The Development of Integrated Watershed Flood Risk Assessment Ontology

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Abstract—**Floods belong to the most threatening natural hazards for human society and economics, and are enhanced by urbanization and climate change. Integrated assessment is defined as an interdisciplinary and participatory process of combining, integration, interpreting, and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena. Ontology, as a formal knowledge representation, will provide methods for the interdisciplinary integrated flood assessment. This paper will develop integrated watershed flood risk assessment ontology from different perceptual models of watershed flood risk. First, different conceptual models, such as Pressure-State-Impact-Response model, are introduced. Then the development framework of ontology is given. The flood risk assessment ontology is designed based on the upper level ontology of Semantic Web for Earth and Environmental Terminology (SWEET). Finally the rainfall excess indicator computing ontology and vulnerability index computing ontology were given as the examples of application development.**

Keywords- flood risk; integrated assessment; ontology; perceptual model; environmental change

I. INTRODUCTION

Floods belong to the most threatening natural hazards for human and their property [1, 2], which are damaging to the environment and human health across globe. Reducing the threat and impact of flooding is both a necessary and timely effort, particularly given increasing attention to and evidence of climate change[3, 4], increased development in areas at risk of flooding, and man made changes in river hydrology and land use [5]. Flood risk management as a flood protection measure has been discussed extensively [6, 7].

Flood risk management is the process needed to operate an existing system. When the system is no longer adequate to meet the needs of people, then the next process starts, i.e. the planning for a new or revised system [6].

Integrated assessment of flood disaster risk involves a broad definition of the flooding system. Generally physical and organizational systems influence or are influenced by flooding [8, 9]. The physical systems include the physical attributes of earth's surface involved in the water cycle, e.g., the processes of rainfall, overland runoff, and flood inundation in floodplains. The organization systems include the artificially created systems, e.g., storage, drainage, dam, and levee. The economic, social, and environmental assets located in floodplains, and government organizations or stakeholder groups.

The methods of flood risk assessment are various, including multi-criteria analysis approaches [1], probability approaches [6, 10, 11], and knowledge based approaches [12, 13, 14].

Integrated assessment is defined as an interdisciplinary and participatory process of combining, integration, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena [15]. However, integrated assessment for environment has the problem of different systems with heterogeneous data and information [16]. The knowledge based approaches and the unified conceptualization and common ontologies are necessary [17, 14].

An ontology is a formal representation of technical concepts and their interrelations in a form that captures domain knowledge [18]. The use of ontologies enables the representation of knowledge and the necessary processes in the flood risk assessment, and provides homogeneous terminology and a shared understanding of the problem [17, 14].

The design of integrated flood risk assessment ontology will use a kind of development method, reuse upper level ontology and select an ontology representation language. Using ontology in integrated assessment and modeling has been discussed for defining assessment project [17]. Based on the workflow of multi-criteria flood risk assessments, a flood risk assessment ontology has been studied [14]. However, the complex process involving physical systems and organizational systems in flood risk assessment is not discussed.

This paper will propose an integrated flood risk assessment ontology from different perceptual models of watershed flood risks. The development methodology will be based on flood perceptual models and information pyramid hierarchical method. Based on the upper level ontology of Semantic Web for Earth and Environmental Terminology (SWEET), the design of flood risk assessment ontologies will be given.

II. PERCEPTUAL MODELS OF FLOOD RISK

Hydrological systems are sufficiently complex that they have different perceptual models [19]. Flooding systems related both with physical hydrology and organizational system also have many perceptual models. Low level perceptual models will emphasize data, facts, and features, which provide system property variables and data for flood risk assessment. While the high level perceptual model will focus on indicator or index of flood risk assessment. Generally, there exists three kinds of perceptual models of flooding hazard and risk, i.e., Pressure-State-Impact-Response (PSIR) model; Hazards- Exposure-

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Vulnerability (HEV) model; and Source-Pathway-Receptor (SPR) model.

A. Pressure-State-Impact-Response (PSIR)

Change in the flooding system can be conceptualized using the Pressure-State-Impact-Response (PSIR) model [20, 8], or Driver–Pressure–State–Impact–Response (DPSIR) model [2]. The PSIR model is a conceptual framework to identify the key issues, questions, data/information availability, land use pattern, institutional framework, timing and spatial considerations, etc.[20].

Drivers, such as demographic change, economic growth, and climate change, create pressures including the development of hard surfaces in urban areas and loss of natural floodplains, resulting in land cover type change, and furthermore, the land surface runoff change. Climate change has an impact on the hydrological cycle, producing pressures including rainfall intensity and frequency change, land surface temperature, and evaporation change.

Pressures, such as increased impervious area and hard surfaces, vegetation loss, loss of natural drainage systems, rainfall intensity and frequency, will change hydrologic system states, such as flood peak and frequency, flood duration, etc.

The states of hydrologic and flooding systems have the impact on socio-economic and environment systems. States such as increased runoff, flood peak and inundated depth, increased loss of soil, and erosion will impact on the security of humans and properties, and furthermore lead to the susceptibility of humans and infrastructure. The impacts include loss of habitat, damage to property, economic costs, social costs and disruption, etc.

The impacts on social, environmental and economic lead to the responses to mitigate the frequency, duration, and intensity of these flooding impacts. The responses include flood defense schemes, flood operation, and hydraulic structure measures, etc.

The PSIR model provides cause-effect relationships among flood systems and properties. However, the high level concepts of flood risks, such as hazard, exposure, vulnerability, risk indicator and index, etc. are not discussed in this model. Generally, the PSIR model only consider properties in flood risk assessment, which is a low level perceptual model. The Hazards-Exposure-Vulnerability model provides a high level perceptual model of flood risk assessment.

B. Hazards-Exposure-Vulnerability (HEV) Model

Hazard, exposure, susceptibility and vulnerability as elements of risk have been discussed in many literatures [6, 21, 22, 23]. We called this model as Hazard-Exposure-Vulnerability (HEV) model, which provides a high level perceptual model which use indicator or index to describe flood risk.

Flood hazards are defined as the probability of the occurrence of flood events [7]. The flood hazard analysis focuses on the characteristics of floods, including investigating the probability distribution of floods of different magnitudes, the illustration of overland flow paths, and relevant hazard indicators, e.g., flood inundation depth and velocity [22]. The flood hazard assessment comprises the extreme external loading of the system (such as rainfall) and hydrologic system states (flood flow, flood depth, etc.). Climate change will impact precipitation pattern, such as rainfall intensity, duration, frequency, and the return period of extreme external loading. The states of flood peak, discharge and duration are estimated by hydrologic system models with precipitation loading.

Exposure can be defined as the nature and degree to which human or buildings are present at the flood hazard areas [24, 21, 25], such as houses had been built in floodplains.

Susceptibility is represented as damage function of human or properties exposed to flood hazard [26], which is usually described by relative damage functions. such as flood depth–damage curves or flood return period–damage cost of properties. Susceptibility is also related to system characteristics, including the social context of flood damage formation.

Vulnerability is related with exposure and susceptibility [26]. There are different concepts of vulnerability and there is no agreed understanding of this term [27, 23], such as vulnerability as the same with susceptibility [14]. From the view of quantitative computing, distinguishing them is useful. Vulnerability is usually viewed as exposure to risk with inability to cope with it (or with susceptibility), and vulnerability index can be represented as $FVI=f(E, S, R)$, where E is exposure, S is susceptibility, and R is resilience [28, 23].

C. Source-Pathway-Receptor (SPR) Model

The Source-Pathway-Receptor (SPR) model has been proposed for flood risk description [7, 8, 21], which is based upon the causal linkage between the source of flood hazard, through the pathway of discharge and inundation, to the physical impacts on elements at risk (receptors). The causal chain of source, pathway and receptor refer to the physical process.

Sources refer to the flood events that result in flood hazards. Pathways are mechanisms that covey flood waters to places where they may impact upon the exposed receptors, including fluvial flows in and out river channels, overland flow. Receptors are the people, property and natural environments that may be impacted upon by flooding.

SPR model is a low level perceptual model, which describes foundation features and properties of flooding systems, and provides system state variables for flood risk assessment. SPR model can be combined with Hazards-Exposure-Vulnerability (HEV) model [21].

D. Combination of Perceptual Models

Integrated flood risk assessment will not only consider facts, data and features of flooding system in low level perceptual model, but also index and indicator in high level perceptual model. Furthermore, the resilience and coping capacity of human society as a feedback of flooding system is also considered. Resilience and coping capacity describe the ability of a system to preserve its basic roles and structures in a time of distress and disturbance. Indicators showing resilience including dikes and levees, flood operation, insurance, etc.

The three perceptual models described above correspond with low or high levels of perception of flood risk. Combination of them will constitute a synthesized flood risk assessment ontology.

III. Development Methodology and Ontology Design

Integrated assessment will couple physical systems and organizational systems, which is an integration and fusion issue from different perceptual modeling systems and different conceptual levels.

The development of integrated flood risk assessment ontology will be based on the perceptual models discussed above. The different perceptual models, from low level model of system property to high level model of indicator and index, need to be combined to form a unified integrated assessment framework.

A. Combination Method

Indicators development generally is defined as an aggregation process of variables or basic data, followed by processed information and indicators, and finally ending up with highly aggregated indices [29]. Indicators and highly aggregated indices top an information pyramid whose base is primary data derived from monitoring and data analysis [30]. This kind of data fusion from low level to high level is also discussed in cognition synthesis [31].

In our method, the low level property variables and data are discussed in low level perceptual model, such as PSIR and SPR models. The high level indicator and index are discussed in high level perceptual model, such as HEV, or HEV and SPR models. Combining the conceptual models, a three level informational pyramid is constructed (shown in Fig. 1). Data level corresponds to the PSIR and SPR, information indicator level the SPR and HEV, and Index level the HEV.

In low level model, the variables and data from PSIR model include rainfall intensity (Pressure), land use type, river flood stage (State), flood depth, human (Impact), infrastructure, buildings, flood operation (Response), dam, levee, etc. These variables and data will be described as entity property in ontology, i.e. Entity property ontology. In the terms of SPR model, the Sources include rainfall, storm, etc. Pathways include floodplains, river segment, channel network, etc. Receptors include people, buildings, infrastructure, etc.

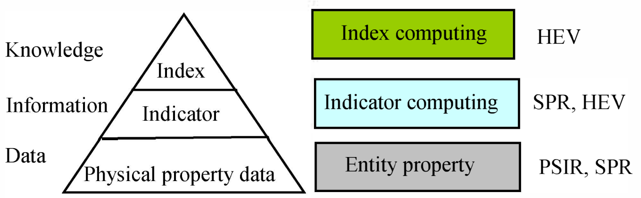

Figure 1. Information pyramid

The indicator and index in the high level perceptual model from HEV or SPR include hazards, vulnerability, susceptibility, etc. described by indicator ontology and index ontology. A brief hierarchical conceptual framework is shown in Fig. 2, where the arrows represent condition or association relationship.

Information pyramid and hierarchy framework gives a general method and path to constitute the flood risk ontology by combining different conceptual models. However, flood hazards have different types, such as river flood, flash flood and coastal flood, etc. each type has an intrinsic content. In our approach, a watershed flood risk will be discussed following.

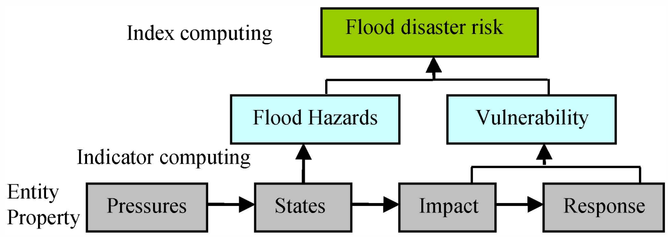

Figure 2. Hierarchy framework of integrated flood risk assessment

B. Framework of Integrated Watershed Flood Risk Assessment

The PSIR model identify property variables and data of flood systems, such as rainfall data, land use information, infrastructure, people, flood protection measures, etc. (shown as Entity property in the right column of Fig. 3), which will be used for hazard or vulnerability indicator computing, such as rainfall excess, runoff, exposure, etc. (shown as Indicator computing and Index computing in the middle and left column of Fig. 3), where arrows represent condition relations (vertical) or association relations (horizontal).

There may exist a feedback in the flooding system particularly as the consequence of an impact on the environment, which result in an alternation of the flood pathway and then influence future SPR relationships [8]. For example, flood as a source may cause exposure of receptors which are located in the pathway. The susceptibility of receptors will cause the response of society and organization to alternate flood and mitigate exposure, such as coping capacity and resilience [28, 32]. The feedback is shown as arrows from Resilience to Flood and Exposure in the middle column of Fig.3.

Rainfall excess is a kind of pressure indicator, which indicate direct contribution of rainfall to flood. Runoff represents state indicator of flood hydrology, such as stream flow. Flood hazard represent another state indicator of flood hydraulics, such as flood area, depth, velocity, and flood duration. Flood hazard indicators are assessed by flood routing models, such as 1D or 2D hydraulic models. Exposure indicates which receptors are within flood hazard. Susceptibility or sensitivity represents damage generation processes of exposed object, generally represented as hazard-damage curves, hazard-damage functions or intensity-damage ratio.

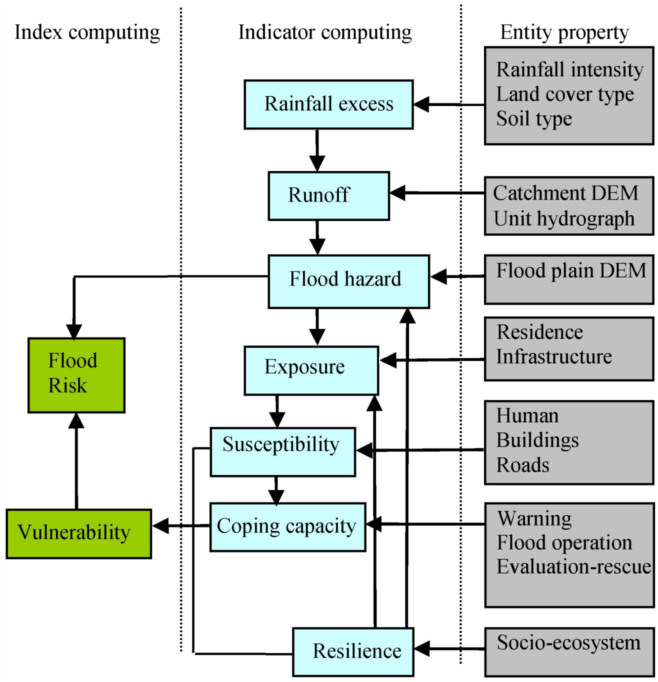

Figure 3. Framework of integrated watershed flood risk assessment

Flood risk is generalized defined as *Risk=Hazard Probability*Consequence* [33, 1, 23], where *Probability* is the probability of flood hazard event, *Consequence* is potential damage or vulnerability of exposure in the flood event. In a general quantified formal [6]:

$$RI(D) = \int_0^\infty K(x \mid D) f_x(x \mid D) dx$$

Where x is flood hazard event load magnitude (such as flood depth or velocity), D is the vector of decisions (such as the height of a levee), $f_x(x|D)$ is the probability density function of hazard x, and $K(x|D)$ is consequence function (damage function), which is quantified measurement of impact or vulnerability.

This general definition is needed extension for actual application. The extended definition has many forms, such as integral formula considering hazard, consequence and decision variables [6], multiple criteria or indicators calculation based on flood risk perceptual models[1, 7, 29].

C. Ontology Design

An ontology is a formal concept and their interrelations which is used to improve discovery and use of earth and environmental data and information, through software understanding of the semantics of distributed web sources. Semantic understanding is enabled through the use of ontologies [18, 17].

In the context of integrated assessment, ontologies are useful to define the shared conceptualization of a problem. Ontology of integrated flood risk assessment will be developed based on the conceptual framework on integrated flood risk assessment discussed in previous sections.

Collecting terms and keywords in the domain, making classification and association of terms, reusing existing ontologies are common ontology development methods [34]. In our methods, the existing upper level ontology of SWEET [18, 35] is reused. Based on the SWEET ontologies, flood risk index and indicator, the entity property of flood systems are design.

1) Entity property ontology

Entity property represents data, facts, and features in low level perceptual models, such as PSIR and SPR models. In SPR models, the data, facts, and features are named as flooding system state variables [8]. In SWEET ontologies, the data and facts are represented as “Physical Properties”, which have the characteristics of space, time and units, These properties are the measured physical quantities with units [35].

The entity properties in integrated flood risk assessment are from low level perceptual models. In PSIR model these include environmental pressures (rainfall intensity, land cover type, stc.), states (evaporation, river stage, etc.), impact (human, infrastructure, etc.), and response (flood operation, levee, dam, etc.). In SPR model the properties include sources (rainfall, snow melt, etc.), pathway (channel network, floodplains, urban surfaces, etc.) and receptor (people, houses, industries, infrastructure, etc.). Part of these entity properties are shown in Fig. 3.

In SWEET the classes of flood and event are defined, but the properties in integrated flood risk assessment discussed above are not defined because the SWEET is a upper level ontology of earth and environment terminology, which comprise general concepts and properties, and need to be extended to include more diverse and specific domain vocabularies [35].

The properties in integrated flood risk assessment are defined as a class of “Entity property” based on SWEET “NumericalEntity” with extension of contents (shown in Fig. 4).

Feature is used to represent vector data type used in GIS, such as point, line and network data, and could be modeled as geographic object entity.

Coverage data are raster data, such as surface data, grid data, digital elevation model data, and remote sensing data, which could be modeled as geographic field entity.

2) Indicator computing ontology

Each assessment problem is associated with a set of indicators that are of interest for policy expert. Indicators synthesize relevant data and model outputs and indicate the change or define the status of thing [17].

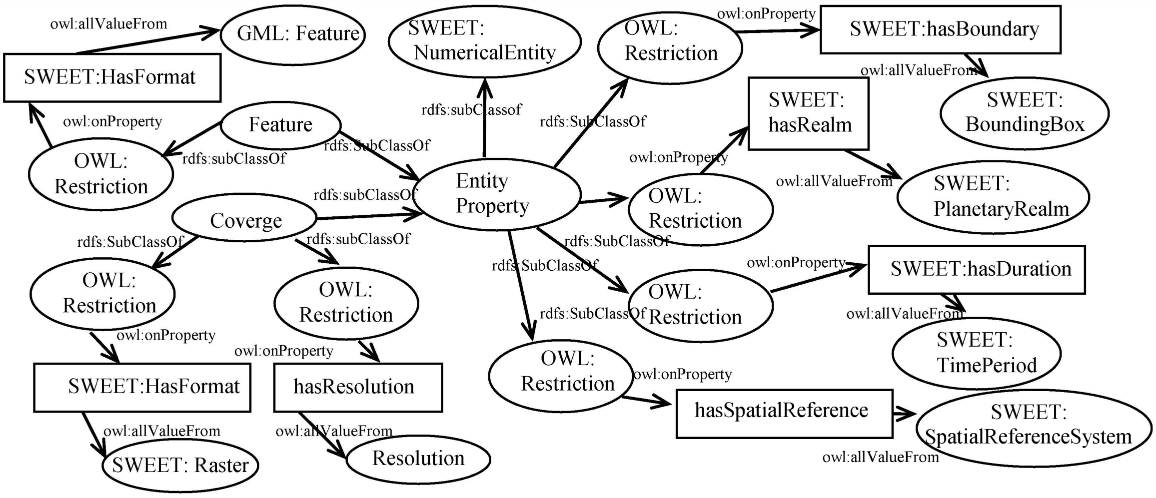

Figure 4. OWL representation of entity property

The high level conceptual mode of flood risk assessment describes concepts about probability of hazard, vulnerability, and society value systems, which can be represented as indicator or index. In flood risk assessment, indicators are quantities based on variables. Variables are aggregated to form indicators, which form a basis for decision making [29].

Indicator computing is realized by Indicator function, involving two kinds of input and an output. Input includes entity properties and other related indicators, such as feedback indicator shown in Fig. 3. Output is an indicator represented by SWEET Numerical entity, shown in Fig. 5. The corresponding pseudo-code is as:

```
Class: Indicator function
SubClassOf: SWEET:Operation
SubClassOf:OWL:Restriction
        (Owl:Onproperty SWEET:hasInput;
     OWL:minCardinality:1)
        (Owl:Onproperty SWEET:hasInput;
OWL:AllValueFrom: Feature )
        (Owl:Onproperty SWEET:hasInput;
     OWL:AllValueFrom: Coverage)
        (Owl:Onproperty SWEET:hasInput;
     OWL:AllValueFrom: Indicator)
        (Owl:Onproperty SWEET:hasOutput;
     OWL:AllValueFrom: Indicator)
```

In integrated flood risk assessment, the indicator is computed by indicator function, which is a sub-class of "SWEET:Operation" (shown in Fig. 5). This data, variables, and related model outputs used for indicator computing are defined as input of indicator function. Three types of input variables are the related indicator of model output, spatial related feature data and grid related coverage data. The output of the indicator function defined as Indicator, which is the sub-class of "SWEET: NumericalEntity".

3) Index computing ontology

One method for flood vulnerability index is represented as $FVI=(E*S)/R$, where E-exposure, S-susceptibility and R-Resilience[23]. Vulnerability index can also be calculated by consequence function $K(x|D)$, where x is hazard for object exposure, D is resilience indicator, and $k(x)$ is object susceptibility under hazard x (also called as damage function).

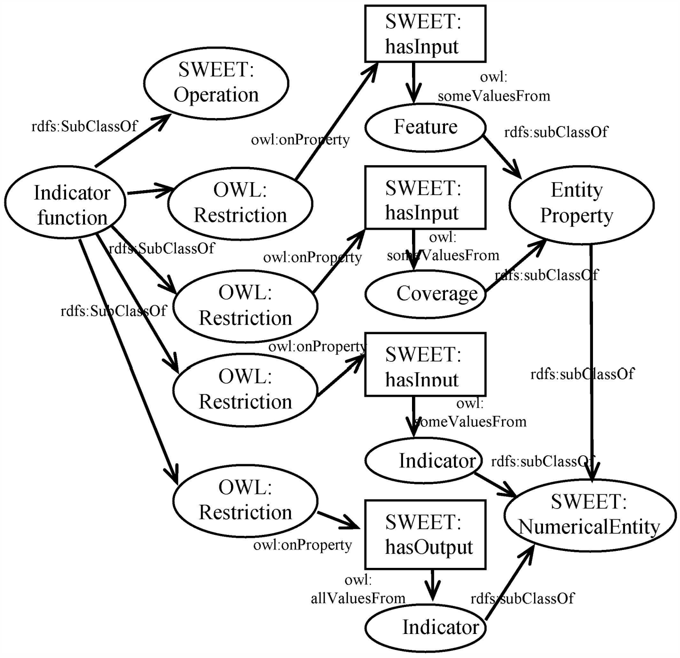

Figure 5. OWL representation of Indicator computing

As a general formal representation, x represents exposed hazard for receptor, $k(x)$ susceptibility of receptor within the exposed hazard, D resilience, then the vulnerability index (FVI) is represented as $FVI= K(x|D)=(x*k(x))/D$. If $p(x)$ represents probability density function of hazard x, then flood risk index is represented as $RI=p(x) *K(x|D)$[28].

Index computing is realized by Index function, including different indicators as input. Output is an index represented by SWEET Numerical entity. The corresponding pseudo-code is as:

```
Class: Index function
SubClassOf: SWEET:Operation
SubClassOf:OWL:Restriction
        Owl:Onproperty SWEET:hasInput
        OWL:AllValueFrom: Indicator
SubClassOf:OWL:Restriction
        Owl:Onproperty SWEET:hasOutput
```

`OWL:AllValueFrom: Index`

IV. CONCLUSION

The three kinds of perceptual models of flood risk, i.e. PSIR, SPR, and HEV, have been analyzed. Based on information pyramid hierarchic framework, the flood risk assessment indicator, index and related entity property have been identified from the perceptual models. An integrated watershed flood risk assessment framework is developed, which serves as a design foundation of integrated flood risk assessment ontology. Based on upper level ontology of SWEET, the ontologies of flood risk index, indicator and entity property were designed. This approach has given a new development method of integrated flood risk assessment ontology.

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