff. It is the ratio between the volume of runoff and the volume of rain in a given area.

EarlyWarning: Since rainfall can be forecast, and the flood wave takes time to reach a given section (position), it is possible to estimate flow characteristics time before the event. In the case of large catchments, this time can be up to few days. This means that it is possible to warn the population in advance (Early Warning) in order to take the actions to reduce the risk.

FloodWave: As rainfall is not uniform (it may be a design hyetograph) and the response of a catchment to the rainfall is not immediate, runoff normally starts at a minimum (dry weather flow), increases to a maximum, and then decreases to reach the dry weather flow, forming a wave that propagates from upstream to downstream in the channel or river.

ACKNOWLEDGEMENTS

The authors would like to thank Carlos Brebbia for his invaluable help. This research has been partially financed by projects (CICE) P07-TIC-02913 and P08-RNM-03584, funded by the Andalusian Regional Government.

REFERENCES

Baader, F., Calvanese, D., McGuiness, D., Nardi, D. & Patel-Schneider, P. F. 2003 *The Description Logic Handbook: Theory, Implementation and Applications*. Cambridge University Press, UK, 574 p.

Chau, K. W. 2007 An ontology-based knowledge management system for flow and water quality modeling. *Advances in Engineering Software* **38**, 172–181.

Chow, V. T., Maidment, D. R. & Mays, L. W. 1988 *Applied Hydrology*. McGraw Hill, New York, 572 p.

Delgado, M., Pérez-Pérez, R. & Requena, I. 2005 Knowledge mobilization through re-addresable ontologies. In *EUSFLAT Conference*, September 7–9, Barcelona, Spain, pp. 154–158.

Dey, A. & Abowd, G. 2000 Towards a better understanding of context and context-awareness. In *Proceedings of the Workshop on the What, Who, Where, When and How of Context-Awareness (CHI)*, The Hague, Netherlands, pp. 1–6.

De Wrachien, D., Mambretti, S. & Sole, A. 2010 Mathematical models in flood management: overview and challenges. In: *Flood Recovery, Innovation and Response II* (D. De Wrachien, D. Proverbs, C. A. Brebbia & S. Mambretti, eds). WIT Press, Southampton, pp. 61–72.

De Wrachien, D., Mambretti, S. & Schultz, B. 2011 Flood management and risk assessment in flood-prone areas: measures and solutions. *Irrigation and Drainage* **60**, 229–240.

Fernández, M., Gómez, A., Pazos, J. & Pazos, A. 1999 Ontology of tasks and methods. *IEEE Intelligent Systems and Their Applications* **14**, 37–46.

Gómez, A., Fernández, M. & Corcho, O. 2004 *Ontological Engineering with Examples from the Areas of Knowledge Management, E-commerce and the Semantic Web*. Springer-Verlag, London. 415 p.

Garrido, J. & Requena, I. 2011 Proposal of ontology for environmental impact assessment. An application with knowledge mobilization. *Expert System with Applications* **38**, 2462–2472.

Garrido, J. & Requena, I. 2012 Towards summarising knowledge: brief ontologies. *Expert System with Applications* **39**, 3213–3222.

Gruber, T. R. 1995 Toward principles for the design of ontologies used for knowledge sharing. *International Journal Human-Computer Studies* **43**, 907–928.

Gu, H., Perl, Y., Geller, J., Halper, M. & Singh, M. 1999 A methodology for partitioning a vocabulary hierarchy into trees. *Artificial Intelligence in Medicine* **15**, 77–98.

Haan, C. T., Barfield, B. J. & Hayes, J. C. 1994 *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, San Diego, CA. 588 p.

Kim, J., Caralt, K. & Hilliard, J. 2007 Pruning bio-ontologies. In *Proceedings of the Annual Hawaii International Conference on System Sciences*, Hawaii, January 3–6, 2007, pp. 196c.

Kundzewicza, Z. W. & Takeuchi, K. 1999 Flood protection and management: quo vadimus? *Hydrological Sciences Journal* **44**, 417–432.

Lamond, J. E. & Proverbs, D. G. 2008 Flood insurance in the UK – a survey of the experience of floodplain residents. In: *Flood Recovery, Innovation and Response I* (D. Proverbs, C. A. Brebbia & E. Penning-Roswell, eds). WIT Press, Southampton, pp. 325–334.

Maidment, D. R. 1993 *Handbook of Hydrology*. McGraw-Hill, London. 1400 p.

Mascarenhas, F. C. B. 2005 *Flood Risk Simulation*. WIT Press, Southampton. 456 p.

McGuiness, D. & Harmelen, F. 2004 *OWL Web Ontology Language Overview*. Online. W3C Recommendation. Available from: http://www.w3.org/TR/owl-features/.

Nature 2000 2012 Nature 2000 network. Available from: http://ec.europa.eu/environment/nature/natura2000.

Noy, N. & Musen, M. 2009 Traversing ontologies to extract views. *Lecture Notes in Computer Science* (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) **5445**, 245–260.

Padilla, N., Iribarne, L., Asensio, J. A., Muñoz, F. J. & Ayala, R. 2008 Modelling an environmental knowledge-representation system. In *WSKS'08: Proceedings of the 1st World Summit on the Knowledge Society*, Berlin, Heidelberg. Springer-Verlag, Berlin, pp. 70–78.

Rose, C. B., Proverbs, D. G., Manktelow, K. & Booth, C. A. 2010 Psychological factors affecting flood coping strategies. In: *Flood Recovery, Innovation and Response II* (D. De Wrachien, D. Proverbs, C. A. Brebbia & S. Mambretti, eds). WIT Press, Southampton, pp. 305–310.

Sirin, E., Parsia, B., Grau, B., Kalyanpur, A. & Katz, Y. 2007 Pellet: a practical OWL-DL reasoned. *Web Semantics* **5**, 51–53.

Staab, S. & Studer, R. 2004 *Handbook on Ontologies*. Springer-Verlag, Berlin. 660 p.

Stuckenschmidt, H. & Schlicht, A. 2009 Structure-based partitioning of large ontologies. *Lecture Notes in Computer Science* (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) **5445**, 187–210.

Zschau, J. & Kuppers, A. N. 2002 *Early Warning Systems for Natural Disaster Reduction*. Springer, Berlin, Heidelberg, New York. 834 p.

First received 12 May 2011; accepted in revised form 12 December 2011. Available online 20 March 2012