Urban Flood Simulation and Integrated Flood Risk Management

– Case Study in Changsha Central City, China

Dissertation submitted in partial fulfillment of the requirements of the degree "Doctor of Engineering (Dr.-Ing.)" of the Faculty of Spatial Planning at the Technical University of Dortmund, Germany

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ABSTRACT

Climate change induces the probability of occurring natural disasters; e.g. floods, Sea Level Rise, Green House Gases. Flood is considered one of the most dangerous phenomena that tremendously and dramatically threatening the human being and environment worldwide. Rapid urban growth, demographic explosion, and unplanned land uses have exacerbated the problem of urban flooding, particularly in the cities of China. In addition to that, the concept of flood risk management and adaptation measures and strategies are still missed in the cities' development future plans.

The main objective of this Ph.D. dissertation is to investigate the flood risk analysis and assessment based on flood simulation and adaptive strategies for flood event through two case studies of Changsha city in south-central China.

In case study I, fluvial flooding was considered on mesoscale and an MCA-based approach was proposed to assess the integrated flood risk of Changsha central city. HEC-RAS 1-D model was used to simulation the inundation characteristics for hazard analysis based on four risk dimensions: economic, social, environmental, and infrastructural risk. For infrastructural dimension, apart for direct damage on road segments, network analysis method was combined with inundation information and macroscopic traffic simulation to evaluate the impact on traffic volume as well as a decrease of road service level. Closeness centrality weighted with a travel time of pre- and after- flood was compared in order to measure the impact on urban accessibility. Integrated risk values were calculated using various weighting criteria sets. Sobol' indices were used as a tool of spatially-explicit global Uncertainty Analysis and Sensitivity Analysis (UA/SA) for damage models.

In case study II, an agent-based modeling approach was proposed to simulate the emergency pluvial flood event caused by a short-time rainstorm in local areas of cities aiming at developing an interactive flood emergency management system capable of interpreting the risk and reduction strategy of the pluvial flood. The simulation integrated an inundation model with microscopic traffic simulation. It also reveals that all agents can benefit significantly from both engineering measures and the only pedestrian obtain relatively more benefits from risk warning with high awareness. The method provided potentials in studies on the adaptive emergency management and risk reduction, help both decision-makers and stakeholders to acquire deeper and comprehensive understanding of the flood risk.

This Ph.D. study has investigated holistic methods and models' selection in flood risk assessment and management to overcome data deficiency and to achieve the integration of different data. The results of the first case study reveal that the integrated methods have proved to be able to improved flood risk analysis and assessment especially for indirect damage of infrastructural system with network features. The global UA/SA based on Sobol' method and visualization with maps enable to gain the spatial distribution of uncertainty for various factors, the validation of damage models, and deeper and more comprehensive understanding of flood risk. Then based on the integrated risk assessment, functions of spatial planning in flood risk management were discussed, potentially providing guidance and support for decision-making.

The results of the second case study denote that agent-based modeling and simulation can be effectively utilized for flood emergency management. Two scenarios focusing on specific risk reduction interventions were designed and compared. Engineering measures by improving capability of the drainage system and the surface permeability of waterlogging areas are the most effective means for damage mitigation. High public risk awareness still has great potential benefits of the in the event of emergencies, which can greatly enhance the effectiveness of the official warning. The agent-based modeling and simulation provided an effective method for analyzing the effectiveness of different strategies for reducing flood risk at the local scale and for supporting urban flood emergency management. The case studies also indicate the significance and necessity of establishing a platform and database to realize full sharing and synergies of spatial information resources for flood risk management, which is a vital issue to manage the urban flood risk and take effective measures correspondingly with responding to emergency extreme flood event.

Keywords: urban flood; flood risk assessment; network analysis; flood simulation; flood risk management

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ABBREVIATIONS

AAD:	Average Annual Damage
ABM:	Agent-Based Modeling
ADPC:	Asian Disaster Preparedness Center
ADT:	Average Daily Traffic
APA:	the American Planning Association
APL:	Average Path Length
ARI:	Average Recurrence Interval
BMLFUW:	Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (The Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management)
CA:	Cellular Automaton
CBA:	Cost-Benefit Analysis
CC:	Clustering Coefficient
CMA:	China Meteorological Administration
COSFCDRH:	China Office of State Flood Control and Drought Relief Headquarters
DEFRA:	the U.K. Department for Environment, Food and Rural Affairs'
DEM:	Digital Elevation Model
DHM:	Distributed Hydrological Model
DKKV:	Deutsches Komitee für Katastrophenvorsorge
DSM:	Digital Surface Model
DTM:	Digital Terrain Model
FEMA/EMI:	Federal Emergency Management Agency/Emergency Management Institute
FRM:	Flood Risk Management
GFDRR:	The Global Facility for Disaster Reduction and Recovery
GIS:	Geographic Information System
GWP:	the Global Water Partnership
ICE:	the U.K Institution of Civil Engineers
IFM:	Integrated Flood Management
LULC:	Land Use/Land Cover
LiDAR:	Light Detecting and Ranging

MCA:	Multi-Criteria Approach
NASG:	National Administration of Surveying, Mapping & Geo-information of China
NDVI:	the Normalized Difference Vegetation Index
NDRC:	National Disaster Reduction Centre of China
NIH:	the U.S. National Institutes of Health
OD:	Origin–Destination
PCU:	Passenger Car Unit
POI:	Points Of Interest
RIBA:	Royal Institute of British Architects
SAR:	Synthetic Aperture Radar
SPRC:	the Source-Pathway-Receptor-Consequence concept
UA/SA：	Uncertainty analysis and sensitivity analysis
UNDESA:	Department of Economic and Social Affairs of the United Nations
UNDRO:	the United Nations Disaster Relief coordinator Office
UNISDR:	The United Nations Office for Disaster Risk Reduction
USACE:	US department of defense, Army Corps of Engineers
VBA:	Visual Basic for Applications
WFD:	the EC Water Framework Directive
WMO:	the World Meteorological Organization

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Increasing urban flood

Flood is one of the most threatening natural hazards that have severe negative impacts on human beings. According to the statistics of Munich Re Group (2009), there was an overall trend of increasingly severe natural disasters in recent decades worldwide, out of which, 93% were caused by atmospheric conditions and flood events (Figure 1-1). It is not a new finding that climate changes induced by anthropogenic factors have undermined the water cycle and directly exacerbated the global flood risk. The climate change, to a large extent, has increased flood frequency and uncertainty, making it more challenging to predict and causing massive fatalities and amount of property loss (Parry et al., 2004; Milly et al., 2007; Bernstein et al., 2008; Huong & Pathirana, 2013).

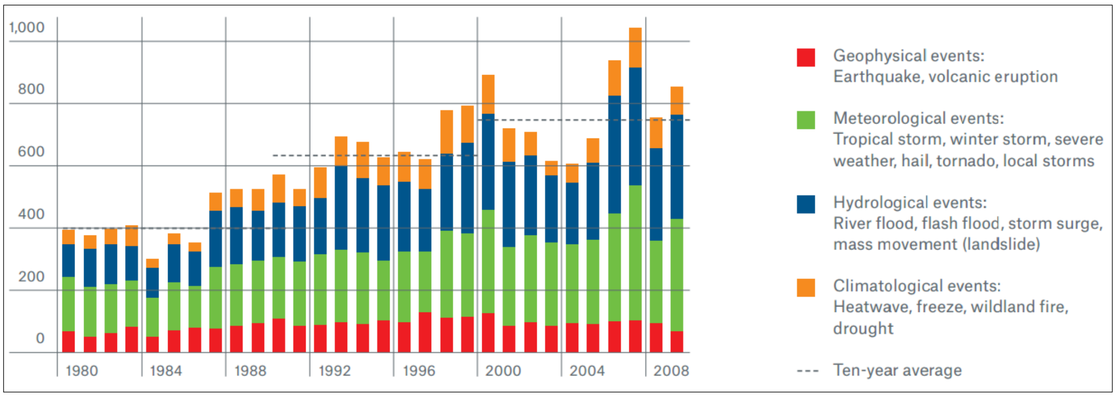


Figure 1-1: Number of natural catastrophes since 1980 (Source: Munich Re Group, 2009)

The situation is even worse in many urban areas. On one hand, some cities around the world locate in low-lying areas and close to water bodies, which in turn makes them more exposed to the flood hazards. On the other hand, due to the high density of population and wealth, cities usually take on a huge loss when the floodwaters come. Moreover, there is an obvious global urbanization trend. According to UNDESA[1], in 1950 only less than one-third of the population was urban in the world. While in 2014 the proportion of urban population reached 54%. And the number will be 66% by 2050 (UNDESA, 2014). Therefore, in the light of global climate change and on-going urbanization, urban flood becomes

[1] the Department of Economic and Social Affairs of the United Nations

a crucial problem that many cities are confronted with across the world (Figure 1-2).

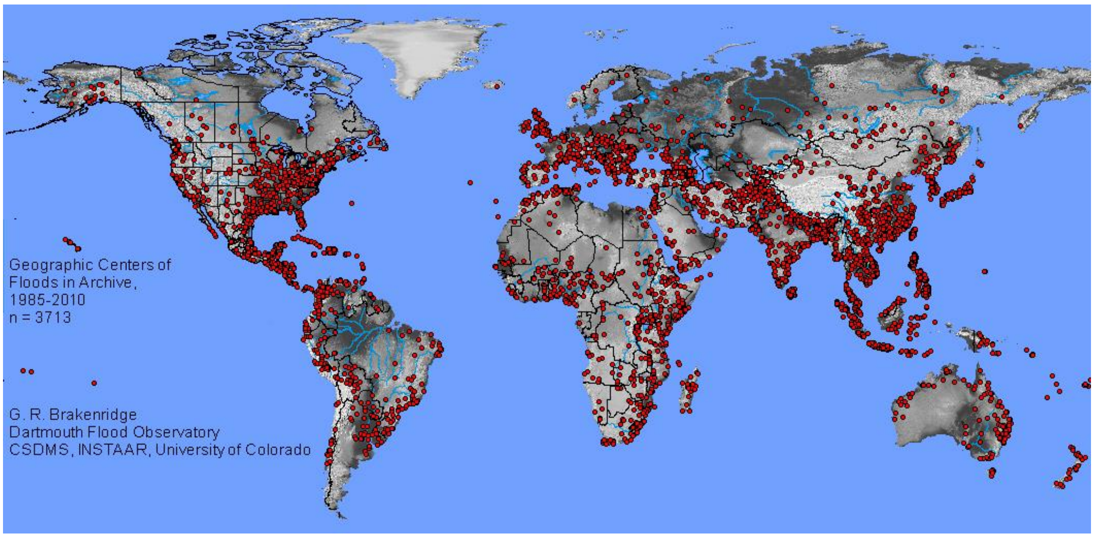


Figure 1-2: Geographic Centers of floods in the Flood Archive GIS file, 1985-2010 (Source: http://floodobservatory.colorado.edu/Flood Observatory)

1.1.2 Urban flood in South China

China is one of the most flood-affected countries in the world. The world's top 5 severe floods in history have all occurred in China. In the year 1931, the world's deadliest flooding disasters in China took away millions of lives (Pietz, 2002). According to the 2012 statistics from China's Office of The State Flood Control and Drought Relief Headquarters (COSFCDRH), the flooded land use accounts for about one tenth, covering 40% of the population, 35% of agricultural land and 70% of gross domestic product (COSFCDRH, 2012) (Figure 1-3).

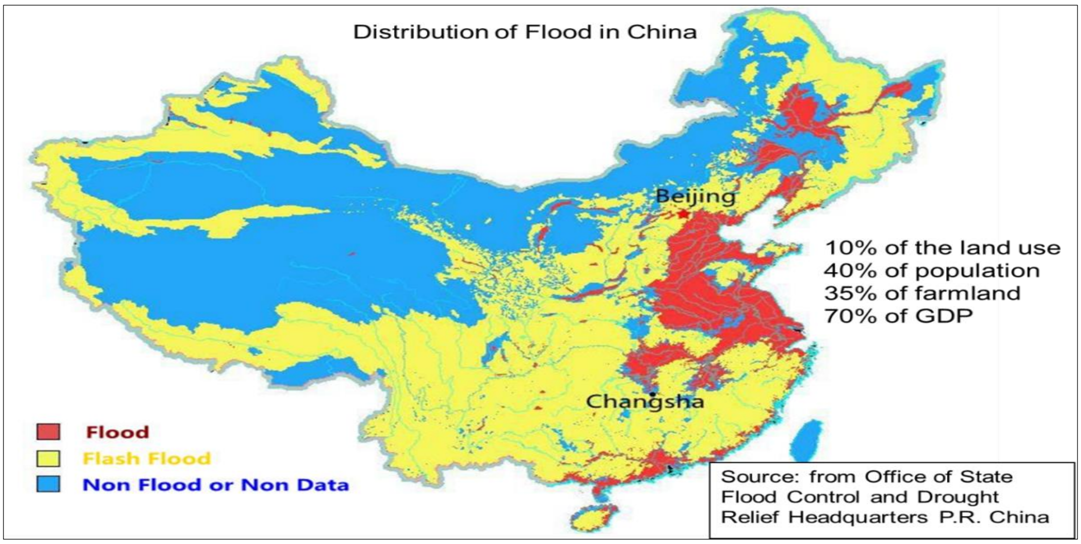


Figure 1-3: Spatial distribution of flood in China (Source: China's OSFCDRH, 2012)

Over the years, the urban flood damage increases dramatically in China, especially in the light of the rapid socio-economic development and rapid urbanization. In the last two decades, the share of agriculture was reduced in the national economy, falling below 10% in 2014. Due to changes in land use, the major losses have shifted from the countryside to cities (Kenyon et al., 2008; Neuhold & Nachtnebel, 2008; Schanze et al., 2009a, b; BMLFUW, 2009). Moreover, owing to the process of urbanization, the increasing areas of the impermeable cover change the run-off mode of the urban stream and reduce the capacity of water storage and penetration. Problems such as urban heat island and rain island effect could change the local climate and then influence the intensity and distribution of rainfall (Santamouris, 2013). Given rapid urbanization and unplanned urban construction and development, the requirements of the adaptation strategies for sustainable flood management in many cities of China are still missing, which has increased the potential damage (Du et al., 2012). According to COSFCDRH Annual Report 2012, about 95% of the 672 Chinese cities, are suffering from flood hazards, causing heavy economic losses (COSFCDRH, 2012).

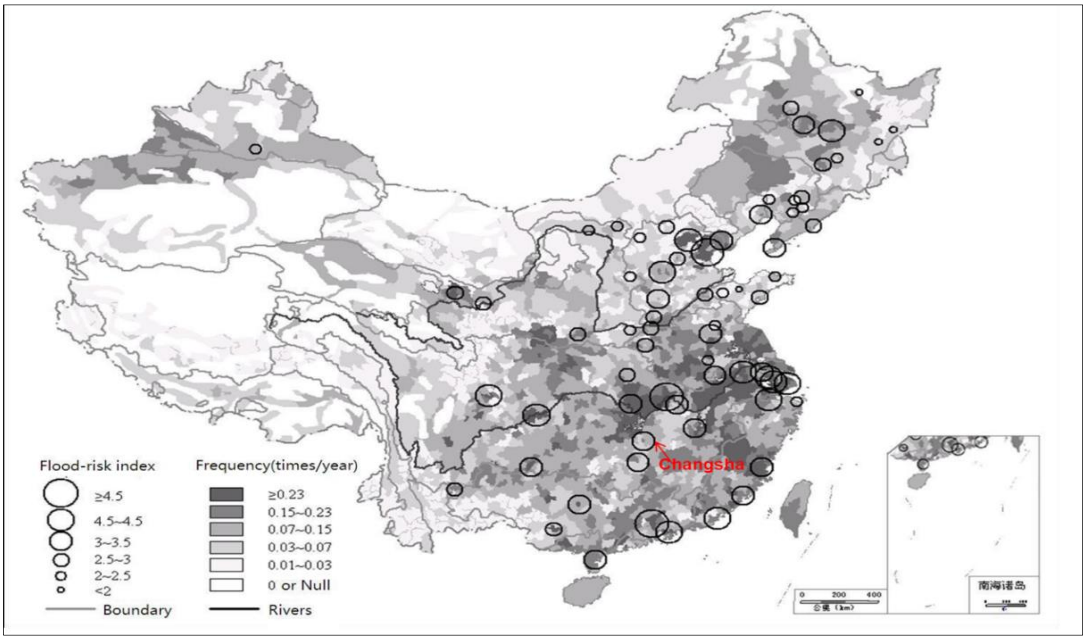


Figure 1-4: 70 flood-prone cities in China (Source: COSFCDRH, 2012)

Figure 1-4 shows 70 major flood-prone cities in China. As can be seen from the figure, the flood frequency in the middle and lower reaches of the Yangtze River area, which hosts about 1/3 people and around 40% GDP of China, is obviously higher than other regions. Apart from the climate factors that heavy precipitation caused by tropical air masses and tropical cyclones, another primary factor is agricultural reclamation and urban expansion in floodplains. In the year 1998, heavy flood left about 4,000 death tolls and an economic loss of US$25 billion (Pittock & Xu, 2011). Statistics from China Meteorological Administration (CMA, 2011) show that although the death toll of flood decreases dramatically since 1950, flood losses per unit area continue to grow over the years (Figure 1-5).

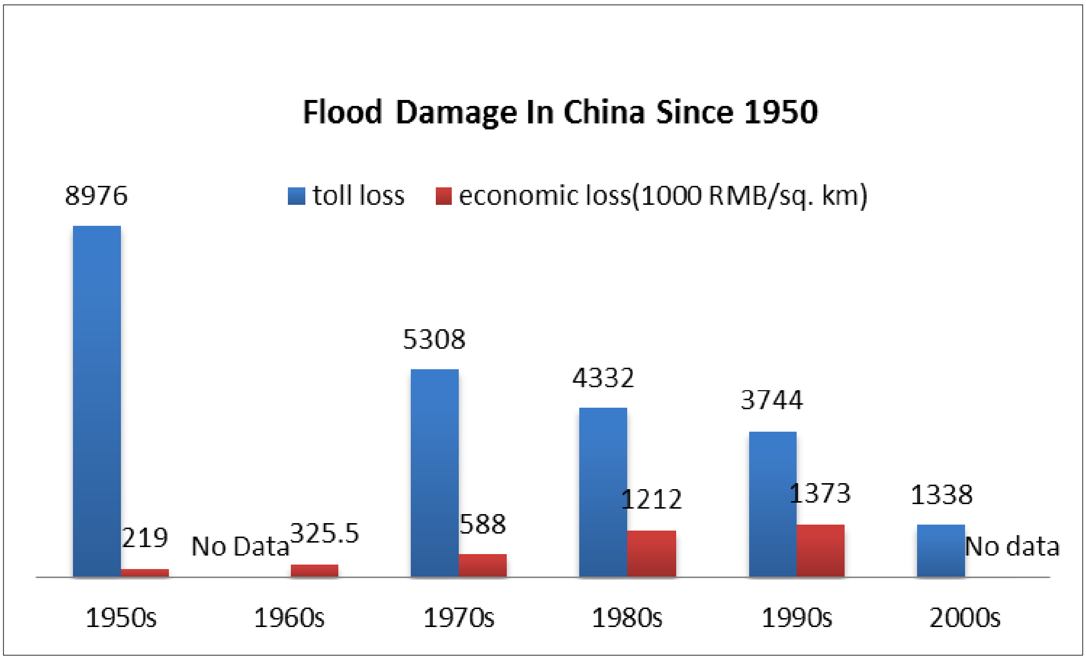


Figure 1-5: Flood damage in China since 1950 (Source: CMA, 2011)

Besides, urban rainfall-waterlogging disasters caused by the heavy rainfall increased without effective coping strategies. Urban systems in some cities could be semi-paralyzed or even totally paralyzed because of rainfall-waterlogging. The obsolete drainage system and insufficiency of urban flood management result in the frequent occurrence of flood disaster (Huang & Xu, 2006; Liu & Guan, 2013; Che et al., 2010). Therefore, cities in China urgently require effective and sustainable Flood Risk Management (FRM), developing comprehensive approaches to deal with the conflicts between urban development and flood disasters.

1.1.3 Challenges of Flood Risk Management in China

Cities in China are confronted with many challenges referring to many aspects of FRM. Firstly, the paucity of data and ineffective integration of FRM into urban planning constrains the implementation of effective FRM strategies. Thoroughly understanding of flood risk system is the key factor to achieve successful FRM in the urban areas. Thus, a comprehensive database is essential to supply a baseline of required data; e.g. rainfall-runoff records, land use, facilities systems, etc., which are very critical for decision-making. Unfortunately, in China lack of data sharing greatly restricts development of knowledge and technology with regard to FRM. Until now, two out-of-date national geographic coordinate systems, the Beijing Geographic Coordinate System 1954 (GCS Beijing 54) and Xi'an Geographic Coordinate System 1980 (GCS Xi'an 80), still exist and widely used. Even in the same city, different government sectors adopt different ones. For instance, the land bureau usually uses GCS Xi'an 80 while the urban planning bureau uses GCS Beijing 54. Though in 2008 the State Council put forward to the implementation plan on a unified coordinate system, China Geographic Coordinate System 2000 (GCS 2000) to replace the old systems, all those co-existing in many local authorities. In the meanwhile, it is difficult for researchers to obtain the essential data from relevant authorities. Accurate terrain data privacy significantly hinders the scientific research and increases management costs. Moreover, the lack of sharing information and knowledge transfer can take place among varying departments. For example, management plans from the engineering department may be not accessible by the staffs in the department who are in charge of maintenance. This highlights that the absence of integration protocols and regulations can also hinder significantly achieving effective FRM. Hence, confusion and conservative in data management and integrated FRM with urban planning are the most critical issues.

Secondly, cities are complex systems formed by increasingly multifunctional and interdependent infrastructures, e.g. transportation system, power transmission and drainage system, which have the network characteristics. It can inevitably lead to cascading failures across all the infrastructure systems, resulting in much wider and more long-lasting impacts when deluged partly. In some flood events, a local waterlogging can result in transport disruption and power cut or the collapse of the electrical system, bringing enormous loss to people's lives and properties. The flooding actions are threatening most of the cities and countries worldwide not only in China, for instance, in the year 2007 floods in British caused hundreds of thousands of residents living without water and electricity supply for many days and 10 thousand people being stranded on motorways or railways (Pitt, 2008). While among 640 Chinese cities, the lagging drainage system and insufficiency of urban planning are the most important reasons for the occurrence of flood disaster (Huang & Xu, 2006; Liu & Guan, 2013). Especially in the summer season in southern China, it is frequent to be waterlogging caused by such insufficient design for floods with a reasonable

Average Recurrence Interval (ARI) in the urban area, plunging the whole city into an almost standstill. However, there is a lack of effective approaches for such indirect flood damage assessment. Hence, the overall risks are usually underestimated because of neglecting the interconnectedness of infrastructures.

Thirdly, urban flooding not only causes socio-economic losses but also affects citizens’ lifestyle-related behaviors, which is most conspicuous in residents’ travel. Hence, taking individual behaviors into consideration in research, it can be benefitted to make well-designed risk reduction strategies. Transportation is the vital system and the fundamental service in the urban areas. Transport system undertakes the function of moving people and logistics to maintain the normal operation of society. A very convenient urban transport can significantly contribute to making cities work in an efficient and effective way. As outlined above, the networking features of the transport system often influence a large area of the city or even the whole for the urban flooding. The resultant disorder of transportation greatly weakens urban mobility and influence humans' behavior. It is also a difficult issue to assess that indirect and intangible flood damage and react to it.

Although China has built series of flood control engineering system and proposed relative laws and regulations for flood control and management of river courses, there are still great gaps for Changsha city to adapt and facing the hazard. Several reasons contribute to this problem. First of all, for a long time, the government emphasis on using hydraulic engineering to control flood. Even so, non-structural measures are coming to be valued, people are still deeply affected by "thought inertia" when making a decision. Flood management does not only mean building large-scale water projects like dam and reservoir but rather should be reflected in every detail of urban design and construction. Flood water should be made full use as a natural resource rather than be controlled and protected from the urban system.

In many less-developed regions and cities, FRM still is not regulated as there is a lack in historical records and statistics, non-standard procedures for flood risk assessment or even no risk evaluation. The causes of the problem are the imbalance of risk distribution and economic development; thus, the affluent regions have a great financial capability to invest for flood management even though they locate in considered low flood risk areas. On contrary, some impoverished regions in high flood risk areas could not bear such burdens, which requires the upper governments reasonably allocate the public resources at higher levels.

In addition, public participation is absent in FRM process. On one hand, the governmental agencies usually play dominated roles in flood management as if they were adults. On the other hand, the public are relatively indifference to flood risk and accustomed to being protected as children. Though there are some regulations referring to compensate of damage of residents in a floodplain or high-risk area and flood insurance are still not popular in China. One reason is lacking the participation of commercial insurance company. The other is the common low awareness of residents. It should be realized that the whole society ought to bear the social responsibility for FRM. Such issues may also influence decision makers and city managers before revealing the actual level of risk applying to an area to the public, which sometimes has much bigger negative impacts on the flood risk situation in the area. There must be awareness amongst residents and proper cooperation between decision makers, risk management authorities and the public in the process of FRM; otherwise, it will be very difficult to control the deterioration of the global urban flood risk situation (Jha et al., 2012). Thus, all the government, especially the local government, insurance company as well as residents at risk should cooperate and work through flood mitigation.

1.2 Research objectives, questions and scope

1.2.1 Research objectives

The main objective of this research is to elaborate multiple approaches to improve flood risk assessment for cities of China and to make policy recommendations in accordance with the result in the context of low availability, quality of data, and a lack of public participation. It consists of specific objectives as follows:

(a) to select an appropriate method to analyze and assess the flood risk along with case studies at different special scales, providing good examples of FRM in cities of China. Due to the relatively coarse spatial resolution of terrain data, varying types and sources of flooding and the complexity of urban environments, accurate flood risk assessment remains a great challenge;

(b) to find an effective approach to improve flood risk assessment for infrastructure system. Current research seldom focuses on the indirect impact of the urban flood, which thus needs to be investigated to provide an effective approach to assess the indirect damages;

(c) to study on the influence of flood risk on citizens' behaviors and in turn public participant on risk reduction in a flood emergency. One of the main goals of FRM is to reduce flood damages and improve the urban development strategy. Simulation supports "what if" experiments for evaluating the effectiveness of different flood risk adaptive strategies and thus making suggestions on urban decision-making.

1.2.2 Research questions

In essence of the trend of more severe urban flood disaster and the above-mentioned challenges, it is imperative for cities of China to improve the level of FRM. Moreover, as a broad range of issues FRM covers, the research will focus its exploration and discussion through three main research questions and several sub-questions, as follows:

(1) How can flood risk assessment be conducted in case of data deficiency?

a) How to make full use of open source data in flood risk assessment?
b) What kind of criteria categories should be covered in risk assessment?
c) What is the spatial uncertainty and sensitivity of the assessment model?

(2) What is the flood impact on urban infrastructure networks?

a) What is the topological characteristic of urban infrastructure networks and why it is important to flood impact?
b) How can the flood damage to infrastructure networks be evaluated?
c) Is the indirect flood impact on urban infrastructure networks too trivial thus can be neglected?

(3) How to manage urban flood risk in consideration of public participation in flood emergency management?

a) What are the individual roles in flood risk reduction?
b) What is the effectiveness of measures and are instruments with public participation for flood risk reduction feasible and in practice?

1.2.3 Research scope

This dissertation focuses on flood risk assessment and the response phase of flood event by simulation techniques and tools. Two types of flooding: fluvial flood and pluvial flood, the most frequent flood in cities of China, are covered, which are conducted through two case studies.

First, river flooding is relative low-density and slow-onset hazard. Even though, a complication of influence factor of the flood (the flood peak level and flood peak discharge), to some extent, could be forecasted. Flood protection facilities also enable people gained time to evacuate from potentially flooded and damaged areas. However, river flooding is a type of hazard with strongly destructive power. The entire catchment was taken as a whole on the long term. Moreover, it has already considered that FRM concerns the governmental responsibilities by a series of means such as land use planning, spatial planning, or constructing engineering facilities, adopting administrative, legal and regulatory approaches etc. It also involves interests of both governmental institutions and citizens who should share the responsibility. Thus, the base of implementation of the measures is an in-depth understanding of flood risk. Therefore, the first case study focuses on fluvial flood risk assessment on a city scale, oriented toward further decision-makings for spatial planning and development of the city.

Next, a pluvial flood occurs frequently in Changsha. The Changsha central city is often subjected to waterlogging disasters due to poor FRM, resulting in significant damages all over the city. Unlike fluvial flooding, pluvial flooding usually gets into waterlogging, and large traffic jams or disruptions rather than death. It is often caused by a sudden and high uncertain meteorological phenomenon and is characterized by abruptness and nonlinearity. To reduce the flood risk, it is crucial to involve stakeholders in FRM. The feature of sudden and correlation of life makes pluvial flood cannot only test urban emergency response mechanism but also the public consciousness about flood risk. The aim of the second case study is to demonstrate the potential and utility of flood simulation for flood risk reduction by dynamic risk analysis. Hence, it focuses on pluvial flooding caused sudden rain and study on the public participation in flood emergency management and comparison of different adaptive strategies on a community scale.

The scope of research focus can be visually expressed in Figure 1-6 as follow:

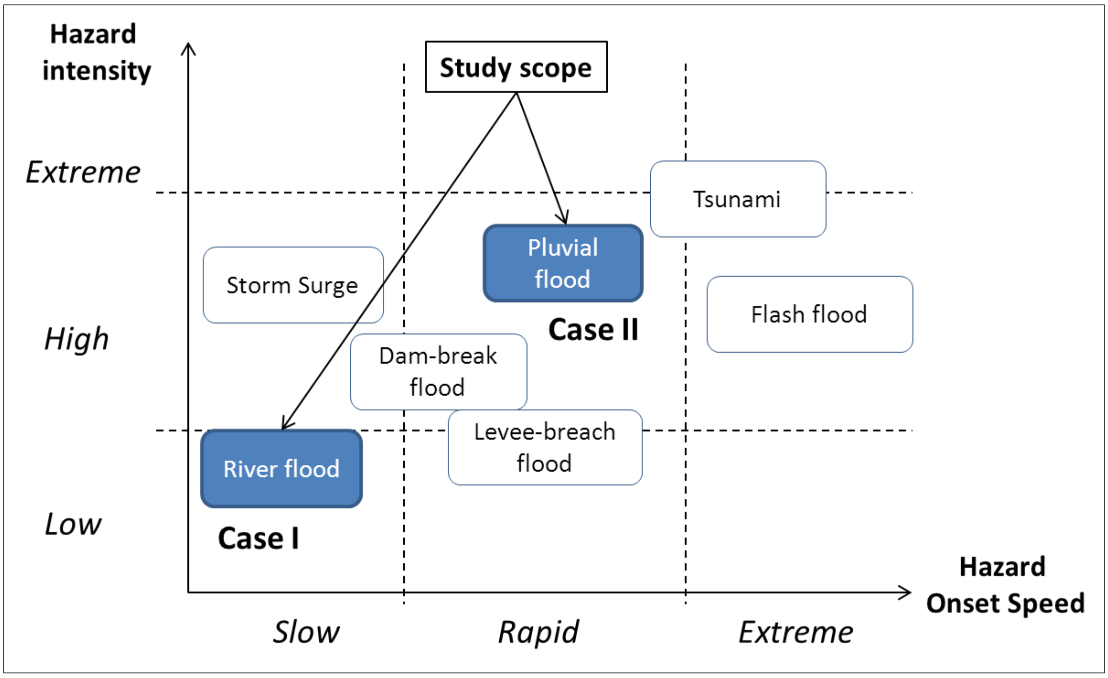


Figure 1-6: Research focus and consideration of case studies (modified based on Johnstone, 2012)

1.3 Study area

1.3.1 Overview of the study area

The Changsha central city was chosen as the study area, which is not only the administrative center of Changsha municipality but also the capital city of Hunan Provence, in south-central China. It is situated along the Xiangjiang River, a branch of the Yangtze River. It is far away from the sea, experiencing a humid subtropical climate. The mean annual precipitation reaches 1,330 mm. It is located in the alluvial basin and low-lying north high south. Cold air from the north can invade and gather here easily. It is colder than that of other regions at the same latitude in winter and hotter in summer. The annual average temperature is 17.0 °C (Changsha Statistical Yearbook, 2014).

Urban flood happened frequently throughout Changsha's history, causing heavy economic losses and many human casualties. Over the past three decades, urbanization of Changsha has been continuously increased. More and more population live in the central city. By the year 2010, the population density of central Changsha reached up to 10,326/km^2. Until 2013, the urbanization ratio was over 70%, and the built-up area was about 5 times larger than in the year

1978 as shown in Figure 1-7. Accompanied by the growth of population, the economic proportion is increasingly on the rise in the urban area. Consequently, the loss of urban flood per unit area has been on the rise in decades, especially since 1994 (Table 1-1).

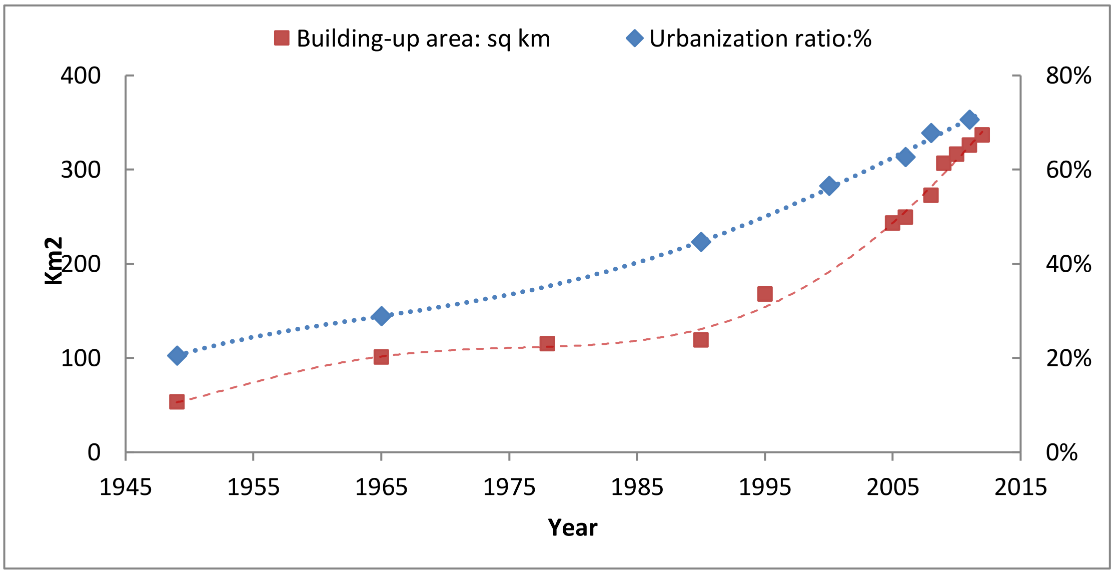


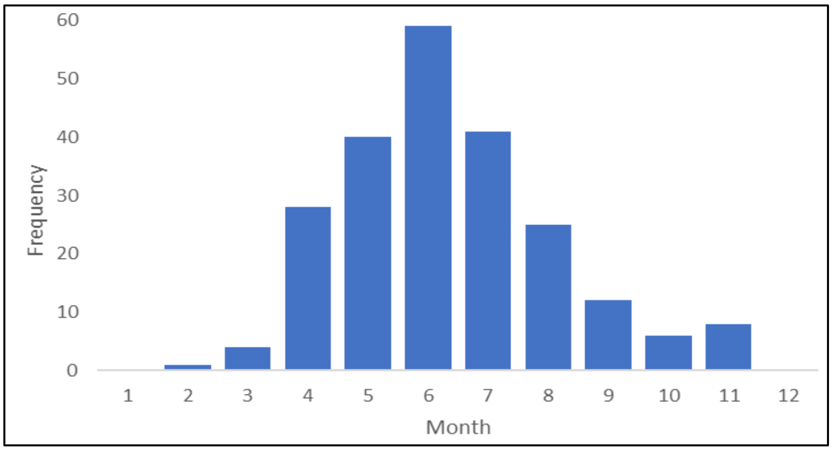
Figure 1-7: Rapid development of Changsha City

Table 1-1: Statistics of Flood in Changsha's History

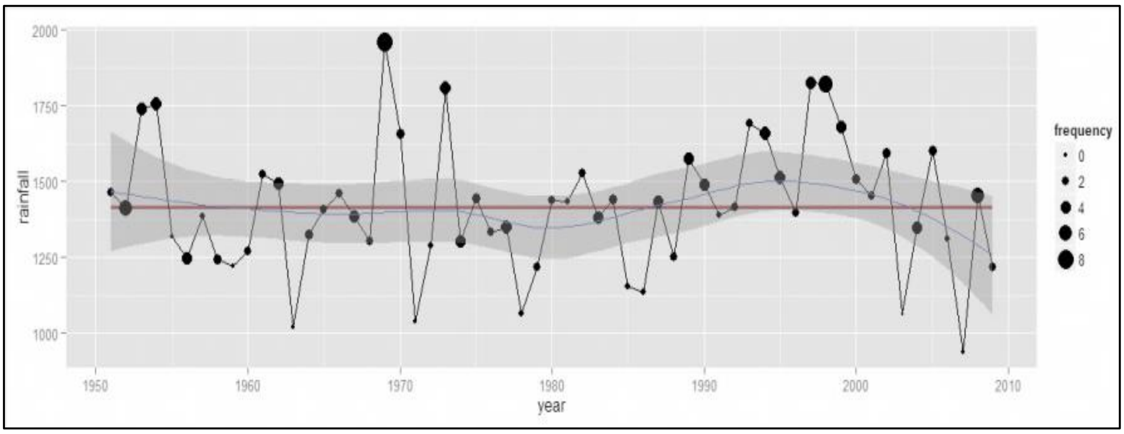
Year	Affected people (th.)	Affected farmland (ha.)	Flooded houses	Direct-economic loss (th. RMB)
1950	26.5	1600	5856	16,820
1954	45.6	4367	6100	34,900
1964	45.2	933	14941	39,170
1965	13.1	1840	1245	12,450
1976	101	593	48296	126,190
1982	130.6	3107	15770	45,130
1983	94	2620	6136	19,550
1990	10	2860	2337	10,950
1992	11.2	5000	8411	23,890
1994	444.2	4745	78282	783,520
1998	465.4	18080	24009	1,859,200
2002	0.7	32830	3700	410,000
2003	400	1087	700	251,000
2006	460	4600	8000	272,000
2007	282.9	119660	/	481,000

Source: Water Affairs Bureau of Changsha, 2009

The main aspect that influences the Changsha's flooding is natural climate. According to annual precipitation data series, Changsha has large precipitation variability. The max annual precipitation is 2100 mm for the year 1998, 628.9 mm more than normal year and 2.3 times as much as the minimum of 898.9 mm for the year 1969. Pluvial floods in urban area are often triggered by heavy downpour in summer as in Figure 1-8a. As shown in the Figure 1-8b, although the annual mean precipitation decreases gradually over recent years, storms hit Changsha city frequently rather than reducing accordingly. Besides, annual precipitation distribution is also unevenly, as it rains frequently and concentratedly every year with 152 mm daily average of precipitation. The mean continuous rain lasts common 15-20 days, with the maximum value at 23 days in May of the year 1958. And most of the precipitations are distributed between May and August (accounting for 70%-80%). The short-term storms are usually included in longer ones. From 1949 to 1998, the probability of 1-day storm included in 3-day storm is 57.1% and storms are usually followed by another one, lasting at least 5 days. Once the precipitation is above 200 mm, severe floods will consequently occur.



(a) Storm Frequency



(b) Annual Mean Precipitation of 1951~2009

Figure 1-8: Statistics of Changsha's precipitation and storms

Another aspect contributing the Changsha's flooding is terrain. The city is located in the low-lying floodplain and ringed on three sides by multiple rivers. Due to on the level 1~4 terraces along the river, the ground elevation is generally 30~33 meters. The annual mean highest water is 1~3 meters above ground level. Thus, the city is exposed to floods which originate from either north or south, listed in one of 31 cities vulnerable to floods (CMA, 2009).

1.3.2 Spatial scales of case studies

The first case study refers to fluvial flooding simulation and risk assessment, which is carried out at the mesoscale, covering the central part of Changsha city. The investigation area covers 5 districts of Changsha City, including 55 sub-districts. It has an area of 362.62 km^2, with maximum horizontal distance thing 23 km north-south and maximum vertical distance 12 km. According to the 2010 and 2013 Census, it has a population of 2.9 and 3.1 million respectively. The average population density of the area is 15515 people per km^2. Figure 1-9 shows the location and the spatial range of the Changsha central city.

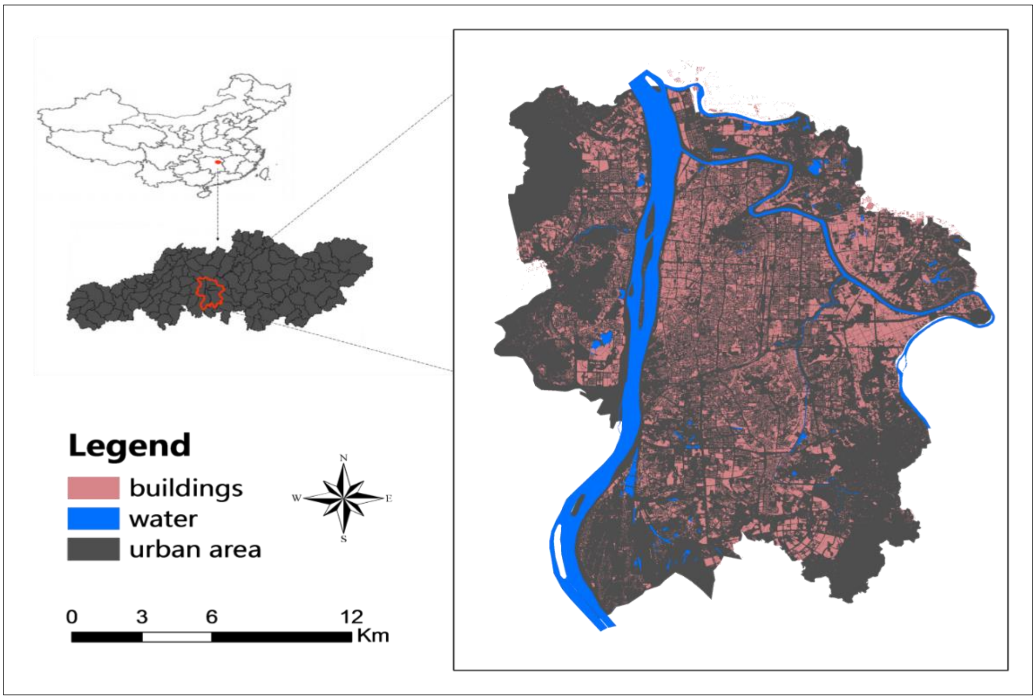


Figure 1-9: Location of Changsha central city

The second case study investigates the pluvial flood at the sub-district level. The investigation area in this case study is Furong Square and its surrounding areas locate in the east of Changsha's inner city where it is far away from floodplain. As the provincial political, economic and cultural center, in this area most of the administrative authorities are localized, high-density population, important transportation hubs and clusters of shopping centers, department stores, and supermarkets, etc. The investigation area gathers a large number of population and economic output. According to the 2013 Census, the permanent residents is about 220,000 and the population density is over 40,000 persons per km^2, which is about 7.5 times as large as the average value. The GDP per unit area is 3 times more than the whole central city (CMA, 2014). Precipitation in the area is abundant. The annual average precipitation is circa 1500 mm. Particularly in the stormy summer months (April~June), heavy rains are concentrated inside and surrounding this area, causing water accumulation and inundation in traffic-heavy places. Figure 1-10 and Table 1-2 show the detailed information about waterlogging situations in recent years.

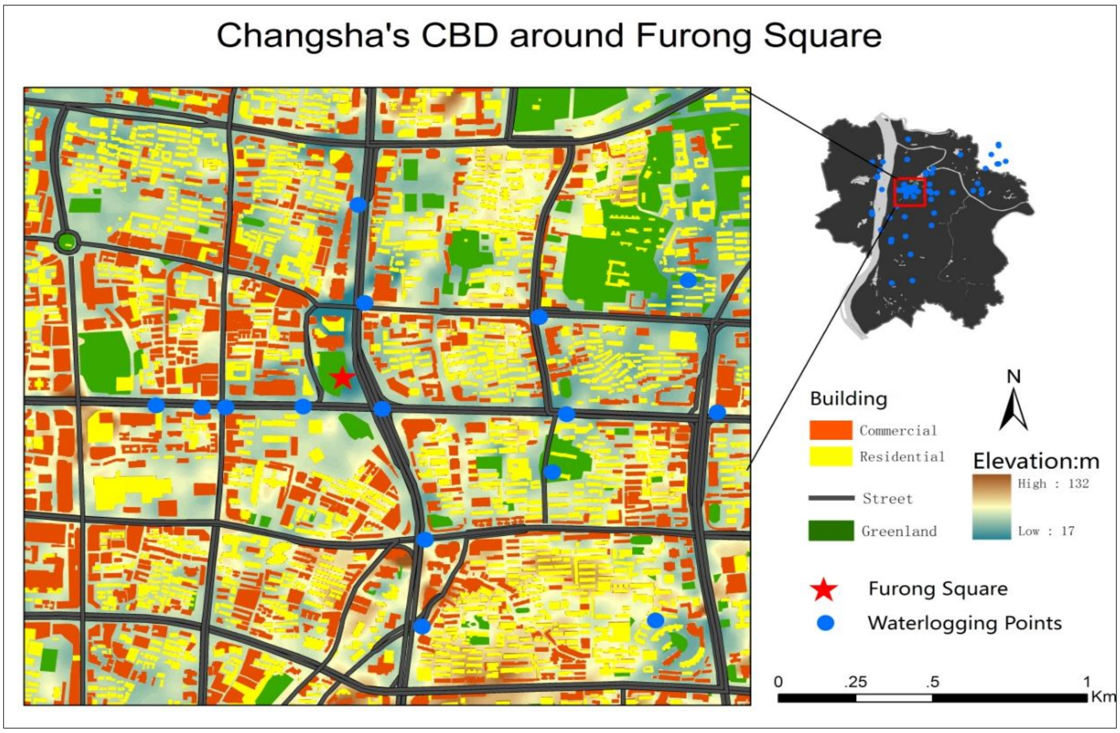


Figure 1-10: Location of Changsha's CBD around Furong Square

Table 1-2: Waterlogging records in recent years

Time	Location	Accumulated water depth
June, 2009	Yuanjialing overpass	800mm
May, 2010	Furong road-Liuyuan overpass	500mm
June 28, 2011	Furong-Wili road	1500mm
	Bayi road	800-1000mm
May, 2012	Wanjiali road-Bafang community	200mm
	East Renmin Road, Jing-Zhu Highway	500mm
May, 2013	9th provincial admin bureau parking lot	500mm
2014	Yuanlong Science Park, Yada Road	800mm
March 15, 2015		1200mm

1.4 Structure of the dissertation

In this section, the organization of the dissertation will be illustrated. From a content point of view, it includes flood hazard analysis, flood risk assessment and discussion on strategies of flood risk reduction investigating two types of floods; fluvial flood and pluvial flood covering two scales; urban and local scale respectively. Those elements were compiled into 6 chapters. Chapter 1 was about an introduction to the study, including background, research objectives, problem and scope, and the overview of the study area, the Changsha central city. In Chapter 2, basic conceptions of the urban flood (i.e. the sources and causes, the impacts, types of the urban flood) were introduced in advance. Then it reviews current studies on spatial scales in flood risk assessment, network analysis on urban infrastructure systems, and simulation methods for FRM as well as public participant in emergency flood management. In Chapter 3, the theoretical and methodological frameworks of the study were presented. Also, common methods and specific methods of two case studies are denoted. In Chapter 4 and chapter 5, two case studies were investigated to address FRM based on flood simulation at different levels. In Chapter 4, standardized procedures of flood risk assessment based on Multi-Criteria Approach (MCA) were stated with scenario analysis. Especially, a network analysis method was proposed in vulnerability analysis and indirect damage assessment for the urban infrastructural system. Moreover, a spatial global method was adopted for analyzing the uncertainty and validation of the damage models. While in Chapter 5, flood emergency management is explored in the local urban environment. This part deliberated on evaluating flood adaptive strategies with consideration to engineering measures, risk warning and public risk awareness. An agent-based model was proposed to pursue dynamic even real-time risk assessment. The model integrated inundation simulation and citizens' behaviors simulation. Then scenarios with different risk reduction interventions and public participation were compared to the baseline scenario. Finally, Chapter 6 was the conclusion and discussion of the whole dissertation.

CHAPTER 2: LITERATURE REVIEW

The aim of FRM is simply to minimize human, economic and environmental losses. Integrated strategic measures to flood hazards include structural (e.g. like dams, dikes, drainage networks, and natural sustainable approaches wetlands and natural buffers) and non-structural (e.g. insurance, flood zoning and flood forecasting) measures (Birkmannet et al., 2010; Gumbo, 2011; GFDRR, 2014). The USA and EU countries have accumulated very good experience in FRM. Countries like Japan, Netherlands, China, Egypt, and several countries from the former Soviet Union, which used to give priority to structural measures, start to focus on non-structural ones as well, adjusting their strategies moving away from flood control to integrated FRM (Grabs et al., 2007; Schanze, 2006; 2009a, b).

The term “management” means a set of effective and efficient control measures as well as all activities of actors and network of organizations (Weihrich & Koontz, 1992). A number of wide and deep knowledge has been obtained through the practice of FRM. Modern FRM requires continuous, holistic and sustainable way of reducing the flood risk, which is based on (i) a comprehensive understanding of risks and uncertainty; (ii) an understanding of whole-system behavior and integrated risk assessment comprising multiple spatial scales and all damage and risk dimensions; and, (iii) Implements a portfolio of measures and instruments (Hall et al., 2003; Evans et al., 2004; Sayers & Meadowcroft, 2005; Dawson et al., 2009; Coulthard & Frostick, 2010; Li et al., 2013; Thorne, 2014). Combined with the research questions and the characteristics of modern FRM, this chapter reviews the state-of-the-art of related fields as follows.

2.1 The components of flood risk

2.1.1 Flood hazard, vulnerability and risk

It is fundamental to understand the components of flood risk and its multiple dimensions. The Source-Pathway-Receptor-Consequence (SPRC) concept, forces a systematic understanding the sources, pathways and receptors of risk, considering of all aspects of the flooding system (ICE[2], 2001; Evans et al., 2004; Schanze, 2006; Sayers et al., 2013). According to this structured framework,

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[2] ICE: the U.K Institution of Civil Engineers

flood risk can be decomposed further into their essential components (see Figure 2-1).

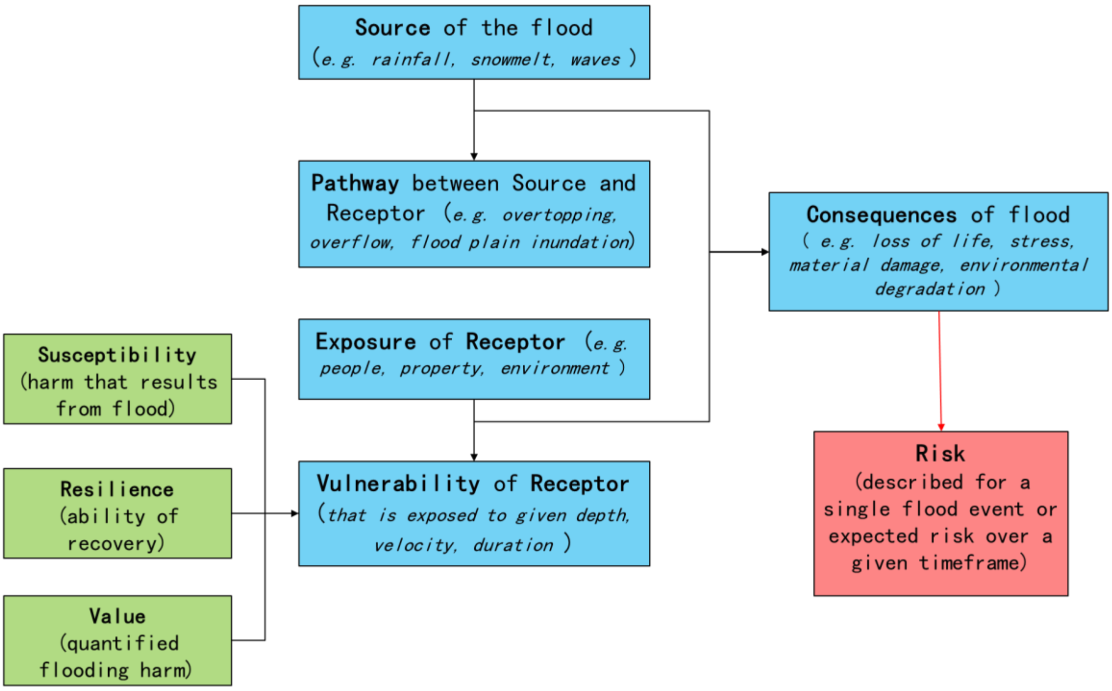

Figure 2-1: the SPRC concept and the components of risk (modified based on Sayers et al., 2013)

Two main components of risk are the probability of a flood hazard event occurring during a specified period within a given area and have a given intensity and the impact associated with that event. It measures the degree of vulnerable element exposed to hazard (UNDRO, 1991; Godschalk, 1991; Gouldby & Samuels, 2005; Schanze, 2006; Tierney, 2007). The concept of hazard is defined as "the potentially damaging physical event, phenomenon or human activity that may cause the loss of life or health, property damage, social and economic disruption or degradation environmental resources and functions" (UNISDR, 2009; WMO, 2016). Studies on flood hazard assessment concentrated on three aspects: the probability of occurrence, the magnitude and intensity of occurrence, and the expected time of next future occurrence (ADPC[3], 2002). The probability of occurrence refers to both source and pathway of a flood. It reflects the probability of the occurrence of the initiating event, e.g. a rainfall or a marine storm (source) and the probability that flood waters will reach a particular location in the floodplain that considering the performance of natural

[3] Asian Disaster Preparedness Center

or artificial intervention system, control and protection structures, e.g. wetlands, channels, dams, levees, floodwalls (pathway).

The consequences of flooding reflect both the exposure and vulnerability of the receptors. The former refers to the number of properties, population, habitat area, etc., that may be exposed to a given flood event. The latter denotes the capacity for given receptors to resist or recover from the harmful impacts of a flood hazard in the short or long term, which hinges on values or functions, susceptibility and coping capacity (Messner et al., 2006; Lerner-Lam 2007; Schanze, 2009a). In line with the triangle concept of sustainability, it can fall into social, ecological and environmental domains (Serageldin, 1994). For further understanding vulnerability, it is the degree of loss depending upon three aspects: susceptibility, value and resilience, which respectively describe the propensity of a particular receptor to experience harm (e.g. human death or injury), the degree of loss to receptors externalized (e.g. adopting a development or welfare economic basis), and the recoverability of the harmed receptors (without aid) during a given flood event.

There is an inter-relation among flood hazard, vulnerability and risk (Figure 2-2). Vulnerability related to many factors; e.g. land use, extent and type of construction, contents and use, the nature of populations (mobility, age, health), warning of an impending hazardous event and willingness and ability to responsive actions. That means that flooding with the same exposure may differ greatly with vulnerability within an identified flood hazard area (FEMA/EMI[4], 2016).

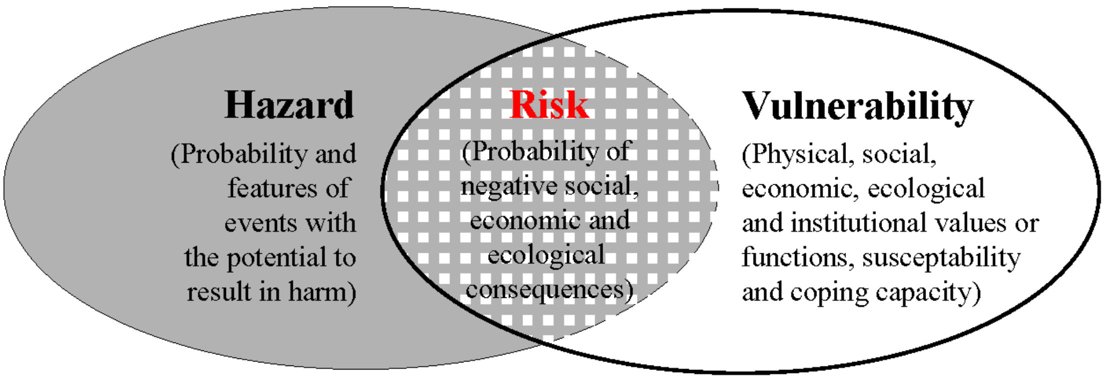

Figure 2-2: The inter-relation among flood hazard, vulnerability and risk (Schanze, 2009a)

Generally, based on risk components, the flood risk is defined as "a combination of the recurrence probability of a flood hazard and number of potential negative

[4] FEMA/EMI: Federal Emergency Management Agency/Emergency Management Institute

consequences (referring to exposure and vulnerability) in a given area" (Gouldby & Samuels, 2005; Schanze, 2006; Kubal et al., 2009; Wang et al., 2011). It can be expressed as the following formula:

$$flood\ risk = function\ (hazard, exposure, vulnerablity)$$

2.1.2 Sources and causes of urban flood

In the SPRC concept, "source" of flood event is the basis to specify the processes of flood risk generation. Knowledge of sources and causes of flooding is essential to understand the possible adverse impact on cities. Then it will be reasonable to adopt relevant responses and solutions. In fact, urban floods typically derived from complex sources and causes.

First, people frequently settle down in urban areas where is highly exposed to flooding. In many cultures, due to convenient, aesthetic and economic reasons, people prefer dwelling close to water bodies such as sea and rivers. About one-fourth people dwell within 1 meter of high tide level and the number rises to around 40% in the case of 5 meters during high tide (Anthoff et al., 2006; Rowley et al., 2007). The corresponding numbers in many developing countries are growing more rapidly. In that case, new weak and hazardous regions may emerge for the reason of the relatively lagged flood defense mechanisms.

Furthermore, both natural and social system changes are accompanied by human activities affects the urban environment. Engineering facilities; e.g. like the design and the improvement of drainage capacity, rebuilding of old district and the improvement of housing standards are used to reduced urban waterlogging hazards and vulnerabilities. Cities and environment are equally vulnerable to the natural hazards. High-intensity precipitation can bring a flood to drainage systems which are not capable to cope with flows. The water sometimes resurfaces somewhere else (Jha et al., 2012). This type of flood takes place frequently in low-lying regions of Europe, like the floods affecting England in the summer of 2007 (Pitt, 2008; Whittle et al., 2010). In addition, overexploitation of groundwater has multiplied flooding risk, which severely occurred in the 20th century.

Urban flooding can also be caused by deficient or inappropriate land-use planning. Unplanned land-use changes will increase flood risk during the process of increasing urbanization. On one hand, the process reduces the permeability of city underlying surface and produces surface flow concentration, i.e. drainage systems that were overburdened by augmented flows as stated before. On the other hand, new buildings and developments in addition to regeneration of the brownfield lands are already under flooding risks, especially in the essence of the currently existing policies and regulations to control the construction of new infrastructure, which are often not properly implemented but prioritize more development within the floodplain area, causing obstruction of surface water flow and flooding (RIBA, 2009).

2.1.3 Impacts of urban flood

Cities are not only the distillate of human civilization in living spaces but also the junction of modern hazard and risk. Cities suffer from a relatively high-risk flooding owing to the high density of population, diverse economic activities and numerous infrastructure and property (Pelling, 2003). Consequently, it is crucial to delimit the different forms of flood damage that will be involved prior to flood risk analysis and flood damage assessment (Meyer & Messner, 2007).

Flood damage refers to a wide range of negative consequence caused by flooding, which can be categorized in direct or indirect damage, and tangible or intangible damage (Smith & Ward, 1998; Penning-Rowsell & Wilson, 2003; Messner & Meyer, 2006). It includes commercial and industrial production, public facilities, cultural heritage, ecological system, humans' health, and belongings. Direct damages are the losses caused by direct contact with floods, e.g. damage to buildings, their contents and infrastructure. They are tangible and can be easily specified by a numerical or monetary value. Indirect damages are losses due to certain activities being interrupted by a flood. For example, losses of industrial production or traffic disruption due to disruption to business both within and outside the affected area (Gouldby & Samuels, 2005). These indirect damages also cover the additional costs of emergency and other actions for preventing flood damages and losses. Some indirect, tangible damages can be measured in terms of money (Meyer & Messner, 2007). Intangible damages are damages that hard to be weighed up in monetary terms. They may include casualties, health effects, the stress induced by the flood, the disruption of social and life caused by the flood, damages to ecological goods and services as well as those are not traded in a market (Markantonis & Meyer, 2011). Many studies have indicated that social impacts on victims of floods can be more important than their suffered property damages. The following Table 2-1 and Figure 2-3 provide examples of different types of damages (Smith & Ward, 1998; Penning-Rowsell & Wilson, 2003).

Table 2-1: Types of flood damages

	Tangible	Intangible
Direct	Physical damage to assets: buildings contents infrastructure	loss of life health effects loss of ecological goods
Indirect	loss of industrial production traffic disruption emergency costs	inconvenience of post-flood recovery from hazard increased vulnerability of survivors

Source from: Penning-Rowsell & Wilson. 2003; Smith & Ward 1998

(a) (b)

(c) (d)

(a,b flood in Dresden, Germany, 2002, Source: FLOODsite; c,d storm in Changsha, China, 2013 and 2014; Source: Wangyi News)

Figure 2-3: Examples of flood damage

2.2 Flood risk assessment

2.2.1 Spatial scales in flood risk assessment

Many techniques and approaches have been proposed and formulated for flood risk assessment. The spatial scales of those case studies range from global to local level. Flood risk may be assessed for even the whole world or just for a particular stretch of a river, or coast or small town. On the one hand, there is no appreciable distinction among the methodological frameworks of most studies, but on the other, there are some notable differences in assessments at different spatial scales (Moel et al, 2015).

2.2.1.1 Risk assessment at different scales

In many cases of FRM, a priority was given to the assessment of flood events and their consequences (Moel et al., 2015). The logic of these assessments considers the expected consequences initiate the discussion on how to cope with them. Furthermore, such frameworks can be also adopted to evaluate measures in standardized processes, supporting decision-making process in possible measures for flood-prone areas where the action is required. For decades, many studies of flood assessment have focused on various spatial scales for different purposes. In the meanwhile, the core method is quite general among various studies on risk assessment. Differences notably reflect in terms of methodology and the utilization of those assessments, e.g. data availability and the methodological applicability (Moel et al., 2015).

Generally, flood risk assessment can be divided into supra-national, macro-, meso- and micro-scale. The supra-national scale refers to assessments of the entire globe or continent, for example, transboundary river basins. The macro-scale concerns assessments of entire countries, which may cover multiple watersheds, requiring consistent or national data. Both scales will take the administrative units as a whole into account. For instance, the production of the two-yearly Global Assessment Report (GAR) on Disaster Risk Reduction coordinated by the United Nations International Strategy for Disaster Risk Reduction (UNISDR), the development of public disaster relief funds in Europe to adapt to climate change, or flood risk assessment for an entire municipality (UNISDR, 2009, 2011, 2013; Hochrainer, et al. 2010; Van Renssen, 2013). The mesoscale is generally sub-national, e.g. a large river stretches or cities on a regional scale. It usually uses aggregated land use units such as residential areas, commercial areas and industrial areas etc. The microscale, based on an object-oriented approach, which relates to a town or specific river stretch. Damages may be assessed at single buildings level. Different scales usually call for different methods when it comes to assessing flood risks and assessments at different scales have different objectives. But different scales approaches are not absolutely independent in practice, but rather in conjunction with the others. For example, in some case studies, the selected approach is a mesoscale method on the whole but partially in microscale (Kubal et al., 2009).

2.2.1.2 City-scale flood risk assessments

City-scale flood risk assessment is perceived as a local or micro level. They allow planners and decision makers to identify the most at-risk areas, to assess how risk may change in the future, and to achieve flood risk reduction effectively by various adaptation measures (Ward et al. 2011a, b; Budiyono et al., 2016). At the microscale, flood risk assessment is conducted with detailed information and data, e.g. terrain elevation via Light Detecting and Ranging (LiDAR) data, hydraulic structures, the location of constructions, types of land use etc. Studies on such scale were generally undertaken for investment optimization through evaluating the cost-effectiveness of structural measures and other measures for flood risk reduction (Merz et al., 2010). In some other studies, hazard and risk maps were developed to support the microscale flood management and urban planning. Spatially explicit and quantitative risk information enables communities, companies and residents to prepare for disasters (Takeuchi, 2001, 2013; Merz et al., 2004). There have been many case studies at the city or sub-city scale, such as Dresden, Germany (Kreibich et al., 2011; Gerl et al., 2014); New York City, USA (Aerts et al., 2013; 2014), Ho Chi Min City, Vietnam (Lasage et al., 2014); Jakarta, Indonesia (Budiyono et al., 2016). In these studies, the size of some large cities was similar to regions. The distinctions between meso- and microscale were gradually disappearing.

2.2.2 Integrated risk assessment and MCA-based method

In modern FRM, integrated risk assessment comprises all damage and risk dimensions to enhance decision-making process. For flood damage assessment, many approaches, such as risk elements classification, exposure analysis and asset assessment, susceptibility analysis (depth-damage function), have been proposed and most of the risk analysis focuses on economic damages (Hall et al., 2003; Roos, 2003; Jonkman et al., 2008; Schwarz &

Maiwald, 2008). Classification approaches, dividing economic damage into vary sectors, households, business, public facilities and agriculture. Case studies show that different economic sectors presented diverse characteristics (Förster et al., 2008; Thieken et al., 2008a,b; Schwarz & Maiwald, 2008; Kreibich et al., 2010). Exposure analysis is commonly based on types of land use and inundation characteristic (Moel et al., 2015). In some cases, official statistics were directly used as exposure data for flood risk analysis (Merz et al., 2010). Coarse values were decomposed to avoid the problem of spatial mismatch between hazard and exposure data. There are few studies expressing the method of asset assessment explicitly. Asset values are varying types of risk elements as well as time and space. However, varying categories of assets could be identified within one type of risk element (Thieken et al., 2006)

Impacts of floods are not only physical systems but also social, economic and environmental (Renzetti & Dupont, 2016). The studies conducted by Tapsell et al. (2002) and Jonkman (2007) related to the flood impact on health and life was a positive start. In Europe, Cost-Benefits Analysis (CBA) and Multi-Criteria Analysis (MCA) are becoming the institutionalized methods in FRM (Parliament E, 2007). In all the cases analyzed, CBAs were used mainly for analyzing the impact of structural flood protection measures. But for non-structural flood prevention, such as floodplain restoration or land use changes, CBA as a monetary method, has exposed some limitations (Broekx et al., 2011; Meyer et al., 2012). The MCA uses comprehensive criteria and fuzzy thresholds, which allows integrating more "soft" information in qualitative ways (Meyer et al., 2009a; Kubal et al., 2009; Wang et al., 2011).

2.2.3 Flood impact on urban infrastructure network

Many public infrastructures like roads, railways, bridges and power supply, are usually situated in locations exposed to river or coastal, groundwater and surface water flooding. They are thereby significant vulnerable to flood and potential for lengthy disruption and high costs of repair. However, there is no well-established way to assess damage on infrastructure because it involves many uncertainties. A set of generic fragility curves have been widely used for types of flood risk models (Hall et al., 2003; Environment Agency, 2003; 2007). Dutta and Herath developed a method for assessing direct flood damage on infrastructure inspired by the methods for estimating the damage of lifeline facilities in earthquakes (Dutta & Herath, 2001). Deshmukh et al. assessed the flood impact on infrastructure and the related industries and communities in terms of criticality and vulnerability of infrastructure based on questionnaire surveys, individual interviews and site visits (Deshmukh et al., 2011).

Nevertheless, those researches discussed less about the importance of network features of urban infrastructure. Infrastructure has distinct network features and systematisms. Understanding risk to urban infrastructure requires a systematic view (iBUILD, 2015). Complex network theory has inspired urbanists permanently. Many infrastructure systems nowadays are entirely complex, e.g. streets and the municipal subway systems, electric power grids and water supply system. These tangible networks are usually closely related to individual civic life thus affecting the abstract network, such as a social network (Zhenting et al., 2011). Complex network modeling can be of great use in describing such kind of urban systems. In literature, urban subsystems such as power system and logistics network are abstracted as complex networks (Fouad et al., 1994). Some researches on urban problems have been conducted with the theory of complex system and complex network (Batty, 2008; Volchenkov, 2008). Chen X. Z. et al. (2015) proposed an accessibility-based method dealing with flooding disaster and compared and discussed the method with Hansen accessibility index method (Hansen, 1959). A Web-GIS was developed for analyzing the flood resilience of urban networks in (Lhomme et al., 2013). The studies were GIS-based with complex calculations for the indicator. Another example is space syntax network analysis. Space syntax theory studies the spatial configuration of urban patterns and human behavior in an urban environment (Hillier et al, 1976; Biggs et al., 1986; Jiang, 1998; Karimi, 2012). It was established based on urban complex network analysis and sophisticated speculation. Gil and Steinbach (2008) evaluated street network performance before and after the flooding and indirect flood impact based on space syntax network analysis. The method demonstrated that it provides useful indicators to denote the indirect flood impacts on urban transport network performance and socio-economic conditions. It provides a new way to test various interventions and to support investment decisions concerning preventative strategies, disaster management and repair (Gil & Steinbach, 2008). However, most of the current studies yet give no considerations to flood loss involving economic loss or disaster-affected populations indirectly linked to damage of the infrastructure systems.

2.2.4 Uncertainty

When it comes to risk, it is always necessary and inevitable to discuss uncertainty. In the fields of FRM, the decision-making process is usually supported by complex hydrological models and simulation results, which are surrounded by uncertainties (Merz & Thieken, 2005; 2009). Thus, it is crucial to recognize and quantify uncertainty for appropriately managing risk and making adaptive strategies.

2.2.4.1 Types of uncertainty

Uncertainty can stem from many different types of factors (Figure 2-4). Generally, it can be aleatory or epistemic uncertainty (Rumsfeld, 2011; Bradley & Drechsler, 2014). Aleatory uncertainty is a type of natural uncertainty referring to inherent variability in the physical world. It stems from the assumption of inherent randomness and basic unpredictability in a system that cannot be reduced in principle, for instance, the variability of precipitation over time and space, or spatial variability of roughness and slope in a water environment system (McMillan et al., 2012). Epistemic uncertainty, or knowledge uncertainty, refers to an inadequate scientific understanding of natural processes and events, and incompleteness of analysis in a physical system, which can be reduced by increasing knowledge of the system in theory and practice. For example, hydrological and hydraulic models are based on some assumptions and an abstraction of the real hydrologic process that can never be considered true (Apel et al., 2008; Moel et al., 2014). Besides, uncertainty can also stem from the decision model due to diverse objectives and evaluation criteria in FRM (Hartford & Baecher, 2004).

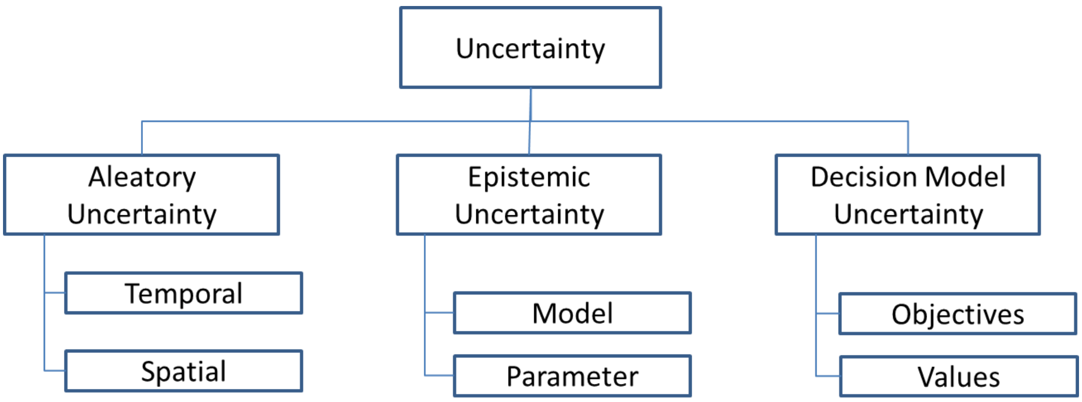

Figure 2-4: Types of uncertainty (re-edit based on Hartford & Baecher, 2004)

2.2.4.2 Uncertainty and spatial scales

As spatial scales change, uncertainty in flood risk assessment also appears different characteristics. On a large scale, it is scarcely possible for a country or a region to observe and record detailed information of flood extent or recurrence interval for a long, stable, or uninterrupted period. Thus, some simulated and unverifiable information is inevitable. In some cases, inundated areas may be exaggerated and the flood risk is often overestimated due to unavailable detailed information (Cook & Merwade, 2009; Penning-Rowsell, 2015). Many studies illustrated that uncertainties at mesoscale risk assessments in damage and risk assessment, considering the probability and duration of different flood events, and the damage functions (Apel et al., 2008; Merz & Thieken, 2009; Freni et al., 2010; Moel et al., 2014; Saint-Geours et al., 2015). On the micro scale, model uncertainties become particularly apparent. It is usually a type of epistemic source concerning the selection of appropriate model parameterization and calibration, caused by the variability of inputs and parameters, model algorithms or structure, calibration data and boundary conditions etc. (Xu et al., 2007; Thieken et al., 2008a; Apel et al., 2009; Schumann et al., 2009; Merz et al., 2010; Schumann & Di Baldassarre, 2010; Seifert et al., 2010; Jongman et al., 2012). Moreover, decision-making in FRM is often based on those results of models and simulations, of which the uncertainty is one of the major concerns (Shirmohammadi et al., 2006).

2.2.4.3 Methods of Uncertainty Analysis and Sensitivity Analysis

Uncertainty Analysis and Sensitivity Analysis (UA/SA) improves transparency during the decision-making process (Alex Mara & Rakoto Joseph, 2008; Reichert et al., 2007) and puts a value on the findings by communicating their limits (Pappenberger & Beven, 2005; 2006). To obtain an insight into the extent of model uncertainty, UA/SA methods are invaluable tools in flood risk assessment and decision making. Methods of UA/SA include local and global sensitivity analysis.

The local sensitivity analysis method is types of deterministic approaches of imposing large number of input variables with small input perturbations on the model and observe the corresponding output at a specific point. They have the advantages of simplification and small amount of calculation and are commonly used in solving large-scale environmental systems (Cacuci, 1981; Van Griensven et al., 2006; Castaings et al., 2009; Gabriella & Carlo, 2015; Sharda & Voß, 2015). However, local methods are based on linearity and normality assumptions and local variations, which limit the accuracy and comprehensiveness of parameters sensitivity analysis (Saltelli et al., 2000). In contrast to local methods, global methods are developed in a statistical framework and make full advantages of computer technology and numerical methods to get over those limitations, considering the whole variation range of the inputs (Helton, 1993; Saltelli et al., 1999, 2000; de Rocquigny et al., 2008; Faivre et al.; 2013; Gabriella & Carlo, 2015; Sharda & Voß, 2015). Different kinds of global methods have been proposed including qualitative analysis method such as Morris method, Fourier amplitude sensitivity testing (FAST), Generalized Likelihood Uncertainty Estimation (GLUE), and quantitative analysis method such as Extend FAST, Sobol' method (1993), etc. In a Monte Carlo framework, model components can be parameterized based on the results of models and they can be further used for the risk and uncertainty analysis (Apel et al., 2004; Dyck & Willems, 2013). Global UA/SA allows cognition in the integration of uncertainties and deals with them by balancing them against other decision-relevant factors (Aven, 2010; Willows et al., 2003; Höllermann & Evers, 2015)

Flood risk assessment is greatly depending on geospatial data and analysis. Both inputs and outputs have significant spatial characteristics and attributes. Uncertainty associated with spatial heterogeneity of input factors may affect model uncertainty. For example, the topographical factor is very important in flooded models. Very slight uncertainty in the terrain may also have a relatively large impact on the prediction of the flooded models, especially in relatively flat areas (Burrough & McDonnell, 1998; Wilson & Atkinson, 2004; Moel & Aerts, 2011). However, UA/SA methods are generally rare and limited account for the spatial context of model processes and the spatial uncertainty of model inputs in scope (Crosetto et al., 2000, Crosetto & Tarantola, 2001; Francos et al., 2003, Hall et al., 2005; Tang et al., 2007). Hence, it is necessary to consider global UA/SA incorporating spatial heterogeneity (Rossi et al., 1993). Spatial global UA/SA has been adopted in some studies on analyzing the sensitivity of 1D and 2D flood models, which also allows Sobol' indices mapping (Hall et al., 2005; Pappenberger et al., 2008; Saint-Geours, 2012; Alliau et al., 2015; Jung & Merwade, 2015; Nguyen et al., 2016). Willis implemented a screening method for 2D flood modeling to rank the uncertainty of input parameters using points and zonal approaches (Willis, 2014). In other types of water-related issues, computation of sensitivity maps based on global UA/SA has also been achieved (Marrel et al., 2011).

2.3 Risk reduction and public participation

2.3.1 Flood risk reduction

In response to flood risk, efficient measures and instruments, structural or non-structural, direct or indirect, were proposed for flood risk reduction. Measures (permanent or temporary) are interventions based on direct physical actions. Instruments for FRM may be in action indirectly by influencing human behavior (Olfert & Schanze, 2005; Heidari, 2009). Ideally, flood risk reduction strategies should consider a range of measures. Faisal et al. (1999) in the case study of Dhaka City considered that structural measures do not ensure effective flood mitigation and Heidari (2009) considered that multiple interventions should be included in a flood mitigation plan. However, the non-structural solutions have not obtained to value enough in practice of flood risk reduction. Studies on the economics of flood risk reduction, clearly focus analysis on structural measures rather than on a broad set of non-structural ones in flood disaster mitigation (Hawley et al., 2012).

These interventions can be differentiated according to various perspectives (USACE, 2006). Based on the modes of FRM, they can be summarized as pre-flood, flood event and post-flood interventions (Kundzewicz & Samuels, 1997). Pre-flood is a type of planning-based interventions consist of prevention, protection and preparedness for avoiding unexpected impacts in flood-prone areas, e.g. strategic spatial planning like zoning and building construction, flood-control engineering like dikes and reservoirs and the preparatory work for probable flood events (DKKV, 2003; Schanze, 2006; Schanze et al., 2007). Flood event management refers to strategies during the ongoing process of flooding, which covers mainly risk forecasting and communication; i.e. The operation of flood control infrastructures like dynamic flood storage by operations of reservoirs and emergency response like evacuation activities. Post-flood interventions involve recovery and reconstruction in the disaster area. For example, in China, governments are responsible for carrying out rescue and disaster relief work, e.g. supplying necessities, health care and immunity, rebuilding of homes, repairing engineering structures damaged by flooding etc. Another example is flood insurance. Better preparation for a flood is highly efficient in the past flood events (Environment Agency, 2008b).

Besides, in the view of social subjects, the measures and instruments consist of national or local interventions (such as zoning plan, code of building design, engineering measures for flood control etc.) and individual-based means (like household or business flood-proofing engineering and flood insurance) (see Figure 2-5). While some intervention, like risk communication, could be both top-down ways based on government and individual-centered ways based on social network (Fekete, 2012; Field et al., 2012; Martens et al., 2009).

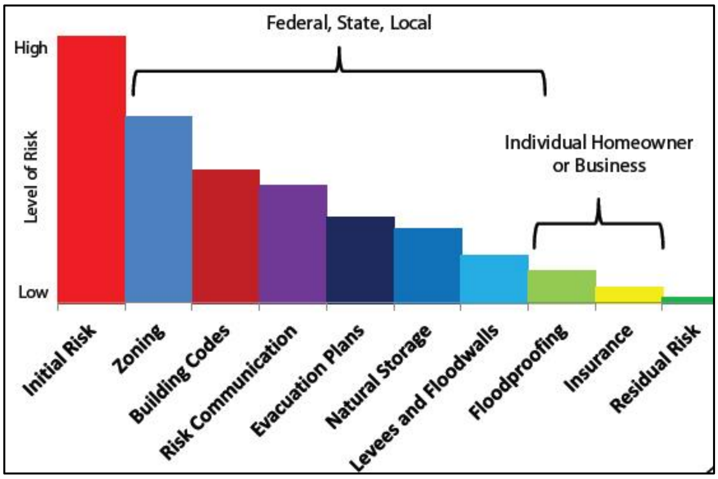

Figure 2-5: Flood risk reduction interventions (Source: modified from USACE, 2006)

2.3.2 Public participation in flood risk management

Loss of life and injury has attracted much attention to most of the flood events. The main aim of FRM is to minimize the harmful impacts of flooding and to promote recovery. Effective forecasting, warning and response in flooding emergency management influence greatly on the scale of the loss of life and injury (Jonkman, 2007). Public awareness of risk and participation play important roles in flood risk reduction.

One new trend is to consider the common people's behaviors in research. The implementation of the European Flood Directive 2007/60/EC required the establishment of public participation mechanisms to ensure citizens' involvement in the cycle of FRM. Some researchers have recognized the importance of public participation in decision-making in FRM (Holden, 2006; Rojas-Caldelas & Zambrano, 2008). Jonkman and Dawson (2012) denoted that integrated risk management involving public authorities, research scientists, companies and citizens is required to address the interconnectivity between physical infrastructures, economic systems and the role of human factors.

Nowadays, information and communication technologies provide new ways for public participation such as citizen observatories and individual-centered risk communication (Holden, 2006; Rojas-Caldelas & Zambrano, 2008; Wehn et al., 2015). Moreover, it has been proposed that well-designed risk reduction strategies act derived from strengthening public awareness of flood risk and public participation exerting virtuous cycle. For example, risk communication used to be implemented in a top-down way from key providers to the public. However, such a strategy could not always achieve the desired effect. In contrast, individual-centered risk communication is more accessible and disseminate faster through new media such as a social network (Field et al., 2012).

2.3.3 Simulation methods for flood risk management

The Science of Complex System has developed a type of bottom-up approach, named “simulation science or technique”, aiming at capturing interactions and processes at the local scale. Computer simulation methods try to explain the phenomenon by numerous running of the model and statistical analysis rather than an inductive and deductive way. Unlike reconstruction, the logic of simulation is: generation is just the explanation (Figure 2-6). In many fields, observation experiments control experiments are difficult to design like natural sciences, particularly in the study that refers to social sciences, including urban design and planning. Hence, the simulation method becomes an ideal way to carry out experiments for social phenomena (Macy & Willer, 2002; Takahashi et al, 2007; Malleson, 2011). Computer simulation supply approaches for studying flood risk system that refers to many factors with uncertainty. Based on simulated data, not only inundation characteristics can be analyzed but also various risk reduction measures can be discussed and compared repeatedly and economically. There has been many theories and technologies proposed in the field of flood simulation and emergency management, such as Cellular Automata, Agent-based modeling (Yan et al., 2015).

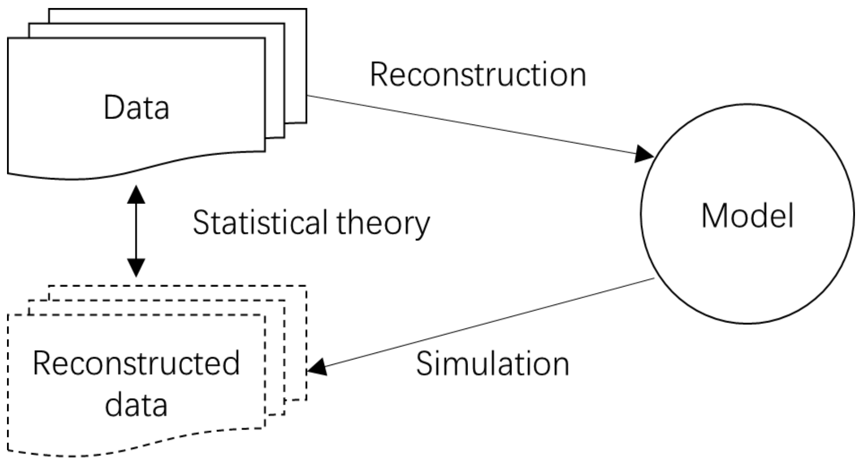

Figure 2-6: Reconstruction and simulation as inverse problems in science

2.3.3.1 Cellular Automata and Agent-Based Modeling

In the early of 1950s, Cellular Automata (CA) model was proposed for the study of biological systems (Wolfram, 2002). A cellular automaton is a dynamic system made up of a set of cells on a grid of specified shape that evolves through a number of discrete time steps according to a series of rules based on the states of the neighboring cells (Santé et al., 2010). In the year 1970, Conway from Cambridge University developed the famous “Game of Life” that was a type of 2D cellular automaton. In the game, people found that even very simple rules may produce sorts of results. CA has been used widely in modeling and simulating for urban development, Land Use/Land Cover (LULC) change (Longley & Batty, 2003; Dai et al., 2008).

Agent-based Modeling (ABM), by definition, means establishing models based on agents. An agent is a discrete entity with goals and behaviors, which take the place of subjects like people in simulating the experiment. In Agent-based modeling and simulation, agents are regulated by many attributes and behavior according to a set of rules (Bonabeau, 2002; Hillier et al, 2007; Macal & North, 2010). Differing from cells in cellular automata, one agent can interact with others by movement and make a decision in somehow for its own behavior. Hence, more formally speaking, Agent-based Modeling and Simulation (ABMS) is a system based on a number of autonomous decision-making entities (so-called agents), which has proved useful in simulating complex systems. Role-play methods (Lonsdale et al., 2008) and desktop exercises such as Exercise Triton (Environment Agency, 2004) provide useful insights into human beings by gathering experts together for decision-making discussion in different scenarios. It is evident that ABMS reduces the cost (time and resources) significantly to run models and enable researchers to explore many different scenarios. As ABMS is more underlying, flexible and low-cost framework, it has been widely used in a number of fields, from population studies to biology, ecology, economics and urban planning (Batty, 2005). In flood studies, assessment based the historical flood data can analyze the spatial and temporal characteristics of flood disasters, but generally requires a large amount of historical data (Quan, 2014; Demirkesen, 2012; Wu et al., 2006; 2012). In contrast, hydrological model simulation-based assessment can improve on the shortcomings of both methods by utilizing parameter processing with less data (Mark et al., 2004; Pan et al., 2007).

2.3.3.2 Computer simulation in flood management

Urban flood issues usually concern with many uncertain factors that could bring difficulties to parameters control. Computer simulation techniques based on many running models and statistical analysis provides a pretty way to study such kind of complex problems. FRM refers to not only hydraulic and hydrological engineering but also strategies for flood risk reduction, such as warning, evacuation and other responses. It is one of the most suitable methods to deal with the challenges of simulating processes of flooding because it is capable of capturing interactions and dynamic responses in a spatial environment. On one hand, distributed hydraulic and hydrological model and simulation have been welled developed these decades, which can be well integrated with CA models. CA models have been applied to distributed hydraulic and hydrological processes simulation (Fewtrell et al., 2008, 2011; Bates et al., 2010; Sampson et al., 2012; Liu et al., 2015). On the other hand, individual responses to flood risk and flood risk reduction strategies are strongly associated with the experience of flooding, and as well as to the learning process (Parker et al., 2007). ABM is very efficient for modeling the dynamics of systems. It also has a good pedigree in testing the effectiveness of warning dissemination mechanisms and the susceptibility of evacuation routes to overcrowding in the emergency events simulation, such as fire and terrorist incident (Galea et al., 1996; Luo et al., 2005) and situations of ‘panic’ (Helbing et al., 2000; Zarboutis & Marmaras, 2005), making them natural tools in FRM.

Involving transportation model in the simulation are helpful or even indispensable for risk analysis and emergency planning (Dash & Gladwin 2007; Lindell & Prater, 2007; Pel et al., 2012). Yuling et al. and Dawson et al. developed a method integrating a hydrodynamic simulation with an agent-based model of evacuation decision-making and the facility management in a flood incident (Yuling et al., 2009; Dawson et al., 2011). Another application of ABM on flood incident management is the case study of Towyn, the coastal town of UK by Dawson et al. (2011). The study proposed a framework for integrated flood risk analysis and incident management based on agent-based modeling (Figure 2-7). In the study, the hydrodynamic model and transportation model were combined to simulate a flood event. Based on the structure, the model simulated the interactions of multiple agents and different environments like risk warning and evacuation strategies were compared and the effectiveness was evaluated. By the agent-based modeling and simulation, the framework realized flood emergency management dynamically and interactively.

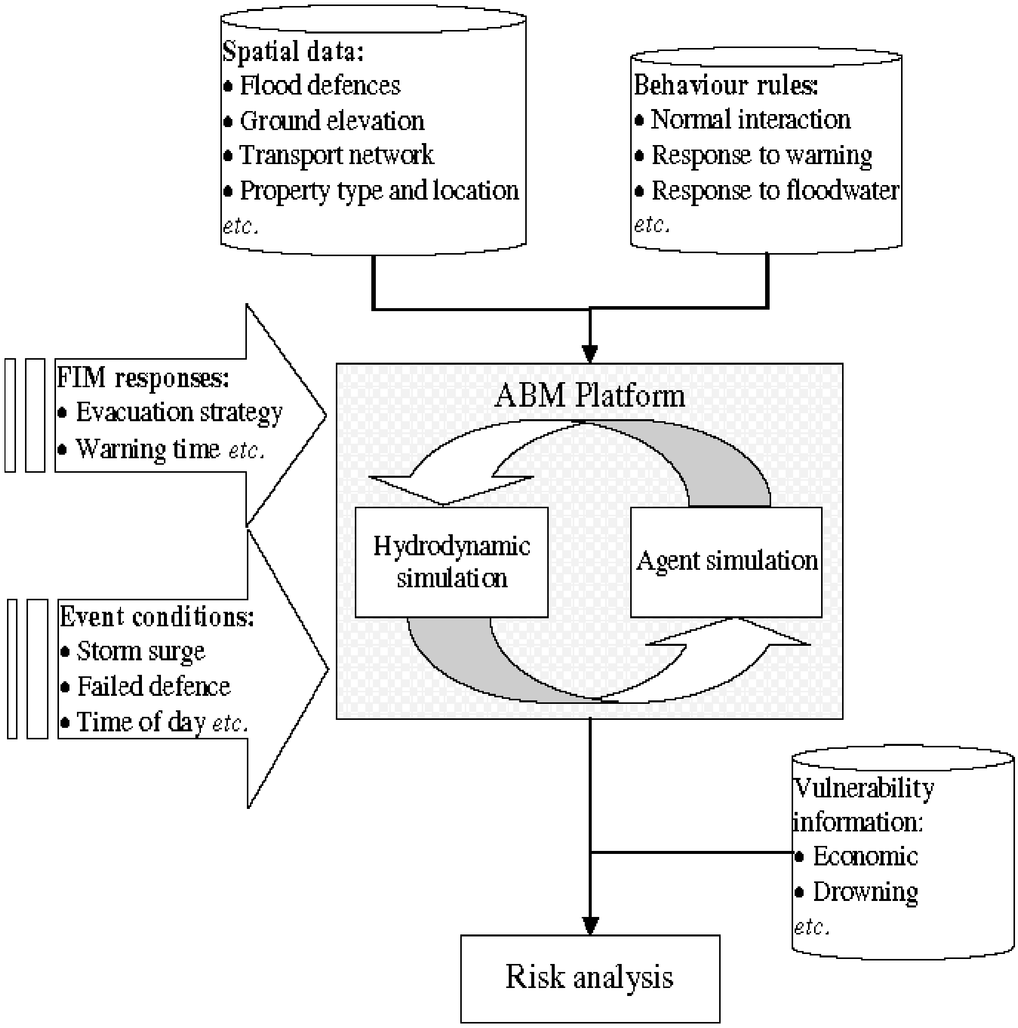

Figure 2-7: Structure of the risk analysis system for flood management (Source: Dawson et al., 2011)

Besides, the Life Safety Model (LSM), which is a dynamic modeling framework. It represents people's interactions with floods, providing a credible evaluation of loss of life in flood hazards and the required evacuation time (Jonkman & Vrijling, 2008; Johnstone & Lence, 2009; Johnstone, 2012). It supports resource planning and the exploration of the consequences of different decisions by simulating emergency scenarios. It also adopts readily available government and commercial GIS-based datasets, representing the results and animations that can improve the emergency response and plans for such disasters (Johnstone, 2012).

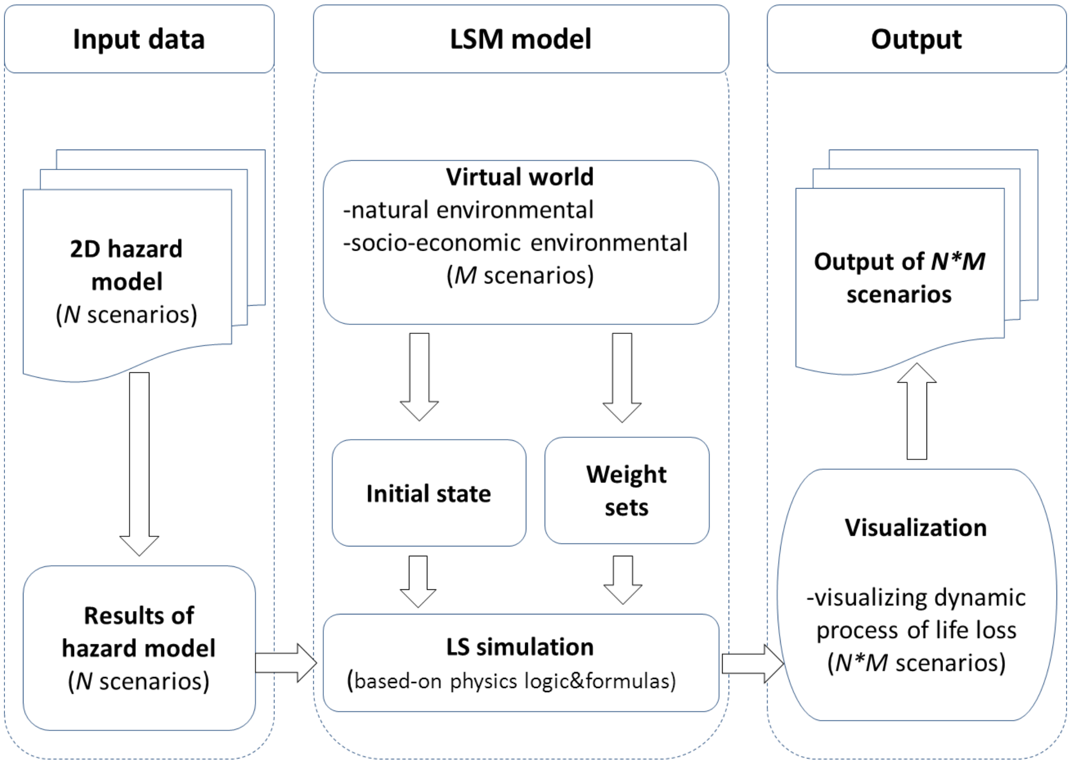

Figure 2-8: Conceptual framework of LSM model (modified based on Johnston, 2012)

The advantage of agent-based modeling is that it represents important information about social phenomena not easy to capture with other traditional models. Agent-based models can explore the heterogeneous behaviors of agents with diverse information, rules, and environment to the macro behavior of the overall system (Lempert, 2002; Anantsuksomsri & Tontisirin, 2013). In the case of disasters where the future is unpredictable, decision makers do not rely on forecasts. Thus, ABM becomes an increasingly powerful tool for decision-makers, providing great solutions for multi-scenario simulation and comparison of adaptive policies.

CHAPTER 3: METHODOLOGY AND DATA

Urban flood risk analysis is a complex issue due to the dense buildings and population, various types of land uses, drainage systems and numerous flood control measures (Chen et al., 2015; Li et al., 2016). This dissertation proposes a practical framework for flood risk analysis and assessment and applies it to a Chinese city-Changsha central city-in case studies. A risk-based method and the general procedures are proposed for urban flood risk analysis and assessment based on the SPRC conception. The framework consists of three main sections: method determination, procedures for flood risk analysis and assessment models, and, the means of risk presentation as well as the corresponding adaptive strategies. The three sections further involve several sub-modules, e.g. preliminary analysis, selection of method, method and tools for flood hazard and exposure analysis, damage assessment, uncertainty analysis, etc. (Figure 3-1).

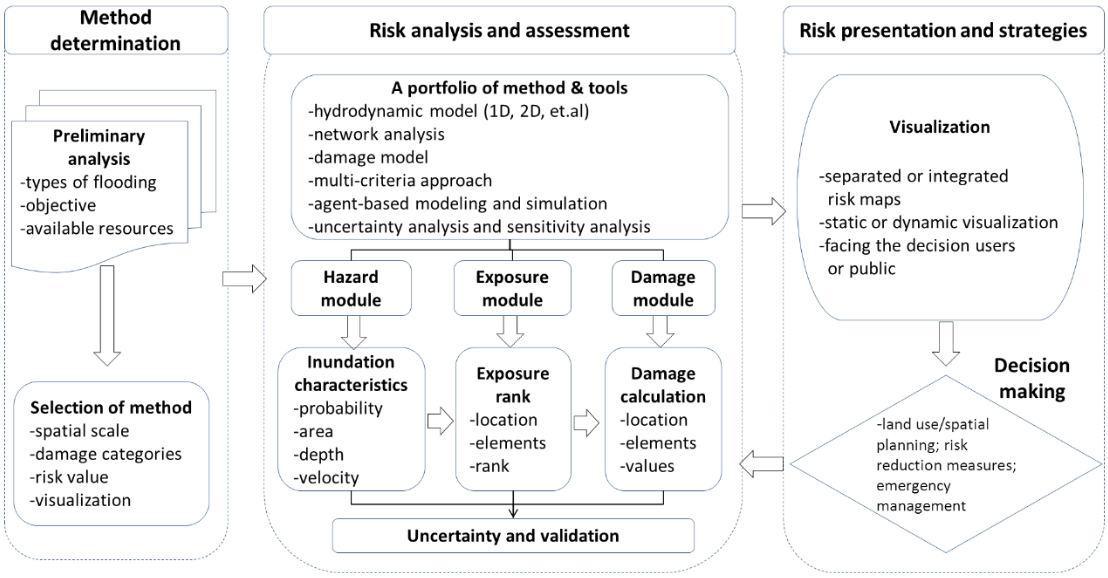

Figure 3-1: Conceptual framework of risk-based flood management

Based on combined portfolio analysis methods and two case studies within this conceptual framework, the dissertation carries out the research with two cases according to different flood types, spatial scales, data richness and objectives to answer the proposed research questions. Some are common to both two cases, e.g. data collection, preliminary processing, selection of approaches and tools. Some others are specific to each case. For case study I, it covers river flooding simulation based on HEC-RAS 1-D model, the definition of risk dimensions, risk calculation and mapping, and uncertainty and sensitivity analysis. For case study II, it consists of a CA model for surface water simulation, an agent-based modeling urban mobility simulation, scenario settings, and evaluating the effectiveness of adaptive strategies. The following sections will introduce common methods and specific methods for each one respectively. Then the used data are listed

3.1 Common methods for both cases

3.1.1 Data collection and preliminary processing

The primary step is to collect necessary information and preliminarily analyze and process data for damage and risk assessment, which usually depends on very much on the spatial scale, objective of the project, the available data and resources in hand. For flood modeling and simulation work, the datasets used must at least consist of inundation information, land use data, depth damage function and some other data like social hot spots, and loss statistics in history. Data and Information about the flooded area and inundation depth are the minimum requirements. For more detailed evaluation, other features of inundation, such as flow velocity and flood duration are also necessary. If Annual Average Damage (AAD) is used, inundation information of different return period events (e.g. 10, 20, 50, 100 and 200 year) should be in preparation too. Generally, three or even more flood events were considered the calculation of annual average damage. Aggregated land use data or more detailed land use data in buildings level should also be included in datasets. In the condition of lacking primary data, address-point data with surveys may work as an alternative. For social damage or ecologic damage assessment, hot spots will be also helpful. Depth-damage functions assume inundation depth as the determinant of direct damage that describes how the damage amount change as water depth grows (Appelbaum, 1985; Smith, 1994; USACE, 1996; Pistrika et al., 2014). Different land use types and depth-damage functions should be mapped with each other. Generally, at least five damage functions are needed. Land-use data requires a reclassification processing to the nearest types of land use for matching the most appropriate curves. Depending on different detailed data, absolute damage or relative damage will be used respectively.

During the data collection process, various types of data sources (official or open source) and standards of data formats (quantitative or qualitative) require being rectified and normalized to achieve a unified data management. The China's National Science Data Sharing Infrastructure is an official platform offering the geospatial data service, which is the main source for spatial data. Through accessing APIs of Tianditu, a government-linked open-source web map service, detailed traffic network and partial buildings information can be crawled as complementary and reinforced data. For the mass of qualitative data, like survey data, newspapers, reports, yearbooks, photos et al., they require being organized systematically and converted to available attribute information. Geographical data can describe all the necessary objects and information (terrain, socio-economic information, demographic data, hydrological, meteorological and environmental objects, land use, buildings and infrastructure et. al) in terms of the vector (points, lines, and polygons) or unstructured imagery with attributes tables. By GIS tools, these data from various sources can be successfully integrated and implement graphical representation and uniform storage, management and access (Figure 3-2).

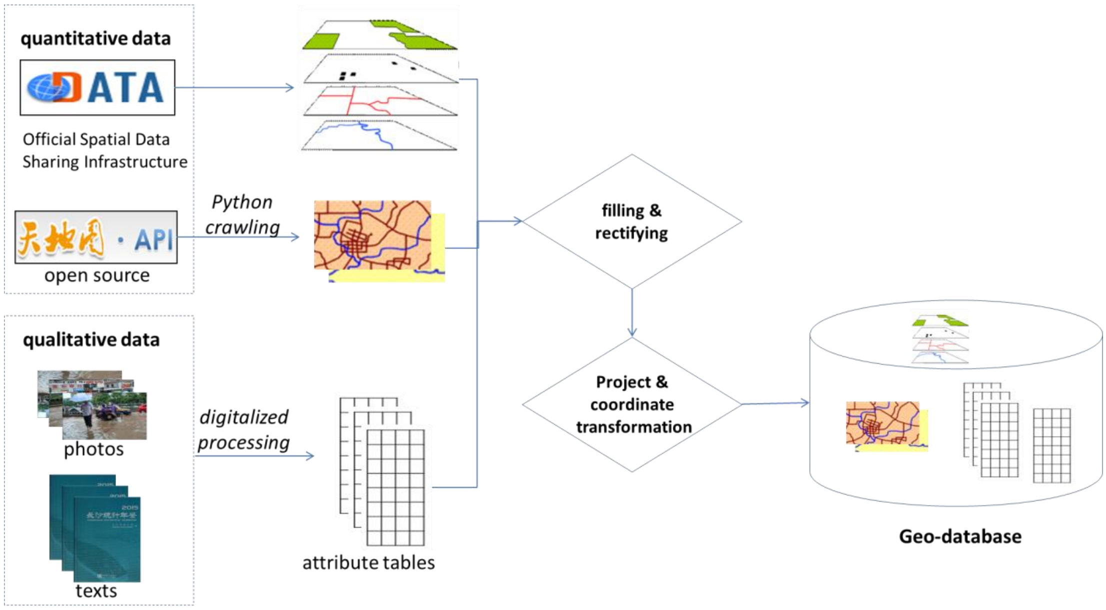

Figure 3-2: Data collection and preliminary processing

3.1.2 Selection of approaches and tools

The approaches and tools for flood risk assessment should take comprehensive aspects into consideration: spatial scales, hydrodynamic models, damage categories and method for risk calculation. An appropriate spatial scale usually ensures to produce more accurate results in flood risk assessment. Apart from spatial scale, hydrodynamic model, exposure, vulnerability and damage models should be preliminarily confirmed as well for different risk dimensions according to the features of flooding and total available resources. For example, there are significant distinct hydrological environment and processing between fluvial and pluvial flooding, which determines different models should be chosen.

3.1.2.1 Selection of spatial scales

The first case study focuses on fluvial flooding within the central city of Changsha. One of its main objectives is to show complete and standardized procedures to assess flood damage and risk due to less regular procedures have been done in cities of China except for few developed cities such as Shanghai, Guangzhou. Viewed from the spatial scale of the study area, Changsha central city, a mesoscale approach was applied. Meanwhile, the spatial scale and the accuracy of the collected data are also on a mesoscale, e.g. the land use data, terrain data, etc. Hence, from the perspective of data, a mesoscale and partly micro scale were chosen. Rationally, an even larger basin was chosen as the calculation domain and conditions, including the central city of Changsha. Another aim of the first case study is to present an approach integrated risk assessment and mapping involving various risk dimensions, providing the spatial decision support for risk management and urban master planning in the medium-long run. From this perspective, a microscale method should perform better if it is possible, a mesoscale will be sufficient to support the aim. Besides, in consideration of the capital cost and the time cost of the project, a mesoscale approach has significant economic and feasible value and is finally confirmed.

The second case study investigates waterlogging disaster caused by sudden heavy rain with great uncertainty in spatial distribution. On one hand, this emergency flooding has an obviously centralized distribution in both time and spatial. Uncertainty caused by spatial difference, cost and efficiency of obtaining data as well as computational consumption of simulation can be greatly reduced at the local level. On one hand, this case pays major attention to study on emergency management and risk reduction measures. At the local level, detailed information of urban environment (e.g. terrain, buildings, population distribution and traffic flow) gives support to high-accuracy flood simulation, dynamic risk analysis and timely prediction. Loss of life and properties can be measured at the individual level. For example, instead of social risk, the individual risk for every location can be calculated for the local urban areas.

3.1.2.2 Selection of hydrodynamic models

Flood hazard analysis based on hydrodynamic simulation is an important preliminary stage of flood risk analysis and assessment. It is related to physical aspects and phenomena (ADPC, 2002; Morita, 2014). Development of a flood forecasting platform is a very crucial element in the process of flood simulation and modeling. Simulation of the hydraulic models can generate inundation maps which are of extreme importance to the community officials and public authorities working in flood risk evaluation. Based on historical real-time records, flood hazard analysis can help people understand the inundation characteristics of flooding and improve decision making. Flood hazard maps are usually made according to specified flood frequencies, varying and clarifying the type of flooding, water depth, extent and duration of flood water as well as velocity and direction of flow. For some even more extreme events such as the 1000-year flood must be taken into consideration (Hauer & Habersack, 2009).

The popular one- and two- dimensional hydraulic models have been concluded by comparing their capabilities, strengths and shortfalls (Frank et al., 2001; MHL, 2006; Werner, 2004; Hicks & Peacock, 2005; Patro, et al., 2009; Simonovic, 2012; Salvadore et al., 2015). Table 3-1 illustrates types of hydraulic models commonly used. As aforementioned, fluvial flooding disaster and waterlogging caused sudden rainfall remains a major challenge that Changsha city is confronted with. For the two different types of flooding, different hydrodynamic models were adopted correspondingly.

Table 3-1: Types of common hydraulic models

Type of models	Useful in areas	Advantages	Disadvantages
2DH grid	Good for estimation of duration of flood, volume propagation, Useful in compact channels	Low to medium cost, simple calculation, low runtime (minutes to hours)	Does not give good results for vast areas or vast floodplains
1D/2D and 2D and finite element models	Good for broad scale modeling, urban inundation, useful for compound channels	Medium to high cost, accuracy and run time (hours to days), can get outputs like percolation and seepage other than depth, velocity and volume	Broad scale application requires coarse grid otherwise the computational time becomes immense, high data demand
Third generation models	Good for showing breaching in 3D and flood propagation in 2D, useful for local predictions	High cost, accuracy, computation time (days), flow velocity and flood boundaries accurately simulated	High run time, high demand for data, high cost
Erosion models Vellinga (1986)	Predicts final erosion profile based on wave height and storm surge water level	Can be used in coasts of different morphology	Does not include wave period
Komar et al (1999, 2001)	Predicts maximum erosion during an extreme event	Simplistic model	Does not take into account the storm duration
Sheach Model	Analytical more versatile	Estimation of cross shore transport rate in different shore zones	Demands high level of data, huge dataset
TIMOR3 and SWAN	Process based model, useful for short term	Detailed morpho-dynamic result	Not efficient to calculate initial response

Source: Floodsite Report T03-07-01 2008

For river flooding simulation, simple hydraulic models perhaps are sufficient to approximate propagation of flood peaks through river channels. The most commonly used models are one-dimensional (1D) models, in which it hypothesizes that the water-level across the cross-section is perpendicular to the flow and the flow has uniform velocity longitudinally, e.g. HEC-RAS[5] 1D model, Mike-11[6] model (Wurbs, 1997; Tayefi et al., 2007). However, 1D models show their limitation in modeling extreme events of large river systems and in representing water depths sufficiently. The outputs are usually sensitive to both the spacing and positioning of the cross-sections (Hunter et al., 2007; Cook & Merwade, 2009).

In some cases, complex hydraulic models could be necessary to incorporate more detailed physical phenomena, but this may increase the uncertainty (Gilles & Moore, 2010). 2D models can balance the computational and processing disadvantages of 1D and 3D models, being moderately complicated to use or being comparable with 2D models (Horritt & Bates, 2002). Yet, they also have the problem of requiring computational skills for various parameters (Werner, 2001). Meanwhile, the performance in processing the mesh is usually slow when the resolution is higher and the floodplains are large (Fewtrell et al., 2008). In the first case study, HEC-RAS 1D model was used for fluvial flood simulation, which has remarkable simplicity, usability and economy. It performs well based on less input information with lower uncertainty, solving the problem of the limitation of available data and the insufficient performance of the computer platform.

For urban waterlogging disaster and emergency management, rainfall-runoff simulation models are crucial for predicting the urban surface hydrodynamics and risk assessment (Chen & Adams, 2007; Kubal et al., 2009; Mahmoudi et al., 2013; Dunn et al., 2014; Tsakiris, 2014). The models require handling subtle urban surface features, sufficiently considering the blocking effect of densely buildings, different types of land use and flood control works (Ghimire et al., 2013; Li et al., 2016). One-dimensional hydrodynamic modeling could play a role in urban drainage or street flow simulation but shows great limitations in surface water simulation (Mark, 2004). 2D simulation models, such as SWMM, DIVAST, JFLOW, and LISFLOOD-FP et al., requiring sufficient input data, have better accuracy and reliability in terms of simulating water surface diffusion over a wide surface area containing complex urban features based on hydraulic equations,

[5] Hydrologic Engineering Center's River Analysis System developed by the US Army Corps of Engineers
[6] Mike-11 developed by the Danish Hydraulic Institute (DHI)

and providing detailed information on inundation dynamics (Bradbrook et al., 2004; Hunter et al., 2005, 2008; Neal et al., 2009; Schumann et al., 2011; Chen et al., 2012; Zhang & Pan, 2014; Liu et al., 2015).

2D Cellular Automata (CA) provides an alternative solution for spatiotemporal simulation by simplifying physics-based 2D hydrodynamic models that describe a hydrological system based on local interactions of their constituent parts through incorporating gravitational rules to represent surface-flow runoff (Parsons & Fonstad, 2007; Burks, 1970; Wolfram, 1984; Gregorio & Serra, 1999). Assuredly, high computational efficiency can also be achieved through parallel computing. A CA-based hydrodynamic model generally considers four basic components:

$$CA = < H, N, P, T >$$

H is the covered hydrological processes during pluvial flooding; *N* is defined neighborhood; *P* refers to the finite parameters for describing the environment of flooded areas; and *T* is transition rules and corresponding functions that determine the flow routing among cells regarding adaptive flood management strategies (Burks, 1970; Wolfram, 1984; Preston & Duff, 2013). Case study two aims to develop an effective storm-water runoff simulation based on CA model and emergency management by considering complex urban environment.

3.1.2.3 Determination of considered damage categories

The determination of considered damage categories contains confirming types of damage and criteria system related to various risk elements (Smith & Ward, 1998; Messner, 2007; Merz et al., 2010; Bubeck & Kreibich, 2011; Jongman et al., 2012; Zabret et al., 2016). It is usually difficult to measure indirect or intangible flood damage. Consequently, flood damage refers to only tangible damage in many cases (Merz et al., 2010; Jongman et al., 2012). However, normally all tangible costs should be covered in principle (Meyer & Messner, 2007). There has been a basic consensus on direct flood damage and put more attention on economic sector. Economic flood damages assessment is purpose-related and therefore context-dependent to a great degree (Merz et al., 2010). According to historical flood damage statistics of Changsha, direct damage accounted for the most part of the total damage, especially the direct economic damage.

As flood damages cover various sectors, criteria selection should fully take comprehensiveness and hierarchy into the consideration. In most of the current flood researches, multi-dimensions (economic, social and environmental) are covered. Direct damage in the economic sector, which generally dominates the total amount of damage, can further be categorized into several sectors according to types of land use or buildings (on microscale). Furthermore, damages to land use or buildings usually take a great proportion of the total damage. Excluding economic sectors, damages in social and environmental dimensions may not be easy to monetary quantification, but still have a major impact on society and ecological environment (Brouwer & Van Ek, 2004; Meyer et al., 2009a, b; Kubal et al., 2009; Wang et al., 2011). Besides, the elements of risk were divided into sub-criteria hierarchically. Figure 3-3 shows a general sketch of dimensions of risk and hierarchies of criteria system.

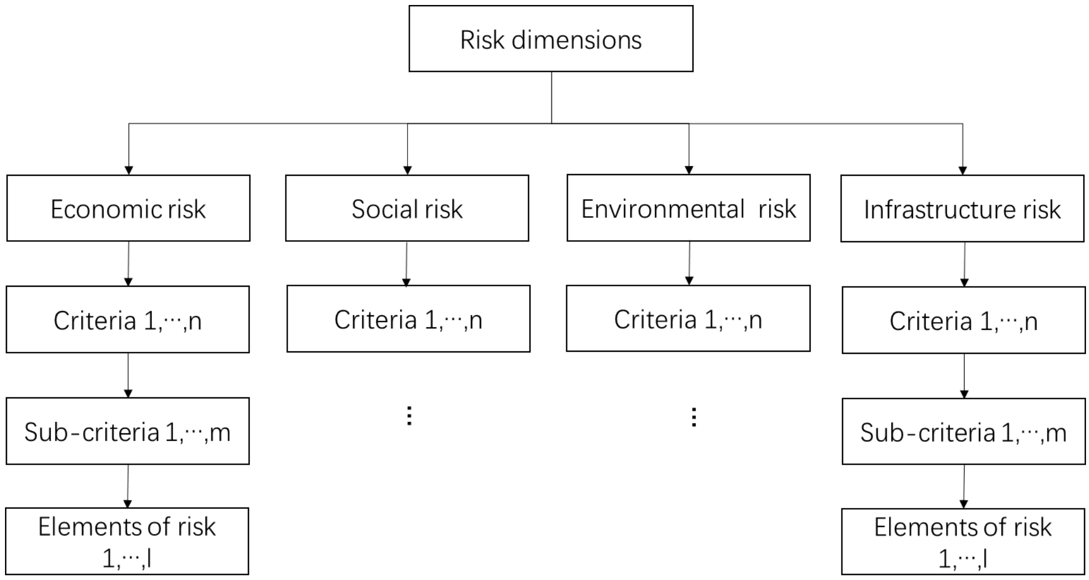

Figure 3-3: A sketch map of criteria system with multi-dimensions and multi-hierarchies

Among these damage sectors, infrastructure systems have specific characteristics. Many urban infrastructure systems have significant network features. Damage on local of the system often triggers a chain reaction and even causes system crashed totally. For example, local inundated road segments usually result in traffic disruption and congestion and decrease of road accessibility. It refers to not only direct economic damage on road segments and cars, and indirect economic damage like increased oil cost, but also to social damage on the loss of life as well as indirect intangible damage such as urban space mobility and increased travel time cost. Therefore, at a city level, infrastructure systems couple with other urban subsystems dramatically. It is difficult to allocate the damage of infrastructure into the other three risk dimensions. For the reasons above, infrastructure systems are considered as separated risk dimensions in the first case study.

By contrast, in local or micro scale, damage and risk calculation are objective-oriented directly, involving immovable objectives like buildings, and movable agents like pedestrians and vehicles (such as private cars and buses), which offers the opportunity for lower coupling among subsystems. The boundaries among different risk dimensions fade. Hence, in such a scale, the second case seek an objective-oriented approach to evaluate the impact of flooding.

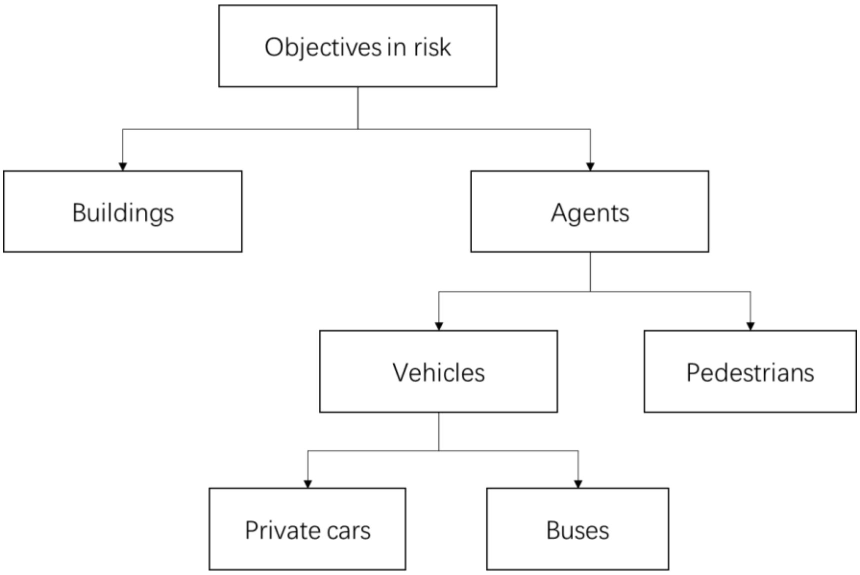

Figure 3-4: A sketch map of objective-oriented criteria hierarchy

3.1.2.4 Selection of methods for risk calculation

According to the component of risk, selection of risk models consists of the selection of exposure model, vulnerability model and damage model. Some receptors of flooding, like residential assets and infrastructure, can be handled by static analysis. However, other receptors, like residents and vehicles, may keep on moving during the flooding event. Therefore, dynamic exposure enables more accurate risk assessment. In the first case study, steady flow simulation, a static method, which largely constricts the selection of exposure models. On the other hand, static exposure of risk elements is acceptable to flood risk assessment on the city scale. While in the second case, dynamic exposure is required due to not only the feature of rapid hazard onset speed of pluvial flood but also the local spatial scale in the study.

Using hydraulic models, inundation maps for different return periods can be delineated. Combined with social and economic spatial data, they can be further used in potential flood damage assessment. As for vulnerability and damage calculation, damage values can be represented as an absolute currency amount or a relative percentage loss. As for which spatial scale and what kind of models to choose, the determination generally should balance the study objective and the pre-existing and potential resources, such as funds of the study, project period and various datasets (e.g. damage functions for various categories). In this dissertation, the relative value is adopted for all the damage calculation.

3.2 Methods for case study I

Under the simulation-assessment framework, relevant method and technical details must be determined according to case studies. The section will introduce the three main modules of the method (Figure 3-5): First, analyzing flood hazard based on the hydrodynamic model. Then, risk criteria determination and the relative assessment approaches (exposure and vulnerability models) for different dimensions of risk spatially. Third, integration of assessment and mapping for different dimensions using MCA method and GIS tools.

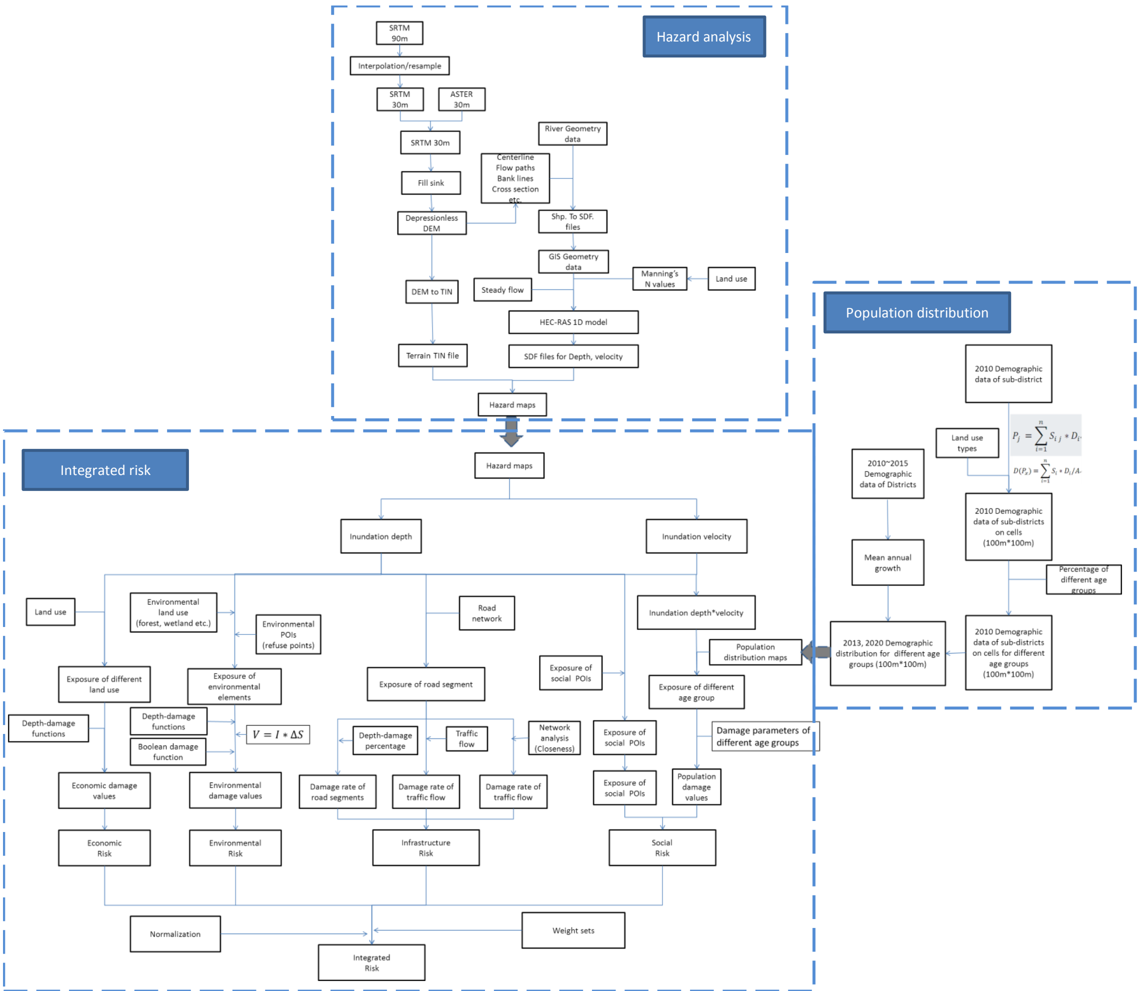

Figure 3-5: Flowchart of case study I

3.2.1 River flooding simulation: HEC-RAS 1D model

HEC-RAS 1D model was chosen for fluvial flood simulation in the first case study. HEC-RAS model requires a minimal requirement for input data and computer performance compared to other models. It also offers a non-commercial application and inputs and outputs can be conveniently combined with GIS tools (Kubal et al., 2009; Wang et al., 2011). Thus, it is a suitable tool under the circumstances of limited resources with higher feasibility, dependability and practicability. Users can perform one-dimensional steady or unsteady flow. It hypothesizes that the flow has a constant velocity, depth and discharge at all cross-section positions. Unsteady or non-uniform flow recognizes the changes in both depth and velocity over time (Wurbs, 1997; Dyhouse et al., 2003). The mathematical basis for computing steady flow in the HEC-RAS model is 1D Saint Venant Equations (USACE, 1996):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} + g(S_0 - S_f) = 0$$

where $\frac{\partial u}{\partial t}$ is the local acceleration term, $u\frac{\partial u}{\partial x}$ is the convective acceleration term, $g\frac{\partial h}{\partial x}$ is the pressure gradient term, $g(S_0 - S_f)$ is the gravity term and the friction term.

HEC-GeoRAS is a plugin for ArcGIS integrated with HEC-RAS. It is used in data preliminary processing. Besides, with the help of HEC-GeoRAS (Figure 3-6), the user can abstract the cross-section information from the terrain data and set the other necessary attributes, such as the rivers information (covering stream central lines, flow path and bank lines), land cover and land use, Manning coefficient of roughness and so on. To a very great extent, that will improve the accuracy of calculation for flow profiles as well as reduce time and effort quietly. Figure 3-7 denotes the process of the river modeling and the flood hazard mapping with HEC-RAS.

An appropriate selected value for Manning's roughness coefficients (Manning's n) influence significantly on the accuracy of computed water surface profiles. It can be calibrated according to observed water surface profiles. The HEC-RAS model was adopted for the flow simulation of Xiangjiang River (Xiangtan to Wangcheng). To arrive the optimal parameters for the model, the simulated water surface elevation of the flood of the year 2007 and 2010 were compared with the corresponding observed values at Changsha gauging station by using

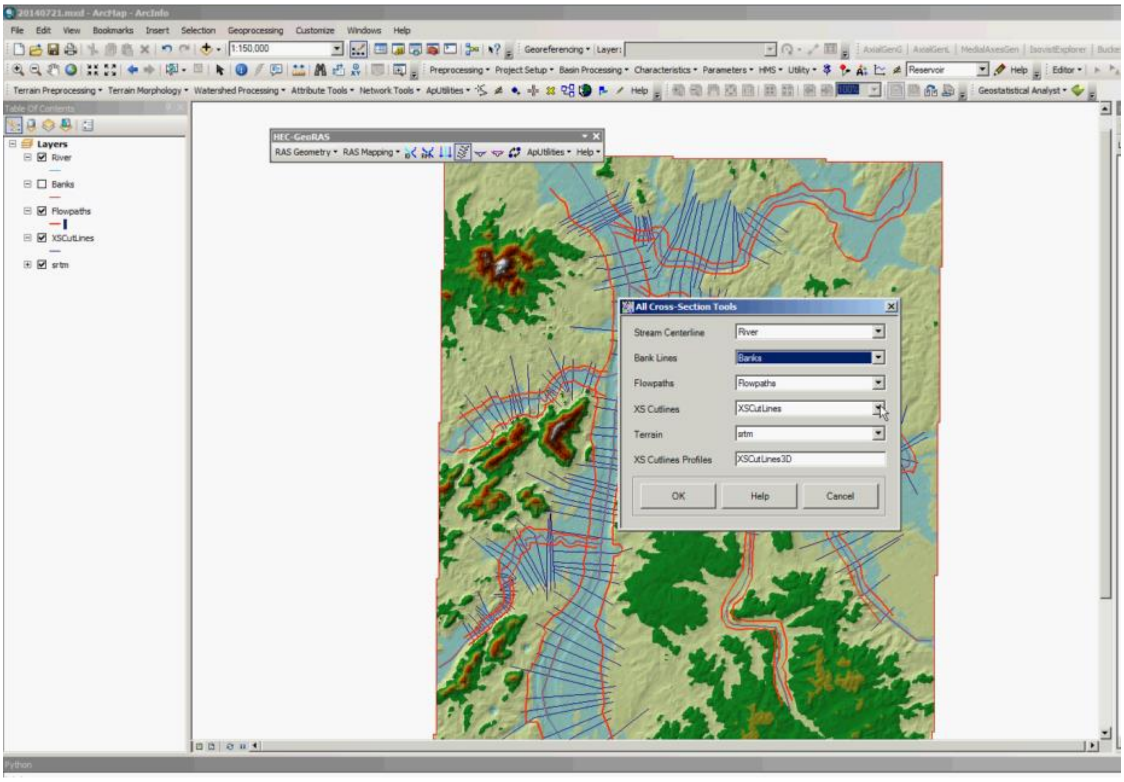

Figure 3-6: Screen-shots from ArcGIS for data preparation in HEC-GeoRAS

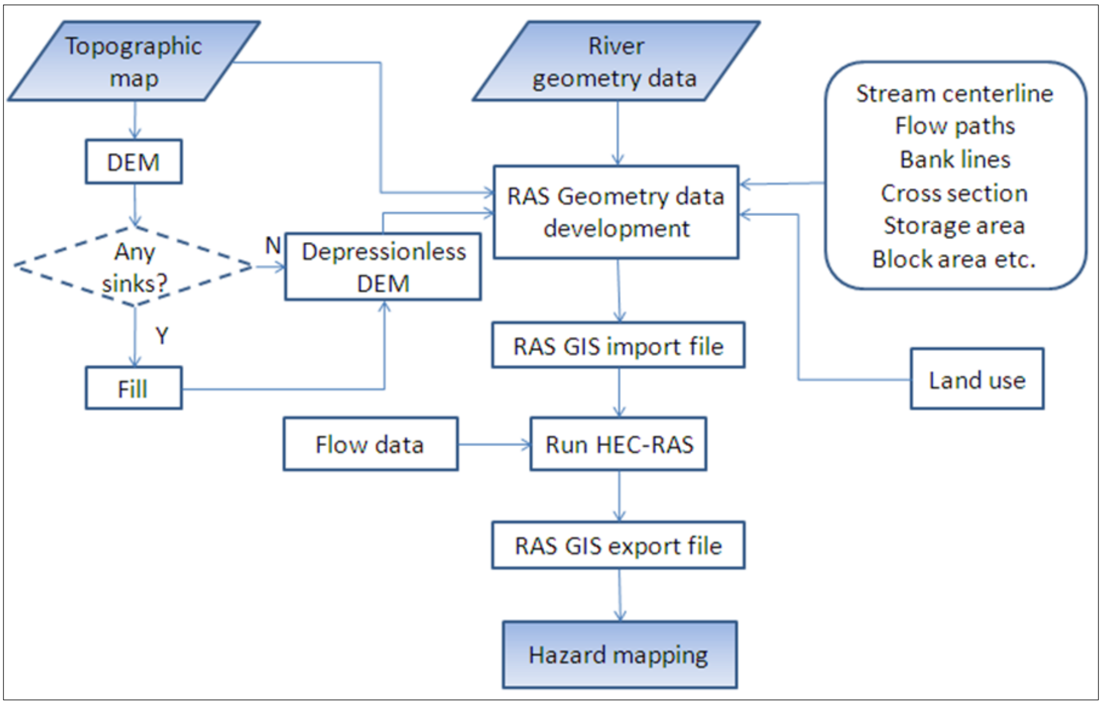

Figure 3-7: Flowchart of hazard mapping with HEC-RAS

different combination of Manning's roughness coefficients. Nash-Sutcliffe efficiency test was adopted for comparison for various Manning's coefficients (Nash & Sutcliffe, 1970; Parhi et al., 2012). The Nash-Sutcliffe coefficient (E_{NS}) is defined as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_o})^2}$$

where $Q_{o,i}$ and $Q_{s,i}$ are the i-th pair of the observed and simulated values, $\overline{Q_o}$ is the average of the observed values, and n is the total number of paired values. E_{NS} ranges from $-\infty$ to 1. It indicates that the simulation fits perfectly when E_{NS} is up to 1.

3.2.2 Risk models for various dimensions

The criteria selection considers comprehensiveness of the whole problem and low-complexity of the assessment process. Through a great variety of methods exist, some basic categories should be covered in most studies. In case study one, the risk criteria are selected based on many pre-existing researches in flood risk analysis in different countries (Thinh & Vogel, 2007a,b; Meyer & Messner 2005; Meyer et al., 2009 a, b; Kubal et al., 2009; Wang et al., 2011). The framework of integrated risk assessment approach including multiple dimensions is shown in Figure 3-8. To assess the damages and risks induced by fluvial flooding comprehensively, a city in the floodplain can be considered as a system consisting of three risk dimensions corresponding to various sub-systems: economic, social and ecological. Thus, the flood risk for each risk dimension can be assessed separately. Especially, damages on infrastructures are also particularly taken into full account due to a broad socio-economic impact. A hierarchical criteria system was used, covering three different risk dimensions-economic, social, environmental sectors. In addition, the risk of infrastructure system was treated as a separate dimension, and the referred risk elements were elaborated and analyzed individually.

3.2.2.1 Economic risk model

Direct economic damage, particularly buildings and inventories, generally dominates the total amount of damage. According to the statistics from the Flood Control and Drought Relief Office of Hunan province, direct economic damage accounts for 84% of the total loss. Specifically, residential land use accounts for

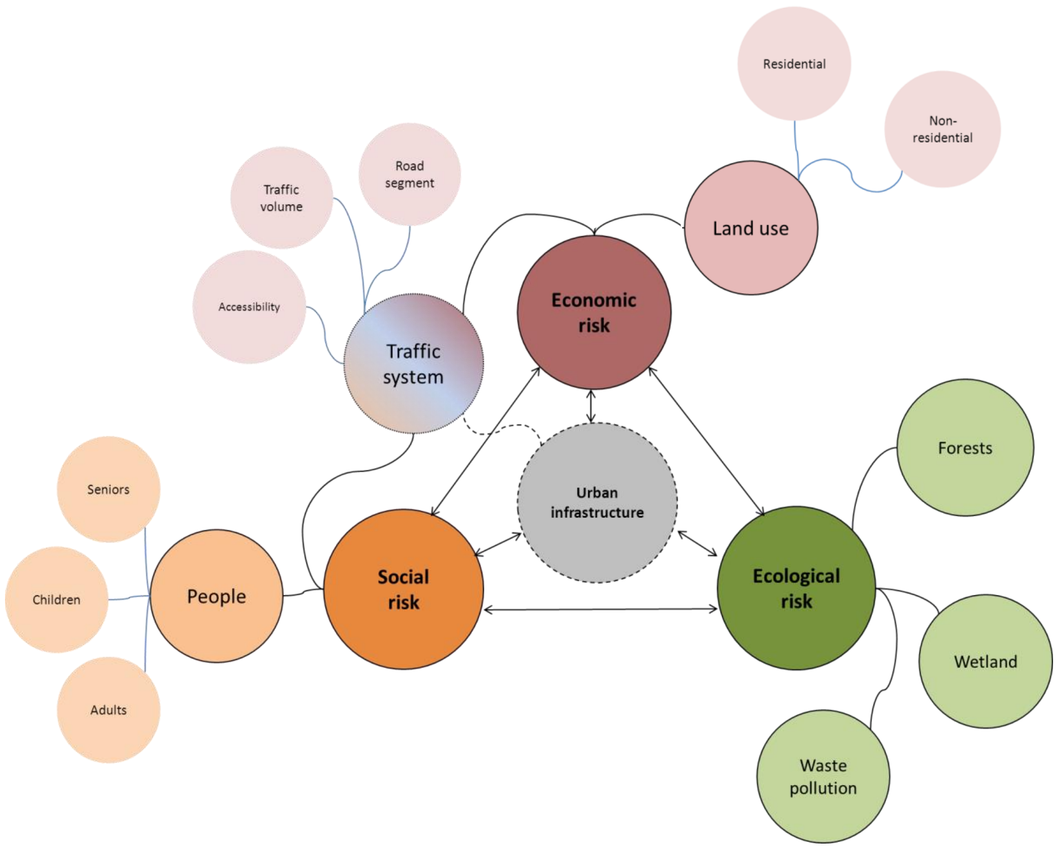

Figure 3-8: Multiple risk dimensions in integrated risk assessment

the largest part of the flooded area. In this case study, the economic flood damage is corresponding subdivided into five parts based on five types of aggregated land use, which is residential area, commercial area, manufacture area, administration and public utilities as well as the warehouse. Besides, HEC-RAS 1D simulation offers inundation characteristics of depth and velocity. Due to the lack of information of duration and velocity-damage curves, the damage is generally related to only water depth in economic damage calculation. Depth-damage curve, which is sometimes called depth-damage function, depicts the relationship between inundation depth and flood damage on different types of land use. Information of depth-damage function functions are offered by National Disaster Reduction Centre (NDRC) of China and ANFAS project (Wang & Xiang, 2002; Tariq, 2013). As types of land use are larger than types of depth-damage curves, the land use data have been categorized to match the closest proximal curves (Figure 3-9).

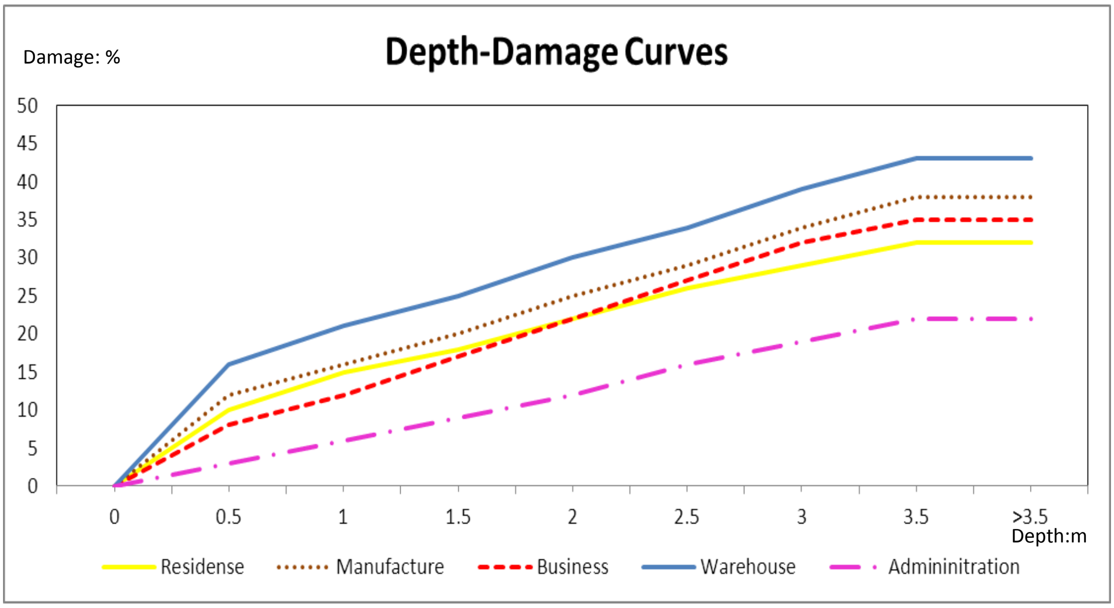

Figure 3-9: Depth-damage curves of Changsha City (Source: National Disaster Reduction Centre of China; Wang & Xiang, 2002; ANFAS[7] project)

3.2.2.2 Social risk model

Humans are the most valuable assets in flood prevention and control. Flood risk to people stems from a combination of their exposure and vulnerability. People exposed to flood may have different degrees of vulnerability owing to their own characters, such as physically or mentally capable, knowledge or experience etc. For instance, children, seniors, sick people or disabled people represent age classes as well as individual mobility which are particularly vulnerable to floods (Cutter et al., 2003; Meyer et al., 2009a; Balica et al., 2012). However, it is often difficult to consider the individual characteristics of vulnerable people on a meso scale. Therefore, it is necessary to define groups for the potentially vulnerable people considering the statistics of people with one or multiple characteristics. In this case study, the vulnerable people are defined affected population and grouped into children, adults (excluding senior) and seniors based various ages and constitutional mobility. Although in theory infants and young children could face more risk, it is unlikely that they would deal with the flood independently. Thus, they are excluded from children group.

7 The ANFAS project is to develop a Decision Support System for flood prevention and protection, integrating the most advanced techniques in data processing and management (1 January 2000 - 31 December 2002). The partners involved INRIA, Matra Systems (France), Bureau des Recherches Géologiques et Minières (France), Reading University (United Kingdom), FORTH, Slovak Academy of Sciences, CLRC, Chinese Acedemy of Sciences: Institutes of (i) Automation (ii) Remote Sensing Applications (iii) Atmospheric Physics, ERCIM.

Demographic characteristics are among the most commonly applied social vulnerability indicators. Due to the deficiency of detailed building data, the spatial distribution of population is quantified based on a mesoscale approach. Land use density method, which has been wide range of applications in simulating spatial distribution urban population with very high accuracy (Galeon, 2008; Wünsch, 2009; Ural et al., 2011). The assumption of this approach is that it has an equivalent population density in the same type of land use. Supposing there are m sub-districts and n types of land use, $P_j\,(j = 1,2,\dots,m)$ denotes the population of sub-district $D_i\,(i = 1,2,\dots,n)$ presents the population density of land use i area of each type of land use within a sub-district will be denoted as $LU_{i\,j}$. Thus, linear equations can be established as follows:

$$P_j = \sum_{i=1}^{n} LU_{i\,j} * D_i$$

Where $i = 1,2,\dots,n;\ j = 1,2,\dots,m$

When *m* > *n*, the equations can be solved by the least square method, then the estimated population P_e can be obtained, and the error can be calculated using:

$$\Delta P = \frac{|P_j - P_e|}{P_j}$$

After getting the evaluated population density of each types of land use, population are distributed into spatial grids according to:

$$D(P_x) = \sum_{i=1}^{n} LU_i * D_i / A$$

Where $D(P_x)$ is the population density of grid x; LU_i is the area land use type i; A is the area of the grid.

In this case, population of 55 sub-districts were used, and land use types are constructed into three groups-residential, business and industrial, green and open space and square, which can decrease the number of iterations and improve the prediction precision. The grid size is 100m*100m, thus A equals 0.01 km^2.

Social risk is often expressed in an F-N curve, which presents the complement of the distribution curve of the number of fatalities (N), showing the probability of exceedance (F) in one year of a certain number of fatalities (Jonkman & Vrijling, 2008; Kassa, 2010). Nevertheless, unlike economic damage assessment, there are no F-N curves for social damage assessment in Changsha city until now. By reviewing study progress on estimating the loss of life induced by flood, most of them assess the damage based on inundation depth, and secondly based on flow velocity (Middelmann-Fernandes, 2010; Papathoma-Köhle et al, 2011; Jonkman, 2007). Netherlands' research organization HKV Consultants and WL/Delft Hydraulic (2001) has established a "standard method for predicting damage and casualties", which considers both water depth and the increasing rate of water depth in the assessment model. However, the model did not match with actual situation very well. For example, in 1953 Dutch flood one-third casualties happened at places where the depth of floodwater is less than 3 meters (Jonkman, 2007). Flow velocity is another important factor leading to human mortality because high-velocity water flow likely makes people loses their balance (Jonkman & Penning-Rowsell, 2008; Chanson et al., 2014). Besides, it is a fact that survivals are always exists in flood events. Almost no flood causes all affected persons lost their lives except for some extreme situation. Boyd et al. (2005) used S type curves to analyse the relationship between death rate and water depth, which has an asymptote representing the maximum of death rate at 0.34. The results accord with the facts basically.

In addition, though human mortality is the most widely used indicator in damage assessment, impact on survivors exposed to flood should not be neglected. In this case, the damage potential of flood is scored referring to depth times velocity, which is based on experimental studies. People with high parameters mean that they are in life-threatening conditions owing to lose their balance in water. The damage parameter D_{hv} depends on weight, height and mobility capacity, and is divided into three levels: low, medium and high. The corresponding damage parameters of different groups are listed in Table 3-2. For example, the threshold of high level for adults (D_{hv}) is 0.7 m^2/s.

Table 3-2: Damage parameters of different age groups

Group	**Damage parameter D_{hv} (m^2/s)**		
	Low	**Medium**	**High**
Children	<0.1	0.1-0.25	>0.25
Seniors	<0.3	0.3-0.5	>0.5
Adults	<0.5	0.5-0.7	>0.7

Source from Jonkman, 2007; Jonkman & Penning-Rowsell, 2008; Chanson et al., 2014

Then the relative damage values are assigned using a 1-5-9 ranking system. Traditional 1-2-3 rankings work, but often lead to close scores if not outright ties, with a small differentiation between the lowest and highest scores. A 1-2-3 system usually results small differentiation between the lowest and highest damage level. In contrast, the 1-5-9 scoring method is borrowed from a technique called Quality Function Deployment (QFD) and Analytic Hierarchy Process (AHP) 1-9 scoring method (Kahraman et al., 2006; Chen & Ko, 2010; Abdolshah & Moradi, 2013), tried, and evaluated, popping one damage level clearly above the rest, and also shows the lower-level being lower, more effectively distinguishing the extent of damage. Then the aggregated damage values are got by accumulating scores. For other social hot spots like facilities with point features are simply used binary code to evaluate the damage. These facilities include hospitals, bus stops and squares, which are eventually covered in social risk dimension.

3.2.2.3 Environmental risk model

Elements of environmental risk dimension are listed in Table 3-3. To assess the environmental risk, three sub-criteria are selected. First, inundated forest, factitious ecological green land as well as park cause negative ecological effects. The percentage of damage is assessed based on a synthetical damage model (shown in Table 3-4). Second, flood water may conducive to the spread of pollutants. In many fast-developing cities in China, including Changsha City, refuse points are one of the important potential sources of contamination because of shabby facilities and the lack of standardized management. Third, types of inundated land use such as wetland and factitious ecological green land, as well as park, are also covered. Flooding water decreases the ecosystem services and cause loss of biodiversity conservation value equivalent. Referring to studies on evaluation of ecosystem services wetland (Xin & Xiao, 2000; Liu et al., 2007; Zhang et al., 2015), the ecosystem service value:

$$V_{BD} = I * S$$

Where I is biodiversity conservation value equivalent;

S is the area of wetland.

According to the model, I is a constant. As the relative risk value is used, I will not finally affect the standardized risk value. The loss ecosystem service value of wetland $D_{wetland}$ can be assessed based on the inundation area ΔS:

$$D_{wetland} = I * \Delta S$$

For refuse points, a damage function based on simple binary code method is used for a grid cell according to whether the area is affected or not.

Table 3-3: Risk elements of environmental flood risk assessment

Elements of risk	Spatial unit	Damage value calculation
Forest, ecological green land, park	Area	Synthetical damage model
Wetland	Area	Loss of ecosystem services
Refuse points	Point	Boolean yes/no damage function

Table 3-4: Forestry synthetically damage model

Water depth: m	0-1	1-2	2-3	>3
Damage rate: %	15	30	40	50

3.2.2.4 Infrastructure risk model

Urban infrastructure, like road network, plays crucial roles in mediating both the risks and opportunities to people and the economy but must be reconfigured as part of a strategy to increase resilience in urban environments. For road network, referred risk elements embrace inundated road segments, effects on traffic flow, accessibility of road that related to service level of road as well as the increase of transport costs.

As for impact on road networks, an integrated assessment framework based on network analysis method that combines hazard modeling and graph theory is adopted. The vulnerability of a road network depends on both its role in the network and the number of users who rely on the asset during their use of the network. Figure 3-10 shows the technique process of impact evaluation on infrastructures.

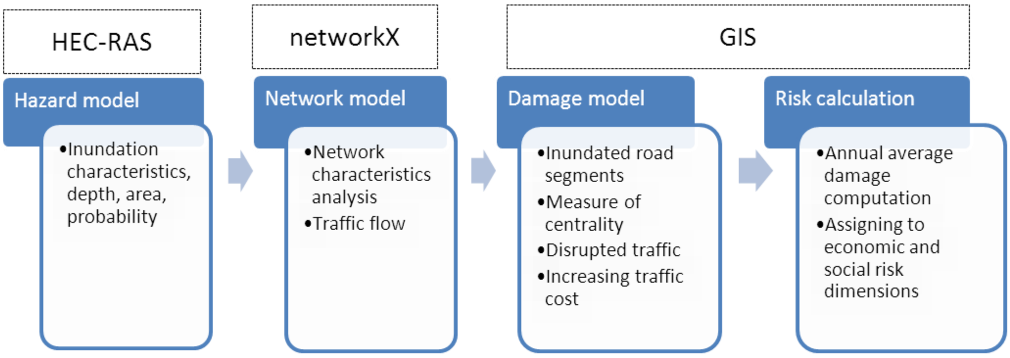

Figure 3-10: Technique process of infrastructures loss analysis

In order to conduct the vulnerability analysis of transport system, a road network model was developed based on graph theory. Formally, a network can be represented by a graph G, which is formed by a set of vertices V and edges E connecting the vertices (Stam & Reijneveld, 2007; Ruohonen, 2013):

$$G = (V, E)$$

Moreover, a given planar graph G, an equivalent dual graph can be defined geometrically (Harary, 1994; Donges, 2013). For example, the urban space and environment (a network of the spatial elements) can be derived from maps of open spaces (streets, places, and roundabouts), morphologically representing the urban network as a dual graph (Volchenkov, 2008). That is, roads and convex spaces may be treated as the spatial elements (nodes of a morphological graph), while either the junctions of roads or the overlaps of convex spaces may be considered as the edges linking spatial elements into a single graph unveiling the topological relationships between all open elements of the urban space (Volchenkov, 2008) (Figure 3-11).

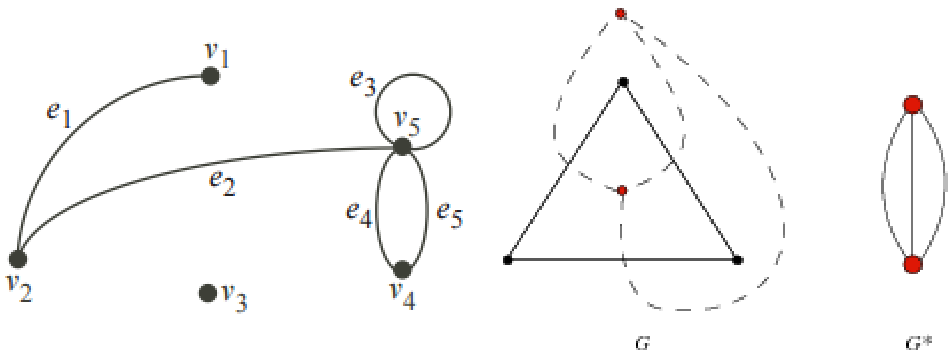

Figure 3-11: Examples of graphic representation of network

In a network, Degree, Average Path Length (APL) and Clustering Coefficient (CC) are three basic parameters used for description of topological structure (Donges, 2013). Degree is a sort of description of node centrality. For a node k_i the degree is the number of edges that connect with it, which is also called connectivity (Liu et al., 2013). Also, the basic topology of a graph G can be characterized in terms of the degree distribution $P(k)$, defined as the probability that a node chosen uniformly at random has degree k (Jiménez et al., 2008; Steinbacher, 2013). The shortest path length d_{ij} is the length between node i and j, which may play important roles in the transport or communication network. The maximum value of d_{ij} is called the diameter of the graph. The Average Path Length (APL) measures the typical separation between two nodes in the graph. It is defined as the average of length over all pairs of nodes:

$$APL = \frac{1}{N(N-1)} \sum_{i,j\in N, i\neq j}^{n} d_{ij}$$

Clustering coefficient (CC) is another characteristic parameter to depict the degree of connection of neighbor nodes and also known as transitivity. In complex network, if node i is connected with k_i nodes, its CC C_i can be quantified as the ratio between actual number of connected edges E_i within such k_i nodes, namely:

$$C_i = \frac{2E_i}{k_i(k_i - 1)}$$

The CC of the whole network is then given by the average of C_i over all the nodes in graph G:

$$C = \frac{1}{N}\sum_{i=1}^{n} C_i$$

By definition, both C and C_i are between 0 and 1.

By the characteristics parameters, topological features of network can be delineated. It has been found that networks from the real-world usually have small Average Path Length and higher Clustering Coefficient, which is called “small world” (Watts & Strogatz, 1998). Besides, in many networks, few hub-nodes are of high importance, known as scale-free networks (Barabási & Albert, 1999). Owing to the traits of “small world” and “scale-free”, networks in the reality are usually rather vulnerable. Even one removed hub-node locally may severely destroy the global topology and structure of network. To evaluate the vulnerability of nodes and the corresponding damage, we can calculate and compare characteristics of network before and after removing the node. One of the most common approaches is evaluating loss of node importance. Other than degree, local, eigenvector, betweenness, control and closeness are also indicators to measure centrality of nodes (Table 3-5).

As mention above, there are two approaches by abstracting a system as a complex network: primal approach and dual approach. Though primal approach can describe the spatial attributes of road network simply and intuitively, parameters of network characteristics, like Centrality, APL and CC, cannot be obtained. Dual approach eliminates the limitations with road network topology, which enables to make comparison among road segments in spite of not directly characterizing the spatial information. In this case, dual graph is used, namely, road segments are represented by nodes and junctions are treated as edges. A VBA (Visual Basic for Applications) script is used to convert the primal road networks (in format of ArcGIS shapefiles) to dual ones with geospatial information as corresponding attributes of nodes and links. After network analysis, the results are fed back into the primal network by joining tables (Figure 3-12).

Table 3-5: Indicator of node importance in network

Indicator	Merit	Demerit	Time complexity
Degree	Simple and intuitional	Only local features considered	$O(N)$
Local	suitable to large network, more accurate than degree	Without considering close connection with neighbors	$O(N^2\langle k\rangle)$
Eigenvector	Considering importance of neighbors	Linear overlay simply	$O(N^2)$
Betweenness	Considering capacity of information load	Not suitable to large network	$O(N^3)$
Closeness	Considering both local and global influence	Not suitable to large network	$O(N^3)$

(N: number of nodes, $\langle k\rangle$: mean degree)

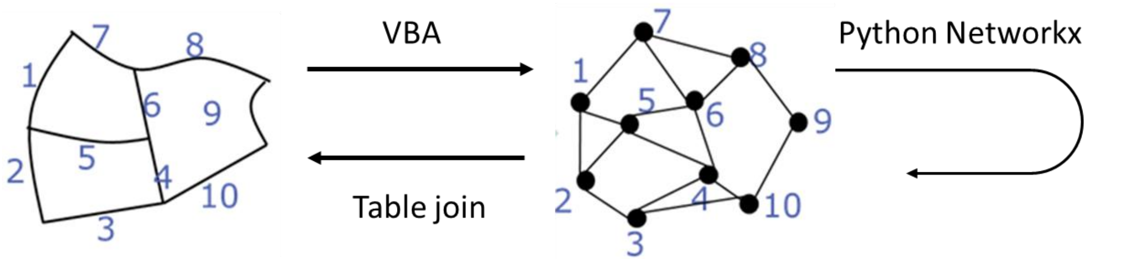

Figure 3-12: Technology roadmap for network analysis

Direct physical damage on road segments and traffic flow are evaluated also based on flood depth. Hazard model based on HEC-RAS 1-D simulation has been denoted above. Inundation maps of different probability of flood with water depth and area are overlaid with urban road network. Then damage of road segments can be calculated based on depth-damage function. Based on Origins and Destinations census and travel survey data (OD matrix), traffic volume is assigned to road link under each flood scenario. Research data indicates that the vehicles' speed will slow down and the travel will be disrupted absolutely when water depth reaches 30 mm. Combining inundated map, the affected traffic is assessed by measuring affected average daily traffic (ADT). As there is no available statistical data of ADT, 12-hours (07:00~19:00) traffic volume, taking up 80%~90% of ADT for most roads, is used instead.

On the other hand, flood depth on a road influence vehicle speed and even cause road disruption, thereby intangibly increasing travel loss due to various factors, i.e. distance, free-flow speed, congestion and reschedule trips. Degradation of the state of the roads brings a decrease in the level of road service. To measuring transportation system performance, closeness considers both local and global influence of nodes, is considered as a measure of accessibility. Closeness centrality is defined as the reciprocal of the sum of its distances from all other nodes (Freeman, 1978; Wasserman & Faust, 1994; Opsahl, 2010), that is:

$$C^c = \frac{N-1}{\sum_{j=1,j\neq i}^{N} d_{ij}}$$

Where N is the total number of nodes, and;

d_{ij} is the shortest path lengths between node i and j.

In other word, closeness depicts the transmission efficiency of from one node to the others in network. It considers both local and global influence though it is not suitable to large network. Decrease of closeness could be a kind of measurement of accessibility loss of road segments. However, in reality, people usually plan their trips according to travel time cost rather than choosing a shortest path. Hence, networks are weighted by average travel time. The flood damage of node i, D_{C_i} can be calculated based on the loss of weighted closeness centrality:

$$D_{C_i} = C_i' - C_i$$

Where C_i' is the closeness centrality in baseline scenario without flooding, and C_i is the closeness centrality for flooding of a certain return period. Being similar to the definition of Annual Average Damage (AAD), the annual average damage of closeness centrality AAD_{C_i} can be expressed as:

$$AAD_{C_i} = \sum_{j=1}^{k} \frac{D_{C_i}(P_{j-1}) + D_{C_i}(P_j)}{2} \left| P_j - P_{j-1} \right|$$

Where; P_j is the recurrence probability of flood event *j*.

Details of relative damage parameters of road infrastructure are shown in Table 3-6:

Table 3-6: Risk elements of road infrastructure

Types of loss	Risk element	Damage calculation	Unit	Exposure degree
Physical damage	Road segments	Depth-damage parameters	Unitless	Inundated road
Traffic	Traffic flow	ADT traffic (12 h)	PCU[8]/day	
Service level	Accessibility	Closeness weighted by time cost	Unitless	All roads

3.2.3 Risk calculation and mapping

As flood risk is more multifaceted in urban areas, flood risk analysis and assessment should use comprehensive approaches including both economic

[8] A Passenger Car Unit (PCU) or Passenger Car Equivalent is essentially the impact that a mode of transport has on traffic variables (such as headway, speed, density) compared to a single car.

and non-economic impacts (e.g. ecological and social damages) (Schanze, 2006; Haque & Etkin, 2007). Hence, a multi-criteria analysis for flood risk assessment becomes necessary (Kubal et al., 2009). Some case studies develop integrated approaches for different types of natural hazards, focusing on social vulnerability indicators or the evaluation of flood mitigation measures (Thinh & Vogel, 2006; Kaplan et al., 2009; Kubal et al., 2009; Scheuer et al., 2011). Some other approaches put particularly emphasis on a multicriteria flood risk assessment and mapping (Kubal et al., 2009; Meyer et al., 2009a, b; Wang et al., 2011). Multi-Criteria Approaches (MCAs) involve a number of techniques for problems of assessing decision characterized by a range of diverse attributes where these do not need to be represented in monetary terms. There are several methods that are applicable to spatial MCA, such as conjunctive/disjunctive approaches, AHP, MAUT (Multi-Attribute UTility), outranking approaches and so forth (Meyer et al., 2009a, b; Kubal et al., 2009; Wang et al., 2011). Quantitative scoring systems and quantitative weights can be considered as core in MCA processing.

3.2.3.1 Scoring the criteria and standardizing the value

In MCA systems, quantitative and qualitative descriptors are usually used in conjunction with each other. For quantitative descriptors, numerical ranges can be set up based on standard measurement units for different impacts and scores assigned against these. For qualitative descriptors, related scores can be used for measuring elements without natural units. Moreover, there must keep a balance between the sufficient detail and the simplicity.

Scoring the criteria refers to exposure and the corresponding vulnerability of risk elements. Exposure features depend on the spatial distribution of elements and the inundation characteristics. For example, in the first case study, land use exposure can be obtained by overlapping inundation maps and land use map. For social risk, demography data can be assigned according to statistic data based on land use method. With regard to infrastructure system, the exposure and vulnerability are analysis by integrating hazard model, traffic assignment based on macro-traffic simulation model as well as network analysis method. While in the second case study, micro-traffic model combined with inundation model are used to simulate waterlogging and traffic condition in real time. Detailed information of buildings in local scale is used. The exposure of buildings, people, cars and road segments to flood are dynamically obtained with the running of simulation model.

For damage parameters and damage values, impacts of many categories cannot be assessed in the form of money. Therefore, all the impacts then must be presented in the same units and can be combined. An approach is to assign the “maximum” damage a score of 1 and then score all other options relative to 1. In the first case study, due to the limited available data and the calculation of integrated risk value, relative damage value is used. The final elements of risk were scored to measure the impacts the standardized value between 0 and 1. The damage units depend on the elements of risk, such social damage in number of population or unitless number (percentage of damage for land use). Economic damage is calculated based on combing layers of land use, inundation maps, and depth-damage functions. Social and individual damages depend on spatial distribution of demography as well as inundation depth and flow velocity. While damage categories that have only less impacts on the total damage amount can be covered in a relatively approximate way. For example, and environmental damages are usually calculated considering ecological value equivalent which mainly relates to inundation area without exact depth of water or by a typical percentage of the total damage, handled as binary information.

3.2.3.2 Weighting and mapping

The relative importance of the different impact categories can be identified by assigning weights to the individual scores within each category. MAUT, an additive weighting approach, is applied to calculate the integrated risk value. It generates a weighted average of the single criterion value for each area (or alternative). It allows the decision maker to determine the weights given to each criterion and provides the possibility to carry out the point allocation approach, a rating technique and the swing weight approach (Meyer et al., 2009a). It usually involves three steps. First, the weighted value for each criterion is calculated by multiplying the standardized value with its weight. Then, the weighted values of each criterion are summed to get the overall value for each alternative. Finally, rank the alternatives according to their aggregated value. The integrated risk values R are finally calculated with weights:

$$R = \sum_{i=1}^{n} w_i r_i$$

Where; r_i is the risk value of category i, w_i is the corresponding weight.

Average Annual Damage was calculated based on damages of all kinds of floods. Then the criteria scores were standardized to values between 0 and 1 and were set weights for eight different scenarios as Table 3-7 lists: In equal weight scenario, four risk dimensions share the weight equally. In the next three scenarios (economic inclined weight, social inclined weight, environmental inclined weight), the inclined risk dimensions are respectively assigned a weight with 0.4. The following four scenarios are urban mobility extreme weight, life safety extreme weight, economic extreme weight and environmental extreme weight. In each one, an extreme high weight with 0.8 are set for one of the risk dimensions. Combining AAD value with the weight sets above, the integrated flood risk values for different scenarios were calculated, which equals the sum of each of dimension's risk value with the respective weight.

Integrated flood risk values are calculated based on both cell level and administrative sub-district level. As the formats of geospatial data are different, they required to be converted into unified raster data with grid size of 100 meter by 100 meter and then are summed up. At administrative sub-district level, all dimensions of standardized risk values are summed to count the overall risk level. The completed process of integrated flood risk assessment is showed in Figure 3-13. Technologically, all the calculations and mapping are usually carried out in ArcGIS environment. ArcGIS software VBA scripts calculate most of the damage and risk value and format transformations of network files except that the network analysis processed in Python with NetworkX package (Hagberg et al. 2008), which is a high-productivity software for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks (Hagberg et al., 2008; Varoquaux et al., 2008). Finally, using ArcGIS, all elements at risk are converted to raster and risk maps are weighted overlaid. Except for integrated risk mapping, separate risk (or sector risk) mapping is also implemented according to diverse of risk dimensions.

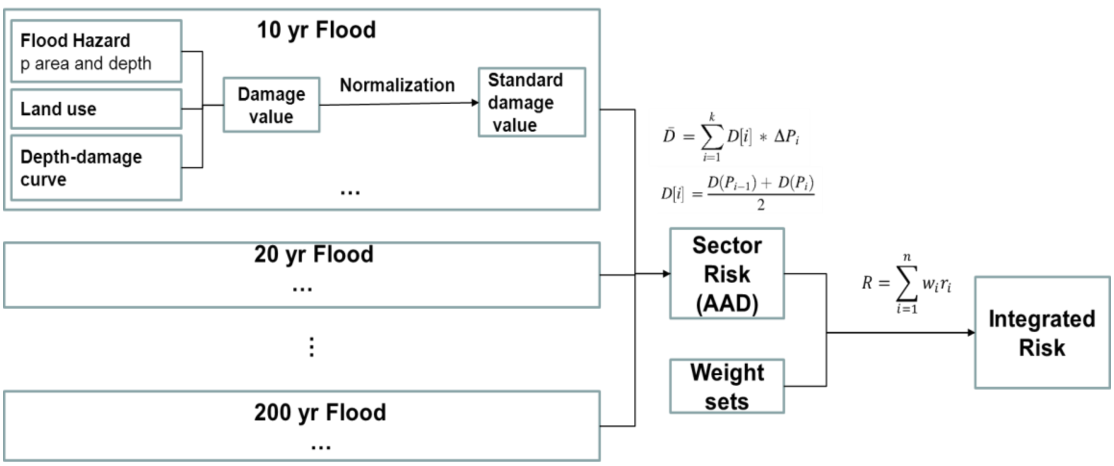

Figure 3-13: Flowchart of integrated risk calculation

Table 3-7: Weights of Different Criteria Sets

Risk Dimension		Economic	Social		Environmental	Infrastructure		
		Aggregated economic. risk	Aggregated social risk	Social Hot-spots	Aggregated environmental risk	Road segment	Travel volume	Accessibility of roads
Criteria Set	Equal	25	12.5	12.5	25	8.4	8.3	8.3
	Eco.	40	10	10	20	6.7	6.6	6.6
	Social	20	20	20	20	6.7	6.6	6.6
	Envi.	20	10	10	40	6.7	6.6	6.6
	Urban mobility	13.4	6.6	6.6	13.4	20	20	20
	Life safety	6.7	60	20	6.7	2.2	2.2	2.2
	Economic EX.	80	3.3	3.3	6.7	2.2	2.2	2.2
	Environmental EX.	6.7	3.3	3.3	80	2.2	2.2	2.2

3.2.4 Uncertainty and sensitivity analysis

3.2.4.1 Sobol' index

As many uncertainty components stem from the procedures of risk assessment in both case studies, local uncertainty and sensitive analysis methods show insufficient to the case studies. This dissertation uses a method of uncertainty and sensitivity analysis (UA/SA) based on statistic simulation method. In the first case study, the UA/SA focuses on what kinds of uncertain factors and the relative extent of uncertainty and sensitivity for damage model. Sobol' index with incorporation of spatial uncertainty of model inputs for flood risk assessment. Sobol' index computation, a global SA approach, allows to quantify the contribution to the output variance of the main effect of each input parameters (Sobol', 1990; Saltelli et al., 1999; Saint-Geours, 2012; Abily et al., 2016). It is a form of variance-based sensitivity analysis based on functional decomposition of variance, considering Y the model output of interest as follow:

$$X = f(X)$$

where f is the model function, $X = (X_1; ...; X_i)$ are i independent input uncertain parameters with known distribution.

The so-called Sobol' indices S_i of parameter X_i are defined as (Gabriella & Carlo, 2015):

$$S_i = \frac{D_i(Y)}{Var(Y)}, \qquad S_{ij} = \frac{D_{ij}(Y)}{Var(Y)}, ...$$

Where; $D_i(Y)$ is variance generated by parameter X_i , $D_{ij}(Y)$ is variance generated by interaction between parameter X_i and X_j.

S_i is first-order sensitivity index. It is the variance of conditional expectation of Y for $X_i$over the total variance of Y, that is, the share of variance of Y due to a given input or input combination, expressing the main effect explained by X_i, ranging between 0 and 1 (Gabriella & Carlo, 2015). And S_{ij} is the second-order sensitivity index, expressing the amount of variance of Y explained by X_i and X_j. And, the total sensitivity index:

$$S_{T_i} = 1 - \frac{D_{-i}(Y)}{Var(Y)}$$

Where; $D_{-i}(Y)$ is the variance of parameters except X_i. S_{T_i} expresses the total effect of parameter X_i, which also equals the sum of the main effect of X_i

and its indirectly variance generated by interaction with other parameters.

Sobol' index is also suitable for sensitivity mapping. Using GIS software and programming technique to deal with spatially distributed inputs, results of sequential simulation and the variance values can be visualized on map, showing the global uncertainty and sensitivity spatially.

3.2.4.2 Considered input parameters

It is unavoidable that uncertainty caused the condition of incomplete information and accuracy of different models. Although the first case study covers various risk dimensions and comprehensive risk elements, uncertainty originated from limitation of knowledge and information exists. Separately from uncertainty due to knowledge, uncertainty of the integrated risk model comes from four components: a) inundation simulation, b) exposure information, c) damage models, and d) weighting sets. All these factors contain various degree of uncertainty propagation through the calculation and accumulation in the final damage and risk assessment. This study specifically concerns about the influence of inundation simulation and damage models on the sensitivity and uncertainty of the total damage. It was conducted by varying the components in a global uncertainty and sensitivity approach following the Monte Carlo approach.

In inundation simulation, inundation depth varies systematically which is regarded as the most important factor contributing to the on uncertainty (Merz et al., 2007; Aerts et al., 2008; Moel et al., 2009; Moel & Aerts, 2011). In this case study, the inundation depth was assumed incrementally lowered down or increase at small intervals, which was an approach proposed in Moel et al.'s case study on UA/SA of coastal flood damage assessment in the west of the Netherlands (Moel et al., 2012). In their research, the inundation depth was set lowered down to -150cm at 5cm intervals. In this dissertation, the 2007 and 2010 simulated water depth of Changsha station showed a variation of -0.6 m and 0.84 m down and up compared to the observed data. The absolute error generated was no more than 3%. Therefore, a reasonable +/- 5% deviation is assumed following uniform distribution between the upper and lower values. As there is no detailed information on spatial distribution or autocorrelation of uncertainty in the inundation map, all adjustments from the base inundation map were considered no difference within floodplain area. The inundation depth here was assumed to follow uniform distribution between the upper and lower values.

For exposure information, disagreement of demography statistical caliber causes the variation in population evaluation for each cell, which is also different in spatial distributions. Registered population P_r and census population P_c are used as lower and upper value of triangular fuzzy numbers. As studies on the geographical differences in life loss tend to use a census population rather than a registered population (Khang et al., 2005), census population was chosen. The damage parameters of social risk refer to 9-point scale that NIH (National Institutes of Health) scoring system used. There is a little different that 9 means the most severe damage in high-level impact while in NIH score system it denotes just in reverse a poorest score in low-level impact (NIH, 2016). The upper and lower bounds of low, medium and high are [1, 3], [4, 6] and [7, 9] respectively.

For damage that calculated using depth-damage curves, involving direct economic damage, environmental damage as well as road segment damage, uncertainty factors covers the max damage values and the shape of depth-damage curves. As this case study used relative risk value, the max damage values are unitless; thereby being considered together the shapes of damage curves. Both factors defined the lower- and upper-risk values on different place in curve. Uncertainty evaluation of maximum relative risk value and shapes of for various types of land use referred to Wang and Xiang (2002) and the ANFAS project (2000-2002) in China (Tariq, 2013). As Beta distribution can be concentrated on narrower intervals and have lower probability densities in the tails, it was used to denote the uncertainty caused by the shape of depth-damage curves (Egorova et al., 2008). The approach uses a coefficient k between (0, 1) to describe the uncertainty of curves:

$$\alpha = \left(\frac{1}{k} - 1\right) * D(h)$$

$$\beta = \left(\frac{1}{k} - 1\right) * (1 - D(h))$$

Where α and β are both positive parameters of Beta distribution, $D(h)$ is the relative damage value at water depth h, and k is the coefficient factor.

It was suggested to use a smaller value less than 0.3 and better not over 0.1. However, the damage curves that used in this case study were all much less steep. When 0.1 is used given a 0.9 confidence range, the highest and lowest relative damage value on the same place in curve are of a great difference and the lower values were almost close to zero even a deeper inundation. In this case study, a uniform distribution k value ranges from 0.005~0.3 was finally used to obtain reasonable variance with 0.995 confidence interval.

As for damage of traffic flow, 12h traffic flow that was used in calculation, which fluctuates -15% and +12.8% upper and lower respectively. All the input uncertainty factors that considered and the associated distributions are listed in Table 3-8:

Table 3-8: Parameters in flood damage assessment

Input data	Uncertainty factor	Distribution	As input in risk dimension
Inundation model	Depth, velocity	Uniform: [d*0.95, d*1.05]	All dimension
Depth-Damage models of land use	Relative risk value: Shape of 6 depth-damage curves	Beta: range depending on category (Wang & Xiang, 2002; ANFAS project); k: [0.005, 0.3]	Economic, environmental dimensions
Population distribution	Population statistical caliber	Triangular: [P_r, P_c, P_c]	Social dimension
Social damage parameters	(1,5,9) scoring method	Low: [1,2,3] Medium: [4,5,6] High: [7,8,9]	
Road segment	Damage model	Beta: range depending on category (Wang & Xiang, 2002; ANFAS project) k: [0.005, 0.3]	Infrastructural dimension
Traffic flow	12-hour Traffic	Triangular, [0.85*V_{12h}, V_{12h}, 1.128*V_{12h}]	

3.3 Methods for case study II

Flood emergency management requires fast flood risk analysis during flood event to help decision maker and receptors respond to real-time changes of flooding. Agent-based modeling provides means to obtain dynamic exposure information by simulating individual behaviors. Moreover, agent-based modeling and simulation can couple hazard model and damage model with adaptive strategies in a unified operational framework. An experimental framework of dynamic flood risk analysis for flood emergency management is developed and the feasibility tests are conduct in the second case study at local scale. The dynamic risk analysis framework is shown in Figure 3-14. Geospatial environmental and social data are input to build a virtual world. A 2D rainfall-runoff model based on Cellular Automata is adopted for surface water simulation. Based on social data, human behaviors are simulated to generate dynamic exposure information. Combining with damage models, the risk analysis and mapping are conducted in near real-time. Technically, they are based on data input and output among different simulation platform and the combination of GIS tools. In addition, the application of scenarios comparison with various adaptive strategies could be greatly useful in discussion on emergency response and risk mitigation. The UA/SA focuses more on human behavior models in that case of well-calibrated inundation model. Simulation of various scenarios is based on some basic hypothesis of different adaptive strategies, which are the main uncertainty source. Similarly, by operating multiple simulation and statistic method, the results of uncertainty are represented in forms of probability distribution. The results of UA/SA are mainly to help compare and measure the effectiveness of various adaptive strategies and validation of the framework for dynamic risk analysis. This section highlights surface water simulation model, human behavior model, settings of scenario and the method of evaluating effectiveness of adaptive strategies.

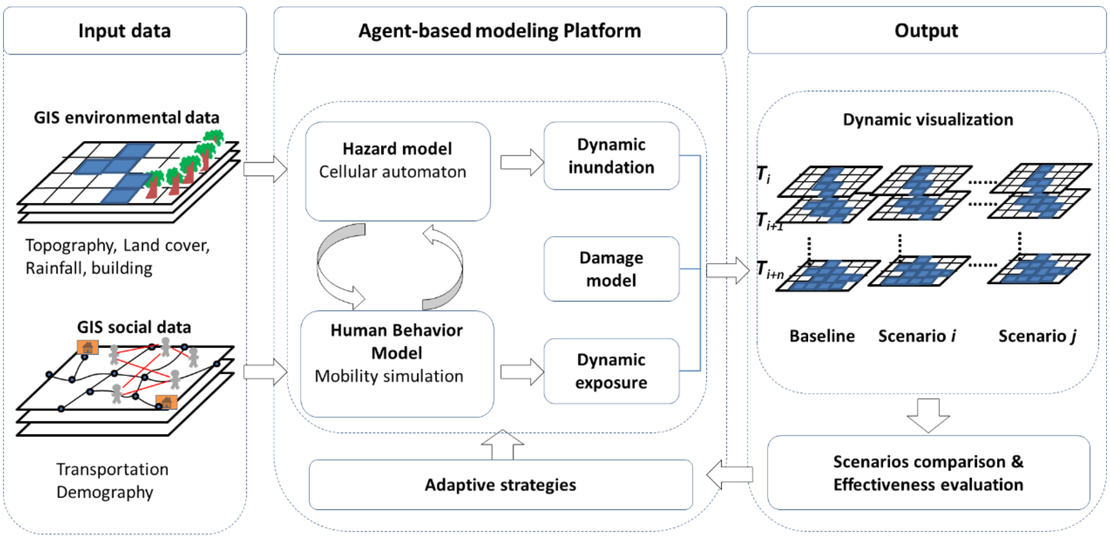

Figure 3-14: The framework of dynamic risk analysis supporting flood emergency management

3.3.1 Surface water simulation model

3.3.1.1 Hydrological process

Hydrological process is a highly complex and non-linear process, which generally covers precipitation, canopy storage, evapotranspiration, infiltration and runoff (Figure 3-15). Cellular Automata (CA) is perfectly aligned with the distributed hydrological model. However, absence of detailed data makes sophisticated model covering all hydrological process impossible. In addition, the aim of the model is to simulate a storm environment instead of exact hydrological processes such as canopy, evaporation etc. It focuses on surface runoff and whether the stormwater accumulated area significantly influences the travelers' choice and behavior. The transform from precipitation to runoff was calculated through rainfall capacity and runoff coefficient. Simplifying the model's structure can also help to reduce uncertain inputs.

The surface flow was assumed as open channel flow and described in terms of continuity and momentum equations, discretized over a raster grid of squares. The Manning formula describes flow between neighboring cells.

$$v = \frac{k{R_h}^{2/3}\sqrt{S}}{n}$$

The average velocity of cross-section v is a function of the hydraulic radius R_h, S the slope of the water surface, k is a conversion factor if required and n is the Gauckler-Manning friction coefficient, which is unitless. If the depth of the surface water is pretty small relative to the wetted-perimeter, the hydraulic radius R_h in the formula above can be replaced by the depth. That can be expressed according to the following equation as:

$$v \approx \frac{depth^{2/3}\sqrt{S}}{n}$$

Drainage system plays an important role in hydrological cycling of rainfall in urban environment. Though there is no detailed drainage network information, the drainage capability can be described by drainage volume in unit time. Such approach ignores physical details but considers the drainage capability as a constant (Yang & Thinh, 2014).

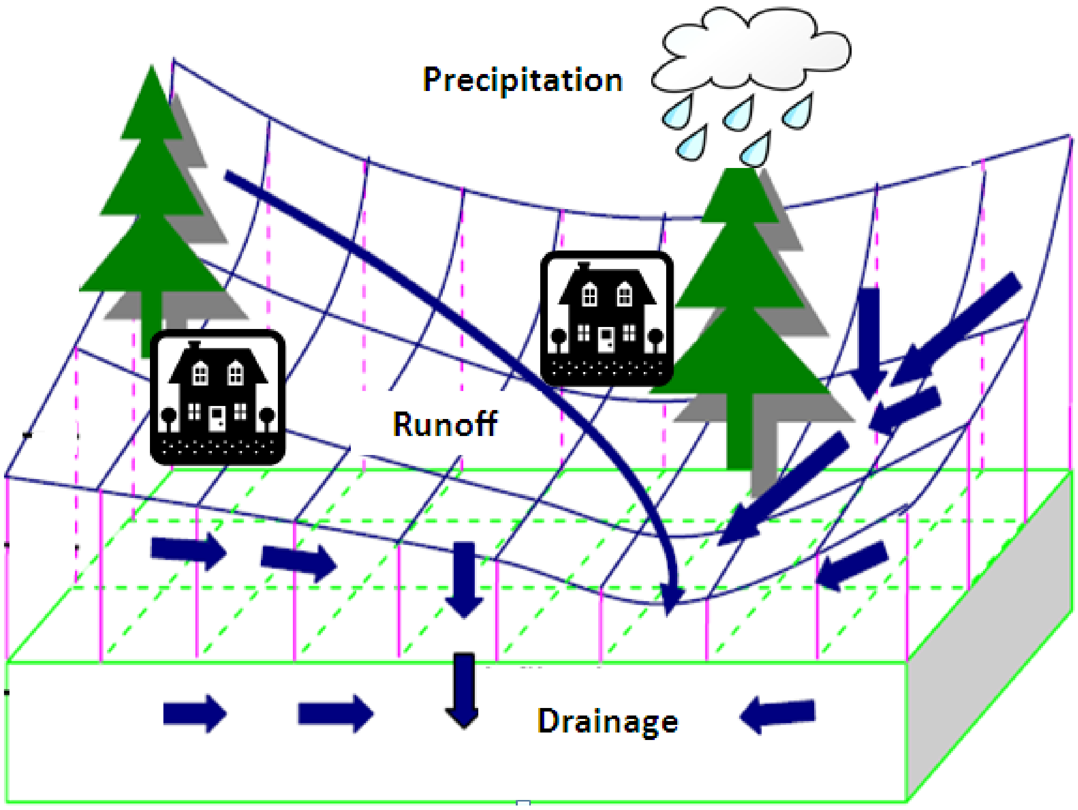

Figure 3-15: Structure of Distributed Hydrological Model (Modified based on Jicai Dai, 2008)

3.3.1.2 Transfer rules

D8 algorithm is one of the most commonly used method for automated drainage recognition and catchment area determinations (Fairfield & Leymarie, 1991; Martz & Garbrecht, 1998; Jones, 2002). It assigns the downstream flow from one point on the Digital Elevation Model (DEM) grid to one of its 8 adjacent Moore neighbor cells by the direction of steepest descent, which can figure out the problem of streaky drainage pattern caused by utilizing only the adjacent (Jones, 2002). However, when there are more than one lowest neighbors, D8 algorithm randomly choose one of them as the flow direction. In this dissertation, for overcome this insufficiency, case study II adopted an approach by distributing the flow volume equally when there are more than one cells in the model (Figure 3-16).

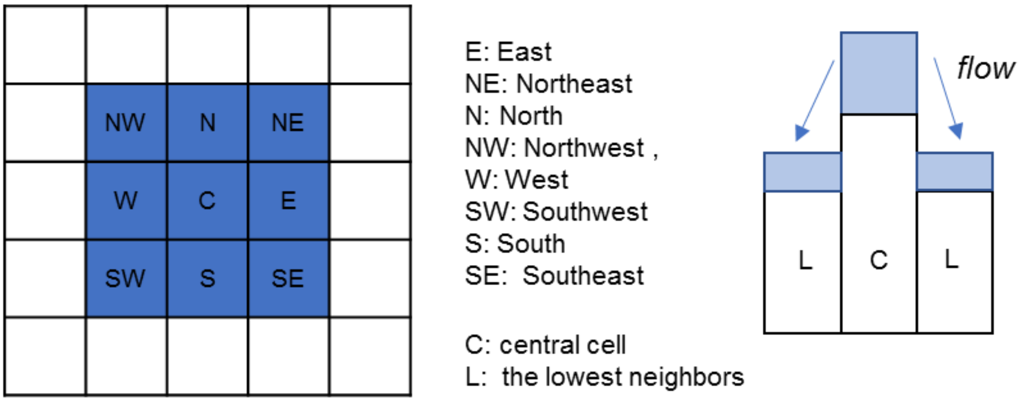

Figure 3-16: Moore neighbor and runoff between neighbor cells

3.3.1.3 Variables and parameters

Both global and local parameters were used for the inundation simulation. The global parameters cover the size of patch and the interval of iterations. They domains the space and time scales respectively. Local parameters and variables that depict the hydrological processes, the relative physical properties and states of drainage and water depth include precipitation accepted of cells, runoff coefficient, drainage capability, drainage capability, runoff of cells depth of surface water, manning friction coefficient (Table 3-9).

Table 3-9: Global and local parameters in inundation simulation

Variables & parameters		Description
Global	***Patch***	the cell size, 10m * 10m
	Tick	the time for one iteration, 60s
Local	***P***	precipitation accepted of cells
	RC	Runoff coefficient
	D_r	Drainage capability
	P_r	Runoff of cells
	Depth	Depth of surface water
	n	Manning friction coefficient

3.3.2 Agent-based modeling and urban mobility simulation

3.3.2.1 Types of agents

Agent-based Modeling was applied to simulate human behaviors during the storm. Generally, an agent-based model requires defining types and behaviors of the used agents. Agents in this case study were classified in two types: citizens and vehicles. For citizens, attributes were assigned such as gender, age, employment state, household size as well as trip mode. For vehicles, attributes like type, length, seats, acceleration, max speed and move speed were considered. The details of parameters are listed in Table 3-10 and Table 3-11. According to means of transport, individuals are divided into three groups: pedestrian, bus and private cars, corresponding 3 types of individual rules in the simulation. All the agents' attributes were initialized based on population structure, car ownership ratio, information of bus system and local traffic report.

Table 3-10: Attributes of citizens

<table>
<tr><th>Gender</th><th>Age</th><th>Walk speed</th><th>Employment</th></tr>
<tr><td rowspan="2">Male</td><td>4-14 (9.4%)</td><td>2.3~5.43km/h</td><td>Full time</td></tr>
<tr><td rowspan="2">15-59 (78%)</td><td rowspan="2">3.75~5.43km/h</td><td>Part time</td></tr>
<tr><td rowspan="2">Female</td><td>Self-employed</td></tr>
<tr><td>> 60 (12.6%)</td><td>3.2~3.9km/h</td><td>unemployed</td></tr>
</table>

Table 3-11: Attributes of vehicles

Type	Length	Max speed	Seats	Acceleration
Bus	9~12 m	40~50 km/h	40~70	0~2 m/s^2
Car	1.5~4.3 m	40~80 km/h	4~6	0~2.8 m/s^2

3.3.2.2 Behaviors of agents

The agents' behaviors were initialized with trip origin and destination according to transport census of Furong district. To simulate individual trips, traffic demand and pathfinding were considered as two main factors. The simulation runs in the condition of a 3-hour storm and starts at 17:00 and lasts until 19:00, covering the rush hour. The origins of agents depend on the time of day and their attributes set. During the time agent travel to the destination, traffic demand was subdivided into many types according to citizens' statistics of daily travel. The trip statistics for different aims can be summarized as in Figure 3-17 and Table 3-12.

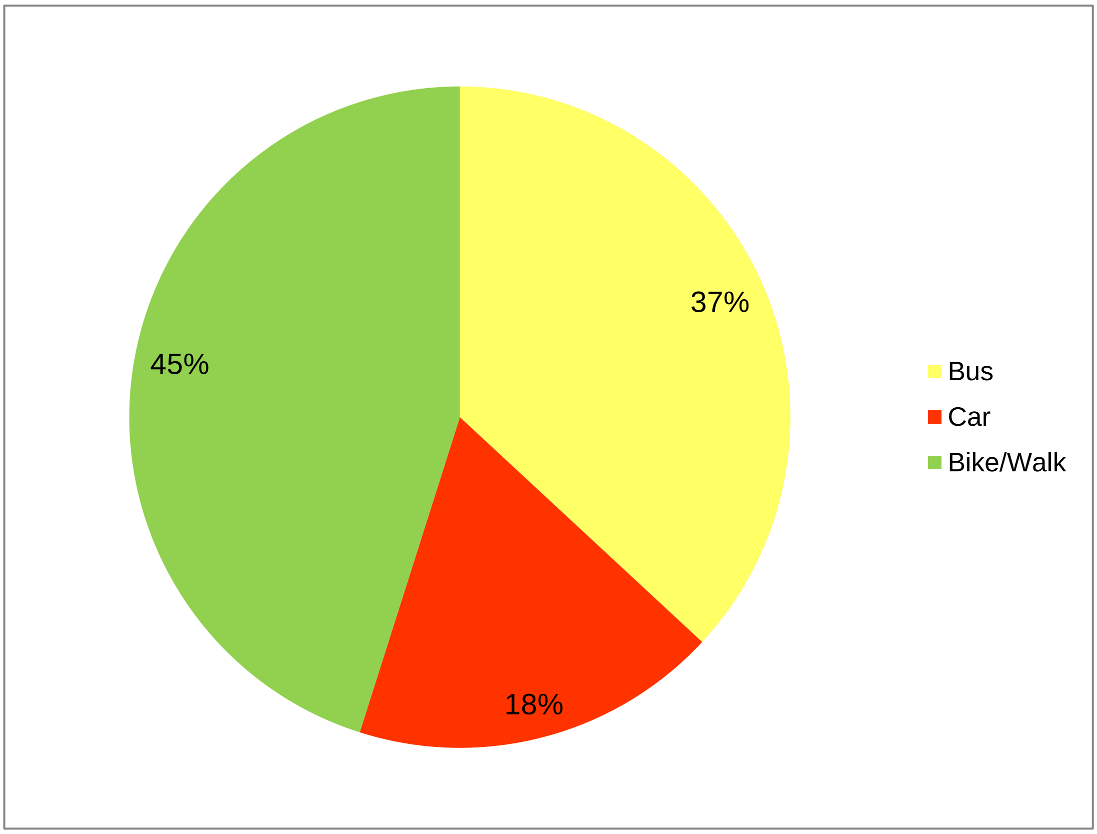

Figure 3-17 Composition of trip modes

Table 3-12: Travel statistics of Furong district

Travel aim	Percentage
Home (from school)	5.7%
Home (from workplace)	22.6%
Home (from other places)	41.9%
Leisure	2.5%
Shopping	10.6%
Work	4%
Other aim	12.7%

Apart from origins and destinations of trip, path-finding algorithm controls how agents select route during the simulation. The Dijkstra algorithm (Cormen et al., 2001), one of the most famous shortest path algorithms, it is used when there is no rainfall. If some road segments in route of agents were inundated in storm, they will find new route based on travel time to their destinations, which might be not the shortest path rather than the fastest one. The buses travel along fixed routes that are stored in lists in advance. Thus, they don’t need to search for routes, only in case of parts of bus lines were inundated. In this case, affected buses will try to find a nearest alternative path. Besides, the daily routines of agents that were warned inundation information can be interrupted. They will choose new routines to avoid the inundated area with a certain probability. Agents without the flood warning information will try to continue their trips as normal. Transit road transport at the boundary of the investigation was controlled through statistic traffic flow of the 17 entrances and exits.

3.3.3 Scenario settings

A unimodal three-hour of 10 years return period storm was set as the baseline scenario, in which no risk reduction strategies are used. It considers an extreme case that the peaks of rainfall and traffic flow peak overlapping in time at 17:00. Two types of risk adaptation intervention were evaluated by comparing with a baseline scenario. Exemplary scenario with strategies had to be defined based on operable and practical consideration. These strategies were selected based on cost, useful life, considerations and effectiveness that advocated by other practice, as shown in Table 3-13.

Table 3-13: Scenario sets with varying flood risk reduction strategies.

Scenario	Intervention	Description	Effect	Cost
Baseline	No interventions	-	None	None
I	Municipal engineering	Pre-flood	Improve permeable and drainage ability, add green coverage rate	Moderate
II	Up-to-bottom risk warning & public participation	Flood event	Publish waterlogging information and flood risk warning centrally, lower acceptance rate;	Low to Moderate
			citizen observatories via social media, timely and effective communication with high acceptance rate	Low

3.3.3.1 Scenario I: Municipal engineering

In scenario I, pre-flood municipal engineering measures were emphasized. Compared to other strategies like greening roof, the base flood elevations, increasing green areas has relatively low impact as they utilize existing urban space and cityscape, and has more economic feasibility. In this case, the central business and trade area of the city with high density of buildings, 57.2% land cover of the Furong Square became impermeable. Such land-cover types have exacerbated the waterlogging in storm event. Moreover, the current drainage capability is only “one year” (30~40mm/h theoretically) and often cannot function adequately due to clog. Despite the design reaches the minimum standard, it is obvious that tackling largish and frequent storm insufficient. According to the action plan of the 2020 of Changsha, drainage capability will be improved to “five years” to adapt with (55mm/h) in this area and will increase permeable concrete paving surface. In scenario I, it is supposed to reduce risk by engineering approach, involving increasing the green coverage rate, retrofitting impermeable surface and improving drainage system.

3.3.3.2 Scenario II: Up-to-bottom warning with public risk awareness

Scenario II concerns risk warning and communication during the flood event. An effective flood early warning system is considered as an important component in FRM. In emergency pluvial flood event, early warning cannot only reduce people of exposure to flooding, sometimes may also save lives. Most of the time, it enables people to re-plan their travel and routes, avoiding the inundated areas or evacuating to areas of safety. Flood warning is mainly organized in an up-bottom form during flood events. By up-bottom warning, the flood information is usually published by designated official authority.

The Changsha central city has established the emergency coordination mechanism and the emergency linkage mechanism with meteorology, urban management, municipal departments etc. The Furong's Emergency Plan for Flood Event (2015) gives some specification items about publishing risk warning. Normally, the operators of duty room closely track dangerous condition of flood. Once significant inundation occurs, the operators have to report incidents and hazards to the supervisors, level by level. The response time is usually between 10~30 minutes. Besides, as the mesoscale monitoring network for precipitation based on the mobile GRPS[9] wireless communication technology, dozens of automatic weather stations were gradually adopted for collection and transmission of observation data every 10 minutes, which has greatly shortened overall response time in emergency management. By the year 2015, the geo-hazards early-warning information system of Hunan province, including Changsha city, has 85% of monitoring rate for rapid-onset disasters and 90% public coverage rate.

Up-bottom warning information can be collected by governments or organizations that disseminate information about floods may or may not be received by individuals (Fekete, 2012). It has been recognized as a neglected component that causes a huge gap between the information produced by official level forecasting agencies. To raise public awareness and preparedness serves effective approach for flood risk reduction (Yamada et al., 2011). In risk communication, the public are more likely to receive risk information, to make preparation for risk reduction as well as to play actively roles in flood management.

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[9] General Packet Radio Service (GPRS) is a packet oriented mobile data service on the 2G and 3G cellular communication system's global system for mobile communications (GSM).

In this scenario, various warning time were set according the total response time. It supposes faster response and more frequent updating and publishing inundation information. The emergency planning and management center publishes the waterlogging information ranging from 5~30 minutes. The probability of risk warning reaching 90% of agents is given by $P_1 \sim N$ (0.85, 0.05). Citizen with high risk awareness involve in inundation feedback and knowledge exchanges by time, such as via social network apps to participate in decision-making, providing a potential and distinctly different role for citizens (i.e. involvement in data collection) compared to earlier conceptualizations of citizen participation in decision-making (Wehn et al., 2015). The probability of whether a risk warning can be received successfully or not by citizens refers to individual risk awareness, which can be described by probability P_2. For discussing the relationship between citizens' awareness of flood risk and the effectiveness of adaptive strategies, it was assumed to follow a normal distribution with mean value ranges 0.2~0.95 and with a standard deviation at 0.05. In other word, it was supposed that citizens collect inundation information, communicating risk condition timely with almost full participation and high acceptance of information by social network in the best case (when P_2 =0.95).

3.3.4 Evaluating effectiveness of flood risk adaptive strategies

3.3.4.1 Flood risk assessment

As emergency management pays more attention to timely releases information, flood damage estimation has a practical significance and is more accessible to public than integrated risk value. Therefore, this case study focused on damage calculation on risk elements involving buildings, population, vehicles and transportation. All the scenarios were set as a 10-year storm, namely $P(X)$ equals 0.1. Thus, for a given probability of flood, the risk value r depend on the varying damages of elements X_i. It can be expressed as a vector of respective risk, r_i:

$$R = \{r_i\} = \{P(X_i)D(X_i)\}$$

X_i refers to inundated buildings, exposed agents involving pedestrians, private cars and buses.

Damage value of buildings was calculated based on types of buildings and depth-damage functions. In order to measures vulnerability of agents (people and vehicles), dynamic and accumulated exposure of population was considered rather than mortality because pluvial flooding has lower fatality rate and even with mortality, too many uncertain factors to confirm whether mortality it can be directly related to the event. In this case, damage to population refers to the total number of people trapped in waterlogging areas according to water depth. The number of exposed population was reported. The damage was leveled according to water depth. Water depth over 100 mm and area larger than 100m^2 is considered as waterlogging according to the standard of waterlogging prevention of Furong district (2014). In addition, the standard also gives 270mm as the warning line of fording depth for private cars, which is close to the value 250mm from DEFRA and Environment Agency (Ramsbottom, 2003; DEFRA, 2005). According to Ishigaki et al. hydraulic experiment (Ishigaki, 2005; Ishigaki et al., 2010), it becomes difficult to escape when the water is above 300mm. Synthesizing these factors, 300mm was set as the threshold of water depth whether it exerts damage on agents. In addition, this case does not pursue an integrated flood risk calculation but try to achieve timely and specific impacts of flooding. It simply calculates the dynamic and accumulated number of various types of affected agents respectively.

3.3.4.2 Benefit of risk reduction interventions

In the second case study, benefit of various feasible concrete interventions was calculated and compared so as to, evaluate the effectiveness of risk reduction measures. Flood risk, r was calculated as the previous definition, a function of the probability of an event, P and the consequences of that event, D:

$$r = \int P(X)D(X)dX$$

Where the variables in vector X represent set of input conditions associated with different scenarios. The strategies that reduce either the consequences or probability of flooding can be represented by additional variables in the vector X used to describe the flood risk system, for instance, the factors may include the number or the proportion of citizens those who receive the risk warning message. The method was successfully applied for assessing the economic damage associated with the risk of flood defense failure both nationally (Hall et al., 2003) and in the flooding of Towyn 1990 (Dawson et al., 2011).

The effectiveness of the strategies was calculated for combinations of different scenarios and the baseline scenario without any strategies. In some case studies, benefit-cost ratio was calculated for assessing the effectiveness of flood risk reduction strategies (Lasage et al., 2014). However, those Cost-

Benefit Analysis (CBA) pay more attention to quantifiable factors. Actually, the cost of a strategy also refers to some non-economic factors that are difficult to be evaluated. There are no good estimates of total cost, especially for a rapidly developing region. In addition, the method is not applicable as the potential inaccuracies in identifying and quantifying costs and benefits, increased subjectivity for intangible costs and benefits etc. (Shreve & Kelman, 2014). In this part of methodology, evaluating benefits of strategies was emphasized. Based on the definition of risk above, the effectiveness of risk reduction strategies can be calculated as:

$$B_s = \int P(X_b)D(X_b)dX - \int P(X_s)D(X_s)dX$$

Where X_b is the state of the system of baseline scenario, and X_s is the state for a single or risk reduction strategy in scenario *s*. The output of the ABMS can quantify the impacts with risk reduction strategy in place, $D(X_s)$, or without, $D(X_b)$, such as the number of people exposed to flooding or building damages avoided.

The benefits of the risk reduction interventions are calculated by the reduction of risk value, noted as B_s, which can be calculated as:

$$B_s = \Delta R = P(X) * D(X) - P(X_s) * D(X_s), s = \{I, II\};$$

And the relative benefit b_s can be denoted as:

$$b_s = \frac{\Delta R}{R} = \frac{P(X)*D(X) - P(X_s)*D(X_s)}{P(X)*D(X)} * 100\%, s = \{I, II\};$$

Where $P(X) * D(X)$ denotes the flood risk of baseline scenario, $P(X_s) * D(X_s)$ represents the residual flood risk of scenarios.

3.4 Data

The datasets of the two case studies are derived from various sources for the development of the flood delineation models. They are mainly publicly available and up-to-date, obtained from the local official database, China Data-Sharing Network of Earth System Science and web crawler. The collected data cover spatial data like Terrain, land use data, administrate boundary, soil types, economic and social data such as municipal statistics, news, photos, population, hydrological and flow data.

Data for hazard analysis relies mainly on geospatial data involving terrain data, catchment hydrological data. Most of the geospatial data are obtained from municipal census and social statistics data of the Changsha City and China public geospatial information services website. The terrain data for extracting cross-sections and flood inundation mapping is obtained from the Digital Elevation Model (DEM) with 20-meter horizontal resolution. Particularly, depressions are filled iteratively until they did not exist anymore to avoid the errors caused by resolution of the terrain data or rounding of elevations to the nearest integer value. 186 cross-sections are extracted from the terrain data. The steady flow data used for hydraulic modeling of the reach include the observed water surface with a reach boundary condition of downstream normal depth.

The types of land use in the analysis are from Changsha urban-rural planning bureau, referring to historic land use (the year of 2003) and recent land use map (2013) as well as the overall plan of land use for 2006~2020. Current land use status is compiled from TIANDITU (http://en.tianditu.com), a website providing ‘one-stop’ geospatial information services, which is created by National Administration of Surveying, Mapping and Geo-information of China (NASG), the scale is 1: 9,028 and additional high grain topographic maps (1: 10,000) which are classified with supervised method and then checked manually.

Several types of information are necessary for the flood damage assessment and calculation, including inundation characteristics, land use, high-risk points, demographic data and finally depth-damage curves. Inundation area and inundation depth are considered the results of hazard analysis. Six different return periods flood events (10-year, 20-year, 30-year, 50-year, 100-year and 200-year flood) are used in calculation. The inundation information is raster data storage. Aggregated land use data are merged into 6 different categories as stated above, for the limit of depth-damage functions. Combined with buildings data, the land use information was assigned to footprints in finally risk assessment. Both land use data and footprints data were stored as vector data, polygons in ArcGIS to be precise. Moreover, the high-risk points are also vector data, which includes three types of places where vulnerable groups (such as juveniles, seniors and physically disabled) is of concentration, namely, schools (kindergarten, primary schools and middle schools), senior activity centers and hospitals. Besides, the spatial data come from various sources, were in different projections. So, all the spatial data were transformed into a common projection, a self-defined Albers projection according to the location and scale of the study area, which is a type of equal-area projection (see Table 3-14). Basically, it is considered as one of important factors in calculating flooded area accurately for raster data.

Table 3-14: Detailed information of projection

Spatial Reference	WGS_1984_Albers
Linear Unit	Meter (1.000000)
Angular Unit	Degree (0.017453292519943295)
False_Easting	0
False_Northing	0
Central_Meridian	113.0702524427778
Standard_Parallel_1	27.85304299972222
Standard_Parallel_2	28.66024799972222
Lattitude_Of_Origin	0
Datum	D_WGS_1984

Social statistic data are perceived as primary data and were obtained from official statistics, the Changsha's statistical yearbook 2003-2015, and through market survey. Demographic data of municipal district in the city's annual census of 2010-2015 are disaggregated to the land use cover to determine population distribution and growth. The predict population in the year of 2020 is calculated based the existing statistic population data. All the statistical data were also distributed to each building and finally turned into spatial data in vector form. Ecological criteria are either derived directly from the land use information or taken from the urban tree cadaster database. Traffic volume data were set from 2009 and 2012 Changsha Annual Traffic Reports. Depth-damage curves used in the case are offered by National Disaster Reduction Centre (NDRC). As types of land use are larger than types of depth-damage curves, the land use data have been categorized to match the closest proximal curves. Detailed information of all the necessary data for flood risk assessment, in this case, are listed in Table 3-15.

Table 3-15: Prepared data of Changsha Central City

Index	Data	Source	Scale or resolution	Description
1	Catchment data	China Meteorological Data Sharing Service System; Changsha Metrological Administration; Changsha Water Resource Bureau	Changsha Station 2007, 2010	Steady flow data, Observed water surface elevation of Changsha gauging station Bank lines, block areas, et al.
2	Terrain	International scientific data service platform	30m*30m	ASTER GDEM (V2)
			30m*30m	SRTM4(UTM/WGS84)
3	Land use	Changsha planning bureau, Tianditu.com (NASG) 18 level (Mosaic and digitalized)	100m*100m 1:9,028	-aggregated land use data (100m*100m) of 2003, 2013, 2020 (planned) -6 different categories land use -scale socio-economic data, eg: buildings shapefiles
4	Soil	Institute of Soil Science, Chinese Academy of Sciences	1: 1,000,000	—
5	Statistics	Changsha municipal statistics (2003~2015)	—	population structure, hot spot, economic, industry statistics
6	Road network	Changsha planning bureau, Web crawler	—	1~4 level
7	Traffic volume	Changsha Annual Traffic Report 2009, 2012	—	OD matrix
8	Inundation information	River Flood Analysis based on HEC-RAS	20m*20m	six events of different frequency (10yr, 20yr, 30yr, 50yr, 100yr, 200yr): - Area - Depth - Velocity
9	Damage Functions	IWHR, 2015	—	types of land use depth-damage curve; forest damage rate; road damage rate

CHAPTER 4: RESULTS AND DISCUSSION: CASE STUDY I

4.1 Inundation statistics and mapping

The comparison of observed and simulated water surface elevation at Changsha gauging station is shown in Table 4-1. All HEC-RAS simulations were conducted based on the steady flow state assumption. It has been indicated that the performance of the model depends mainly on the friction of channels (Parhi et al., 2012). In this study, based on types of land use, the Manning's roughness coefficient value (Manning's n) of the reach main channel ranges from 0.04 to 0.08. In the floodplains, it ranges from 0.03 to 0.15. 576 simulations were conducted by using a combination of different Manning's coefficients. The various Manning's roughness coefficients were randomly selected and the values were uniformly distributed. The most effective Manning's roughness coefficient calibrated for Changsha gauging station of the Xiangjiang River was (0.15, 0.04, 0.08), with a high agreement (78% efficiency) between simulated and observed water surface elevation. The inundation information including inundation boundary, water profiles and velocity were exported, which later were imported to ArcGIS 10.0 with the plugin HEC-GeoRAS, getting ready for inundation mapping.

Table 4-1: Comparison of observed and simulated water surface at Changsha gauging station

Flow year	Manning's n			Observed elevation (m)		Simulated elevation (m)		E_{NS}
	n1	n2	n3	2007	2010	2007	2010	
2007, 2010	0.15	0.04	0.08	39.18	38.93	40.02	38.33	0.78
	0.145	0.1	0.08			40.19	38.4	0.77
	0.142	0.045	0.04			39.75	38.06	0.68
	0.125	0.1	0.08			39.24	37.52	-0.70
	0.12	0.04	0.08			38.71	37.08	-22.24

**n1,n2 and n3 are the Manning's roughness coefficients of floodplains and main channel respectively.*

HEC-GeoRAS was applied to extract water surface profiles from HEC-RAS. The water surface TINs (Triangular Irregular Networks) were converted into grid format (20 m * 20 m by default). It was then compared with the terrain data to calculate the inundation depth within the polygon of boundary. Six different water surface elevations were stored in the inundation depth grids, which were then converted into a vector dataset defining the floodplain boundary. Finally, combining with the inundation information as well as terrain data, HEC-GeoRAS generated hazard maps automatically. Inundation map for different possibility of flood event were generated. Figure 4-1 shows an example of the inundation map of 200-year flood with water depth and flow velocity information.

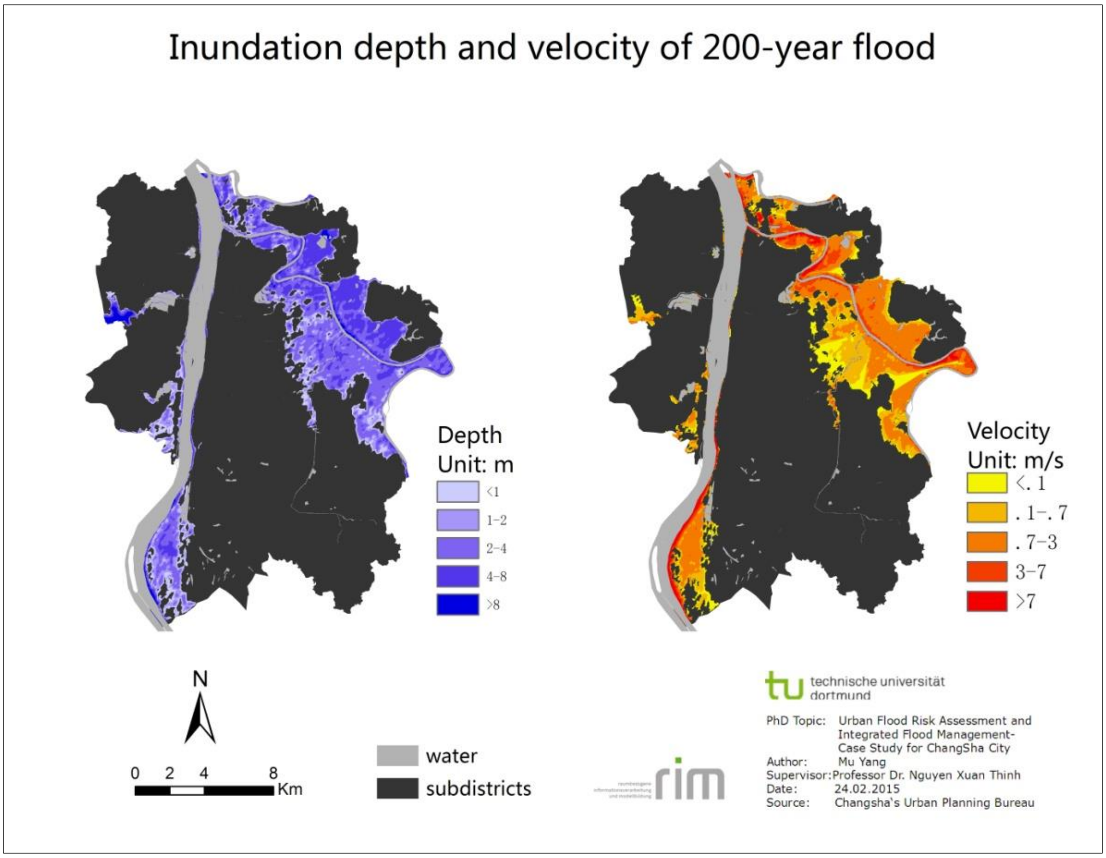


Figure 4-1: Inundation map of 200-year flood of Changsha central city

Curves in Figure 4-2 denote the inundation characteristics of six different return period floods. It gives a general sense that high-recurrence interval floods cause deeper inundation and larger inundated areas. As shown in the figure, the 100, 200-year floods trigger significantly larger inundated areas with depth above 3 meters more than the 10-year flood. However, in a narrow range corresponding to smaller inundation depth (less than 1.7 meters), the flooded areas of 200-year and 100-year floods are smaller than that low-recurrence interval floods. It can be interpreted by the flat terrain of the Changsha drainage area.

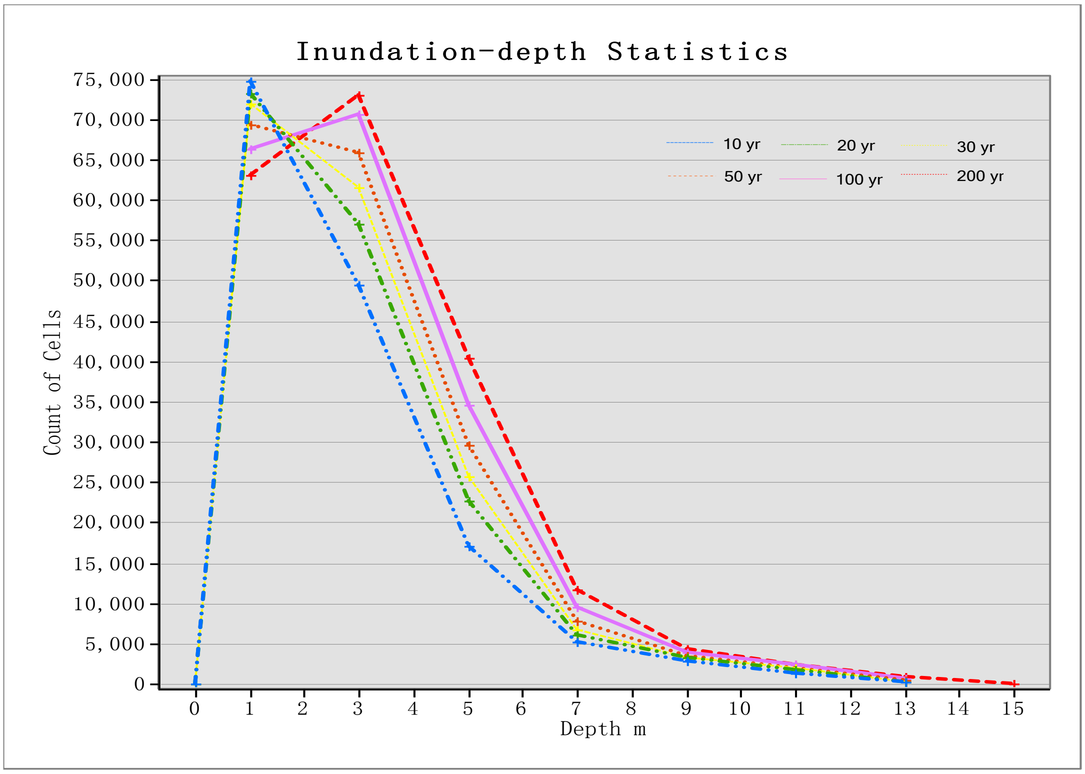


Figure 4-2: Statistics of inundated depth

According to the new standard of flood control planning, flood prevention standard rises from 100-year flood to 200-year flood. Spatial distribution of changes of inundation characteristics can be recognized through the following map (Figure 4-3). Overall, there is no dramatic change in inundation area (increased by 3.08 km^2) and the max inundation depth (increased by 0.17 m) between 200-year flood and 100-year flood. Compared to 100-year flood, the inundation depth increases at bends of the Liuyang River. The maximal water depth time velocity (Max *D*v*) also increases slightly. However, the average water depth time velocity (Mean *D*v*) increases over one-third (Table 4-2).

Table 4-2: Statistics of inundation characteristics

Inundation Characteristics	10-year	20-year	30-year	50-year	100-year	200-year
Area (km^2)	58.41	63.69	66.42	69.34	73.09	76.17
Mean *D* (m)	2.37	2.56	2.66	2.79	2.96	3.13
Max *D* (m)	12.70	12.95	13.18	13.45	13.79	14.10
Mean *D*v* (m^2/s)	0.85	1..00	1.09	1.21	1.37	1.86
Max *D*v* (m^2/s)	30.13	31.71	33.36	34.96	37.03	37.49

**D* and *v* refer to water depth and velocity respectively

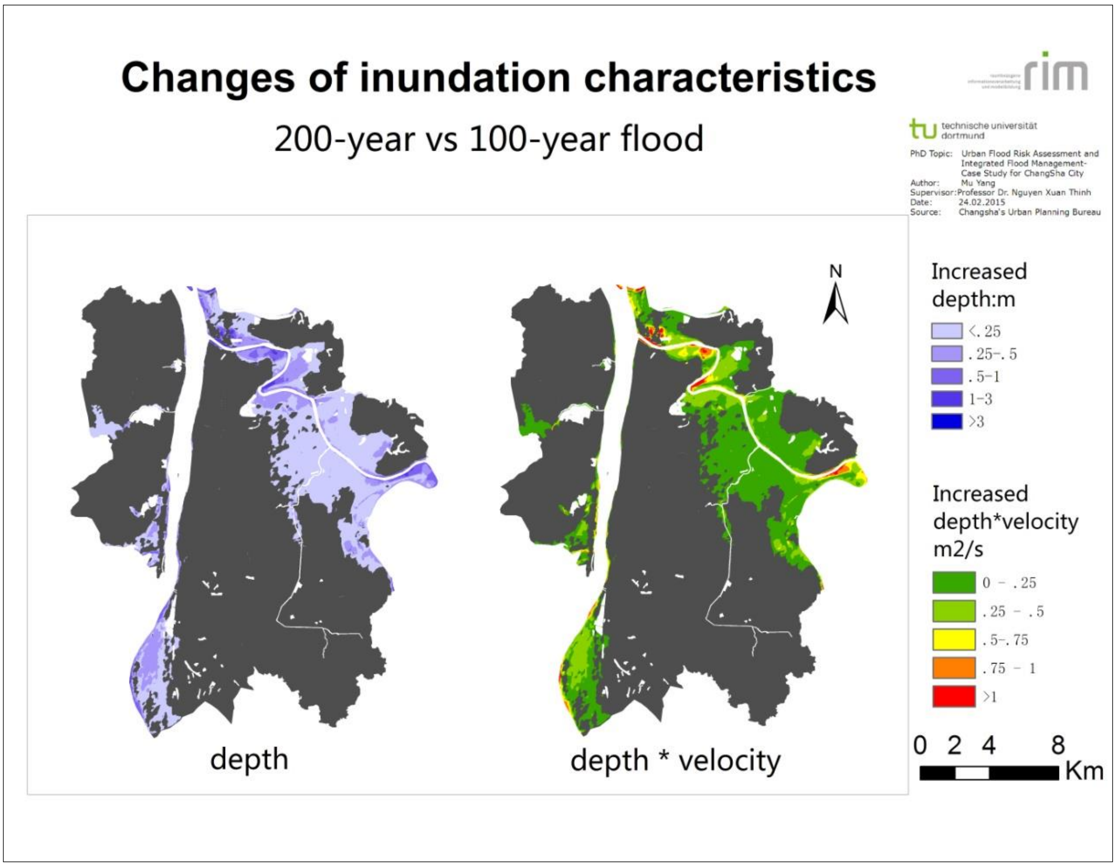


Figure 4-3: Comparison of inundation characteristics between 100-year and 200-year flood

4.2 Risk analysis

4.2.1 Exposure of land use

The results of inundation analysis show that the inundated areas differ obviously (Figure 4-4). Also, the sub-districts inundated by tributaries are larger than the inundated areas by the mainstream, especially in the river confluence reaches. This feature is particularly evident along the Liuyang River. Residential and business land rank as the top two types of land use and have the most obvious rise. They are followed by, administrative, warehouse and manufacture land. Furthermore, there was no significant incrementally in flooded administration, warehouse and manufacture land as flood return period increases. For the largest considered flood (200-year flood), about 76.17 km^2 (totaling 103 km^2 if water bodies are also included) areas were inundated, accounting for 27.7% of total area. Similar to the statistics of inundated depth, even 10-year flood could cause large areas inundated due to the low average altitude (only 44 meter).

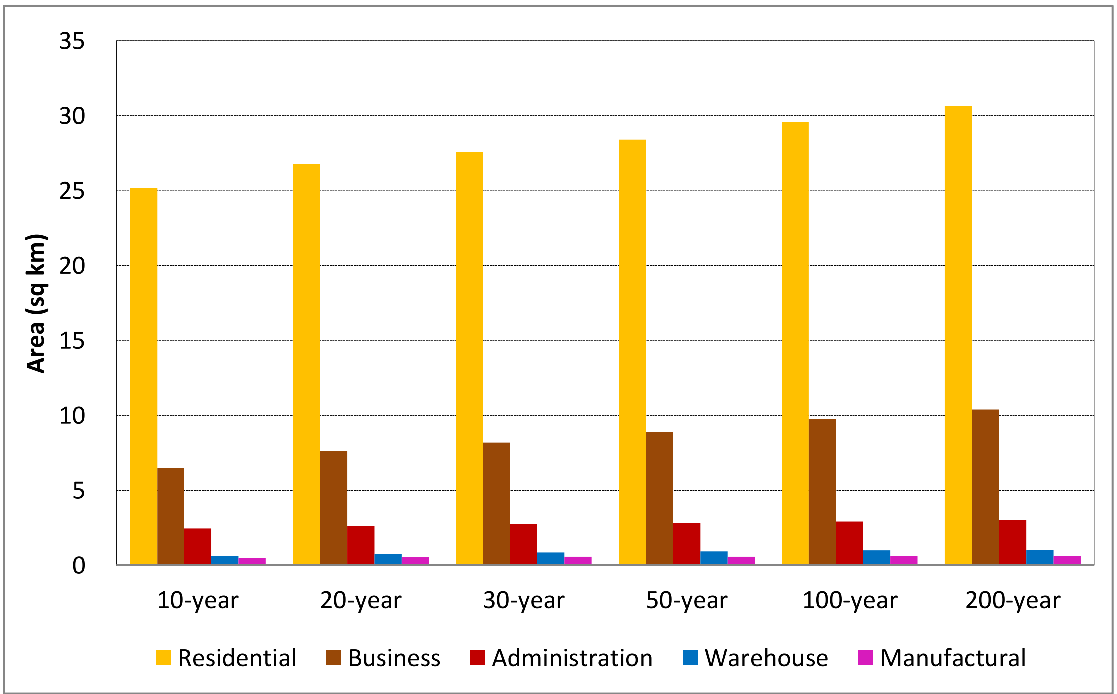


Figure 4-4: Statistics of inundated land use

4.2.2 Exposure of population

The land-use based method offers a good performance on accuracy of population distribution. Since the 2010 demography has high level of data integrity, demography for the year 2010 was used as a baseline year. The total estimated population shows good agreement with demographic data of the baseline year with a very small error (0.57%). At the sub-district level, estimated precision of 51 sub-districts were up to or more than 90%. The other four ones, Yinpenling, Northern-Furong, Wangchengpo and Wenyuan sub-district, reach 88.3%, 85.5%, 85.1% and 79.3% respectively. However, other data are available until 2013. Though the up-to-date total population of each district can be obtained from the yearbook, at sub-district-scale demography cannot be acquired. In order to ensure the data temporal consistency, population of 2013 was predicted using average annual growth method. Except the Yuelu district (including 9 sub-districts) and Tianxin (including 12 sub-districts) district with regression coefficient 0.85 and 0.9 respectively, all others reach or are above 0.97. For distribution of different age group, the composition of seniors over 60 years and children between 3~14 years of each district can be obtained from statistics. In this case, it was assumed that there is no spatial variability about the age structure within a district. The predicted population distribution map of 2013 is shown in Figure 4-5:

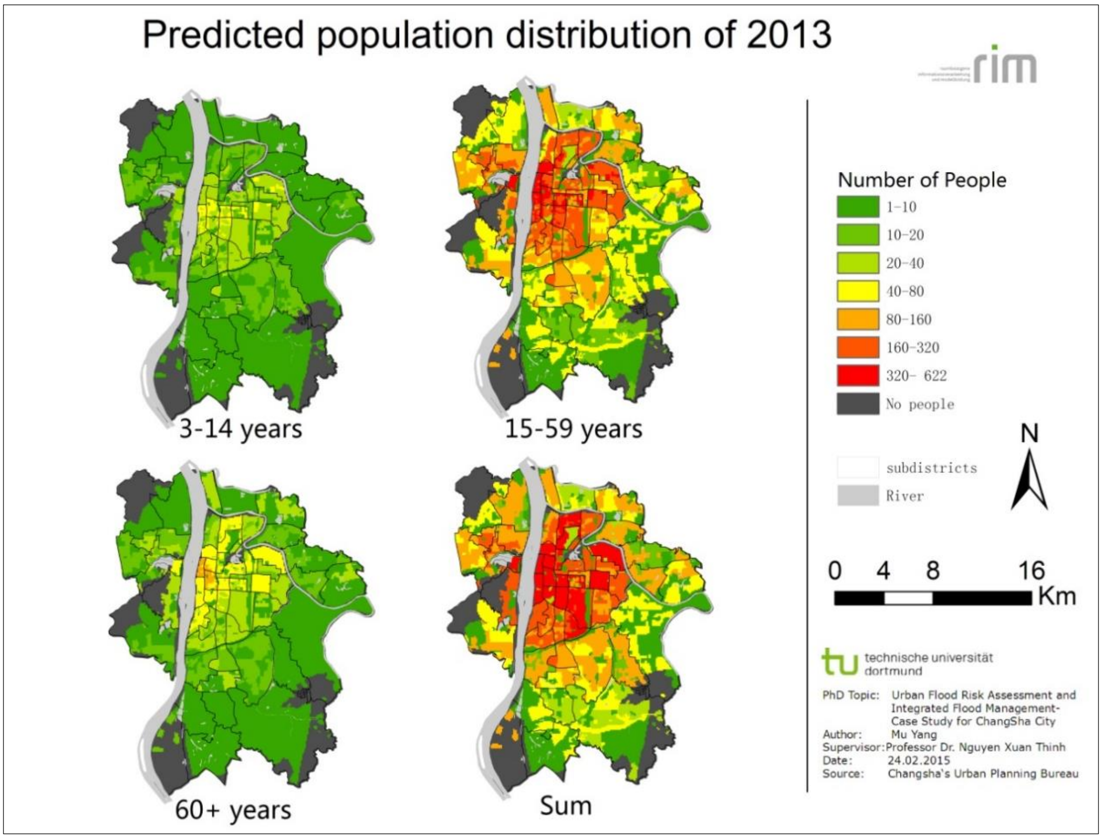


Figure 4-5: Spatial distribution of total population and different age groups

The exposure maps of population were obtained through overlying the demography maps with inundation maps. Figure 4-6 presents the exposure map of population with different age group of 200-year flood. The map shows that high- and low-level exposure takes up a large proportion. The inundation characteristics were mapped according to the corresponding exposure level based on water depth and velocity. Based on thematic maps of various flood scenario, exposure details of three age groups were summarized as shown below (Table 4-3). The statistical result indicates that 200-year flood will make an increase of 26100 people exposed to flood compared with 100-year flood. Nevertheless, the inner city, which is the most densely populated districts, is almost out of the flood area.

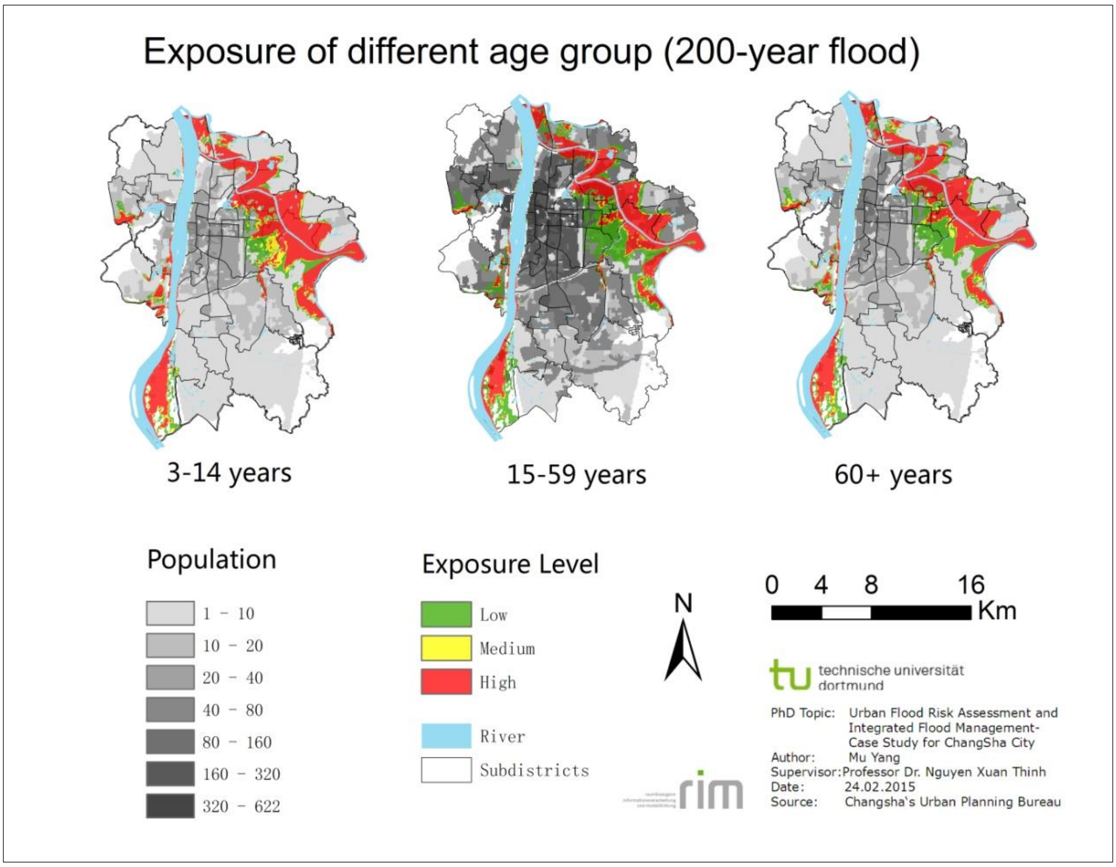


Figure 4-6: An example of exposure level of different age groups

Table 4-3: Statistics of exposure of different age groups

Population group	10-year	20-year	30-year	50-year	100-year	200-year
3-14 years	42526	46875	48834	50952	53926	56312
60+ years	64536	70712	73658	76681	81060	84589
others	352659	387120	403964	421321	446402	466587
Sum	459721	504707	526456	548954	581388	607488

4.2.3 Environmental exposure

Land use to the north of Liuyang River that refers to environmental elements has higher exposure to flood more than the south. In the south, along the east Xiangjiang, a large area of wetland exposed to flood. The statistics in Table 4-4 shows that, from 10-year flood to 200-year flood, the affected area almost doubles. Especially, the area inundated wetland increases by 81.4%. In contrast, relative increase of inundated forest, ecological green lands not remarkable (16%). Refuse points within inundation area concentrate mostly along the west side of the middle reach of Liuyang River. Particularly in 200-year flood, inundation depths in many areas were above 3 meters, which would have a great hazardous influence on urban ecological environment (Figure 4-7).

Table 4-4: Statistics of exposure of environmental elements

Environmental risk elements	10-year	20-year	30-year	50-year	100-year	200-year
Forest, park (km^2)	5.48	5.77	5.93	6.08	6.24	6.38
Wetland (km^2)	5.37	6.62	7.24	7.91	8.95	9.74
Number of refuse points	17	20	20	20	20	21

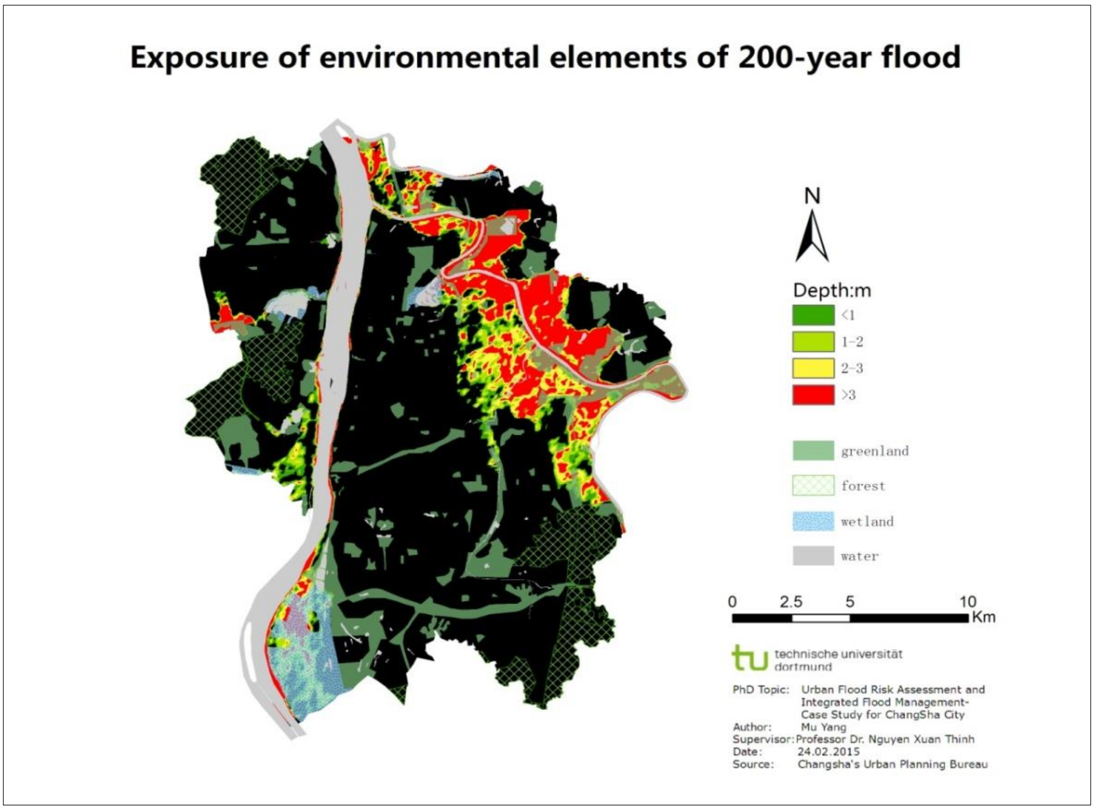


Figure 4-7: An example of exposure map for environmental risk elements

4.2.4 Infrastructure network analysis

4.2.4.1 Damage on road segments

By comparing the situation, before and after the flood event, total length of segments reduces significantly in all scenarios. Based on the inundation depth, the relative damage values are calculated. Due to the more serious inundation depth and area along the Liuyang River, floods will cause widespread damages on roads in the surrounding areas. Relatively, roads across the Xiangjiang River that connect the east and west urban area suffer physical damage. From 10-year flood to 100-year flood and 200-year flood, inundated and isolated road length increases 38 km and 44 km respectively. In the most serious case, a 200-year flood can cause 295 km roads submerged directly or isolated from the overall network, accounting for almost one-third of total length. Even 10-year flood can cause 300 road segments directly affected, over 250 km. Among the affected road segments, about a third of them suffer high physical damage rate (40%). When it comes to 100-year flood and 200-year flood, the percentages are both over a half, up to 53.8% and 58.5% respectively (Figure 4-8 and Table 4-5).

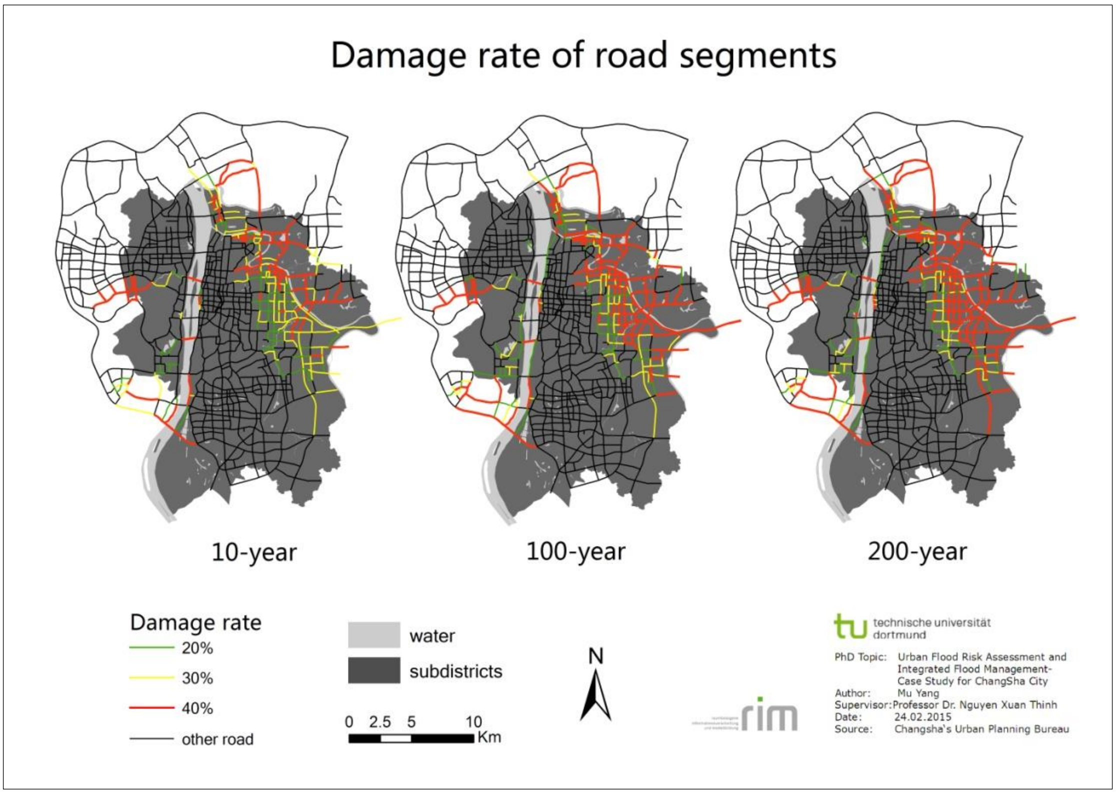


Figure 4-8: Comparison of damage rate of road segments among 10-year, 100-year and 200-year flood

4.2.4.2 Damage on traffic flow

The distribution of traffic volume is assigned to road network according to OD census based on the principle of using shortest travel time in TransCAD, which is software fully integrates GIS with traffic demand modeling and logistics functionality (Li et al., 2007). The 12-hour (07:00~19:00) traffic flow map is shown in the left of the following map in Figure 4-9. Overlapping with inundation information (water depth is above 30 cm), average annual damage is calculated and risk map of traffic is produced as in the right of Figure 4-9. Most directly inundated road segments are in medium risk. The roads under highest risk locate in the north of the city, North 2nd Ring Road and Furong Bridge, which connect the two sides of the Xiangjiang River. East 2nd Ring Road also burdens massive traffic volume traffic heading north and south every day thereby suffering high damage (9560 PCU/ Year・12h).

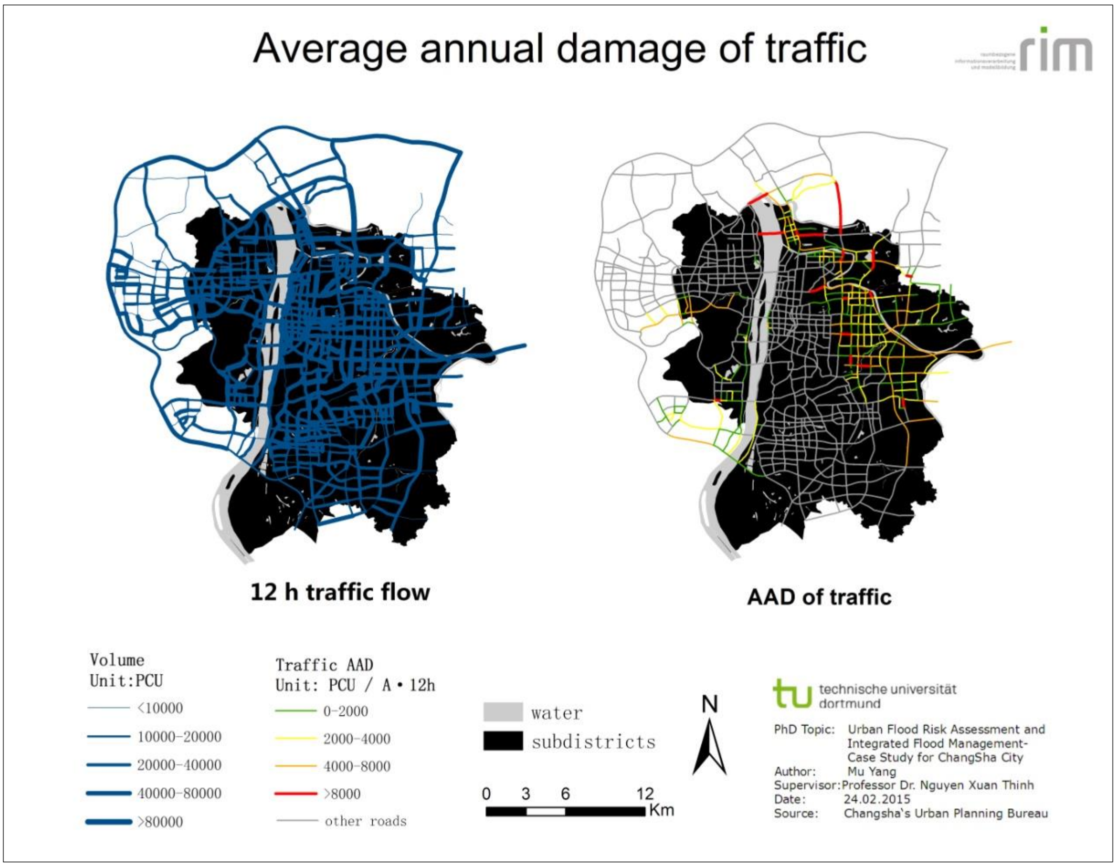


Figure 4-9: Traffic flow distribution and Annual Average Damage on traffic

With regard to the characteristics of road networks, there were great distinctions among no weighted method and weighted methods. Overall, all the average degree and clustering coefficient (CC) decrease in all flood conditions, which denotes the total connectivity were reduced in different degree, the more severe flooding, the more remarkable decrease. Average path length (APL) increased due to the path re-planning, which indicates that total transport consumption is getting even more after flooding. But the maximum reduction percentage did not occur in 200-year flood because the removed road segments have also caused dramatic size reduction of network. Moreover, network with no weight describe only topology features. Network weighted with distance shows modest extent of changes in parameters aside from the APL variation in 100-year and 200-year flood, which is also because greater extent of reduction of network size than the increase of shortest path length. However, using weighted network, changes of all the parameters were indeed significant, especially using weighting of travel time, which better matches the real-life situation that people usually schedule their trip according to least time principle (Table 4-5).

Table 4-5: Comparison of pre- and after-flood road network parameters

Parameters			Pre-flood	10-year	20-year	30-year	50-year	100-year	200-year
Road segments	Total length (km)		949	698	688	678	670	660	654
	Affected length (km)		—	251	261	271	279	289	295
		Decrease %	—	26.4%	27.5%	28.6%	29.4%	30.5%	31.1%
Network with no weight	Average Degree		4.556	3.655	3.604	3.577	3.493	3.442	3.408
		Decrease %	—	19.8%	20.9%	21.5%	23.3%	24.5%	25.2%
	CC		0.377	0.303	0.299	0.295	0.290	0.288	0.286
		Decrease %	—	19.7%	20.8%	21.7%	23.0%	23.6%	24.2%
	APL		13.9	15.1	15.0	15.9	16.1	16.4	16.4
		Increase %	—	8.6%	7.9%	14.4%	15.8%	18.0%	18.0%
Network weighted with distance	Average Degree		7.560	6.111	6.036	5.945	5.855	5.786	5.255
		Decrease %	—	19.2%	20.2%	21.4%	22.6%	23.5%	30.5%
	CC		0.073	0.058	0.057	0.057	0.056	0.055	0.051
		Decrease %	—	20.9%	21.7%	22.3%	23.5%	24.2%	30.9%
	APL (km)		12.4	14.2	14.2	14.3	14.3	14.2	12.7
		Increase %	—	14.5%	14.5%	15.3%	15.3%	14.5%	2.4%
Network weighted with travel time	Average Degree		3.883	2.083	2.058	2.026	1.992	1.967	1.948
		Decrease %	—	46.4%	47.0%	47.8%	48.7%	49.4%	49.8%
	CC		0.0528	0.0286	0.0281	0.0277	0.0273	0.0272	0.0270
		Decrease %	—	45.9%	46.8%	47.5%	48.2%	48.5%	48.8%
	APL (min)		18.2	34.7	34.5	41.1	41.0	40.8	40.9
		Increase %	—	90.7%	89.6%	125.8%	125.3%	124.2%	124.7%

4.2.4.3 Damage on accessibility

Analysis on network parameters of degree, clustering coefficient, and average path length describe the changes of total loss of transport efficiency of the road network. Between pre- and after flood, road networks weighted with travel time show remarkable change. Based on the closeness centrality weighting with travel time, the evaluation of accessibility loss of each road segment has been assigned for each travel time imposes practical implications compared to the one based on topology of network, which were also affected in the medium damage (Figure 4-10). From the network analysis above, road segments around Liuyang River show high vulnerability. Once river flooding comes rushing, the road segments can be severely damaged and the accessibility decreases markedly. Moreover, among 11 roads that connecting both sides of the Xiangjiang River, five (North 2nd Ring Road, Fuyuan Road Bridge, G319 Road, South 2nd Ring Road and G0401 Road) are high damaged in accessibility. Thus, though the inner city is not exposed to flood, the transport efficiency could be badly affected indirectly.

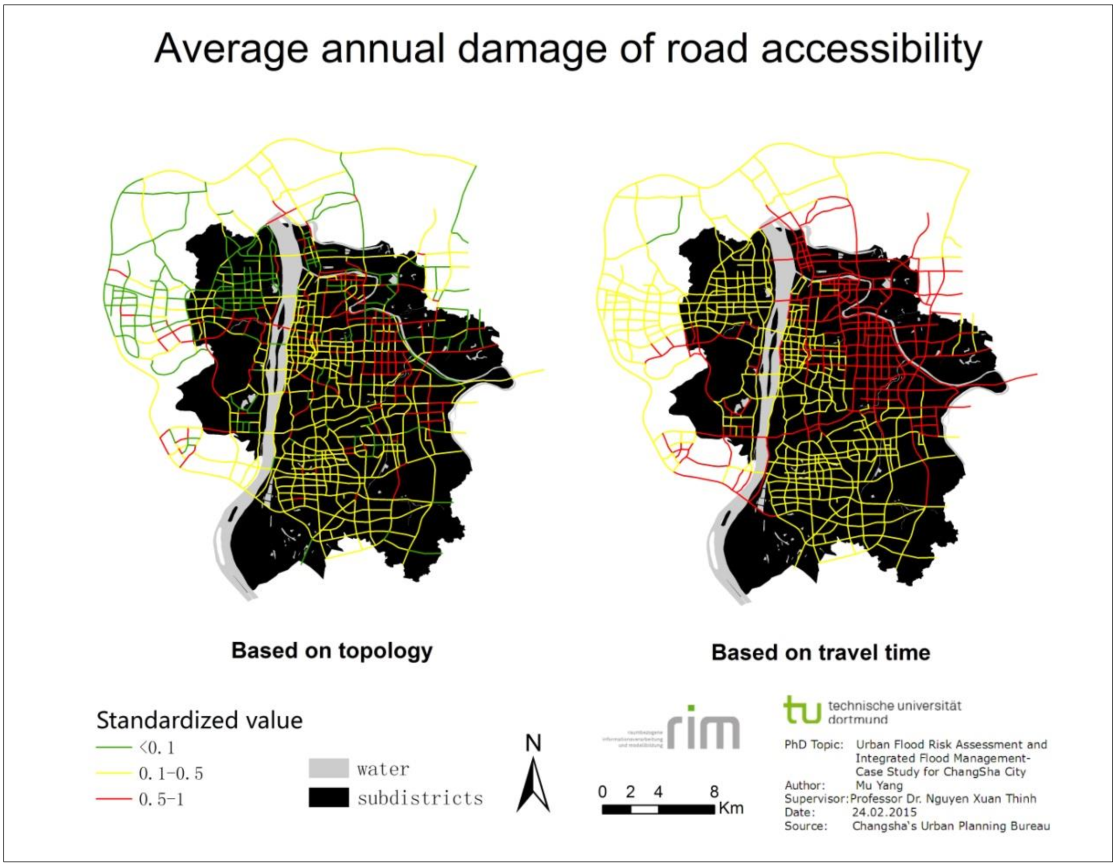


Figure 4-10: Average annual damage of road accessibility

4.3 Uncertainty of the damage model and integrated risk

4.3.1 Sampling parameters and generating problems

The uncertainty and sensitivity analysis were conducted by calculated the integrated damage percentage value which were normalized and summed up. As uncertainty of probability and weighting were not covered, the uncertainty and sensitivity analysis were discussed with single flood event, 200-year flood, and with equal weights, one as it is also value. A Sobol' sensitivity analysis was performed. Parameter values were generated using Saltelli sampler. The Saltelli sampler generates samples according to number of inputs and the number of evaluation. It generates *N*(2D+2)* samples, where *N* is the supplied argument and *D* is the number of inputs matrix of parameters. In this case study, damages were calculated according to risk dimensions respectively. Take economic damage model as an example, 6 inputs (depth and five curves) were considered and *N* was set as 1000. That is totally 1000*(2*6+2) = 14000 times calculation for each cell, which will be tremendous computing workload for the whole areas. Therefore, a test area was chosen covering all the parameter with sufficiently wide difference and parameter combination (Figure 4-11).

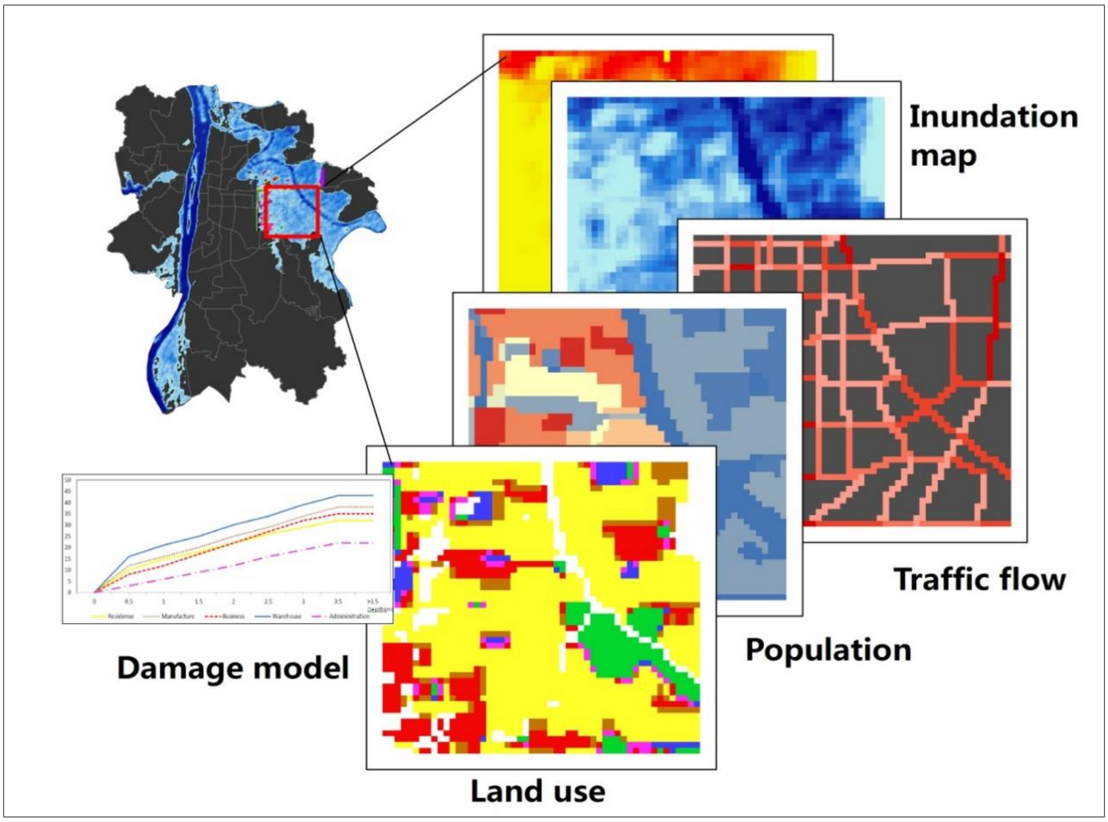
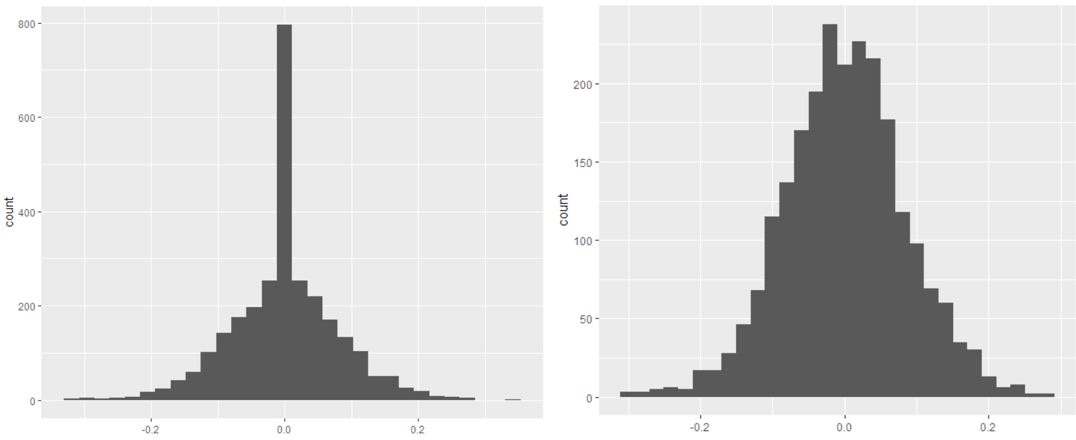


Figure 4-11: Test site and uncertainty of input parameters of the model

4.3.2 Distribution of first- and total- order indices

Python SALib package (Herman & Usher, 2017) was applied to calculate the Sobol' indices typically with a confidence level of 95%. The results show that the sensitivity differs in not only damages models and but also spatial distributions greatly. In economic damage model, inundation depth (X_{11}) appears first-order effects in some place and presents a random distribution spatially. And it shows nearly no second-order effect other than very few scattered cells.

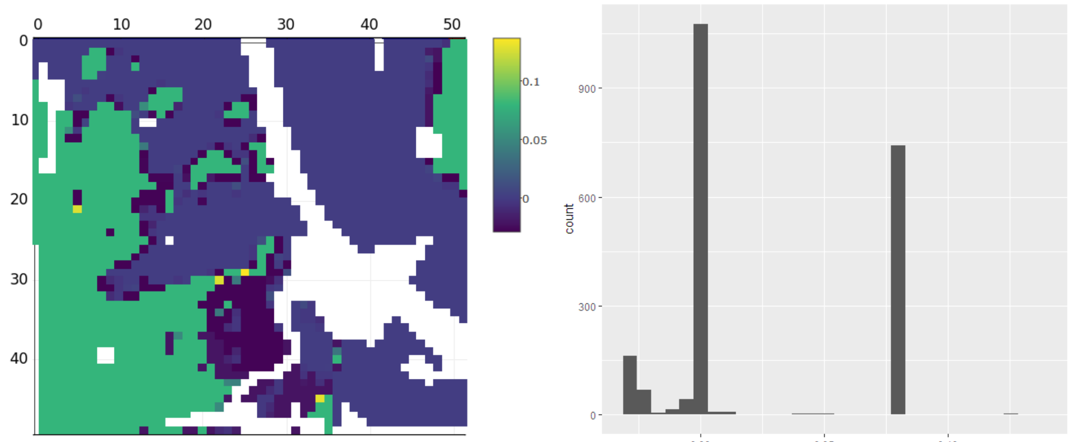
Figure 4-12 gives the distribution First-order indices of economic shapes of damage curves for residential (X_{12}) and environmental (X_{16}) land use respectively.



S1 of X_{12} (residential land use) S1 of X_{16} (environmental land use)

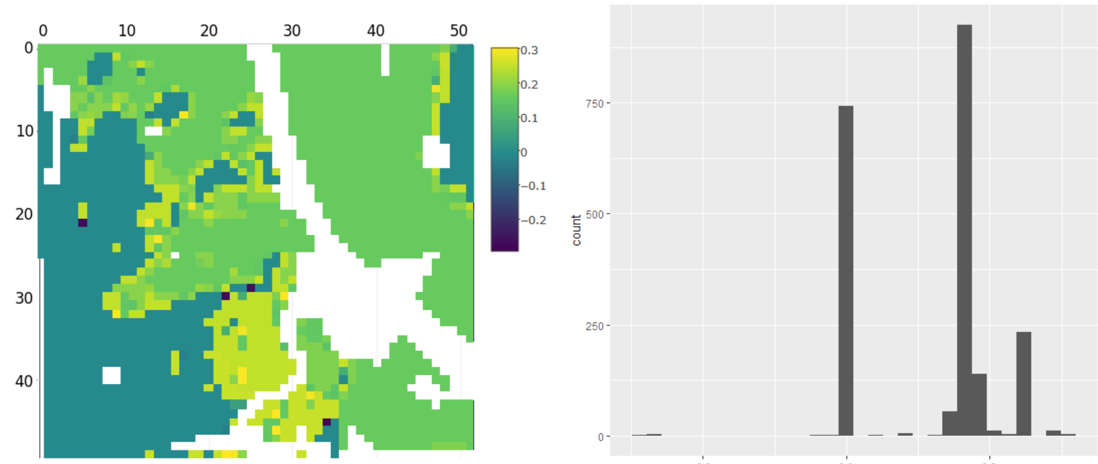
Figure 4-12: Distribution First-order indices of economic damage curves

By contrast, five input parameters in social damage model, shows no significant first-order effects in most locations except X_{21} (population statistical caliber) and X_{24} (social medium damage parameter) denote significant first-order effects in partial places with sensitivity indices at 0.08 and 0.15~0.25 respectively. Parameter X_{21} exerts relatively high first-order effect in the west of test site. While parameter X_{24} impacts in areas along the rivers with even higher first-order effects. The detailed spatial distribution and frequency distribution of Sobol' sensitivity indices of social damage model parameters (X_{21} and X_{24}) are shown in Figure 4-13, 4-14.



S1 distribution map of X_{21} (population statistical caliber) S1 of X_{21} (population statistical caliber)

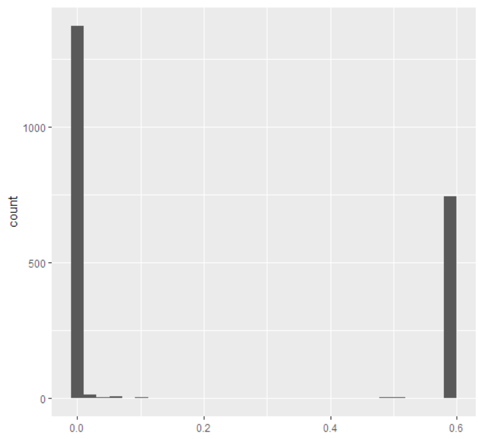
Figure 4-13: Distribution First-order indices of population statistical caliber



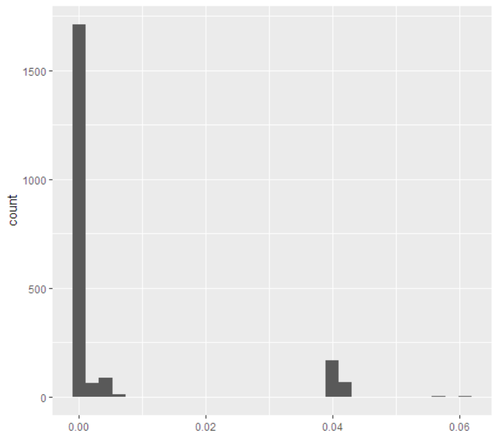
S1 distribution map of X_{24} (social medium damage parameters) S1 of X_{24} (social medium damage parameters)

Figure 4-14: Distribution First-order indices of social damage parameter (medium)

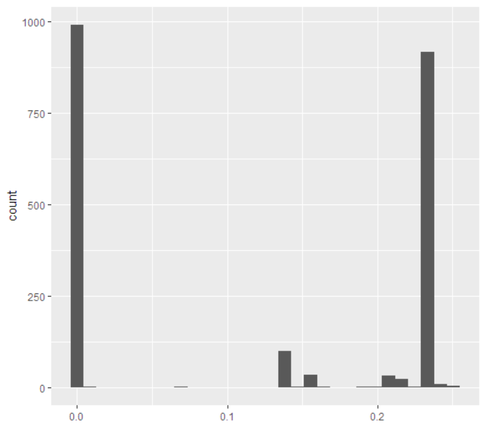
As total-order indices of land use show obvious randomness in distribution as first-order indices, which should to great extent reason from the spatial distribution of different types of land use as well as the randomness of distribution of the inundation depth, the following analysis focuses on input parameters of social damage model, the total-order sensitivity indices frequency distribution of parameters of social damage model are shown in Figure 4-15. The larger the sensitivity indices value, the more important parameters are for the model. The results indicate that inundation depth (X_{22}) impacts slight total effects on social damage model. In few cells with relative lower values below 0.05, while demography data (X_{21}, the population statistical caliber) and damage parameters (X_{23} and $X_{24,}$ the low and the medium social damage parameters respectively) play crucial roles in social damage assessment.



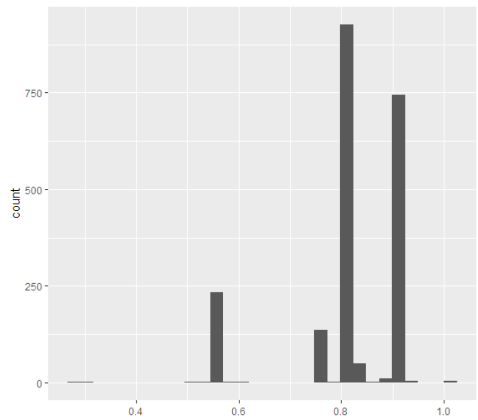
S1 of X_{21}



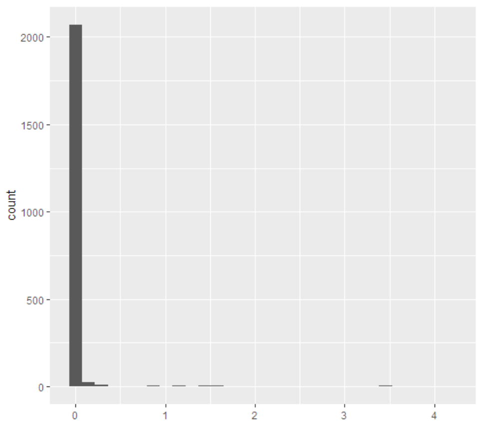
S1 of X_{22}



S1 of X_{23}



S1 of X_{24}



S1 of X_{25}

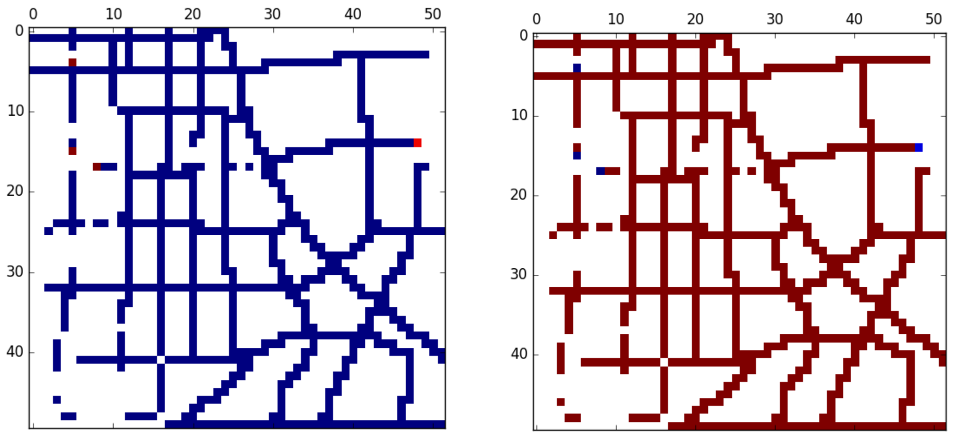
*X_{21}: population statistical caliber

X_{22}: inundation characteristics

X_{23}~X_{25}: the low, medium, high social damage parameters respectively

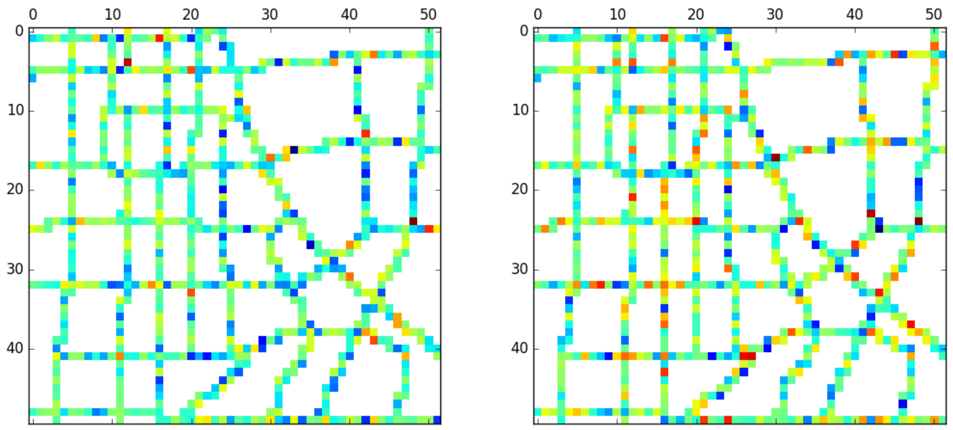
Figure 4-15: Distribution Total-order indices of social damage parameters

The factor of inundation depth presents neither first- nor total-order effects on traffic flow damage evaluation. It can be explained that the damage model simply used 30 cm of water depth as a threshold in binary method for calculating the relative damage. While the most of the inundation depth is much high than that value, thus the traffic flow values exert high effects on both first- and total-order indices value, almost close to 1. As for road segments, similar situation occurs in total-order indices value. Inundation shows no obvious total-order effects. However, both parameters water depths and damage curves show random feature in spatial and frequency distribution. Figure 4-16 and Figure 4-17 show the spatial distribution of first-order indices referring to traffic infrastructure. For total-order indices, the conditions are largely identical but with minor differences in spatial distribution.



*the left map refers to factor of inundation depth; the right one relates to traffic flow amount. The blue color means a value almost close to zero, while the red color corresponding to high value close to 1.

Figure 4-16: First-order indices of traffic flow and road flow damage parameters



*the left map refers to factor of inundation depth; the right one relates to damage function. The blue color means a value almost close to zero, while the red color corresponding to high value close to 1.

Figure 4-17: First-order indices of traffic flow and road segments damage parameters

4.4 Risk mapping

4.4.1 Separate risk maps

Based on different requirements, separate risk maps (such as economic, social, environmental) can be generated for different dimensions (Figure 4-18 ~ Figure 4-20). As the aggregated economic risk map shows, about 44% of the areas with a moderate economic risk (values below 0.1) and 45.6% with a high economic risk (values from 0.1 to 0.5). Risk areas scatter in the northeastern part of the city and along the floodplain of Liuyang River (Figure 4-18). However, the inner city, the most densely populated areas, just nearly all avoids the social risk of flooding (Figure 4-19). The areas under high risk locate at the same side, the west bank of Liuyang River in Mawangdui sub-district and northern of Wujialing and Sifangping sub-district. In the north, Furongbeilu sub-district along the Xiangjiang River is an area with moderate social risk. Most of the other exposed places show low-risk values. As for aggregated environmental risk, except along Liuyang River, there are also a large area with high risk distributed in the south at the east bank of Xiang River. Among flood-prone area, high-risk area accounts for 78%. Only 4% is low in environmental risk (Figure 4-20).

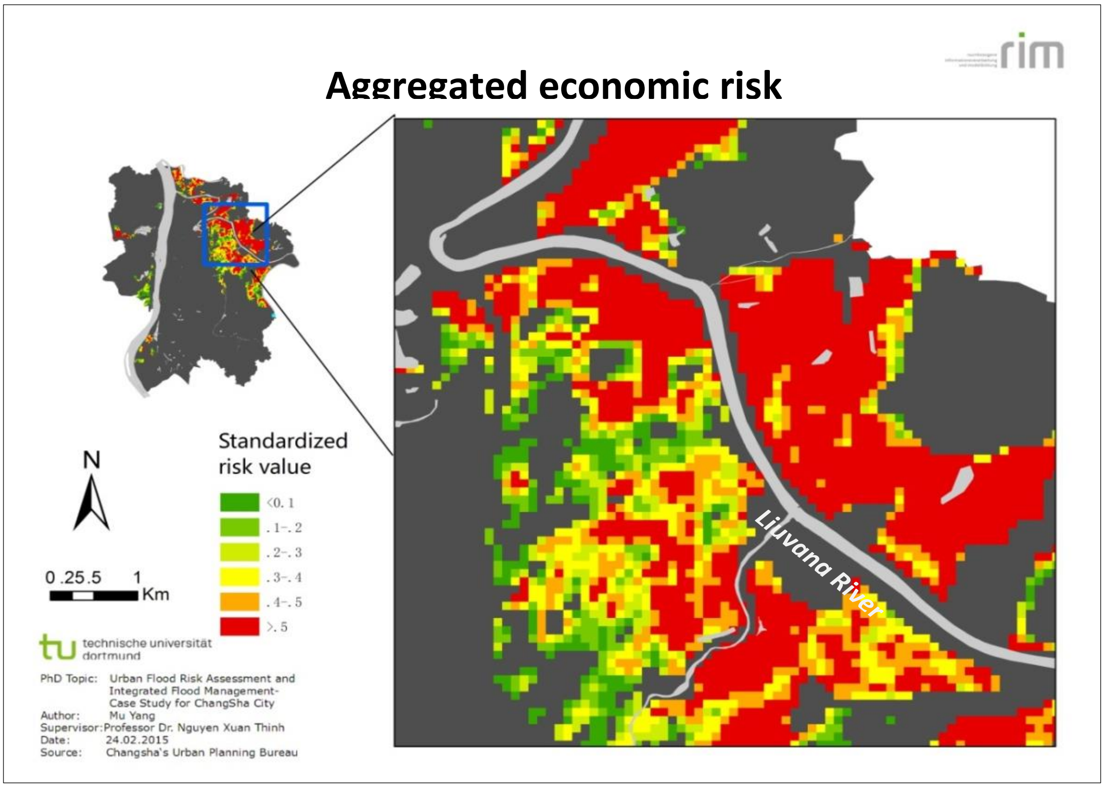


Figure 4-18: Zoom-in aggregated economic risk map

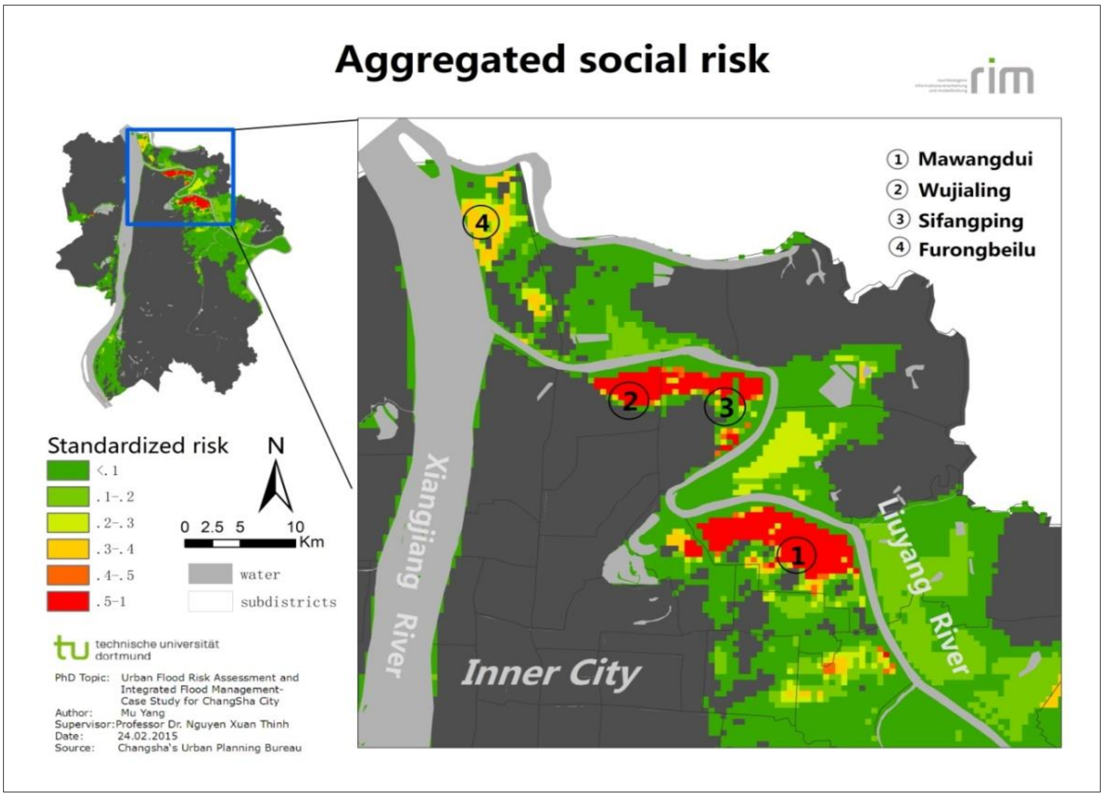


Figure 4-19: Zoom-in aggregated social risk map

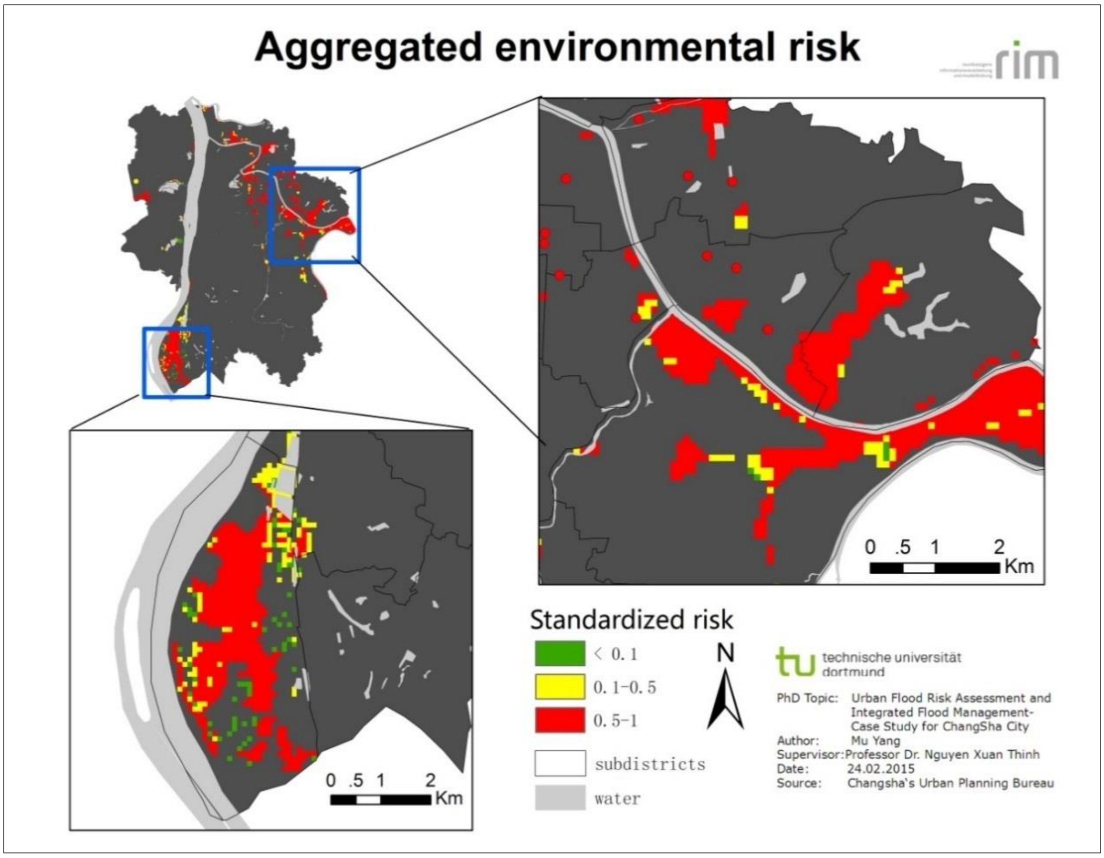


Figure 4-20: Zoom-in aggregated environmental risk map

4.4.2 Integrated risk maps

Integrated risk maps were obtained by sum separate risk map with weights. The space distribution of flood risk for all dimensions were finally overlapped and composed with different sets of weights. For integrated risk assessment, values of different weights are also an important factor causing uncertainty. Swing weighting approach was used to estimate the sensitivity of flood damage estimations to this component sensitivity of weights, which enables to display the results in maps for different sets of priorities or weights that urban experts such as planner or risk managers might have (Kienberger et al., 2009).

Figure 4-21 compares the integrated risk value composition for different weight sets. The Equal weighting criteria sets were defined as the baseline scenario. In the baseline scenario, high, medium and low-risk area allocates 25.5%, 69.5% and 5% respectively. In the Economic, Social and Environmental scenarios, there is a minor swing for each risk level. Medium risk value fluctuates between 57.6%~68.9%, occupying the largest percentage. Using Traffic weighting criteria set, medium and high-risk value portions both increase slightly accompanied by the low-risk decrease to 16.2%, which is the minimal share compared with all other scenarios. In the final three extreme weighting sets, there are more low-risk values with significant increase and the medium portion compressed. And all high-risk values have an obvious increase except in the Life scenario, accounting for only 1.2%. Figure 4-22 shows the integrated risk map in different scenarios with various weighting sets, which denotes the spatial distribution of risk more intuitively. With regard for the network feature of infrastructure, flood risk distributes across almost the whole urban area. By map representation, areas with high-risk value respectively concentrates along Liuyang River and Xiangjiang River in Econ. EX and Envi. EX scenarios.

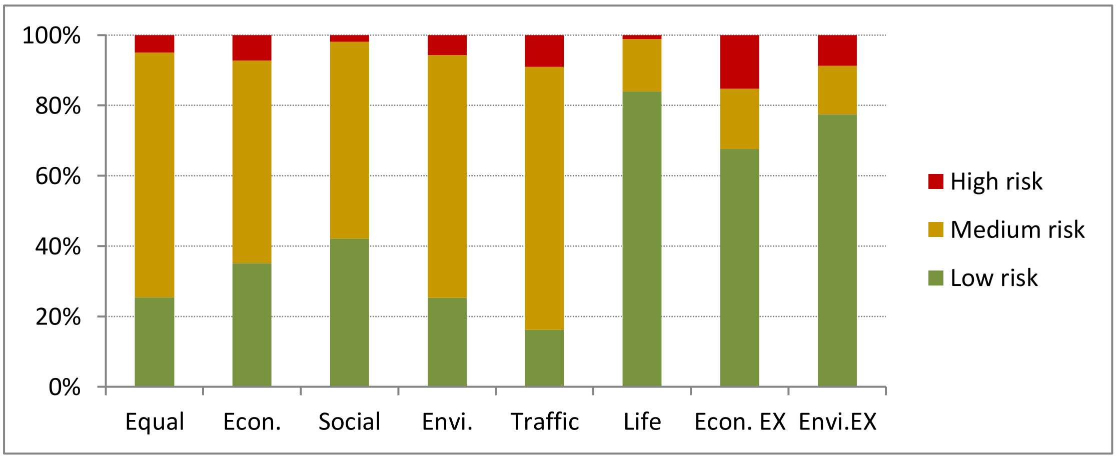


Figure 4-21: Composition of risk value statistic based on cells

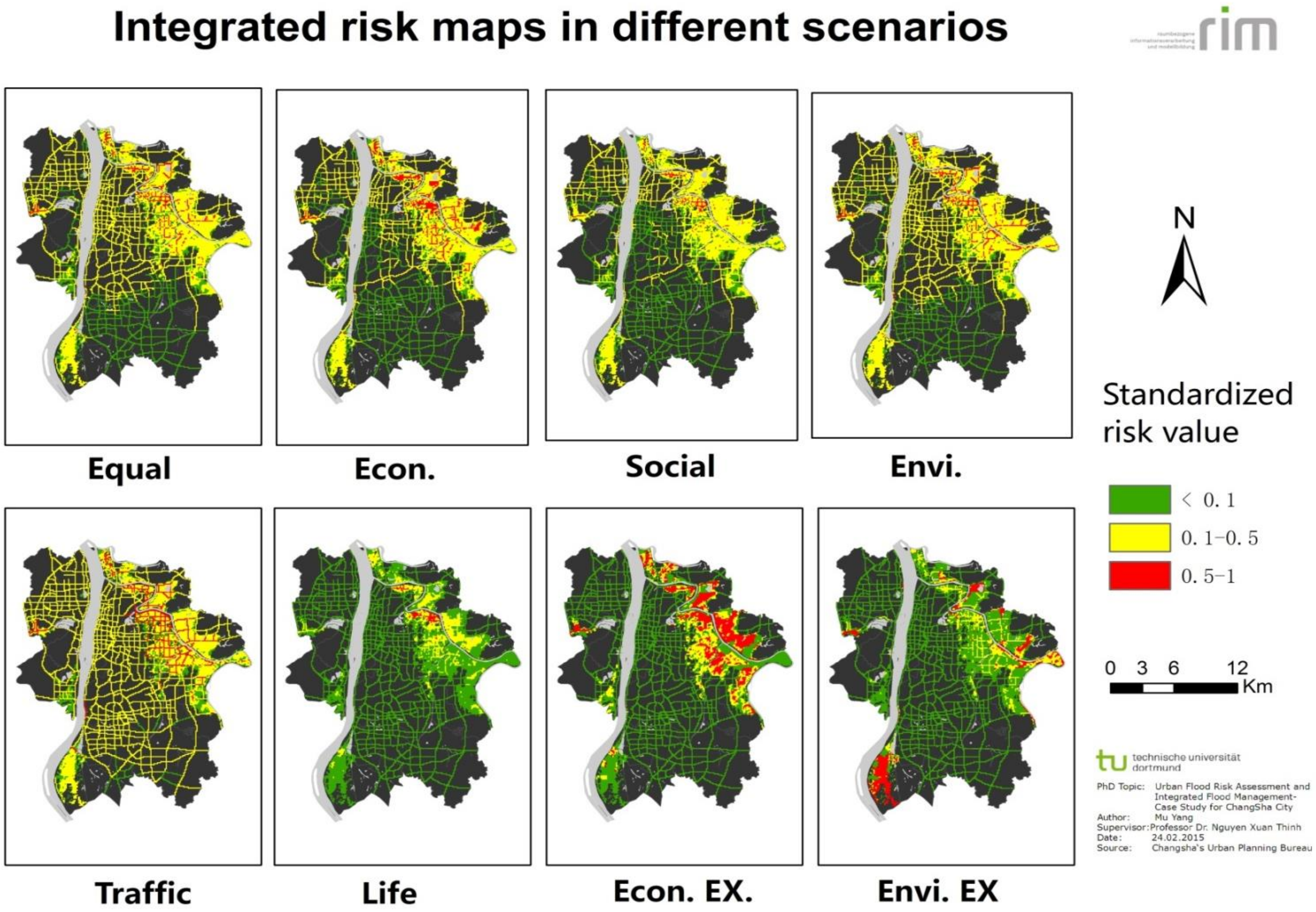
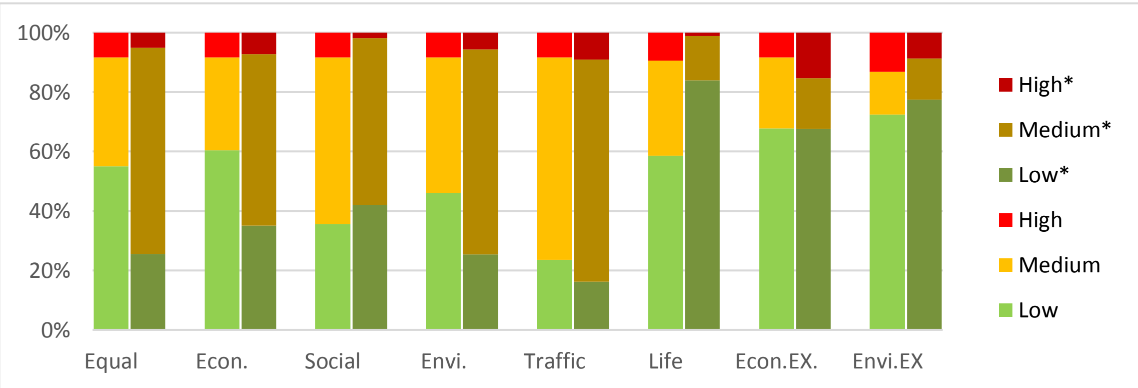


Figure 4-22: Integrated risk value in different scenarios on cell scale

4.4.3 Risk value statistic based on sub-districts

FRM organizations that are responsible for spatial planning (generally local government, urban organization or national policy-makers), will negotiate and reach agreements on the change of traditional development planning. In principle, FRM should not impose its requirements on the urban organization of spatial planning. Whereas the policy-makers should recognize that the refined disaster risk management is crucial to promote a sustainable economic society. For this reason, in spatial planning policy flood risk should be paid more attention, but at the local level, it has not fully implemented. Hence, risk values for sub-districts were also calculated, which equal sum of damages and then is statistic within a boundary of sub-district. By using the statistic maps based on administrative region, which is helpful for further policy-making and resources assignment of FRM as such decision usually taken according administrative region. Hence, it is also necessary to evaluate the total flood impact on each sub-district.

According to statistics, if the spreading effectiveness of road network is not taken into account, among 55 sub-districts, 31 ones are affected by flood directly. In all of the 8 different scenarios, Lituo sub-district is named in the top risk ranking (Figure 4-23). Besides, Mawangdui and Datuo sub-districts are also in high-risk rank in Life and Environmental weighting criteria set respectively. Sub-districts located in inner city, south of the city are generally in low risk. In the northwest, Guanshaling, Wangyue et al., several sub-districts swing among low and medium risk rank. Compared with risk maps based on cells, the distribution of risk value characterizes differently in details due to the scale effect. Nonetheless, to some extent, that still presents similarity trend across space roughly. This kind of similarity is also shown in the proportions of the three different risk groups (low, medium, high-risk areas) except in Equal, Econ., Envi. and Life scenarios (Figure 4-24).



Low, Medium, High denote statistics at sub-districts level; Low*, Medium*, High* denote statistics at cells level

Figure 4-23: Comparison of risk level on different spatial scales based inundated areas

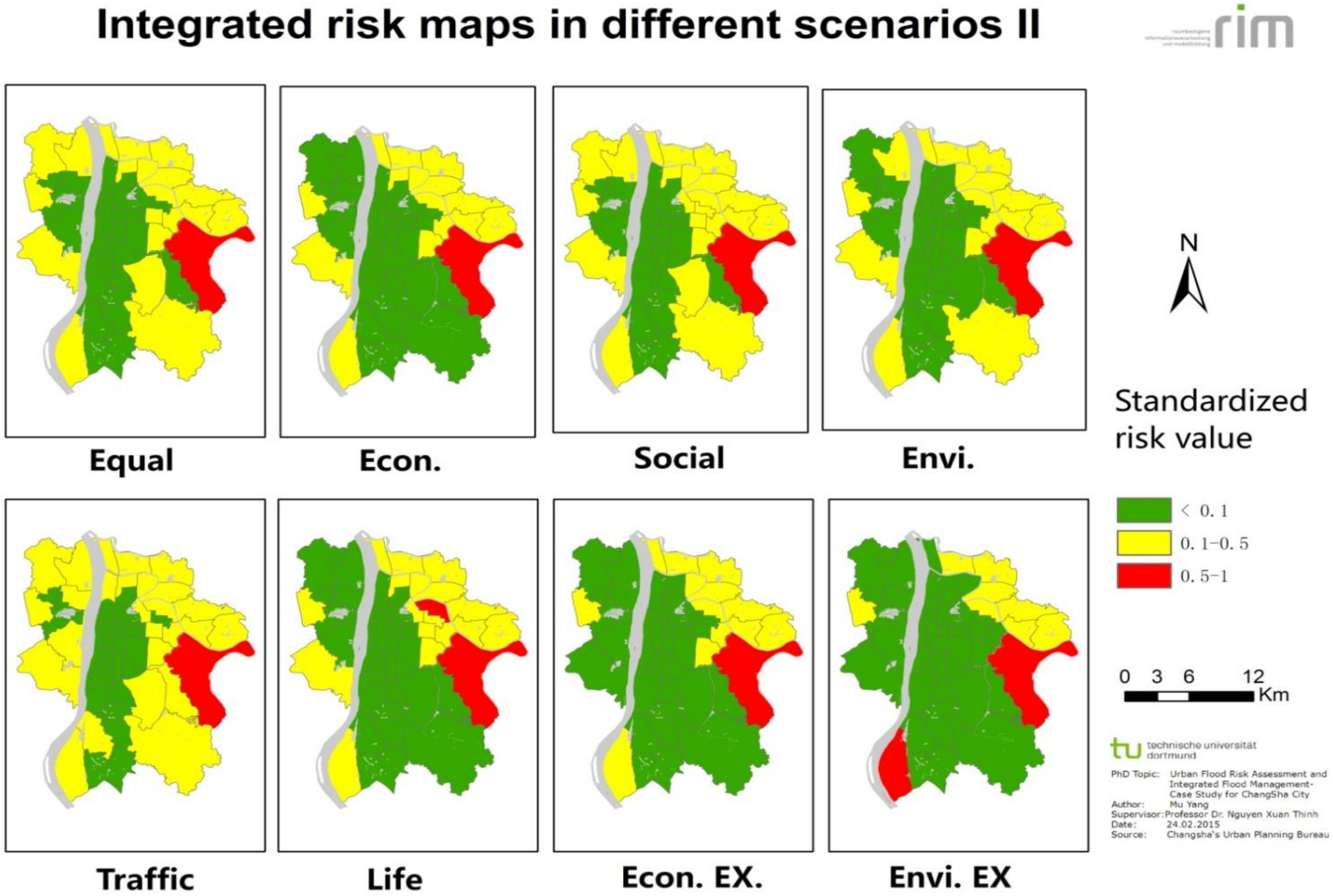


Figure 4-24: Integrated risk value in different scenarios on sub-district scale

4.4.4 Utilities of flood maps

By risk analysis and mapping, the risk level and spatial distribution were visualized quantitatively and intuitively. The results can give beneficial inspiration to both citizens and decision maker. Spatial planning is the most effective way to reduce flood risk, since it can massive control redevelopment and utilizing of the land in risk zone. In general, the original intention of these spatial planning is not for purpose of giving service to FRM but for purpose of fulfilling other social goals. However, spatial planning and control development can directly reduce flood disaster risk in many ways, which is significant guarantee for sustainable FRM.

4.4.4.1 Adjustment of flood control standard

Although non-structural measures are becoming an increasing factor in the FRM, traditional engineering measures still play major roles in river flooding prevention and control. The level of flood control standard should not only think comprehensively about importance of the flood protected objects, degree of casualty and damage, but also should be coordinated with the national economic and social development plan.

For Changsha city, there was a dispute that it is necessary to advanced flood control standard to 200-year flood. At the beginning of formulation of flood control and overall planning, Mao et al. (2003) have presented that the highest water level of 200-year flood rise only 0.24m and 0.39m for Xiangjiang River and Liuyang River respectively. Thus a 200-year flood might be a safe-biased design standard. The results of hydrodynamic simulation emphasis that there is no great change in inundation depth and even area. According to the damage and risk analysis, 200-year flood could respectively cause 3.9% and 4.5% growth of land use and affected population compared with 100-year flood. Including 200-year flood in the annual average damage (AAD) calculation, the average of economic and social relative risk values of increase only 1.71% and 0.32%. However, giving considerations to the large economic and population base as well as rapid social and economic development of the city, the growth of absolute risk values will not be even more considerable.

4.4.4.2 Change of demographic composition

Any development activities in flood zone, for example, changing land use or transforming from the opening leisure area for the landscape to the densely residential area, increases the probability of flood disaster and the flood risk would also increase. Increasing of population and population density, the impact of the flood on the society would also aggravate significantly. Such increasing threat to people might motivate and force more people to prevent and reduce the negative influence through risk analysis and mapping.

According to the 2020 land use planning, there is seldom change in the Central city compared to the current land use. However, population will grow dramatically with great change in age structure (Table 4-6). The Changsha city is experiencing a rapid population growth and aging problem. By 2020, population over 60 years old will account for about one fifth and the old-age dependency ratio will reach 29.2% for the whole Changsha. For the central city, though the percentage of elder people is not so large, there is also clearly tendency of aging. Compared to 2013, Kaifu and Yuhua district have relative larger growth in predicted total population by 2020. Each district will have faster increase in percentage of senior people (Table 4-6). Based on the land use method, predicted population was assigned to a map and then overlapped with inundation map to obtain a predicted population exposure and further to evaluate the social damage and risk.

Table 4-6: Population comparison of 2013 and 2020

Districts	Total population			Percentage of senior		
	2013	2020	Yearly growth	2013	2020	Yearly growth
Furong	533300	562848	1.8%	14.6%	18.5%	4.0%
Tianxin	481600	506296	1.3%	13.5%	17.4%	4.3%
Yuelu	813800	845362	1.5%	12%	16.0%	4.9%
Kaifu	588400	639376	3.7%	13.6%	17.5%	4.3%
Yuhua	748200	804025	3.3%	11.5%	15.5%	5.1%

According to the predicted population distribution of the year 2020, the social risk value of 2020 (in Equal Scenario) was also calculated. By comparing the risk values, about 1.3% of area grows from low to medium and high, covering 0.8-km^2 area and 8971 people. Spatial distribution of those places is shown in the following map (Figure 4-25). The social risk maps considering changes of demography can potentially help decision-making, for example in residence planning, site planning, etc.

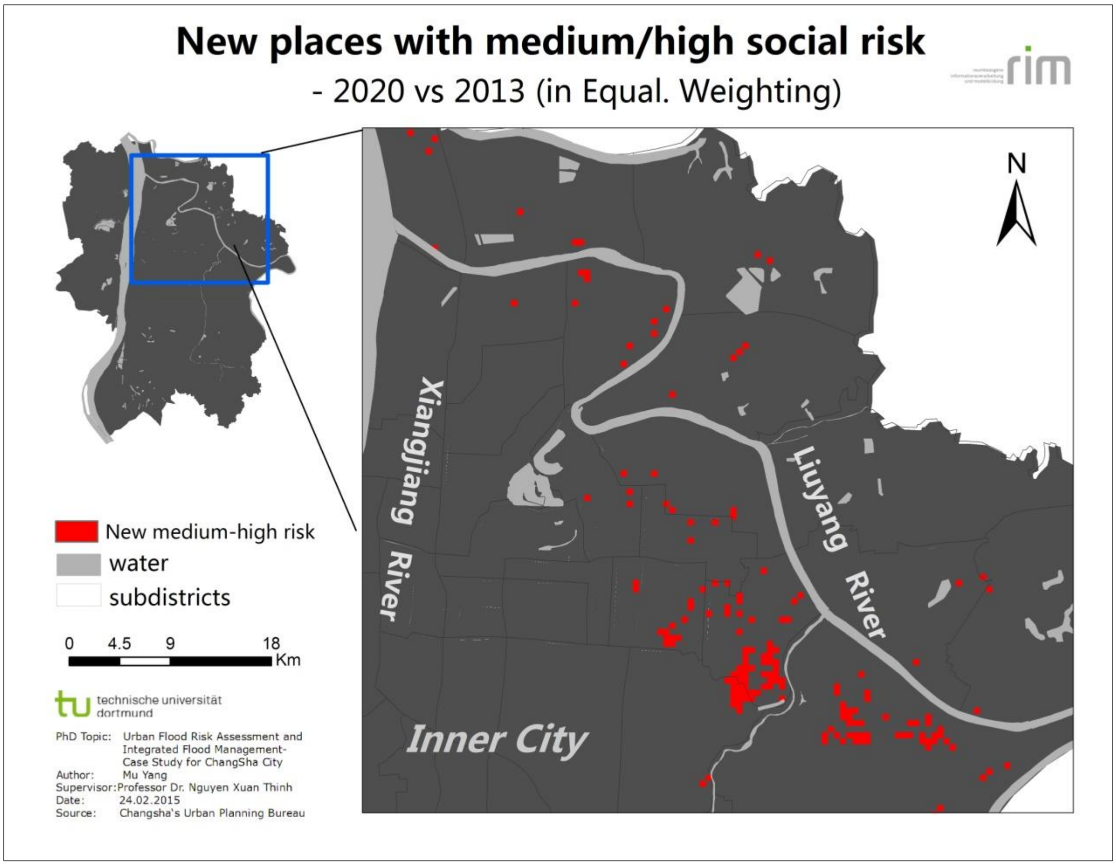


Figure 4-25: New places with medium or high social risk due to demographic change

4.4.4.3 Potential application in spatial planning and land use management

Floodplain zoning is generally used to classify the area with different flood hazard level, thereby confirming the different development modes and land use modes, which match to different flood risk zones. Hazard and vulnerability mapping could help to regionalize the flood zone and to confirm a kind of development activity (Table 4-7). For example, in areas close to river and fast flow zone (hv > 7) should not construct any buildings, only allowed to develop places for recreational and leisure activities. in floodplain where flood prevention standard under 100 years, should not allow to construct residential buildings.

Besides, risk maps can also play a part in establishing evacuation shelter, emergency route, land use management in land suitability evaluation etc. Table 4-8 ranks land use categories according to their vulnerability referring to the Climate Change Tools, *Designing for Flood Risk,* a package of guidance developed by the Royal Institute of British Architects (RIBA, 2009) for architects to respond to the challenges of climate change and global warming (Gething & Puckett, 2013). In the table, different categories of land use are set against low, medium, high and very high levels of flood risk to form a "land use ready reckoner" to assist in the selection of compatible uses. It highlights that some uses could be feasible when suitable flood risk reduction measures or a combination of mitigation and control measures are put in place. However, the ultimately reckoning relies on full consideration of individual land use proposals and the specific set of local circumstances in conjunction with the control and mitigation in practice (Gething & Puckett, 2013).

Table 4-7: Flood risk vulnerability and flood zone compatibility

Vulnerability	Land use	Risk			
		Zone 1	Zone 2	Zone 3a	Zone 3b
Water-compatible development	Water infrastructure and pumping stations	🟢	🟢	🟢	🟢
	Sewage infrastructure and pumping stations	🟢	🟢	🟢	🟢
	Sand and gravel workings	🟢	🟢	🟢	🟢
	Docks, marinas and wharves	🟢	🟢	🟢	🟢
	MOD defence installations	🟢	🟢	🟢	🟢
	Shipbuilding, fish processing	🟢	🟢	🟢	🟢
	Amenity open space, outdoor recreation	🟢	🟢	🟢	🟢
Less vulnerable	Buildings, shops, professional restaurants, Storage, distribution, assembly and leisure	🟢	🟢	🟢	🔴
	Land and buildings for agriculture and forestry	🟢	🟢	🟢	🔴
	Waste treatment plant	🟢	🟢	🟢	🔴
	Minerals	🟢	🟢	🟢	🔴
	Water treatment and sewage plants	🟢	🟢	🟢	🔴
More vulnerable	Hospitals, health and educational	🟢	🟢	🟡	🔴
	Residential institutions and dwellings	🟢	🟢	🟡	🔴
	Hotels and nightclubs	🟢	🟢	🟡	🔴
	Landfill sites and hazardous waste	🟢	🟢	🟡	🔴
	Holiday caravans and camping	🟢	🟢	🟡	🔴
Highly vulnerable	Emergency services and command centres	🟢	🟡	🔴	🔴
	Emergency dispersal points	🟢	🟡	🔴	🔴
	Basement dwellings, permanent caravans	🟢	🟡	🔴	🔴
	Installations of hazardous substances	🟢	🟡	🔴	🔴
Essential infrastructure	Essential transport and evacuation routes	🟢	🟢	🟡	🟡
	Strategic utility infrastructure, power stations and primary substations	🟢	🟢	🟡	🟡

🟢 Development appropriate 🟡 Exception test required 🔴 Development should not be permitted

Source: the Practice Guide that accompanies planning guidance

Table 4-8: Flood risk and land use management

Land use category	Suitability of Land with Risk levels			
	Low	Medium	High	Very high
Agriculture and fisheries	Suitable use	Suitable use	Suitable use	Suitable use
Forestry	Suitable use	Suitable use	Suitable use	Suitable use
Utilities and infrastructure- renewable energy production and distribution	Suitable use	Suitable use	Suitable use	Requires mitigation
Recreation and leisure-outdoor amenity and open spaces	Suitable use	Suitable use	Suitable use	Requires mitigation
Defence	Suitable use	Suitable use	Requires mitigation	Requires defence and mitigation
Transport-car parks, vehicles storage, goods and freight handing	Suitable use	Suitable use	Requires mitigation	Avoid use
Minerals (extraction)	Suitable use	Requires mitigation	Requires mitigation	Avoid use
Utilities and infrastructure – refuse disposal	Suitable use	Requires mitigation	Requires mitigation	Avoid use
Industry and business– storage and wholesale distribution	Suitable use	Requires mitigation	Requires mitigation	Avoid use
Industry and business– manufacturing	Suitable use	Requires mitigation	Requires defence and mitigation	Avoid use
Industry and business– offices	Suitable use	Requires mitigation	Requires defence and mitigation	Avoid use
Recreation and leisure– indoor	Suitable use	Requires mitigation	Requires defence and mitigation	Avoid use
Retail	Suitable use	Requires mitigation	Requires defence and mitigation	Avoid use
Transport-tracks, ways, terminals and interchanges	Suitable use	Requires defence and mitigation	Requires defence and mitigation	Avoid use
Residential-hotels, boarding and guesthouses	Requires mitigation	Requires defence and mitigation	Requires defence and mitigation	Avoid use
Residential-dwellings	Requires mitigation	Requires defence and mitigation	Requires defence and mitigation	Avoid use
Utilities and infrastructure-energy production and distribution, water storage and treatment	Requires mitigation	Requires defence and mitigation	Requires defence and mitigation	Avoid use
Residential-residential institutions	Requires mitigation	Requires defence and mitigation	Avoid use	Avoid use
Community services-medical, healthcare, education, and community services	Requires mitigation	Requires defence and mitigation	Avoid use	Avoid use

Suitable use · Requires mitigation · Requires defence and mitigation · Avoid use

Source: Royal Institute of British Architects, RIBA

In Changsha city, the current regulations and strategies for land use management and planning are general provision that were adopted for flood zoning, and many issues related without any definite and specific explanations. Flood risk mapping can serve as scientific basis for rational land use planning. In addition, by using the experiences of developed countries (e.g. flood zoning), Changsha city can improve the overall efficiency of land use and coordinate the conflict between comprehensive planning and land use planning, e.g. developing a set of guidelines and criteria responding to climate change and urban flood combined with the local situation. Under those guidelines, FRM may achieve better implementation.

CHAPTER 5: RESULTS AND DISCUSSION: CASE STUDY II

5.1 Data preprocessing and importing

5.1.1 Revising of terrain data

In order to assess damages and risk at the micro level, both availability and detail level of data required to be improved. A surface runoff model based on cellular automata was proposed for inundation simulation. Studies have denoted that terrain data can greatly affect the performance of hydrological models (Guo-an et al., 2001; Zhang et al., 2009; Vaze et al., 2010). Unlike Digital Surface Model (DSM) data, DEM data lacks details information and some flat areas cannot reflect the real shape of the surface. Hence, the raw DEM data requires being corrected properly. The interpolation method is firstly used to improve the detailed topographic change of raw DEM data. Moreover, Quan (2014) proposed a city terrain model, which revises the elevation according to types of buildings:

$$R_{ij} = H_{ij} + A * B_{ij} * P_{ij} \,, (i = 1, \dots, n; j = 1 \dots, m)$$

Where; i, j are numbers of row and column, A is a constant for elevating buildings according to the maximum probable inundation depth, H_{ij} is the original elevation of cell, B_{ij} is the binary code to describe where the cell belongs to buildings or not. P_{ij} is the revising factor according to China's General Principles of Civil Building Design (GB 50352-2005), and R_{ij} refers to the revised elevation.

Table 5-1: Revising factors of different types of building

Types of buildings	Revising factor R_{ij}
Administration, Business, and Manufacture	0.5
Warehouse	0.6
New-style residence	0.33
Old-style residence	0.3
Villas	0.2

Building information was crawled from Tianditu, an open web map service platform, and extracted by supervised classification. Based on the city terrain model, DEM was revised and detailed surface topographic features were added, improving the data precision significantly. The comparison between the raw terrain data and the revised one are shown in Figure 5-1. The interpolation method and the city terrain model have dramatically increased the detail of terrain surface. By revising, nonlinear waves caused by artificial constructions can be covered and make the flood spreading closer to the reality.

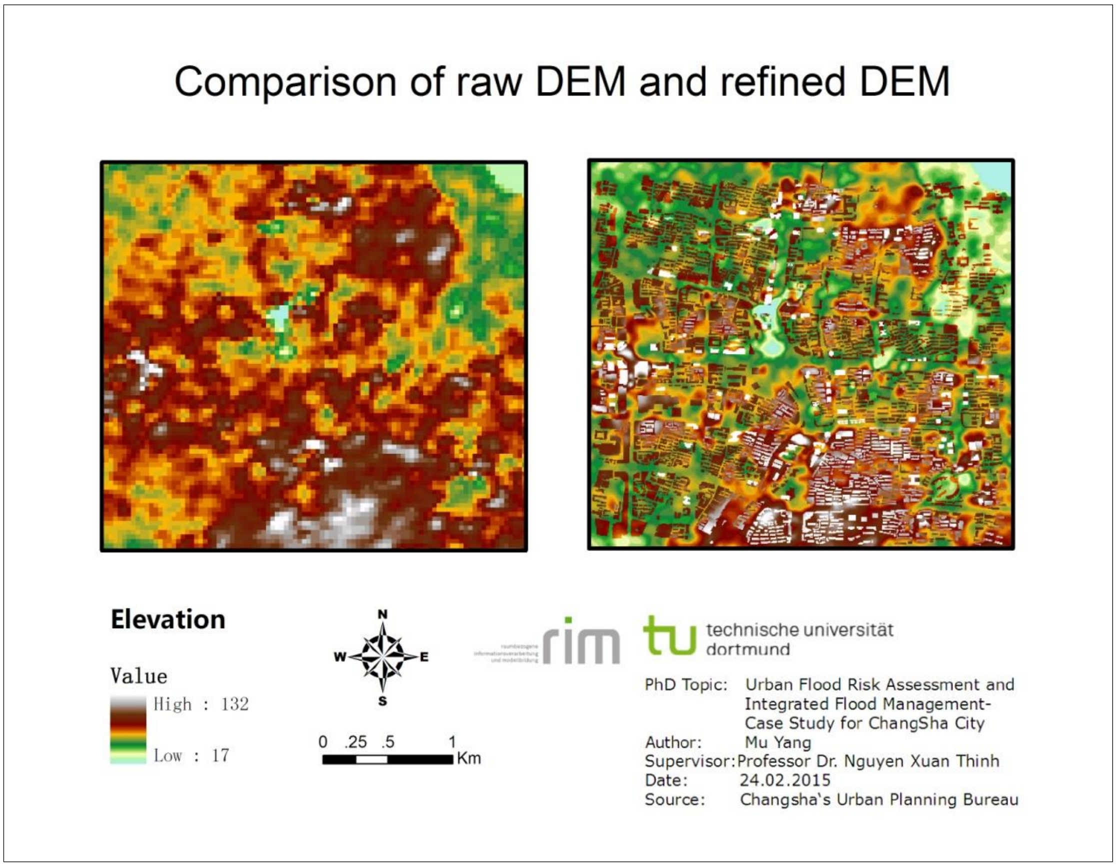


Figure 5-1: Comparison of raw and refined terrain data

5.1.2 Designing of storm

The precipitation volume was set according to the formula of Changsha's storm design.

$$q = \frac{1141.9(1 + 0.54 \log T)}{(t + 8.277)^{0.5127}}$$

Where *T* is the designed return period (in year) and *t* is the duration (in minute) of the storm. The scenario of inundation simulation was a 10-year storm of

Changsha. A three-hour of 10-year return period storm was used, namely *T=10* and *t=180*.

The rainfall intensity was distributed according to Chicago design storm (Keifer & Chu, 1957). The time to peak intensity is 55th minute. Figure 5-2 shows the time distribution of the rainfall.

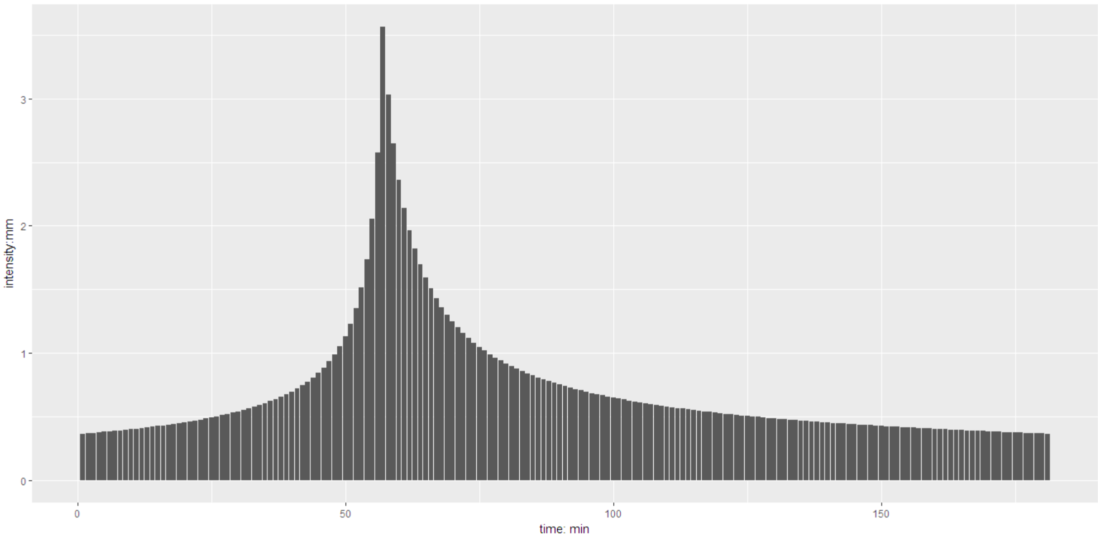


Figure 5-2: Time distribution of rainfall of Chicago storm (10-year, 3-hour)

5.1.3 Generating of transport data

Spatial data include roads network, buildings and points of interest (POI). Roads network within the investigation area was extracted from the Open Street Map (OSM) and improved in JOSM[11] where attributes of roads were added. Then it was converted into shapefile. Buildings information, POIs and bus lines and stops were crawled from Tianditu through some programming with JavaScript API. Then the data were projected and utilized in the simulation.

The traffic flow took both spatial and temporal distributions into consideration. Spatially, transport was assigned according to traffic flow, traffic speed as well as the length of road segments. Parameters cover the number of inhabitants and households, limited ages of youth and senior, the rate of unemployment, the probability for an adult to own an automobile, maximum distance one would go by foot and the numbers of inhabitants coming inside and working outside of city or districts. Temporally, the time distribution of traffic flow is evaluated based on survey data of 2007~2012. It was assumed that the traffic flow

[11] JOSM is an extensible editor for Open Street Map (OSM)

increases with no change in distribution. The corresponding routes were generated according to trips information. As the part of the CBD, the temporal distribution of traffic flows of most road segments does not fluctuate distinctly during 17:00~19:00. There was only a slight change in two roads (Bayi road and Shaoshan road). Hence, the traffic flows were simply considered unchanged to generate trips.

Details information of used data in the simulation is shown in Table 5-2:

Table 5-2: Dataset used in agent-based modeling and simulation

Data	Source	Description
Terrain	GDEM, revised with city terrain model	Interpolated & revised raster
Precipitation	Storm design, Changsha Water Bureau	formula, Text, 10-year
Land use	Changsha urban planning bureau	The year of 2013, vector
Building	Changsha urban planning bureau, Tianditu.com	With layers' information, vector
Traffic flow	Statistic traffic flow, Yearbook,	2007~2012, text
Bus system	Tianditu web map service	Lines, stops, interval time
Demography	Yearbook	The year of 2013,2014, text

5.1.4 Using GIS data in NetLogo

Spatial data like terrain, land use and precipitation are necessary inputs for inundation simulation. However, most of current CA and ABMS platforms are limited in expressing geographic phenomena. Geographical Information Systems (GIS) are particularly useful tools for geospatial modeling and spatial analysis but not well suited to dynamic modeling (Goodchild & Haining, 2004; Maguire, 2005). There have been a few simulation tools integrated GIS in use already, e.g. Swarm, Repast, MASON and NetLogo (Minar et al., 1996; Luke et al., 2005; Davila & An, 2010; North et al., 2013). NetLogo is a widely used multi-agent programmable modeling environment (Wilensky, 1999). The programming language that used by the platform is a dialect of Logo, which is so easy to get going that researchers could concentrate on establishing models rather than writing codes. NetLogo can integrate GIS and ABMS to provide a platform for the dynamic modeling of individuals across space and time. It is possible to import both raster and vector data (in the form of ASCII files and shapefiles) by a powerful built-in GIS extension. The following pseudo codes in Logo style show an example for loading raster data and shapefiles into NetLogo.

```
; import NetLogo GIS extension
extensions [ gis ]
to load-data
  clear-all
  ; set the world's coordinate
  gis:load-coordinate-system (word "./yourpath/projectionFile.prj")
  ; set raste- and shapefile- dataset
  set raster-dataset gis:load-dataset "./yourpath/yourRasterData.asc"
  set shapefile-dataset gis:load-dataset "./yourpath/shapefileFile.shp"
  ; set the world envelope to the union of all of the dataset's envelopes
  gis:set-world-envelope (gis:envelope-union-of
                                  (gis:envelope-of chosen-dataset1)
                                  (gis:envelope-of chosen-dataset2)
                                  …
                         )
```

The inundation simulation was developed based on a distributed hydrological model and Cellular Automata in NetLogo 5. Figure 5-3 and Figure 5-4 show the result of loading geospatial dataset of case study II and the graphic user interface in running simulation in NetLogo 5.

Figure 5-3: The result of loading geospatial dataset of case study II in NetLogo 5

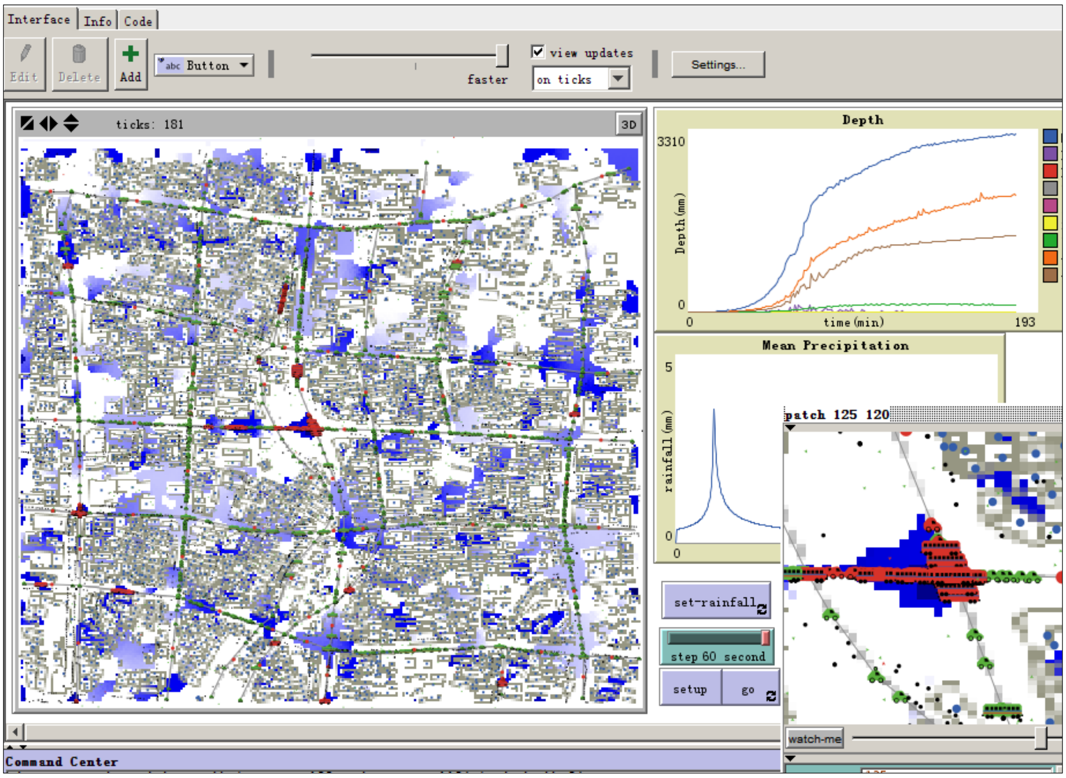


Figure 5-4: Graphic user interface of case study II in NetLogo 5

5.2 Calibration of inundation model

The ratio of cell size and velocity of water flow that calculated according to Manning's equation determine the simulation time interval. For each cell, the ratio was calculated and the minimum value was used as the global time-step in order to keep the stability of water accumulation and traverse among neighboring cells. The interval Δt meets:

$$\Delta t = \frac{l}{\max(v) + \sqrt{g * max(dH)}}$$

Where; l is the size of cells, v is the runoff velocity calculated based on Manning's formula, g is the gravity coefficient and dH is effective water depth.

Calibration of inundation model was undertaken for the June 28th 2011 storm event to calculate parameter and optimize model for this case study. Runoff coefficients and drainage capability are the parameters used in the process of model calibration (Table 5-3). Based on observed discharge curve, 635 simulation runs were generated totally in order to obtain the optimal parameters. Root mean square deviation (*RMSD*) was used to measure the differences between the simulated depths with the observed depth at 1-minute interval:

$$RMSD = \frac{\sqrt{\sum_{i=1}^{n}(d_i^{sim} - d_i^{obs})^2}}{n}$$

Where d_i^{sim} and d_i^{obs} are respectively simulated and observed surface water depth; n is the total number of compared observed value.

Table 5-3: Parameters for model calibration

Parameters	Description	Distribution
Runoff coefficient	Roof, road	[0.85,0.95], Uniform
	Green land, park	[0.10,0.20], Uniform
	Paved surface	[0.55,0.65], Uniform
Drainage rate	Sewer system, pumping out capability	[15,36] mm/h, Uniform

The max inundation depth of three observation spots were used to compare with simulated water depths. The optimal set of parameters with a runoff coefficient value of 0.85 (roof and road), 0.15 (green land and park) and 0.65 (paved surface) and a drainage rate of 18 mm/h produced the lowest *RMSE* value (5.8 cm).

5.3 Dynamic flood risk analysis in baseline scenario

After calibration, the inundation model and traffic model were integrated, so dynamic exposure information can be obtained. To measure the flood damage and risk on the local scale, types of indicators needed to be covered, involving population, vehicles, buildings and road segments. For each indicator, dynamic inundation and exposure information was counted and updated.

5.3.1 Flood risk analysis on buildings

For buildings, dynamic inundation maps were produced. As inundation model runs, water depth was calculated and then exported as raster data. Based on depth-damage functions, risk values for 3061 buildings were calculated. Figure 5-5 shows the dynamic damage rate of building by time in baseline scenario. It is found that inundation area and damage value of buildings change over time and differs in spatial. According to statistics in Table 5-4, buildings within the study area suffer less-severe damage in total. During the whole rainfall process, the maximum damage rate is up to 16.9% and remains at the value after the 150th minute. Buildings with damage rate over 5% accounts for no more than 4% (99 buildings in 180th minute). The number of inundated buildings reached the maximum at 60th minute when the storm peak has just arrived for 5 minutes. However, most of the damage rate is below 5% and the maximum value is only 7.1%. At the 90th minute, after half an hour of the storm peak, through the total affected buildings decreases slightly and fluctuates due to the uncertainty caused by dynamic and rapid changing in particularly shallow inundated depth. As for buildings with damage rate over 5% or 10%, total number grows significantly without this type of instability.

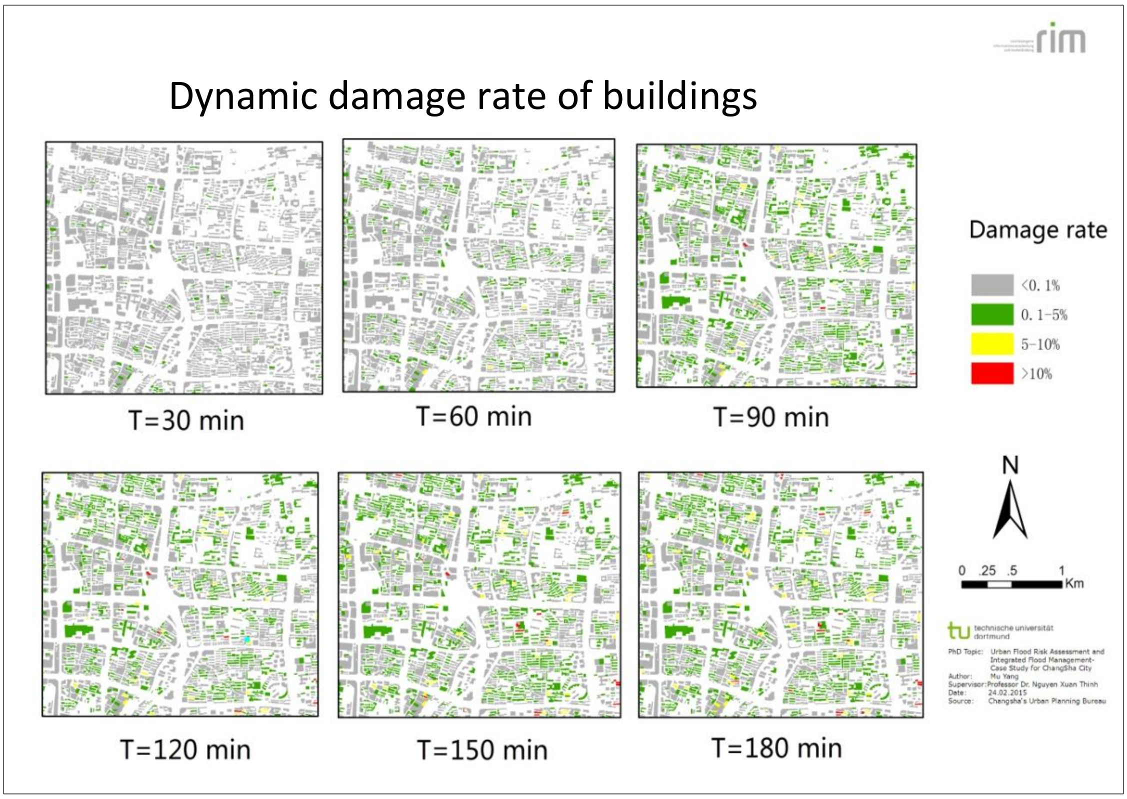


Figure 5-5: Dynamic flood damage maps on buildings in baseline scenario

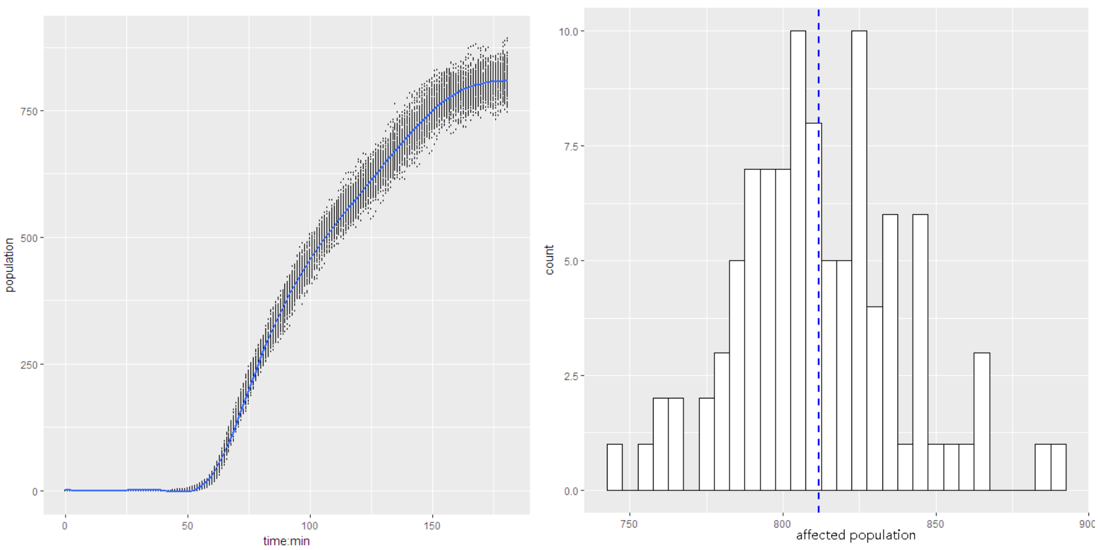
Table 5-4: Dynamic flood damage rate of buildings

Time: min	**30**	**60**	**90**	**120**	**150**	**180**
Inundated building	115	1229	1043	971	1212	1170
Damage rate <5%	115	1224	999	908	1122	1071
Damage rate 5-10%	0	5	40	54	71	77
Damage rate >=10%	0	0	4	9	19	22
Max damage rate	1.4%	7.1%	13.8%	14.3%	16.9%	16.9%

5.3.2 Affected agents

Agents like population and vehicles which are movable presented relatively greater uncertainties in dynamic exposure. Arguably, the affected population can be divided into three components: people without trip that trapped in inundated buildings, people travel on foot as well as people travel by car or bus, which is also closely tied up with the number of affected vehicles. This case focused only on the number of different agents: people that travel by foot, buses and private cars. The total affected population can be further calculated based on the percentage of different means of travel and the so-called occupancy rate of buses.

On the basis of a statistical output of simulation, in baseline scenario, affected population shows complex changes as rainfall progressed. Population of varying four degrees of security (safe, low risk, medium risk and high risk) was recorded in real time. Figure 5-6 presents the results summing up based on 101 times simulation, which focuses on statistic until the rain stopped. The threshold of water depth in the statistic results is 300 mm. Affected population denotes the total number of people located in areas where inundated depth of water > 300 mm. The left figure records the accumulated affected population dynamically. As shown in the figure, the number starts a sharp increase from 60th minute when the storm peak reaches. After the 150th minute, the accumulation tends to steady and finally reaches the maximum until the rain stop. The right one shows the frequency distribution of final total affect population.



* The left figure records the accumulated affected population dynamically; the right one shows the frequency distribution of final total affected population; the blue vertical dotted line marks the mean number of affected people.

Figure 5-6: Statistic results of affected population

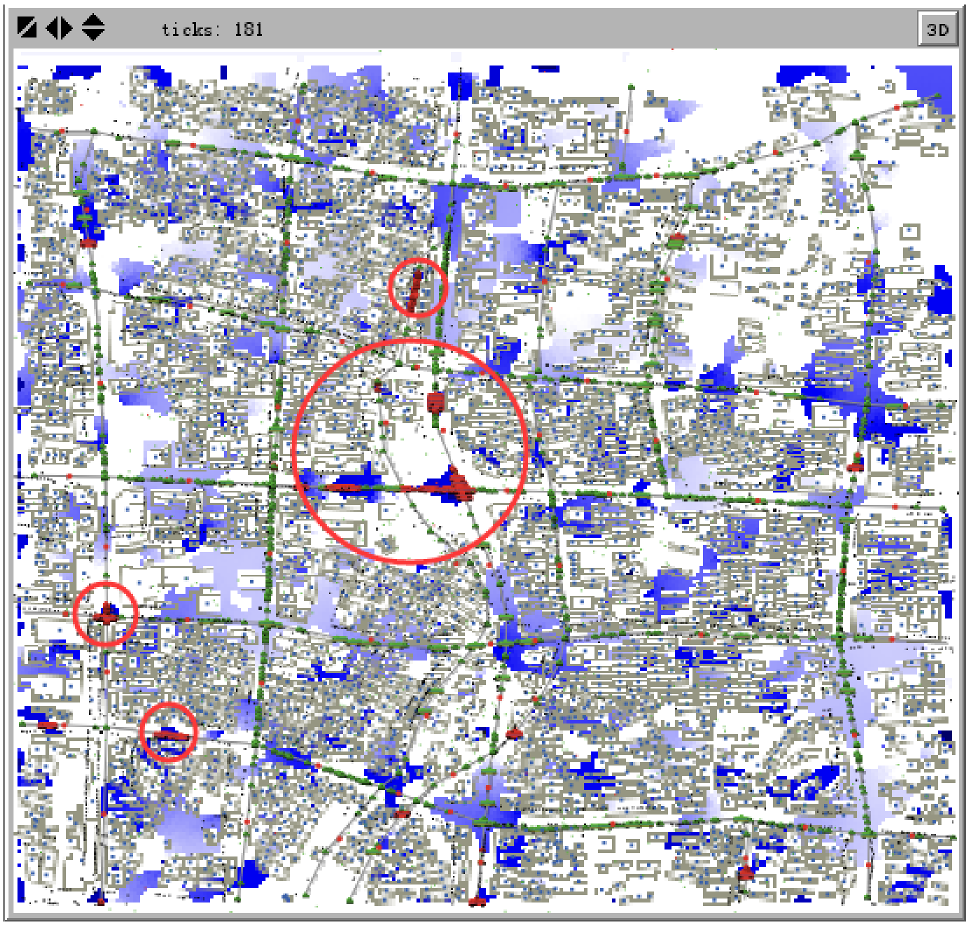


Figure 5-7: Major inundated road segments and crossing according to simulation

As some road segments inundated (Figure 5-7), traffic condition become influenced dramatically. For affected vehicles, they were summed up according to both types of vehicle (private cars or buses) and the extent of effects (trapped in water directly or trip interrupted indirectly). Figure 5-8 shows the statistic of total number of affected private cars and buses and the frequency distribution of simulation results. Affected vehicles start to increase at the 43rd minute, 12 minutes before the storm peak arrives. At the beginning, the number of indirectly affected cars showed the fastest growth and then the speed slows down and show almost linear growth steadily. The number of directly affected cars begins to increase slightly later but then grows fast and stably all the time. The numbers of directly and indirectly affected buses both keep growing as well. Figure 5-9 show the statistic of total number of affected private cars and buses. The bar charts denote the frequency of each simulation. Taking the indirectly affected bus as an example, the total number of indirectly affected bus ranges from 308 to 360 with the average being about 332.

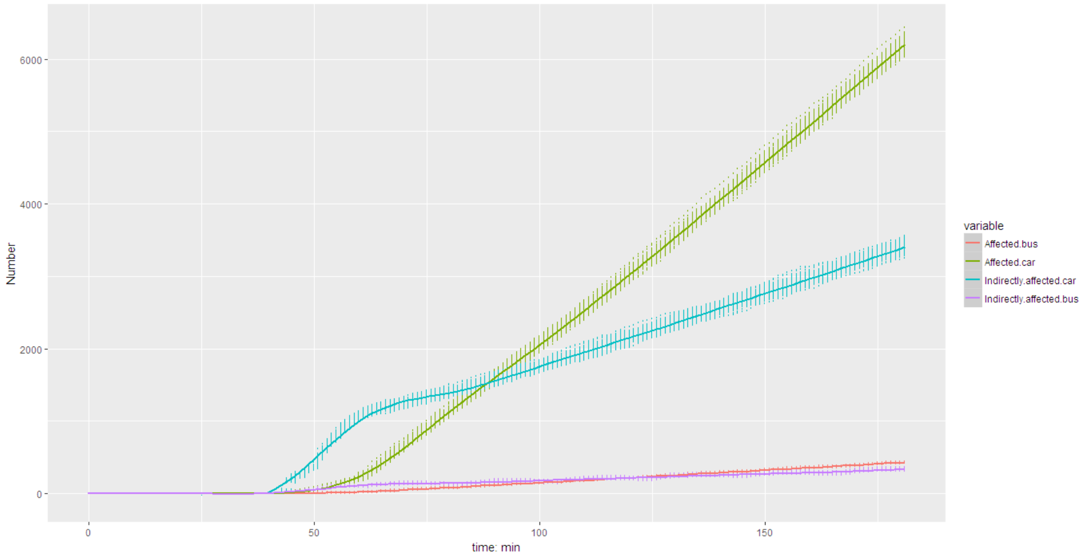
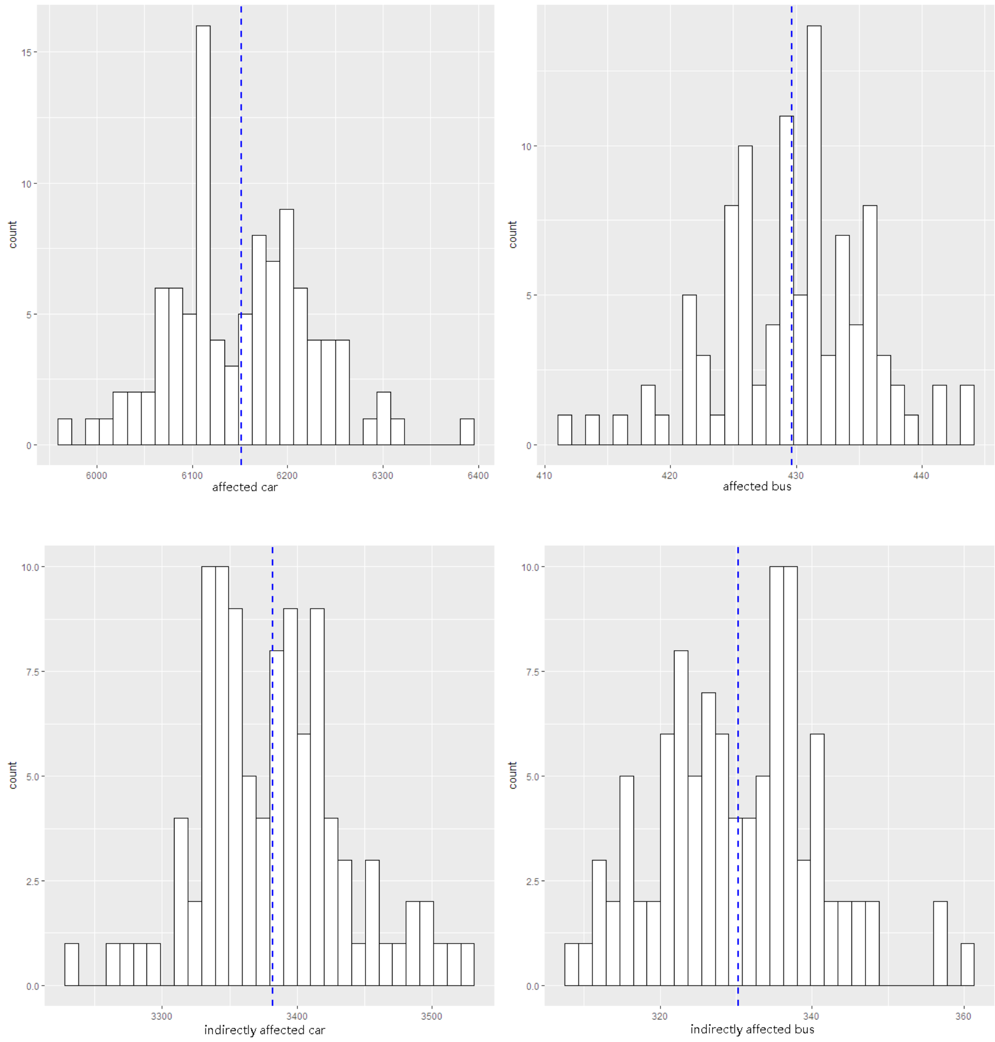


Figure 5-8: Accumulated affected private cars and buses



*The threshold of water depth in the statistic results is 300mm. Affected car and bus denote vehicles located in areas where inundated depth of water > 300mm; indirectly affected car and bus mean vehicles are not inundated or located areas where water depth below 300mm, but their trips are disrupted or changed. The results are summed up based on 101 times simulation.

Figure 5-9: Statistic of total number of affected private cars and buses

5.4 Comparison of flood risk adaptive strategies

5.4.1 Benefit of municipal engineering strategies

The statistic results showed that the number directly or indirectly affected vehicles (cars and buses) as well as people, decrease with the improving drainage capability and surface permeability. Take the directly affected cars and population as examples (Figure 5-10), the total number reduces from 6150 and 810 to 4300 and 110 respectively when the drainage capability reaches 36 mm/h and the surface permeability in waterlogging areas with corresponding runoff coefficient at 0.35. The trend surfaces based on linear regression can intuitively outline how much per unit improvement in drainage capability or surface permeability, which could reduce the loss of elements correspondingly. According to the calibration, the drainage capability was only 18 mm/h, half of the theoretical value. According to this simulation result, if the drainage can be take the maximum advantage of its capability (such as regular cleaning and maintenance), it can play great roles in damage mitigation by relatively low cost.

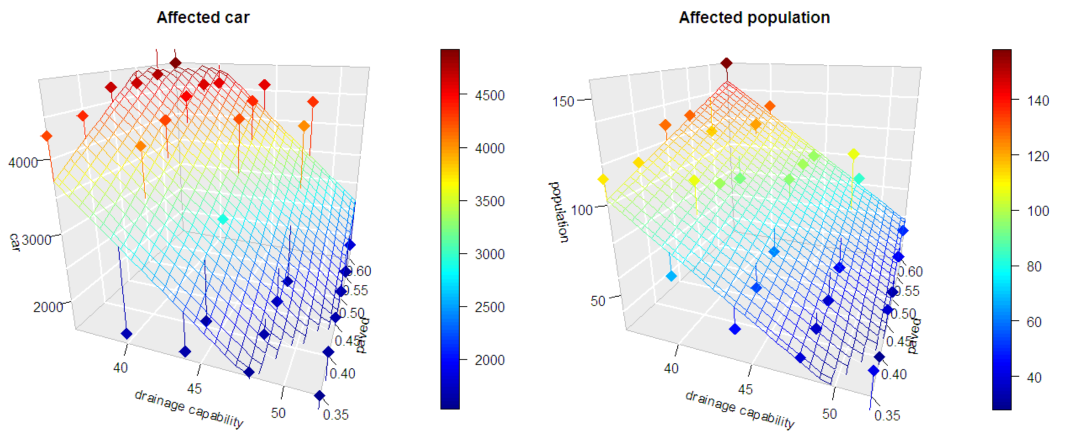
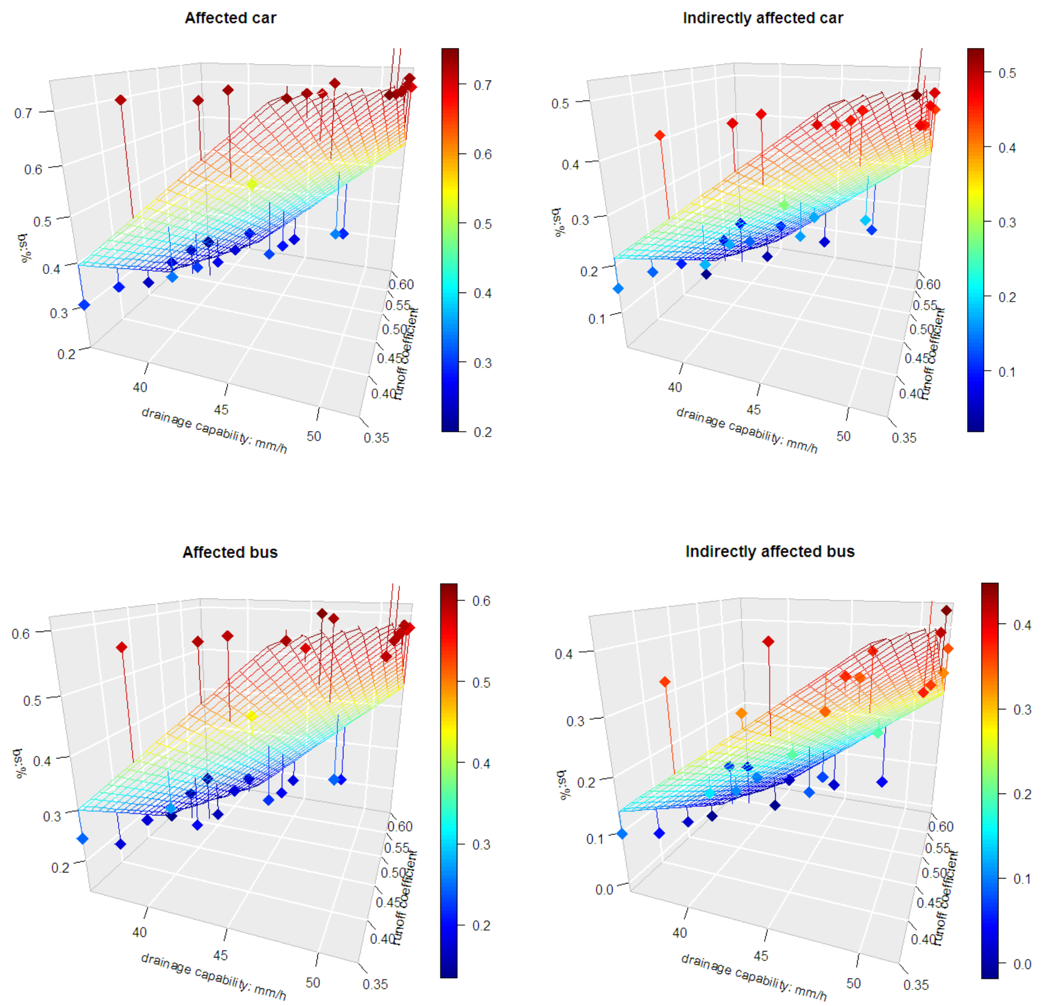
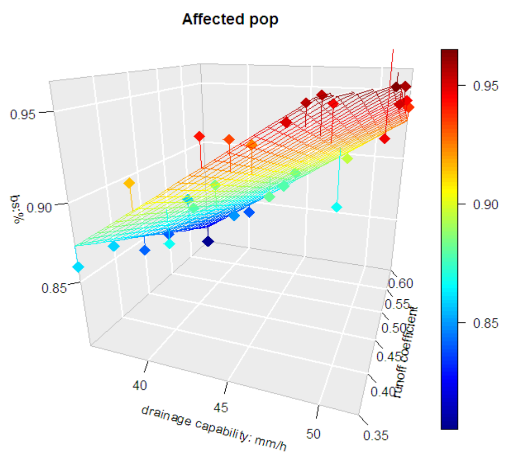


Figure 5-10: Loss reduction in various combination of engineering adaption

By comparing with baseline scenario, the relative damage reduction can be calculated. Based on the risk-based method, the relative benefit b_s were calculated to measure the effectiveness of various combination of engineering adaptive strategies. Figure 5-11 presents a visualization of benefit percentages for different types of agents in scenario I. The results show that people traveling by foot benefit most from municipal engineering. If the drainage capability was improved to 5 years, it could further reduce about 10%~30% loss compared to current condition of municipal engineering.





*The threshold of water depth in the statistic results is 300mm. Affected car, bus and people denote vehicles or persons located in areas where inundated depth of water > 300mm; indirectly affected car and bus mean vehicles are not inundated or located areas where water depth below 300mm, but their trips are disrupted or changed. The results are summed up based on 30*10=300 times simulation.

Figure 5-11: Benefit rate of municipal engineering strategies by improving drainage capability and paved surface permeability

5.4.2 Benefit of risk warning with various public risk awareness

The results show that early warning exerts no significant positive effect for damage reduction. However, as public risk awareness increase, agents can more likely to receive the risk information successfully. Statistical output showed that the number of affected pedestrian will decrease as they have higher awareness about risk. The maximum benefit percentage can achieve almost 78%, with affected population decrease from 810 to 180 (Figure 5-12).

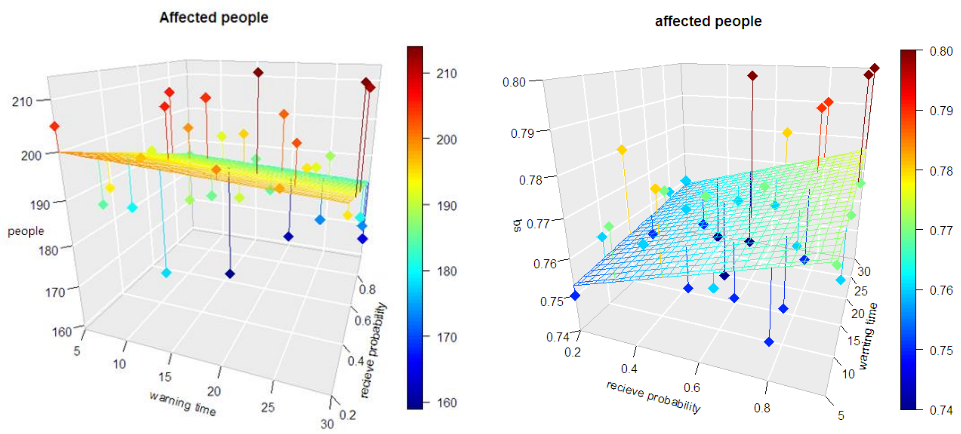


Figure 5-12: Reduction of affected people considering risk warning and risk awareness

According to statistics of vehicles, the reduction seems slight. Take affected car as example, the benefit percentage ranges between 0.5%~1.5%. Also, the benefit percentage values show greatly uncertainty and there is no sensible difference as parameters (receive possibility and waiting time) change, which are all shown as surfaces with small gradients (Figure 5-13). Here offered three reasons explaining why the effectiveness of warning has no dramatic benefit. Firstly, large of local area are inundated, especially on road segments. So, vehicles cannot move freely like pedestrians. Hence, the travel mode constrains more possible choice to avoid waterlogging areas. Secondly, the total number of simulation was not large enough to describe closely to real world. Results were summed up based on only 101 times simulation. Besides, simulation was conducted in a relative local area. Thus, the warning time still could be relatively longer compared with the spatial scale.

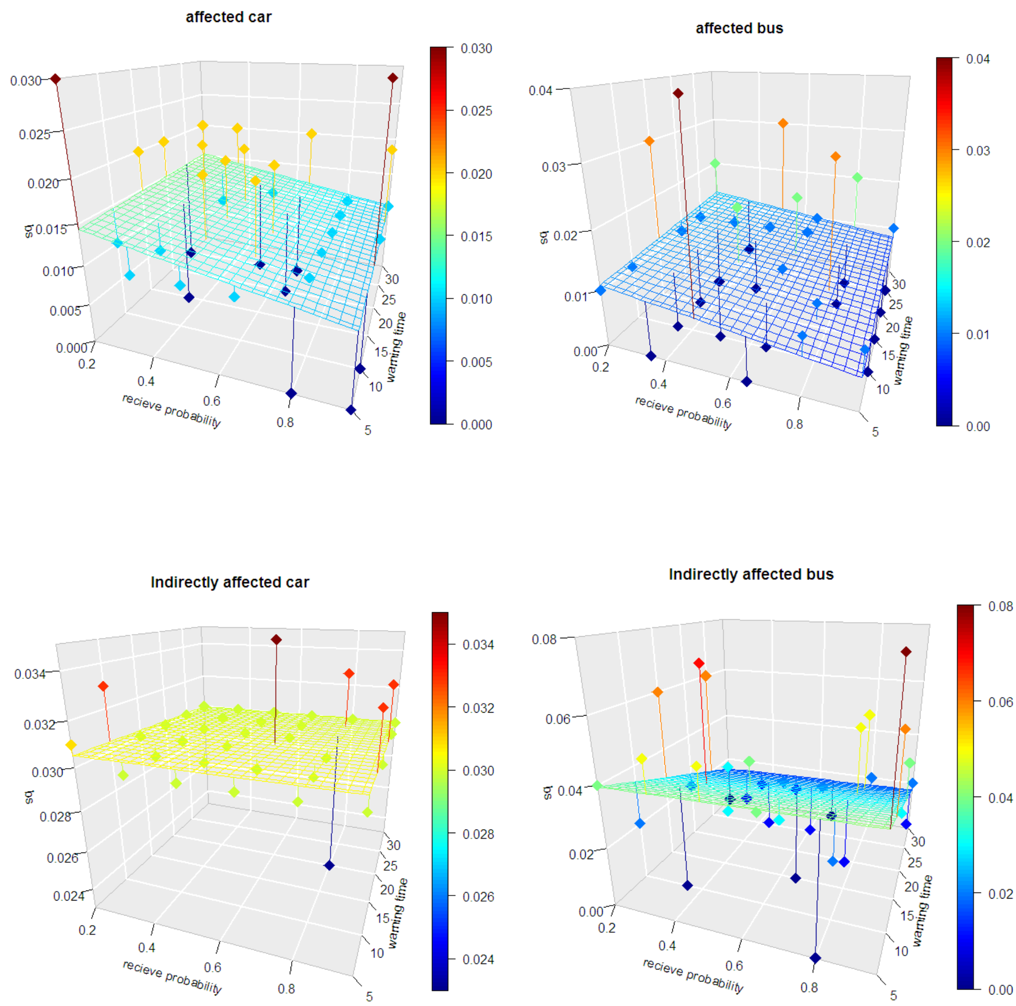


Figure 5-13: Benefit rate of risk warning and improving risk awareness

5.4.3 Scenarios comparison

Table 5-5 shows a short summary about the two considered adaptive strategies for the two scenarios. The first scenario adopted engineering measures by improving capability of drainage system and the surface permeability of waterlogging areas are the most effective means for damage mitigation. The simulation results denote that the benefit percentages of private car and bus (directly or indirectly) are medium or medium to high. The corresponding cost is also relatively moderate. The second scenario considers risk warning. Though the cost is low to moderate, all the benefit percentages are quite low except for pedestrian. By contrast, pedestrian can obtain the maximum benefit from both the strategies. Though, vehicles seem obtain no significant benefits from the second policy. Principally, high public risk awareness has great potential benefits of the in emergency event, which can greatly enhance the effectiveness of the official warning. Consequently, FRM should pay more attention to flood risk communication so as to improve public awareness and participant, which itself is a process of risk education, achieving a long-term profit.

Table 5-5: Benefit and Cost of Scenario I and II

Scenario	**Intervention**	**Benefit**		**Cost**
I	Engineering measures	Pedestrian	High (0.86~0.96)	Moderate
		Private car (directly)	Medium to high (0.40~0.70)	
		Private car (indirectly)	Medium (0.22~-0.48)	
		Bus (directly)	Medium (0.30~-0.57)	
		Bus (indirectly)	Medium (0.14~0.41)	
II	Risk warning	Pedestrian	High (0.75~0.78)	Low to Moderate
		Private car (directly)	Low (0.005~0.015)	
		Private car (indirectly)	Low (0.030~0.032)	
		Bus (directly)	Low (0.005~0.014)	
		Bus (indirectly)	Low (0.018~0.040)	

CHAPTER 6: CONCLUSIONS

The previous five chapters elaborate FRM based on flood simulation with two case studies. It firstly proposed a general framework of FRM with extensive applicability, which integrates varying methods and tools, e.g. hydraulic modeling, cellular automaton, agent-based modeling, multi-criteria analysis, uncertainty analysis and sensitivity analysis as well as geospatial processing and modeling with GIS tools. Then, based on the methods and tools, results and discussion are denoted. The research has investigated two case studies with different concerns and offers different solutions for flood risk analysis and assessment as well as risk adaptive strategies.

From the perspective of the first case study (fluvial flooding) at the whole city level, hazard analysis, damage and risk assessment play vital roles in urban construction, providing the theoretical support to the decisions made in overall city plans. In contrast, flood risk analysis and assessment at a local scale is associated with the city designing and infrastructure construction. The two cases are designed for different aims, corresponding to different scale level of urban organization and management and planning and design. In addition, the second case study focuses more on urban emergency management in waterlogging area caused by sudden storm-caused flood rather than assessing damages of buildings or infrastructures. Due to different types of flood and the relative consequences and different aims, there are various used methods and procedures utilizing different datasets, technologies and software. The comparison of the two case studies can be summarized according to series of factors: flood type and features, spatial scale, applied method, decision support and the corresponding research questions (Table 6-1).

In the following part, the answers to the research questions and the main findings are concluded. And finally, the strengths and limitations as well as further step are proposed.

Table 6-1: Distinctions and relations between Case study 1 and Case study 2

	Case study 1	**Case study 2**
Flood type and features	Fluvial, slow on-set, relative low frequency	Pluvial, rapid on-set, high frequency
Spatial scale	Meso- and Micro- /Central city	Micro- or Local /CBD
Method	MCA-based method Integrated flood risk Weighted adding River hydrodynamic model Network analysis Static exposure	Dynamic risk analysis Different risk factors Statistic method Surface water runoff simulation Agent-based modeling Dynamic exposure
Decision support involved	Master planning & Special planning, Long-term	Emergency planning and management, Public risk awareness
Corresponding research questions	Question 1, Question 2	Question 1, Question 3

- Question 1: How can flood risk assessment be conducted in case of data deficiency?
- Question 2: What is the flood impact on urban infrastructure networks?
- Question 3: How do we manage urban flood risk in consideration of public participation in flood emergency management?

6.1 The answers to the research questions

Along with two case studies, some examples and scenarios analysis were investigated in this Ph.D. research. Multiple approaches were developed and integrated to estimate the flood risk and effectiveness of risk reduction strategies in order to answer three main scientific research questions, which are formulated with regard to data processing and method selection, flood impacts on infrastructure network as well as discussion on adaptive strategies. In the following sections, answers of the research questions in the essence of the developed approaches and methods were answered.

Q1: How can flood risk assessment be conducted in case of data deficiency?

a) How can make full use of open source data?

b) What kind of criteria categories should be covered in risk assessment?

c) What is the spatial uncertainty and sensitivity of the assessment model?

It is crucial to collect sufficient and accurate data for flood risk assessment. Some approaches were adopted to alleviate the restriction of data in both case studies. In section 3.1.1, approaches for data collection and preliminary processing were introduced. Data from various sources were successfully integrated and implement graphical representation and uniform storage, management and access by means of geo-information system. Open source data serves as supplementary information and knowledge through spatial processing and transformation (including web scraping, manual and automatic digitalization, image registration, coordinate transformation etc.), playing important roles in preliminary phase of data preparation and fusion. For example, land use data were calibrated according to the up-to-date information from China's National Geographic Information Public Service platform named Tianditu map service. The bus lines, stops data and local buildings were obtained by web crawling via API of Tianditu as well. Moreover, in section 5.1,

Interpolation method and the city model (DEM depressed with height information of local buildings) have dramatically increased the detail of terrain surface in rainfall-runoff simulation, according with the realistic urban complex surface environment more than the raw data. In addition, data rectifying and fusion by establishing local unified coordinate system ensured the normalization, consistency and validity of data. The method of using open source data by data scraping, transformation, refining and fusion, in Chapter 4 and Chapter 5 presents that it can achieve relatively high precision and great reliability and low costs in carrying out the project. It turns out to be an effectively method to solved the problem of data deficiency.

On the other hand, in order to choose appropriate damage categories and risk assessment model, the two cases have taken into account comprehensive factors involving the objective of project, features of flooding, economic feasibility and current available resources. In section 1.2, after expressing the research objectives and questions, it defined the basic principle and guidance for case studies. Fluvial flood bears on drainage density and river discharge.

Thus, the basin should generally be considered as a whole. Moreover, fluvial flood is usually caused by natural factors like storm or melting snow, so, river water level rose dramatically, bringing about great economic loss and widespread social influence on floodplains. Fluvial flood risk assessment plays an important role in land-use planning and specialized planning, which need to make decisions in long-term strategic perspective and holistic approaches. Hence, it focused at relatively large scales (macro- or meso- scale) rather than micro level, thereby obtaining an integrated and systematic analysis. Urban water accumulation caused by sudden storms and the water-logging which are heavily frequently concentrated in certain local areas of the city, interfering with the people's normal daily life, and causing property and people loss. Thus, pluvial flood with high-density and rapid on-set hazardous features requires more detailed information and focusing on the instantaneity and interactivity. The agent-based modeling and simulation method has demonstrated its utilities and great potentiality in the second case study. Based on existing available data and resource as well as reasonable and scientific hypothesis, micro-level individual-based simulation method recompenses the incompleteness of data. The low-cost social experiments with different scenarios can produce a large number of outputs for studies on human social behaviors, supporting for the decision-making process and emergency management. It has also demonstrated that the available data have great influence on selection of hazard model and damage model, which further dominates what kinds of risk model and criteria categories should be covered in risk assessment. In Chapter 3, section 3.1.2 specified the selection of method through four aspects: spatial scales, hydrodynamic models, determining of considered damage categories and method for risk calculation. The detailed risk models and assessment procedures introduced in section 3.2 and 3.3 were then adopted in two cases, In Chapter 4, the standardized integrate risk value based on MCA approach covering multi-dimensions, especially considering the infrastructure network as an independent risk dimension, provides more comprehensive understanding of flood risk rather than partially in economic risk. Varying scenarios analysis shows great uncertainty and sensitivity of weight. In Chapter 5, case study II adopted an individual-oriented method to calculate the damage. The results were represented with a group of statistical bar charts and risk maps separately. The inundated building and directly or indirectly affected agents (pedestrian, private car, bus) were also denoted dynamically, which seems to be a potential way for risk monitoring and prediction.

For uncertainty analysis, the statistical simulation method was used to extract the uncertainty features of input parameters. In river flooding risk assessment, the uncertainty analysis and sensitivity analysis focused on damage model. Spatial global method based on Monte Carlo simulation provided efficient capability to measure the uncertainty and sensitivity of multiple input parameters. In section 4.3, the results of uncertainty were represented in terms of Sobol's indices and maps. Various input parameters show different degrees of effects in uncertainty and sensitivity. It is implied that inundation depth is one of the most prominent of all in terms of uncertain factors in each damage model. It shows demography data has significant first-order effect in social damage assessment. Uncertainty and sensitivity mapping further provided intuitive spatial expression to help absorb and understand sources and extent of uncertainty. The distinctions were also reflected in spatial distribution. As for agent-based modeling, the uncertainties mainly generate from the probabilistic initialization of agents and the designed scenarios with random assignment in section 5.3. By performing experiments with models for many times, systematically varies the model's settings and records the results of each model run. The uncertainties were summed up and described in terms of probability distributions. Relying on uncertainty and sensitivity analysis, by means of mapping or statistical graphics, flood risk can be more comprehensively and intimately understood.

Q2: What is the flood impact on urban infrastructure networks?

a) What is the topological characteristic of urban infrastructure networks and why it is important to flood impact?

b) How can the flood damage to infrastructure networks be evaluated?

c) Is the indirect flood impact on urban infrastructure networks too trivial thus can be neglected?

Due to the locality of the investigated area of the second case study, network features became insignificant on the micro scale. The damage and risk were evaluated individually. Consequently, this question was mainly addressed in the first case study. In order to assess the impact of flooding on urban infrastructural system, this dissertation in section 3.2.2 introduced a new infrastructure risk model coupling hazard model, macro-traffic model and network analysis to measure the loss of infrastructure and adopted it in damage calculation of road network. As the coupled property of urban system, the first case study considered the transport system as a risk separate dimension.

Based on graph theory, the network features of transport system were described by basic network performance parameters. The related performance parameters were calculated on both simple topological structure and as networks weighted with travel distance and time. Results demonstrated that the topological characteristics of urban infrastructure networks can change greatly and thereby impacting deeper on the physical characteristics and even further on the service level. The time-weighted networks reflected realistic condition of traffic network very well (See section 4.2.4). The new infrastructure risk model that based weighted network showed its great potential to identify the most critical and vulnerable road segments and provided an efficient approach to measure not only the direct and tangible damage on road segments and traffic volumes, but also to describe the degree of indirect and intangible damage caused by traffic disruption, with reference to increasing travel time and decreasing accessibility of urban space.

Furthermore, the results of quantitative analysis denoted that outside of flood-prone areas could suffer from severe loss due to the system's entirety and nonlinearity. Local disruption of crucial roads may significantly reduce the service level and the efficiency of the whole system. The network analysis method is not limited to describing transport system. For urban system with significant network features, such as power transmission system, water supply system, drainage system etc., it also provides a potential vision for flood risk analysis and assessment. The network analysis may also further supply helps for improving the construction of the infrastructure such as transportation, electricity and telecommunications to respond to flood risk.

Q3: How do we manage urban flood risk in consideration of public participation in flood emergency management?

a) What are individual roles in flood risk reduction?

b) What is the effectiveness of measures and are instruments with public participation for flood risk reduction feasible and in practice?

In the first case study, citizens are categorized into different groups according ages and their vulnerability to physical characteristics of flood (depth and velocity). Individual heterogeneity was neglected in flood risk assessment with long-term orientation on a meso spatial scale. However, in the real world, citizens are not only the receptors of flood risk but rather the actively responder. In the second case study, a systematic framework was developed for the adaptive strategy in emergency flood situation through integrating inundation simulation with an agent-based model of human activities, which is introduced in section 3.3. The framework provides effective tools for utility-probability in studies of mitigation strategies covering the individual social behavior. In section 5.4, the result of scenarios comparison presents that engineering measures including improving capability of drainage system and the surface permeability of waterlogging areas, are still the most effective ways to reduce inundation and flood loss. Compared to vehicles, pedestrians can obtain the much more benefit from the strategies.

Besides, high public risk awareness shows great potential benefits in emergency event, which can greatly enhance the effectiveness of the up-bottom warning approach. In practice, timely prediction and emergency management in urban floods continue to be a major challenge (Yamada et al., 2011). Thus, FRM for pluvial flooding should focus more non-structural measures in emergency planning and management, such as improved flood proofing, flood forecasting, warning, risk communication and insurance as well as public participation are advocated (Bradford et al., 2012). Therefore, flood risk communication should pay more attention to FRM. The people-centered approach is mainly based on high public awareness and participant, which itself is a process of risk education. Effective risk communication, which in turn, encouraging increasing citizens participate in risk management and further training risk communication principles, driving a virtuous cycle that pushes the whole flood risk communication and emergency planning and management into making a long-term profit.

6.2 Strengths and limitations

6.2.1 Strengths

To start with, this Ph.D. research has provided good cases in the field of flood risk analysis and assessment. In many cities of China, flood control planning and risk assessment have not been given enough attention. Hazard and risk mapping were given no priorities in land use plans and still far from being integrated in FRM studies. Study in depth-damage functions and flood hazard and risk mapping nationwide just started from the year 2014. The establishment of regarding database for flood risk systems is still in the process. Few cases were adopted systematical, scientific and specific procedures for flood risk analysis and assessment. This study has also utilized the most of open source data and web map resources to fill shortages of data deficiencies. By preprocessing, digitalized, transformation and revision, these data were integrated with current data effectively, achieving a good unification. also, this study has initially built a database of FRM for Changsha City, offering a good reference for further following and development works.

Then, this Ph.D. research has introduced and adopted some innovative tools in flood risk assessment. The method of network analysis for damage assessment for urban transport system, presented great potential in risk analysis and damage assessment for those infrastructure systems with network characteristics. Though graph theory and methods of complex network are not new arguments and have widely used in studies of urban issues, they were seldom mentioned in flood damage assessment. Parameters of network characteristics are successfully describing the internal nonlinear interactions among system. By network analysis, traditional boundary between direct and indirect damage turns to be blurred due to the systematic view that considers the system as a whole. The perspective of network is characterized not only by topology relationships but also describes the correlations between components of system. For example, a travel-time weighted transport network well depicted the urban spatial structure and accessibility. Compared to other risk dimensions, the damage assessment of infrastructure network has high uniformity and multi-scale potential. This study has also adopted a spatial and global method for uncertainty analysis and sensitivity analysis (UA/SA) to the final validation of risk assessment models. Sobol' indices were represented with maps and statistical graphics enable both decision-makers and flood receptors to gain a deeper and more comprehensive knowledge of flood risk. By spatial and global UA/SA method, flood risk can be understood and communicated more accurately and effectively.

Finally, this Ph.D. research has also provided an integrated framework for dynamic risk analysis based on agent-based modeling and simulation. The framework was then verified by a case study in local area (pluvial flood). Agent-Based Modeling method provides a novel insight into in study of emergency management in sudden pluvial flooding. It realized a dynamic risk calculation and risk mapping almost in real time. By scenario analysis, it is convenient to evaluate the effectiveness different risk reduction interventions repeatable with less expense in both time and economy.

6.2.2 Limitations

Although the research has achieved its aims, there were some unavoidable limitations. First, because of the data limitation, the research was conducted only with relative low accuracy in hydrological simulation. In network analysis, some detail parameters of urban networks, such as the length and the voltage of power lines were ignored. For transportation simulation, the traffic flow was not up-to-date statistical data but a regenerated estimated condition. Second, still some scholars argue that MCA is, to some degree, a controversial approach, even though it has been widely adopted in flood risk assessment in many case studies. Actually, in terms of subjectivity can unavoidable be found in the conducted assessment. In addition, the framework of the agent-based modeling for risk comparison of risk reduction strategies is low coupling. Although such framework could be more flexible in study, it may usability in some degree is reduced due to the non-uniform of the approach. Flood risk assessment refers to a number of inputs information with high uncertainty. Simulation method has its limitation and could be a supplement for FRM rather than taking place of laborious practical work.

6.3 Future research

Further steps in the future could focus on issues of urban flood simulation and dynamic flood risk assessment. Firstly, more detailed data could be used to improve the accuracy of the model and as well as the calibration of the model. More urban sub-systems can be covered in the network analysis. Based on an Augmented Reality sand table that integrates with agent-based modeling may realize a 3D inundation simulation and in real-time visualization. Especially, LiDAR data might be used to building 3D terrain model for investigation area.Current computer performance and algorithm combining with massive data provides a brightly future and more possibility for simulation closely to real world. Hence, it is possible that the follow-up research could focus on human being’s social behavior simulation with detailed information and big data. Besides, a WebGIS of FRM will be developed as well. By these technical approaches for intuitive simulation, the public perception of flood need to be improved, which will benefit for providing the public the information and education of flood risk. Besides, real data and empirical analysis could be helpful to evaluate the effect the risk reduction strategies by Agent-Based Modeling, providing decision-making in FRM.

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EIDESSTATTLICHE VERSICHERUNG

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertationsschrift zum Thema

“Urban Flood Simulation and Integrated Flood Risk Management – Case Study in Changsha Central City, China”

selbstständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Quellen entnommen wurden, habe ich als solche gekennzeichnet.

Des Weiteren erkläre ich an Eides statt, dass diese Arbeit weder in gleicher noch in ähnlicher Fassung einer akademischen Prüfung vorgelegt wurde.

Dortmund, 12.05.2017 Mu Yang