Integrating scientific modeling and supporting dynamic hazard management with a GeoAgent-based representation of human-environment interactions: a drought example in Central Pennsylvania, USA

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Abstract:

Recent natural disasters indicate that modern technologies for environmental monitoring, modeling, and forecasting are not well integrated with cross-level social responses in many hazard-management systems. This research addresses this problem through a Java-based multi-agent prototype system, GeoAgent-based Knowledge System (GeoAgentKS). This system allows: (1) computer representation of institutional regulations and behavioral rules used by multiple social institutions and individuals in cross-level human-environment interactions, (2) integration of this representation with scientific modeling of dynamic hazard development, and (3) application of automated reasoning that suggests to users the appropriate actions for supporting cooperative social responses. This paper demonstrates the software architecture of GeoAgentKS and presents such an integrated approach by modeling the drought-management processes in Central Pennsylvania, USA. The results show that it is possible to use GeoAgentKS to represent multilevel human-environment interactions and to use those interactions as input to decision making in hazard management.

Keywords: hazard management, GeoAgent, knowledge representation, geographic information systems (GIS), drought, modeling, decision support

1 Introduction

Natural hazards, such as drought, tsunami, hurricane, flood, wildfire, and earthquake, are likely to become ever more costly in human lives and economic development (World Bank Independent Evaluation Group 2006). The lessons learned from the 2004 tsunami in the Indian Ocean and 2005 Hurricane Katrina in the southern United States indicate an urgent need to develop new means for early warning and response systems to enhance human collaborative capabilities in coping with large-scale natural hazards (UNDP 2005, The White House 2006). While modern remote sensing, spatial modeling, and geographic information technologies now allow early detection, simulation, and forecasting of many environmental changes, such technology is not yet well integrated with multilevel social cooperative responses. In the Katrina case, for example, although NOAA (National Oceanic and Atmospheric Administration) accurately predicted the size, scale, and path of this hurricane (NOAA 2005), the federal, state, and local government agencies and private departments were not able to achieve effective collaboration in crisis response. All levels of the emergency preparedness plans, even after enhancements following the terrorist attacks on September 11, 2001, "*failed to adequately account for widespread or simultaneous catastrophes*" (The White House 2006). Hurricane Katrina, as well as the Indian Ocean Tsunami, aroused not only a worldwide awareness of the need to improve human preparedness for catastrophic events, but also a scientific and technological challenge to increase our capabilities in dealing with large-scale hazards by integrating environmental monitoring and modeling with cross-level human cooperative responses.

One way to address this challenge is to digitally represent both social and natural systems and their interactions in order to integrate hazard monitoring and modeling with social responses for supporting decision making and cross-level cooperation. This representation demands development of tools that are capable of storing and modeling social rules at multiple levels, analyzing diverse hazard situations, and performing automated reasoning to choose appropriate actions for supporting collaborative responses. Resulting tools can be used in hazard management not only to analyze data, but also to remind decision makers of important tasks and provide guidelines to non-expert users about how to respond in varying circumstances.

GIS (geographic information systems) and related software are widely utilized as essential tools for representing and analyzing environmental phenomena, but have limited capabilities for representing how the phenomena work (Goodchild 2004), especially the processes of social interactions over given places. Agent-based modeling is a promising approach for representing interactions among multiple agents and their environments as artificial institutions and individuals (Fornara *et al.* 2007). Agent-based approaches can, therefore, be applied to represent the social interactions in hazard management. In another paper (Yu and Peuquet in press), we introduced a concept of *geographic agents* (*GeoAgents*) for representing entities with goals and social characteristics in the geographic world. We also developed a Java-based prototype system, called the *GeoAgent-based Knowledge System* (*GeoAgentKS*, see Yu 2005). GeoAgentKS integrates agent-based technologies with expert systems, concept maps, scientific models, and geospatial data for representing human-environment interactions to support decision-making in hazard management.

The current paper demonstrates the overall software architecture of GeoAgentKS, as well as the methods for integrating GeoAgent-based representation of social interactions with scientific modeling of dynamic hazard development to support hazard management. This paper also shows a practical use of sharable knowledge (e.g. ontology and rules) for facilitating agent communications. To demonstrate the potential, we apply this prototype system in a case study that represents drought-management processes in Central Pennsylvania, USA.

Section 2 provides a contextual background of both agents and drought management in Central Pennsylvania. Section 3 introduces the software architecture of GeoAgentKS and its implementation. Section 4 focuses on knowledge-engineering and drought modeling methodologies for simulating the process of dynamic human-environment interactions. Section 5 presents the performance of GeoAgentKS in modeling the human-environment interactions in the Pennsylvania drought-management process using a 1999 drought event. The final section summarizes this study and discusses future research.

2 Background

Human-environment interactions in widespread hazards often are highly dynamic, diverse, complex, and uncertain. The current research aims to enhance hazard management by modeling human-environment interactions in a GeoAgent-based approach, and demonstrates a practical application in a drought example.

2.1 Agents-based approach

An agent can be conceptualized as an entity situated within a part of a simulated virtual environment (e.g. its digital surroundings, and other agents) with its own knowledge and behavioral rules. It can interact with this environment, communicate with other agents, and perform goal-driven actions in a distributed manner (Jennings *et al.* 1998, Luck and d'Inverno 2001, Luger 2002). Agents therefore can represent how multiple social organizations and individuals use their knowledge or rules to interact with diverse environmental changes in hazard conditions. In the past decade, there have been numerous efforts to develop agent-related theories (Brooks 1991a, 1991b, Shoham 1993, Wooldridge and Jennings 1995, Jennings *et al.* 1998, Luck and d'Inverno 2001) and technologies in artificial intelligence and many other fields that can be applied to enhance hazard management. These technologies include knowledge representation (Luger 2002, Luck *et al.* 2003), agent communication (Finin *et al.* 1994, Singh 1998, Yen *et al.* 2004), cooperation (Luck and d'Inverno 1996, Axelrod 1997, d'Inverno *et al.* 1997, Doran *et al.* 1997, Wooldridge and Jennings 1999), task planning (Ferber 1999), and automated reasoning (Parsons *et al.* 1998, Wooldridge 2000, Excelente-Toledo *et al.* 2001, Schut *et al.* 2001).

The importance of agent-based approaches for facilitating emergency and hazard management has been recognized in recent years. There are various research efforts to develop agent-based systems, algorithms, and methodologies, such as training for disaster-management (Schurr *et al.* 2006), optimization of disaster policy (Wu *et al.* 2007a, Wu *et al.* 2007b), simulation of decision making (Yen *et al.* 2007), and effective information handling (Szymanski *et al.* 2003). Most of these research efforts, however, place emphasis on conceptual-level discussions of system design, technical development, or methodology exploration, rather than on real-world applications.

Agent-based approaches have also been applied to simulate the reactions and interactions of autonomous individuals over a geographic environment. The general purpose of such applications is to discover simple rules that drive complex systems with a bottom-up strategy (Epstein and Axtell 1996). Practical examples include simulation of land-use and land-cover changes (Balmann 2000, Manson 2000, Parker *et al.* 2003, Chong 2004, Evans and Kelley 2004, Manson 2006), an influenza pandemic (Ferguson *et al.* 2005, Ferguson *et al.* 2006), habitat changes of giant pandas (An *et al.* 2005), way finding (Raubal 2001), natural resource management (McDonald *et al.* 2006, McDonald *et al.* 2008), and movement of animal predators and prey (Westervelt and

Hopkins 1999). In such individual-oriented ABM approaches, as pointed out by Parker *et al.* (2003), the modeling of institutions remains a challenge because of agents' limited capabilities in representing complex institutional rules, maintaining mental and environmental states, and performing inter-agent communications. The current research meets this challenge with a focus on modeling institutional behaviors based on a GeoAgent-based representation framework.

2.2 GeoAgents

Current GIS research is focused on representing form rather than process, namely, 'how the world looks' rather than how it works (Goodchild 2004). The basic elements for geographic representation include objects, fields, and time. Objects are used to represent discrete entities in geographic environments; fields represent continuous phenomena; and time is used for representing dynamics. In this object-field-time view, however, elements with goal-driven behaviors and social characteristics are not particularly addressed, and there is no unified framework to integrate these elements within a representation of complex geographic processes. In Yu and Peuquet (in press), we proposed two major steps to enrich this conventional geographic representation. First, we introduced the concept of geographic agents (GeoAgents) as another basic element to represent entities with goals and social characteristics in the geographic world. Second, we presented a conceptual framework, called FOTAR (**F**ield, **O**bject, **T**ime, Geo**A**gent, and **R**elations), which aims to address the interaction processes among both natural and social elements (i.e. 'how the world works'). We contend that fields (e.g. air pressure and temperature) have movement and driving forces in addition to their continuous characteristics. Objects have characteristics more than their discrete form; they have actions, and their actions are passively driven by external forces. For GeoAgents, their actions can be driven by internal motivations or social dictates, in addition to external forces. The prefix of ‘Geo’ to agents primarily means that the development of GeoAgent-related theories, technologies, and systems seeks to meet geographic requirements (especially focusing on human–environment relations), rather than for other purposes of agent applications, such as improving internet search engines, manufactory management, or email systems. The central part of this FOTAR framework is the representation of relations, interactions, and driving forces among geographic elements. Achieving this new representation framework essentially requires GIS to go beyond the current data-centered strategy to address high-level knowledge.

The FOTAR framework has been implemented in the prototype software GeoAgentKS, as initially described in Yu (2005). The current paper summarizes components of this work with emphases on the following three themes: (1) the software architecture of GeoAgentKS; (2) the integration of the GeoAgent-based representation of social organizations with scientific modeling; and (3) the approaches to knowledge sharing among GeoAgents for reducing redundant behavioral rules and overcoming semantic barriers in communications. As noted above, we demonstrate the application of GeoAgentKS for drought-management in Pennsylvania, USA.

2.3 Drought management in Pennsylvania

We chose drought as a starting point to represent complex hazard-management processes using multi-agent technologies because drought management systems have been relatively well developed in Central Pennsylvania. Many drought-related social behaviors are explicitly regulated and enforced by laws. In Pennsylvania drought management, the state-level DEP (Department of Environmental Protection) and local CWSs (community water systems) play a central role in managing daily water supply and drought mitigation. In addition, there are many other social agencies and individuals involved, such as the state Governor, PEMA (the Pennsylvania Emergency

Management Agency), fire departments, news media, individual water operators, and water users (Figure 1).

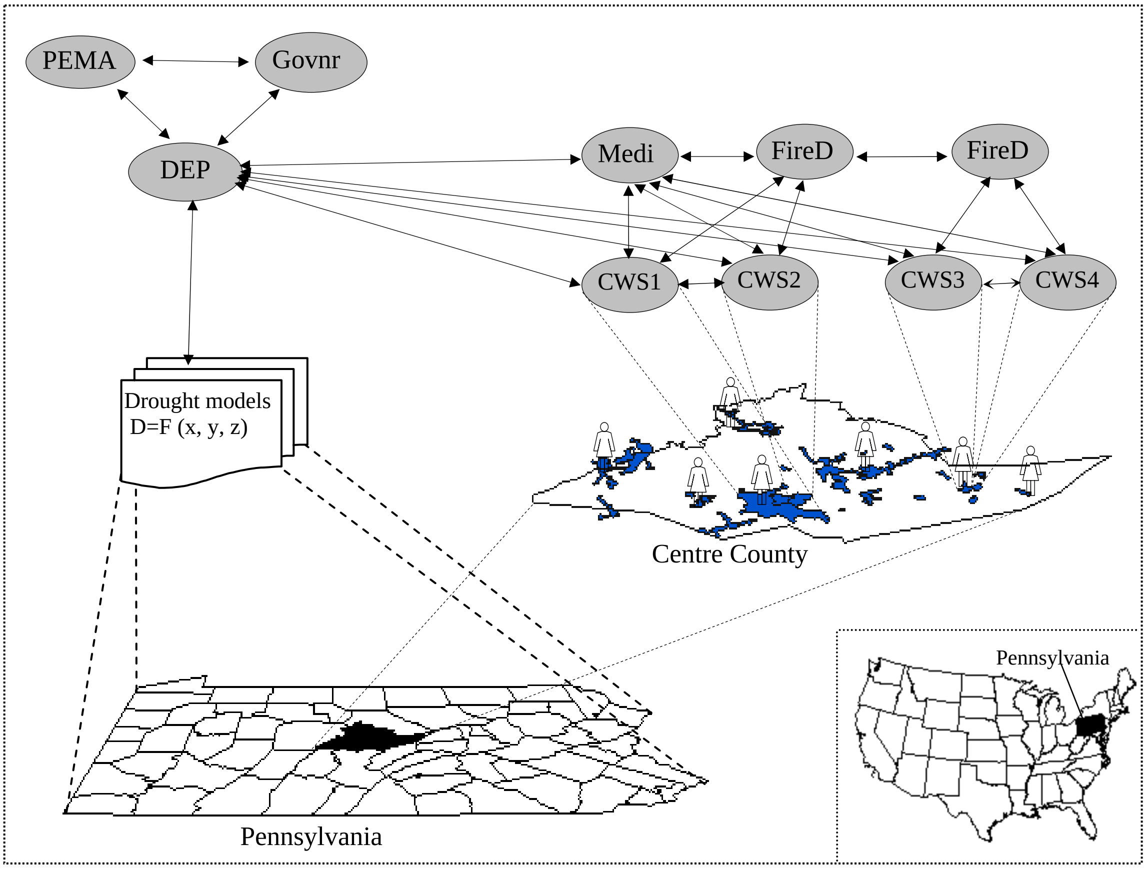


Figure 1 Cross-level drought management in Central Pennsylvania, USA. The DEP monitors statewide drought development using drought models, and coordinates with state-level or local agencies to achieve drought-management goals cooperatively. PEMA: PA Emergency Management Agency; DEP: Department of Environmental Protection; Govnr: the state Governor; FireD: fire department; CWS: community water system; Media: news media

Each organization or individual may have unique behavioral rules for interactions in particular situations, places, and scales. For example, the DEP monitors statewide drought development, uses different indices and models (e.g. Palmer Hydrologic Drought Index (PHDI)) to classify the drought into different stages (e.g. drought watch, drought warning, and drought emergency), and guides drought management in the affected areas. CWSs, rather than focusing on statewide environmental changes, may be more interested in their local environmental status, such as geology, groundwater table, surface water sources, land use, and local water usage. Most CWSs have developed their own drought contingency and other preparedness plans to cope with diverse environmental changes (e.g. contamination, power outage, drought, flooding, extreme cold, etc). When a hazard event happens, the involved social agencies usually need to interact with each other to achieve cooperative responses.

3 GeoAgent-based Knowledge System (GeoAgentKS)

We used GeoAgentKS to model the processes of both physical drought development and social interactions (Figure 1) to support dynamic decision making in hazard management. This section briefly introduces the GeoAgentKS software structure.

3.1 The software architecture

To achieve GeoAgent-based representation, techniques should be able to support agent-related operations, represent high-level knowledge, handle geospatial databases, simulate environmental changes, and represent the complex relationships among GeoAgents and their environmental elements as demonstrated in Figure 1. Figure 2 shows that GeoAgentKS includes the following modules: agent kernel, knowledge bases, expert system (inference engine), concept map, scientific models, geospatial database, and graphical user interface (GUI).

The “Agent Kernel” module in GeoAgentKS manages GeoAgents’ groups, roles, lifecycles, and communications. Expert systems are used for storing GeoAgents’ knowledge of behavioral rules and performing automated reasoning. A knowledge base (KB) in expert systems is a centralized repository for storing knowledge (e.g. ‘IF…THEN…’ rules) in a logically consistent way (Luger 2002, Friedman-Hill 2003), and it provides the means to collect, organize, and use knowledge to support automated

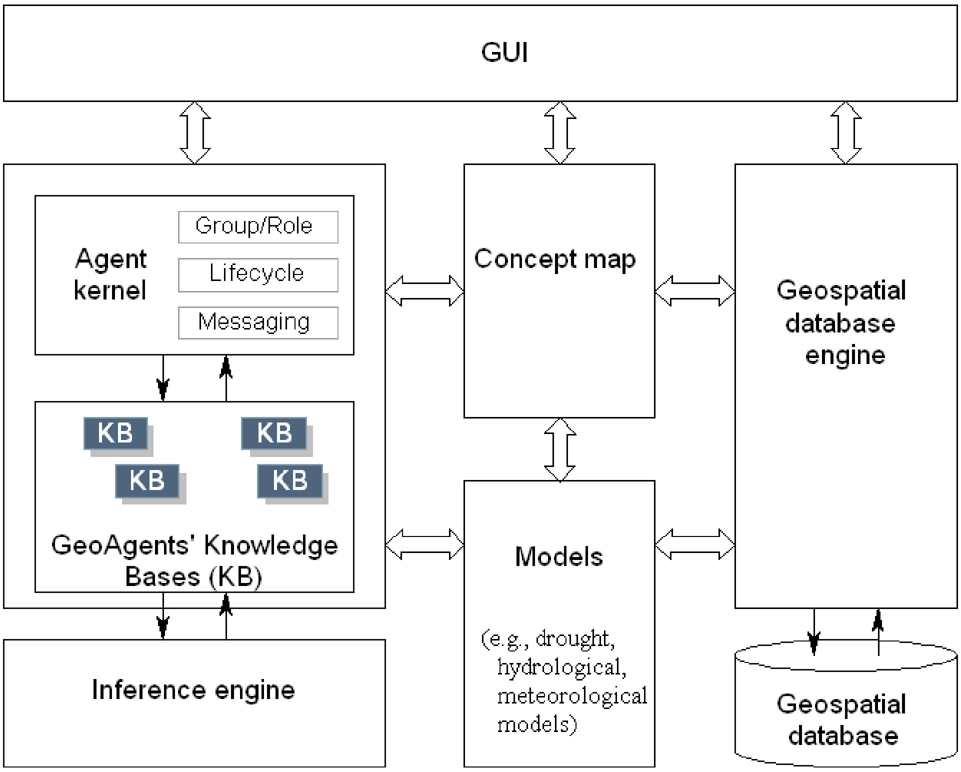
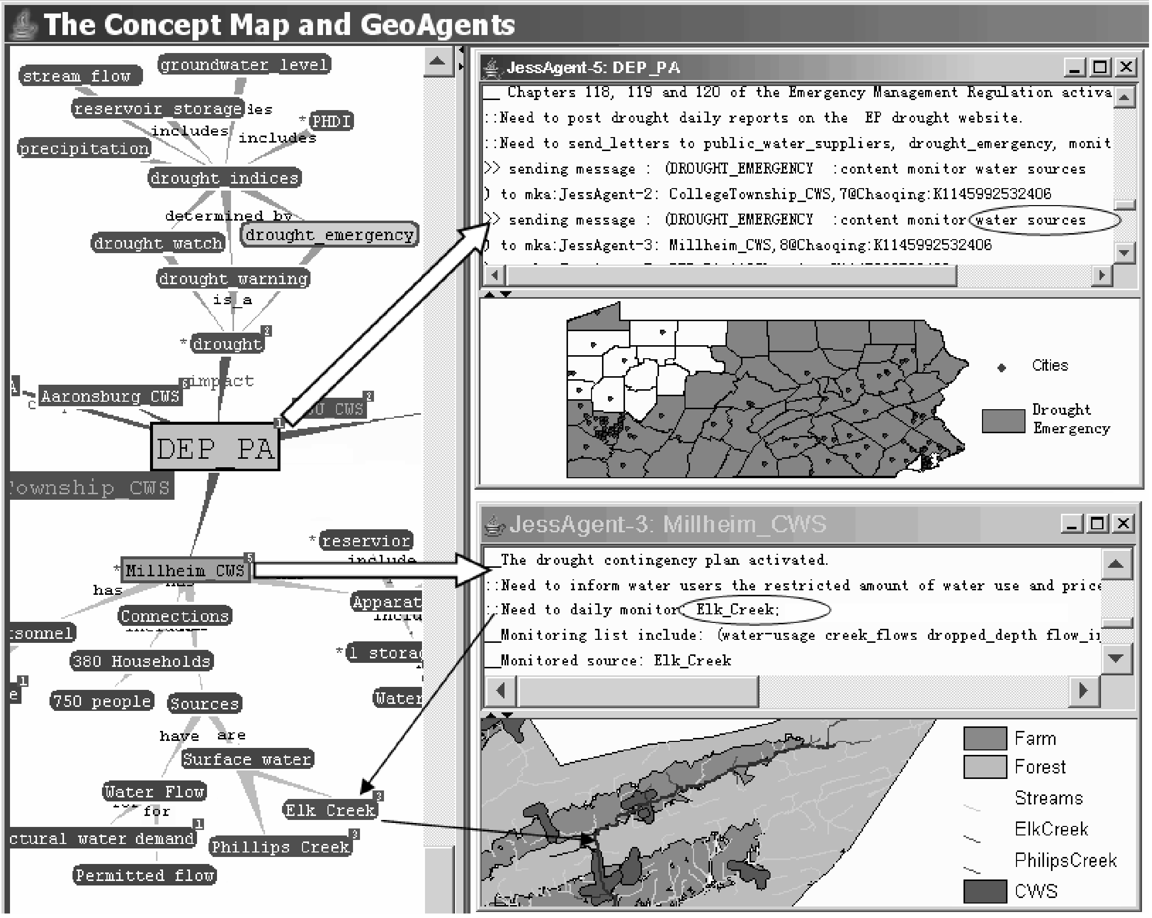


Figure 2 The software architecture of GeoAgentKS

reasoning. Each GeoAgent can have a knowledge base to store its own behavioral rules, internal states (e.g. goals and tasks), and perceived environmental states (e.g. drought status). The inter-GeoAgent communication actions are defined in the behavioral rules. When such rules are executed, the agent-kernel module can send and receive messages for GeoAgents. An "Inference engine" (Figure 2) is a program in expert systems that controls overall execution of rules and performs either inductive or deductive reasoning to derive new conclusions by using particular reasoning algorithms (which are called *forward-chaining* and *backward-chaining* algorithms, Friedman-Hill 2003). The "Concept map" module includes a concept map that consists of a network of labeled nodes (i.e. concept nodes) and edges (Novak 1991). It provides the user with a graphical interface to display the various relationships among GeoAgents and their environmental elements. The concept map also plays a pivotal role by functionally linking GeoAgents with the other modules within GeoAgentKS. For example, each concept node can have an internal attribute table. In this table, users can define a link (i.e. file path) pointing to the relevant GIS database files, a link pointing to a scientific model (e.g. a drought model), and another link pointing to a particular GeoAgent. When the concept map is launched, the related GeoAgents, models, and data are loaded into GeoAgentKS. The “Models” module contains sets of algorithms for scientific models. For example, PHDI (Palmer Hydrologic Drought Index) is a scientific model for assessing drought severity. The “Models” module includes the PHDI calculator that is executable with the required input data. The “Geospatial database engine” module retrieves data and information from the databases for GeoAgents, concept maps and scientific models, performs spatial analysis, and displays maps and spatial relationships. The “Geospatial database” module saves geographic data in standard GIS databases (e.g. in shapefile and grid formats).

As seen in the screen image of the user interface of GeoAgentKS (i.e. GUI module in Figure 2), the concept map (see the left panel of Figure 3) represents the relationships among the social and environmental elements as links and labeled concept nodes. A concept node can designate a social component (e.g. the DEP or a CWS), a model (e.g. a drought model), or a feature (e.g. a well or river). For example, the ‘DEP_PA’ node designates the Pennsylvania DEP, and the ‘Millheim_CWS’ node represents a local CWS, the Millheim Water System. The window of ‘JessAgent-5: DEP_PA’ in Figure 3 (right) is a GeoAgent-based representation of the Pennsylvania DEP, which has a knowledge base to store the state-level drought-management rules and a database to store the statewide geospatial data. Once this GeoAgent is initialized, its behavioral rules and data environment are loaded. If a set of time series data for the model variables is stored in the database, the database engine can retrieve these data for the models to simulate the dynamic environmental changes (e.g. the drought development from start to end). The GeoAgents stay ‘aware’ of their environmental conditions by interpreting the modeling outputs.



```
__ Chapters 118, 119 and 120 of the Emergency Management Regulation activa
::Need to post drought daily reports on the  EP drought website.
::Need to send_letters to public_water_suppliers, drought_emergency, monit
>> sending message :  (DROUGHT_EMERGENCY  :content monitor water sources
) to mka:JessAgent-2: CollegeTownship_CWS,7@Chaoqing:K1145992532406
>> sending message :  (DROUGHT_EMERGENCY  :content monitor water sources
) to mka:JessAgent-3: Millheim_CWS,8@Chaoqing:K1145992532406
```

```
__The drought contingency plan activated.
::Need to inform water users the restricted amount of water use and price
::Need to daily monitor Elk_Creek;
__Monitoring list include: (water-usage creek_flows dropped_depth flow_i
__Monitored source: Elk_Creek
```

Figure 3 A part of the GeoAgentKS GUI

In the drought example, the GeoAgents may interpret the modeling results as a particular drought stage (e.g. drought warning or drought emergency). In addition to such a general drought signal, many users will need to know how to respond in their specific locations. Different GeoAgents can analyze their local environmental data, communicate with each other, and use their stored knowledge and reasoning capabilities to provide suggestions to users. In Figure 3, for example, the executing results displayed in the text windows are the appropriate steps suggested by the DEP_PA GeoAgent and the

Millheim_CWS GeoAgent to the users about how to cope with a drought emergency. Using GeoAgentKS, therefore, diverse patterns of human-environment interactions can be represented to support cooperative decision-making in hazard management.

3.2 Implementation

GeoAgentKS has been implemented with Java. To facilitate implementation, multiple pre-existing open-source software packages were adopted. The agent kernel in Figure 2 was derived from MadKit (a Multi-agent Development Kit, www.MadKit.org), which managed the life cycles, roles, organization, and communications of the GeoAgents. FIPA ACL (Foundation for Intelligent Physical Agents, Agent Communication Language, http://www.fipa.org) was encoded in MadKit for inter-agent communication. The expert system used in GeoAgentKS was JESS (Java-based Expert System Shell, http://herzberg.ca.sandia.gov/jess/). The concept-map function was derived from Touchgraph (www.touchgraph.com/), in which concept nodes and relations are saved in XML (Extensible Markup Language) format. Finally, GeoTools (www.geotools.org) was used as a geospatial database engine to handle the GeoAgents' spatial databases. These open-source components were integrated within GeoAgentKS to support functions needed in modeling social and natural interaction processes. In the current version, GeoAgentKS can run on a single computer or across multiple computers over TCP/IP networks.

4 Knowledge engineering and drought modeling

As noted, the documented laws, regulations, rules, and preparedness plans in Pennsylvania regulate many drought-related social responses. These official documents provide an excellent knowledge source for formalizing the behavioral rules in GeoAgents' knowledge bases. This section introduces the knowledge-engineering process for formalizing GeoAgents' behavioral rules and building sharable knowledge bases to facilitate inter-GeoAgent communications, and then discusses the drought modeling approaches used.

4.1 Formalization of GeoAgents' behavioral rules

The primary drought-related regulations and plans used in the Pennsylvania drought management system include the state-level drought management plan (i.e. *Drought Management In Pennsylvania*, www.dep.state.pa.us/dep/subject/hotopics/drought) and the laws of PA Code 35: Chapter 118 (i.e. "*Reductions of Major Water Use in a Commonwealth Basin Drought Emergency Area*"), Chapter 119 (i.e. "*Prohibition of Nonessential Water Uses in a Commonwealth Drought Emergency Area*"), and Chapter 120 (i.e. "*Local Water Rationing Plans*"; see www.pacode.com/index.html). At the local level, the knowledge sources used include the CWSs' emergency preparedness plans and drought contingency plans. Through text analysis, the key concepts, events, and geographic features, as well as their relationships are represented in the concept map. More detailed concept-mapping methods can be seen in Novak (1991), Bruillard and Baron (2000), Brewer (2005), and Yu (2005). This section concentrates on introducing the methods used to formalize the goals, tasks, and actions (Ferber 1999) for GeoAgents' behavioral rules by using the DEP GeoAgent as an example.

As shown in Figure 4, in the state-level drought management plan (www.dep.state.pa.us/dep/subject/hotopics/drought/facts/FS2472DroughtMgmtInPA.htm), the DEP monitors the statewide drought development by modeling and interpreting drought data. The indices for determining drought severity include precipitation, stream flow, groundwater levels, reservoir storage levels, and the PHDI (Palmer Hydrologic Drought Index). These indices are calculated independently from different data and mathematical models. Based on a combination of these indices, drought is classified into three stages: drought watch, drought warning, and drought emergency. For instance, the DEP identifies a drought emergency condition when three or more of the five indices indicate a drought emergency in a given county.

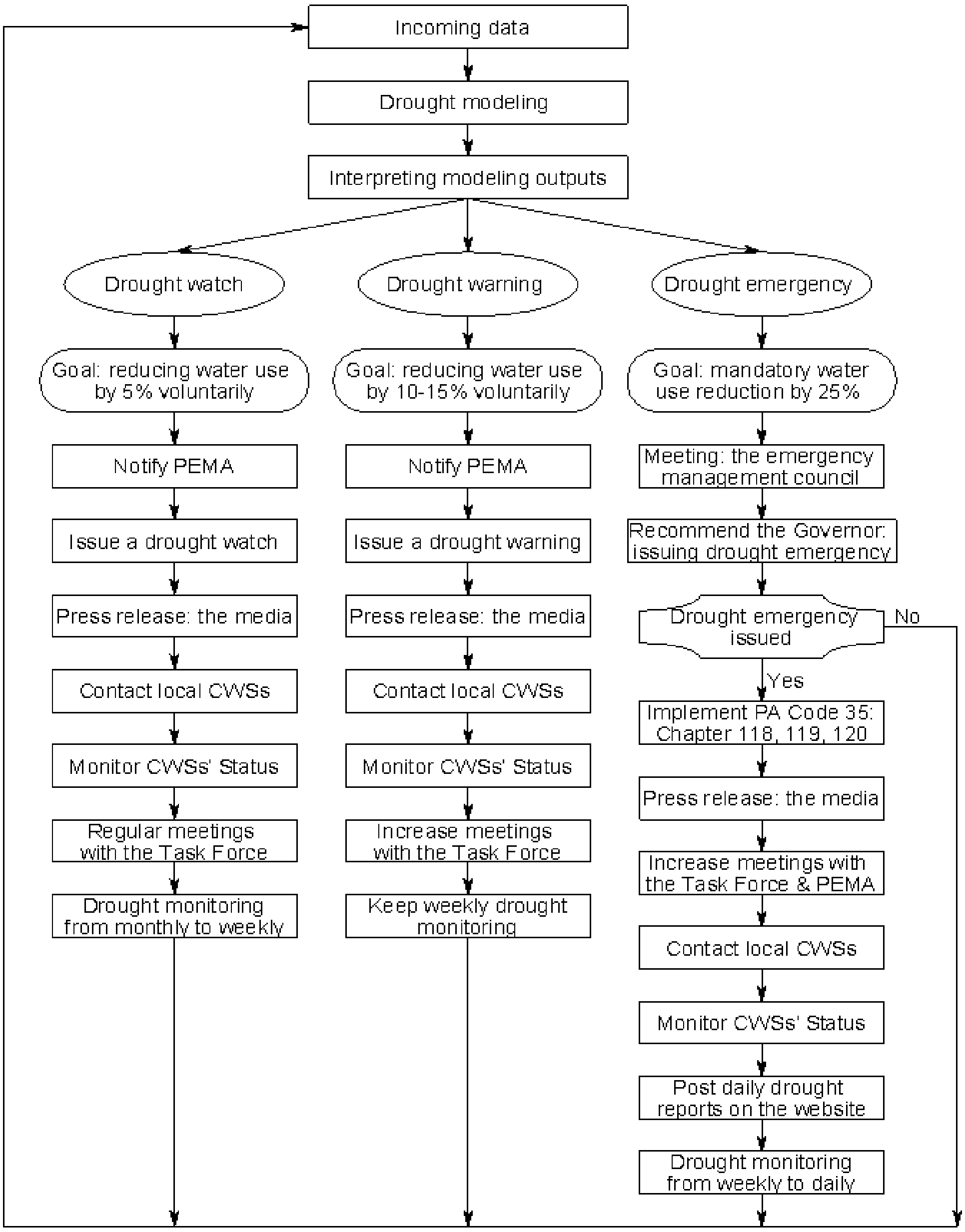


Figure 4 Planning the goals and tasks for the DEP GeoAgent's behavioral rules

Drought management goals and tasks taken to meet them differ in different drought stages. In a drought watch or warning, the goal is to reduce water use by 5% or 10-15%, respectively, in the affected area. Citizens are asked to voluntarily do so without enforcement measures. Once the governor issues a proclamation of a drought emergency, however, relevant laws become effective to enforce special drought-management measures to meet the goal of reducing water use by 25%.

In each of these drought stages, the DEP needs to accomplish multiple tasks (Figure 4) to coordinate with other agencies to reach the goals. Each task may consist of several actions. For example, to accomplish the task of “Contact local CWSs”, it is necessary to identify which CWSs are in the drought watch, warning, or emergency areas, and send messages to them about the current drought status. Using a similar knowledge-engineering approach, the behavioral rules (including tasks and actions) for the CWS GeoAgents and others are formalized and stored in their knowledge bases.

The DEP cannot achieve the overall goals by itself. Instead, the state-level goals are transferred to local CWSs and adopted as their goals in the local drought contingency plans. For example, when a drought emergency is identified, the goal of the DEP is to reduce water use by 25% in the entire emergency region. Once a CWS receives a message from the DEP that a drought emergency is in effect, the CWS automatically sets its own goal to reduce water use by 25%. This CWS then follows its own drought contingency plan and undertakes the planned tasks to meet the goal, such as adopting different water prices and restricting non-essential water supplies.

4.2 Sharing knowledge among GeoAgents

Complementary to DEP GeoAgent’s behavioral rules, each local CWS GeoAgent has its own knowledge base to store its unique drought-management rules for coping with the local environmental changes. In addition to such unique rules, all local CWSs need to follow the state-level regulations and laws. In the knowledge-engineering process, therefore, we also attempted to make some of the rules sharable in order to increase reusability of the rules and reduce redundancy. To enhance communication, it is necessary to define an ontology that is sharable among the GeoAgents to deal with semantic differences in their communication language.

4.2.1 Sharable rule bases

In a shared rule base, the stored knowledge can be accessed and used by multiple individual GeoAgents. For example, the Chapter 119 of PA Code 35 (“*Prohibition of Nonessential Water Uses in a Commonwealth Drought Emergency Area*”) regulates that, in all drought-emergency areas, water is not allowed to be used for filling swimming pools, washing streets, watering lawns, and so on. All certified water operators in local CWSs should know these regulations through the training provided by the DEP. In GeoAgentKS, this regulation therefore can be represented in a sharable rule base. All CWS GeoAgents can access this rule base and use it for their own automated reasoning. Some other GeoAgents (e.g., individual water users) may not know these regulations and thus do not access this rule base, but they can query CWS GeoAgents to learn the regulations.

4.2.2 Sharable ontology for communications

In computer-related research and applications, the term ‘ontology’ has multiple notions, such as explicit specification of a conceptualization (Gruber 1993) and theories about the sorts, properties and relations of objects (Chandrasekaran et al. 1999). Agarwal (2005) asserts that an ontology is generally considered a shared understanding of a domain for accurate and effective communications of meaning. Swartout et al. (1996) state that an ontology is a hierarchically structured set of terms for describing a domain that can be used for a knowledge base. Ontologies can be used for knowledge sharing, knowledge reuse, and system interoperability (Agarwal 2005).

In drought management, the DEP GeoAgent often uses more general concepts or terminologies than what local CWS GeoAgents use. For example, when a drought emergency is identified, the DEP usually sends letters to CWSs and requests them to monitor their "*water sources*". But for a particular CWS, the general concept "*water sources*" needs to be specified as concrete instances in their actions, such as a well, a river, or a spring. To overcome the semantic barriers in communications among the GeoAgents, an ontology (Figure 5) that consists of the taxonomic category of water sources is encoded in GeoAgentKS as a set of hierarchical templates (i.e. similar to a class or a structure in any programming language that consists of multiple elements and attribute values (or facts), Friedman-Hill 2003) in a shared knowledge base. As shown in the example in Figure 3, the Millheim_CWS GeoAgent has *Elk Creek* and *Phillips Creek* as defined instances of "Creek" in its knowledge base. In communications, the Millheim_CWS GeoAgent can interpret the term "water sources" in the DEP GeoAgent's messages as Elk Creek and Philips Creek by using the ontology (Figure 5).

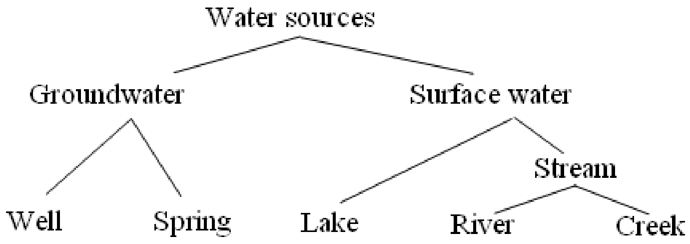


Figure 5 An ontology for water sources shared by multiple GeoAgents

4.3 Drought modeling in Central Pennsylvania

As noted above, there are five major indices to determine drought severity (drought watch, drought warning, or drought emergency) in Pennsylvania. These indices include precipitation deficits, stream flows, groundwater levels, reservoir storage, and PHDI. For drought analysis, the state calculates the values of these indices independently from different sources of monitoring data.

To measure drought severity, data for precipitation deficits, stream flows, and groundwater levels are compared against the corresponding ‘normal’ values. The National Weather Service, for example, defines the ‘normal’ precipitation of a place in a given period (e.g. a day or a month) as the past 30-year average value in the same period. The ‘normal’ stream flow is the average value of historical records at each monitoring station. The ‘normal’ value of groundwater levels comes from the USGS (United States Geological Survey) groundwater monitoring network. For the index of reservoir storage, the percentage of the current usable storage in the reservoir is used to determine drought severity. Using the above four indices, drought-severity evaluation can be calculated relatively easily using the monitoring data, and the results compared with the predefined range of the drought triggering criteria. Such criteria are defined in the publication *Drought Management in Pennsylvania* (www.dep.state.pa.us/dep/subject/hotopics/drought/facts/FS2472DroughtMgmtInPA.htm; also see Smith 1998).

PHDI is a sophisticated mathematical model, which includes multiple parameters such as precipitation, evapotranspiration, recharge, runoff, and soil moisture. We used the PHDI calculator developed by NADSS (National Agricultural Decision Support System, http://nadss.unl.edu/PDSIReport/pdsi/calculation.html) to compute PHDI values. For evaluating drought severity, PHDI values of –2.00 to –2.99 indicate a drought watch, values of –3.00 to –3.99 indicate drought warning, and values of –4.00 and less indicate a drought emergency.

We used drought data from 1999 to demonstrate the simulation of dynamic drought development using the above indices. According to the Pennsylvania DEP, the complete sets of the original data used for the drought are no longer available because these data are not well archived. Therefore, we downloaded, for demonstration only, the weekly drought data in the study area from multiple Websites, including the USGS (e.g. at http://pa.water.usgs.gov/gw_report/index.html, http://pa.water.usgs.gov/ar/wy99/susq_intro.html, and http://pa.water.usgs.gov/monitor), and the drought information center of the DEP (http://www.dep.state.pa.us/dep/subject/hotopics/drought/DroughtTech.htm). The weekly Palmer Drought Severity Index (PDSI) from the Climate Prediction Center in NOAA (see http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/palmer/1999/weekly_PALMER_1999.shtml) was also utilized as a reference. For displaying the background information on the maps, we collected the relevant geospatial data and saved them into each relevant GeoAgents' GIS database (Figure 3). Most of these digital maps, such as land use and land cover, geology, surface water, cities, and roads, were collected from PASDA (Pennsylvania Spatial Data Access, http://www.pasda.psu.edu/) and the USGS (http://www.usgs.gov).

4.4 Integrating GeoAgents' behavioral rules with drought modeling

As discussed earlier, GeoAgents can monitor and respond to their environmental changes by interpreting the model outputs. The Pennsylvania drought management rules specify drought severity based upon three or more of the five indices indicating the same drought stage. In GeoAgentKS, a rule is encoded to compare the model results of each index with the predefined drought criteria, count how many indices are in the same stage, and then evaluate the current drought status. Once the drought data time series are input into the calculation models of the five indices, GeoAgentKS can simulate dynamic drought development. The GeoAgents can dynamically interpret the model outputs as normal, drought watch, drought warning, or drought emergency.

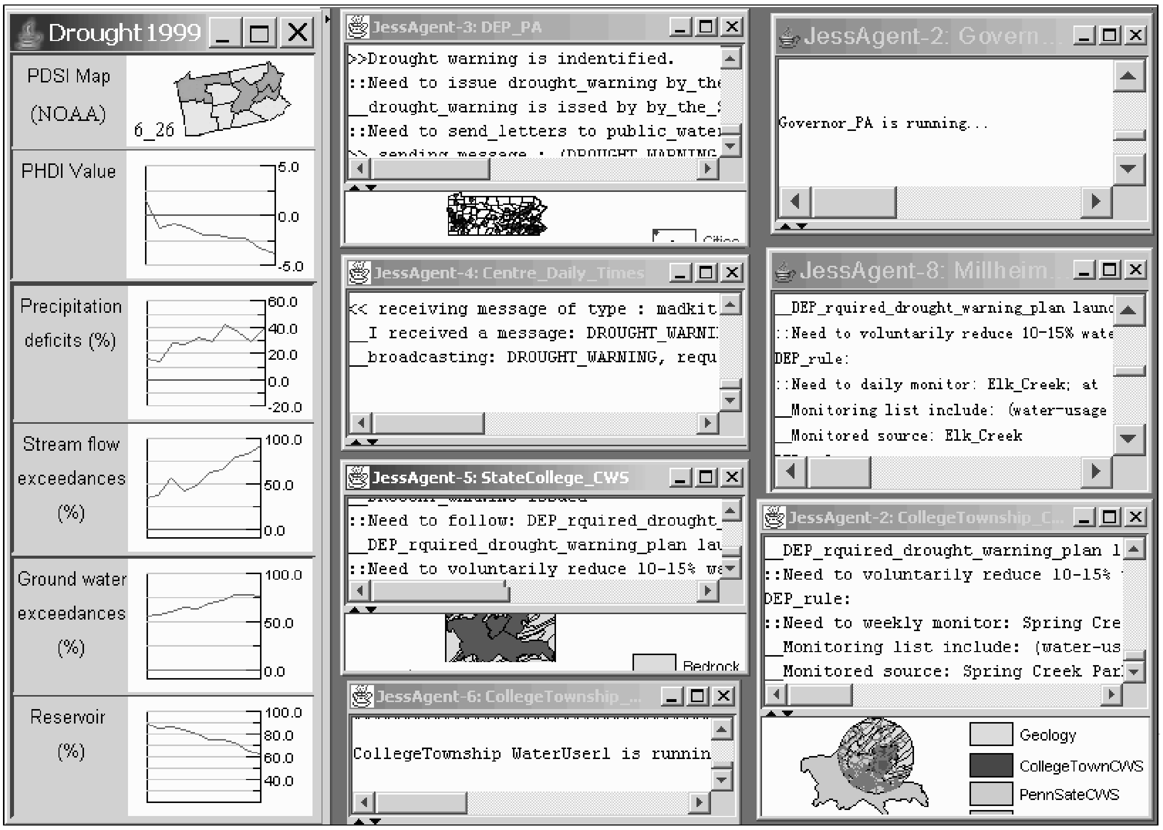
Figure 4 shows the integration of drought modeling with GeoAgents' behavioral rules. Once the DEP GeoAgent identifies a given drought stage, it will take a set of tasks and actions to coordinate with other GeoAgents to achieve cooperative responses. As such, GeoAgentKS can both model natural hazard development and represent cross-level social responses.

5 Results and evaluation

In droughts, as well as many other types of hazards, interactions among numerous social and natural elements are often extremely complex. To demonstrate how GeoAgentKS works, here we use several GeoAgents to illustrate the simulation of the drought management process in the Pennsylvania study area, including inputs from the DEP, the state Governor (*Governor_PA*), PEMA, three local CWSs (*College Township CWS, Millheim CWS,* and *State College CWS*), a local newspaper (*Centre Daily Times*), and two individual water users (*Millheim_WaterUser1* and *CollegeTownship_WaterUser1*).

5.1 Simulation results

Figure 6 shows screen images of how some of these GeoAgents respond to the drought modeling outputs using the weekly drought data for the study area in summer 1999. The dynamic drought development (left) is simulated via modeling the observed weekly data based on the five drought indices; the GeoAgents' responses (i.e. the results of rule firing) are displayed in the text windows. In the Central Pennsylvania study area (see Figure 1 and the small maps in Figure 6 (upper left)), no drought is identified before May 1999 so the GeoAgents do not need to respond at that point.



```
>>Drought warning is indentified.
::Need to issue drought_warning by_the
__drought_warning is issed by by_the_
::Need to send_letters to public_wate
>> sending message : (DROUGHT_WARNING
```

```
<< receiving message of type : madkit
__I received a message: DROUGHT_WARNI
__broadcasting: DROUGHT_WARNING, requ
```

```
::Need to follow: DEP_rquired_drought_
__DEP_rquired_drought_warning_plan lau
::Need to voluntarily reduce 10-15% wa
```

```
CollegeTownship WaterUserl is runnin
```

```
Governor_PA is running...
```

```
__DEP_rquired_drought_warning_plan launc
::Need to voluntarily reduce 10-15% wate
DEP_rule:
::Need to daily monitor: Elk_Creek; at
__Monitoring list include: (water-usage
__Monitored source: Elk_Creek
```

```
__DEP_rquired_drought_warning_plan l
::Need to voluntarily reduce 10-15%
DEP_rule:
::Need to weekly monitor: Spring Cre
__Monitoring list include: (water-us
__Monitored source: Spring Creek Par
```

Figure 6 The GeoAgents automatically identify drought severity by interpreting the modeling outputs and provide suggestions to different users. The screen image shows GeoAgents' responses in a drought warning

On June 26th, 1999, a "drought warning" is identified from the outputs of the drought models (Figure 6). The DEP_PA GeoAgent announces a "drought warning" and sends messages to local CWSs requiring them to follow the drought-warning operations, and to the news media for broadcasting the drought warning. On the local level, according to the request from DEP_PA, the CollegeTownship_CWS monitors its groundwater source the *Spring Creek Park Well*, and the Millheim_CWS monitors its surface water sources *Elk Creek* and *Phillips Creek*. The Centre_Daily_Times GeoAgent broadcasts the drought warning to the public, including the request for a voluntary reduction of water use by 10-15%. Note that the GeoAgent of Governor_PA does not have to respond to this drought warning because only voluntary water-use reduction is required, and no endorsement is needed from the Governor_PA to activate the drought-related laws.

Continuing the simulation, on July 17, 1999, a “drought emergency” is identified in Centre County and other areas from the drought indices. The DEP_PA GeoAgent recommends that the Governor_PA proclaim a drought emergency. Once the Governor does so, the related laws and drought-management regulations are activated in the declared regions. DEP_PA then schedules a weekly meeting with the Commonwealth Drought Task Force, starts daily updates to the drought report on its website, and increases the drought monitoring frequency from weekly to daily (also see Figure 3 for similar results).

Mandatory water conservation measures are activated at this point. The state-level goal of an immediate reduction of water use by 25% is transferred to individual-level water users via local GeoAgents. For instance, DEP_PA informs the news media to broadcast to the public enactment of the law prohibiting non-essential water use. After receiving the message from DEP_PA and by accessing the shared rule base, which contains the rules of the PA Code 35, Chapter 119 (as discussed in Section 4.2), the GeoAgent of Centre_Daily_Times begins to broadcast the water-use restriction policies, e.g. prohibition of watering grass, watering golf courses, and filling swimming pools.

The DEP_PA GeoAgent also sends messages to local CWS GeoAgents requesting them to monitor their water sources daily and implement their own drought contingency plans. After receiving the messages from DEP_PA, the CWS GeoAgents follow their own plans. For example, the CWSs’ emergency backup plans for secondary water sources are triggered during the simulated drought emergency condition, and different CWSs adopt different solutions appropriate for their varying situations. The CollegeTownship_CWS GeoAgent sends a message to its neighboring CWS, the

StateCollege_CWS GeoAgent, to use an existing interconnection for sharing water. Millheim_CWS monitors the water source, detects that the flume flow in the primary source Philips Creek was less than 0.037 cubic feet per second, and switches the water source to Elk Creek.

The CWS GeoAgents also inform their water customers of the special water conservation measures during the emergency condition. For instance, the CollegeTownship_CWS sends messages to its water users that the allotted daily water use is 40 gallons per person per day, with notes about monthly charges for excess use. The Millheim_CWS sends similar messages to its water customers but with different prices. The GeoAgents of the individual water users, such as CollegeTownship_WaterUser1 and Millheim_WaterUser1, correctly receive the messages from their corresponding water suppliers. We used these two individual-level GeoAgents for the purpose of examining and demonstrating the communication mechanisms between institutions and individuals in GeoAgentKS.

In addition to the top-down interactions described above, bottom-up communications are also tested in two CWSs. In the first case, assuming the CollegeTownship_WaterUser1 GeoAgent intends to use water for filling a swimming pool during this drought emergency condition, it sends a message to the CollegeTownship_CWS GeoAgent to apply for this water use. After automated reasoning by accessing the shared rule base, the CollegeTownship_CWS answers that this application is not approved, and explains to this applicant that "*the use of any water to fill and top off swimming pools*" is prohibited in a drought emergency (i.e. the law of PA Code 35 Chapter 119). In the second case, the GeoAgent of Millheim_WaterUser1 sends a message to Millheim_CWS GeoAgent to apply for water use to water new grass during non-working hours. According to the encoded water use laws, the Millheim_CWS approves this application, but the applicant has to use water only from 5:00 pm to 9:00am using restrictive means such as a bucket, a can, or a hand-held hose with an automatic shut-off nozzle.

5.2 Evaluation

In the evaluation stage, we interviewed local experts to examine the performance of the above GeoAgents' behaviors and the potential use of GeoAgentKS in hazard management. Three independent interviews were conducted with four experts, including two water managers and two local planners. The water managers were from the College Township CWS and the Millheim CWS, and they were interviewed in separate locations. The two local planners who had expertise in all CWSs in Centre County were interviewed together. During the interviews, the interviewees were requested to check the GeoAgents' outputs under different environmental conditions, and then count how many errors occurred during the simulations. Together with the representation of other types of emergency responses (such as in water-contamination and power-outage conditions (Yu and Peuquet in press)), the experts evaluated about 70 suggestions (or actions) provided by the GeoAgents. None of the experts identified inappropriate actions from the outputs of rule firing. One of the water managers explained that the GeoAgents could indeed accurately follow what was defined in the documented regulations and plans. Thus no obvious errors were identified. In reality, however, water operators' actual actions could be much more flexible than the ways the GeoAgents performed in the experiments.

One of the water managers said that GeoAgentKS was "*a very useful tool for small municipalities or county level offices* [with limited professional staff]." The local planners said that they face many laws and regulations everyday, which change frequently and are difficult to memorize, and GeoAgentKS could be useful in that regard. The Millheim manager noted that the automated-reasoning results about the bottom-up water use application were reasonable, and it was "*for sure*" that this drought example was able to represent the complex process of human-environment interactions in hazard management. Another water manager said this system could be useful for larger agencies or policy makers, such as the DEP, to test their operational rules and to verify how their (current or proposed) policies would work in response to particular events, with the possibility of modifying their rules and policies, if needed; but he did not further explain how to use this system for such a verification.

6 Discussion

6.1 Summary

From the simulation results presented in this paper, the GeoAgents can successfully use their stored knowledge (from the real-world regulations and rules) to interpret quantitative modeling outputs as meaningful drought signals. They can communicate with each other to respond cooperatively to the dynamic drought development according to their own internal behavioral rules and environmental states, and then provide suggestions to different users about the appropriate response steps. The experts' evaluation results showed that using GeoAgentKS could accurately simulate the human-environment interactions required by the documented preparedness plans and regulations. We therefore believe that it is feasible to use the multi-agent approach in GeoAgentKS to integrate a variety of techniques for modeling the complex social cooperation and human-environment interactions involved in hazard management.

Agents in the drought example are considered "GeoAgents" for the following three reasons. First, the GeoAgents are applied to represent social rules and goal-driven behaviors that are beyond the conventional GIS representation of discrete and continuous phenomena. Each GeoAgent represents or designates a particular social element (e.g. the

DEP or a CWS) operating in the real world. Second, each GeoAgent interacts with a scale-dependent data environment in Pennsylvania. Third, the integration of GeoAgents with scientific models and geospatial databases are utilized to represent human-environment interaction processes, and can be used to support real-world hazard management decision-making. In contrast to the GeoAgents developed here, agents in other types of applications (such as in internet search engines and email systems) do not interact in such “geo” environments.

GeoAgents in this research also have several characteristics different from most individual-oriented agent-based modeling (ABM). A number of AI (artificial intelligence) approaches have been applied in GeoAgentKS. For example, GeoAgents’ knowledge or behavioral rules are derived from multiple sets of regulations and laws via knowledge engineering. They have memories, and can perform automated reasoning to choose appropriate actions to achieve their goals. They can use an explicit agent-communication protocol (e.g. FIPA ACL) to perform ontology-driven communications for representing hierarchical institutional interactions. Most of the current ABM applications, as mentioned by Parker (2003, see section 2.1), have limited capabilities in modeling such complex institutional behaviors.

6.2 Usefulness of GeoAgentKS

GeoAgentKS could be useful for (1) supporting decision making in hazard management and (2) facilitating knowledge sharing. For decision support, this system could be used as a daily tool to provide users with hazard development information and response guidelines. Hazard or crisis management is challenging because it is usually complex and time-critical. Under emergency situations, people can easily forget important information or tasks, and usually do not have enough time to perform complicated data analysis or search complex laws, regulations, or plans to figure out what to do. The GeoAgent-based representation of the multilevel human-environment interactions could be used to help decision makers or technicians interpret the relevant data, recall the basic required responses or tasks, and facilitate communication and cooperation among institutions. The system therefore could be particularly valuable for hazard management non-experts who work in regions with limited professionals.

GeoAgentKS could also be valuable in knowledge sharing. Hazard management often requires decision makers and their supporting experts to be highly familiar with policies and their multi-scale environments. GeoAgentKS could be used to store various human expertise and social rules so that human knowledge and experiences could be accumulated through the knowledge bases. When experienced individuals leave their positions, their knowledge could be maintained in the hazard-management systems and shared by their successors. Novices could use this system for training purposes through visualizing the stored knowledge and data and by testing GeoAgents' responses in different hypothetical hazard situations. Although an expert in the interview mentioned that this system could be potentially used to assess the existing regulations and policies, the current research has not addressed such examination, and we believe that this requires further research.

It is important to note that the capabilities of such a computer system are not unlimited. As pointed out by Dennett (1990), users are likely to put too much faith in computer systems and therefore might use less judgment in their decision making. We believe that judgments of experienced experts in dynamic hazard situations are an indispensable component of hazard management. Therefore, it is important that users fully understand the system capabilities, limitations, and shortcomings, and use the system wisely.

6.3 Limitations and future study

GeoAgentKS is still far from a mature decision-support tool that could be used daily on decision makers' desktops. It has limitations in both capabilities and usability. We outline these limitations and future research directions for improvement as follows.

Conflicting goals: The present work only focused on representing how agencies cooperate with each other to achieve shared goals. In reality, however, different organizations may have different or conflicting goals, and they may not cooperate with each other. For example, water becomes a very limited resource in drought conditions; if multiple communities share the same water source during droughts, it is often difficult to reach an agreement on balanced water use among these communities. A possible approach to studying conflicting goals among GeoAgents would be first to use traditional knowledge-acquisition approaches (e.g. interviews) to capture conflicting goals and corresponding behavioral options, then to use knowledge-engineering approaches to encode the behavioral rules into knowledge bases, and finally to evaluate how conflicting goals affect the pattern of human-environment interactions.

Learning capabilities: In the current version of GeoAgentKS, what the GeoAgents can do is dependent upon what knowledge is encoded in their knowledge bases. They have limited learning capabilities and have no historical hazard cases to learn. Future studies should pay attention to encoding learning algorithms and reconstructing the hazard-management processes in historical events (e.g. Hurricane Katrina) so that GeoAgents can learn lessons from the past experience to avoid repeating the same mistakes. Although there are many machine learning algorithms available, such as decision tree learning, artificial neural networks, Bayesian learning, genetic algorithms, and reinforcement learning (Mitchell 1997), further research on practical applications of these algorithms in GeoAgentKS for real-world hazard management is required. In addition to learning, research should also place emphasis on improving automated planning, task allocation, and optimal decision-making for GeoAgents.

Modeling human impacts on environment: In the case study, we only use the GeoAgent-based approaches to model how humans should react to environmental changes, without considering human impacts on environment changes. For example, in a drought emergency, water users are required to reduce water use by 25%. In GeoAgentKS, it is practical to allow GeoAgents to interpret the actual water use in different places and dynamically input the amounts of water use as independent variables into the next round of surface-water or groundwater modeling to obtain more accurate information of the environmental changes.

Integrating institutional and individual behaviors: The current research focused on modeling institutional behaviors. Although we represented an example of interactions between individuals and institutions, using the knowledge-engineering approach to build a complex knowledge base for each individual is not practical for a large population. The existing individual-oriented ABM approaches are feasible to simulate many individual actions by using limited numbers of rules. Building cause-and-effect mechanisms in GeoAgents' knowledge bases could enhance the integration of individual and institutional behaviors in modeling both bottom-up and top-down human-environment interactions. For example, institutional behaviors could affect individual behaviors by changing the input variables (or facts) for individual rules; and individual-induced environmental changes could result in responses of institutional GeoAgents.

Ontology: Building ontologies for a shared cultural understanding of key geographic concepts is critical for avoiding miscommunications when disasters happen. Although this research encoded an ontology for facilitating inter-GeoAgent communications, it is relatively simplistic and is far from adequate for actual hazard management. Constructing geographic ontologies is so challenging that no commonly shared ontology is yet available (Smith and Mark 2001, Agarwal 2005, Fonseca and Martin 2005). Managing large-scale natural hazard events often involves multiple decision makers in different disciplines or cultures across regions or countries; thus building a sharable ontology is crucial for sharing information and reducing misunderstanding or miscommunication. The ongoing research on geographic ontology theory (Smith *et al.* 2001, Winter 2001, Mark *et al.* 2002, Fonseca *et al.* 2003) and tools (Horrocks *et al.* 2002, Sure *et al.* 2003, Pike *et al.* 2007) could be helpful for this problem.

Usability: The current version of GeoAgentKS was mainly designed for proof-of-concept, rather than daily practical use. Its usability is poor for novice users. In addition, constructing and updating a comprehensive knowledge base is challenging even for a well-trained knowledge engineer. Overcoming this challenge requires a more user-friendly knowledge system that allows easier construction and updates of the knowledge base. Moreover, it is necessary to ensure that GeoAgentKS can run stably in different conditions and can always provide correct guidelines for users. One possibility is exhaustive testing, modifying, and retesting of the GeoAgents' rules in various natural and socioeconomic environments before disasters.

Other hazards: For different natural hazards (e.g. floods, earthquakes, wildfires, etc.), different rules and responses would have to be encoded into GeoAgentKS than those were encoded for drought in Pennsylvania. Yet, compared with other types of hazards, drought management is relatively less time-critical than other natural hazards. Thus, GeoAgentKS should also be applied and examined for more urgent hazards to test its usability and reliability. Doing so could require integrating GeoAgents with multiple

Earth-monitoring technologies, such as satellite remote sensing, weather radar networks, and GPS (Global Position System), for better support of real-time decision making.

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References

1. AGARWAL, P., 2005, Ontological considerations in GIScience. *International Journal of Geographic Information Science*, 19 (5), pp. 501–536.
2. AN, L., LINDERMAN, M., QI, J., SHORTRIDGE, A. and LIU, J., 2005, Exploring Complexity in a Human–Environment System: An Agent-Based Spatial Model for Multidisciplinary and Multiscale Integration. *Annals of the Association of American Geographers*, 95 (1), pp. 54-79.
3. AXELROD, R.M., 1997, *The Complexity of Cooperation: Agent-based Models of Competition and Collaboration*, Princeton, NJ: Princeton University Press.
4. BALMANN, A., 2000, Modeling Land Use with Multi-Agent Systems: Perspectives for the Analysis of Agricultural Policies. IIFET 2000: Microbehavior and Macroresults proceedings of the International Institute of Fisheries Economics and Trade, Oregon State University, Corvallis, OR, http://citeseer.ist.psu.edu/392946.html
5. BEER, M., D'INVERNO, M., JENNINGS, N., LUCK, M., PREIST, C. and SCHROEDER, M., 1999, Negotiation in Multi-Agent Systems. *Knowledge Engineering Review*, 14 (3), pp. 285-289.
6. BHARWANI, S., 2006, Understanding Complex Behavior and Decision Making Using Ethnographic Knowledge Elicitation Tools (KnETs). *Social Science Computer Review*, 24 (1), pp. 78-105.
7. BREWER, I., 2005, Understanding Work with Geospatial Information in Emergency Management: a Cognitive Systems Engineering Approach in GIScience. Ph.D Thesis, The Pennsylvania State University, University Park.
8. BROOKS, R.A., 1991a, Intelligence without reason, *Proceedings of IJCAI-91*: Morgan Kaufman, San Mateo, CA, pp. 569-595.
9. BROOKS, R.A., 1991b, Intelligence without representation. *Artificial Intelligence*, 44, pp. 139-159.
10. BRUILLARD, E. and BARON, G.L., 2000, Computer-based concept mapping: a review of a cognitive tool for students. In: D. Benzie and D. Passey (Editors), *Proceedings of ICEUT2000, 16th IFIF World Computer Congress*, pp. 332-338.

11. CHANDRASEKARAN, B., JOSEPHSON, J.R. and BENJAMIN, V.R. 1999, What are Ontologies, And Why Do We Need Them? Intelligent Systems And Their Applications, IEEE, 14, 20-24
12. CHONG, P., 2004, Understanding Residential Expansion Using MAS/LUCC Models. M.S. Thesis. International Institute for Geo-Information Science and Earth Observation, Netherlands.
13. COMMUNICATION, F.T., 2002, FIPA ACL Message Structure Specification (standard): http://www.fipa.org/specs/fipa00061/SC00061G.html.
14. D'INVERNO, M., LUCK, M. and WOOLDRIDGE, M., 1997, Cooperation Structures, *Fifteenth International Joint Conference on Artificial Intelligence*. Nagoya, Japan 1997. pp. 600-605.
15. DARÉ, W.S. and BARRETEAU, O., 2003, A role-playing game in irrigated system negotiation: between play and reality. *Journal of Artificial Societies and Social Simulation*, 6 (3).
16. DENNETT, D.C., 1990, Can Machines Think? In: R. Kurzweil (Editor), *The Age of Intelligent Machines*: MIT Press, pp. 48-61.
17. DORAN, J.E., FRANKLIN, S., JENNINGS, N.R. and NORMAN, T.J., 1997, On cooperation in multi-agent systems. *The Knowledge Engineering Review*, 12 (3), pp. 309-314.
18. EPSTEIN, J. and AXTELL, R., 1996, *Growing Artificial Societies: Social Science from the Bottom Up*, Washington, D.C.: Brookings Institutions Press.
19. EVANS, T.P. and KELLEY, H., 2004, Multi-scale analysis of a household level agent-based model of land-cover change. *Journal of Environmental Management*, 72, pp. 57–72.
20. EXCELENTE-TOLEDO, C.B., BOURNE, R.A. and JENNINGS, N.R., 2001, Reasoning about commitments and penalties for coordination between autonomous agents, *5th International Conference on Autonomous Agents (Agents-2001)*. Montreal, Canada.
21. FARATIN, P., JENNINGS, N.R., BUCKLE, P. and SIERRA, C., 2000, Automated negotiation for provisioning virtual private networks using FIPA-compliant agents, *5th Int. Conf. on the Practical Application of Intelligent Agents and Multi- Agent Systems (PAAM-2000)*. Manchester, UK. pp. 185-202.
22. FERBER, J., 1999, *Multi-Agent Systems: An Introduction To Distributed Artificial Intelligence*, New York, NY: Addison-Wesley.
23. FERGUSON, N.M., CUMMINGS, D.A., CAUCHEMEZ, S., FRASER, C., RILEY, S., MEEYAI, A., IAMSIRITHAWORN, S. and BURKE, D.S., 2005, Strategies for containing an emerging influenza pandemic in Southeast Asia. *Nature* (437), pp. 209-214.
24. FERGUSON, N.M., CUMMINGS, D.A., FRASER, C., CAJKA, J.C., COOLEY, P.C. and BURKE, D.S., 2006, Strategies for mitigating an influenza pandemic. *Nature* (442), pp. 448-452.
25. FININ, T.W., FRITZSON, R., MCKAY, D. and MCENTIRE., R., 1994, KQML as an agent communication language, *Proceedings of the 3rd International Conference on Information and Knowledge Management (CIKM'94)*. Gaithersburg (Maryland): ACM Press, pp. 456–463.
26. FONSECA, F., DAVIS, C. and CAMARA, G., 2003, Bridging Ontologies and Conceptual Schemas in Geographic Information Integration. *GeoInformatica*, 7, pp. 355-378.
27. FONSECA, F. and MARTIN, J., 2005, Toward an Alternative Notion of Information Systems Ontologies: Information Engineering as a Hermeneutic Enterprise. *Journal of the American Society for Information Science and Technology*, 56 (1), pp. 46-57.
28. FORNARA, N., VIGANÒ, F. and COLOMBETTI, M., 2007, Agent communication and artificial institutions. *International Journal of Autonomous Agents and Multi-Agent Systems* (14), pp. 121-142.
29. FRIEDMAN-HILL, E., 2003, *Jess in Action: Java Rule-Based Systems*, Greenwich, CT: Manning Publications.

30. GOODCHILD, M.F., 2004, The Validity and Usefulness of Laws in Geographic Information Science and Geography. *Annals of the Association of American Geographers*, 94 (2), pp. 300-303.
31. Gruber, T.R. 1993, A Translation Approach To Portable Ontology Specifications. Knowledge Acquisition, 5, 199-220
32. HORROCKS, I., PATEL-SCHNEIDER, P.F. and HARMELEN, F.V., 2002, Reviewing the Design of DAML+OIL: An Ontology Language for the Semantic Web. http://www.cs.vu.nl/~frankh/postscript/AAAI-BNAIC02.pdf
33. JENNINGS, N.R., FARATIN, P., LOMUSCIO, A.R., PARSONS, S., SIERRA, C. and WOOLDRIDGE, M., 2001, Automated negotiation: prospects, methods and challenges. *International Journal of Group Decision and Negotiation*, 10 (2), pp. 199-215.
34. JENNINGS, N.R., SYCARA, K. and WOOLDRIDGE, M., 1998, A Roadmap of Agent Research and Development. *International Journal of Autonomous Agents and Multi-Agent Systems*, 1 (1), pp. 7-38.
35. JENNINGS, N.R. and WOOLDRIDGE, M., 1998, Applications of Intelligent Agents. In: N.R. Jennings and M. Wooldridge (Editors), *Agent Technology: Foundations, Applications, and Markets*, pp. 3-28.
36. KINNY, D., GEORGEFF, M. and RAO, A., 1996, A methodology and modeling technique for systems of BDI agents. In: W. Van de Velde and J.W. Perram (Editors), *Agents Breaking Away: Proceedings of the Seventh European Workshop on Modeling Autonomous Agents in a Multi-Agent World*. Springer-Verlag: Berlin, Germany, pp. 56-71.
37. Ligtenberg, A., Wachowicz, M., Bregt, A.K., Beulens, A. and Kettenis, D.L., 2004, A design and application of a multi-agent system for simulation of multi-actor spatial planning. *Journal of Environmental Management*, 72, pp. 43-55.
38. LUCK, M. and D'INVERNO, M., 1996, Engagement and Cooperation in Motivated Agent Modelling. In: Zhang and Lukose (Editors), *Distributed Artificial Intelligence Architecture and Modelling: Proceedings of the First Australian Workshop on Distributed Artificial Intelligence*. *Lecture Notes in Artificial Intelligence, 1087*: Springer-Verlag, pp. 70-84.
39. LUCK, M. and D'INVERNO, M., 2001, A Conceptual Framework for Agent Definition and Development. *The Computer Journal*, 44 (1), pp. 1-20.
40. LUCK, M., MCBURNEY, P. and PREIST, C., 2003, *Agent Technology: Enabling Next Generation Computing (A Roadmap for Agent Based Computing)*. http://eprints.ecs.soton.ac.uk/7309/1/al2roadmap.pdf.
41. LUGER, G.F., 2002, *Artificial Intelligence, Structures And Strategies For Complex Problem Solving*, Harlow, England: Pearson Education.
42. MARK, D., EGENHOFER, M., HIRTLE, S. and SMITH, B., 2002, Ontological Foundations for Geographic Information Science. *UCGIS White Paper 2002, www.ucgis.org*.
43. MANSON, S.M., 2000, Agent-based dynamic spatial simulation of land-use/cover change in the Yucatan peninsula, Mexico. *Fourth International Conference on Integrating GIS and Environmental Modeling (GIS/EM4)*. Banff, Canada.
44. MANSON, S.M., 2006, Land use in the Southern Yucatan Peninsular Region of Mexico: scenarios of population and institutional change. *Computers, Environment, and Urban Systems*, 30 (3), pp. 230-253.
45. MATTHEWS, R.B., 2006, The People and Landscape Model (PALM): An agent-based spatial model of livelihood generation and resource flows in rural households and their environment. *Ecological Modelling*, 194, pp. 329-343.
46. MITCHELL, T.M. 1997. *Machine Learning*, McGraw Hill,.
47. MCDONALD, A.D., LITTLE, L.R., GRAY, R., FULTON, E., SAINSBURY, K.J. and LYNE, V., 2008, An agent-based modeling approach to evaluation of multiple use management strategies for coastal marine ecosystems. *Mathematics and Computers in Simulation*, 78:401-411

48. MCDONALD, D., FULTON, E., LITTLE, L.R., GRAY, R., K.J., S. and LYNE, V.D., 2006, Multiple use management strategy evaluation for coastal marine ecosystems using InVitro. In: P. Perez and D. Batten (Editors), *Complex Science for a Complex World: Exploring Human Ecosystems with Agents*. ANU E. Press
49. MOREAU, L., MILES, S., GOBLE, C., GREENWOOD, M., DIALANI, V., ADDIS, M., ALPDEMIR, N., CAWLEY, R., DE ROURE, D., FERRIS, J., GAIZAUSKAS, R., GLOVE, R.K., GREENHALGH, C., GREENWOOD, M., LI, P., LIU, X., LORD, P., LUCK, M., MARVIN, D., OINN, T., PATON, N., PETTIFER, S., RADENKOVIC, M.V., ROBERTS, A., ROBINSON, A., RODDEN, T., SENGER, M., SHARMAN, N., STEVENS, R., WARBOYS, B., WATSON, P. and WROE, C., 2002, On the Use of Agents in a BioInformatics Grid, *Network Tools and Applications in Biology (NETTAB'2002) - Agents in Bioinformatics*. Bologna, Italy.
50. MOSS, S. and EDMONDS, B., 2005a, Sociology and Simulation: Statistical and Qualitative Cross-Validation. *American Journal of Sociology*, 110 (4), pp. 1095-1131.
51. MOSS, S. and EDMONDS, B., 2005b, Towards Good Social Science. *Journal of Artificial Societies and Social Simulation*, 8 (4) http://jasss.soc.surrey.ac.uk/8/4/13.html.
52. NOAA, 2005, Hurricane Katrina, a Climatological Perspective. http://www.ncdc.noaa.gov/oa/reports/tech-report-200501z.pdf.
53. NOVAK, J.D., 1991, Clarify with concept maps: A tool for students and teachers alike. *The Science Teacher*, 58 (7), pp. 45-49.
54. NUTE, D., POTTER, W.D., MAIER, F., WANG, J., TWERY, M., RAUSCHER, H.M., KNOPP, P., THOMASMA, S., DASS, M., UCHIYAMA, H. and GLENDE, A., 2004, NED-2: An Agent-Based Decision Support System for Forest Ecosystem Management. *Envirnomental Modeling and Software*, 19, pp. 831-843.
55. PARKER, D.C., MANSON, S.M., JANSSEN, M.A., HOFFMANN, M.J. and DEADMAN, P., 2003, Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers*, 93 (2), pp. 314-337.
56. PARSONS, S., SIERRA, C. and JENNINGS, N.R., 1998, Agents that reason and negotiate by arguing. *Journal of Logic and Computation*, 8 (3), pp. 261-292.
57. PIKE, W. and GAHEGAN, M., 2007, Beyond ontologies: Toward situated representations of scientific knowledge. *International Journal of Human-Computer Studies*, 65, pp. 674-688.
58. RAUBAL, M., 2001, Human wayfinding in unfamiliar buildings: a simulation with a cognizing agent. *Cognitive Processing*, pp. 363-388, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.91.6389&rep=rep1&type=pdf
59. SCHURR, N., PATIL, P., PIGHIN, F. and TAMBE, M., 2006, Lessons Learned from Disaster Management, *Agent Technology for Disaster Management Workshop at The Fifth International Joint Conference on Autonomous Agents and Multi-agent Systems (AAMAS)*, Hakodate, Japan, 2006
60. SCHUT, M., WOOLDRIDGE, M. and PARSONS, S., 2001, Reasoning about intentions in uncertain domains, *Sixth European Conference on Symbolic and Quantitative Approaches to Reasoning with Uncertainty (ECSQARU-2001)*, Toulouse, France.
61. SHOHAM, Y., 1993, Agent-oriented programming. *Artificial Intelligence*, 60 (1), pp. 51–92.
62. SIERRA, C., JENNINGS, N.R., NORIEGA, P. and PARSONS, S., 1997, A Framework for Argumentation-Based Negotiation, *Fourth Int. Workshop on Agent Theories, Architectures and Languages (ATAL-97)*. Rhode Island, USA. pp. 167-182.
63. SINGH, M.P., 1998, Agent communication languages: Rethinking the principles. *IEEE Computer*, 31 (12), pp. 55–61.
64. SMITH, B. and MARK, D., 2001, Geographical Categories: An Ontological Investigation. *International Journal Of Geographical Information Science*, 15 (7), pp. 591-612.
65. SMITH, E.E., 1998, An Expert System Approach to Regional Drought Monitoring in Pennsylvania. M.S. Thesis, The Pennsylvania State University, University Park, 159 pp.

66. SWARTOUT, B., PATIL, R., KNIGHT, K. and RUSS, T., 1996, Toward distributed use of largescale ontologies. In Proceedings of 10th Knowledge Acquisition for Knowledge-Based Systems Worskhop, Banff, Canada. http://ksi.cpsc.ucalgary.ca/ KAW/KAW96/KAW96Proc.html.
67. SURE, Y., ERDMANN, M., ANGELE, J., STAAB, S., STUDER, R. and WENKE, D., 2003 OntoEdit: Collaborative Ontology Engineering for the Semantic Web. In I. Horrocks and J. Hendler (Eds.). *Proceedings of the First International Semantic Web Conference 2002 (ISWC 2002),* Sardinia, Italia: Springer, pp. 221-235.
68. SZYMANSKI, B., CHEN, G. and WILSON, L.F., 2003, Component-Based Simulation and Agent-Based Brokering: Towards Ad Hoc Simulations in Crisis and Emergency Management, *Proceedings of Computer Networks and Distributed Systems Modeling and Simulation, CNDS'03*. Orlando, Florida. http://www.cs.rpi.edu/~szymansk/papers/cnds03.pdf.
69. TAMMA, V. and WOOLDRIDGE, M.D., I., 2002. An Ontology for Automated Negotiation, *the Workshop on Ontologies in Agent Systems*. Bologna, Italy. http://www.csc.liv.ac.uk/~mjw/pubs/oas2002.ps.gz
70. TAYLOR, R.I., 2003, Agent-Based Modelling Incorporating Qualitative and Quantitative Methods: A Case Study Investigating the Impact of E-commerce upon the Value Chain, Metropolitan University, Manchester, UK. http://cfpm.org/cpmrep137.html
71. THE WHITE HOUSE, 2006, The Federal Response to Hurricane Katrina: Lessons Learned. http://www.whitehouse.gov/reports/katrina-lessons-learned/.
72. UNDP, 2005, Reducing Risks from Tsunamis: Disaster and Development, Bureau for Crisis Prevention and Recovery, United Nations Development Programme. http://www.undp.org/cpr/disred/documents/tsunami/undp/rdrtsunamis.pdf
73. WESTERVELT, J.D. and HOPKINS, L.D., 1999. Modeling mobile individuals in dynamic landscapes. *International Journal of Geographical Information Science*, 13 (3), pp. 191-208.
74. WINTER, S., 2001, Ontology: Buzzword Or Paradigm Shift In GI Science? *International Journal of geographical information science*, 15, pp. 587-590.
75. WOOLDRIDGE, M., 2000, *Reasoning About Rational Agents*, Cambridge, MA: MIT press.
76. WOOLDRIDGE, M. and JENNINGS, N.R., 1995, Intelligent Agents: Theory and Practice. *The Knowledge Engineering Review*, 10 (2), pp. 115-152.
77. WOOLDRIDGE, M.J. and JENNINGS, N.R., 1999, Cooperative Problem Solving. *Journal of Logic and Computation*, 9 (4), pp. 563-592.
78. WORLD BANK INDEPENDENT EVALUATION GROUP, 2006, Hazards of Nature, risks to Development. Washington D.C.: World Bank Publications.
79. WU, S., KELLEY, M., BALABAN, C., SHUMAN, L.J., LAWSON, B., BIDANDA, B. and SOCHATS, K., 2007a, System Implementation Issues Of Dynamic Discrete Disaster Decision Simulation System (d4s2). In S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton (Editors), *Proceedings of the 2007 Winter Simulation Conference.* http://ltl13.exp.sis.pitt.edu/Website/Webresume/WinterSimulation/WinterSimulationConference2007Paper.doc
80. WU, S., SHUMAN, L., BIDANDA, B., KELLEY, M., SOCHATS, K. and BALABAN, C., 2007b, Disaster Policy Optimization: A Simulation Based Approach. In: G. Bayraksan, W. Lin, Y. Son and R. Wysk (Editors), *Proceedings of the 2007 Industrial Engineering Research Conference*. http://www.cnp.pitt.edu/pittframework/documents/IERC07_SWu.pdf
81. YEN, J., FAN, X. and R. A., V., 2004, Proactive Communications in Agent Teamwork. In: F. Dignum (Editor), *Advances in Agent Communication*: Springer, pp. 271-290.
82. YEN, J., MAITLAND, C. and TAPIA, A., 2007, Simulated Decision Making for ICT Coordination in Disaster Relief Using Cognitive Agents, *AI in ICT for Development – Workshop at IJCAI, Twentieth International Joint Conference on Artificial Intelligence*. Hyderabad, India, January 6-12, 2007.

83. YU, C., 2005, GeoAgent-based Knowledge Systems. Unpublished Ph.D Thesis, The Pennsylvania State University, University Park.
84. YU, C. and PEUQUET, D.J., in press, A GeoAgent-based Framework for Knowledge-oriented Representation: Embracing Social Rules in GIS. *International Journal of Geographical Information Science*, (published electronically 21 May, 2008, pp1-38).