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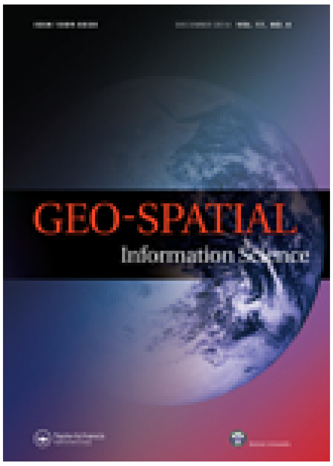

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An integrated virtual geographic environmental simulation framework: a case study of flood disaster simulation

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An integrated virtual geographic environmental simulation framework: a case study of flood disaster simulation

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Dynamic flood disaster simulation is an emerging and promising technology significantly useful in urban planning, risk assessment, and integrated decision support systems. It is still an important issue to integrate the large assets such as dynamic observational data, numerical flood simulation models, geographic information technologies, and computing resources into a unified framework. For the intended end user, it is also a holistic solution to create computer interpretable representations and gain insightful understanding of the dynamic disaster processes, the complex impacts, and interactions of disaster factors. In particular, it is still difficult to access and join harmonized data, processing algorithms, and models that are provided by different environmental information infrastructures. In this paper, we demonstrate a virtual geographic environments-based integrated environmental simulation framework for flood disaster management based on the notion of interlinked resources, which is capable of automated accumulating and manipulating of sensor data, creating dynamic geo-analysis and three-dimensional visualizations of ongoing geo-process, and updating the contents of simulation models representing the real environment. The prototype system is evaluated by applying it as a proof of concept to integrate *in situ* weather observations, numerical weather and flood disaster simulation models, visualization, and analysis of the real time flood event. Case applications indicate that the developed framework can be adopted for use by decision-makers for short-term planning and control since the resulting simulation and visualization are completely based on the latest status of environment.

Keywords: flood; virtual geographic environments (VGE); dynamic data driven active simulation; geo-model and geo-data integration

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1. Introduction

Flood hazard is a global phenomenon which causes widespread devastation, economic damages, and loss of human lives (*1*). As the consequences of climate changes and developments of urbanization in recent decades, flood disasters have significantly increased in magnitude and frequency (*2–4*). Therefore, more dynamic decision-making tools are urgently needed. As an emerging and promising technology, dynamic flood disaster simulations are frequently used for the evaluating, planning, and risk assessment in advance the natural hazard evolution and impacts of management decisions (*5*).

However, being the fundamental step to any simulation application, collaboration between and integration of massive homogenous resources for simulation is a serious limitation, which is important for the usability and efficiency of the simulation based decision-making tools. As it is important for the usability and efficiency of the simulation based decision-making tools, problems related to the limitation have been addressed in extensive literatures (*6, 7*). Unified disaster flood simulation frameworks are urgently addressed, which foregoes passive, isolated, and centralized simulation patterns and instead supports active, holistic, and intelligent simulation way. However, most existing disaster simulations operate in a typical passive static data driven mode. The limitation of the passive static data driven simulation mode lies essentially in two aspects: collecting accurate and reliable information from raw field data providing by multiple *in situ* sensors, and injecting the simulation needed information into the executing simulation process to validate the model parameters dynamically. For the former one, while dynamic observations can provide accurate estimates of the ongoing environment's status, these data are sometimes subject to inevitable errors caused by various effects (such as equipment breakdowns) produced by the environment they are monitoring. The introduced additional layers of uncertainty will significantly slow down the data collection progress and affect the simulation process by ways of model misspecification, biased parameter estimation, incorrect data-based analysis results, and so on (*8*). Even though all such data are collected, it is still a time- and labor-intensive task to handle these raw observations to meet the input needs of simulation models. Scientists need to waste considerable time on labor intensive and time consuming operations to integrate such disparate data-sets rather than focusing on real scientific analysis and decision-making (*9*). One reason is that the

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various native protocols of sensors are defined by their manufacturers, since standard encodings for sensor protocols are not widely accepted (*10*). To inject such sensor data into the simulation model, the raw sensor data need to be translated to the standardized format at first. On the other hand, dynamic and interdependent simulation models needs to be run, among others, to provide evolution prediction results and represent all the details needed for more complex environmental processes. Due to the limited compatibility among these inhomogeneous models and the varying model input needs, traditional simulation paradigms are more like a disjointed series of tasks. The input–output data flow in these multiple models are often performed offline and manually oriented. Therefore, in many cases, especially under emergency situation, the sub-simulators have to work with static, outdated, interpolated, or even absolutely unknown data values. The impediment of the typical simulation mode is being partially addressed by the increasingly complex decision-making requirements, as well as by the growing availability of diverse resources, including observation data sources, models, geo-tools, and sensors. That is why policy developers and decision-makers are asking for and processing information synthesized and automated from holistic systems-based simulation approaches (*11*).

To overcome these limitations, Darema (*12*) raised the need for a new simulation paradigm shifting from static data driven mode toward the provision of dynamic data driven simulation paradigm (DDDAS), which is capable of automated collecting and imparting of additional raw sensor data into the corresponding simulation model at runtime (*13–15*). They foresee the use of dynamic asynchronously collected data into the executing simulation to make more accurate and efficient prediction (*16, 17*). A rich set of new challenges created by the new paradigm has been addressed, which include challenges like dynamic data-collection, adaptive pre-/post-processing and visualization of data, dynamic simulation execution support environments, adaptive data selection and injection of input data, and so on (*15*). Addressing these problems will require a coordinated effort from the environmental community in partnership with computer and information researchers. The presented study responds to their call and addresses some of these unresolved research topics in terms of dynamic data discovery, retrieving, adaptive data selection, and injection for the executing simulation. Aimed at moving beyond the traditional simulation paradigm of the static, disjointed, and offline operating mechanism, this paper focused on a novel holistic and automated solution to manage the execution and data flow among multiple simulation models and addressed the following issues:

- Providing a dynamic simulation execution support environment for the integration of multi-domain simulation models.
- Providing an adaptive data collection and operating mechanism to solve the lack of accessibility and interoperability of multi-source and heterogeneous data for fulfill the input needs of simulation model sets.
- Exposing common data pre-/post- operations as modular components to be reused in workflows within the executing simulation process.
- Enhancing integration and adaptive combination of processing capabilities with data reformatting, resampling, transformation, interpolation, and visualization tasks.

In order to achieve the above goals, it is desirable to offer an adaptive dynamic architecture that allows for easy assemblage, modifications, display of data, functionalities, and models; and also enable discovery desirable observational and geospatial data for the executing simulation models as well as support data processing, visualization, and simulation executing in a holistic environment. This study presents the design and implementation of virtual geographic environments (VGE)-based simulation framework that meets the challenges in integrating multiple simulation models, functionalities, and data in the realm of the disaster management domain.

The remainder of this paper is organized as follows. In the Section 2, the developed methodology and the implementation of the proposed approach are presented. Section 3 presents the architecture of our approach and elaborates on the key components and modules of the prototype system. Applications of the system are also described in this section. Finally, Section 4 concludes by summarizing the key features of our approach and discussing ongoing work.

2. Overall design

In this section, a conceptual framework is presented according to the definition of VGE in Ref. (*18*). In the following, we do not attempt to an exhaustive, dimensions discussion of our research but present that are the most important aspects in our work.

2.1. Conceptual architecture overview

The key concept of an active disaster simulation mechanism is to dynamically steer the simulation process under uncertain and dynamic conditions and entail the ability to incorporate dynamic and heterogeneous resources into an executing simulation application. In such a simulation mechanism, simulation process could be dynamically improved, as the data, model, and model parameter uncertainties can be dynamically steered and controlled according to the real-time injected observational data stream. To provide an innovative way to make full use of existing and emerging resources (including sensors, data sources, models, geo-tools, software packages, and computing resources), and to discover and aggregate the required information for models in an executing simulation process, we present an active dynamic data driven disaster simulation mechanism to couple real-time observational geo-data and heterogeneous geo-models (Figure 1).

The working mechanism presented in Figure 1 could be presented in three core steps. First, driven by input requests of heterogamous models (including the numerical metrological model, hydrologic model, and hydraulic model), the diverse information requests will be dissolved and aggregated into the abstract, normalized task space through semantic understandings. Second, the multi-source heterogeneous resources will be described and organized in the normalized resource space. After this step, the multi-source heterogeneous resources will be organized and represented in an integrated way based on the unified semantic description. Third, the semantics of simulation tasks will be dynamically generated by automatically matching and mapping the task space and resource space into a quantifiable capacity space, where the resources are self-organized. The semantics of the simulation task provide a composition mechanism in the resource space to represent complex tasks as a set of scientific workflows consisting internally of integrated chains of distributed geospatial services. In these three steps, the information space for the corresponding simulation model requests will be gained by orchestrating according to the semantics of simulation tasks.

2.2. *Unifying semantic description model*

The principal aim of this research is to increase the availability of high spatial-temporal resolution sensor observations for running models and improving the simulation adaptability. As mentioned in the previous section, we can know that the first challenge for model-demanded automated discovery, retrieving and integrating information from multi-source data repositories is to alleviate heterogeneity problems.

Based on our previous study on spatial-temporal model (*19*) and the semantic web for earth and environmental terminology (SWEET) ontology (Figure 2) (*20, 21*), a unified semantic description model is defined in Figure 3.

The SWEET (available from http://sweet.jpl.nasa.gov/sweet) is a complex set of ontologies, which is an investigation in improving discovery and use of observational data, through automated software understanding of the semantics of multiple resources. To support potential semantic activities in earth system science, the SWEET ontologies have defined numbers of terms and relations. Figure 4 presents the core ontologies. Each box on the graph indicates an independent ontology. Each connecting line presents the major properties used to descript concepts in the ontology spaces. The SWEET ontologies are holistic, unified, in derivation, and application-independent. Being scalable, specialized lower level domains can add diverse and specific domain extensions to form

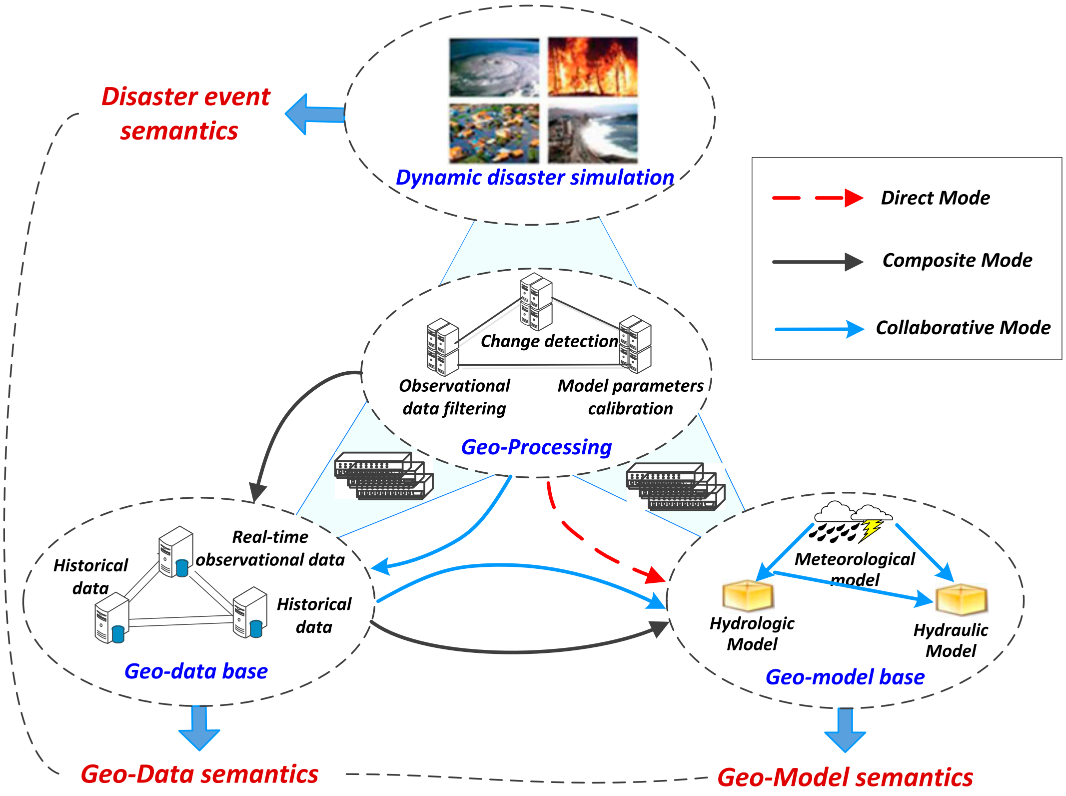

Figure 1. The conceptual architecture of the VGE-based active disaster simulation mechanism.

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a domain-specific ontology, even across multiple platforms.

Moreover, the spatiotemporal change-oriented three-domain model presented in our previous study (*19*) has been adopted to extend the SWEET ontologies. In order to support the explicit change representation of real-time observational data and constantly changing natural phenomenon, the novel spatiotemporal change-oriented conceptual model is designed to explicitly model the change mechanism and the elementary semantic association relationships between the changes using three domains of feature, process and event, as well as the domain links. Figure 3 gives the detailed description of the conceptual model for flood disaster.

As shown in Figure 3, the core conceptions including *Feature*, *Event*, *Process*, *and Observation* are all formalized into SWEET ontologies. The SWEET ontologies are extended to include part of the hydrology and geo-science domain. Serving as base classes of the domain concepts, the SWEET natural phenomena ontology is extended to present metrological, hydrologic, and hydraulic composed natural flood disaster phenomena.

Moreover, the proposed model presented in Figure 3 uses the interaction of four domains to represent the mapping relations between observational data and multiple simulation models. The model is formalized as a tuple as follows:

$$\begin{cases} C(s) = f_c(O,E,P), \quad O = f_0(S,Te), \quad E = \bigcup\limits_{t=0}^{n} Pattern_t, \; P = \bigcup\limits_{i=0}^{m} p_i = \bigcup\limits_{i=0}^{m} f_p(M,D) \\ Pattern(t) = \bigcup\limits_{i=0}^{n} f_{change}(D) \\ M = \bigcup\limits_{i=0}^{m} (Mw,\ Mhyo,\ Mhya)_i,\ (Mw,\ Mhyo,\ Mhya) \in Model \\ Model = (URI,\ Mtype, InputVarS,\ OutputVarS,\ InputParasS,\ OperaParas,\ Relations) \\ D = \bigcup\limits_{i=0}^{n} (d_i) \end{cases}$$

where $C(s)$ is a change of flood-related phenomenon in certain scale; O, respectively, represents the involved the multi-dimensional objects; E points to a set of defined events, while each event can be represented by a set of change patterns; P is the physical process including several sub processes, for example, a flood disaster process including a sub process of precipitation process, surface run-off process, and so on. As in the simulation process, a natural process is modeled by a numerical simulation model and the real-time observations, thus, P here is abstracted into an aggregation of models M and observational data D. The change pattern for an event is presented by the change mode of the observational data stream. The numerical simulation models M involved in flood disaster process include numerical metrological model Mw, hydrologic model $Mhyo$, and hydraulic model $Mhya$. For each model m, it is composed of seven parameters. The URI presents the unique identification of the model. The *InputVar* and *OutputVar* indicate the input and output of the model, respectively. The *OperationParas* represents the run-time environment parameters, including system platform, IP address of the model, and so on. The *Relations* shows the relationship with other models.

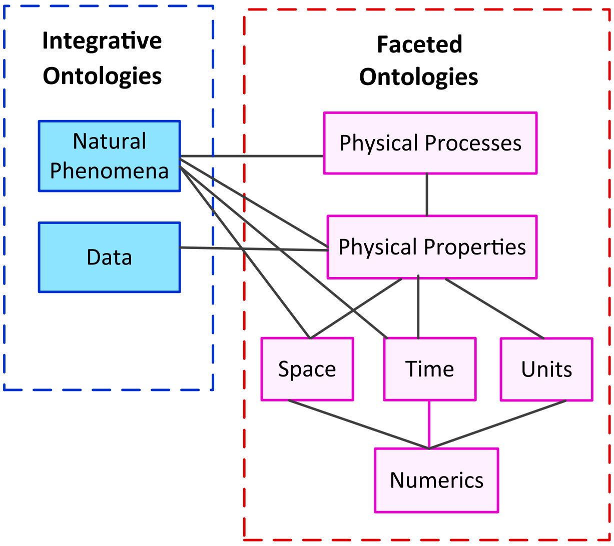

Figure 2. Architecture of SWEET ontologies.

Based on the VGE-based active disaster simulation mechanism and the unifying semantic description model, the mapping relations between geo-models and geo-observational data could be represented as the multiple sheets that refer to each other, as shown in Figures 5 and 6.

3. Implementation and experimental results analysis

3.1. System architecture

Based on the VGE-based active disaster simulation mechanism and the unifying semantic description model, the designed architecture for the prototype system is illustrated in Figure 7. The system is designed to provide a new disaster simulation paradigm that shifts from a static data driven mode toward the active dynamic data driven simulation mode. This system could be able to

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Figure 3. The unifying semantic description model.

provide on-demand disaster information for homogenous models handling various disaster management tasks in a holistic way. As the core of the system, components of numerical flood-related simulations and VGE are integrated with each other by coupling numerical geo-models with VGE functions of geo-data management, information visualization, and spatial analysis to enable more precautions and countermeasures of flood-related disasters. According to its functional characteristics, the system includes six modules: *Geo-Data Base*, *Geo-Computing Module*, *Dynamic Visualization Module*, *Geo-Model Base*, *Geo-simulation Module*, and *Geo-Processing Module*. In order to make these modules “plug and play” easily, the prototype system is implemented based on hierarchical message bus (HMB), which provides uniform plugin interfaces for easy communication among modules in the whole system. In *Geo-Data Base*, the distributed database is used to manage and store data including DEM, observational, and predicted meteorological data. *Geo-Model Base* gives geo-model packaging and management functions. Multiple heterogeneous models and multiple platforms will be managed in this module. The main function of *Dynamic Visualization Module* is to present flood-related scenarios including dynamic visualization of metrological information, flood evolution process, and large scale DEM. *Geo-Computing Module*
]

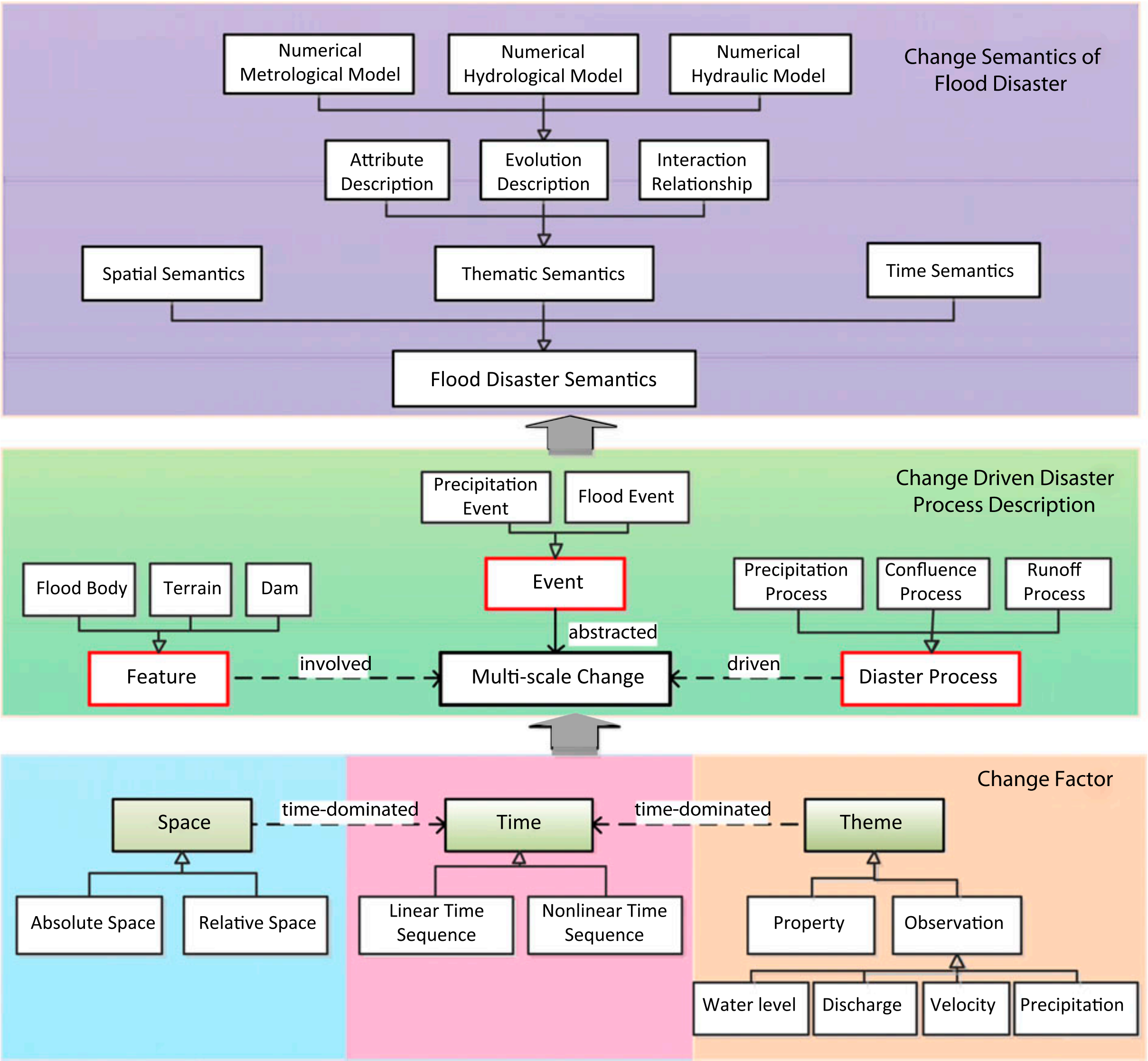

Figure 4. Spatiotemporal change-oriented conceptual model of flood disaster.

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will provide spatial and scientific computing support for *Geo-Simulation Module*. *Geo-Processing Module* is to inject and filter dynamic observational data stream to provide model-demanded input for *Geo-simulation Module*. However, the implementations of the models and geo-functions that involve disaster management operations (including early detection, forecasting (*1*), loss assessment and efficient analysis of disaster reduction, and Geospatial data processing (*22*)) have not been discussed in detail in this paper.

To check its reliability and efficiency, this approach has been applied to reconstruct a historical flood event as described in the following subsections.

3.2. Study area

Shenzhen is a coastal city in the south of Southern China's Guangdong Province, situated immediately north of the Hong Kong Special Administrative Region. Restricted by the geographical environment, typhoon, and long-lasting heavy rainfall events often hit here in winter and summers. Precipitation in Shenzhen has been extremely heavy in the hurricane season. Disasters caused by heavy precipitation often resulted in great damage as the city's poor drainage system. From year 1998 to 2014, the city was struck by excessive rainfall and flooded three times. According to site investigations, Shenzhen City in China, with high level of rainfall, lots of lakes, and rivers, frequent floods, is selected as a study area to demonstrate the efficiency and accuracy of hydrological modeling, simulation, and assessment (as shown in Figure 8).

The developed system is practical and can be applied to a wide variety of watershed scenarios where real-time observational rainfall data, water level data is dynamically injected to the system. This paper is not concerned with the hydrological model used, but rather with the provision of a methodology for a rapid, easy to-use, and cost-effective means for implementing flooding analysis.

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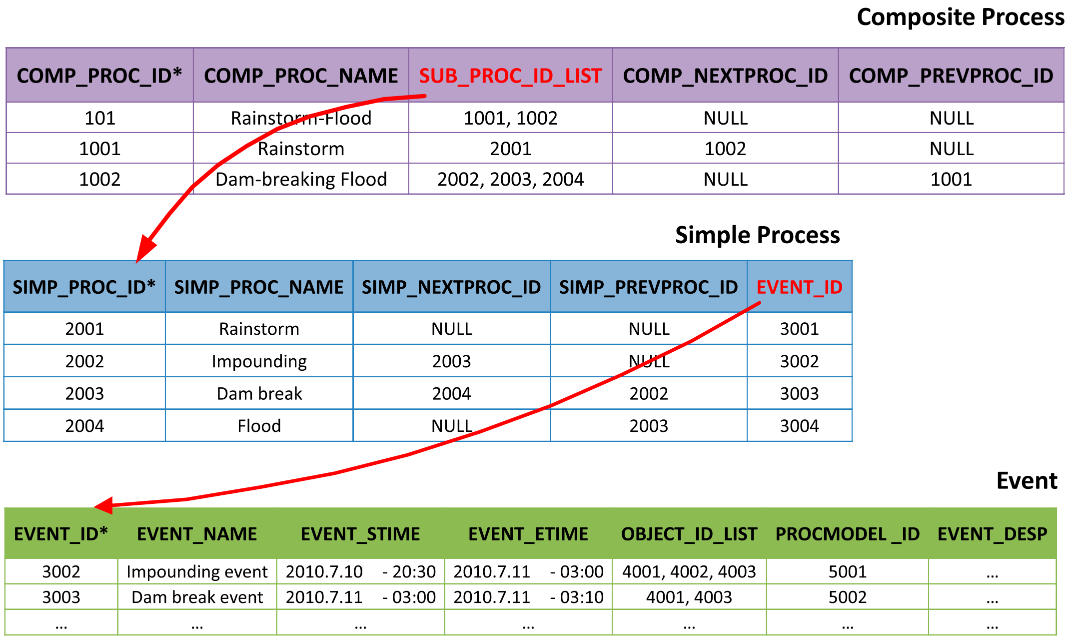


Composite Process

COMP_PROC_ID*	COMP_PROC_NAME	SUB_PROC_ID_LIST	COMP_NEXTPROC_ID	COMP_PREVPROC_ID
101	Rainstorm-Flood	1001, 1002	NULL	NULL
1001	Rainstorm	2001	1002	NULL
1002	Dam-breaking Flood	2002, 2003, 2004	NULL	1001

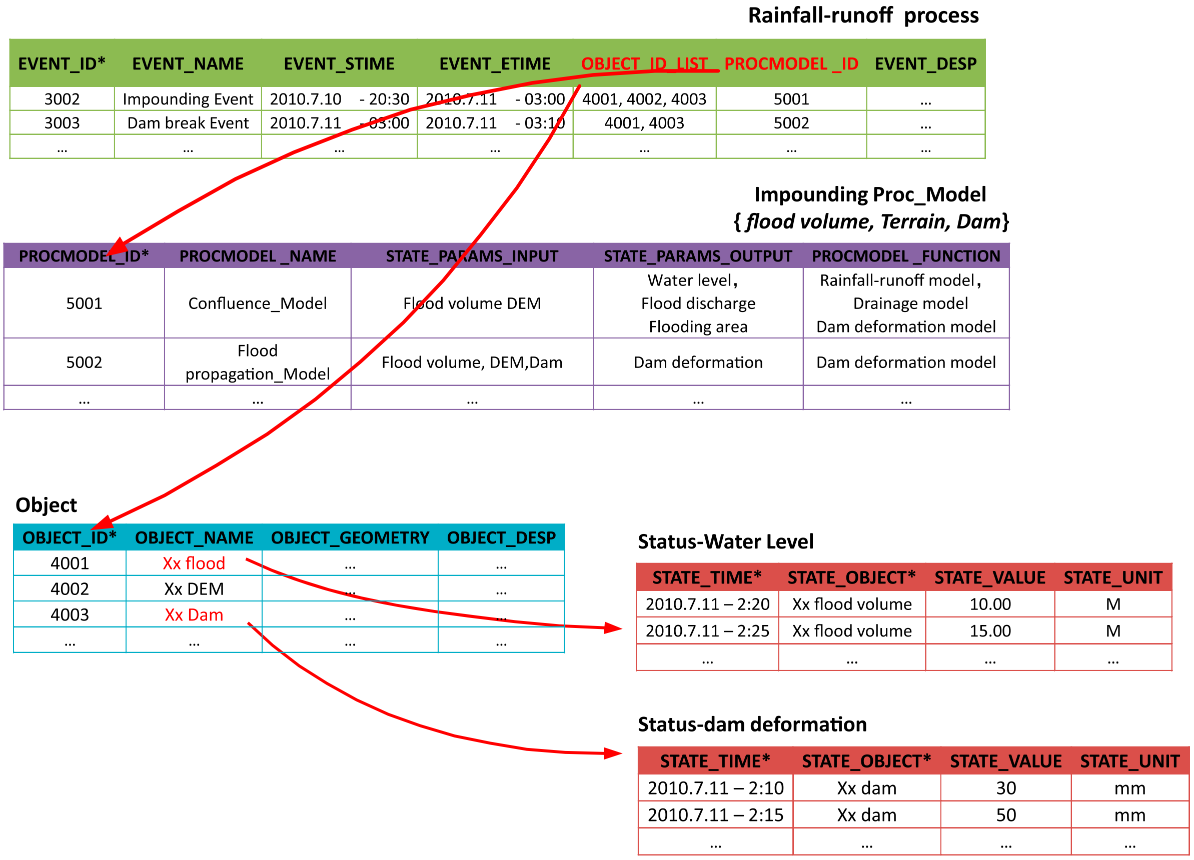
Simple Process

SIMP_PROC_ID*	SIMP_PROC_NAME	SIMP_NEXTPROC_ID	SIMP_PREVPROC_ID	EVENT_ID
2001	Rainstorm	NULL	NULL	3001
2002	Impounding	2003	NULL	3002
2003	Dam break	2004	2002	3003
2004	Flood	NULL	2003	3004

Event

EVENT_ID*	EVENT_NAME	EVENT_STIME	EVENT_ETIME	OBJECT_ID_LIST	PROCMODEL _ID	EVENT_DESP
3002	Impounding event	2010.7.10 - 20:30	2010.7.11 - 03:00	4001, 4002, 4003	5001	…
3003	Dam break event	2010.7.11 - 03:00	2010.7.11 - 03:10	4001, 4003	5002	…
…	…	…	…	…	…	…

Figure 5. Tight link of event and process.



Rainfall-runoff process

EVENT_ID*	EVENT_NAME	EVENT_STIME	EVENT_ETIME	OBJECT_ID_LIST	PROCMODEL _ID	EVENT_DESP
3002	Impounding Event	2010.7.10 - 20:30	2010.7.11 - 03:00	4001, 4002, 4003	5001	…
3003	Dam break Event	2010.7.11 - 03:00	2010.7.11 - 03:10	4001, 4003	5002	…
…	…	…	…	…	…	…

Impounding Proc_Model
{ *flood volume, Terrain, Dam*}

PROCMODEL_ID*	PROCMODEL _NAME	STATE_PARAMS_INPUT	STATE_PARAMS_OUTPUT	PROCMODEL _FUNCTION
5001	Confluence_Model	Flood volume DEM	Water level, Flood discharge Flooding area	Rainfall-runoff model, Drainage model Dam deformation model
5002	Flood propagation_Model	Flood volume, DEM,Dam	Dam deformation	Dam deformation model
…	…	…	…	…

Object

OBJECT_ID*	OBJECT_NAME	OBJECT_GEOMETRY	OBJECT_DESP
4001	Xx flood	…	…
4002	Xx DEM	…	…
4003	Xx Dam	…	…
…	…	…	…

Status-Water Level

STATE_TIME*	STATE_OBJECT*	STATE_VALUE	STATE_UNIT
2010.7.11 – 2:20	Xx flood volume	10.00	M
2010.7.11 – 2:25	Xx flood volume	15.00	M
…	…	…	…

Status-dam deformation

STATE_TIME*	STATE_OBJECT*	STATE_VALUE	STATE_UNIT
2010.7.11 – 2:10	Xx dam	30	mm
2010.7.11 – 2:15	Xx dam	50	mm
…	…	…	…

Figure 6. Tight link of event and feature.

3.3. *Data source*

Three digital base maps are prerequisite in the experiment to define the three-dimensional flood scenario and derive spatial model parameters: spatial data, hydrological data, and some other auxiliary data. Spatial data encompass digital base maps of DEM data, DOM data,

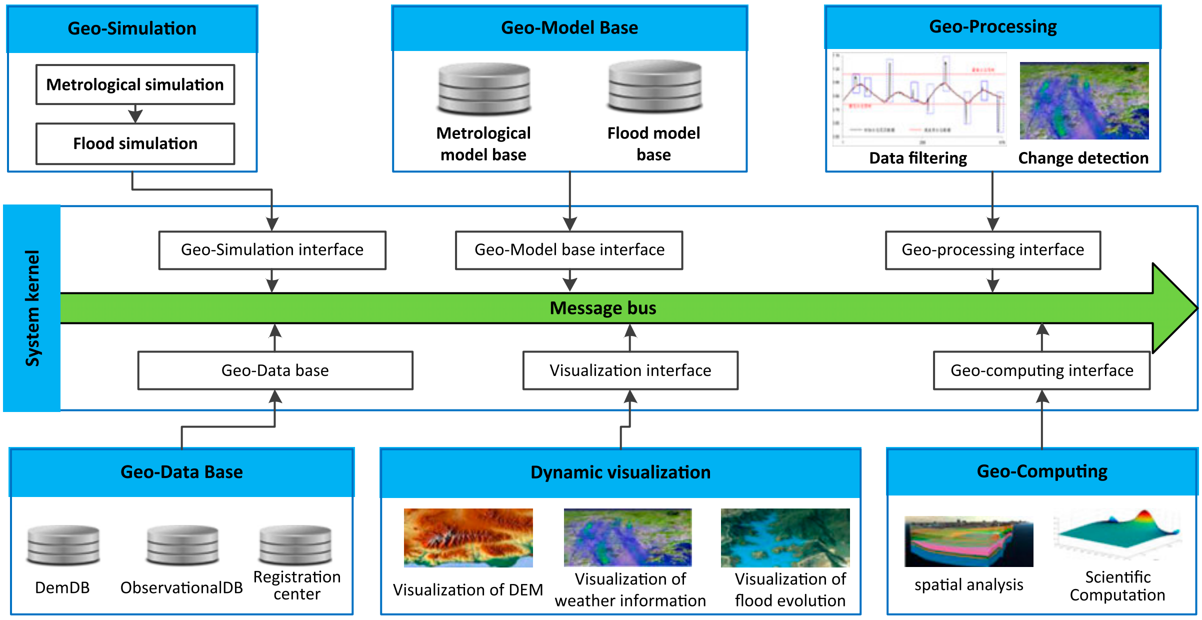


Figure 7. System architecture based on HMB.

Figure 8. The study area.

political boundaries (country, city, etc.), and rivers. A DEM with 5 m × 5 m grid size for the flood spreading and simulation was constructed using 2-m resolution elevation contours and the official river network. Hydrological data conclude water levels, daily rainfall data, and evapotranspiration data. Water levels were recorded at a 15-min time step. Daily rainfall is disaggregated into hourly rainfall series according to the nearest hourly reference rain gages for being used in the experiment. Potential evapotranspiration was estimated with daily meteorological data from hydrological network, and applied to the whole study area.

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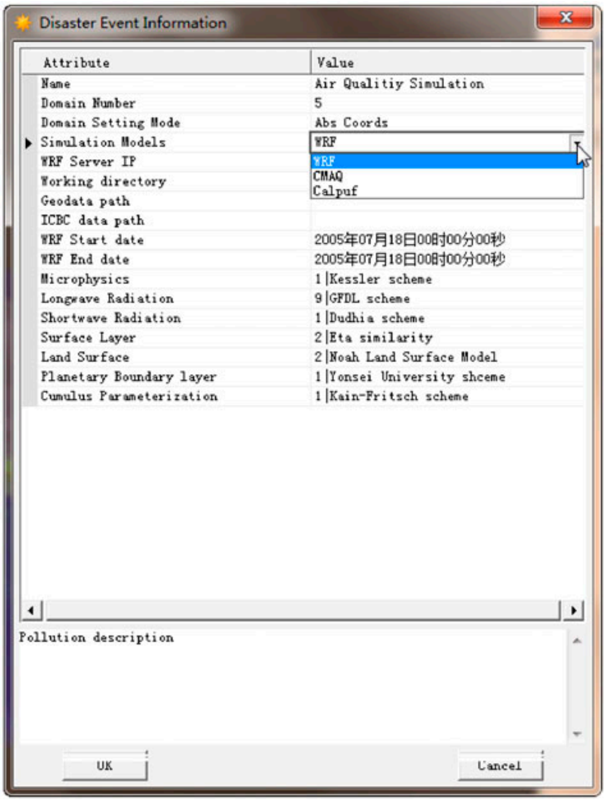

Attribute	Value
Name	Air Qualitiy Simulation
Domain Number	5
Domain Setting Mode	Abs Coords
Simulation Models	WRF
WRF Server IP	
Working directory	
Geodata path	
ICBC data path	
WRF Start date	2005年07月18日00时00分00秒
WRF End date	2005年07月18日00时00分00秒
Microphysics	1|Kessler scheme
Longwave Radiation	9|GFDL scheme
Shortwave Radiation	1|Dudhia scheme
Surface Layer	2|Eta similarity
Land Surface	2|Noah Land Surface Model
Planetary Boundary layer	1|Yonsei University shceme
Cumulus Parameterization	1|Kain-Fritsch scheme

Figure 9. Parameters demanded by the WRF model.

3.4. *Simulation results*

In this session, we tested our method by reconstructing the “8•30” flood event in 2013, which was one of the greatest tragedies in the history of Shenzhen. In that time, there was a heavy and continuous rainfall. A more detailed discussion of the event, including observations, analytical results, and other factors, was collected by local governmental authorities to assess the damage and losses and to determine a plan for recovery and reconstruction.

3.4.1. *Weather research and forecasting integration and dynamic data driven computation*

Weather conditions including precipitation, temperature, and wind information are requisite inputs for flood simulation. In the presented prototype system, weather research and forecasting (WRF) model (*23*) is integrated for environmental modeling and weather condition simulation. WRF is time consuming in computation. To decrease model computation time and consequently improve system efficiency, WRF is installed in one high-powered computation server. The integration of WRF into VGE-based flood disaster simulation system is based on the designed active framework and the unifying semantic description. Based on the semantic description, the demanded parameters in Figure 9 could be explicitly depicted. Meteorological observations, including wind velocities, temperatures, and precipitation obtained via the onsite observation, were adopted as the test case. By the VGE interface, a user defines the simulated area and

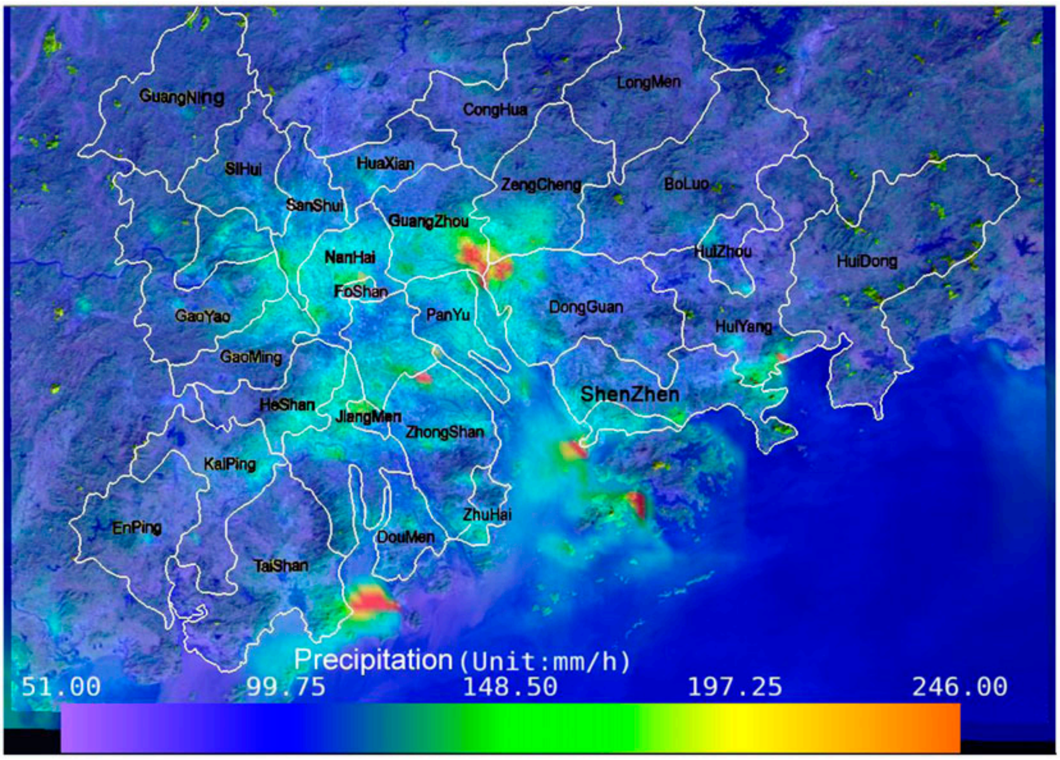

Figure 10. The simulated precipitation results from WRF.

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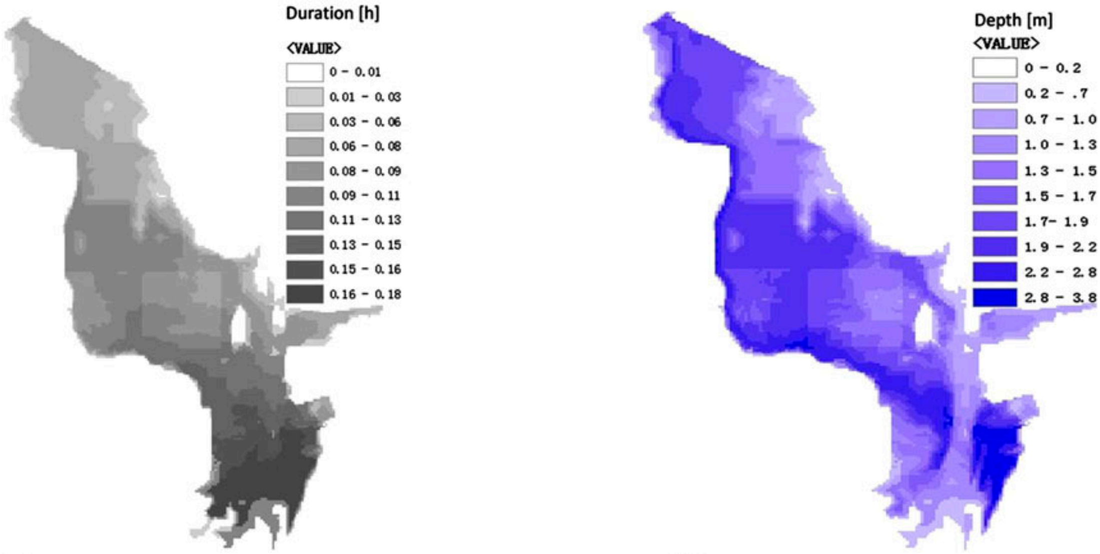
(a) Scenario 1 : heavy rain lasting for 3 hours

(b) Scenario 2 : heavy rain lasting for 3.5 hours



(c) Flooding duration distributution map of Scenario 2

(d) Flood depth distribution map of Scenario 2

Figure 11. The simulated flood disaster results.

simulation type by user interface interaction; then simulation demanded data including real-time observational data stream will be dynamically injected through intelligent semantic retrieval. These data, together with the computation server's local data, such as the world terrain and environmental boundary conditions, will be aggregated into WRF. WRF here is pre-packaged with a set of web services. When the web service receives the trigger message, the WRF installed on the computation server will be executed. Figure 10 presents the simulated precipitation results at different sections of the research area. The simulated results show that the precipitation on 30 April 2013 in the Pearl River Delta region had characters of centralized distribution and large amount, which produced great hydrological effects in the rainfall centers including Shenzhen city, Guangzhou city, and so on.

3.4.2. Storm water management model integration and dynamic data driven computation

In the same way, the storm water management model and DEM-based hydraulic model are integrated to obtain the flooding information. Different flooding scenarios in Shenzhen city produced by the prototype system are shown in Figure 11(a) and (b). These scenarios provide qualitative insights into the flood routing process. The live-recording frame rate of the three-dimensional visualization of these scenarios is about 46–52 fps, which provides an intuitive and insightful information for early warnings, severity assessments of monitored areas and information for decision support. The simulated results given by the system can be easily converted to applicable thematic maps. The output maps of the flooding duration distribution, and flood depth from the system which can be saved in a general format for subsequent assessment, are shown Figure 11(c) and (d).

4. Conclusions

In this paper, a comprehensive survey of the integration and management of geospatial information resources to serve the flood disaster simulation is presented. Aiming at the bottlenecks of existing passive static data driven disaster simulation mode, a novel VGE-based active dynamic data driven paradigm is introduced, focusing specifically on the seamless integration, collaboration, and reuse of geo-models and geo-data to better support stakeholders by performing disaster simulation applica-

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tions in a holistic way. The active dynamic data driven simulation paradigm has the following characteristics: (1) the paradigm provides the seamless integrating and mapping of multiple real-time observational data (geo-data) and homogenous simulation models (geo-models); (2) based on the paradigm, active on-demand data processing (Geo-Processing) for complex simulation model information requests can be adaptively generated through the adaptive information aggregation; and (3) through the unifying semantic description model, multiple resources (including sensors, data sources, models, software packages, and computing resources) can be easily embedded into the system. Applications show that the system has promoted in the scientific decision-making levels of disaster management.

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