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Supporting collaboration in interdisciplinary research of water–energy–food nexus by means of ontology engineering

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ABSTRACT

Study region: We do not target particular region, but we implement the workshop experiments towards the researcher groups in the laboratories.
Study focus: When we discuss hydrology in the context of water–energy–food nexus, the discussion will inevitably include interdisciplinary contents. For example, in the impact assessment of groundwater use we need understanding whole mechanisms composed of all kinds of causal linkages from the groundwater concept or the groundwater issues. In this article we focus on ontology engineering, which is one of the base technologies in Semantic Web technology, as a method providing common terms, concepts, and semantics.
New hydrological insights: We discuss the effectiveness of ontology engineering approach in the process of collaborative research, and propose the way of ontology use contributing to interdisciplinary research through the experimental workshops of research development.

The introduction of ontology engineering approach will enable us to share a common language and a common theoretical basis. But the development of the new method based on ontology engineering is necessary. For example, knowledge structuring according to each perspective of researchers and simple figure accompanied with a reasoned argument in the background are the directions of tool development.

1. Introduction

When we discuss hydrology in the context of water–energy–food nexus, the discussion inevitably includes interdisciplinary content. For example, in the impact assessment of groundwater use, we need to understand all of the mechanisms comprising all causal linkages. Considering the case of groundwater pumping for geothermal power generation, the volume of groundwater used will change if the pumped groundwater is discharged into a surface water stream, such as a river, In this case it is necessary to understand the impacts of such a volume change on the ecosystem and fisheries. This assessment process includes a discussion of solving the problems that involve multiple fields, as well as discussions from various perspectives and temporal–spatial scales. The Committee on Facilitating Interdisciplinary Research (2004) states that interdisciplinary research is typically collaborative and involves people from disparate backgrounds because such research is pluralistic in both method and focus.

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In the field of the science of team science (SOTS), is various methods and frameworks to support interdisciplinarity and transdisciplinarity have been proposed. However, as the SOTS fields matures, there is a need to develop more sophisticated methods and research designs,such as prospective quasi-experimental research designs (Stokols et al., 2010), to assess processes and outcomes of team science. In particular, as a new perspective, process-oriented approaches have been discussed in the field of sustainability science (Miller, 2013). But how do we facilitate the collaboration process in interdisciplinary and transdisciplinary approaches? Defila and Di Giulio (2010) reported that the existence of many different frames, or definitions of the problem, suggests a need to develop common goals and a common language. In particular, in the interdisciplinary field, Defilia et al. (2006) demonstrated that researchers having achieved a synthesis were also successful in the development of a common language and a common theoretical basis.

In this article we focus on ontology engineering, which is a base technology in Semantic Web technology, as a method providing common terms, concepts, and semantics. This article discusses the effectiveness of ontology engineering approach in the process of collaborative research. For this purpose, we first describe how to identify/design the research question in an interdisciplinary activity. Second, we describe the ontology as a domain-neutral metamodel and represent (illustrate) its construction process in a domain-neutral manner. Third, we attempt to apply the ontological approach to the experimental environment of the interdisciplinary research process. Finally, we discuss the future direction of collaboration support by means of ontology based on the problems of ontological approach which were revealed through a series of experiments.

2. How do we identify/design research question in interdisciplinary activity?

2.1. Related research

The approach discussed in this article introduces the collaborative design approach (Holsapple and Joshi, 2002) in the context of the transition management approach in sustainability science approach (Loorbach, 2007; Grin and Rotmans, 2010). As Miller (2013) reported, it is crucial to create a space for a more democratic and reflexive research agenda in process-oriented sustainability science. In other words, SS must deal with dynamics in the sense that SS can adaptively react according to the goals/requirements of the users.

In particular, since new developments will bring unexpected risks and sustainable development is a long term, open-ended goal, it is necessary to construct a base of knowledge that can flexibly correspond to the current situation (Kemp and Martens, 2007; Kajikawa, 2008). For this reason, a conceptual framework that facilitates collaboration and communication between researchers from different academic fields plays a crucial role in the knowledge structuring process. Kumazawa et al. (2009) proposed a framework of knowledge structuring in the sustainability science that includes a dynamic process of knowledge production, usage, and updating, based on ontology engineering. In response, Mizoguchi et al. (2011) discussed more concrete and technological aspects of knowledge structuring with the goal of implementation on a computer. Based on the framework proposed in Kumazawa et al. (2009) and Kumazawa et al. (2014a) we designed the initial design process for constructing an ontology for SS from the aspect of a knowledge-sharing tool to support co-deliberation.

2.2. Method for understanding the production process from initial interest to the development of a research question

Difficulty in interdisciplinary research involved in developing a research question can be identified through understanding the individual research interests of researchers and their areas of expertise. Documents used in meetings for research development, individual interviews with researchers, discussions and meetings during research and development, and structural drawings written on whiteboards and papers are materials that make up the texts used to clarify the contexts of a proposed research question and the interests of individual researchers.

However, the question arises as to how individual events, processes, reasons, questions, emerging problems and impacts, and goals are interconnected and are considered in developing the research question As Fig. 1 shows, we can find the research questions from the context underlying discussions. We then must consider what connects the texts and contexts. The authors recognize that the layer of concepts and semantic relationships are positioned between the layer of text as an individual instance and the layer of a general context. Then, we must consider the relationship between researchers and the research domains of these concepts, as well as semantic relationships. this hypothetical framework, in Section 2.3, we discuss the framework upon which to understand this relationship.

2.3. Metamodel framework to share the knowledge structures of researchers and general models

Consider the following question: How does honeybee's world exist? Uexküll and Kriszat (1934) proposed the concept of the "unwelt" to explain the state of their existence. The "unwelt" is different from the environment, in that each actor constructs the unwelt by giving meanings to objects and events experienced in the environment. Uexküll reported that what really exists for each actor is not objective environment but rather a subjectively constructed world. From the same perspective, we attempt to grasp the knowledge structure of each researcher.

On the other hand, Giqch (1991) defines a model as an output obtained from the process of modelling, and defines modeling as one component of system design by which real-world problems are given a representation to facilitate decision making and problem solving. Furthermore, the epistemology of modeling originates in metamodeling.

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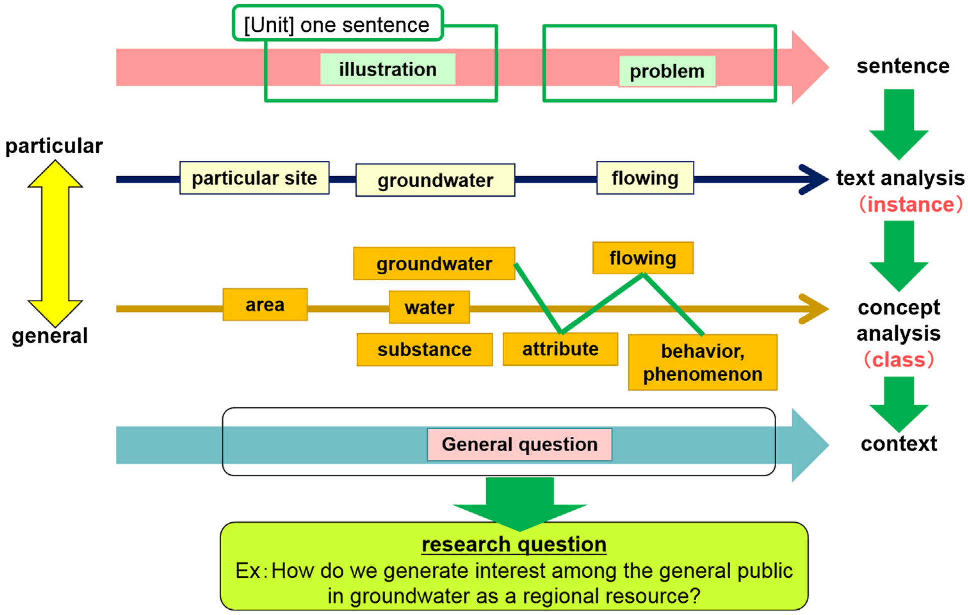

Fig. 1. Hierarchical classification of analysis target and method.

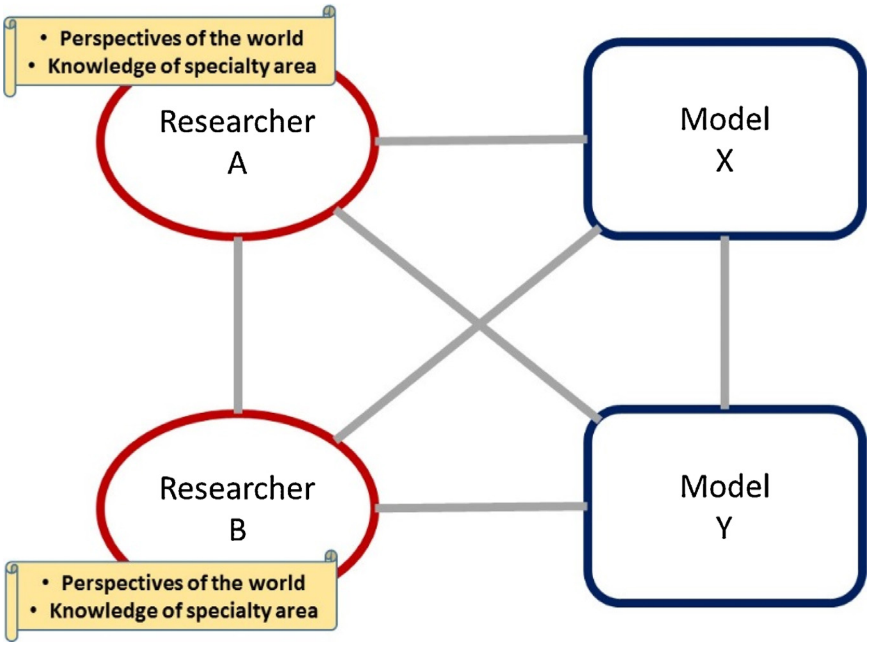

Fig. 2. Mutual linkages between researchers or/and models.

The representative model in the field of the water–energy–food nexus is the framework of the water–energy–food nexus itself. However, why was the model of the water–energy–food nexus originally designed (selected)? How are water, energy and food linked? How is the water–energy–food nexus model linked to the worldview of researchers or their areas of expertise? In order to answer these questions, we need some type of tool to relativize the worldview of a researcher or model, i.e., a metamodel. A tool that enables us to interconnect multiple researchers or/and models, as shown in Fig. 2, is thus required. Such a tool would enable researchers to collaborate while sharing a common language and a common theoretical basis.The ontology engineering approach enables us to understand researchers or/and models and the differences between them by providing a common language and a common theoretical basis.

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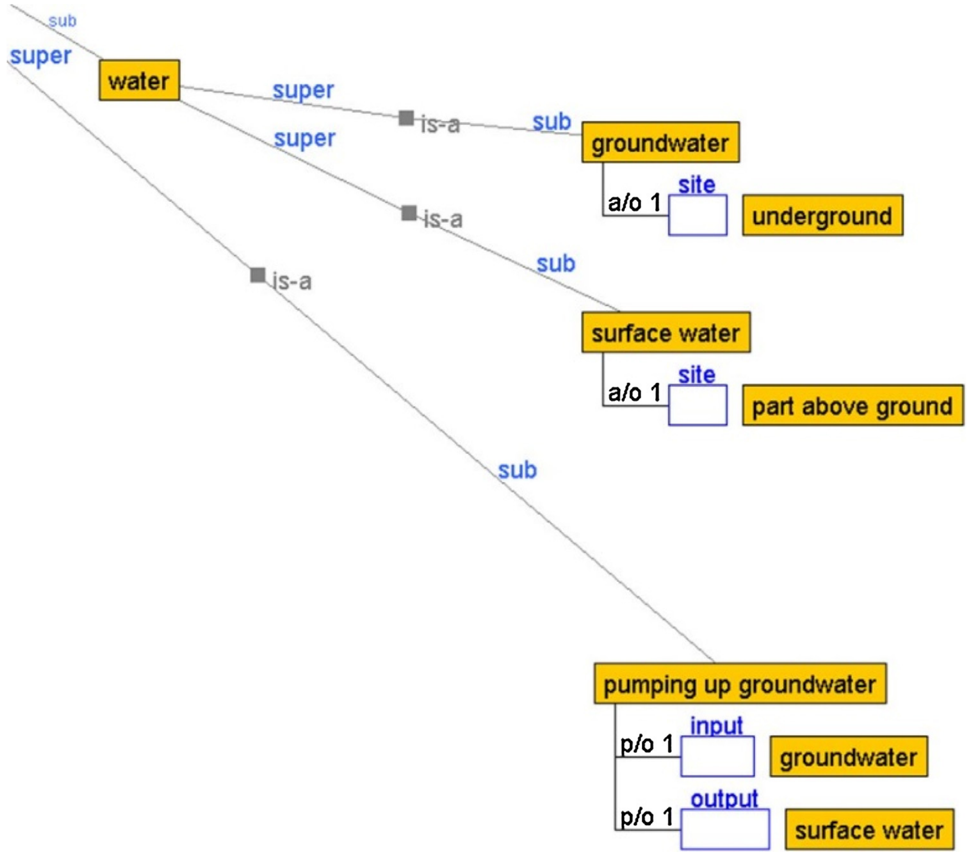

Fig. 3. Concept definition using ontology engineering.

3. Ontology as a domain-neutral metamodel

3.1. What is ontology engineering?

In the artificial knowledge field ontology is defined as "explicit specification of conceptualization" (Gruber, 1993). Ontology engineering is a key method for information technology that can be understood by people and computers. An ontology consists of concepts and relationships that are needed to describe the target world and provides common terms, concepts, and semantics by which users can represent content with minimum ambiguity and interpersonal variation of expression. An ontology is expected to contribute to the structuring of the knowledge in the target world. The construction of a well-designed ontology enables an explicit understanding of the target world. An ontology, however, is identified not by the form of the knowledge, such as description languages and representation forms, but rather by the content of some described knowledge and the roles that the described knowledge plays.

Fig. 3 shows the concept definition using the Hozo ontology development tool, which is based on fundamental theories of ontology engineering. In Fig. 3, the is-a relationship describes the categorization of the concepts. Meanwhile, the introduction of other relationships, including part-of relationships (has-part relationships) and attribute-of relationships, refines the definition of the concepts. In Fig. 3, input or output includes concept-dependent on a context, referred to as roles. The greatest characteristic of Hozo is to be able to deal with a role concept. A role concept enables us to create a model to explicate what plays a role. For example, humans, fruits or heating oil can play the role of teacher, food, or fuel, respectively.

3.2. Constructing ontology in a domain-neutral manner

Although ontology is domain-neutral, it is probably impossible to structure the target world if it is completely domain neutral. For example, water will be not only dealt with as entity but also discussed based on its uses. Therefore the roles of water are identified according to a particular context. However, the approach for structuring knowledge by ontology engineering is implemented in a domain-neutral manner. In addition, several top-level ontologies which define the basic concepts used to describe the world, including objects, time, space and processes, have been developed (Kitamura, 2012). The

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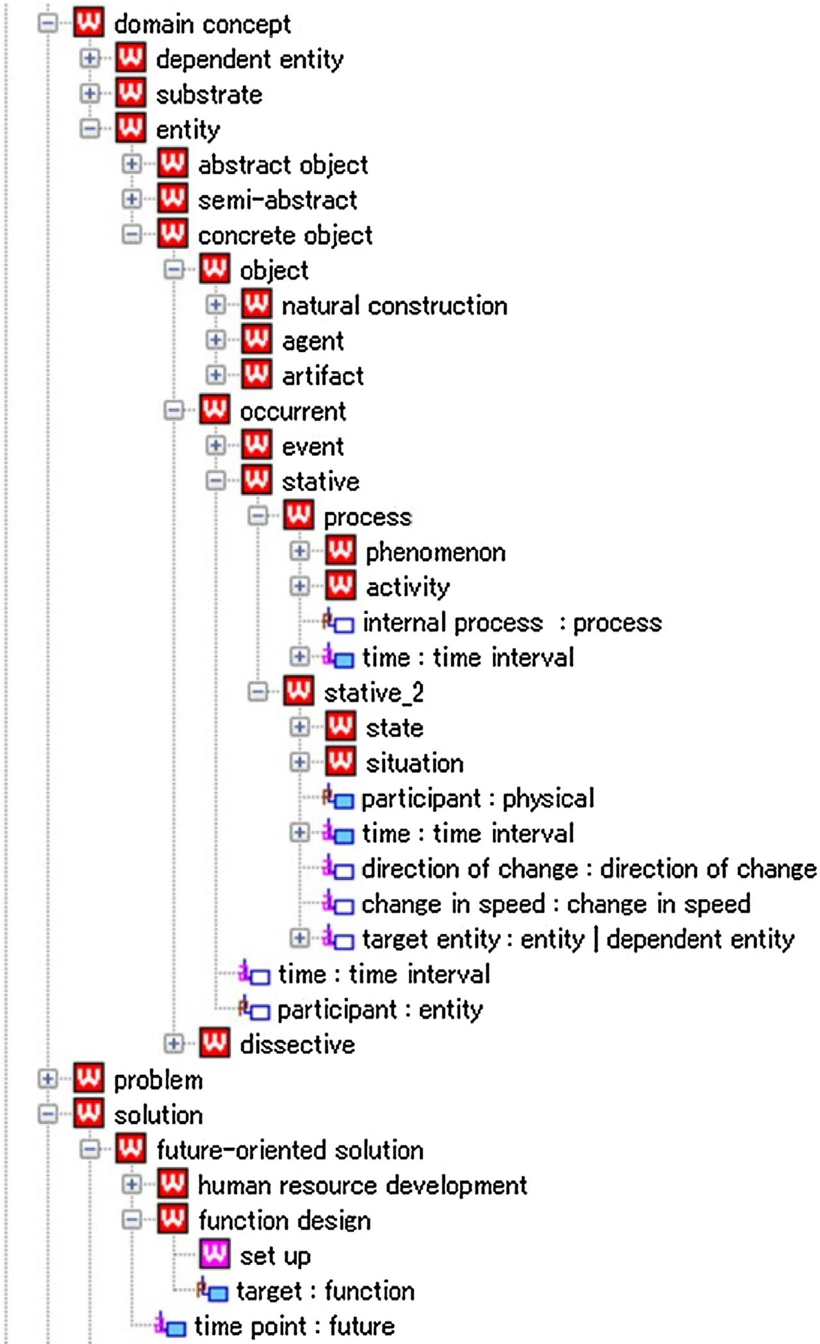

Fig. 4. An example of the sustainability-context ontology constructed according to YAMATO.

descriptive ontology for linguistic and cognitive engineering (DOLCE), basic formal ontology (BFO), suggested upper merged ontology (SUMO), Open Cyc, and general formal ontology (GFO) (Mizoguchi, 2012) are examples of top-level ontologies.

The yet another more advanced top-level ontology (YAMATO) (Mizoguchi, 2010, 2012) is also a top-level ontology that was developed at the former Mizoguchi Laboratory, Osaka University. The ontology we have been constructing according to the sustainability context is based on YAMATO, as shown in Fig. 4. The basic distinction plays a crucial role in terms of a top-level ontology (Mizoguchi, 2012). In the constructed ontology, we first divide the concept in the sustainability domain into *entity*, *dependent entity* and *substrate*. Second, we divide the *entity* into the concepts of *abstract object*, *semi-abstract (object)*, and *concrete object*. The concept of *concrete object* is classified as *object*, *occurrent* and *dissective*. *Occurrent* can be classified as *process*, *event* or *state*.

Table 1
Outline of experiment A.

Date		May 19th, June 3rd (approximately 2.5 hours)	
Site		Osaka University	
Basic research issue		Research on water use and water resource management (including forest management and biomass use)	
Goal		Proposing the research theme and its framework	
Member of experiment group A			
Researchers of Lake Biwa Environmental Research Institute		Researchers of Osaka University	
ID	Specialty - Affiliation - Position	ID	Specialty - Affiliation - Position
1	Environmental system engineering - Division of Integrated Analysis - Research scholar	3	Development of technologies for wastewater treatment, environmental conservation, and resource recycling using biotechnology - Assistant professor - Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering
2	Environmental management - Division of Integrated Analysis - Research specialist	4	Material cycles (Resource Circulation), Design for Sustainability and Social Fabrication - Assistant professor - Creative Design Studio on Technology, Graduate School of Engineering

In the lower hierarchy, we can find the concepts in the context of sustainability. For example, *natural construction* is defined as a subconcept of *object*, while all kinds of actors identified in the sustainability domain are defined as subconcepts of *agent*. On the other hand, *occurrent* is divided into concepts including *phenomenon* and *activity*. *Phenomenon* is defined as a basic (fundamental) phenomenon for discussing issues in the sustainability domain, whereas *activity* is defined as a basic activity of living things including humans, under the same condition.

As a result of such (definition) process, an ontology is constructed in a domain-neutral manner. The concepts related to researchers and models are incorporated as subconcepts of the constructed ontology. The connection between models and the constructed ontology is realized by linking the concepts of these models with the models themselves.

4. Collaboration experiment of research development supported by an ontological approach

4.1. *Outlines of the collaboration experiments*

What kind of effectiveness can be expected if we implement the collaboration between researchers while sharing a common language and a common theoretical basis? In this section, we examine what the ontology contributes to a tool for supporting collaboration through the discussion in the experiment of collaborative research development. The research flow is as follows:

(1) We design an experiment of the collaborative research development by researchers in different fields related to sustainability science and environmental studies.
(2) We implement the research development experiment in the style of a workshop, and obtain a visualized output.
(3) We construct an ontology based on the current version of the ontology dealing with the sustainability of social-ecological systems (Kumazawa et al., 2014b; Kumazawa et al., 2015), and extract points as issues to be discussed by means of the ontological structure based on the constructed ontology.

Experiments A and B is implemented at Osaka University and the Research Institute for Humanity and Nature (RIHN), respectively. The outlines of these experiments are shown in Tables 1 and 2, and Figs. 5 and 6 show photographs of the experiments being conducted.

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Table 2
Outline of experiment B.

Date		June 15th, September 14th (approximately 2.5 hours)	
Site		Research Institute for Humanity and Nature	
Basic research issue		Research on water and water resource management	
Goal		Proposing the research theme and its framework	
Member of experiment group B			
Water–Energy–Food Nexus Project researchers of RIHN		Other researchers	
ID	Specialty - Affiliation - Position	ID	Specialty - Affiliation - Position
1	Resource Governance - Research Department - Project Researcher (Human-Environmental Security in Asia-Pacific Ring of Fire: Water–Energy–Food Nexus)	3	Agricultural Resource Economics - Faculty of Agriculture Department of Agricultural Science, Kinki University - Associate Professor
2	Hydrology - Research Department - Project Researcher (Human-Environmental Security in Asia-Pacific Ring of Fire: Water-Energy-Food Nexus)	4	Soil Science - Research Department - Project Researcher (Designing Local Frameworks for Integrated Water Resource Management)

Fig. 5. Photograph of experiment A at Osaka University.

4.2. *Proposed keywords and research theme*

4.2.1. *Group involved in experiment A*

Fig. 7 the proposed product, including the research theme and keyword relationships attained after the 150-minute discussion. The research proposal for experiment A targets the way of water use of a particular area by focusing on household water usage. This group provided a research framework that is relatively easy to understand.

After the first workshop we constructed an ontology in Fig. 7 by adding concepts that define the extracted keywords and tentative research theme while dealing with the sustainability of social–ecological systems. For example, *water use in a local area* and *water use by households* are newly added as a subconcept of *water use,* as shown in Fig. 8.

Fig. 9 shows the structure that was partially extracted from the constructed ontology engineering, which was corresponded to Fig. 7, but an obviously complexed figure. If the group members reach a consensus, the contents of Fig. 7 are sufficient to determine a research direction without such an ontological structure.

Actually, we asked the group involved in experiment A to fix the proposed research theme with this ontology and had the group implemented. However, the discussion was not necessarily facilitated, not only because it took a great deal of time to understand the constructed ontology but also because the ontology consisted of a more complex structure than the original

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Fig. 6. Photograph of experiment B at RIHN.

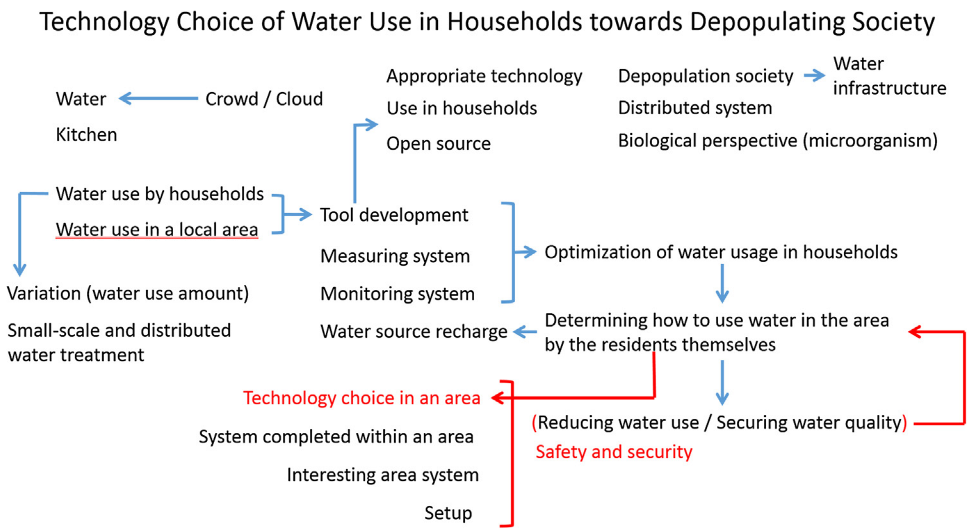

Fig. 7. Organized structure proposed as a result of experiment A.

structure shown in Fig. 7. Nevertheless, Fig. 9 also shows that there are actually a number of concepts and relationships in the background. An ontology enables us to use such background information and to explicate an ambiguous part of "when, where, who, which, what, how" as shown in Fig. 9. In addition, the linkage through *by-product* and *waste and emissions* was the linkage that was not described in this workshop experiment.

To be sure that the limited number of terms in the structured glossary apparently hamper creativity, but we consider that creativity is actually ensured by facilitating the discussion based on such terms in the glossary. In addition, one of the researchers involved in experiment A stated that it is important to draw on individual experiences in designing a conceptual map (based on the knowledge structure of the researchers). A map tool that realizes map generation based on a particular perspective of each actor satisfies this requirement (Hirota et al., 2008) (Fig. 10). Further development into a map tool that is more applicable to a workshop is a future task. For example, if the map tool realizes design and visualization such that a participating researcher himself/herself can understand the knowledge structure of each researcher and can understand the model based on general concepts without difficulty, the map tool will be more adaptable to a workshop.

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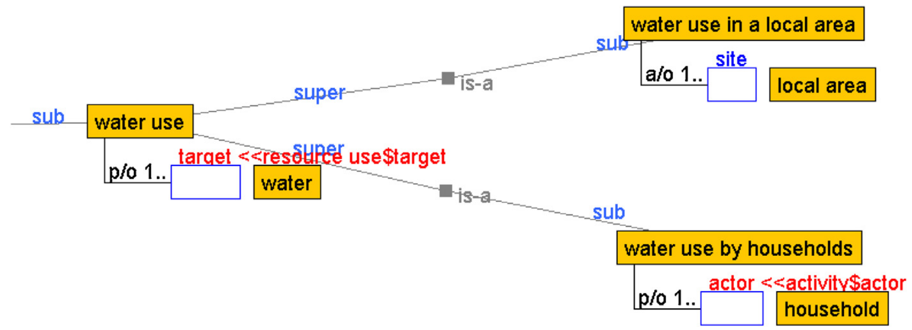

Fig. 8. Example of newly added concepts to the ontology dealing with the sustainability of social–ecological systems.

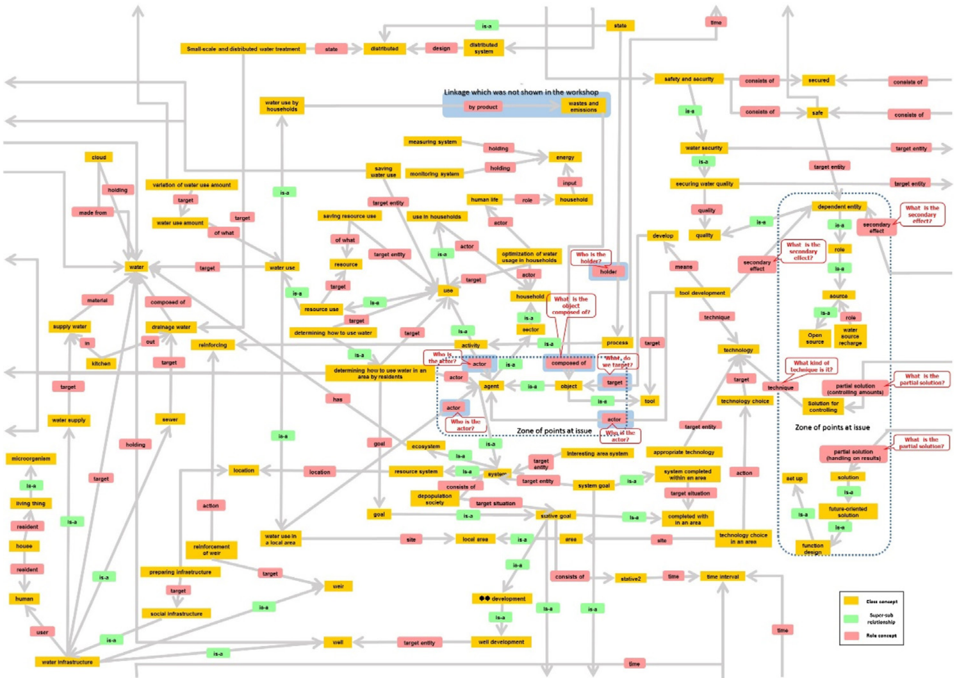

Fig. 9. Constructed ontology mapped by further points to be specified.

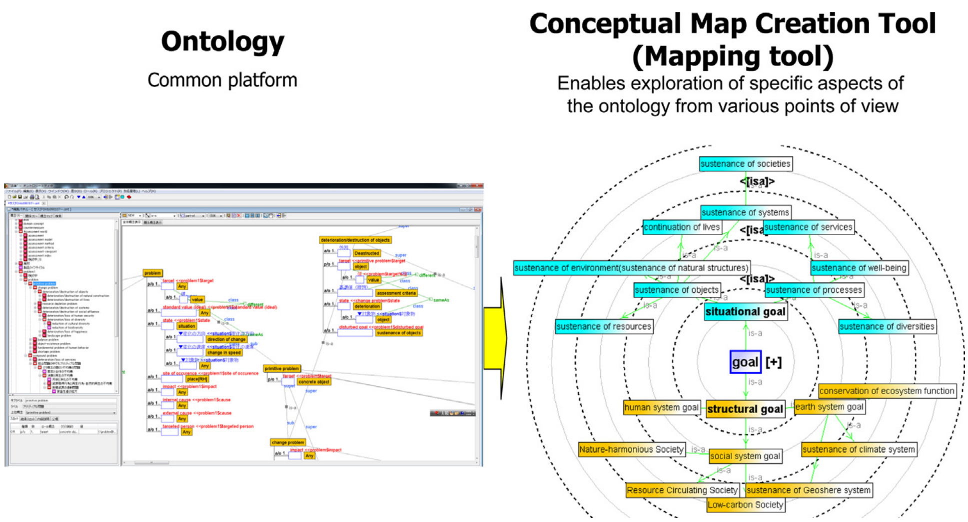

Fig. 10. Map generation from the ontology (Kumazawa et al., 2014a).

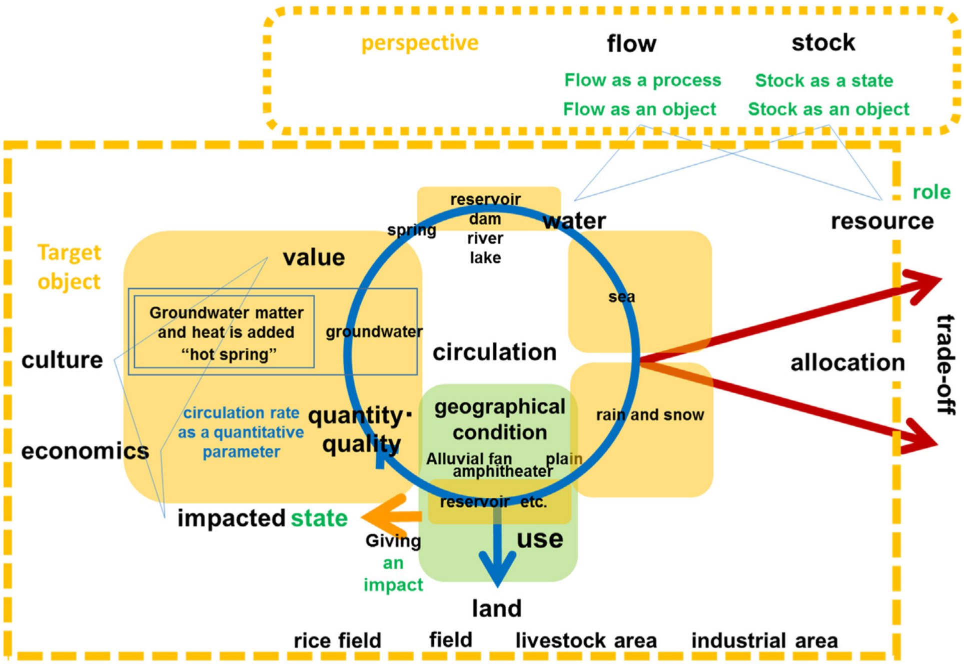

Fig. 11. Concepts and relationships between concepts corresponding to ontological analysis.

Table 3
Fixed research issue and its basic research direction in experiment B.

Main title	"Climate change and basin society"
Sub title	"How will the value of water change in the circulation process?"
Characteristics	• Obtaining deeper understanding of the value of water in the circulation process • Implementing water circulation simulation

4.2.2. Group involved in experiment B

An ontology is a tool for visualizing unorganized issues and for synthesizing organized issue structures. Experiment B suggests such a role of an ontology. The group of experiment A obtained a research theme and framework through comparatively smooth discussion, whereas the group of experiment B took almost 150 minutes, but did not reach the systematization stage visualized on the whiteboard.

However, the discussion itself was productive and generated thoughtful contents. Concretely, they attempted to propose a research theme focusing on multifaceted values, and the discussion was steered toward an investigation of the relationship between the values of water and the flow volume, the circulation velocity and the quality of water. The following three were the primary areas of focus: 1) the meanings of the values of water in the hydrological circulation process, 2) the scale of the hydrological circulation, and 3) how to distinguish field cases and how to select the target cases. These issues indicate that further coordination is required in terms of concept, target scale and case classification. The researchers who were involved in experiment B also desired a method for explicating the issue structure, which not only reflects the discussion in experiment B, but also ensures a reasoned argument. This is considered to be why we use ontology in the process of research collaboration.

Based on the situation of experiment A, we prepared an organized map corresponding to the ontological approach, which represents the basic concepts and semantic relationships reflecting the discussion context of experiment B, as shown in Fig. 11. This figure was sometimes used as a reference for the discussion in the second workshop, but the participants managed to fix the research issue and the basic research direction was fixed as shown in Table 3.

Considering the relationship between the proposed research and Fig. 11, a hydrological circulation system is a micro-system of a climate system. Therefore, the primary research incorporates a broader system perspective as compared to Fig. 11. In addition, the basin includes not only objects other than water but also spatial elements. Furthermore, society indicates a broader research target than is considered in Fig. 11 and has both material and societal dimensions. Therefore, in the future we intend to consider how the dialog contributes to obtaining such broadness by linking the terms in the dialog to the concepts in the ontology. (At present, we construct the corresponding part of the ontology. We intend to report the results of ontology-based analysis in the future.)

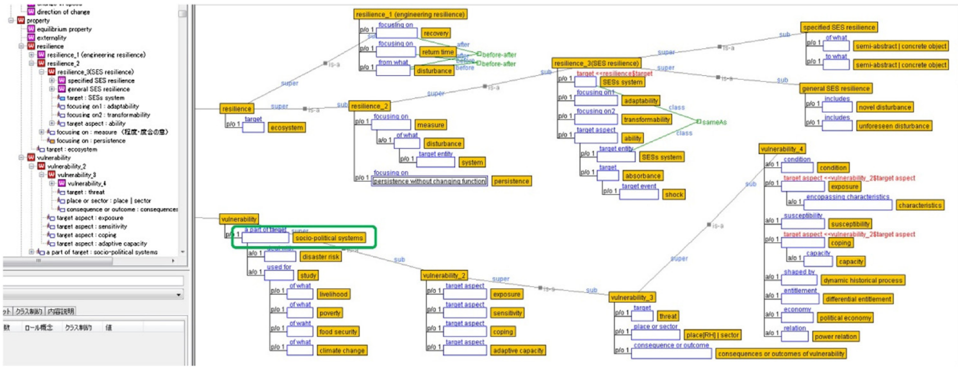

Fig. 12. Hierarchical structure of the definitions of vulnerability and resilience based on Miller et al. (2010).

4.3. Discussion

4.3.1. Implications a comparison between experiments A and B

Compared to the group of experiment A, the discussion by the group of experiment B was more difficult to understand in terms of the discussion context and the relationship between the title and the keywords.

By first discussing the difference in obscurity of the discussion, the obscurity of the group of experiment B was due to abstractness and complexity. For example, the keywords such as circulation and value are very abstract, whereas the targeting system is complex in terms of including multiple scales as a mechanism. Second, the title of experiment A is directly reflected by the relationship between keywords, as shown in Fig. 7, whereas the title of experiment B has a broader perspective than the range of the concepts and relationships between concepts, as shown in Fig. 11. Therefore, the process for developing a research question in experiment A was shorter than that in experiment B.

One reason for this difference was the extent of the difference between researchers. The research fields of the members of the group of experiment A were somewhat similar, whereas the research fields of the members of the group of experiment B were broader. Thus, the collaboration experiments revealed a trade-off relationship between the broadness of domain and the abstractness and complexity of the discussion.

4.3.2. Contribution of ontology to interdisciplinary research

As a result of organization and the proposed way that ontology contributes to interdisciplinary research from the processes of the two collaboration experiments, experiment A showed causal links between the keywords written on the white board based on ontology engineering, whereas, from experiment B, we understood the potential to ensure reproducibility by building causal links between individual issues in the discussion and the fixed research issue. Correspondingly, we proposed items (1) (2) below, as ways that ontology contributes to interdisciplinary research. In addition, we proposed item (3) based on our previous research.

(1) Explicating how researches who have particular areas of concern, techniques, research styles and worldviews are interlinked in the organization process

An ontology cannot explicate a researcher's areas of concern, technique, research style or worldview, but we can share and understand differences from other researchers through an ontology.

(2) Supporting facilitation to identify a research issue and framework

An ontology can facilitate the clarification of difficult to identify problems, problems that are complex because of multiple interrelated issues, and abstract and confusing problems.

(3) Facilitating the understanding of the researcher himself/herself and other researchers

An ontology can support understanding the range of researchers' domain, the model, framework and terminology which particular researchers use. For example, Kumazawa et al. (2014c) examined the definitions of resilience and vulnerability in the existing literature proposed by Miller et al. (2010) (Fig. 12). In this way, an ontology enables us to share and explicitly understand a difference of term definition in terminology.

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5. Concluding remarks

Through the experiments involving two groups, we examined the use of an ontology engineering approach in research collaboration process. As a technological solution to overcome problems with this approach, the combination of ontology engineering approach and another approach is considered to be more effective. One option involves the use of a text-mining approach. For example, terms and paths that occur frequently can be shown in larger letters. In addition, central keywords can be extracted through analyzing the co-occurrence relation. These analyses will lead to the identification of key considerations. Another option is the combined use of ontology engineering and a network analysis approach. For example, the collaboration strategy reflecting the analysis of the difference between conceptual relationships and actual academic relationships can be proposed by measuring the actual extent of linkages between reports in the literatures or actors.

The present article discussed the effectiveness of ontology engineering approach in the process of collaborative research. First, we discussed a method by which to identify/design a research question and proposed a metamodel framework to share the knowledge structures of researchers or/and general models. Second, we reviewed ontology as a domain-neutral metamodel and represented (illustrated) its construction process in a domain-neutral manner. Third, we proposed a method by which to use ontology contribute to interdisciplinary research through experimental workshops of research development.

The introduction of an ontology engineering approach will enable us to share a common language and a common theoretical basis. However, the development of a new method based on ontology engineering is needed. For example, knowledge structuring according to the perspective of each researcher and simple figures accompanied by reasoned arguments in the background are the directions of tool development. Future issues are to design these requirement specifications and frameworks.

In addition, connecting the constructed ontology and all kinds of web resources with the format of resource description framework (RDF) is also a goal of this approach. The RDF is a semantic web language that can be used to connect the URL of a website to an ontology described by a web ontology language. Using the characteristics of ontology engineering will enable the realization of research collaboration with knowledge sharing between different researchers and outside of interdisciplinary research groups.

Conflict of interest

There is no conflict of interest with other people or organizations within three years of beginning the submitted work.

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