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Efficient GIS-based model-driven method for flood risk management and its application in central China

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Abstract

In recent years, an important development in flood management is a focal shift from flood protection towards flood risk management. This change greatly promoted the progress of flood control research by the multidisciplinary way. Moreover, given the
5 growing complexity and uncertainty in many decision situations of flood risk management, traditional methods, e.g. tight-coupling integration of one or more quantitative models, are not enough to provide decision support for managers. Within this context, this paper presents a beneficial approach for dynamic adaptation of support to the needs of the decision maker. The overall methodology combines various engineering
10 and geoinformation methods to analyse flood risk as well as calculate major damage processes. The main innovation is the application of model-driven concepts, which are promising for loose-coupling of GIS and multidisciplinary models. This paper defines the new system as Model-driven Decision Support System (MDSS) and proposes its framework. Two characteristics differentiate the MDSS are as follows: (1) it is made
15 accessible to a non-technical specialist and (2) it has a higher level of adaptability and reusability. Furthermore, the MDSS was employed to manage the flood risk in Jingjiang flood diversion area, located in central China near the Yangtze River. Compared with traditional solutions, we believe that this model-driven method is reasonable, reliable and flexible, thus has bright prospects of application for comprehensive flood risk ma-
20 nagement.

1 Introduction

Flood disasters are among the most frequent and devastating types of disasters over the world (International Federation of Red Cross and Red Crescent Societies, 1998). In China, up to two-thirds of the land are at different types and levels of risk from river
25 and coastal flooding (Feng et al., 2001; Wang et al., 2004). Within this context, we are facing a paradigm shift in dealing with flood issues from flood protection towards flood

risk management (Evers et al., 2012). Moreover, given the growing complexity and uncertainty in many decision situations of flood risk management, personal experience and single model is not enough to provide decision support for managers. Therefore, comprehensive flood risk management has widely been used in flood insurance, flood
5 plains' management, disaster evacuation, disaster warning, disaster evaluation, flood influence evaluation, improving the public's flood risk awareness and understanding of flood disasters (Zeng et al., 2007; Ray, 2007; Escuder-Bueno et al., 2012; Chen et al., 2011; Schinke et al., 2012; Li et al., 2012; Evers et al., 2012).

Traditionally, tight-coupling integrations of one or more quantitative models were the
10 dominant flood-risk-management approaches. However unique aspects of flood-risk-management problems require a special approach for dynamic adaptation of support to the needs of the decision maker. Once, Bijan et al. (1997) believe that there is an additional intelligent "Adaptation" component that can achieve the absolute adaptation. We cannot prove that this assumption is feasible, but our approach is to ensure that
15 the algorithms and models are in a loose-coupling framework, e.g. can be easily re-constructed to accommodate the demand. Over the past 10 yr, we focus on the need for flood control by integrating remote sensing and GIS techniques with qualitative or quantitative models, including hydrologic analysis, flood simulation, flood risk analysis, and disaster assessment (Zou et al., 2012a, b; Guo et al., 2011; Song et al., 2011b).
20 Since, we got a lot of experience through these engineering applications.

In recent years, the purpose of our research has increasingly become to propose a universal approach for flood risk management by the model-driven method, which provides an accessible interface to a non-technical specialist, such as a manager. Furthermore, the method is intended for some repeated use in the same or a simi-
25 lar decision situation (Power and Sharda, 2007). In order to achieve these objectives, many research studies have been carried out on this topic. They can be outlined as follows: (1) model-driven method for flood risk management; (2) loose-coupling frame-work of hardware and software system; (3) multidisciplinary optimization and mathe-matical programming models.

For reader's convenience, the reminder of this paper is organized as follows:

– Next section provides an overview and analysis of past model-driven method research, then identifies research challenges related to behavioural and technical aspects of implementing and using the method for flood risk management.

– Section 3 defines our model-driven method and proposes an architecture for designing and developing a Model-driven Decision Support System (MDSS).

– Section 4 illustrates the loose-coupling technical framework through identifying and incorporating the key components for our model-driven method.

– Section 5 presents how we adopt the method in the Jingjiang flood diversion area, where we are commissioned by the government to assist the operation of the engineering and control the flood risk.

– Section 6 demonstrates the benefits of our model-driven method through comparing with some traditional solutions.

– The final section provides a summary of observations and recommendations for future directions of research in model-driven method for flood risk management.

2 Background

2.1 Overview of model-driven method research

Nowadays, developing applications for non-technical end users is becoming increasingly complex as they want to access these applications everywhere, at every moment of the day and the night and with many different devices (Gates, 2008). At the other hand, the model which address the decision support problem for flood risk management is become multidisciplinary (as discussed last section). Therefore, economists,

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geographers, water resource specialists, operation researchers and management scientists had to integrate their respective models together to support managers decision-making and planning.

Traditionally, by using of the object-oriented software engineering, many computer programs, which are based on tightly coupled integration of models and interface, is presented to help the decision maker make effective decisions. It is commonly believed that this way can guarantee the stability and high performance of the system. However, given the growing complexity and uncertainty in many decision situations of flood risk management, we need a special approach for dynamic adaptation of support to the needs of the decision maker. This approach needs to provide an integration platform for multidisciplinary model, not subject to geographical distribution, research area, development language, software tool and other constraints, and to guarantee that the system has a higher level of adaptability and reusability. Take above factors into consideration, focus of the study will be divided into two parts: (1) model-centric on the decision-making processes for the adaptability and (2) loosely-coupled on the implement for the flexibility.

Model-driven method (or Model-Driven Engineering) is a recent trend in software engineering whose main proposal is to focus on models rather than on computer programs (Bézivin, 2004). And it is being increasingly applied to enhance system development from perspectives of maintainability, extensibility and reusability (Mehmood and Jawawi, 2013). With the rapid development within the field of Web service technologies and Service-Oriented Computing (SOC), the model-driven method has widely been used in the area of Business Process Management (BPM) (Watson, 2008). Eom (2003) identified a wide variety of DSS applications reported in the academic literature. There are more than 1800 related articles, and many of them focused upon our research direction with good results. However, by querying this large number of scientific papers, we noticed that the model-driven research within the field of natural disasters is at the beginning stage, especially, the loose-coupling framework for resolving behavioural and technical challenges is more rare. Furthermore, we believe that

this approach would address the issues raised by the managers, end users and scientists from different disciplines. Therefore, we began the research, and will prove this hypothesis in later sections.

2.2 Behavioural and technical challenges

Behavioural and technical research on model-driven method needs to address many unresolved issues, which is identified by Power and Sharda (2007) as follows: (1) construction of specific quantitative models, (2) storage and retrieval of data needed by different types of models, (3) communication of parameters among models and other DSS (Decision Support System) components, (4) multi-participant interaction in model use and value elicitation, (5) impact of user interface design alternatives on model-driven DSS effectiveness and ease of use, and (6) building, deploying and using model-driven DSS. In addition, with the remarkable improvement of spatial representation research, there is a new challenge associated with the integration of geographic information systems (GISs) with multidisciplinary models (Merz et al., 2010).

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We define our model-driven method as a methodology that supports human decision making judgements by loose-coupling platform with multidisciplinary optimization and mathematical programming models. In this section, we will describe the behavioural aspects of this method, i.e. how it works (see Fig. 1). The technical aspects of implementation will be discussed in the Sect. 4.

All in all, the general types of models used in a model-driven DSS is numerous. They include algebraic and differential equation models; various decision analysis tools, including analytical hierarchy process, decision matrix and decision tree; multi-attribute and multi-criteria models; forecasting models; network and optimization models; Monte Carlo and discrete event simulation models; quantitative behavioural models

for multi-agent simulations. Therefore, the focus of research work is placed on how to provide a simplified representation of a situation that is understandable to a decision maker (Power and Sharda, 2007).

Our model-driven method is developed for various user groups, including man-
5 agers, practitioners and scientists from different disciplines. The main innovation is, our method makes the DDS in a Continuous-Integrated state. In other words, based on the loose-coupling platform, these systems can continue to "grow". Scientists can register their fresh models to address a new decision-making task at any time, or improve the adaptability of old models for reusability problems. Practitioners can customize the
10 decision process by combining models, and design the client by system interface (i.e. Interface Service, which will be referred in the Sect. 4.5). Managers, who have the right to make decisions, can use the common client or the recommended client by practitioners. Furthermore, the feedback mechanisms make the requirements clearer, and help systems more reasonable and reliable.

15 ## 4 Loose-coupling framework for the model-driven method

4.1 Overall framework

In this section, we will illustrate a technical solution, i.e. loose-coupling framework, for the model-driven development through identifying and incorporating the key compo-
nents. All in all, loose-coupling is the concept typically employed to deal with the re-
20 quirements of scalability, flexibility, and fault tolerance. The aim of loose coupling is to minimize dependencies. When there are fewer dependencies, modifications to or faults in one system will have fewer consequences on other systems. On the other hand, it makes the joint analysis of cross-regional models to be possible, e.g. mechanical ex-
perts in Beijing address the risk assessment, at the same time, hydrodynamic experts
25 in Wuhan deal with the damage estimation of flood routing.

The software is worked in a simple and clear structure. Client is only responsible for the function of user interaction, which collects user's command by events of various controls, then translate the order into a XML data stream and push it to Central Communication Service in Service Layer, the Load Balancing Server deal with this command and assign it to the right server. Finally, the process ends in the database changes. Therefore, scientists can register their models into Service Layer for easy uses, and manager can get results by beautiful interface.

The software architecture is composed by a three-layer structure (see Fig. 2), which is identified as follows: (1) base layer, supporting the distributed systems, including networks, softwares, operating systems, databases, etc., (2) services layer, service-oriented specific functionalities. Among them, a service provider publishes its description of service and interface in formation to the service registry. A service requester will find relevant service from this registry and binds to it to invoke the service, and (3) implementation layer. It provides web service applications to implement the service-oriented architecture (SOA). Details on this layer are discussed in later sections (see Sect. 4.3). In addition, The Services layer or its implementation layer can also project itself onto an operational layer, which consists of workflow components of publishing, discovery, composition, binding and execution (Hu et al., 2011).

We define the loose-coupling DSS as Model-driven decision support system (MDDS). In a MDDS, first, a uniform data platform (as Database Service) is presented to share multi-source data. Next, an open library (as Multidisciplinary Model Service) is presented to integrate cross-platform models. And, a universal linkage (as GIS Service) between GIS and models is presented by use of Service-oriented approach. Finally, a flexible interface system (as Interface Service) is presented to help practitioners customize the application for decision makers.

4.2 Uniform platform for data sharing

A GIS-based MDDS needs to deal with numerous raw data for decision-making, which includes the traditional structured data and other special data. The special data is

originated from remote sensing image, live video, live audio, and sensor stream and so on. In essence, it is multi-modal data with the characteristics of semi-structured or unstructured.

Many challenges are associated with the integration of the multi-source data. They include efficient structured treatment, heterogeneous data fusion, and cross-platform communication. By considering the specific problem in distributed systems and following the design concepts of SOA, this paper proposes a common unified data platform, which is divided into two parts, monographic data support and geographic data support. We will focus on the integration of these two in the following section. Finally, for different sources of the data, the Database Service provides various types of packaged web services interface to enable efficient interaction between the model library and user interface (see Fig. 3).

4.2.1 Similarity-based monographic data integration

The discrepancies in multi-source data occur both during eliminating duplicates from semantic overlapping sources and during combining complementary data from different sources (Schallehn et al., 2003). A similarity-based data integration model (SDIM) is used to deal with discrepancies in multi-source data. The discrepancies in structured data can be directly solved by existing operations of common relational database, such as SQL operations like grouping or join. However, for the unstructured or semi-structured data, integration process will be much more complicated. The processing steps of the unstructured data are as follows:

1. Extracts the features of data, automatically generate the data source configuration file and set the index item.

2. Supported by XML document conversion model, preprocesses the raw data in order to get the proposed keyword, and generates the XML index document. In XML, contexts are given through element and attribute names, and relationships by organizing data into trees and subtrees, and through id references.

3. Groups the XML information with similarity measures by its attribute and logical combination. The similarity formula is determined by the user preference, which will not be discussed here. It can be a simple threshold value or a complex comprehensive approach.

4. Add formatting information, and uses the relational database management software operations to sort the processed data.

4.2.2 Demand-oriented geographic data integration

The data for representing geology is diverse, heterogeneous and multi-source, so it is difficult to identify the correlation between them. The traditional integration methods are dedicated to the technical problems of data integration performance (Wu et al., 2005), such as data transmission and data query. In this paper, a demand-oriented geographic data integration model is used to establish a logical association between these data. First of all, the demand for geographical data in GIS-based decision support system is divided into two, spatial analysis and visual simulation. Then the proposed model builds the data schema from multisource data in a stepwise manner and involves six steps: (1) digitizing various geological data using existing software systems like ArcGIS or Microsoft SQL Server; (2) registration and fill in the details; (3) making sure they have uniform dimensions and data types; (4) building a hierarchical link list for each demand of models; (5) creating the geographic cache; and (6) modifying the index information for service's access.

4.3 Open library of optimization and mathematical programming models

In this section, we will describe how we address the loosely-coupling integration problem for multidisciplinary model.

The service-oriented architecture (SOA) is employed to solve the integration problems. In a SOA, each model can be published as a service, and can communicate with another model even though it has a different underlying operating system. These

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services are virtually unrelated functional units, but loose-coupling spread over inter-connected networks (Hu et al., 2011). It uses the Web Service Description Language (WSDL) for describing services; a mechanism called Universal Description Discovery and Integration (UDDI) for service registry and service discovery; then the simple object access protocol (SOAP) for exchange of messages. Web services use XML-based standards as a format.

The implementation layer, consists of various web service applications, is used to establish the loose-coupling open library, which accepts heterogeneity and leads to decentralization. The core of implementation layer is a specific infrastructure, called the Enterprise Service Bus (ESB), that allows us to combine the multidisciplinary models in an easy and flexible manner.

It is the responsibility of the ESB to enable managers to call the models providers supply (see Fig. 4). Depending on the technical and organizational approaches taken to implementing the ESB, this responsibility may involve (but is not limited to) the following tasks: Providing connectivity; Data transformation; (Intelligent) routing; Dealing with security; Dealing with reliability; Monitoring and logging; Model composition management; Model registry and deposit.

There are two ways for scientists to manage their models, personal management or delegated management. Both methods only need scientists to register models on the server by filling some parameter information. The managers still use an official end-point, which delegates the real task: when messages arrive, the load balancer sends them to the different physical service providers that it knows about.

4.4 Service-oriented linkage between GIS and models

Regional flood risk, generally considered at the river basin scale, is a decision making problem based on the physical and socio-economic conditions (McKinney and Cai, 2002). Spatial representations of the region consist of spatial objects and thematic objects. Spatial objects represent real world entities, with both geographical and physical, environmental and socioeconomic attributes. Thematic objects represent methods and

topics relevant to the spatial objects. Therefore, It is the responsibility of the GIS to represent the real spatial entities and provide spatial analysis and data processing. ArcGIS Server 9.3 is used to provide technical support. The key components can be listed as follows (ArcGIS Resource Center, 2008):

5
- Mapping Service. It serves cached maps and dynamic maps from ArcGIS.

- Geocode Service. It Finds address locations.

- Geodata Service. It provides geodatabase access, query, updates, and management services.

- Globe Service. It serves digital globes authored in ArcGIS.

10
- Image Service. It provides access to imagery collections.

- Network Analysis Service. It performs transportation network analysis such as routing, closest facility, and service area.

- Geometry Service. It provides geometric calculations such as buffer, simplify, and project.

15
- Geoprocessing Service. It provides spatial analysis and data processing services.

In our model-driven method, the first seven service is used to interact with managers by the GIS-Based client to represent the real spatial entities. The last one (i.e. Geoprocessing Service) is re-developed and integrated in the open library, similar in behaviour to a particular model. A geoprocessing service takes the simple data and turns it into
20
something extraordinary: the probable evacuation area for flood hazard, the map of land cover back five years, the risk-sensitive areas after a dam-break and so on. Because of the service is executed on the server computer, using resources of the server computer, the clients can be lightweight applications, and we do not need to cover the cost of GIS for each individual application.

4.5 Flexible user interfaces with expanded GIS

The goal of making model-driven DSS accessible to non-technical specialists implies that the design and capabilities of the user interface are important to the success within the system (Power and Sharda, 2007). The user interface controls how the user views results and influences how the user understands results and hence influences choices. In our model-driven method, the clients are lightweight, i.e. they only know how to send packets of simple requests to a server, and show the results through rich controls. Therefore, our client can be developed by a variety of technologies, such as Java Server Pages (JSP), Active Server Page (ASP), Qt, Winform, Windows Presentation Foundation (WPF), Objective-C (ObjC) and so on. The following section, we have a WPF which is described as an example.

Developed by Microsoft, the WPF is a computer-software graphical subsystem for rendering user interfaces in Windows-based applications. Extensible Application Markup Language (XAML) is employed to define and link various User Interface elements. Because of XAML is a XML-based language, it can be designed with any text editor. In our model-driven method, the Interface Service is presented to help practitioners customize the application for decision makers.

By Interface Service, practitioners can define that how many steps the decision-making process will be completed, then design the control's layout and operate logic for each step. Finally, designs will be translated into text, sent to the server and automatically generate to be corresponding XMAL documents. Decision makers run the program by downloading clients or landing web page.

Section on GIS, ArcGIS API (Application Programming Interface) for WPF is employed to create rich desktop applications that utilize the powerful mapping, geocoding, and geoprocessing capabilities provided by ArcGIS Server. Similarly, considered to be a normal control, practitioners can generate instances of GIS by XMAL.

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5 Model-driven Decision Support System in Jingjiang flood diversion area

5.1 Basic information about the case study area

The methodology and the model was performed and tested in the Jingjiang flood diversion area, situated in central China near the Yangtze River. It covers an area of 921.34 km^2 (see Fig. 5). It is the first large-scale hydraulic engineering built by the government of the People's Republic of China in 1952. Its main composition contains the incoming flood gate (North Gate), sluice (South Gate) and 208.38 km long embankments. The project's principal role is to ensure the safety of Jianghan Plain and the Wuhan City. Distinct from developed countries, China's flood diversion area is inhabited by a large number of people, its social and economic cost is very high, 581.8 thousand people living in eight towns, and the annual production value is USD 700 million. We are commissioned by the government to assist the operation of the engineering management and control the flood risk. The model validation is based on the successful application of this project in 1954.

5.2 A feasible decision process for flood risk management

In this section, we will show an example of the feasible decision process (as shown in Fig. 6). Multisource remote sensing images, DEM and hydrological data were coupled with the uniform data-sharing platform. Flood forecasting models can derive the flood process in the next two weeks. Based on hydrodynamic calculations of flood routing simulation models, flood risk assessment and damage estimation models can provide the qualitative or quantitative results, generate various thematic maps to describe the distribution of flood risk, provide guidance on the evacuation and assist control flood path for government policy-makers.

5.3 Hydrology analysis and forecasting

The flood characteristics, such as the frequency, return period, coefficient of skew, co-efficient of variation, and so on, are analysed based on historic observed stream flow data. It can provide the basis for choosing those typical flood processes. Meanwhile, to dynamic evaluate the risk and damage of flood hazard in real time, the actual-time flood forecasting model is integrated in our system. At first, we analyse the characteristics of the hydrological system in the sensitive area of flood. Based on this, a conceptual model, the famous Xinanjiang model (Zhao, 1984), is constructed to simulate the flood processes. Currently, the traditional calibration of hydrological models with single objective cannot properly measure all the behaviours within the system. To circumvent this backward, an efficient evolution algorithm entitled Multi-objective Culture Shuffled Complex Differential Evolution (MOCSCDE) algorithm (see Appendix A) is proposed by us to optimize the model parameters. This algorithm can get better convergence and spread performance, and can significantly improve the calibration accuracy (Guo et al., 2012). These results provide an important basis for studying the mechanism of flood routing.

5.4 Flood routing simulation

The flood dynamic routing simulation and the flood risk maps drawing are based on DEM (Digital Elevation Model). The hydrodynamic member of our research team develops a well-balanced Godunov-type finite volume algorithm for modelling free-surface shallow flows over irregular topography with complex geometry. The research results have been published in many academic journals (Song et al., 2011a). This two-dimensional hydrodynamic model is based on a new formulation of the classical shallow water equations in hyperbolic conservation form (see Appendix B), and running to describe the state of flood, such as water depth, velocity, duration and submerged area.

The computational domain was triangulated with 77 741 elements, 39 389 nodes and 117 129 lines. Area of the smallest unit is 4246 m^2, area of the biggest unit is 20 000 m^2, and length of the shortest line is 69 m. In addition, triangles were more densely organized along the river to ensure the calculation accuracy. The total value of the flood is 2.35 billion m^3, and the largest flood diversion flow is 6190 m^3 s^{-1}.

We obtained the bottom elevation of computational grid by bilinear interpolation with high resolution DEM data, and set the roughness values of each computing unit by land use data. Based on hydrodynamic calculations, the risk mapping module generate various thematic maps to describe the distribution of flood risk, provide guidance on the evacuation and assist control flood path for government policy-makers. Figure 7 shows the simulation results, e.g. the water depth changes within the flood routing, which lasted about 131 h.

5.5 Flood risk assessment

As we have known, the flood risk assessment is a synthetic evaluation and consists of many factors, and due to the factors are natural and socioeconomic in various areas, and several of them have not unified quantitative criteria, which make the flood risk assessment index system complex and difficult to operate (Du et al., 2006; Li et al., 2008; Jiang et al., 2008). Based on disaster system theory, taking into consideration the factors, following the systematic, quantitative and operability, universality principle, the primary flood risk assessment index system of flood diversion district is established. According to local investigations, references to historical information, public participation, expert judgments and so on (Du et al., 2006; Li et al., 2008), we obtain the grading criteria for each factor.

Several methods, such as fuzzy comprehensive assessment method (Jiang et al., 2008), variable fuzzy sets theory (Chen and Guo, 2006), attribute interval recognition theory (Zou et al., 2011) are employed for flood hazard assessment and flood vulnerability assessment.

Recently, a new model for comprehensive flood risk assessment was presented by us, named set pair analysis-variable fuzzy sets model (SPAVFS) (Zou et al., 2012c), which is based on set pair analysis (SPA) and variable fuzzy sets (VFS) theory. This model determines the relative membership degree function of VFS by using SPA method and has the advantages of intuitionist course, simple calculation and good generality application. Its flow chart is shown in Fig. 8.

The flood-risk-analysis module is made up with the management of risk analysis data, the risk assessment models for flood risk analysis and the flood risk maps, and it could show results with a map and chart mode. And the specific technical route of this module is as follows:

– Based on GIS, statistical data and yearbook, we collect the precipitation data, elevation data, land use data, social-economic data and so on.

– Then taking the towns as the basic assessment units, we count out four hazard assessment indexes characteristic values (see Table 1 and Fig. 9) by the simulation results of hydrodynamic models, including average maximum flow velocity and flood depth, flood submerging range and flood arriving time. Moreover, considering the fact that the weather, terrain and river distribution had a greater impact on flood hazard assessment, we add up the other three hazard assessment indexes, e.g. annual average precipitation, average ground elevation and land use rate. What's more, for flood vulnerability assessment, there are corresponding six indexes (see Table 2), which are the population density, industrial output density, agricultural production densities, breeding area percentage, animal's density as well as road network density. Hence, according to the situation of Jingjiang flood diversion area, we collect the data for flood hazard and vulnerability analysis respectively.

– After the establishment of the flood-risk-assessment-index-system and the grading criteria, respectively, thus the flood hazard and vulnerability assessment results can be obtained by SPAVFS method. Here the flood hazard, vulnerability

and risk are divided into five grades, noted as very low, low, medium, high and very high.

– With the flood hazard and vulnerability assessment results by the assessment methods step by step, and the flood-risk-grade-classification-matrix (Du et al., 2006), we get access to the corresponding risk grade for each assessment unit. And finally, we are able to carry out the flood risk maps (see Fig. 10) for the Jingjiang flood diversion district.

5.6 Flood damage estimation

The final part is the flood damage estimation. First, we collect the data of flood ranges. As the Fig. 11 shows, affected area with different depth of water is marked by diverse colours, and we can seek the estimation results of each town. At the same time, we also can see the relation of time and damage estimation by grid-based flood analysis model.

The processing steps of grid-based flood analysis model (see Fig. 12) are as follows:

– Using the result of the two-dimensional hydrodynamic model, the water depth and the flow velocity are recorded in the nodes, then use GIS spatial analyst component, IDW (Inverse Distance Weighted) interpolation method to obtain the flood submerge raster.

– Damages of different aspects, including the loss of houses, industry, affected population, and economic loss (see Table 3), can easily be quantified by a flood disaster evaluation model (Xie, 2011). Its equation is as follow:

$$W = \sum_i \sum_j \sum_k \alpha_i A_{ij} \eta_{jk}, \tag{1}$$

where i, j, k is respectively the cell code of calculation grid, the land utilization type, water depth. A_{ij} represent for the i calculation unit the j type of disaster-affected-body original related social-economic cell value. η_{jk} stand for the loss

rate of j type of disaster-affected-body combined with k level of water depth. α_i is representative for the state of the calculation grid. When $i = 1$, means the land utilization type is used to calculate the loss; when $i = 0$, means the cell land utilization type is others.

- – A series of tools in Geoprocessing Service, which mentioned in the Sect. 4.4, was published to handle raster data. All the flood evolution raster is reclassified to grades of water depth, and mixed up with the submerge information by time sequence.

6 Method benefits

The method described in this paper was applied to five projects in the past four years. It has been playing the role of substitute for existing programmes. Compared with traditional solutions, this section identifies and discusses the benefits of our model-driven method.

6.1 Supporting heterogeneity

By nature, all large systems are heterogeneous. These systems have different purposes, times of implementation, and ages, and it is commonly found that the system landscapes are accretions of different platforms, programming languages, programming paradigms, and even middleware. In the past, the traditional solutions attempt to solve the problems of scalability by harmonization, sometimes they work, but the maintenance cost becomes incredibly expensive with the expansion of the system (Josuttis, 2009).

In our model-driven method, ESB (see Sect. 4.3) is employed. The idea behind it is that instead of creating and maintaining individual communication channels, each model only has to connect to the bus to be able to connect to all other models. In order to be extended for the larger system, we have identified the research directions

related to the technical and organizational rules of implementing a flexible framework. The heterogeneous models are virtually unrelated functional units, but loose-coupling spread over interconnected networks.

6.2 Dynamic adaptation of support to the needs of the decision maker

Dynamic adaptation, which be defined in this paper, means that the system can be flexible and reliable restructuring to meet the different needs of the decision maker. Compared to the traditional method, the main advantage of our method is software life-cycle, which at its core consists of phases of design, implementation, integration, and bringing into production. Most traditional methods are waterfall-like approaches, i.e. gradually complete the process by one way. It does not work because of requirements as well as contexts change over time (Josuttis, 2009).

Our method makes the DDS in a Continuous-Integrated state (see Sect. 3 and Fig. 1). Open library (see Sect. 4.3) can provide the suitable model composition by iterative service development with managers' feedback. New clients are also available at any time through a simple XAML design by practitioners (see Sect. 4.5). Therefore, our method can provide the dynamic adaptation of support to the needs of the decision maker.

6.3 Protection of intellectual property rights

In traditional object-oriented programs, the models are running as plugins, extensions or code block. Illegal software technicians can get the source code by some simple decompile tools. This is major hazard of the interdisciplinary cooperation.

In our model-driven method, by using SOA, the web service mode restricts the behaviour of user access models. When a user accesses the service, we focus on three aspects of security: (1) authentication, which has to do with verifying an identity. This means finding out who is calling the service; (2) authorization. It has to do with determining what an identity is allowed to do, i.e. this means checking whether the caller is

allowed to call the service and/or see the result, and (3) auditing, which involve recording all security-relevant information, so that we can detect or analyse security holes and attacks. This mechanism ensures that users cannot use the model until they pass the legal validation.

7   Conclusions

Quantitative models embedded in a DSS can help managers make better decisions (Power and Sharda, 2007), and the effectiveness of DSS is enhanced through dynamic adaptation of support to the needs of the decision maker (Bijan et al., 1997). This paper presents a beneficial approach to ensure the adaptability of DSS for flood risk management, and the main innovation is the application of model-driven concepts, which are promising for loose-coupling of GIS and multidisciplinary models.

During the course of model-driven method, several important issues specific to the implementation effort became apparent and had to be resolved. The service-oriented architecture (SOA) is employed to solve the integration problems. SOA accepts that the only way to maintain flexibility in large distributed systems is to support heterogeneity, decentralization, and fault tolerance (Josuttis, 2009). It is not a specific technology, but a way of thinking. Our model-driven method is a strategy that includes both technical and organizational aspects. Organizationally, we need appropriate processes so that it is clear how to design new solutions and identify new services (see Sect. 3). Technically, we need some infrastructure to provide interoperability (see Sect. 4). In addition, our Model-driven Decision Support System (MDSS) is running successfully to manage the flood risk in Jingjiang flood diversion area, located in central China near the Yangtze River (see Sect. 5). Section 6 demonstrates the benefits of our model-driven method through comparing with some traditional solutions. It demonstrates that MDSS is reasonable, reliable and flexible, thus has bright prospects of application for comprehensive flood risk assessment.

Appendix A

MOCSCDE algorithm for hydrology forecasting

Suppose the optimization is done under the framework of multi-objective. If the pre-defined objective functions conflict with each other, then the final optimization results cannot be one individual but a set of individuals who are the so-called non-dominated results. If all the objective functions are aimed to be minimized, this optimization problem can be defined as follows:

$$\min\{f_1(X), f_2(X), \ldots, f_M(X)\}$$

$$X = [x_1, x_2, \ldots, x_D],\tag{A1}$$

where M is the number of objective functions, X denotes the model parameters, $f_i()$ is the i-th objective function. In this paper, the objective functions are as:

$$\text{MSLE} = \frac{1}{N} \sum_{i=1}^{N} \left(\ln Q_i - \ln \hat{Q}_i \right)^2 \tag{A2}$$

$$\text{M4E} = \frac{1}{N} \sum_{i=1}^{N} \left(Q_i - \hat{Q}_i \right)^4, \tag{A3}$$

where N is the sample length, Q_i denotes the i-th observed streamflow value and $\hat{Q}_i$ is the i-th simulated streamflow value. And the flowchart of the proposed algorithm MOCSCDE is shown in Fig. 13.

Appendix B

Shallow water equations in hyperbolic conservation form

The classical shallow water equations are referred to the formulation of hydrostatic pressure and bottom slope effects and their division between fluxes and source terms. Song et al. (2011) proposed a formulation of the classical two-dimensional shallow water equations in conservation form:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = S. \tag{B1}$$

In which,

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \quad E = \begin{bmatrix} hu \\ hu^2 + g(h^2 - b^2)/2 \\ huv \end{bmatrix}, \quad G = \begin{bmatrix} hv \\ huv \\ hv^2 + g(h^2 - b^2)/2 \end{bmatrix},$$

$$S = S_0 + S_f = \begin{bmatrix} 0 \\ g(h + b)S_{0x} \\ g(h + b)S_{0y} \end{bmatrix} + \begin{bmatrix} 0 \\ -ghS_{fx} \\ -ghS_{fy} \end{bmatrix},$$

where h is the water depth; u and v are the velocity components in the x and y directions respectively; b is the bed elevation; S_{0x} and S_{0y} are bed slopes in the x and y directions respectively, assume the bed is fixed, i.e. $b = b(x, y)$, then $S_{0x} = -\partial b/\partial x$ and $S_{0y} = -\partial b/\partial y$; g is the gravity acceleration; S_{fx} and S_{fy} are the friction terms in the x and y directions respectively. The friction terms are estimated by Manning formulae:

$$S_{fx} = \frac{n^2 u \sqrt{u^2 + v^2}}{h^{4/3}}, \quad S_{fy} = \frac{n^2 v \sqrt{u^2 + v^2}}{h^{4/3}}. \tag{B2}$$

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Table 1. Hazard characteristic by analysing submerged condition.

Town	Flow velocity (ms^{-1})	Flood depth (m)	Arriving time (h)	Submerging range (km^2)	Precipitation (mm)	Elevation (m)
Fuhe	0.43	1.85	0	177.73	1064	36.18
Douhudi	0.3	2.3	10.41	84.61	1064	33.27
Yangjiachang	0.04	0.7	36.66	61.35	1064	33.77
Mahaokou	0.2	3.14	37.91	169.15	1064	32.27
Ouchi	0.28	3.25	48.74	93.01	1211	32.27
Huangshantou	0.32	3.88	59.58	89.76	1400	33.68
Zhakou	0.35	3.45	28.33	125.75	1064	32.1
Jiazhuyuan	0.37	2.15	15.83	128.54	1064	33.51

Table 2. Vulnerability characteristic within the unit area (e.g. $1\,km^2$).

Town	Population	Road (m)	Industry (10^4¥)	Agricultural (10^4¥)	Animals	Breeding area
Fuhe	440.86	241.17	1104.96	101.43	25.19	3.53 %
Douhudi	1520.18	425.1	3824.32	130.13	77.79	6.01 %
Yangjiachang	393.85	100.18	1534.6	110.01	24.58	5.56 %
Mahaokou	342.38	255.45	762.95	108.79	87.94	8.05 %
Ouchi	475.49	314.74	2539.23	106.19	62.35	20.9 %
Huangshantou	334.16	243.76	292.55	81.38	99.65	11.92 %
Zhakou	404.1	282.33	798.59	92.34	78.42	10.48 %
Jiazhuyuan	427.3	242.9	771.78	128.5	72.11	7.42 %

Table 3. The result of quantitative flood damage estimation module.

Town	Affected houses	Industry (10^4¥)	Affected population	Economic loss (10^4¥)
Puhe	24 614	7441.73	22 260.49	29 931.68
DouhuDi	37 315	9032.57	9617.81	18 903.33
Yangjiachang	4287	1464.52	6683.63	8293.80
Mahaokou	27 484	5929.71	20 300.79	26 418.28
Ouchi	17 279	5737.39	9701.07	15 974.35
Huangshantou	11 768	7.67	6330.81	6545.33
Zhakou	17 574	2355.12	8649.18	11 416.63
Jiazhuyuan	14 388	2424.80	14 270.33	17 021.73

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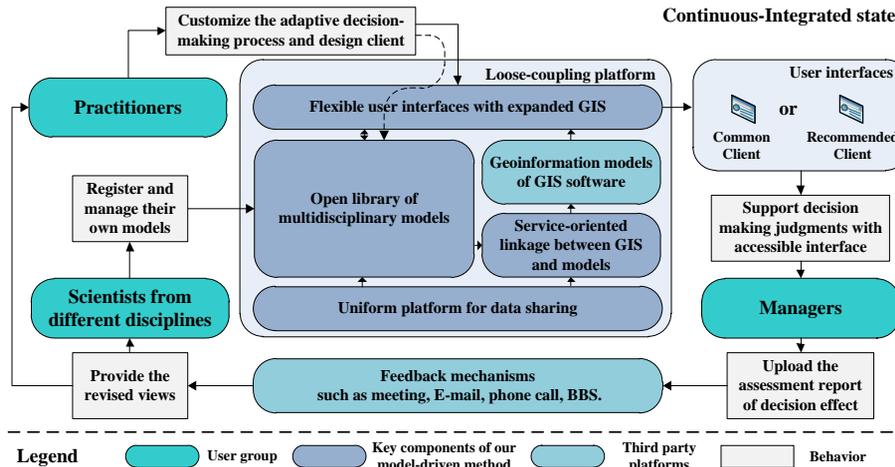
Fig. 1. Behavioural aspects of the model-driven method for flood risk management.
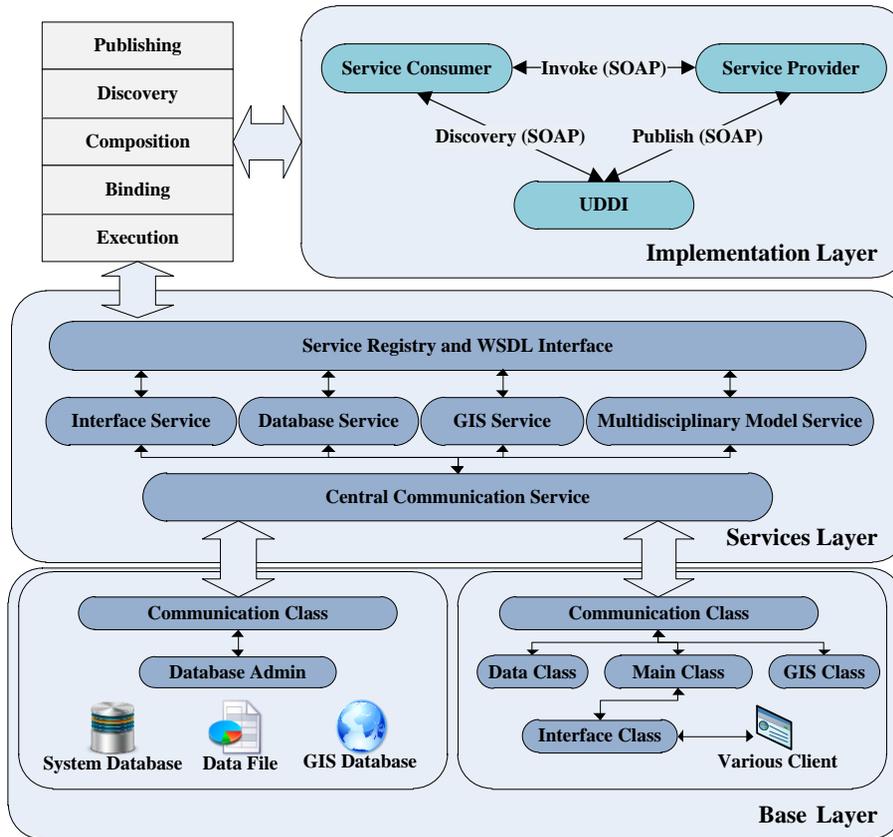
Fig. 2. Loose-coupling framework for the model-driven method.

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Fig. 3. Architecture of the uniform data sharing platform.

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Fig. 4. Open library of optimization and mathematical programming models.

Fig. 5. Location of the study area: **(A)** map of China, in which the annotated area is Hubei province. **(B)** Map of Hubei, in which the annotated area is JianghanPlain, WuhanCity, and Jingjiang flood diversion area. **(C)** Map of Jingjiang flood diversion area.
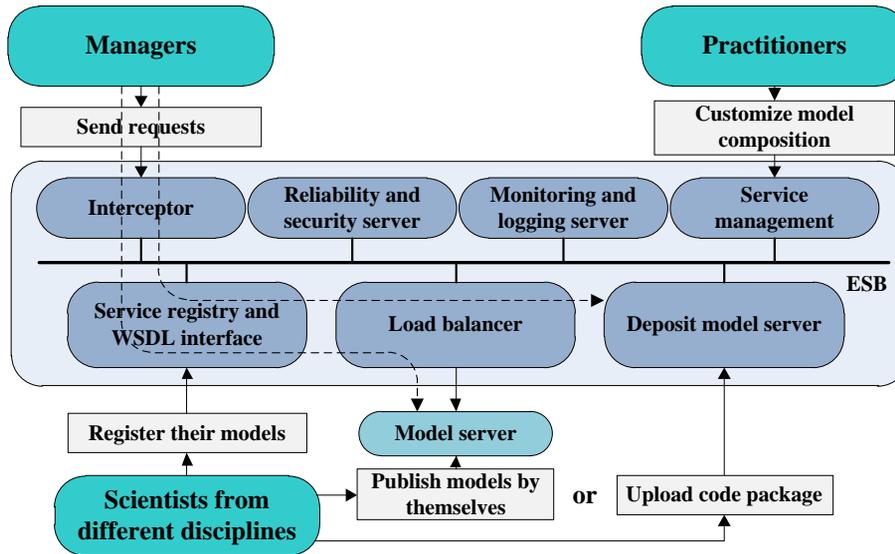
Fig. 6. A feasible decision process for flood risk assessment and damage estimation; data source.

Water depth (m)

- 0
- 0.001–0.5
- 0.5–1.0
- 1.0–1.5
- 1.5–2.0
- 2.0–2.5
- 2.5–3.0
- 3.0–3.5
- 3.5–4.0
- 4.0–5.0
- 5.0–7.0
- Embankment
- Cofferdam

0 6 12 24 36 Km

t = 1.67 h　　t = 11.25 h　　t = 25 h　　t = 35.84 h

t = 58.34 h　　t = 70.84 h　　t = 84.17 h　　t = 130.83 h
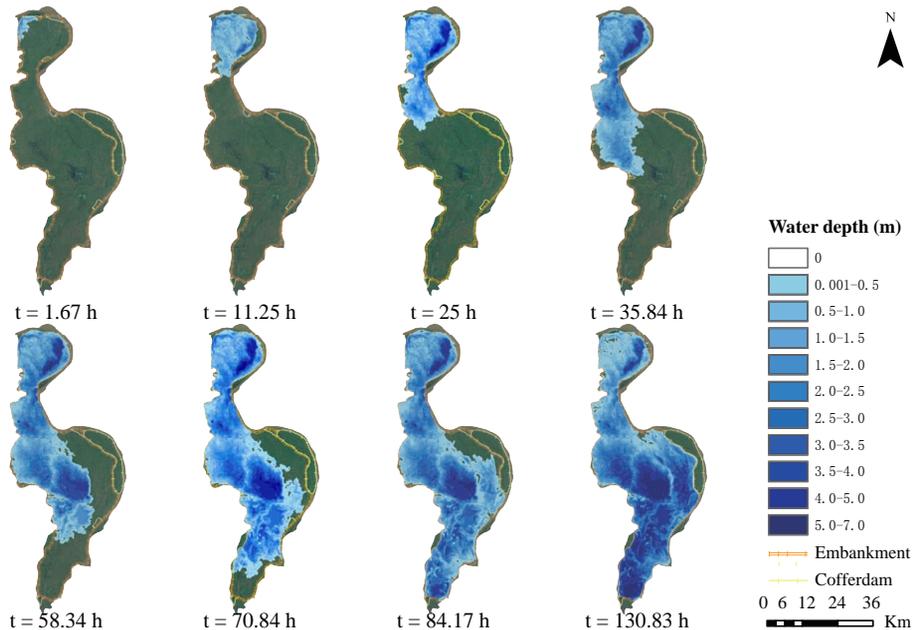
Fig. 7. Filled contours plot of initial and computed water depth given by the present model at time t = 1.67, 11.25, 25, 35.84, 58.34, 70.84, 84.17, and 130.83 h.

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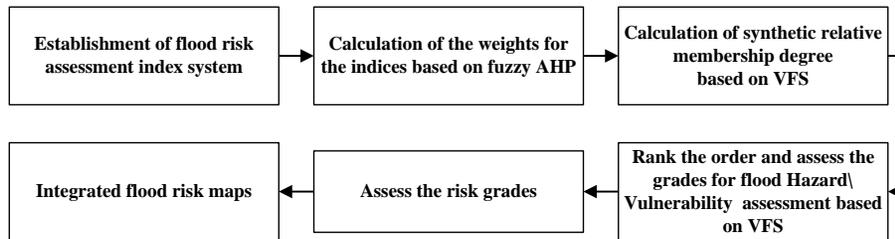
Fig. 8. Flow chart of flood disaster risk assessment.
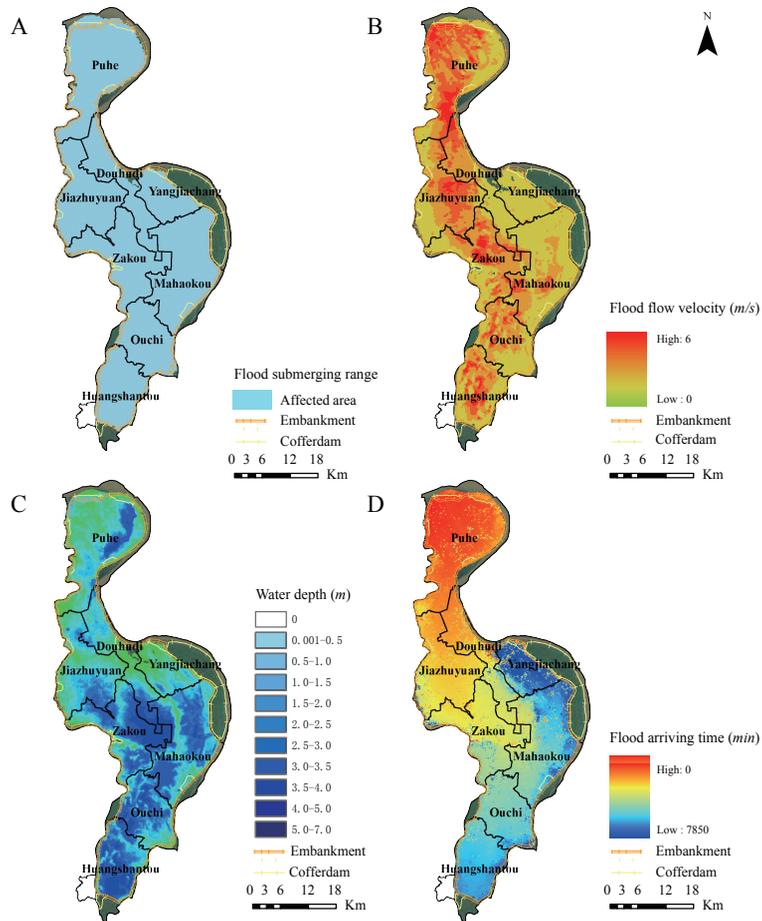
Fig. 9. Four hazard assessment indexes characteristic values from the simulation results of hydrodynamic models: **(A)** flood submerging range; **(B)** flood flow velocity; **(C)** flood water depth; **(D)** flood arriving time.

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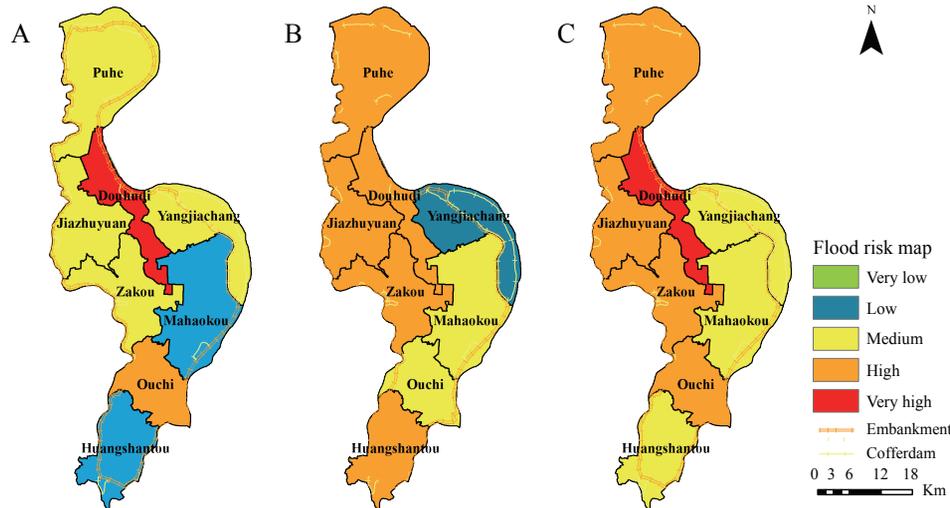
Fig. 10. Integrated flood risk maps for Jingjiang flood diversion district: **(A)** flood vulnerability grade map; **(B)** flood hazard grade map; **(C)** flood risk grade map.
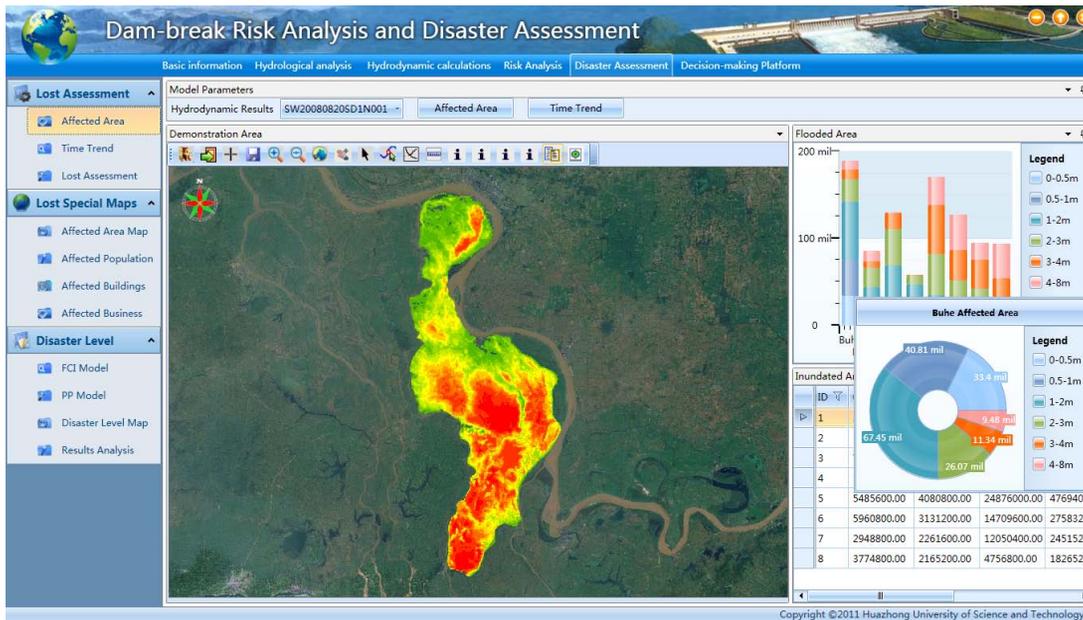
Fig. 11. Interface of submerged condition analysis in quantitative flood damage estimation module.
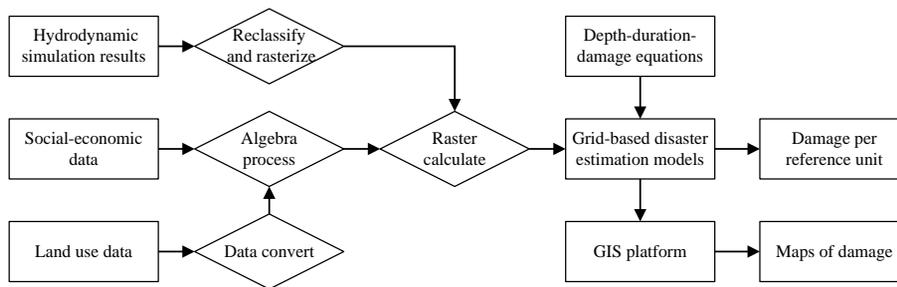
Fig. 12. The process of flood submerging analyst and flood hazard loss evaluation.
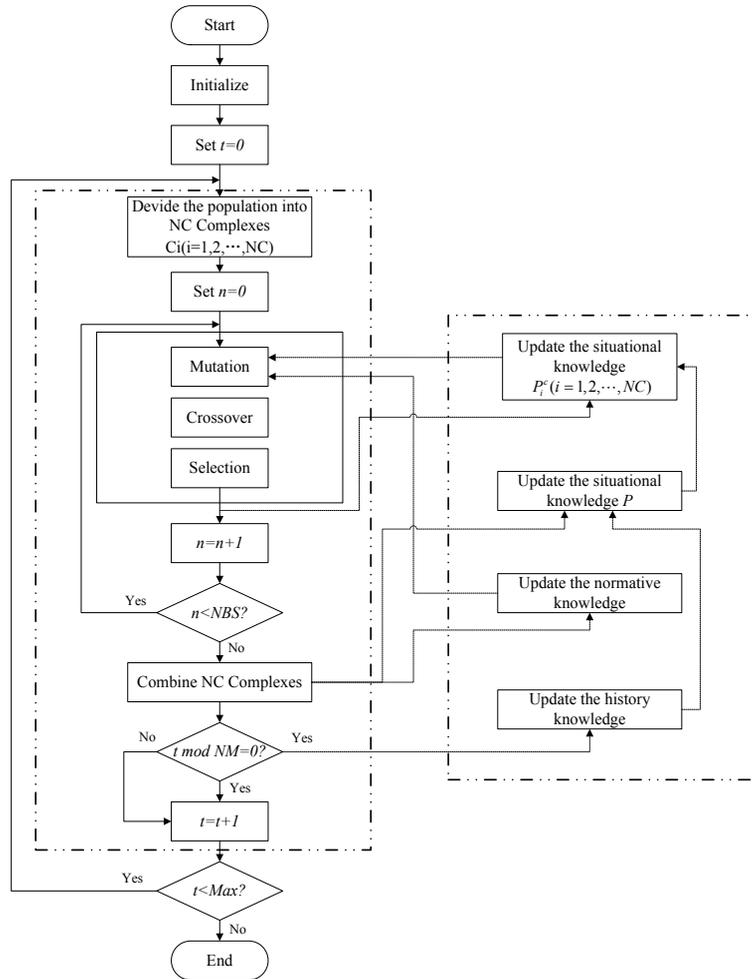
Fig. 13. Flowchart of Multi-objective Culture Shuffled Complex Differential Evolution.

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