Climate Change, Water Risks and Urban Responses in the Pearl River Delta, China

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I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Liang Yang, Hamburg, den 02. Juli 2014

I dedicate this thesis to
my family, my wife, Zhihui, and my daughter, Ruyi
for their constant support and unconditional love.
I love you all dearly.

Abstract

Currently, concerns are increasing that climate change may intensify natural disasters, like droughts, floods and storms which pose risks to human society, especially at the coastal urban area. This thesis studies climate change, water shortage and flood risks as well as human response measures in the highly urbanized Pearl River Delta (PRD) area in South China.

Analysis on climate change in the PRD area is based on existing datasets and model projections, with an integration of literature results. Findings indicate significant climate change in both the past and future of the area, with a trend of increasing mean temperature, fluctuating precipitation, rising sea level and increasing typhoon intensity as well as the frequency of extreme weather events. In particular, the annual mean temperature in the PRD area is likely to rise by around 3℃ and precipitation to increase slightly but with greater fluctuations by 2100, while the sea level is projected to rise with an annual rate of 0.33cm to 1cm in this century.

Climate change is likely to increase rainfall variability, drought intensity and duration, and damages on water-related infrastructure by extreme weather events, which all increasingly threaten the local freshwater availability. The water supply situation is becoming more complicated along with the population growth, economic development and difficulties in response/management. Hence, ensuring sufficient freshwater availability is one of the major water management challenges for all the PRD cities. Taking Hong Kong as a case study, this thesis highlights six interrelated risks within the context of climate change, namely: drought, rainstorm/flood events, sea-level rise, water pollution, social management and policy gaps. It suggests that for a sustainable future, Hong Kong needs to invest in improving water self-sufficiency, diversify water sources and conduct aggressive public awareness to increase individual adaptation to predicted climate change impacts.

Flood implications of climate change trends are pronounced in most of the cities in PRD as well. The frequency and intensity of extreme weather and climate events have assumed significant change, together with continuing development in flood-prone areas, which increase both the scale and degree of urban flood risk. Further estimation was made on the flood risk in the 11 cities of PRD area from both aspects of the probability of a flood occurrence and the vulnerability of the cities. The results suggest that the exposure and sensitivity of Hong Kong, Macao, Shenzhen and Guangzhou are very high because of highly exposed populations and assets located in lowland areas. However, the potential vulnerability and risk is low due to high adaptive capacities in both hard and soft flood-control measures. A novel framework on flood responses is proposed to identify vulnerable links and response strategies in different phases of a flood event. It further suggests that the flood risks can be reduced by developing an integrated climate response strategy, releasing accurate early warning and action guidance, sharing flood related information to the public and applying the advantages of social network analysis.

Further, an agent-based model is developed as an instrument to simulate the process by which individual households optimize benefits through flood response investment and damage control. The model implements a subjective response framework in which households appraise inundation scenarios according to warnings, and decide whether to invest in mitigation measures to reduce potential inundation damages. Households may have variant flood response preferences and activities but they all require investments which are consequently considered as part of the final flood losses. A case study was carried out in the Ng Tung River basin, an urbanized watershed in Northern Hong Kong. First results underline that in-time, accurate and wide-covered flood warning plays a significant role in reducing flood losses. And earlier investments in responding measures are more efficient than late activities. This dynamic agent-based modeling approach finally demonstrates its capacity to analyze the interactions between flood inundation and households responses.

Overall, findings of this study help understand the level of climate change impacts and vulnerability in water domain, which are vital to gauge the cities’ risks and corresponding responses and therefore inform decisions about how best to deal with emerging climate-related water risks like drought and flood.

Zusammenfassung

Es wird zunehmend befürchtet, dass der Klimawandel Naturkatastrophen (wie Dürren oder Stürme) intensivieren könnte. Dies stellt ein Risiko für menschliche Gesellschaften da, insbesondere in urbanen Küstengebieten. Die vorliegende Dissertation beschäftigt sich mit dem Zusammenhang von Klimawandel, Wasserknappheiten und Flutrisiken sowie menschlichen Reaktionen auf diese Veränderungen im stark urbanisierten Perlfluss Delta (PRD) in Südchina.

Eine Analyse auf Basis des existierenden Datensatzes sowie verschiedene Modellprojektionen werden mit der Ergebnissen der ausgewerteten Literatur kombiniert, welche signifikante Klimaveränderungen für das PRD in Vergangenheit und Zukunft diagnostizieren. Der Klimawandel schreitet in dieser Region voran, was sich in höheren Durchschnittstemperaturen, Niederschlagsfluktuationen, einem Anstieg des Meeresspiegels, höherer Taifun-Intensität sowie dem gehäuften Auftreten von Extremwetterereignissen äußert. Insbesondere die Durchschnittstemperatur im PRD wird sich bis 2100 um ca. 3°C erhöhen, während die Niederschläge zwar leicht zunehmen, aber auch stärkere Schwankungen aufweisen werden. Der Meeresspiegel wird in diesem Jahrhundert laut aktueller Prognosen um 0,33 bis 1cm pro Jahr steigen.

Der Klimawandel wird somit wahrscheinlich die Niederschlagsvariabilität, die Intensität und Dauer von Dürren und die Beschädigung der Wasserinfrastruktur durch Extremwetterereignisse beeinflussen. Diese Veränderungen gefährden die lokale Verfügbarkeit von Trinkwasser. Probleme bei der Bereitstellung von Wasser gehen mit Bevölkerungswachstum, ökonomischer Entwicklung und Problemen im Management bzw. bei der Problembearbeitung einher. Die Bereitstellung von Trinkwasser in ausreichenden Mengen ist daher eine der wesentlichen Herausforderungen für das Wassermanagement aller Städte im PRD. Bezogen auf den Fall Hongkong arbeitet die vorliegende Dissertation sechs miteinander verknüpften Risiken im Kontext des Klimawandel heraus: Dürren, Extremniederschläge/Überflutungen, Anstieg der Meeresspiegels, Wasserverschmutzung, soziales Management and lückenhafte politische Regulierung. Um einer nachhaltigen Zukunft entgegenzusteuern muss Hongkong in eine verbesserte Selbstversorgung mit Wasser investieren, seine Wasserquellen diversifizieren und offensive Aufklärungskampagnen durchführen, um die individuelle Anpassung an die prognostizierten Klimawandelfolgen zu erhöhen.

Aktuelle klimatische Trends haben ausgeprägte Implikationen für das Flutrisiko in den meisten Städten des PRD. Die Frequenz und Intensität extremer Wetterereignisse wird sich signifikant verändern. Zusammen mit der kontinuierlichen urbanen Entwicklung in für Überflutungen anfälligen Gebieten steigt somit das Risiko für Überflutungen in städtischen Räumen. Daher wurde eine Abschätzung des Überflutungsrisikos für die 11 Städte im PRD bezüglich der Aspekte

Wahrscheinlichkeit von Überflutungen und Verwundbarkeit der Städte vorgenommen. Die Ergebnisse zeigen, dass die Gefährdung (exposure) und Sensitivität zentraler Städte (Hongkong, Macao, Shenzhen und Guangzhou) auf Grund ihrer stark gefährdeten Bevölkerungen und der Konzentration von Aktiva in tiefliegenden Gebieten besonders hoch ist. Allerdings können die potenzielle Vulnerabilität und das Risiko im Falle ausgeprägter Anpassungskapazitäten (durch harte und weiche Maßnahmen der Flutkontrolle) gering sein. Ein innovativer Rahmen zur Reaktion auf Flutereignisse wird vorgeschlagen, welcher verwundbare Links und Handlungsmaßnahmen in den verschiedenen Phasen eines Flutereignisses identifiziert. Das Flutrisiko kann verhindert werden, wenn integrierte Handlungsstrategien für Klimaveränderungen entwickelt, akkurate Frühwarnungen und Handlungsanweisungen herausgegeben, überflutungsbezogene Informationen mit der Öffentlichkeit geteilt und die Vorteile der sozialen Netzwerkanalyse genutzt werden.

Darüber hinaus wird ein agentenbasiertes Modell entwickelt. Dieses dient der Simulation der Prozesse, durch welche einzelne Haushalte ihre überflutungsbezogenen Handlungs- und Schadenskontrollmaßnahmen optimieren. Das Modell implementiert einen auf subjektive Reaktionen abzielenden theoretischen Rahmen, in welchem Haushalte Flutszenarien auf Grund bestehender Warnungen entwickeln und entscheiden, ob sie in Verhinderungsmaßnahmen investieren, um potenzielle Schäden durch Überflutungen zu reduzieren. Haushalte können verschiedene Präferenzen und Handlungsstrategien bezüglich Überflutungen besitzen, aber sie alle implizieren Investitionen, die daher als Teil der Verluste durch Überflutungen betrachtet werden. Eine Fallstudie wurde im Ng Tung-Becken, einem stark urbanisierten Wassereinzugsgebiet im nördlichen Hongkong, durchgeführt. Erste Ergebnisse zeigen, dass rechtzeitige, genaue und flächendeckende Flutwarnungen eine signifikante Rolle für die Reduzierungen von Verlusten durch Überflutungen spielen. Zudem sind frühzeitige Investitionen in Handlungsmaßnahmen effizienter als erst spät durchgeführte Aktivitäten. Dieser dynamische, auf einem agentenbasierten Modell beruhende Ansatz demonstriert somit seine Kapazität zur Analyse von Überflutungsrisiken und die Effekte der Handlungsmaßnahmen einzelner Haushalte.

Insgesamt verbessern die Ergebnisse dieser Studie unser Verständnis von Klimawandelauswirkungen und Vulnerabilitäten im Wassersektor. Dies ist entscheidend, um das Risiko für Städte und sich daraus ergebende Handlungsmaßnahmen abschätzen, und um informierte Entscheidungen bezüglicher sich abzeichnender klimabezogener Wasserrisiken wie Dürren oder Überflutungen treffen zu können.

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Abbreviations

ABM	Agent-based modeling
Ac	Adaptive capacity
AR4	Fourth Assessment Report (of the IPCC)
ASCII	American Standard Code for Information Interchange
BFRC	Bauhinia Foundation Research Centre
CAS	Chinese Academy of Sciences
CCAP	Center for Clean Air Policy
CEDD	Civil Engineering and Development Department of Hong Kong
CMIP5	Coupled Model Inter-comparison Project Phase 5
CSD	Census and Statistics Department of Hong Kong
DEM	Digital elevation model
DNPC	Hong Kong Delegation of National People's Congress
DSD	Drainage Service Department of Hong Kong
DSWS	Dongjiang-Shenzhen Water Supply project
E	Exposure
ECHAM	European Centre Hamburg Model
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse gases
GIS	Geographical information system
HH	Household
HK$	Hong Kong Dollar
HKO	Hong Kong Observatory
HKSAR	Hong Kong Special Administration Regions
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
MAS	Multi-agent model
MK	Mann-Kendall
MPI-ESM-LR	Max Planck Institute for Meteorology Earth Systems Model run on low resolution
NCAR	National Center for Atmospheric Research Reanalysis
NCEP	National Centers for Environmental Prediction
NGO	Non-governmental organization

NOAA	National Oceanic and Atmospheric Administration
NTR	Ng Tung River
PRD	Pearl River Delta
PRWRC	Pearl River Water Resources Commission
RCP	Representative concentration pathway
RMB	RenMinBi, unit of the Chinese currency
RS	Rainfall scenario
RVD	Rating and Valuation Department of Hong Kong
S	Sensitivity
SBGP	Statistics Bureau of Guangdong Province
SICSS	School of Integrated Climate System Sciences
SRES	Special Report on Emissions Scenarios
TCHK	Tourism Commission of Hong Kong
UH	Unit Hydrograph
UK-DoE	Department of Environment, United Kingdom of Great Britain
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USD / US$	US Dollar
USGCRP	United States Global Change Research Program
V	Vulnerability
WBGU	German Advisory Council on Global Change
WMO	World Meteorological Organization
WSD	Water Supply Department of Hong Kong
WWF	World Wildlife Fund

1 Introduction

1.1 Background

Climate change is one of the greatest environmental, economic and security risks facing the world today (Martens *et al.*, 2009; Scheffran and Battaglini, 2011). Cities, as the concentrated representation of human society development, can hardly avoid the effects of climate change. On one hand, many cities face the crisis in gradual deterioration of the urban living environment, caused by climate-related extreme events, like drought, heat-wave, flood, typhoon and sea-water intrusion (WWF, 2009). On the other hand, great assets accumulate quickly in cities, are exposed directly to climate impacts, and are fragile in the face of climate-related disasters (Sanchez-Rodriguez, 2009). Since disaster risk always exists or is even increasing under climate change, the more the city develops, the more serious the consequences of a catastrophe are. Furthermore, many regions around the world, especially in developing countries, are developing with obvious urbanization and population growth, which further exacerbates the burden on cities and may provoke social instability (Birkmann et al., 2010). Thus, urban areas are among the most vulnerable regions in the context of climate change (IPCC, 2007a; Stern, 2007).

Research shows that developing countries, mostly in Asia, Latin America and Africa, are vulnerable to extremes of climatic variability (Mirzaa, 2003; IPCC, 2012). Due to the lack of the capacity in prevention and resilience, their adaptation to climate change relies on past experiences of dealing with similar risks. Thus, much adaptation effort by farmers, fishers, coastal dwellers and residents of large cities will be autonomous and facilitated by their own social capital and resources (Adger et al., 2003). However, such individual experiences are very limited and unorganized. With a perspective on the climate-related risks in developing countries, the challenge is really serious.

Problems with water become more serious under climate impacts, especially in cities with increasing population in developing countries (Muller, 2007). One of these impacts is the increase in sea level because of the melting of ice on land and thermal expansion of the ocean as it is warmed (Pugh, 2004; Kirshen et al., 2008), which will submerge many coastal cities, erode coasts, salinize freshwater and soil, etc.. According to current research climate change is likely to increase the frequency and magnitude of some extreme weather events and disasters, like heavy precipitation (flood) and long-term drought that both make great pressure on urban drainage and water supply systems (Schreider et al., 2000; Milly et al., 2002; Mirzaa, 2003). As the severity of the impacts of climate extremes depends strongly on the level of vulnerability to these extremes (IPCC, 2012), intensive coastal cities are facing the most serious situation, considering their rapid growing population and wealth.

In short, water resources in cities are under threat as the climate changes, and also as technology, the infrastructure and urban society undergo unprecedented transformations, especially in developing countries (Schellnhuber et al., 2006). Since the planning of comprehensive policies is complex as well as politically difficult, decision makers responsible for the future of cities require the best expert knowledge available (Hunt et al., 2007). Hence, there is urgent need to understand what are the water risks and how the cities would respond in the context of climate change.

The Pearl River Delta has the most concentrated cities, most dense populations, and most developed economy in China. In particular, industrialization and urbanization has accelerated noticeably in this area since the 1980s. This process aggravates climate conditions and produces various effects to the social and natural environment (Duan 2009). Presently, domestic climate security consciousness is still in its infancy in China. Economic development and climate protection are still seen in contradiction. The public is still worried about the economic costs for improving the urban environment, and is lacking awareness of possible future risks (Chan *et al.*, 2010). So far, there has not been an integrated "climate response" strategy that unifies the urban society, environment and water risk. Studies on strengthening urban adaptation and mitigation to climate change impacts are also proposed by more and more scientists and organizations. Research in these special issues will not only contribute to accumulation of human knowledge but also promote urban sustainable development. Thus, it is a good case for exploring the impact links in a climate-water-city system and proposing suitable response strategies.

1.2 Objective and research questions

This thesis studies the consequences of climate change on water resources (both water shortage and flood) in the Pearl River Delta (PRD), a rapid urbanization area at the southeast coast of China. As a foundation, the thesis explores what the climate characteristic of this area is and how it changes, and what the associated consequences on the water system are. In particular, it focuses on how the water supply risks and flood risks are impacted by climate changes, how the resilience of local stakeholders to climate change impacts can be strengthened, and the costs associated with adaptation to water risks, at both city and regional level. To this end, it examines how to integrate climate change adaptation into water supply planning in Hong Kong and how the costs of flood adaptation can be reduced in the PRD area. This synopsis serves to outline the rationale for this research, and to explain the background of addressing the overarching aims of this thesis. Accordingly, the thesis aims to answer, although partly, the four questions below:

- What are the climate change characteristics, trends and associated impacts on the water system of the PRD area?
- What are the water shortage risks in the PRD cities, what responses were carried out, and what responses are still needed?
- How vulnerable to the flood risk are the PRD cities, and for what reasons?
- What are the local dynamics in responding to flood risk, and what are the implications for better adaptation?

The listed questions are all related and each in itself highly complex which adds up to a challenging overall complexity. This thesis organizes the complexities into one research framework (Figure 1-1) and accomplish them using a multitude of research methods at different geographic scales and across disciplinary boundaries.

1.3 Thesis framework

It is necessary to have a good understanding of the climate change in the PRD area, on which to build new and further relevant research activities about its impacts and the urban responses. Therefore, the thesis starts in chapter 2 with an analysis of the climate change trends and impacts on water in the research area, based on climate models and literature review. Since the thesis focuses only on water issues, climate elements that may affect the water resources attract more attention, such as temperature, precipitation, sea level and typhoon. The literature review shows this orientation as well. This builds a basis for the consequent analysis of what the climate impacts (water shortage and flood) would be on the cities.

Water shortage risks are analyzed in chapter 3, with discussion on both region level and city level. Current water supply in the research area are in stress due to uneven distribution of water resources, temporally and spatially, and the rapid growth of water consumption. How climate change will contribute to this situation and how the local communities respond (should do) to this stress are the key focus in this chapter.

The fourth chapter aims to draw a comprehensive picture of the flood risks under the context of climate change in PRD cities. Thus a brief discussion on the flood implications of climate change and a comprehensive analysis on flood risk is given. This discourse enables identification of both the climate impacts which are most likely to trigger a flood occurrence and the vulnerability of the research area to reveal the weak sections in flood responses. Following that, a framework that integrates the flood risk elements with their corresponding pathways and response measures is created and discussed as well.

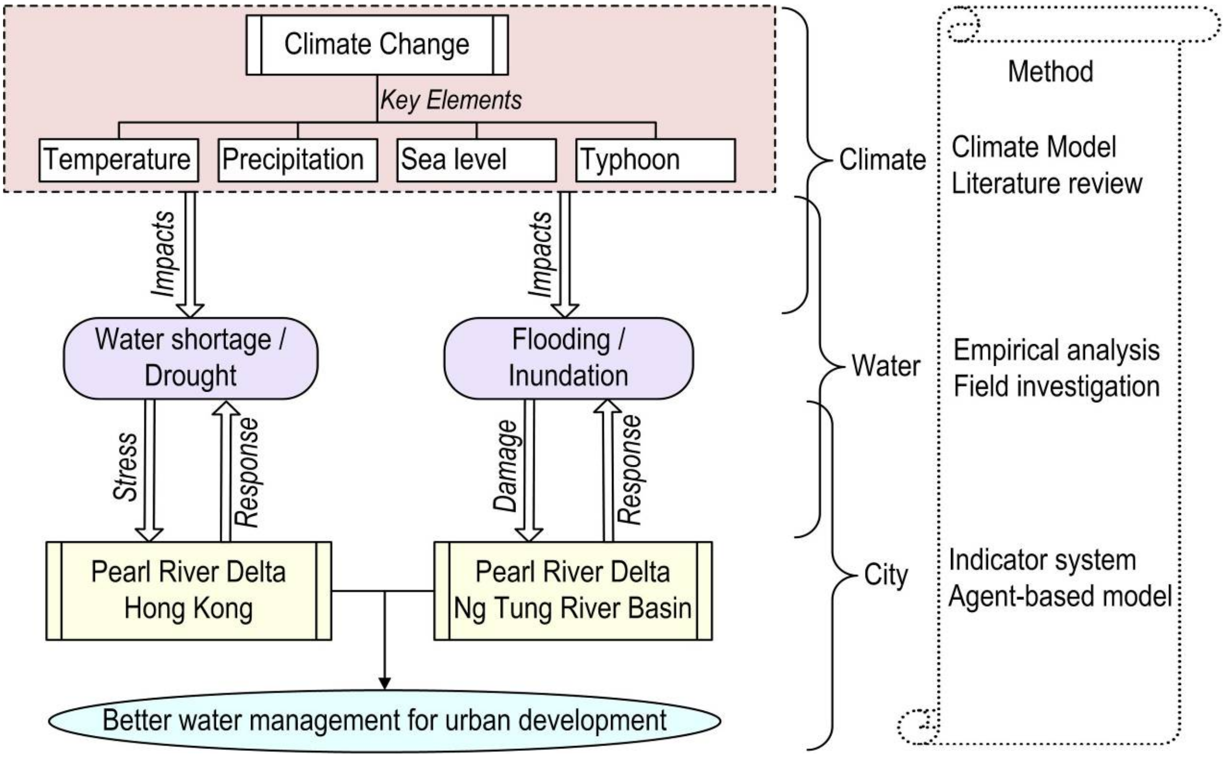

Figure 1-1 Research framework and methods

Chapter 5 then explores in detail how the stakeholders in a city respond to flood threats to reduce their potential flood loss with an agent-based modeling (see section 1.4). The model as an instrument helps to clarify the process by which individual stakeholder agents respond to floods to reduce costs and minimize risks in the framework of an overall flood management system. The model outputs will help improve flood emergency planning, determine the optimal arrangement of response facilities throughout the city and suggest potential preferential measures for flood incident management.

Chapter 6 summarizes the key findings of the previous chapters with respect to the research objective and questions. Conclusions are drawn to inform policy making for better water management and recommend further research.

1.4 Methods and data

The thesis adopts a group of methods to analyze different problems, namely: academic literature review, climate models, field investigation, empirical analysis, indicator system and agent-based simulation. Due to various sub topics addressed in different chapters, these methods are sometimes used in combination.

The whole thesis provides a reference to and review of the academic literature, especially in the 2nd chapter which deals with climate change features in the research area. Future climate change trends in the PRD area are based on own quantitative analysis using the existing models in different scenarios, like the Earth Systems Model run by Max Planck Institute for Meteorology and the semi-empirical approach

(Rahmstorf, 2007) for sea level prediction. The reanalysis dataset of the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) is applied together with the modeling results to draw a long term climate change trend encompassing the past and future. Data used in chapter 2 was mostly derived from the Hong Kong Observatory (HKO), supplemented by data from literature.

The Man-Kendall test (MK-test, Mann, 1945; Kendall, 1975) for trend detection is applied to statistically clarify all the trends of the climate elements analyzed, including the past and future characteristics. The Man-Kendall trend test is a non-parametric test that has been widely used for studying the temporal trends of climatic series (Chen *et al.*, 2011a; Zhang *et al.*, 2012; Fiener *et al.*, 2013; Westra *et al.*, 2013; Bawden *et al.*, 2014). Since the MK-test technique is presently quite mature, there are several platforms to perform it. In this study the MK-test was conducted using the Microsoft XLSTAT 2013, with 5% significance level for all the tests. Finally the findings are integrated with existing literature results to give a comprehensive understanding about climate change in the research area.

The author did a one-month field investigation in the PRD cities from November 19 to December 18, 2011, mostly focusing on Hong Kong and Shenzhen (see Appendix 8.1). The core task of this field trip was to understand the water issues in the research area and the cities' responses. Basic information on the water issues and challenges in the area was collected from interviews with academic experts, engineers and decision makers, as well as from site visits. A questionnaire (Appendix 8.2) was made to target local citizens, and 45 effective answers were collected which support quantitative analysis in several sections of the thesis.

Empirical analysis process is described in the third chapter, which deals with water supply risks in Hong Kong, and section 4.2 dealing with flood hazards in the PRD area.

An indicator system is developed to evaluate the cities' vulnerabilities to flood events, in section 4.3. Then the flood frequency and urban vulnerability are combined to give an overview of the flood risk in the PRD area. Adopted data is from Guangdong Statistic Yearbook (2000-2012) and Guangdong Water Resource Bulletin (2000-2011) as well as research by Huang *et al.* (2000) and Chen *et al.* (2012). Complementary data for vulnerability assessment was collected from academic literature, government publications and news reports in related cities. The information on human-induced hydrological changes was obtained during the field work in the case area as well as some academic literature. Data used for sea water inundation were derived from the elevation data of ASTER GDEM (V1) and is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn).

Agent based models (ABM) represent a modeling approach that is appropriate in dealing with the complex system of flood impacts and stakeholder responses. It has been adopted in flood research focusing on real-time flood forecasting (Georgé et al., 2009), optimizing evacuation (Dawson et al., 2011) and vehicle relief systems (Scerri et al., 2012). However, it has not yet been used in flood loss estimation considering individual adaptation behaviors. The thesis seeks to make up this gap and therefore adopted it in chapter 5 to deal with the interaction between flood inundation and household responses. Agents are self-contained computer programs that interact with one another and can be designed and implemented to describe the rule-based behaviors and modes of interaction of observed social entities (Monticino et al. 2007; Billari et al. 2006). The agent-based modeling paradigm provides a mechanism for understanding the effects of interactions of individuals in a flood event. This project explores how through the use of ABM, and its linkage with complexity theory, allows us to study urban flood event from the bottom-up. Google streetview and open pictures are used to confirm the local situations. Several mathematic equations are also used in evaluating the flood risk and flood loss, for example, the equation of rainfall intensity-duration-frequency revised from Shenzhen Meteorology Bureau.

1.5 Research cases

1.5.1 The Pearl River Delta

The Pearl River Delta (PRD) is located at the mid-south part of Guangdong Province in Southern China (Figure 1-2), and is formed as a deposit plain of the Pearl River with its three branches, namely West River (Xijiang), North River (Beijiang) and East River (Dongjiang). The PRD is dominated by a sub-tropical monsoon climate with abundant precipitation. The long term annual mean precipitation is around 1800 mm and about 85% of precipitation occurs during April to September. The topography of the PRD has mixed features of crisscross river-network, channels, shoals and river mouths (gates). Water flow at the estuary is influenced by both the river runoff and sea tide, with water level variant between 0.86~1.63m in half-day return period.

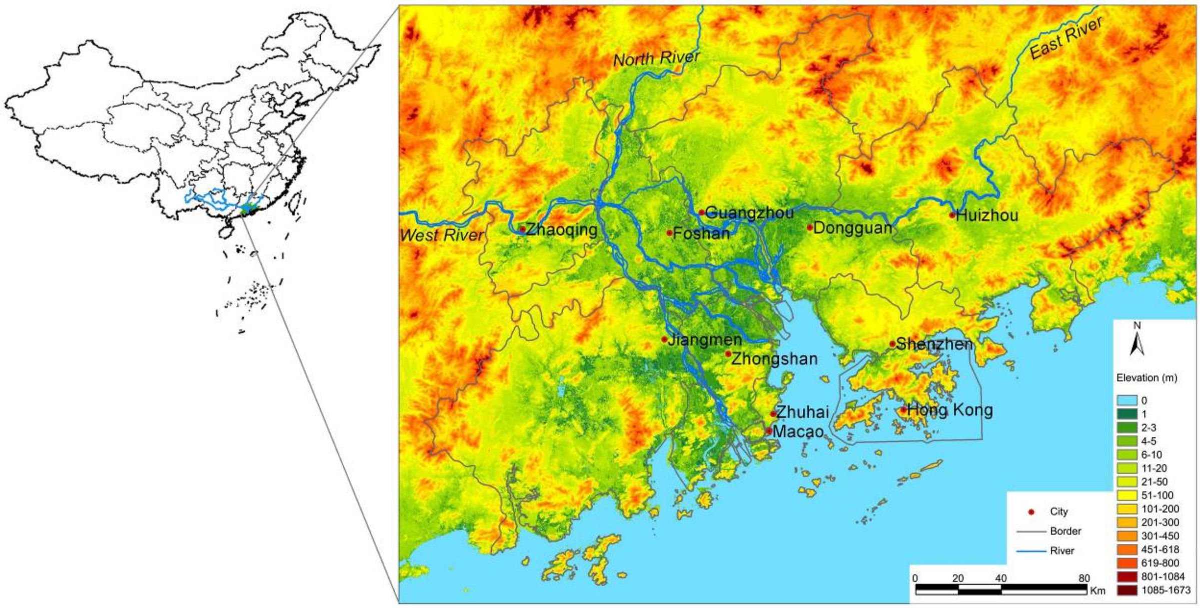

Figure 1-2 Map of the Pearl River Delta , showing its location, elevation, cities and the river system.

There are different definitions of the PRD area according to the orientations on geography, economics or politics. In this article, PRD includes eleven cities, nine in the Guangdong Province (Shenzhen, Dongguan, Guangzhou, Foshan, Jiangmen, Zhongshan, Zhuhai and part of Zhaoqing and Huizhou) plus Hong Kong and Macau (Figure 1-2). Comprising 55869.8 km^2 of land and 55.2 million inhabitants in 2010, the PRD is in rapid urbanization and is now among the most prosperous metropolitan areas around the world. The Gross Domestic Product (GDP) of the PRD area reaches 6137.36 billion RMB Yuan (950.23 billion US$) in 2011 with an average annual rate of 16.2% increasing in the last decade (Table 1-1). The trend is still continuing with positive prospects for future development.

Table 1-1 Social-economy condition of the PRD cities in the year of 2010

Cities	Population (10^4)	Land area (km^2)	Urbanization (%)	GDP (10^8€)	GDP per capita (€)	Remarks
Guangzhou	1033.45	7287.0	82.53	959.51	9353.61	Regional comprehensive center
Shenzhen	891.23	1953.0	100.00	861.14	9741.06	Regional economic center
Zhuhai	149.12	1654.0	87.16	109.06	7338.35	Sub-regional economic center
Foshan	599.68	3848.0	92.36	506.19	8472.03	-
Huizhou	397.21	11356.0	61.27	148.54	3761.00	-
Dongguan	635.00	2472.0	86.39	395.21	5943.11	Rapidly expanding industrial city
Zhongshan	251.74	1800.0	86.34	164.47	6541.92	-
Jiangmen	420.14	9541.0	50.08	140.79	3374.60	-
Zhaoqing	388.83	14822.0	44.89	90.51	2353.58	-
Hongkong	702.64	1104.0	100.00	1550.69	22140.70	One of global economic centers
Macao	54.95	32.8	100.00	154.93	28195.48	Tourism and services center
PRD	5523.99	55869.8	81.00	5081.05	9746.86	Most developed area in China

Source: Guangdong statistic yearbook 2010; Hongkong census and statistic department; Macao statistic and census service

Rate: ￥/ € =0.105, HK$/€ =0.095, US$/€= 0.740

The natural environment of PRD is sensitive and variable due to strong monsoon, dense river-nets and significant effects of erosion and deposition. Since the end of the 1970s, land development driven by urbanization has further intensified fragmentation of the natural environment. These factors combine to make the PRD prone to natural disasters, of which flood is the most serious. In the context of local urbanization and global climate change, the increase in flood threats has become a further concern for local governments and stakeholders (Peng *et al.*, 2008; Chan *et al.*, 2012).

1.5.2 Hong Kong

Hong Kong is a coastal port with a long coastline of approximately 730km and 260 islands. The territory consists of around 1,104 square kilometers, where roughly 7 million residents live. The city of Hong Kong develops with concentration in less than

25% of its total area, resulting in heavy urban development in low lying areas and on reclaimed land. The average annual precipitation during 1981-2010 is 2398.5mm. Despite the large average amount of rainfall in Hong Kong, the inner-annual distribution is very uneven. About 80% is received in storms between April and September while 20% is received in the dry season from October to March (HKO, 2012a).

On the one hand, the water supply of Hong Kong is under stress mainly because the uneven precipitation and its unfortunate nature conditions for water storage. Also, high evaporation and growing water consumption make the water supply condition even worse. On the other hand, local flood (also called waterlogging) often occur and cause great loss to the city and it people, due to the flush of extreme rainstorm to the population-intensive low lands. While Hong Kong is already threatened by mentioned traditional water problems, additional threats posed by climate change are likely to increase the risk scale to the city and its people.

1.5.3 Ng Tung River basin

Ng Tung River (NTR) is a branch river of the Shenzhen River which divides Hong Kong and Shenzhen. Its mainstream is about 15km long and sources from Safflower Ridge in the New Territories of Hong Kong. It flows through the towns of Fanling and Sheung Shui and culminates in the Shenzhen River near the Lo Wu port (Figure 1-3). The NTR forms a flood plain in the midstream and downstream areas, where the regional downtown is located. The NTR basin involves four districts: Sheung Shui, Fanling, Sha Tau Kok and Ta Kwu Ling. The total population in 2013 is about 280,000, of which around 80% lives in Sheung Shui and Fanling.

Due to seasonal rainstorms and the steep topography in the basin, areas along the river frequently suffer from floods. As illustrated by the Drainage Service Department (DSD) of Hong Kong in March 2013, 6 of the 13 flooding blackspots of Hong Kong are located in the NTR basin. Although advanced hydraulic engineering has significantly reduced flood risk in this area, occasional waterlogging still occurs. In recent years, there have been repeated cases of localized rainstorms occurring in the NTR basin and its surround areas, which gave rise to significant flooding there. For example, on 27 September 1993 after the passage of Typhoon Dot, the low lying area of the northern New Territories was completely inundated with flood water (HKO, 2012b). On 22 July 1994, over 300 millimetres of rain were recorded in the northwestern part of the New Territories. 300 hectares of farmland and 150 hectares of fish ponds were inundated. Firemen had to use dinghies to rescue villagers whose houses were surrounded by flood water (HKO, 2012b).

Due to the frequent waterloggings in this area, a “Special Announcement on Flooding in the northern New Territories” was issued by the Hong Kong Observatory whenever heavy rain affects the area and flooding is expected to occur or is occurring in the low-lying plains (HKO, 2012b). The announcement is broadcast by radio and television to the public, and is updated at appropriate intervals until heavy rain ceases.

It is intended to prompt the public to take precautionary measures against flooding and to alert farmers, fish farm operators, engineers, contractors and others who are likely to suffer losses from flooding. The announcement also alerts the relevant government departments and organisations to take appropriate actions, such as opening of temporary shelters, search and rescue operations, closure of individual schools and relief work. Like all weather warnings, the special announcement represents an assessment of the weather based on the latest information available at the time. There could unavoidably be false alarms, that is, after the announcement has been issued, the rain that has actually fallen does not result in flooding. There will also be occasions when heavy rain leading to flooding develops suddenly and affects the area before an announcement can be issued. So rainstorm/flood warnings and active flood preventions are extremely important for local residents to reduce their flood risk, which made the area been selected as the case study in this thesis.

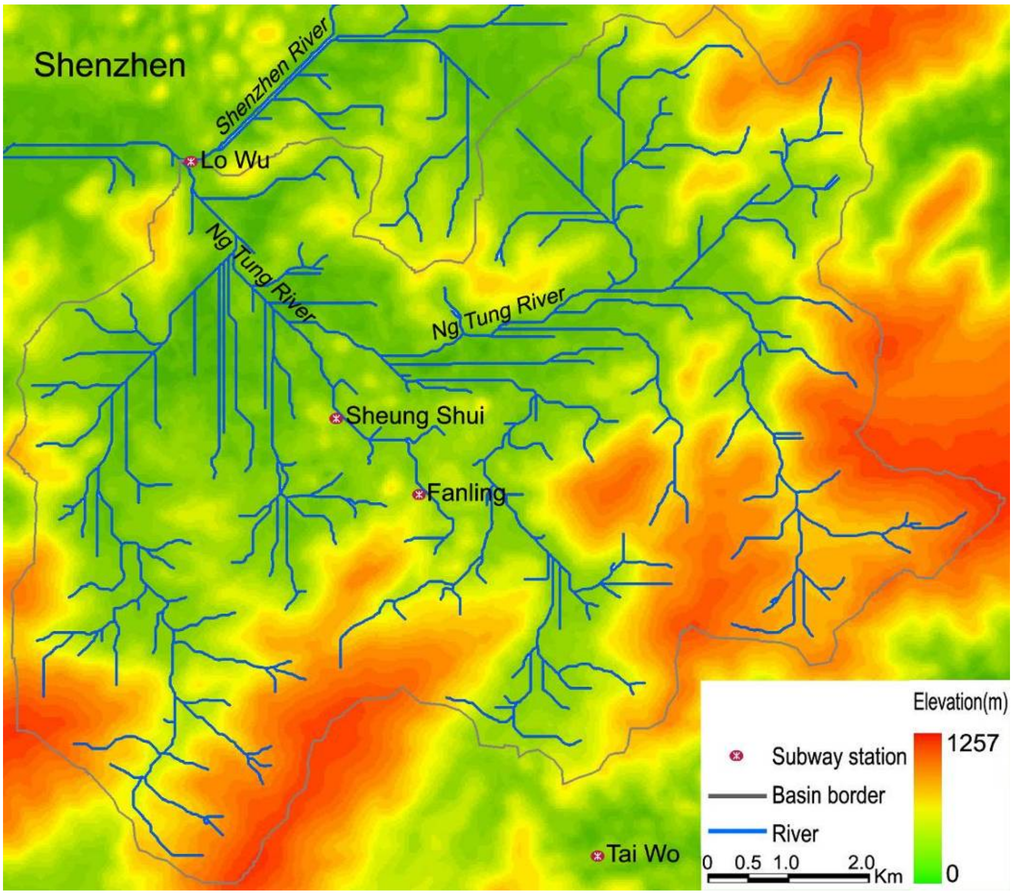

Figure 1-3 Ng Tung River basin in the Northern New Territories, Hong Kong

2 Climate change and its impacts on water of the Pearl River Delta[1]

Climate change is systematic, large scale changes of the earth's weather patterns. These changes are expected to be reflected in, among other things, higher average temperature, rising sea level and a potential shift in the distribution of precipitation (McLeman and Smit, 2006; IPCC, 2007a). The impact associated with climate change is real and extensive, with uncertainties (Adger et al., 2003). It is also one of the greatest environmental, economic and security challenges facing the world today (Martens et al., 2009; Scheffran and Battaglini, 2011).

2.1 Climate change and its trend in PRD

2.1.1 Temperature

Temperature is the core element where climate change is concerned. In the context of the global warming, the annual mean surface temperature has significantly increased during the past 100 years in China, with slightly greater magnitude than that of the globe (Ding et al., 2006). The Guangdong Province in Southern China has experienced noticeable regional climate changes given the dramatic land use changes and the region's increased emissions of greenhouse gases. Yu et al. (2007) reported to the Guangdong Meteorological Administration that the average temperature increase in Guangdong province over the past five decades has been 0.21℃ every 10 years, which is similar to the rate of warming seen nationally in China. The report also showed that the highly urbanized PRD has experienced significant warming and has been hotter than the entire Guangdong province, with an averaging 0.3℃ increase every 10 years. The city centers of Shenzhen, Dongguan, Zhongshan, and Foshan warmed even more than 0.4℃ every 10 years, but the regional warming phenomenon is seen to a lesser degree in Guangzhou (He and Yang, 2011).

Analysis of the annual mean temperature data of Hong Kong, available from the Hong Kong Observatory (HKO), shows that there was an average rise of 0.12°C per decade from 1885 to 2011 (Figure 2-1). The rate of increase in average temperature became faster in the latter half of the 20th century (0.15°C per decade from 1947 to 2011) and accelerated to 0.23°C per decade during 1982-2011. Although the available data in PRD covers a shorter term, it shows an obviously higher increase rate of 0.43°C per decade. And in the latest decade the mean temperature stays above 22.5°C, which indicates a warm period of this region.

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[1] This chapter is an integrated result of two journal papers: Liang Yang, Chunxiao Zhang, Grace W. Ngaruiya, 2013. Water supply risks and urban responses under a changing climate: A case study of Hong Kong, *Pacific Geographies*, 39: 9-15. Liang Yang, Jürgen Scheffran, Huapeng Qin, Qinglong You, 2013. Climate-related Flood Risks and Urban Responses in the Pearl River Delta, China. *Regional Environmental Change* (under review). As the lead author, Liang Yang is responsible for more than 80% of the contents of both papers.

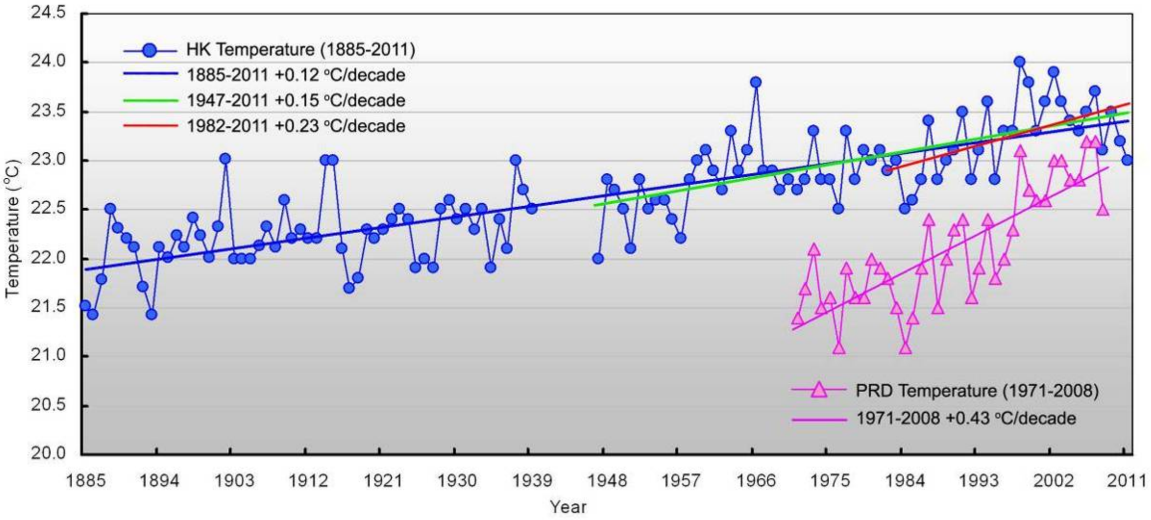


Figure 2-1 Annual mean temperature change in Hong Kong (1885-2011) and the Pearl River Delta (1971-2008).
Source: own representation based on data from Hong Kong Observatory and He and Yang (2011)

2.1.2 Precipitation

The precipitation trend during the last century is not obvious in China, but since 1956 it has assumed a weak increase (Ding et al., 2006). The annual average precipitation in Southeast China (include PRD) increased 60-130 mm during the period 1956-2000. This is consistent with the findings of Zhang *et al.* (2009d) at the national scale that the Pearl River basin is dominated by increasing summer precipitation according to precipitation records of the period 1951-2005 from 160 stations in China. When downscaling to the Pearl River basin, the precipitation is decreasing after late 1990s with variations. In addition, the Pearl River streamflow variations show remarkable relations with precipitation changes in it’s branch rivers (West River and East River), implying tremendous influences of precipitation changes on hydrological processes (Zhang *et al.*, 2009b).

HKO precipitation observation during the 65 years after the Word WarⅡ indicates an increase of 36mm per decade. Aside from this, the interannual variability of precipitation is much more notable relative to the trend variability of precipitation, which suggests that extreme precipitation events occur frequently (Ginn et al., 2010).

2.1.3 Sea level

Reading from the China Sea Level Report 2011, the average sea level rose 2.7mm per year during the year 1980 to 2011 with fluctuations. This general increase shows a considerable similarity to the global change. Since China has a large sea area, the increase has different spatial pattern. Specifically, an increase of more than 100mm in the last 30 years exit in the sea area of east Hainan Province (Pearl River mouth), comparing with the up to 80mm increasing during the same period in West Liaodong Bay, South East-China Sea and Beibu Gulf. According to records of local tide gauges, sea level at the Pearl River mouth and South China Sea rose clearly in the latest 30 years (Figure 2-2).

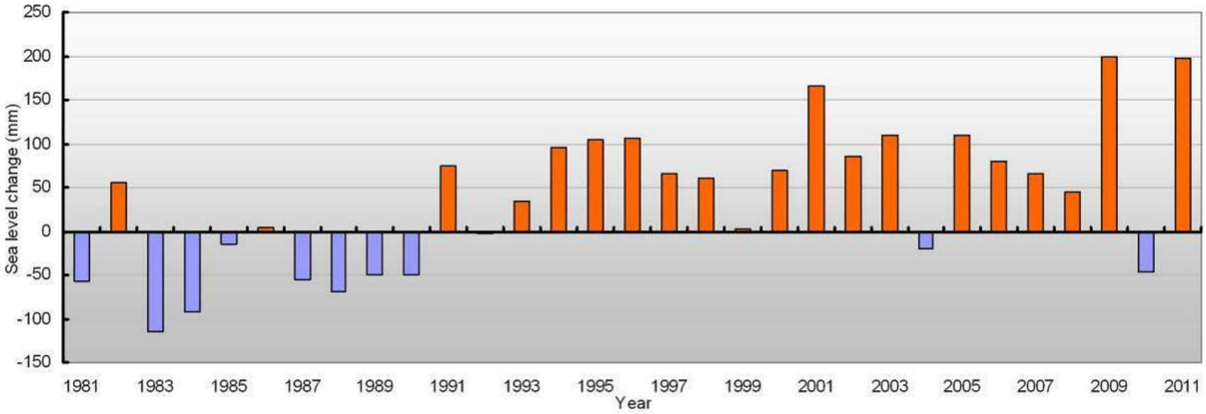


Figure 2-2 Sea level changes at the Pearl River estuary in Septembers of the last 30 years*.
* The value 0 indicates the multi-annual (1975-1993) average sea level. Data sources from China Sea Level Report 2011.

As a result of the sea level rise together with narrowed and silted riverbed, the measured max water level of downstream Pearl River near the estuary increased gradually in the past 80 years (Li, 2011). Main effects of sea level rise on the PRD cities are exacerbating storm surge flood and the incursion to fresh water (Wong and Woo, 2010).

2.2 Observation of extreme climate

An increasing temperature rate of 0.39°C per decade in the PRD has been observed from 1971 to 2011; the city centers of Shenzhen, Guangzhou and Hong Kong warmed even more due to urbanization effects (He and Yang, 2011). Aside from the general increasing trend, the number of annual hot days (daily maximums temperature is greater than or equal to 35°C) is increasing, based on records from 29 monitoring stations in the PRD area during 1956-2005 (Figure 2-3a). After the 1990s the trend rises much more significantly. The urban heat island effect is thought to have a certain contribution to this trend (Chen *et al.*, 2011b).

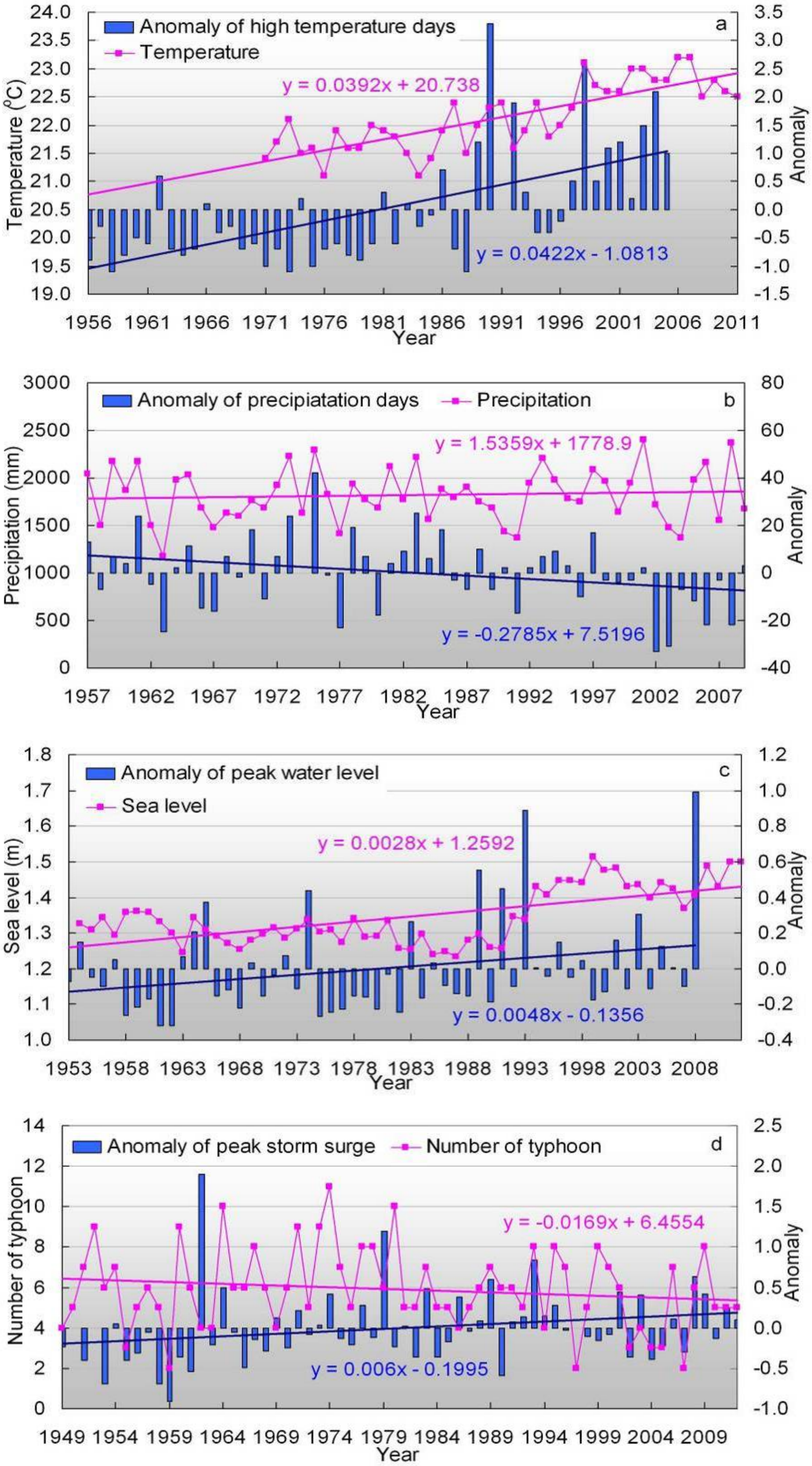


Figure 2-3 Changes of temperature (a, PRD area), precipitation (b, PRD area), sea level (c, Pearl River estuary) and typhoon (d, Hong Kong) in the last several decades.

The value 0 in all anomalies indicates the respective average value. Data sources see the text and refer to section 2.2.

The precipitation trends during the last century are not obvious in China, but since 1956 a weak increase was observed, in particular in Southeast China (Ding *et al.*, 2006). When downscaling to the PRD area, the weak increase was found as well in the nearest five decades, with 15 mm increasing per decade. Further calculation of the annual rainy days during the period 1957-2009 presents a significant reduction rate of 2.79 days/decade (Figure 2-3b). Thus, an increased annual precipitation with a decrease in the number of rainy days means that the rainfall intensity has increased at the PRD area. An example of this is that Huilai County in east Guangdong recorded 603.5mm rainfall within a six-hour period on June 25, 2010, setting a half-century record (Chan *et al.*, 2010).

According to annual data of local tide gauges, the sea level at the Pearl River estuary (Victoria Harbor, Hong Kong) experienced a clear rise with an average annual value of 2.8mm between 1954 and 2012 (Figure 2-3c). Monitored records of the tide gauges at Denglongshan and Hengmen show a trend of rising peak water levels (1953-2008) and extreme high values in 1993 and 2008, as shown in Figure 2-3c (Kong et al., 2010). This places the PRD coastal area in a serious situation as societal impacts of sea level rise primarily occur via the extreme levels rather than as a direct consequence of mean sea level changes.

The PRD is the main landfall area of tropical cyclones and typhoons from the Northwest Pacific and the South China Sea. The annual number of tropical cyclones landed in this area was found to be decreasing (Figure 2-3d), recorded by HKO. However, the landing areas are more concentrated and the strength of landed typhoons is increasing (Yang *et al.*, 2009). The associated peak storm surge was also increasing slightly in the last 60 years (Figure 2-3d). Due to the homogeneity and consistency of climate data and the deficiency of climate models, it is difficult to explain definitely the relationship between global warming and tropical cyclones. However, it is likely that peak wind speed and rainfall in tropical cyclones will increase if the climate continues to warm (Lei *et al.*, 2009).

2.3 Projection of future climate change

2.3.1 Climate change projection

Climate change based on reanalysis and modeling

This section presents quantitative analysis on the trends of changing temperature, precipitation and sea level in PRD and its surrounding areas. The past trends during 1948-2005 are drawn based on the reanalysis dataset of the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR). For the future trends from 2005 to 2100, simulations of the Max Planck Institute for Meteorology Earth Systems Model were run on low resolution (MPI-ESM-LR) within the Coupled Model Inter-comparison Project Phase 5 (CMIP5). Results are adopted under the three representative concentration pathway (RCP) scenarios: a high emission scenario

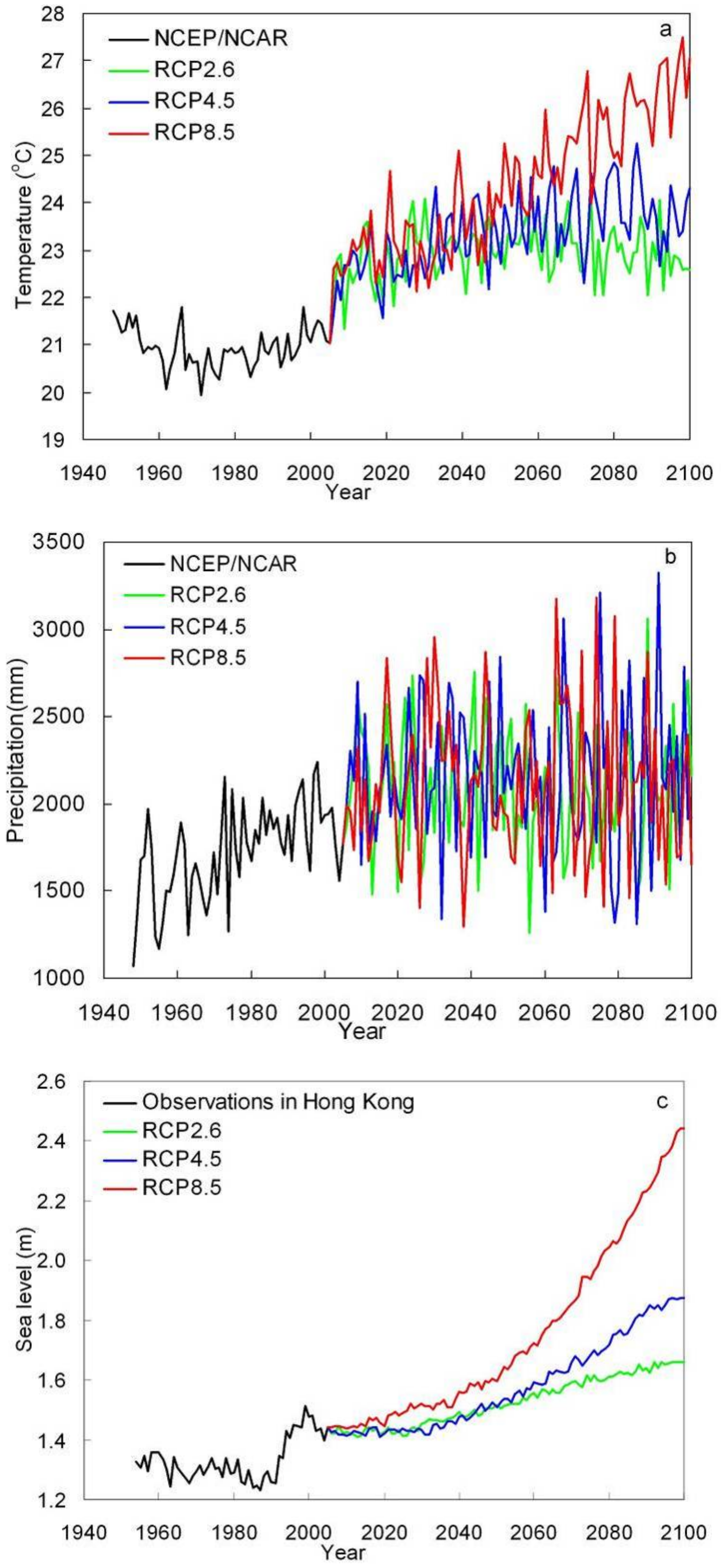


Figure 2-4 Annual mean temperature (a) and precipitation (b) in Guangdong Province (including PRD) for the period of 1948-2100 and sea level (c) in the Pearl River estuary (Hong Kong) during 1954-2100.

The year 2005 divides the past trend under NCEP/NCAR reanalysis (a, b) and observations (c) and the future simulation under RCP8.5, RCP4.5 and RCP2.6.

(RCP8.5), a midrange mitigation emission scenario (RCP4.5), and a low emission scenario (RCP2.6). A detailed description of the reanalysis dataset, MPI-ESM-LR and RCPs can be found in Kalnay *et al.* (1996), Giorgetta *et al.* (2013) and Meinshausen *et al.* (2011), respectively.

Results of reanalysis and simulation draw clear trends of temperature and precipitation change (Figure 2-4a, b). During the past period 1948-2005, there was a decrease in temperature change in the first half and an increase in the second half, while for the whole period temperature changed comparatively little. The trends of temperature change in three RCP scenarios all indicate an increasing tendency, but with a gap of more than four degrees Celsius till the year 2100. The same work on annual mean precipitation shows an increasing trend in the past but no clear trend in the future three scenarios. However, there are significant fluctuations in annual mean precipitation changes under all the scenarios, reaching around 1500 mm difference. In summary, the temperature increase of this area is expected to continue and precipitation is going to show more extremes with no obvious trend. In the context of global climate warming, sea level changes have considerable relevance to surface temperature, in especially decadal/century or even longer time scales (Vermeer and Rahmstorf, 2009). Since the Pearl River estuary and even the South China Sea have no strong local expression (e.g. no additional glacier melting water), the sea level in this region reflects mainly the global ocean and climate situations. Therefore, the semi-empirical approach (Vermeer and Rahmstorf, 2009; Rahmstorf et al., 2012, Equation 1) is applied to simply assess the sea level of the Pearl River estuary and its surrounding area, based on the predicted temperature above:

$$dH/dt = a(T - T_0) + b \cdot dT/dt \qquad 1$$

Here, T_0 is a base temperature at which sea level is in equilibrium with climate, so that the rate of rise of sea level H, dH/dt, is proportional to the warming dT/dt above this base temperature. This model was trained using the observed temperature and sea level data in Hong Kong during 1954-2011, resulting in $a=0.0061$, $b=-0.0137$ and $T_0=22.5430$. Then the above emulated temperature data for 2005-2100 in three RCP scenarios (Figure 2-4a) are used to generate mean sea levels in the same scenarios during the same period. The result (Figure 2-4c) shows an overall sea level range from 1.66 to 2.44 m for the period 2005-2100 at the Pearl River estuary, which is 22 to 100cm higher than the sea level in 2005.

The Mann-Kendal trend test supports further statistical analysis of the modeled climate changes above, showing their trends with 95% confidence level (5% significance level) (Table 2-1). For the past climate characteristics, there is significant increasing trend in temperature, sea level and their anomalies. No clear trend is seen in precipitation and typhoon numbers. However, there is a decreasing trend in the anomaly of precipitation days and an increasing trend in the anomaly of peak storm surge, which indicates that precipitation intensity was increasing and typhoon-related storm surge severity was also increasing. These trend analysis complement the linear regressions in figure 2. For future climate projection, the trend tests show no trend in precipitation by all scenarios and in temperature by scenario RCP2.6. Temperature has an increasing trend within scenarios RCP4.5 and RCP8.5, and sea level is increasing in all scenarios.

Table 2-1 Man-Kendall trend tests with 5% significance level for climate change characteristics in Figure 2-3 and Figure 2-4.

Item*		Kendall's tau	p-value (Two-tailed)	alpha	Trend test Interpretation
Past T	Temperature	0.590	< 0.0001	0.05	Increase
	Anomaly of high temperature days	0.453	< 0.0001	0.05	Increase
Past P	Precipitation	0.041	0.671	0.05	Non-trend
	Anomaly of precipitation days	-0.201	0.036	0.05	Decrease
Past Sl	Sea level	0.324	0.000	0.05	Increase
	Anomaly of peak water level	0.188	0.042	0.05	Increase
Past Tp	Number of typhoon	-0.100	0.274	0.05	Non-trend
	Anomaly of peak storm surge	0.220	0.011	0.05	Increase
Future T	RCP2.6	0.103	0.138	0.05	Non-trend
	RCP4.5	0.439	< 0.0001	0.05	Increase
	RCP8.5	0.704	< 0.0001	0.05	Increase
Future P	RCP2.6	0.006	0.937	0.05	Non-trend
	RCP4.5	-0.006	0.937	0.05	Non-trend
	RCP8.5	-0.007	0.917	0.05	Non-trend
Future Sl	RCP2.6	0.899	< 0.0001	0.05	Increase
	RCP4.5	0.899	< 0.0001	0.05	Increase
	RCP8.5	0.963	< 0.0001	0.05	Increase

* T: temperature; P: precipitation; Sl: sea level; Tp: typhoon.

Climate change based on literature review

Ding et al. (2006) edited the Chinese National Assessment Report of Climate Change in 2006 which gave a comprehensive analysis on the national future climate change. Comparing the average temperature value, the temperature in 2020 will be 1.3℃ to 2.1℃ higher, in 2030 1.5℃ to 2.8℃ higher and in 2050 2.3 ℃ to 3.3℃ higher. Considering the precipitation trend, it is projected that the annual average value will increase by 2％～3％ in 2020 and 5％～7％ in 2050. As a country China would have uneven changing patterns, of which the northern part will warm more than the southern part and the yearly number of precipitation days will increase significantly in north China, while not significantly in the south. A comprehensive report on the climate change of Guangdong (Yu et al., 2007) indicates temperature increase of 2.8℃and precipitation increase 8% by 2100.

Table 2-2 gives a generalized overview of historical trends in the recent past and likely future trends under continued warming conditions for the PRD and the surrounding areas. The analysis findings based on observation records, reanalysis and modeling are also added at the end of the table for comparative purposes. Due to the use of different calculating methods, such as spatial interpolation and statistical averaging, these studies show slightly different results. Overall, an increased trend of temperature, precipitation and sea level at PRD was seen in the past and is expected in the future.

Table 2-2 Literature overview of recent and likely future trends of climate change in Pearl River Delta, China

Source	Region	Recent trend			Future trend		
		T	P	SL	T	P	SL
(Yu *et al.*, 2007)	Guangdong	↑	0	↑	↑	↑	↑
(Huang and Zhang, 1999; Tang *et al.*, 2008)	Macau	-↑	-↑	↑-	-↑	-↑	↑-
(Zhang *et al.*, 2009a; Fischer *et al.*, 2011; He and Yang, 2011; Chen, 2012)	PRD	-↑↑-	00-↑	----	----	----	----
(Huang *et al.*, 2004; Shi *et al.*, 2008; Li, 2011; SOA China, 2011)	PRD	----	----	↑↑↑↑	----	----	↑↑↑↑
(Du and Li, 2008; Li *et al.*, 2012)	South China	-↑	-↑	--	↑↑	↑↑	--
(Wang *et al.*, 2011)	East River	-	-	-	-	↓	-
(Ginn *et al.*, 2010; Hong Kong Observatory, 2012)	Hong Kong	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑
(Li, 2009)	PRD	↑	0	-	↑	↑	-
Own analysis using observation records	PRD	↑	↑	↑	-	-	-
Own analysis using reanalysis and modeling	PRD	0	↑	↑	↑	↑	↑

T: Temperature; P: Precipitation; SL: Sea level.

↑: increase; ↓: decrease; 0: no significant change; -: no result in mentioned source literature. Combination of the symbols indicates results in different literature, e.g. **-**↑ means the 1st literature doesn't give result on the item and the 2nd literature gives an increased result.

Integrated findings about future climate change in the PRD

Industrialization and urbanization is continuing in the PRD area and is generating greater emissions of CO_2 and other greenhouse gases which represent a large latent source of future warming and additional changes (He and Yang, 2011). The changes would include a great increase of warm days and nights in this area. The assessment report on climate change in Guangdong (Yu *et al.*, 2007) indicates a temperature increase of 2.8°C by 2100 and the strongest warming would very likely occur in the highly developed PRD area. The city scale temperature projection in Macau claimed an increase of about 2.7°C by the end the 21st century with a significant reduction of cold days (Tang *et al.*, 2008). Integrating these results with the above simulated temperature trend under the midrange mitigation emission scenario RCP4.5, the temperature in the PRD area is likely to rise 2.5-3°C by the end of the 21st century.

In the future, the specific rates of precipitation change may vary but the trends are mostly increasing, except from an abnormal decrease in the East River basin (Wang *et al.*, 2011). However, the general trend does not necessarily mean a wetter PRD due to more frequent occurrences of extreme weather, as simulated above. For instance, the frequency of extreme rainfall would increase with significant seasonal differences and the increasing precipitation will be composed mainly of rainstorms/heavy rain. Therefore, overall precipitation of the PRD area will probably increase slightly in the later years of this century (Du and Li, 2008; Ginn *et al.*, 2010), but temporary and local precipitation will be highly variable in the area.

The magnitude of mean sea level rise in the PRD area has been predicted as 20 cm to 25 cm (Ren, 1993), 22cm to 33 cm (Huang *et al.*, 2000) and 13cm to 17cm (Chen *et al.*, 2008) between 1990 and 2030, or 40 cm to 60 cm between 1990 and 2050 (CAS, 1993). A recent review in this issue claimed a less than 20cm sea level rise by the year 2030, compared with 2010 (Li, 2011). For better integration and comparability, the annual rate of these predicted mean sea level rises is calculated and it indicates a range from 0.33cm to 1cm per year. Even the lower limit of these predicted rates is higher than those of the previously analyzed historical records.

2.3.2 Perspectives on extreme weather

Apart from the general trend of climate change, extreme weather events affect human society more direct and serious. There are world-wide clear evidences that anthropogenic greenhouse gas contribute to more-intense precipitation extremes (Min et al., 2011) and flood risk (Pall et al., 2011). Research in southern China (Li et al., 2012) and the city of Hong Kong (Lee et al., 2011b) also suggest an increasing precipitation intensity and decreasing precipitation days in a year. A sharp increase in precipitation would require further water storage capacity for flood control and to prevent drought, while the unexpected precipitation reduction would affect the impoundment. The projection results of Lee et al. (2011b) on temperature suggested that, in the 21st century, the frequency of occurrence of extremely high temperature events in Hong Kong would increase significantly while that of the extremely low temperature events is expected to drop significantly. In the context that the frequency and intensity of these extreme weather and climate events have assumed significant change, it is very likely that the area will suffer more serious floods or long-term droughts. Already, the decreased flood times and increased flood-affected population/assets in the last decades have been noticed in the Pearl River basin by Chen et al. (2012).

Land use change together with rapid urbanization plays a role in the change of extreme weather as well. According to the work of Li et al. (2011), the PRD experienced more strong precipitation but less weak precipitation compared to surrounding nonurban regions, and the strong precipitation over the PRD displays a pronounced seasonal variation. Urbanization may, on one hand, reduce precipitation by changing surface properties, such as vegetation cover, roughness, albedo and/or water flows in ways that reduce water supplies to the local atmosphere (Rosenfeld, 2000; Kaufmann et al., 2007). On the other hand, it may promote precipitation by increasing condensation nucleus, enhancing evaporation and vapor circulation (urban heat island) (Jauregui and Romales, 1996; Xu. et al., 2010). Thus, impact of urban expansion on precipitation is complicated in that it increases in some urban areas while decreases in others (Lin et al., 2009).This urbanization effect may exacerbate local extreme weather events by changing the local atmosphere conditions. While the degree of this effect is not clear yet.

Because of the limited availability of daily observations, most studies can only examine the potential detectability of changes in extreme weather through model-model comparisons (Min et al., 2011). Since difficulty also exists regarding definitions and analysis methods of extreme climate events, it is necessary to create a widely agreed framework for further research, e.g. researching on the change of a 20-year extreme climate event (Li et al., 2012).

2.3.3 Uncertainty

As many researches already suggest, projections of future climate change exhibit considerable uncertainties (Allen et al., 2000; IPCC, 2007b; Kopf et al., 2008; Hawkins and Sutton, 2009). Although a majority of the model projections suggest in general consistent trends for the future climate changes, inter-model differences are still rather large with a divergence in the projections. This, to a certain extent, indicates that climate projection is still subject to various uncertainties in the model simulation of the future climate, which depend very much on such factors as future greenhouse gas emission scenarios, the spatial and temporal resolution, model skills, the downscaling methodology, and especially the problems of unknown initial conditions of corresponding variables (Lee et al., 2011a; Schilling et al., 2012). The IPCC concludes that it is necessary to improve the projections of climate change.

Development of human society, urbanization, land use change affects the local climate and environment and also increases the uncertainty. Dynamical and statistical downscaling assessments need major improvements for the wide PRD urban area. For instance it is necessary to gain a better understanding of the specific feedback mechanisms of the rapid urbanization transformation and land use change. In recent years more attention tries to enhance regional climate change information especially for the highly urbanized PRD (Li and Chen, 2008; Li et al., 2009; Lin et al., 2009; Zhan et al., 2011).

2.4 Climate change impacts on water system

This section gives an overview of the water characteristics and the expected climate change impacts in water sector in the Pearl River Delta. So far, understanding the impacts that climate change will have on water resource in specific regions and communities is a mammoth task. For the PRD, this section tries to clarify it from three dimensions based on current water characteristics: (i) water shortage, (ii) flood hazards, (iii) water management and development.

2.4.1 Water shortage

Uneven precipitation and drought

From a hydrological point of view, the Pearl River is a complex system. Three main tributaries (West river, North River and East River) join together and form eight mouths to the sea, which constructs the basic terrain of the Delta. The delta is mostly less than 50 meters above the seal level. The average annual temperature is 21~23ºC, with a variation of 15 ºC between summer (28ºC in July) and winter (13ºC in January). According to the *Water Resources Department of Guangdong Province,* annual precipitation in the PRD is 1600-2600 millimeters, while most of which occurs between April and September (account to 80%), with little to no precipitation during the remaining months. Therefore, the PRD suffers from the temporal uneven precipitation within the dry season. In the years of low rainfall, there will be increased pressure on water resources.

There is uneven precipitation in spatial distribution as well. The highly urbanized PRD area gets relatively less rainfall than the upstream areas, considering water amount per person. In addition, not all cities can easily take advantage of using the Pearl River water, for example Hong Kong and Shenzhen, as the river mainstream does not flow through them. Both the two cities rely highly on natural rainfall and regional water transfer, and are therefore more vulnerable to the impact of weather factors.

Uneven pattern of precipitation courses drought frequently in certain subareas. Significant drought trends could be found in November, December, and January and significant wetting trends in June and July. In terms of drought risk, higher drought risk could be observed in the lower Pearl River basin and lower drought risk in the upper Pearl River basin (Zhang *et al.*, 2012). Due to the uncoordinated distribution of water resource and population, the highly urbanized PRD area is under higher pressure when drought and water shortage occur. Climate change is making profound impact on the global water cycle as well, which is likely lead to the re-allocation of water resources in time and space and will cause a change in the available quantity of water resources.

Projected climate change is expected to aggravate the uneven pattern of precipitation, which will bring further stresses. A decrease in precipitation and an increase in temperature may modify the PRD water balance by increasing the evapo-transpiration rate, decreasing the precipitation runoff and aquifer recharge rates, and decreasing, overall, the water available for PRD. Such changes imply additional stress to the already limited water sources.

Sea water invasion

In the context of global climate change, sea level is expected to keep rising in the future, which would strengthen saltwater intrusion, the invasion of sea water into inland fresh water system. Saltwater intrusion affects the quality of river water, resulting in reduced availability of freshwater resources.

Disastrous saltwater intrusion is normally a combined effect of meteorological, hydrological and astronomical factors. In meteorology, the Pearl River Delta usually receives less rainfall in autumn. Once a drought occurs, reservoir storages reduce sharply and rivers run dry. The meteorological impacts deteriorate the river hydrological conditions in the PRD area. River water level is low because of reducing surface runoff, which therefore gives the chance for sea water to intrude and spread in the Pearl River downstream regions. However, these are even worse situations. For example in the year 2007, three astronomical tides occur one after another from December 18th to 24th in the sea area along the PRD, due to the movement of the sun, the moon and the earth. Tide peaks rose higher than usual and tidal water intrudes further into the costal river system, thereby forming a super saltwater intrusion.

In addition, rising sea level would push more saltwater into inland groundwater system. If there is no enough surface runoff injected to groundwater system, ground water would not be usable.

Water pollution

Large amount of rainfall in wet season helps take away or dilute water contaminants significantly. However, less water will lead to a high level of water contaminants concentration (Figure 2-5). As wastewater and sewage emissions are increasing rapidly in the PRD cities along with fast population growth and urbanization, climate-related water shortage would aggravate the water pollution situation. Serious water pollution would deteriorate water environment and cut down the amount of water useable.

Natural and human made water pollution can be spread with trans-boundary water diversion. Research shows that, increased depositions of Cd, Cu and Zn in Hong Kong’s reservoirs have positive correlation with their depositions in the downstream of Dongjiang River during the period of 1994-2001. And there are also many other substances transported to Hong Kong through the water supply project, which may cause health problems (Ho *et al.*, 2003).

Figure 2-5 Photographs of the highly polluted Shiyan River in Shenzhen during the dry season

Photos taken by Liang Yang on November 24, 2011.

2.4.2 Flood hazards

Flood frequency and intensity

Factors like increasing precipitation, extreme rainfall, typhoon and sea level rise need to be considered when looking at climate-related impacts on flooding.

According to the Intergovernmental Panel on Climate Change (IPCC), the atmosphere is about 0.75 degrees warmer than it was at the start of the century, which means it can hold 5-6 percent more moisture (IPCC, 2007b). That doesn't automatically mean more heavy rainfall for the PRD because complex weather patterns govern the amount, timing and distribution of rainfall. But it does mean that with more water in the atmosphere, the volume of rainfall may increase when it does pour. Wetter weather in some areas can also change the antecedent conditions, which means that floods might occur more often. A recent study found global greenhouse gas emissions increased the risk of flood by up to 90 per cent in England and Wales (Pall et al., 2011). As global temperature continues to rise, many coastal cities could be hit hard, particularly heavily populated cities in Asia, like the PRD area.

The destruction or enhancement of earth's water cycle is considered to be the most basic effects of global climate change (UNEP, 2002). Hydrological situation has changed a lot in the PRD area over the past 30 years: rainfall is slightly increasing with significant fluctuations. Heavy and prolonged rainfall may produce excess run off which will increase the risk of flooding and landslide damage. This could impact buildings and infrastructure and cause disruption to business activities. According to some observation datasets, extreme hydrological events in south China (include PRD area) regardless of the number, frequency or losses is increasing (Wang and Zhou, 2005). Climate change is expected to lead to increases in extreme rainfall, especially in places where mean rainfall is expected to increase. These extreme precipitation will threaten many areas and people and results in great losses.

Extreme rainfall is the most common trigger for floods in the PRD area. However, even though there's a theoretical link between climate change and extreme rainfall, it is hard to find clear evidence yet because the record of measurements is short and doesn't cover all parts of the world. Globally, that makes it hard to distinguish any trend in the intensity or frequency of flooding due to climate change (IPCC, 2012). But in the rough global scale, where certain data on rainfall exist, there is some evidence for a trend towards heavier rainfall. A recent study finds greenhouse gas emissions contributed to observations of more intense precipitation over two thirds of the northern hemisphere between 1950-2000 (Min *et al.*, 2011). The situation is much more serious due to the unknown/uncertain local climate changes and impacts (Lawrence *et al.*, 2013).

Sea level rise and storm surge

As global temperatures rise, oceans get warmer. And when water heats up, it expands and sea level rises. The IPCC reports that from 1993 to 2003, global sea level rose about 3 millimeters each year, and approximately half of that increase is attributed to the ocean expanding as it warms (IPCC, 2007b). Warming water can cause rises in sea levels and strong storms, with the potential to impact people along the coast. The IPCC also predicts that warming tropical seas — hurricanes feed off of warm water — will likely make these storms more powerful, dumping more torrential rains on coastal areas (IPCC, 2012).

A sea level rise of just a few millimeters a year may seem insignificant, but on flat land, it adds up. A half-inch of vertical sea level rise translates to about three feet of land lost on a sandy open coast, due to long-term erosion (Vigran, 2008). Because sea-level rise can increase base levels for coastal river reaches, even a slightly higher sea level can cause more dramatic flood in deltas and estuaries.

Rising sea levels also make coastal areas more vulnerable to storm surges and, in turn, to flooding. There are generally about six typhoons landing in Guangdong Province every year. They bring heavy rainfall and storm surges occasionally to the PRD region, and causing huge damages concerning the further development in the water frontier of low coast area (Figure 2-6). Global warming in recent years causes atmospheric circulation anomalies. Changes in storminess are harder to predict, but it is likely that tropical cyclones will be more intense, and such weather systems can be transformed into intense sub-tropical lows that bring storm surge to the PRD. Based on the higher sea level, storm surge could be boosted to reach further inland.

Indirect effects

Climate change is also likely to have a number of indirect effects. For example, changes in precipitation will lead to changes in sediment transport, in turn affecting the riverbed levels (Woods *et al.*, 2010). However, this is complicated in the coastal reaches of rivers because sea-level rise slows the flow of water out to the sea. Therefore detailed modeling of these effects is still required.

Figure 2-6 Photographs showing the rapid development and urbanization in the low coastal area of the PRD.

Top-left: Sea World near the Shekou Port, Shenzhen; Top-right: Qianhai Bay, Shenzhen; Bottom: The Pak Shek Kok development area, Hong Kong.

Photos taken by Liang Yang in November and December, 2011

2.4.3 Failure of water-related facilities

The impact of climate change on available water resource is very complicated, including the impact on water quantity, quality and distribution, all of which are not clear. Further, the development, utilization and planning of the local water facilities are also involved, which adds a lot of exposure. Long term and severe drought would make water supply facilities failure or junked. Extreme hot weather can depreciate all the social infrastructure including those for water supply, flood control and pollution treatment. Flood as well is a major initiator in destroying human facilities and welfares.

In addition, the health sector may be also affected by damages in the water supply facilities and sewage system of the PRD basin, mainly in the form of an increase in the incidence of water-related diseases and may influence the cities and their people.

3 Water shortage risks in the PRD area with focus on Hong Kong

The Pearl River Delta (PRD), located in southern China, is quite often portrayed as a subtropical area with abundant water resource. However, this is only part of the full picture of the complicated water issues. Theoretically, the PRD has access to water resources as it is surrounded by the South China Sea and the area receives high annual rainfall amount. However, the Guangdong Province (include PRD) suffered 2 billion CNY (approximately 0.2 billion USD) economic loss in 1991 because of a serious drought creating a water shortage (Gu and Yang, 2005). Although the current water supply system supports the water demand effectively, water shortage in this area is still a concern (Xia, 2004; Zhang *et al.*, 2009c; Zhu *et al.*, 2011). Furthermore, global climate change adds new challenges from another dimension, together with population growth and development activities, making the water supply issues more complicated.

Water system management is both complex and politically difficult, requiring the best expert knowledge available for decision-making (Hunt *et al.*, 2007). In order to enrich the adaptive capacity in the PRD area, it is necessary to understand the characteristics of the water supply system and associated risks. This chapter aims to draw a wide, although not exhaustive, picture of the water supply challenges under the context of climate change in the PRD area with focus on Hong Kong. Consequently, a brief discussion on the challenges facing water supply in the PRD is given in section 3.1. Section 3.2 deals with climate change impacts and the associated water supply risks in Hong Kong. This enables us to identify the shortcomings in current water supply system which are most likely to trigger a risk occurrence, in particular the context of climate change. A framework is suggested to analyze the water supply risk elements with their corresponding pathways in the end of section 3.2.

3.1 Risk of water shortage in the PRD area

3.1.1 Water resource and water supply

The PRD has 26820 km^2 rainfall catchment area that supplies average 280.7×10^8 m^3 local runoff annually. And the delta has 3010×10^8 m^3 river water on average passing through every year (Water Resources Department of Guangdong Province, 2008), which accounts 91.5% of the water resource in this area. Therefore the usable river water in the PRD comes mainly from the upstream, and is influenced greatly by the water quality and quantity changes in the upstream areas.

PRD cities rely highly on the upstream water resources. In 2010, the water supply in PRD reaches a high amount of 192.96×10^8 m^3 (PRWRC, 2011). And in 2011, about 90% of the surface water resources in the PRD area were developed and utilized, which is a very high level comparing with the general situation of international river basins (PRWRC, 2011). This decreases the water amount that flows to the sea and also leads to intense water competition in the PRD cities. In addition, uneven water distribution adds further challenge to the delta. Cities in the west and north of PRD have the convenience in using the Pearl River water. While the eastern cities like Shenzhen and Hong Kong have to pump river water to their water supply system because the mainstream does not run through their territory. Further, increasing water consumption pumped from the river implicates an increasing waste water that is emitted back into the river, therefore aggravating the water shortage later.

Although the absolute amount of water resource in the PRD seems a lot, the water amount per person is relatively small considering the intense population and economy. The fresh water per capita in the PRD cities is around 2000 m^3, less than the national average value 2200 m^3, which is only a quarter of the global average. Taking Shenzhen as an example (Table 3-   ), the water per capita (264 m^3) is only 12% of the national average. The city supplied 1.89 billion m^3 fresh water to its people and economy in 2010, of which approximately 70% is from the Eastern River. The river has been nearly fully developed to serve the water demands of cities along it. It is hardly possible to increase supply. Taking into account the potential drought and increasing upstream water consumption, how to get more fresh water supply has become one of the important and urgent task facing Shenzhen municipal government.

3.1.2 Water consumption

Due to population and economic growth, industrial, agricultural and domestic water demand has increased dramatically in the whole PRD (Figure 3-1). The contradiction between supply and demand of water have become increasingly prominent. The number of PRD residents increased from roughly 26.44 million in 1989 to 56.2 million in 2010, a more than doubled increasing. Population growth goes in contrast with nearly stable water resource, therefore available water amount per capita decreases rapidly.

There are more than 400 towns with more than 10 thousand residents in the Pearl River Delta. Many of them have a distance not more than ten kilometers to each other. With highly developed economy, highly populated towns, the PRD area contributes 12.7% of the national GDP in 2010, while its area is only 0.5% of the country. Rapid urban construction and industrial development require substantial increase in water demand. Accelerated urbanization process also dramatically changes the water use patterns. During 1980-2003, the ratio of agricultural water consumption in the total annual amount of water consumption declined from 87.6% to 54.3%. At the same period, the ratio of industry water consumption increased from 12.4% to 44.5%. This changed pattern exposes further contradiction in water supply and demand: agricultural water consumption shows seasonal, temporary features and therefore can be well prepared for peak demand period; while urban water consumption is constant at a certain high amount. Thus urban water supply is more sensitive to climate-related water resource fluctuations and has a significant potential to be threatened by drought disasters (Liu et al., 2005).

Table 3- 1 Precipitation, water supply and consumption in the PRD cities in 2010

		PRD	Guangzhou	Shenzhen	Zhuhai	Foshan	Huizhou	Dongguan	Zhongshan	Jiangmen	Zhaoqing	Hong Kong	Macau
Precipitation/mm		2008.30	1978.20	1716.90	2114.00	1748.60	1790.00	1914.50	1910.60	2316.30	1694.00	1751.20	2127.60
Fresh water consumption /×10^8m^3	Agriculture	48.81	11.08	0.54	1.05	8.45	12.31	1.27	6.46	20.48	13.26	-	-
	Industry/business	93.27	46.25	6.09	1.73	11.70	5.77	9.85	9.94	6.09	3.75	-	0.32
	Public service	14.27	4.74	4.61	0.79	1.59	1.00	1.91	1.04	0.75	0.50	-	0.04
	Urban life	27.84	8.61	6.68	0.99	3.41	1.70	6.27	1.49	1.60	1.20	-	0.31
	Rural life	3.17	1.20	-	0.10	0.93	0.83	0.88	0.21	0.95	1.05	-	-
	Ecosystem	5.60	2.47	1.05	0.12	-	0.18	0.90	0.19	0.09	0.03	-	-
	Sum	192.96	74.35	18.97	4.78	26.08	21.79	21.08	19.33	29.96	19.79	9.31	0.67
Fresh water supply/×10^8m^3		192.96	74.35	18.97	4.78	26.08	21.79	21.08	19.33	29.96	19.79	9.31	0.77
Sea water consumption/×10^8m^3		143.09	-	88.92	16.20	-	3.11	37.97	-	19.80	-	2.69	-

The mark "-" means no data information.

Sources: Guangdong Water Resources Bulletin 2010; Water Supplies Department of Hong Kong and the Macao Water Supply Company Limited.

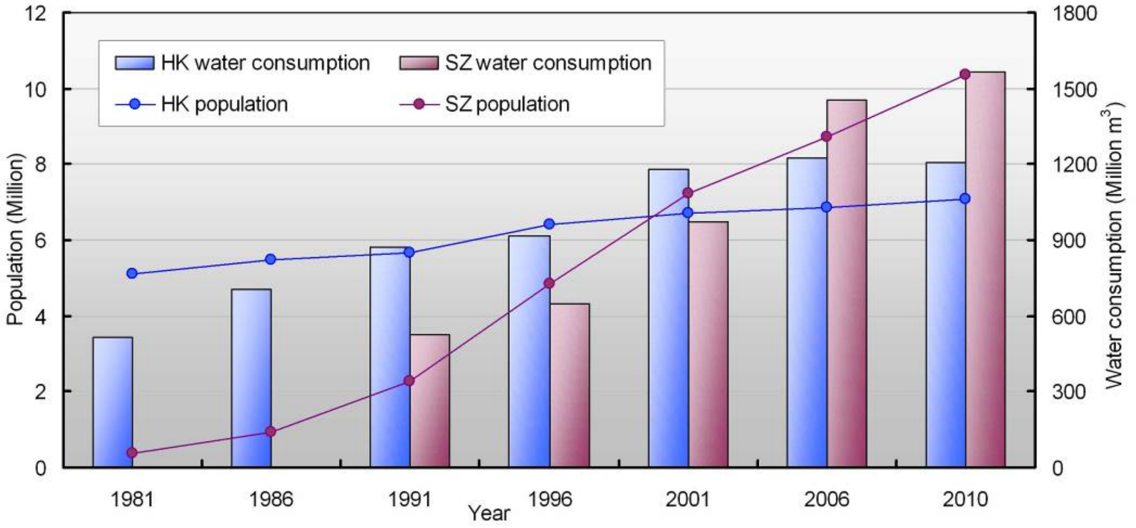


Figure 3-1 Water consumption and population in Hong Kong and Shenzhen

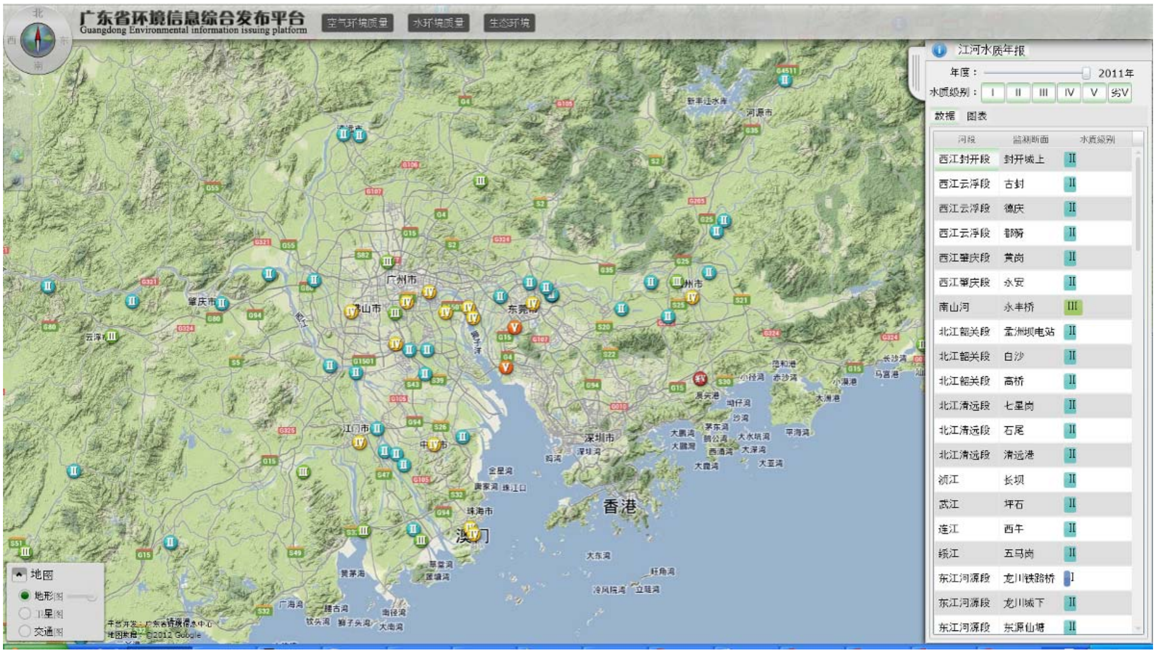
The misconception that the PRD is rich in water resource leads to a long term extensive water consumption in both daily life and industry. The water recycling rate of Guangdong province is 20% to 40%, far below the national standard. The province's per capita water consumption reached 491 m^3, is in top of the nation and is 1.4 times the country's average value. In the province's total water supply volume of 45.7 billion m^3, 17.2 billion are evaporated by the process of transportation and can not return to the surface water bodies or aquifers (Liu *et al.*, 2005).

An amount of 19.296 billion m^3 fresh water was consumed by the PRD cities in 2010 and it will very likely keep increasing in the future. Currently, the GDP per ton fresh water is about 263 Chinese Yuan (40 US dollar), which is comparatively low to those of the developed countries. Extensive water consumption contributes large amount of waste water drained to the river. Increasing sewage water significantly pollutes the river system and reduces the fresh water usable, which forms a vicious circle in water system. In case this situation continues, it’s hardly possible to supply high quality water and efficient wastewater treatment with limited increasing in water facilities. However, it implies at the same time that the water saving potential of the PRD cities would be great when the water saving awareness is broadly enhanced.

3.1.3 Water pollution

In the decades of reform and opening, the urban water systems of the PRD developed quickly along with its rapid urbanization. The basic features are that expansion of the water supply system can basically keep up with the pace of urbanization, while expansion of the sewage treatment system significantly lagged behind the pace of urbanization.

According to a water resource report, the total water resources in the PRD area is decreasing, by pollution. In all the segments of the Pearl River, the PRD segment is highlighted with worst water quality, highest water consumption and largest sewage volume (PRWRC, 2011). About half of the PRD streams are polluted, with river water quality classified as IV, V or worse than V (Figure 3-2). In 2011, 18.81 billion tons of waste water was emitted in the whole Pearl River basin, of which the emissions of the PRD account for 36% (PRWRC, 2011). The most heavily polluted sections are the Pearl River mainstream in the PRD and several small tributaries, like Longgang River, Pingshan River, Foshan Waterway, Dongguan Canal. The major contaminants are ammonia nitrogen, total phosphorus and some aerobic organics.



年度：2011年

河段	监测断面	水质级别
西江封开段	封开城上	II
西江云浮段	古封	II
西江云浮段	德庆	II
西江云浮段	都骑	II
西江肇庆段	黄岗	II
西江肇庆段	永安	II
南山河	永丰桥	III
北江韶关段	孟洲坝电站	II
北江韶关段	白沙	II
北江韶关段	高桥	II
北江清远段	七星岗	II
北江清远段	石尾	II
北江清远段	清远港	II
浈江	长坝	II
武江	坪石	II
连江	西牛	II
绥江	五马岗	II
东江河源段	龙川铁路桥	I
东江河源段	龙川城下	II
东江河源段	东源仙塘	II

Figure 3-2 A screenshot of the Guangdong Environmental Information Issuing Platform (November 30, 2013), focusing on the river water quality in 2011 in the PRD area.

The water quality is classified into five levels (labeled by I, II, III, IV, V with circle) with color range of dark blue, blue, green, yellow and red in this map, which indicate the range from highest quality to lowest quality.

Zhu, et al analyzed the water environment and pollution sources in the PRD and pointed out that domestic sewage is the main source of water pollution (Zhu *et al.*, 2002). They further measured the pollution-caused water loss in 2002, 2010 and 2020, which amounted to 204, 352 and 537 million m^3 respectively. This result indicates the need to effectively control water consumption and sewage emissions in this area. Although the estimated amount of pollution-caused water loss seems not much in the whole PRD, the situation in certain sub-areas are worse. For example in Dongguan, the loss of water resources due to pollution has accounted for 25.5% of its total available water resource, exacerbating the contradiction of water supply and demand (Gong, 2012). The streams of Shima, Hanxi and East Canal converted their original drinking water sources to irrigation and recreation.

In addition, seasonal salty-tidal brings salty water and sea pollutions to the inland river system, which aggravates the water pollution conditions. In case of a drought when river water flows low the pollution even threats water supply for urban living. Further, contaminants deposited in riverbed could be transported to other areas by water transfer project and pose a potential risk (Ho *et al.*, 2003).

3.1.4 Risk of water shortage

Water shortage in the Pearl River Delta is not a mere question of rainfall quantity, which is a natural constraint. But human factors like high demand, high consumption and high pollution are increasingly prominent in the whole system. In the context of climate change, the natural basis of water resources changes and is likely deteriorating the series of problems. Apart from the general trend of climate change, extreme weather events (rainstorm/typhoon, drought, hot wave, et al) also affect water resource. These factors intensify water risks in the PRD area and complicate further water management.

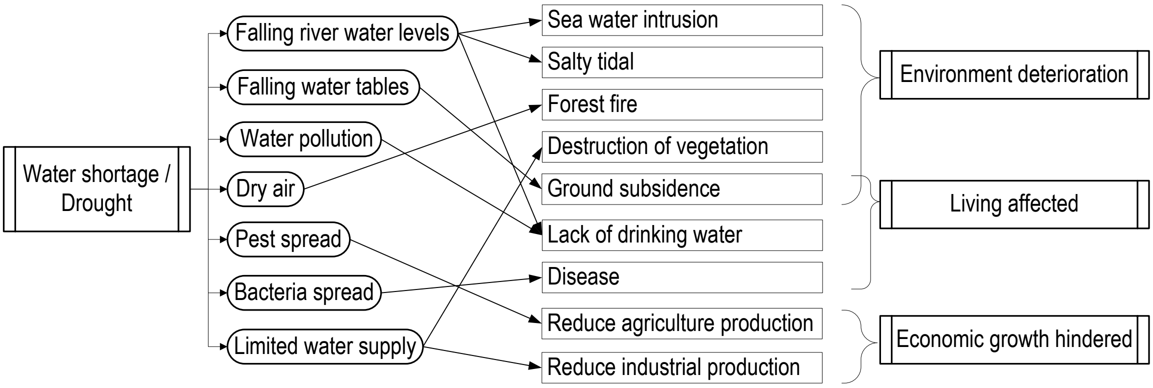


Figure 3-3 Disaster chains of water shortage and drought.
Own representation based on (Liu et al., 2005)

The most severe impact of water shortage and drought is its disaster-chain effect (Liu *et al.*, 2005), which implies not only lack of water but also many indirect sequences, such as pests, diseases, forest fires, ground subsidence, crop reduction and even social instability (Figure 3-3).

Water shortage is a disaster to the environment. Firstly, river water level drops in drought, leading to seawater intrusion and salty tidal. While the emergence of salinity pollutes the already stressful freshwater resources, the drought situation would be further exacerbated. Secondly, people tend to exploit more underground water in times of drought, which used to induce a ground subsidence. And the third, drought environment contributes to dry air and provide a favorable condition for forest fires. Several large forest fires in Guangdong Province in history occurred right in the periods of drought, such as the 1980 forest fires in Huiyang after a continued no-rain (daily precipitation less than 3 mm) day of 104 days (Liu *et al.*, 2005).

Water shortage lowers human-wellbeing. All the PRD cities have the experience of difficulties in drinking water due to drought event. Zhuhai suffers most serious because salty tidal occurs frequently there. In addition, some infectious bacteria and viruses have a strong biological activity in the arid environment and may disperse diseases among human. An example is that, the warm and long term dry environment benefited the spread of SARS (Severe Acute Respiratory Syndrome) in 2002/2003 in Guangdong province (Chen *et al.*, 2004). The emergence of diseases not only affects people's physical and mental health, it is also likely to cause social panic.

Severe water shortage or drought leads to huge economical losses. Drought-introduced pest disaster is the most direct harm to agricultural production. Severe drought also affects industrial production, by reducing producing or discontinuing it. In 1991 the drought forced most of the food, beverage, textile factories in Shenzhen to shutdown their production totally or partly, causing a direct loss of about 200 million Chinese Yuan (37.59 US dollar) (Liu *et al.*, 2005).

Further, the changes or reductions in water availability may cause, bring back or prolong social conflicts between municipalities or between people and authorities on access to water, water use, or water consumption. Three main reasons have been identified as critical factors on the occurrence of water related social conflicts: 1) aggravation of water shortages, a trigger that strains the competition for the resource; 2) public rejection of government decisions that may be perceived as unpopular (e.g. subsidies reduction, increase in tariffs, scheduled reductions in water supply); and 3) additional causes related to local (geographic or sectorial) circumstances, e.g. recurrent drought periods affecting local agricultural activities, lack of infrastructure, or inequitable supply (Brun, 2007). In history, many of the social conflicts that took place in PRD and that were reported by media were related to water resource. Furthermore, the effects of changes in water availability can also generate problems outside the PRD; for instance, water transfer project from the East River (Dongjiang, details in section 3.2).

3.2 Water supply risks in Hong Kong[2]

Even though there are many aspects in dealing with urban water supply, five main points are chosen that are related to the climate change agenda to give an accurate overview of the challenges facing efficient water harvest in Hong Kong.

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[2] This section has been published in the peer reviewed publication: Liang Yang, Chunxiao Zhang, Grace W. Ngaruiya, 2013. Water supply risks and urban responses under a changing climate: A case study of Hong Kong, *Pacific Geographies*, 39: 9-15. As the lead author, Liang Yang is responsible for 80% of the paper's content.

Abundant but hardly usable rainfall: Hong Kong is located in the subtropical monsoon zone with abundant annual rainfall. The average annual precipitation during 1981-2010 was 2398.5mm in HKO's records, which equals an average annual rainfall of 2648 million cubic meters for the whole Hong Kong area. With an actual water consumption of 1206 million cubic meters in the year 2010 (WSD, 2012a), it would appear that Hong Kong could theoretically satisfy its water demands with rainwater. However, it's impossible to collect that high proportion of rainwater in practice because of technical difficulties at the city scale. Another reason is the uneven inner-annual rainfall distribution. Whereby, 80% is received between May and September while 20% is received in the dry season from October to April (HKO, 2012). Thus, it is a considerable level that current Hong Kong rainwater collection has reached around 10% (WSD, 2012a). Nevertheless, this calls for more focused efforts in efficient rainwater harvesting.

Poor conditions for water storage: The landscape of Hong Kong is made up of several peninsulas and a group of small islands, of which about three quarters are covered by hills and another quarter by urban facilities. Due to the small area involved, rivers rise and end quickly, such as the Shing-Mun River and Shek-Sheung River (less than 5 km). Thus the runoff comprising mainly of surface rain water cannot be used after it drains to the sea. Furthermore, Hong Kong has few and small natural reservoirs and it lacks underground water storage capacity due to the granite and volcanic rocks (Su, et al., 2008). Therefore, Hong Kong has unfortunate nature conditions for water storage, which gives another reason why the abundant rainwater is hardly usable. Despite these challenges Hong Kong has artificially constructed several reservoirs which are playing very important role in storing freshwater (see section 5).

Figure 3-4 Poor conditions for water storage with mountainous terrain and highly developed urban areas.

Photos taken by Liang Yang on December 9, 2011.

High dependence on freshwater import: Hong Kong started to import freshwater from Shenzhen in Guangdong Province in 1960. This was further developed into the Dongjiang-Shenzhen Water Supply Project (DSWS Project) that transfers Dongjiang water to Shenzhen and then to Hong Kong. Currently, this DSWS Project supplies more than 70% of the freshwater demand in Hong Kong (WSD, 2012a). Implementation of the Dongjiang Water distribution plan by the Guangdong authorities makes this activity sustainable and mitigated the contradiction between freshwater supply and demand in Hong Kong. Even though this water has contributed significantly in rapid development of the city for the past 50 years, it also shows the high overreliance of Hong Kong on the Dongjiang water.

High water demand: The two main water consumers in Hong Kong are the domestic and service sectors like tourism. These sectors consumed 79.7% of the total freshwater in 2010 (WSD, 2012a). Continual population growth has increased water consumption significantly in the last three decades (Figure 3-1). The graph depicts that the water consumption has increased at a greater rate (2.9%) than population growth (1.1%) in the last three decades, suggesting that water use pattern has changed (increasing consumption per capita). Alongside economic development, tourism has also improved, increasing further the already high water demand. Records show that in 2011, a total of 41.9 million persons visited Hong Kong, of which 22.3 million are overnight visitors and their average stay is 3.6 nights (TCHK, 2011). This is approximately equivalent to 220 thousand additional residents for Hong Kong.

Even though the population of Hong Kong is considered high and very intensive (Figure 3-4), it is still growing. Future population projection shows that the Hong Kong resident population will increase to 8.47 million in the year 2041 (CSD, 2012). Thus, a much higher water demand could be expected in the future and calls for urgent water supply initiatives.

Poor leakage and maintenance management: Although Hong Kong has a complete water supply system, the operational effectiveness of the system is far from expected. The major problem is the annual 20% water loss from the aging water pipe network (WSD, 2012a). This network, comprising underground arterial pipes of about 8000 kilometers in length, is subject to internal water pressure and harsh external influences such as road traffic and ground movement/subsidence and is vulnerable to damage. In addition, natural hazards, like flooding and landslides that often occur in heavy rainfall or storm, occasionally damage water supply infrastructures and result in water loss/outage. Whilst upgrading existing mains is critical in the reduction of water loss along major water mains, this could also be strengthened using district monitoring and pressure management technologies.

3.2.1 Climate impacts on water supply of Hong Kong

Climate change poses a significant challenge on the water resource at many regions around the world. Studies have shown that concentrated areas of human society development such as cities are among the most vulnerable regions to climate change impacts (Stern et al. 2006; IPCC 2007). This section gives an overview of the climate change and its effects on water resource in Hong Kong.

According to data, precipitation increased by 36mm per decade for 65 years after World War II (HKO, 2012) (Figure 3-5). The notable interannual variability indicates that extreme precipitation events occur frequently in Hong Kong during this period (Ginn, et al., 2010). Between 1954 and 2011, the average sea level showed an average increase of 2.8mm annually at the Victoria Harbour (Figure 3-5). Precipitation projection results indicate that annual rainfall in Hong Kong is expected to rise by the end of the 21st century, so heavy rain events from year-to-year are becoming more frequent (Ginn, et al., 2010). But considering the situation of Hong Kong, more rainfall does not mean more usable water. Without proper management, heavy rainfall would even damage the existing water supply system. Furthermore, future rise in sea level near the Pearl River Estuary would exacerbate storm surge flood and the incursion of salty water into fresh water (Wong, et al., 2010).

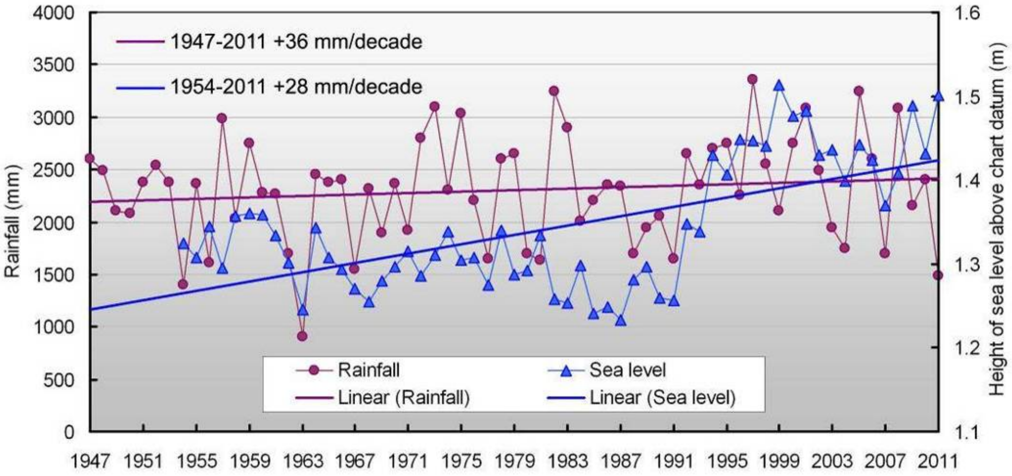

Figure 3-5 Changes of precipitation and sea level in Hong Kong

Source: Hong Kong Observatory

Apart from the general trend of climate change in Hong Kong, extreme weather events (e.g. rainstorm/typhoon and associated landslide, drought, high tides) have even more impacts on the water supply system even more seriously (Wong, et al., 2011). According to the HKO reports, the increasing frequency of extreme weather events would lead to increased flood probability (Ginn, et al., 2010). Water infrastructure is particularly at risk in some low-lying and poorly drained areas near rivers that are marked as flood-prone areas (Chan, et al., 2010). More so in cyclone weather, when seawater is forced up the rivers, invading freshwater systems or damaging engineering facilities. These disasters intensify water risks in Hong Kong and make water management more complicated. In addition, high evaporation in the subtropical region contributes significantly to water losses (Liang, 1997). This should be in concern for water management if it is aware that the average temperature per decade increased from 0.15°C between 1947 and 2011, to 0.23°C between 1982 and 2011 (Hu, et al., 2011), and it will continue in the 21st century (Ginn, et al., 2010).

3.2.2 Water management

The Hong Kong Government has implemented a series of measures to address this water predicament, achieving remarkable success. However, some challenges still exist, which will be elaborated while the measures are introduced in this section.

Dongjiang–Shenzhen Water Supply Project (DSWS Project): Dongjiang (East River) originates in the Xunwu County of Jiangxi Province, flows through Heyuan city, Huizhou city, Dongguan city of Guangdong Province and drains into the sea. Several branch streams flow from Shenzhen to the mainstream (Figure 3-6). The DSWS Project starts from Qiaotou town of Dongguan. Water is pumped and pipelined 46m higher, backwards along the Shima River (a branch of Dongjiang) to the Shenzhen Reservoir and then to Hong Kong.

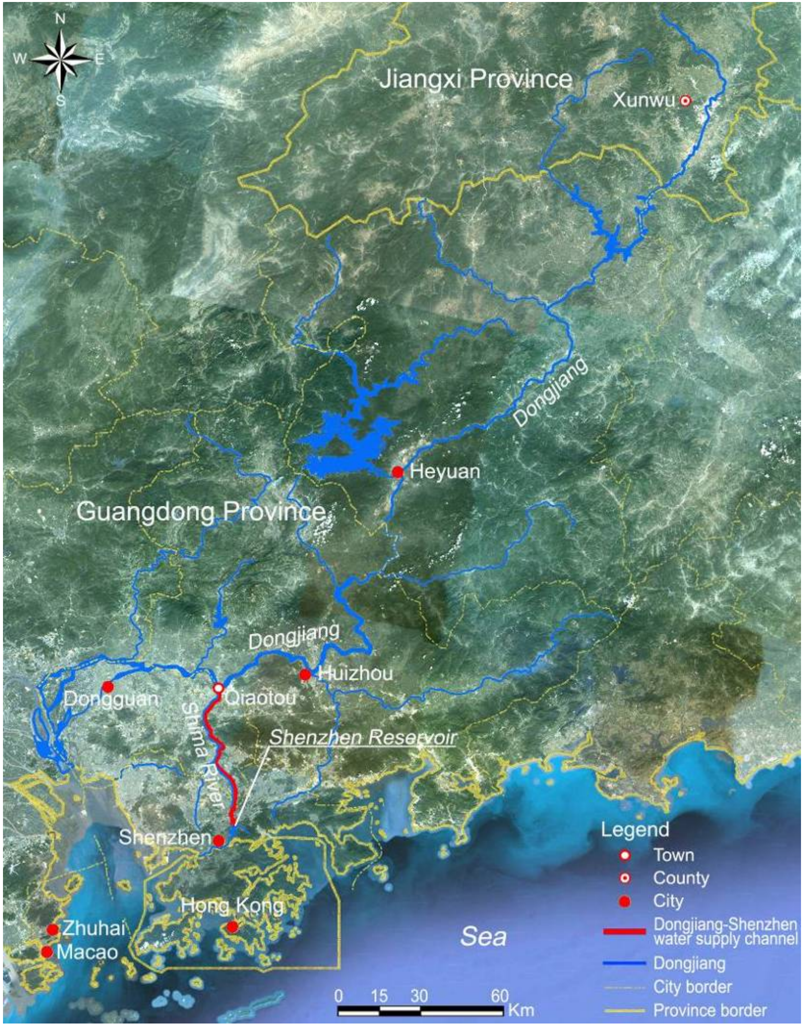

Figure 3-6 Dongjiang river system and the DSWS project.

Source: Edited based on Google map (27.09.2012)

The water supply to Hong Kong has been increasing in the last 50 years (Figure 3-7) with a corresponding change in the agreement.. The significant increase around 1990 can be attributed to population growth and economic development after adoption of the “Sino-British Joint Declaration on the Question of Hong Kong”. The second extension of the DSWS Project in 1987 and the third in 1994 supported this increase in time. Currently, the actual water supply to Hong Kong is 800-900 million m^3 annually, which is nearing the maximum capacity of the project (1100 million m^3 per year) (Hong Kong DNPC, 2011).

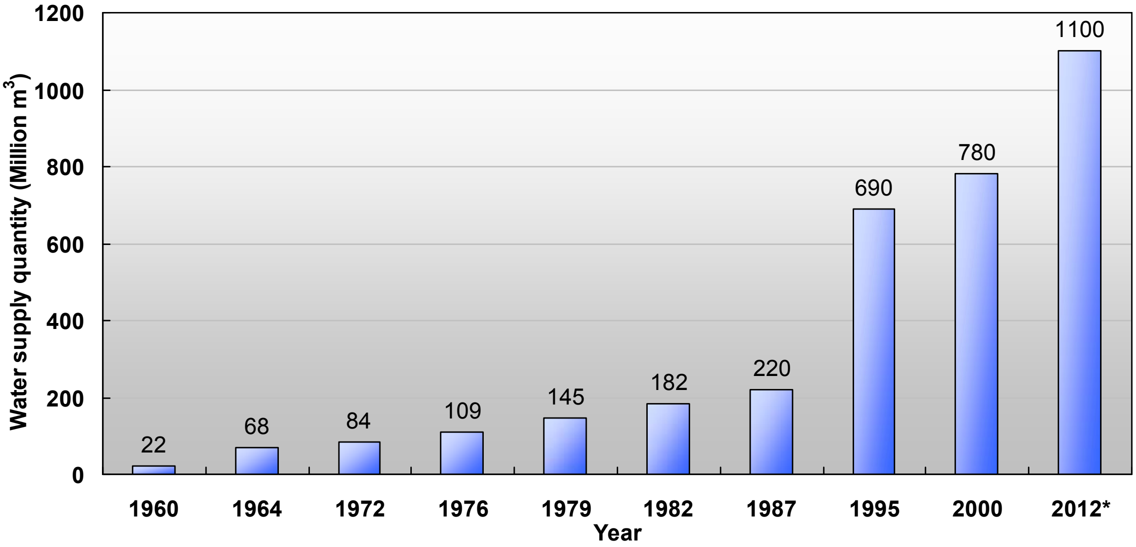

Figure 3-7 Amount of water supply to Hong Kong by DSWS Project

* The value in 2012 is not the actual value, but the maximum capacity of the DSWS project.

However, the project faces many significant challenges due to social and economic differences between the cities in the river basin. Economically, the upper cities (Heyuan, Huizhou) have far lower development level (consider GDP per capita and urbanization rate) than the downstream cities. That means these upper cities are poor, underdeveloped, and have less economic power. The region is also politically complicated. Normally there are four administrative levels (nation, province, city and county), but Hong Kong is a Special Administrative Region between the level of nation and province, and Shenzhen is a Special Economic Zone between the level of province and city. Higher administrative levels have stronger political power. Thus interestingly the Dongjiang water flows down from Xunwu, Heyuan to Huizhou, Dongguan, and is then pumped to Shenzhen and Hong Kong, while the political-economical power goes up in the same city sequence. This means that water resources from the upper area are traded for money or other benefits from the downstream cities, with strong political nature. This system of trade appears to be balanced. But this balance depends highly on both sides’ resource quantity (water in the upper cities and money of the downstream cities) and trade intention (whether they would like to exchange). It could easily be broken by a drought or pollution that reduces the available source water, or a change in social/economic field that raises the unwillingness on trade. Thus, should climate change affect the water supply either in terms of quality or quantity then this will affect the political relationships between stakeholders.

Increased rainwater harvest: Hong Kong has always looked for more effective uses of its rainwater resources. An ongoing project is the construction of diversion channels on hillsides, which channel precipitation and mountain streams into reservoirs (Figure 3-8). So far, rainwater is diverted to 17 reservoirs in a third of Hong Kong area. For example, the High Island Reservoir has the largest storage capacity and Plover Cove Reservoir has the largest area (Figure 3-8). These two large bay reservoirs account for 87% of total reservoir capacity (5.86×10^8 m^3) in Hong Kong (WSD, 2012b). In addition to saving collected rainwater, the reservoirs also play a role in regulating and storing the water from the DSWS Project.

To further increase rainwater harvest, one proposal is to expand the rainwater catchment area and storage capacity of reservoirs in Hong Kong. However, this proposal is not favored by the city because land development in the catchment area would be restricted (Ku, 2003). Actually, one-third of the land has been protected as rainwater catchment area in Hong Kong. And, this plan has a complication in that a larger water catchment area could increase surface contaminants flow into the reservoirs. So the proposal is not a prior option in the near future. Recently, a feasible plan initiated by Hong Kong Government is to identify a number of parks and public buildings to collect rainwater for flushing and irrigation. The plan would be spread if the preliminary experiment works effectively.

Seawater desalination and utilization: Hong Kong established a desalination plan in 1971. Six groups of desalination equipment were built with the production of 30.3 thousand m^3 fresh water per group per day（WSD, 2012c). However, after only operating from 1976 to 1982, it was deconstructed in 1992 due to high running costs and the cheaper and constant water supply by DSWS Project.

Besides seawater desalination, seawater is used widely for flushing toilets, an activity done from 1950 and is now a major feature of the urban water supply in Hong Kong. Seawater is pumped and filtered through grids to remove the larger impurities. It is then disinfected to standard quality requirements and distributed to households. The system has separate water distribution pipes, pumping stations and service reservoirs. Currently the annual consumption of seawater in Hong Kong has reached over 200 million m^3, which saves the same amount of fresh water and accounts for about 18% of the total water consumed (WSD, 2012b). Since about 80% of the residents use seawater for flushing, this percentage is expected to increase to 90% in future (WSD, 2012a). In some areas of Hong Kong, seawater has also been used as the municipal fire water.

Figure 3-8 Photographs of the rainwater collection channels in the Lung Fu Shan Country Park (top two), and the Plover Cove Reservoir (bottom), Hong Kong.

Photos taken by Liang Yang on December 6, 2011.

Wastewater treatment and reuse: Increasing freshwater production inherently results in increased pressure on wastewater treatment and disposal infrastructure. The Hong Kong Environmental Protection Department issued a “Water Quality Indicators of Wastewater Treatment for Landscape Irrigation” guide in 1994. This contained regulations and methods to promote and inform stakeholders on water reuse in irrigation. However, few treated water reuse projects have been launched in Hong Kong presently, one of them being a project of Hong Kong’s new airport on Lantau Island, in which part of the drainage is treated and reused for irrigation. One reason for the low uptake of water reuse initiatives is the absence of water scarcity due to the constant supply by the DSWS Project and seawater flushing. The situation reflects that Hong Kong’s strategy of increasing the sources of freshwater does not address wastewater issues in an integrative way. This might change should the water status change with increase in climate change impacts.

Water demand management: Hong Kong uses a multi-level water charging system to promote water conservation. The payment system has several levels of water consumption levels with corresponding increasing prices. Thus, the water cost per household differs according to their consumption in a certain period. The higher the consumption, the higher price charged by the supplier. This payment strategy enhances public awareness of water conservation by reducing waste and in turn reducing household water demand.

Furthermore, the Hong Kong WSD has also developed a number of other water-saving provisions, such as changing water from swimming pools once a year, using water-saving faucets at public places, which all have further contributed to water conservation and reducing water consumption.

3.2.3 Discussion on water supply risks

As discussed previously, the water supply situation in Hong Kong faces various challenges from both climate impacts and social activities (Figure 3-9). Apart from the challenge of increasing water demand by population growth and economic development, I have discussed six major but interrelated risks, namely: drought, rainstorm/flood events, sea-level rise, water pollution, social management and policy. Figure 3-9 also shows the pathways or area to be addressed to for every risk described.

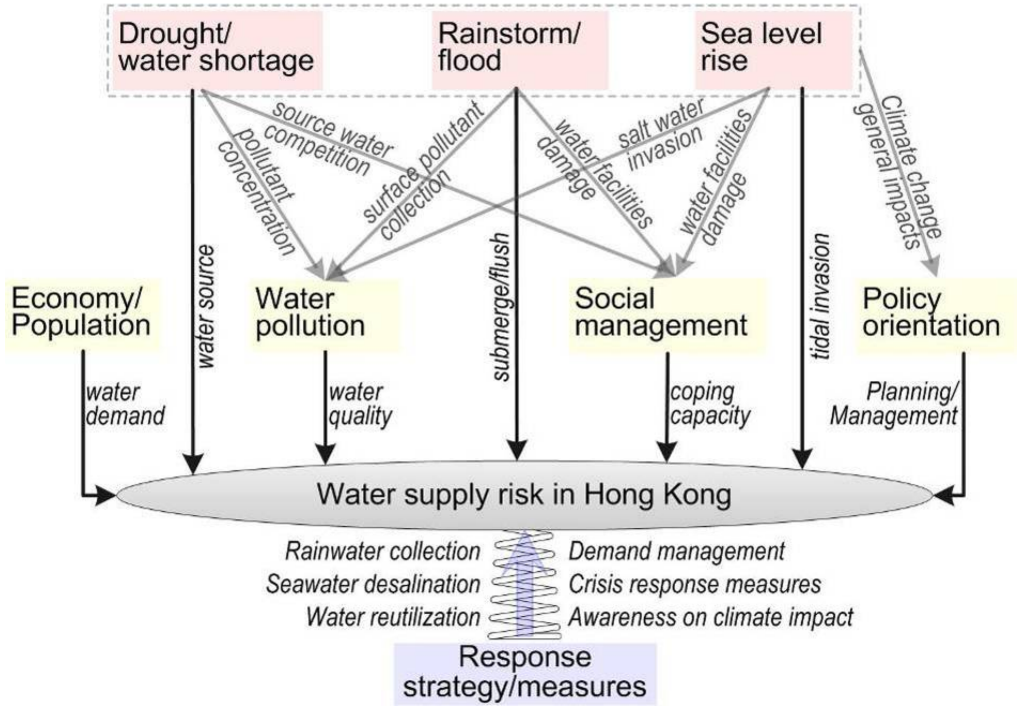

Figure 3-9 Framework of water supply risks in Hong Kong

Drought in the water source area: Given the fast development and growing water demand of the upper cities, competition for Dongjiang water is expected to increase. Despite that Hong Kong gets the water supply guarantee by DSWS Project, should there be a significant drought in the Dongjiang River basin (has occurred in 1963) the effects would be severe and might cause tension between upper stream areas and the downstream cities. Even a moderate drought would have a ripple effect in the system, whereby less flowing water would be more vulnerable to pollutants and would result in an increase in pollutant density. Lower reserve volumes would also make water pumping more expensive due to higher electricity consumption which in turn would increase consumer water prices. Additional water sources need to be introduced into the system as a backup measure.

Rainstorm/flood events: The anticipated increases of rainfall amount from climate change might overload the storm water prevention system and increase the number of flood disasters in Hong Kong. Flood from the rainstorms may not only collect surface pollutants and bring them to freshwater but also damage the water supply pipe network through associated landslides or soil erosion. Thus there is need to invest in flood alarm and prevention, e.g. regular drainage checks to remove blockage and enhance flow.

Sea-level rise: Hong Kong is a highly urbanized city with significant artificial facilities that are threatened by natural riverbed siltation and climate related sea-level rise. In case the sea water entry into the urban system it would threaten water infrastructure through erosion from the salts and flood flushing. The two largest freshwater reservoirs are especially more vulnerable if offshore pollutants along with salty sea water flow into it. The suggested area of action is also regular checks in tidal flows and drainage of sea water from the system.

Water pollution: Cities in the upper reaches of Dongjiang River Basin, Huizhou and Heyuan have accepted setting up of many of the transferred industries from the Pearl River Delta. This combination of industrial contamination, agricultural pollution and dispersive rural sewage is making the water quality of Dongjiang River worse and threatens the supply to Hong Kong and other downstream cities (Liu, et al. 2012). To control water pollution at the source, the upstream cities are restricted in their land development, sewage emission and use of pesticides, which therefore restrict the development of industry and agriculture. Also, Shenzhen and Dongguan demand more water from the DSWS Project but continue to discharge sewage to the Dongjiang River, which makes the situation much more complicated. Even though the upstream cities ask for economic compensation for restricted development and the downstream cities might be willing to compensate them, agreement is hardly reached and no comprehensive compensation mechanism exists (Zhou, 2008; He, et al. 2009), partly due to the complexity of this issue. Another pollution risk for Hong Kong water resource is from the surface ground pollutants that may be transported into reservoirs along rainwater. In such complicated situations on pollution, a multidimensional solution is needed to adequately address all sources of pollution.

Social management aspect: Although Hong Kong returned to mainland China in 1997, social and cultural conflicts between the two still exist although at low intensity. Hong Kong is highly dependent on fresh water, electricity and food from the mainland, but its citizens used to complain about the air pollution from the Pearl River Delta cities in the mainland (Lu, 2007). On the other hand, many mainland people go to Hong Kong for high quality medical care, education or shopping. Some Hong Kong citizens dislike this movement and view it as a reason for the reduction in Hong Kong's public resources. While the mainland people view this attitude as discrimination. These low level societal tensions could be the beginning of large-scale resources conflicts in the future and need to be addressed soon. Another side of social management is to cope with emergency events efficiently and effectively, for example, in a sever water outrage or pollution event, which has been discussed in section 2.

Policy risk: Due to the abundant Dongjiang water, Hong Kong has not seriously invested in self-sufficiency water supply mechanisms in the latest years apart from the experimental seawater desalination. Also, climate security consciousness is still in its infancy in Hong Kong and there has not been an integrated "climate response" policy between urban development, water supply and climate impacts. Even though the public knows about climate change they lack deeper awareness of possible water supply risks under climate impacts. Thus, many options are available but are not implemented because they are not taken seriously. It would be a potential risk for the city if this policy gap continues as it would bring down the public awareness of risk and reduce measures for precaution.

Researchers suggest that the main goal of all adaptation strategies should be to improve local resilience, or the ability of a community to bounce back quickly from climate impacts (CCAP. 2009). Thus to reduce potential water supply risks, the city needs to implement relevant response measures. The response strategy may be done in two ways. One is to improve the self-sufficiency rate of water supply, which is possible by extending the reservoirs' capacity or seawater desalination. The other is to diversify water source options, for example, water treatment and reuse. These will reduce overreliance on imported water which is the biggest potential risk. Apart from these, possible strategies to increase resilience include options of demand management technology and crisis response measures. Also, public awareness campaigns on climate change impacts and response strategies need to be undertaken so that people in Hong Kong can prepare for climate change impacts. Finally, further research on urban responses to climate impacts will support decision making to mitigate potential water risks.

Hong Kong is a city with sufficient average precipitation, but it still suffers from water shortage because of natural and social conditions. Most of the drinking water is transferred by DSWS Project from Guangdong, sustained by political and economic power in a water supply agreement. However, should conditions change, like a severe drought or pollution in the Dongjiang River basin, it could become a potential social security problem. In addition, although urban development and water supply-drainage systems are well designed and planned in Hong Kong, natural hazards like extreme weather events could destroy water related infrastructures, especially in the context of global climate change. Lack of public awareness on climate impacts has also made the government take few measures to deal potential climate risks. It is clear that ensuring sufficient freshwater availability is the major water management challenge for Hong Kong. To reduce risks in the future, it's absolutely crucial for Hong Kong to improve its self-sufficiency rate of water supply and diversify water sources.

3.2.4 Short summary

Hong Kong is often portrayed as a water abundant city because of its location in the subtropical zone. However, Hong Kong currently imports large volumes from the Dongjiang-Shenzhen Water Supply Project (DSWS Project) due to low local freshwater availability. The water situation is becoming more complicated with the population growth, economic development and difficulties in response/management. In addition, studies show that climate change is likely to increase rainfall variability, flood and drought events and damage water supply infrastructure in Hong Kong. Hence, ensuring sufficient freshwater availability is the major water management challenge for Hong Kong. This article discusses the issues in current water supply system and also highlights six interrelated risks within the context of climate change, namely: drought, rainstorm/flood events, sea-level rise, water pollution, social management and policy gaps in Hong Kong. In conclusion, it suggests that for a sustainable future, Honk Kong needs to invest in improving water self-sufficiency, diversify water sources and conduct aggressive public awareness to increase individual adaptation to predicted climate change impacts.

4 Flood risks and urban responses in the PRD cities[3]

4.1 Framework for urban flood risk assessment

A commonly used conceptual Source-Pathway-Receptor-Consequence-Model (SPRC-Model) presents that flood risk is composed of risk source, risk receptor, the pathway from source to receptor and the risk consequence (Sayers et al., 2002; Schanze, 2006). This model reflects the physical processes by which flooding occurs, thus accordingly, the assessment of flood risk can be expressed by the function of the four factors. However, existing research shows assessment methodologies of three types: risk level assessment, risk scale assessment and risk distribution assessment. Risk level assessment uses point estimates (e.g. 95th percentile) to calculate a percentage that indicates the risk level/degree (UN, 1992; Cançado *et al.*, 2008; Apel *et al.*, 2009; Merz *et al.*, 2010a; Escuder-Bueno *et al.*, 2012). Risk scale assessment discusses more about the potential damage/loss value that indicates the possible range of risk consequence . Risk distribution assessment uses distribution of possible lost values to present maximal and minimal risks that might be experienced by different individuals (UK-DoE, 1995; Schafler et al., 2007).

This study integrates the concept and assessment terms of flood risk into one framework (Figure 4-1). It illustrates the simple causal chain ranging from the meteorological and hydrological events (risk source) through the discharge and inundation (pathway) to population or social assets (risk receptor), which would cause damage/loss or related costs (risk consequence). Flood risk usually rises from heavy rain events like typhoon, intensive rainstorm, while dyke breach and tidal surge are also common in special regions. In urban area, drainage blockage could also cause local flood. But it's more of a factor that could worsen the effects of a flood raised from other sources.

Vulnerability is the degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon (UN, 1992), i.e., the exposure of people and assets to floods and the susceptibility of the elements to suffer from flood damage. Vulnerability V represents the societal processes and is composed of exposure E, susceptibility S and adaptive capacity Ac (Merz *et al.*, 2010a).

Exposure is the ratio of susceptible welfare value to the whole welfare value. Exposure can be understood as the values that are present at the location where floods can occur. Due to different understanding on vulnerability, some researches single out exposure as a direct risk factor in specific analysis

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[3] The sections 4.2, 4.3 and 4.4 are parts of a paper submitted to the peer reviewed journal *Regional Environmental Change*: Liang Yang, Jürgen Scheffran, Huapeng Qin, Qinglong You. Climate-related Flood Risks and Urban Responses in the Pearl River Delta, China. As the lead author, Liang Yang is responsible for about 80% of the paper's content.

(Karmakar et al., 2010; Lugeri et al., 2010; Camarasa-Belmonte and Soriano-Garcia, 2012).

Penning-Rowsell and Chatterton defined susceptibility in 1977 as the relative damageability of property and materials during floods or other hazardous events. The IPCC (2001) argued susceptibility as the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.

Adaptive capacity (adaptation, resilience) was considered as an indicator of vulnerability (Karmakar et al., 2010) or as post-incident behavior (Lamb et al., 2010). Even some research does not consider the role of response measures when discussing a flood risk assessment (Apel et al., 2004). In fact, feedbacks exist between risk event and the receptor when a risk event is in occurrence, which significantly adjust the damage degree of the risk event mainly by mitigating the exposure and sensitivity of the elements that are in suffering. Various mitigation measures can be taken for reducing the exposure and sensitivity of risk receptor, or mitigate the flood hazard by increasing drainage capacity or weather modification. Furthermore, depending on the importance of each element exposed (considering environmental, social and economical aspects) and on its adaptive capacity, its vulnerability can be different.

Consequence analysis is always a mixture of the quantitative and qualitative. Some components can be measured, estimated or projected with a relative precision but others rely more on qualitative analysis. A wide range of analytical methods and tools are available for consequence analysis, including sophisticated mathematical modeling using computer programs and software packages (Schafler et al., 2007).

The quantitative risk definition, taking flood risk as an example, it is composed of possibility of hazard occurrence (source), the vulnerability of risk receptor and the value of potential damage/loss (consequence), whereas the pathway/feedback is implicated in vulnerability. But this is often expressed in two ways: risk level assessment and risk scale evaluation. Risk level is the function of the possibility of hazard occurrence and the vulnerability of risk receptor. Risk scale is a quantitative expression of the potential damage/loss plus associated costs in responding in and recovering after the risk event. For flood risk, in quantitative assessment, the most common definition is that it consists of the probability of a flood hazard (risk source) and the vulnerability of a flood-prone area (risk receptor) which implicates the extent of effect (pathway) and response (feedback) (UN, 1992; Cançado *et al.*, 2008; Apel *et al.*, 2009; Merz *et al.*, 2010a; Escuder-Bueno *et al.*, 2012).

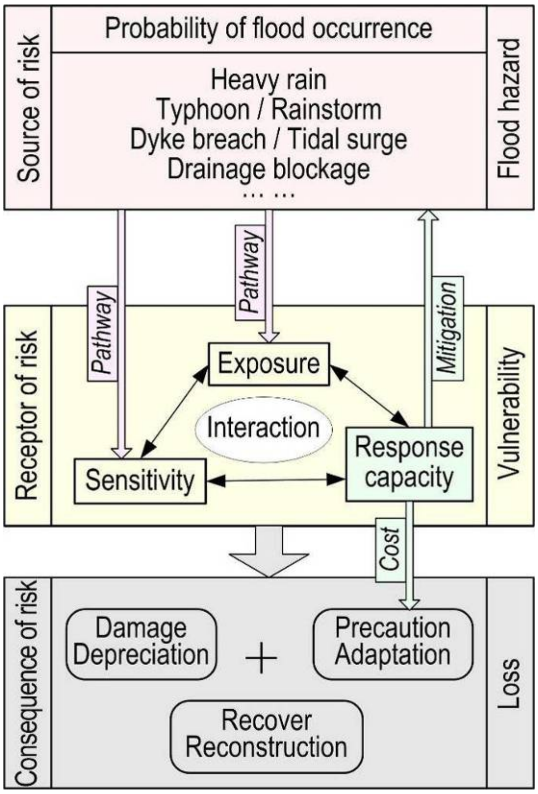


Figure 4-1 Flood risk diagram

Defining the hazard and vulnerability can be undertaken separately in the first place, but have to be combined for the final flood risk analysis (Apel et al., 2009). This study adopts the common definition of flood risk and draws a risk diagram of pluvial flood for quantitative assessment (Figure 4-1). The risk diagram illustrates the components consider for the risk assessment and the relation between some key terms: flood risk of Shenzhen is composed by the possibility of a flood hazard occurrence and the city's vulnerability which associates with its exposure, sensitivity and adaptive capacity. Hazard is a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area (UN, 1992), i.e., the physical and statistical aspects of the actual flooding (e.g., return period of the flood, extent and depth of inundation). The flood hazard is the source of a flood risk, including heavy rain, rainstorm, limit drainage capacity or drainage blockage.

For both the hazard and vulnerability analyses a number of approaches and models of different complexity levels are available, and many of them were used in scientific as well as applied flood risk analyses and on different scales (Apel et al., 2009). For example, methods of mathematical formulation quantify the degree of flood risk in a potential flood area (Dawson et al., 2005; van Manen and Brinkhuis, 2005; Karmakar et al., 2010; Balica et al., 2012; Escuder-Bueno et al., 2012), and methods of hydrological/hydraulic simulation show the process and effects of an assumed flood incident (Anselmo et al., 1996; Morris et al., 2009; Karmakar et al., 2010; Camarasa-Belmonte and Soriano-Garcia, 2012).

In this study a mathematical expression (Equation 2) was developed based on the above risk diagram:

$$FR = PH \times V(E, S, Ac) \qquad 2$$

where flood risk, *FR*, is calculated as a function of the possible flood hazard, *PH*, and the vulnerability of a flooded area, *V*. Here *PH* implicates the possibility of the occurrence of a destructive flood incident, e.g. the possibility of the occurrence of a five-year flood is 20%. While *V*, the vulnerability of a flooded area, is the function of exposure (*E*), sensitivity (*S*) and adaptive capacity (*Ac*), each defined by a set of indicators that represent several particular properties (e.g. population density) of the affected urban area.

4.2 Flood hazards in the PRD area

Flood risk exists on the entire PRD every year as the main causes, local and upstream rainstorms, happen frequently every year. As a coastal metropolitan area PRD suffers also from typhoon and tidal surge especially in the context of climate change. Rapid urbanization, poor drainage system and other human activities further aggregate the occurrence probability of a flood. The following section discusses these causes in detail and gives an overview to the flood risks of the whole PRD area.

4.2.1 Rainstorm and river flood

Flooding in the Pearl River Basin is formed primarily by rainstorm, caused by atmospheric circulation in the first flooding period between April and July and by tropical monsoon and typhoons in the second flooding period of August and September. Floods have very high peak and long duration. When floods in the major tributaries of Xijiang and Beijing encounter each other, devastating floods occur in the Pearl River Delta.

From the large-scale point of view, the frequency and threat of flood in the Pearl River Delta is different spatially. The coastal areas have a higher frequency of floods and more severe flood risks because these areas are highly vulnerable to the influence of the tide, typhoon, heavy rain, as well as a significant rise in sea level. In Huang’s research, three zones are identified as least affected, heavily affected and severely affected. The impacts are also translated into return periods of water level. It is suggested that in a large part of the delta plain, return periods will be shortened and hence will be increasingly vulnerable to tidal inundation (Huang et al., 2004).

The flood threat is relatively mild in the central region of the Pearl River Delta as there are many water conservancy projects that manage and regulate the river water. In fact, the river flood occurs mainly in the western and northern areas of the Pearl River Estuary. While Shenzhen and Hong Kong, locate in the east part, don’t suffer obvious river flood. It’s the reason why some research does not even consider the two cities, though they do research on the flood issues of Pearl River Delta (Chen et al., 2009; Yang et al., 2010). However, the local small-scale flood can be seen every year in Hong Kong and Shenzhen.

Varying along with the rainfall season, heavy rainfall and storms come between May and June in the year, and usually continue a few days which cause large-scale flooding and landslides, and thus serious traffic chaos. As the result of climate change, the increasing frequency of extreme weather event indicates that flood possibility from typhoons and storms will increase. Especially in a storm or typhoon weather, seawater reverses along the river and invades to the freshwater or damages the engineering facilities. Some low-lying and poorly drained areas are affected frequently by flooding. And there are still many people living in these low-lying flood-prone areas, of which the Shan-Pui-Ho River in northern Hong Kong is an example.

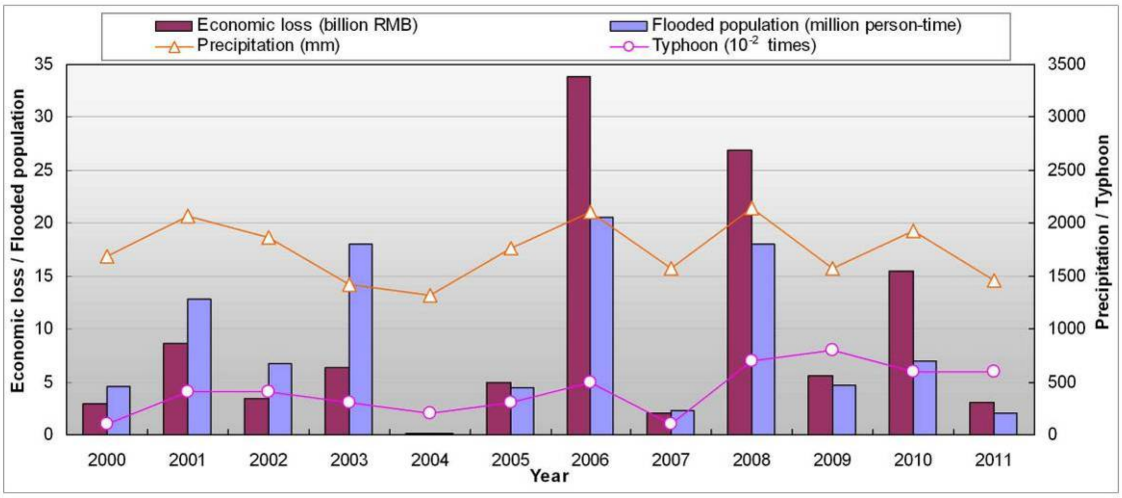


Figure 4-2 Precipitation, typhoon and flood impacts in Guangdong Province between 2000 and 2011.

The flood impacts (economic loss and flooded population) indicate impacts mainly by water flooding, but also include those by tropical cyclones, typhoons and the associated influences. The special unit “person-time” indicates a combination of flooded people and flooded times. The real number of typhoon occurrences is multiplied by a factor 100 for better visualization in this figure. (Own representation based on the Water Resources Bulletin of Guangdong Province from 2000 to 2011).

High precipitation causing flood often affects a large population (2001, 2006, 2008) (Figure 4-2). While during the years of low precipitation flood impacts are low, except the year 2003 when the terrible typhoon Dujuan (international No. 0313) affected PRD directly with short-intensive rainstorm and strong wind. Figure 4-2 also shows that a large number of typhoons does not mean worse flood impacts as in 2009, 2010 and 2011. The reason might be that typhoon doesn’t always bring rainfall and flood.

Inland flooding also occurs as a result of heavy rain. More than 1,700mm of rainfall on average (80% of annual rainfall) is typically recorded from May to September during the typhoon season. The HKO noted that the return period of intense rainstorms of over 100mm/hour has shortened from 37 years to 19 years over the last century. In the last decade, the HKO also recorded that the intensity of short-term (hourly) heavy rainfall has increased from 110mm to above 140mm. However, as the period of record (from 2000-2010) increases, the probability encountering a higher value from an unchanged distribution (from 1970-2000) also increases. Therefore, both the peak intensity and frequency of intense rainstorms has increased.

Annual precipitation and extreme rainstorms are projected to increase over the next century. Hong Kong has recorded heavy rain of more than 200mm over a 24-hour period during some days of every rainy season since 2000, which increases the number of flash floods (sudden-onset flooding) and poses a major problem for the urban drainage system (Chui et al., 2006).

From the large-scale point of view, the coastal areas of the PRD have a higher frequency of floods and more severe flood risks because these areas are highly vulnerable to the influence of the tide, typhoon, heavy rain, as well as a significant rise in sea level (Huang *et al.*, 2004). The flood threat is relatively mild in the central region as there are many water conservancy projects that manage and regulate the river water. In fact, the river flood occurs mainly in the western and northern areas of the delta. While Shenzhen and Hong Kong are located in the eastern part, they don’t suffer obvious river floods. However, the two cities face a lot of local small-scale floods caused by intensive rainfall and stream overflow. Some low-lying and poorly drained areas are frequently affected. For example, still some people live at low land near the river in the northwest Hong Kong, which is marked as flood-prone area (Figure 4-3).

Flooding in cities is usually called waterlogging, which occurs frequently in PRD cities like Guangzhou, Shenzhen and Hong Kong. Heavy rainfall is one of the reasons, while the key cause is often poor local drainage due to lagged up responses in old city areas. In addition, large area of lands are covered by buildings and cements in rapid urbanization, which increase the surface runoff and rainwater accumulation for waterlogging. Although local governments take lots of efforts to address specific waterlogging, the problem still exists and even new places suffer from it occasionally (Zhang and Ouyang, 2011).

Figure 4-3 Riverside residences at Shan-Pui-Ho River, Hong Kong
Photo taken by Liang Yang on December 12, 2011

4.2.2 Sea level rise and flood implication

In case of the previously mentioned 20 to 33cm sea level rise by 2030, large areas would be heavily and severely affected. At the same time, the return period of a certain high water level will be shortened, which will hence increase the probability of suffering tidal inundation (Huang et al., 2004). Adding to this is the fact that a large number of existing tidal flood defenses are below the standard set by the provincial government, posing a serious challenge to the local authorities. If the PRD region fails to take precautions, it will suffer multiple serious impacts of submersion, storm surges, dike failure and drainage difficulties which are described below in detail. A calculation shows that if sea level rises by 30cm in the future 50 years, the dykes must be raised by 1m, which will cost about 6 to 8 billion RMB (Chen and Chen, 2002). Based on current construction prices, a large investment to improve the defenses is needed urgently.

Sea water inundation. The absolute magnitude of sea level rise may be not remarkably great, but its actual impact is huge, considering the combined effects that the delta region is low and the costal ground is subsiding. Huang's research (Huang et al., 2000) has shown a ground subsidence rate of 1.5mm ~ 2.0mm per year in the PRD plain and the magnitude of land subsidence will be between 9 and 12cm in 2050 with respect to the situation of 1990. Using calculations based on the elevation data of ASTER GDEM (V1), the PRD land areas with elevation below or equal to sea level is 541.03 km^2 and accounts for 0.97% of the whole PRD plain. Below 1m the area is 1185.03km^2 (2.12%) and below 3m it is 4390.19km^2 (7.86%). Therefore, even the modest projected sea-level rise of 13cm by 2030 (Chen et al., 2008) will cause sea inundation that affects more than 500 km^2 in the PRD area and a large part of the delta plain will be vulnerable to tidal inundation, if no prevention measures are taken. If the sea level rises by 1m, more than 1000 km^2 of the PRD land will be lower than the sea level where cities like Zhuhai, Zhongshan, Dongguan, Guanghzhou and Foshan will be effected by sea water and more than 1 million people would be forced to relocate.

Storm surge. Areas with elevation above 1m would also suffer notable risks of storm surge. Records between 1991 and 2005 show that the coast of Guangdong was affected by more than 41 typhoon-induced storm surges (an average of 2.7 times per year) (Zhang, 2009). It also shows that the range of maximum sea level rise caused by storm surges in the Pearl River estuary was between 1.9 and 2.6m. In a severe typhoon, such as Typhoon Wanda of 1962, storm surges could be 4m higher than usual (Lee et al., 2010). This is enough to cause coastal flooding. Tidal gauges in Hong Kong recorded storm surges of 2.5 to 3.2m as a result of Typhoon Hagupit in August 2008 and Typhoon Koppu in September 2009, flooding the Town Centre of Tai O and damaging many properties (Chan et al., 2010). This indicates that either Hong Kong has not yet fully mitigated its risks from storm surges, or that the strategy is insufficient to cope with the new situation.

Dyke system failure. One obvious impact from rising seal level is that coastal dikes and other coastal projects will lose effectiveness. Sea level rise greatly increases the possibility of water level to a certain height of storm tide, so that the return period of an extreme tide is significantly shortened. Undoubtedly, this will result in increased opportunities for sea water overtopping the coastal tides. As shown in Huang et al. (2000), the dikes originally designed for 100-year flood prevention in PRD could not even resist a 20-year flood in the case of a 30cm sea level rise. This is likely to aggravate flood risks in the coastal area, considering the shortened return period of the storm surge. The coastal dike system would also be damaged by more salty tides, which erodes dikes although they are not seen as floods. Sea level rise would push saltwater to intrude further into inland rivers and erode inland flood-fighting facilities as well, which poses a serious threat to river bank security.

Drainage difficulties. In case of sea level rise, the backwater flow at river estuary will decrease the drainage capacity and intensity and prolong the drainage duration. Actually, about 1% of the PRD land is currently below sea level and many low areas rely on electromechanical drainage. It is clear that the number will increase along with sea level rise and more lands will suffer longer waterlog and increased flooding losses. In order to ensure the drainage effectiveness in low-lying lands, the installed capacity of mechanical and electrical drainage must increase at least 15%-20% in the case of 50cm sea level rise (Fan, 1994).

4.2.3 Emerging flood risk from human-induced factors

The impact of climate change, from increased storm surge and sea-level rise, are of lesser effect compared to other types of human-induced environmental change in the Pearl River Delta. One significant example is the effect of land reclamation: Large-scale reclamation projects have actively altered coastal ecologies and hydrological patterns, reducing the complexities and resilience of these areas. The effects of climate change amplify these negative effects and increase vulnerable areas within the cities.

Since 1980, the coastline of Pearl River Delta has undergone extraordinary changes in response to rapid urbanization. Land reclamation and long-term riverbed sand excavation to supply the construction industry has increased susceptibility to salt-water intrusion from natural tidal fluctuation, which is further compounded with sea level rise. The annual amount of dredged sand is more than double of the naturally replaced sand through sedimentation, causing shoreline erosion and potentially weakening coastline infrastructure.

As a consequence of economic growth in the PRD, land use is changing dramatically. For example, two-thirds (63.6%) of the agricultural land available in 1979 had been developed for industry, commerce and housing by 2005 (Chan et al., 2010). This level of urbanization means that many more residents and businesses are exposed to potential flood hazards. Such developments also increase the likelihood of flooding due to human-induced hydrological changes, which include:

- Urbanization changes land surface characteristics, thus alters the rainfall-runoff relationship, which leads to increased and earlier flood peak flow, shorter flood duration and increased flood volume.
- In order to meet the water demand of an increasingly dense population, excessive exploitation of groundwater in the PRD led to land subsidence which made the delta more vulnerable to flooding (Huang et al., 2004).
- Rapid urbanization drives significant riverbed dredging for construction materials. Although river dredging could potentially increase the channel cross section and reduce the flood risk, intensive dredging and abnormal riverbed excavation exacerbates river bank erosion and therefore increases the possibility of riverbank outburst.
- The growing population occupies an increasing river beach by land reclamation along the Pearl River estuary, which seriously narrowed the river channel and reduced the river's natural capacity of draining and regulating flood water (Tai, 2011). Flood threats will very likely increase in this situation if no remedy were taken. Moreover, natural flood water storage has been sacrificed as well, as seen in the drainage of large natural wetlands for urban development around the Shekou Peninsula in Shenzhen (Li and Damen, 2010).

4.3 Flood vulnerability of the PRD cities

Apart from high likelihood of flood occurrence, societies worry about flood risk due to their vulnerability (Balica *et al.*, 2012). Consistent with common usage and definitions by Adger (2006), Füssel and Klein (2006) and IPCC (2007a), vulnerability to climate change is a function of the sensitivity of a system to changes in climatic conditions, adaptive capacity, and the degree of exposure to climatic hazards. Accordingly, this section analyses the vulnerability of PRD to flood hazards by identifying its three elements: exposure, sensitivity and adaptive capacity. Then the findings are combined with a quantification assessment to describe the relative vulnerability of PRD cities.

4.3.1 High exposure

Flood exposure is defined as the predisposition of a system to be disrupted by a flooding event due to its location in the same area of influence (Balica et al., 2012). As adopted in the PRD urban area, flood exposure indicates the predisposition degree of urban sections being prone to suffer flood hazard (rainstorm, sea level rise, storm surge caused by typhoon etc.). The urban sections can be anything that are valuable to the urban society. However, people and assets are the two key sections, as more people and assets mean higher potential of flood loss.

The PRD consists of 55869.8 km^2 of land, is now the fourth largest economy in Asia, just behind Japan, South Korea and India, and connects the Hong Kong Special Administrative Region, Shenzhen and 9 other cities (Macau, Guangzhou, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, and part of Huizhou and Zhaoqing) making it one of Asia's mega-regions. The PRD has experienced high population growth from internal domestic migration. In 2010, its population was 56.2 million, and the cities in PRD are planned to merge into a mega-region with population of around 60 million by the 2030s (BFRC, 2008). The PRD served as an export manufacturing zone during the early phase of China's economic liberalization. GDP growth clocked 16.2% per year between 2000 and 2010 and reached 3767.33 billion RMB (SBGP, 2011). Double digit growth is expected to continue in the delta.

The urbanization that follows such economic and population growth can increase flood risk and expose many more people to flood hazards. As mentioned previously land areas with elevation below or equal to sea level currently accounts for 0.97% of the whole PRD plain, that below 1m accounts for 2.12%. Most of these low-lying areas are exposed to flooding. In fact, nearly all the areas of PRD are exposed to different types of floods according to a research on spatial pattern analysis of PRD flood: regions in the upper and middle PRD are exposed to fluvial flood due to the high density of the crisscross-river network, while the coastal region is seriously exposed to flood because it is extremely prone to the emerging typhoons, storm surges, salty tides and well-evidenced sea level rise (Yang et al., 2010). However, urban development has a very prevalent and strong trend of expanding to lower and flatter coastal zone, such as the Qian Bay development in Shenzhen, exacerbating more exposure to both river flood and sea level rise.

4.3.2 Overlapping sensitivities

The concept of sensitivity, or susceptibility, has developed through the years. The IPCC (2007a) argued sensitivity as the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. However, this definition is still in argument and is creating confusion between social and natural scientists (Harvey and Woodroffe, 2008; Wolf, 2012; Crawford-Brown *et al.*, 2013). Sensitivity relates to system characteristics, including the social context of flood damage, especially the awareness and preparedness of people regarding the risk they live with (before the flood), the institutions that are involved in mitigating and reducing the effects of the hazards and the existence of possible measures (Balica et al., 2012). In this thesis, flood sensitivity indicates the degree of urban sections to be harmed by flood hazard (rainstorm, sea level rise, storm surge caused by typhoon etc.). A higher sensitivity means to be easier and more severely damaged.

Sensitivity is first expressed in terms of the situation of the disadvantaged people in PRD cities. Most of the seasonal migrant workers (famers who go to cities for temporary jobs) attracted by rapid industry development of the PRD metropolitans, laid-off workers in state-owned enterprise reform and other local low-income people (fishers, self-employed etc.) are in the weakest positions. They live mostly in informal settlements with poor/substandard housing materials along the low-lying coastal zones of the city, which are affected by pollution, flooding and sea tides. Experiences have shown that they are of the groups that are most vulnerable to hazards, most easily to be harmed and most difficult to recover (Shan, 2011). Aside of this, rapid changes of the cities left a lot of infrastructures with inappropriate planning and construction in flood prone areas, as well as prolonged usage of old buildings, high building density and lack of green areas and shelters, which together significantly increase urban sensitivities in certain sub-regions. Further more, severe flooding in PRD area will lead to recession of the industry and trade in the delta and Hong Kong, even affect the world, as the PRD is one of the main manufacturing and trade centers in China. In fact, continuing development of the industry and trade in PRD is built on the foundation of abundant cheap labor and radical expansion of infrastructures. The superposition of people, infrastructures and economy give the PRD cities a high sensitivity to flood hazards.

4.3.3 Increasing but uneven adaptation capacity

Generally speaking, the adaptation capacity to natural disasters has increased significantly in the last thirty years in all the PRD cities, and it is still increasing. While, uneven adaptation capacities exist evidently between hard and soft aspects, from city scale to community/household scale, and among different cities.

One of the fruits of economic development is reflected in the emergence of various favorable infrastructures. Compared with 30 years ago, the more sturdy housings, convenient transportations, efficient drainage and flood-control facilities are successful outcomes in the PRD cities. There is no doubt that these facilities has greatly increased the ability of adaptation and response to flooding. However, there are severe shortages of the public's awareness and knowledge of disaster prevention. Vulnerable people have weak awareness of taking precaution measures, low capacity of self-help and poor resilience, which form a phenomenon of "flustered before, helpless in and dependent after disaster" (Qu et al., 2009).

Local communities have low capacity in preventing flood hazards, comparing with governments. On one hand, local communities are loose inefficient organizations. They lack not only money but also necessary resources, information, facilities and so on. On the other hand, the PRD cities have a high proportion of immigrants due to great industry development. Previous study has shown that high proportion of immigration is one of the important factors to cause increased heterogeneity within the community (Rosemary and Jennifer, 2003). The population differences are likely to cause psychological disagreements in the community, resulting in reduced social interaction and weak network. Therefore, high social heterogeneity of the PRD cities makes it hard to practice self-rescue and mutual help in the community level, in case of a flood disaster. This is why the micro social system shows typical low capacity of resistance and resilience in the face of sudden disasters.

Obvious differences exist among PRD cities regarding economic strength and development level. These differences may negatively effect cooperation in flood prevention, e.g. arguing the balance of rights and obligations or stressing different focuses and attentions. In addition to the fact that the administrative gap (Hong Kong and Macao are Special Administrative Regions, Shenzhen is a special economic zone) increases institutional differences, all the uneven aspects together results a poor coordination among the cities in adapting flood hazards.

4.3.4 Quantification of integrated vulnerability

For a quantitative assessment of the integrated flood vulnerability in the PRD, the method of the vulnerability indicator system was applied, which has been used and suggested by many researchers (Xie et al., 2008; McLaughlin and Cooper, 2010; Balica et al., 2012). Regarding the institutional differences, data availability and comparability, a simplified indicator system was used in this study. Since vulnerability (V) to flood has been defined as a combination of three elements (E, exposure; S, sensitivity; Ac, adaptive capacity), the indicators are also sorted into three parts accordingly (Table 4-1). A total number of 15 indicators are used in general to quantify the vulnerability of PRD cities to flood, adopted from (Jiang et al., 2009; Yoo et al., 2011; Balica et al., 2012).

Table 4-1 Indicator system for flood vulnerability evaluation

Element	Indicator	Definition	Function
Exposure (E)	Land elevation	Ratio of low-land area (<= 3m above the sea level) in the city	+
	River system	Drainage density defined as river length divided by land area	+
	Precipitation	Average of the annual precipitations (2002-2011)	+
	Urbanization	Urbanization level (the proportion of urban population)	+
	Built-up area	Ratio of built-up area in the city	+
Sensitivity (S)	Population density	Population per km^2	+
	Road density	Average length of roads per km^2	+
	Sensitive Population	Ratio of population less than 15 and elder than 65 years old	+
	Economic density	Gross Domestic Production (GDP) per km^2	+
	Economic section	Number of small & medium-sized enterprises plus individual businesses	+
	Unemployment rate	Ratio of unemployed persons in the labor force	+
Adaptive capacity (Ac)	Economic power	Gross Domestic Production (GDP) per capita	-
	Education level	Ratio of the population with college/university degree or higher	-
	Drainage system	Average length of drainage network per km^2	-
	Vegetation	Ratio of afforestation coverage areas in the city	-

+: the indicator has a positive relationship with vulnerability; -: the indicator has a negative relationship with vulnerability.

In the evaluation, each original value $x_{i,j}$ for the indicator i of the city j was firstly converted into a normalized dimensionless number $NI_{i,j}$ (on a scale from 0 to 1) using the method of min-max normalization (Equation 3, Karmakar *et al.*, 2010), where the max_i and min_i represent the maximum value and minimum value of the given indicator in the 11 cities. It is then assumed that the indicators share equal weights in each of the three elements and calculate the arithmetical mean as the index of E, S and Ac, respectively. Finally, the integrated vulnerability index is assessed by the addition and subtraction function V=E+S-Ac (Cardona, 2007; Cutter and Finch, 2008; Balica and Wright, 2010). Here the alternative function V=E*S/Ac (Karmakar *et al.*, 2010; Balica *et al.*, 2012) is not adopted because it gives unreasonable extreme values once one of the three elements approaches zero.

$$NI_{i,j} = \frac{x_{i,j} - \min_i}{\max_i - \min_i} \qquad 3$$

Primary data for vulnerability assessment was collected from the Statistical Yearbooks of Guangdong Province (2002-2011), statistical yearbooks of each city (2002-2011), the sixth census of each city (2010, except Hong Kong and Macau), government publications and news reports in related cities in 2010. It has to be mentioned that a few indicator values (e.g. economic sector and drainage system) are not exactly comparable due to different statistical criteria of these cities. A more appropriate approach is to describe the three elements (E, S, Ac) in detail and also combine them into one flood vulnerability index (Figure 4-4). Of all the eleven cities examined, Hong Kong is the most exposed city to flood hazards due to the high precipitation, high urbanization and steep terrain, causing extreme river flow. Including Hong Kong, Macao, Shenzhen and Guangzhou, the central cities are generally exposed more than the others as low lands (less than 3m above sea level) are highly developed with intensive human activities and properties. Zhongshan also shows a high exposure because of its large area of low lands and intensive river-nets. Zhaoqing is the least exposed city out of eleven, because it has relatively less assets to expose and it suffers little from the sea.

Macao leads the sensitivity ranking, followed by Hong Kong and Shenzhen, which indicates that high-density population and production are particularly sensitive to impacts and weak sections (e.g. old people, unemployed labor, small business) should be the core concern in addressing flood threats. Zhaoqing and Huizhou, as less developed cities in the PRD area, are also highly sensitive to floods. This is the case mostly because both have a large proportion of sensitive population (less than 15 and elder than 65 years old) which is a result of young labor migrating to central cities in the context of rapid urbanization. Hong Kong and Macau have almost equally high adaptive capacity to flood, mostly because both have obviously more soft flood control measures than the other cities, like better education, information availability, economic power and advanced infrastructures. When combining the exposure, sensitivity and adaptive capacity, the flood vulnerability index ranks Zhongshan, Dongguan and Macao as the top three most vulnerable cities in this area (Figure 4-4) while Hong Kong, Shenzhen and Guangzhou rank in the middle. So, even though the exposure and sensitivity indicators are still significant in the most developed cities, flood risks and potential damages can be mitigated greatly by improving flood-control measures (adaptive capacity).

The advantage of the indicator system method is that one can clearly compare vulnerabilities and see the weak parts of the cities. However, the indicator-based technique cannot present vulnerability with temporal changes. It is also a simplified version of reality without capturing the weight/ interconnectedness of several indicators and potentially ignoring important local specificities. The difficulties in quantifying social and political-administrative indicators, as well as the availability of other indicators, may constitute a considerable weakness as well (Balica et al., 2012).

4.3.5 Flood risk and the uncertainty

The IPCC special report expresses disaster risk as the combination of physical hazards and the vulnerabilities of exposed elements (IPCC, 2012). Accordingly, flood risks in urban area could be understood as a combination of the probability of occurrence of a flood and the vulnerability of the urban system. As a river delta, the PRD has frequently suffered from flooding in the past. Urban settlements in the PRD are typically located and developed along shorelines and the river estuary, putting them at particularly high risk from flooding and an expansion of the water’s edge. A changing global climate is causing rising sea levels and more extreme rainfall events thus would increase the probability of flood occurrence with high variability. Flood vulnerability of the PRD cities is seen as high, based on the evaluation given above. The two parts together indicate a reliable increase of flood risk in the PRD cities, in particular vulnerable cities such as Zhongshang and Dongguan. From the large-scale point of view, the PRD areas has a higher frequency of floods and more severe flood risks in general because it is highly impacted by the combination of urbanization effects and climate-related changes in the future.

However, there are a lot of uncertainties in the flood formation process, which relate to the combined effects of human behaviors at all aspects of the process and specific regional characteristics among cities. Floods in every region, basin, and watershed will be affected differently, depending on the specific precipitation and hydrologic conditions in that area. In addition, land use change together with rapid urbanization plays a role in the change of extreme weather. Urbanization may reduce precipitation by changing surface properties (Rosenfeld, 2000; Kaufmann *et al.*, 2007), or may promote precipitation by increasing condensation nucleus, enhancing evaporation and vapor circulation (urban heat island effect) (Jauregui and Romales, 1996; Xu. *et al.*, 2010). Thus, the impact of urban expansion on precipitation is complicated, and it may

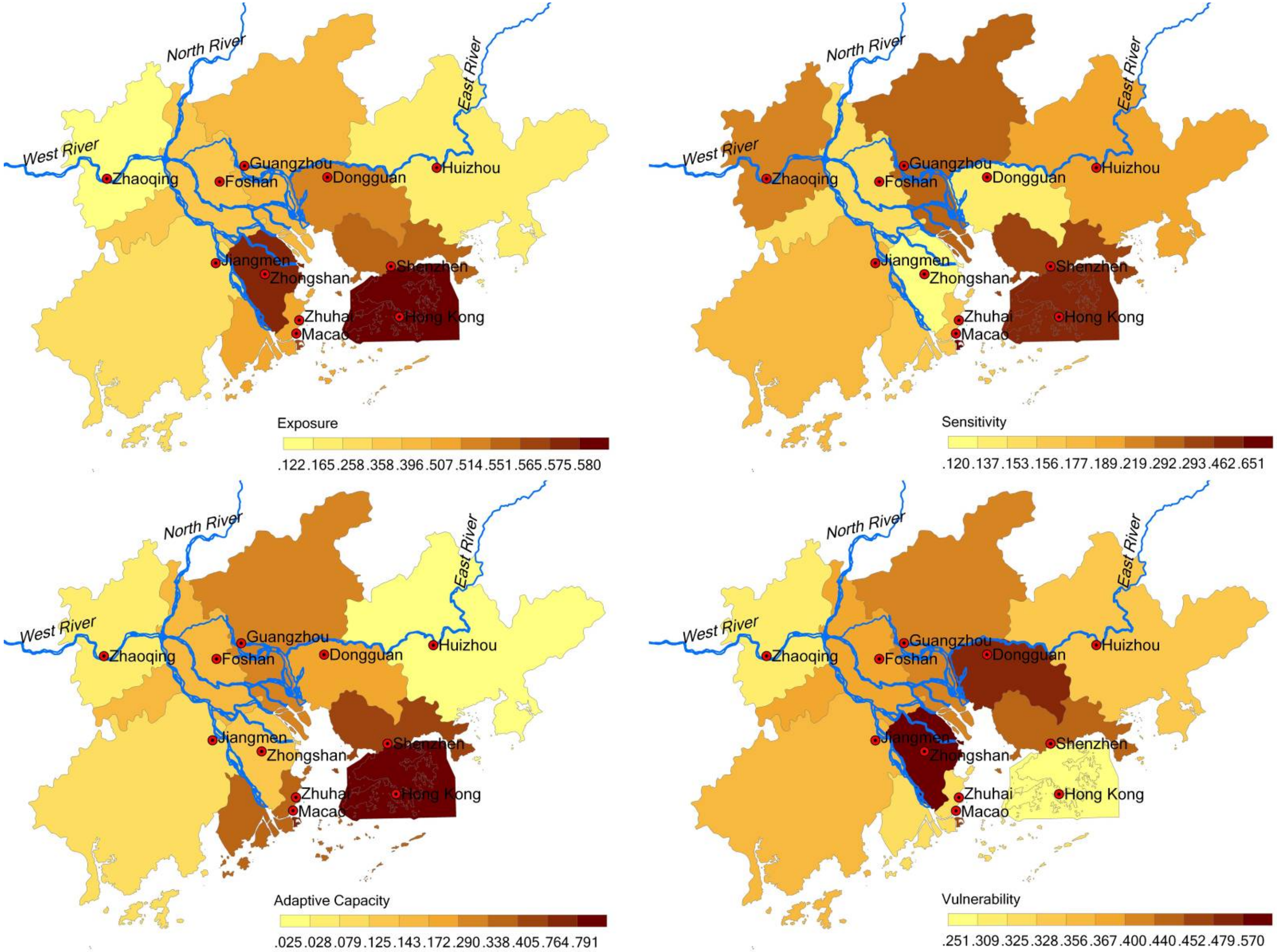


Figure 4-4 Relative assessment of the flood vulnerability of PRD cities. The factor's value of a city is relative to that of the others. Higher value of a factor means the relative higher E/S/Ac/V but not absolute.

exacerbate local extreme weather events by changing the local atmospheric conditions. Water management and development in the cities need to be changed accordingly. While the prediction of local or regional climate futures remains inherently uncertain, decision-makers must proceed with planning and action on the basis of available information and estimates. With such uncertainties lying ahead, responding to climate change and managing flood risks can be more sophisticated and needs new knowledge.

4.4 Flood response measures and the way forward

Although climate change is expected to increase the extent and the frequency of flood events causing significant damages, the damage estimates are also influenced by the urban patterns and response behaviors within a risk (Mokrech et al., 2008). So urban responses are very important. As discussed previously, the flood situation in PRD cities faces various challenges from both climate change impacts (flood causes) and urban vulnerabilities (Figure 4-5). Response strategies should therefore be taken accordingly. This section is going to discuss four major but interrelated responses classified by flood time, namely: precaution by risk identification, warning by forecast, relief through emergency management and post-flood recovery. Figure 4-5 also shows the pathways or area to be addressed for every response measures described.

4.4.1 Precaution strategy

The PRD cities face high flood risks as a result of location, topography, climate change and dense development. Many industrial and residential developments have been built on flood prone areas. The best response to flood risk is precaution, in this research sorted into three aspects: risk identification, policy orientation and infrastructure construction.

Identification and awareness of the flood risk is the prerequisite to respond to potential flood hazards. It’s always important to find out if a particular location is likely to flood. Research based on long term observation and monitoring on rainstorm/flood is helpful to identify flood prone areas and create flood risk zoning maps. Local inhabitants’ and buildings’ experiences are also good clues, even street names with a watery theme in the title, e.g. water, spring, wharf, well, bourne or brook, are all strong hints that water is, or once was, nearby. While, review on the past records and experiences are not enough to help tackle future potential hazards, as they are deteriorating in the context of global climate change and rapid urbanization. The PRD area will suffer increasing flood events, as there are world wide clear evidences that anthropogenic greenhouse gas contribute to more-intense precipitation extremes (Min et al., 2011) and flood risk (Pall et al., 2011). For the scale of PRD area, more research have to be done to support specify knowledge. And an integrated department responsible for awareness improvement is crucial. A good example is the establishment of the Hong Kong Drainage Service Department (DSD) in the 1990s which made a big step forward for flood risk management in Hong

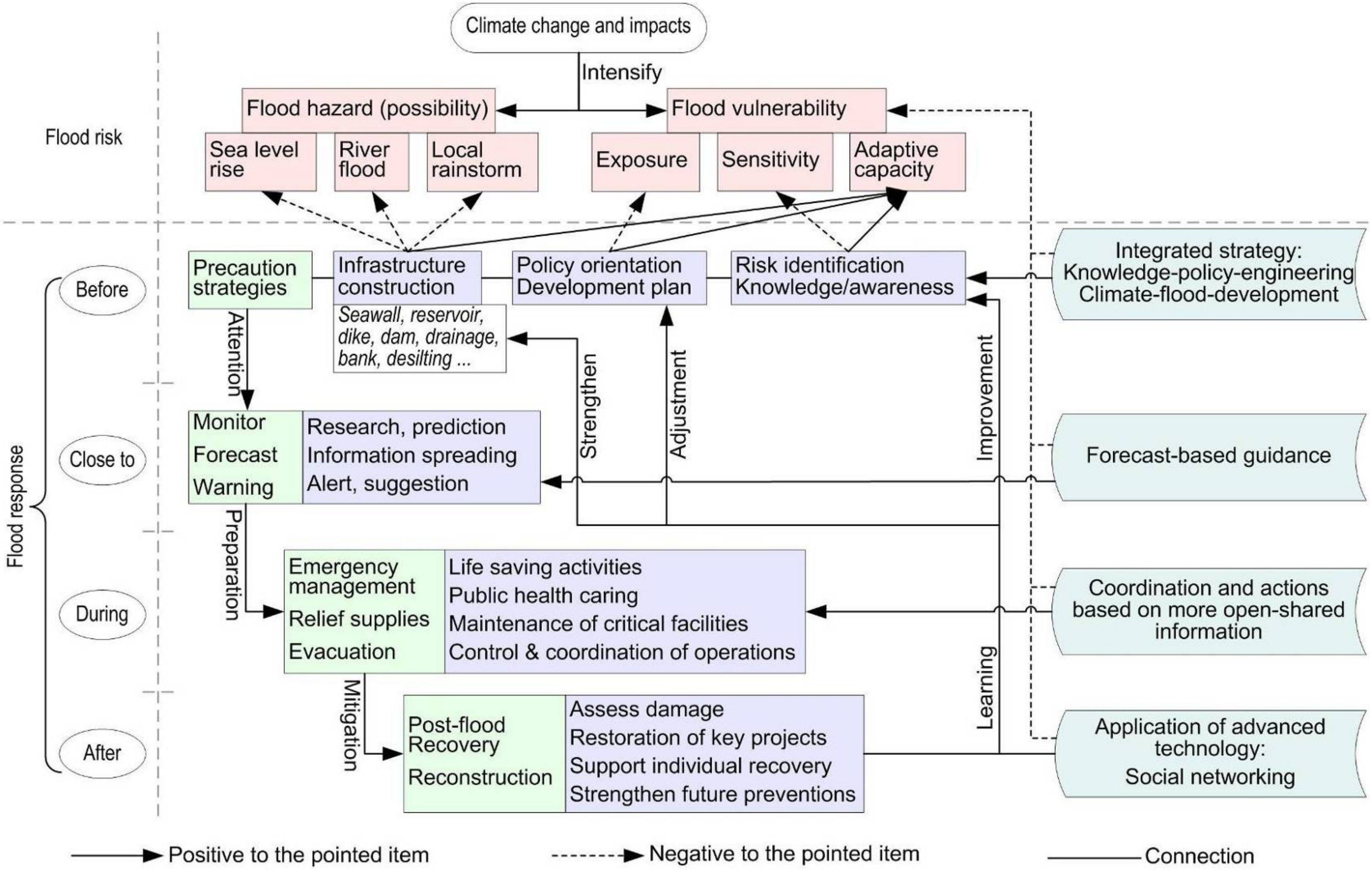


Figure 4-5 Framework for flood responses in cities of the Pearl River Delta.

Kong. It developed urban and rural flood management in Hong Kong, particularly in the identified flood prone areas or zones. Most of its work has focused on widening, channelizing and straightening streams in the New Territories (e.g. Kam Tin and Shan Pui Rivers), and building underground sewerage and storage ponds for collecting flood water (Chan et al., 2010).

According to available knowledge on flood risks, forward-looking policy guidance and development planning can mitigate the risks effectively. There is therefore a strong case for tackling flood risk in development planning, and this necessitates the application of more thorough and open appraisal strategies for development projects that alter flood risk and flood defense works that seek to mitigate that risk. Developing a flood-resilient, urban development plan is a vital step in minimizing damage and optimizing flood management benefits. Moreover, the authorities need to consider the rising flood risk in the whole region and direct development away from floodplains. As the flood risk grows, the capacity to appraise the risk must be integrated into urban and rural planning, and sustainable development may become a driving force rather than remain as rhetoric. If not, both the economic cost of mitigation and the social impact could be substantial.

Engineering infrastructure is the crucial basis in preventing flood impact and reducing flood damage, even reducing the possibility of flood occurrence. In fact, the Datengxia Dam construction project, together with the existing Longtan Reservoir project, is expected to control flood in the West River, similar to the Lechangxia Dam project for the North River. Undoubtedly, large projects play a significant role in flood water adjustment. However, the opinion needs more discussion that a large project can solve all the flood problems. For the basin scale, it’s more necessary to construct a series of projects along the river instead of strengthening only the weak sections. This implies that the sub-regions of the basin should coordinate their capacities in flood control. Otherwise, the partial improvement of the river bank system would increase pressure for the unimproved parts. In addition, local rainstorms are a major flood cause for cities. Reinforcement of river levees is highly important. At the same time, more engineering is needed to drain flood water rather than store it. In some low area where natural drainage doesn’t work, electrical drainage pumps are needed to be set in case of necessity.

With the socio-economic development, PRD cities have the economical capacity to carry out engineering. But the key is that higher flood-control standards are needed to tackle increasing flood intensity and magnitude in the context of climate change impacts. And drainage capacity (including installed electrical pump capacity) needs to be improved as well. There is a new national standard “Specifications of urban flood control engineering (GB/T 50805-2012)” and regional standards in coastal provinces. Flood protection in Hong Kong, set at the 1 in 50 year level, is relatively modest. Although globally, flood protection standards vary considerably, protection against 1 in 100 year events is common, and in economically important sites or in countries where flooding is a major hazard (e.g. The Netherlands), flood protection standards can reach as high as 1 in 1,000 year floods (Chan et al., 2010). However, the tail end of Typhoon Chanthu in July 2010 brought torrential rain, where about 3,000 people were trapped in rural parts of the New Territories, and there were three deaths caused by flash floods. This incident raises the question of what should be done in light of a changing climate to protect people and property.

The costs of building flood protection infrastructure, paying compensation, covering emergencies and delivering remedial engineering works will inevitably be high, but given the damage arising from recent floods, such preventative measures as part of a coherent package of hard and soft measures, are likely to be cost-effective and more life-saving. There are many planned water-related engineering measures in the 12th five-year-plan which aim to address water treatment, water diversion and coastal erosion.

Hard-engineering is very important, but mega-cities in the PRD such as Hong Kong and Shenzhen rely on these approaches too much. Current approaches to disaster management and infrastructure engineering may be less appropriate when climate becomes more variable. The issues may be not simply engineering standards, but the whole approach to engineering (e.g. safe fail designs instead of failsafe). Institutional mechanisms for local risk reduction, disaster preparation and limited self-reliance in some domains may prove to be more resilient than very costly high standard infrastructure that cannot be feasibly protected from extreme events. In low-lying areas this may include planning for floods by designing retention basins and minimizing flow barriers, rather than building dikes. Innovative engineering and infrastructure construction approaches need to be balanced with new approaches to risk assessment and organizational, institutional and social communication methods (awareness building, warning measures, hazard specific responses, credit and strategic reserve facilities for recovery). Some of these innovations are emerging already, but there is need for research on how they can be better integrated at the local level to address diverse and context specific conditions.

4.4.2 Forecast and warning

As mentioned, using a “hard-engineering” approach towards flood risk management is only part of the risk management process, and will likely prove insufficient to deal with the changing flood risk in the PRD. Forecasting and early warning of rainstorm and flood are extremely important to prepare for and respond to the threats, with certain time in advance.

Despite great progress in the last thirty years, forecasting on extreme weather events is still a problem. Flood forecast of 24 hours in advance is most helpful, but its accuracy rate is very low. Shenzhen reaches 90% in rainy/sunny forecast and 82% in rainstorm forecast in 24 hours (He, 2012), which is the highest level in the PRD cities except Hong Kong and Macau. However, this forecast is very rough and lacks information on specific time, location and intensity. Even forecast of 12 hours or 6 hours in advance can reach only the accuracy rate of 60% to 70% (Government Portal of China, 2012). The Hong Kong meteorological department can release fine forecast on rainfall placement six hours ahead. All the meteorological departments face multiple tests and challenges on extreme weather events, which is statistically a small probability event in the chaotic atmosphere with complex non-linear process. Although accurate forecast can be released one or two hours in advance, there is little significance. Further steps should go to bring forward the forecast, improve forecasting accuracy and improve spatial and temporal refinement of forecast. For sure, to carry out these works depends on more scientific research and analysis to provide a reliable method and knowledge.

However, how to pass the forecasting information to the public soon has become a problem. The channels for releasing meteorological information are not well set in most of the PRD cities, and the update frequency of meteorological information is low. These make it unable to spread meteorological information just in time, while most information becomes useless over three hours. The 12th Five-Year Plan of Shenzhen Meteorology plans to increase the public coverage of meteorological warning information from current 80% to 85% in 2015. Nevertheless, the meteorological department should take full advantage of and develop uses of popular channels like television, radio, internet and mobile phone, making more meteorological information available to the public in time. In addition, specify suggestions should be added together with the warning information as some people don’t understand what the warning signals mean and what activities should they take.

4.4.3 Emergency management

Many experiences confirm the extreme significance of early relief when floods occur. But it’s hard to execute just in time, because of that floods often cover roads, destroy buildings and hospitals, breakdown communications, and cause a large number of homeless, which all together makes the flooded areas in a state of confusion. Even organization and management of the continuing rescue of persons, vehicles, or supplies sometimes become a problem. For managers and rescue workers, it is often hard to decide what measures to carry out and they usually do not have the time to formulate and implement appropriate strategies for specific region. However, the relief work must be carried out as early as possible. This requires: 1. the authorities make decisions quickly to choose the least among two evils; 2. help making plans for individuals, families and communities to evacuate by themselves safely; 3. the distribution of relief supplies must follow the principles of conservation, order, openness and fairness.

Strengthening coordination and communication between local governments is necessary. There are still many barriers to adaptation, e.g. the lack of coordination between different government agencies or different levels of government, difficulty of interdisciplinary research. The water management framework of the Pearl River Delta is a combination of river basin management and regional management. On the one hand, there are too much executive orders in this management system. On the other hand, decentralization led to unclear responsibilities and low efficiency. This would require multi-sector and multi-disciplinary collaboration and such exercises have not been common in the practices. Nevertheless, research and planning for adaptation remain at a very early stage. In recent years, governance structures for coastal flood management remain blurred. Relevant institutions for flood management are only interested in their own portion of responsibilities. For example in Hong Kong, the Drainage Service Department (DSD) is responsible for inland flood protection; the Civil Engineering and Development Department (CEDD) for sea wall maintenance and the Hong Kong Observatory (HKO) for tide level monitoring. In light of climate change and emerging flood risks, perhaps it is wise to learn from the UK's experience. Forming a new Strategic Flood Partnership will help ensure that government departments/agencies (i.e. DSD, HKO and CEDD) and local district councils can address flooding issues (including inland and coastal flooding) in an integrated manner (Chan et al., 2010).

Due to different geographical conditions, floods in the PRD cities show different characteristics, as pluvial floods in Shenzhen, fluvial floods in Guangzhou and tides in Zhuhai and Zhongshan. Therefore, each city has its own response strategy. As PRD is a dense urban agglomeration, floods often affect several cities at the same time and need to be coped with by several cities as well. But there are always challenges in identifying the sharing of responsibilities among the cities, like the cases of many other transboundary river managements (Raadgever and Mostert, 2005; Ganoulis, 2006). Special challenges exist between Hong Kong and Shenzhen who operate under different administrative systems and share a border river. Despite jurisdictional and administrative separation, river and sea natural systems must be treated as integrated entities if an optimum flood plan is to evolve. While successful cooperation in emergency needs the accumulation of usual cooperation arrangements. A few joint projects have been proposed between Hong Kong and Guangdong (Shenzhen), though there was limited transparency to the projects. Information related to up-to-date data (i.e. flood risk analysis, flood risk mapping, etc), records of meetings and official reports were not made available. Scholars have called for transparency to better ensure the absorption of stakeholder and public feedbacks, which would improve the infrastructure development, policy and project effectiveness and community resilience, i.e. prevention, preparedness and response for flooding (Chan et al., 2010).

Generally, rescuers, materials and technical equipments are ready and guaranteed in emergency in the PRD cities. There are strong organizations due to executive order. However, local individuals lack initiative and flexibility in case of emergency rescue because of poor information and limited ability. The preparedness measures can not be fully used and the on-site practicality was usually not discussed. In order to improve the efficiency of rescue operations and reduce the probability of the such a predicament, an appropriate emergency response map is suggested (Osti et al., 2009). These response maps can include easy-to-understand instructions and guidance, describing how to use these maps in case of emergency as well as normal times. They will help take appropriate response actions in extreme cases, if people are trained and exercise to use them effectively.

If there is lack of an effective way to significantly mitigate flood damages, then flood impacts to the grassroots will increase in the near future. Therefore, to improve the processing capacity and resilience of flood-prone communities becomes extremely important, because they need better development of self-reliance and self-determination. In doing so, increasing effective responses from individuals in emergency can rescue life as well as engineering measures.

Due to the urgency and complexity of emergency management, it is hard for any people to achieve the best decisions or completely avoid mistakes in decision-making. In fact, mistakes in the emergency response is also a valuable asset for the lessons learned. Many important safety regulations in the world are formed from summing up the lessons in disasters responding.

4.4.4 Post-flood recovery

The recovery process starts as soon as floodwater levels have dropped. Regarding the damages of the flooded areas, recovery depends mainly on the existing local resilience capacity and availability of external rescue resources. A specialized agency is necessary to take responsibility of all the recovery task, like reconstruction of public facilities, support individual recovery and assess/subsidize losses.

Quick and prior restoration of life-projects and product-projects are the key principle for post flood recovery (Zou et al., 2002). Life-projects include mainly settled habitation, food supplies, medicine supplies and communication which support the basic daily life stuff. Product-projects are composed of transportation, hydraulic engineering, agriculture facilities, electric support and so on. While overall rescue measures are unable and unnecessary to take care of each individual situation, self-resilience capacity should be always supported before, during and after a flood. These supports are expected to increase awareness of local flood risk and resilience capacity. In addition, supporting people to reconstruct their lives as soon after flood as possible helps alleviate the stress that can lead to psychological problems (Burke, 2011).

For compensating potential huge flood losses, it is not enough to rely on government aids and social donations. Flood insurance is an important mechanism for loss compensation internationally, though its function is not fully implemented in PRD cities or the whole China. Comparing with the average 30% of the compensation ratio in Europe and the United States, China reaches only 1% (Xiang, 2011). China is in the urgent need for flood insurance system under the framework of the comprehensive prevention of flood risk, of which PRD cities can carry out pilot work in this regard. Indeed, there are already implementation of agricultural insurance in China, much of which has a major flood component, which could be improved to specialized flood insurance. Although, flood insurance can be used as one instrument to address the costs of flooding, this requires flood risk information to be made available to the public and to insurance companies, and most insurance packages are costly and require much governmental financial input in order to ensure their wide availability. Of course, the insurance industry alone cannot prevent that risk from becoming reality, so the government’s policy response to recent natural perils must go beyond insurance, with a broader approach involving all levels of government boosting their investment in mitigation infrastructure and higher quality planning and zoning standards, as well as building standards which reflect the prevailing risk. One barrier is the confusion about the best product in a complex and rapidly-changing market

Whilst it is important to protect people and property from flooding by building and maintaining flood defenses and providing effective flood warnings, flood risk management should include a shift to another type of resilience that includes learning from past events and adapting to future risk. This is particularly important in the context of climate change and changes in population. Infrastructures reconstruction and improvement of flood insurance would not only support post flood recovery, but also increase precautions for next flood incident. Therefore, recovery work should be carried out excellently as it concerns the long-term benefits of the area.

4.4.5 Further improvement for flood response

Flood risks can be mitigated by appropriate adaptive strategies and actions, although specific plans have yet to be executed. Beyond the traditional and basic flood management strategies mentioned above, more specific measures are suggested to improve the flood response system, focusing on issues related to climate change impacts, standards of flood control projects, accurate flood warning and improvement of individual resilience capacity.

- To develop an integrated "climate response" strategy that unifies the climate change impacts, flood risks and urban developments. The local authorities should revisit the region’s development plan to develop a long-term, integrated flood management strategy that recognizes the added risks from climate change together with rapid development. The strategy should also include the vulnerability status of the region and public awareness on the potential length and seriousness of the flooding process. In practice, low impact development (LID, van Roon, 2007) or Green Infrastructure (Gill *et al.*, 2007) will be one of the options to support the strategy.
- To implement potent close-to-flood activities based on accurate forecast and warning. Experiences with decision makers show that, most of the flood responses are set to save life and assets during or after flood. Apart from enhancing hydraulic engineering, little has been done to avoid the

hazards of floods. Forecasting and early warning exist, although with poor timely accuracy, but are not able to play a role without practical actions. Efforts should be strengthened on the research of close-to-flood forecasting and early warning. Thus accordingly a definitive guide of actions should also be issued, suggestively or mandatorily depends on dangerous, one day or several hours before the disaster occurs. Simple options could be to force off work/school, close low-lying roads and transfer people and assets out of high-risk areas.

- To enhance adaptive capacity of grassroots organizations by information transparency and sharing. Increasing the transparency/ availability of knowledge and information to vulnerable populations is crucial so that they can take certain actions in advance. With available information, public participation could also be integrated into the decision-making process and ensure that disaster management and emergency plans are effective. Furthermore, as awareness of one’s own vulnerability to flooding and insights into the effectiveness of coping strategies are driven by direct flooding experiences (Zaalberg and Midden, 2010), simulation research by means of interactive models (e.g. agent-based model) is to be used to support direct flooding experiences on impacts and responses, thereby giving a better understanding of flood impacts.
- To make full use of social networking to improve relief. Social networks are reaching every corner of the world and spreading thousands of messages per minute. People share information about flood warning, rush traffic, inundated area, shelter location, and abound of individual knowledge which could benefit both emergency managers and people in trap. In several main social network, like Tencent QQ, Renren and Sina Weibo, people are networking to respond to crisis in real time, allowing us to understand what is happening at the level of self-organization. It’s a more nuanced approach than a straight emergency proposal. By employing social network, decision makers are able to confirm the efficacy of certain organizations in flood response as well as identify gaps in social media response in flooded areas. As the field of social network analysis evolves, the insight it provides into the nature crisis response - at the organizational and human level - may improve preventive and infrastructural measures.

5 Agent-based simulation of household responses to flood loss

5.1 Background

Although flood loss assessment and flood adaptation are now prominent contents in existing flood-related research, there has been little exploration of the interaction of these two aspects for flood management. The main reason may be that the data about the effects of such interaction is rare, and consequently the efficiency of different precautionary measures is unclear (Kreibich et al., 2005). More difficult to estimate are intangible and unpriced losses which include injuries, fatalities, disruption, psychological trauma, and environmental losses. These losses usually fall outside the scope of cost estimates of natural hazards, but do require more attention, and it is important to note that considering only the priced direct losses is an important limitation of the assessment of total impacts of natural hazards (Bouwer, 2013). Therefore, flood loss assessment studies with dynamic response simulations are urgently needed to help provide an in-depth understanding of the process of flood damage and to identify the weak links within flood adaptation, in order to improve flood management.

Existing methods have undoubtedly provided insightful perspectives into understanding flood loss and responses. However, the system of flood loss assessment and adaptive responses is complex regarding the reality of an interested area in an era of dynamic socioeconomic, and physical hydrological global changes. Attention to loss assessment and adaptive management is fine, but there is a need to go into more systematic changes within a dynamic decision-making process (adaptive management). Enhancing adaptive capacity in this context requires a new vision of the populations and communities of the region, as an integrated system, supported by institutions that facilitate cross-scale and inter-sectoral planning (Eakin et al., 2010). Flood risk management must rely on a proper and encompassing flood risk assessment, which possibly reflects the individual characteristics of all elements at risk of being flooded. In addition to prevalent expert knowledge, such an approach must also rely on local knowledge. In this context, stakeholder preferences for risk assessment indicators and assessment deliverables hold great importance but are often neglected (Scheuer et al., 2013).

Agent-based modeling (ABM) has the advantage that it can monitor the whole situation and the extent of flood damage, and can simulate the response measures of agents (individuals, households, communities) in real time. Agents are self-contained computer programs that interact with one another or with the environment and can be designed and implemented to describe the rule-based behaviors and modes of interaction of observed social entities. The agent-based modeling paradigm provides a mechanism for understanding the effects of interactions of individuals or between the individual and the environment. Through such interactions emergent structures develop, including conflict and cooperation on resources in the social and physical environment of cities.

Until recently, ABM was rarely adopted in flood research, although few exploratory studies have been conducted on real-time flood forecasting (Georgé et al., 2009), optimizing evacuation (Dawson et al., 2011) and vehicle relief systems (Scerri et al., 2012). It has not yet been used in flood loss estimation considering individual adaptation behaviors. This thesis presents a first attempt to use ABM to simulate the dynamic process of flood loss along with individual response actions, in which the usual hydrological models are inadequate. To practice this ambitious task, a few simplifications are thus necessary, for instance regular rainfall scenarios, artificially set property values. As an experimental and pilot approach, the ABM also tries to quantify various response behaviors of the people who suffer from flood inundation, although in a rather simple manner. In the following sections of this chapter, the model will be described in details.

5.2 Conception model of agent-based simulation

ABM was selected as the method to address the challenges of simulating flood loss process, because of its capacity to capture interactions and dynamic responses in a spatial environment. An overview of the ABM used in this thesis is given in Figure 5-1.

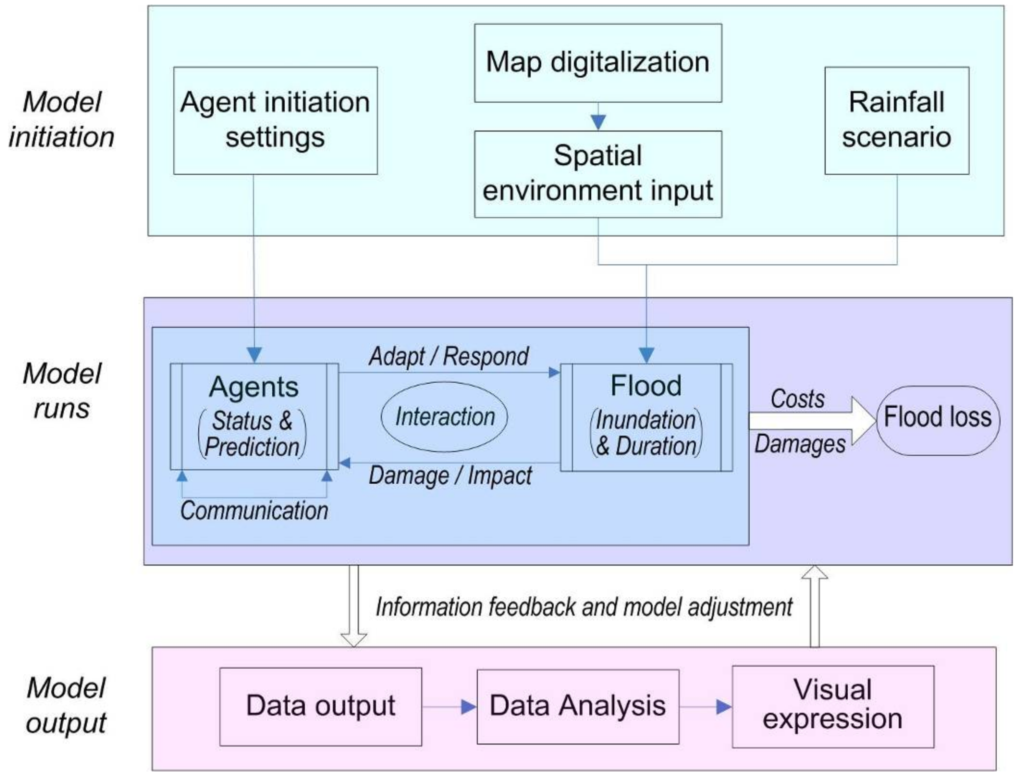


Figure 5-1 Framework of the agent-based model for flood loss/response simulation

To initiate the model, three basic steps must be ready. Rainfall scenario is the key component of this model, which sets the flood water source with different intensities and durations. Modeling environment is set with Digital Elevation Model (DEM) as the topography, which is the main factor impacting rainwater runoff that causes floods. Agents, representative of households in this model, are the active elements which predict their flood inundation probability and take appropriate response measures.

Once the model is initialized using the above components, it runs with starting rain. Households will make their own predictions about flood risk according to flood warning information. These households subsequently take certain measures to cope with the expected flood threat, which means they need to invest a proportion of their properties. If they don't react to any warning information or they failed to take flood control measures, they will suffer inundation damages and losses to parts of their properties, including building depreciation and in-house properties. For instance, setting the total capital of a household as K, the household takes certain response measures when receiving flood warning and during the flood event, which together are the response costs R_C. Adding the damage losses caused by flood inundation L_D, the final flood loss of a household will be R_C+L_D.

The interaction of the flood inundation impact and the agents response drives the model to run step by step, so that the flood and loss process can be simulated and analyzed for better understanding.

The model will output data for analyzing the flood and loss process, and for investigating the relationships between total flood loss and agents response measures. During the model construction period, these outputs help validate and adjust the model structures and parameters to better approach flood events in the real world.

Section 5.3 is going to introduce the details of each component of the model.

5.3 Components and construction of the agent-based model

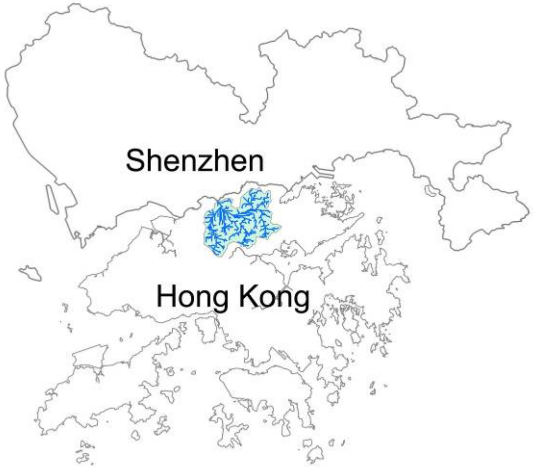
5.3.1 Model environment: topography

The model environment includes topography (elevation), river system, households locations and roads in a clearly identified river basin.

The elevation data (DEM) was converted from a grid file into an ASCII grid file using ESRI ArcGIS, then it was resampled to a suitable resolution to be imported to the Netlogo world (412 * 364 cells). A cell represents 30 * 30 square meters in the real world for this case study. The elevation data is also used to generate the river basin and river system of the Ng Tung River in northern Hong Kong (Figure 5-2).

Each cell has a slope, used for water flow speculation, which is calculated by the difference of its elevation and the minimum elevation of its eight cell neighbors.

The building area map was imported to Netlogo and overlapped with the river basin. Since the exact residence distribution data is not available at the moment, the data of all-buildings is applied. The building area map was provided by the Institute of Space and Earth Information Science, Chinese University of Hong Kong. It displays the building distribution of the river basin in 2008. The original vector data of the map was also converted to an ASCII file for importing to Netlogo, with same resolution as the elevation data.



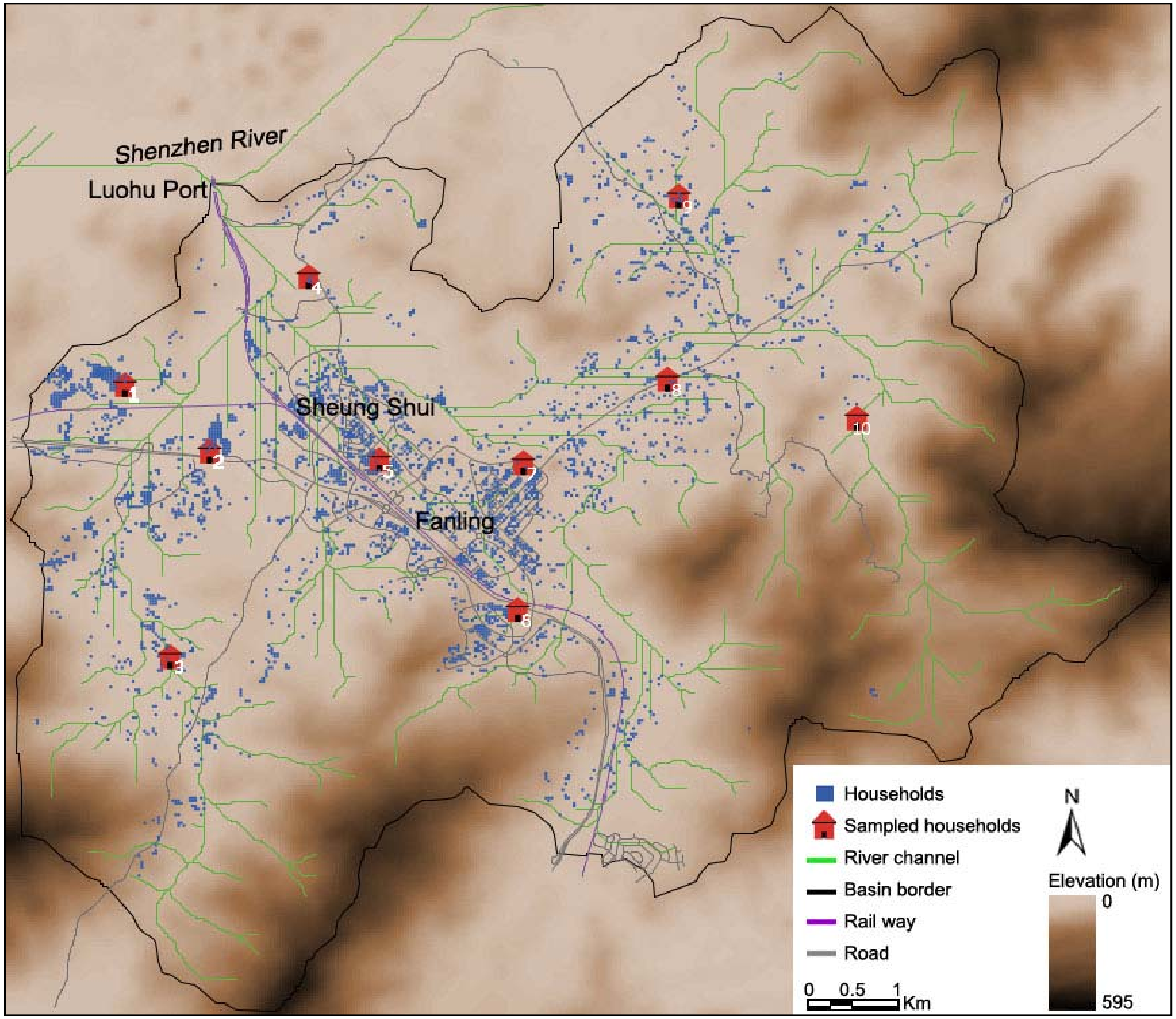


Figure 5-2 Map of the Ng Tung River basin, showing its location, topography, watershed border, river network, building areas and the selected 10 households.

5.3.2 Agent attributes and behaviors

The definition of an agent and its attributes and behaviors are central to an agent-based model. Households are taken as agents in this model as they are the basic units that suffer from and cope with floods. Their responding decisions and rule-based interactions determine the feature and magnitude of flood loss. Household agents don't move spatially but they do take measures to protect themselves from flooding and make predictions about future flood risk based on rainfall/flood warnings. The types and strengths of the measures are not specified but are represented in their costs/investments. Appraisal of higher investment means a stronger protection.

As shown in Table 5-1, each agent possesses several attributes to represent its links to flood event and flood loss, e.g. property, exposure, inundation, flood losses. Agent properties are capitalized and composed of two parts, the construction property (residence building they live in) and the in-house property (contents they own and put at home). Every agent is therefore allocated a starting property level at the onset, which will subject to loss during the course of model runs. In the absence of a comprehensive metric for real household vulnerability (including its components: exposure, sensitivity and adaptive capacity) to flooding, a simplified alternative is applied in the model. The alternative is that only exposure and adaptive capacity are considered. The exposure of a household is calculated according to its location (elevation) and shortest distance to river, and the adaptive capacity is based on the total properties, both using the method in section 4.3.4. Inundation related attributes indicate the flood severity and duration. Agents will take response measures to prevent flood water according to the real time inundation situation and predicted inundation. The measures taken by a household will reduce its exposure. In case the real time inundation is higher than the level an agent ever predicted, it suffers flood damage and loss from the effective inundation (the real-time inundation is larger than the predicted one). Flood damages will reduce households' adaptive capacity. Flood loss is composed of several parts: flood damages and investments for prevention in different flood phases (before, during and after flooding).

Table 5-1 Attributes of household agents

Attribute	Implication of the attribute
exposure	Household's exposure to flood
self-risk	Flood risk known by the household itself
response-rate	The rate of a household's investment to its property values
self-prediction	The household predicts rainfall and flood without receiving warning
adaptive capacity	The adaptive capacity of the household
building value	Value of the household's living building/house
property	Value of the household's non-building properties (in-house assets)
property-loss	Lost value of properties by effective inundation
cost-c	Precaution investment when receive flood warning

cost-d	Responding investments during flood
cost-p	Post-flood recovery costs
warn-rainfall	Rainfall by warning prediction
inundation	Inundation depth of flood water
predict-inundation	Predicted potential inundation depth
drain	Water drainage
duration	Duration of inundation
inundation-duration	Aggregation of inundation
a	Building damage rate
b	Property damage rate
hhloss	Household’s property loss in each step
total-loss	Final total flood loss of a household
hhloss-list	List of the household’s property loss in each step

However, in addition to individual attributes, agent behavior is impacted by several global variables such as rainfall scenarios, lead time and interval of flood warning. As the simulation progress through time and flood situation varies, values of some of these attributes change along with the progress and thus inform the flood loss process of agents.

With the above attributes, agents take response measures according to both the flood warning information received and the real time inundation. An example of a typical agent’s response-loss process is shown in Figure 5-3. In this example, the agent has 90% chance of receiving a flood warning and a 90% chance of taking measures according to this warning. If people are ignorant of flood warnings, they will not account for them at all in their decision-making behaviours and don’t undertake any preventative actions. Even when response measures are taken, there is still the possibility of damage due to flood inundation, although the damage rate may be reduced. On the other hand, those who did not take any measures to prevent flooding will either suffer direct inundation damages or may suffer less if they respond during the flood event. After the flood, all agents have to invest to recover their damaged and depreciated properties.

5.3.3 Scenarios of rain/flood event

Rainfall scenario

A rainfall event can be simply described by the rainfall intensity and duration of rain (Veneziano and Yoon, 2013). The easiest way is to initialize a regular rainfall fluctuation which is expressed as curves in Figure 5-4. Also, as the case study area is not large, it is assumed that the rain drops spatially even in the whole area. Initially, five rainfall scenarios are set in the model and they can be manually chosen by the person who runs the model. If necessary, greater fluctuations could be added.

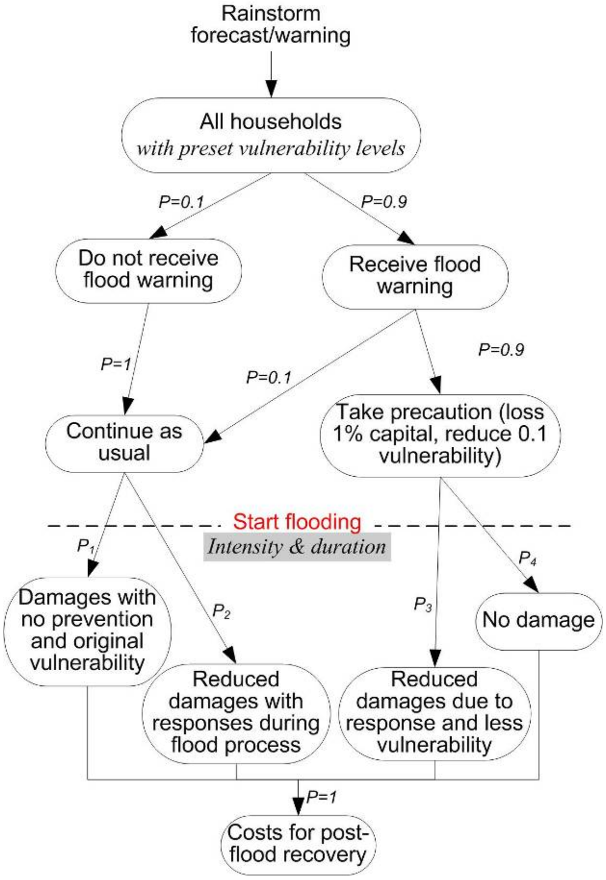


Figure 5-3 Example of a typical agent's response-loss process (p = probability)

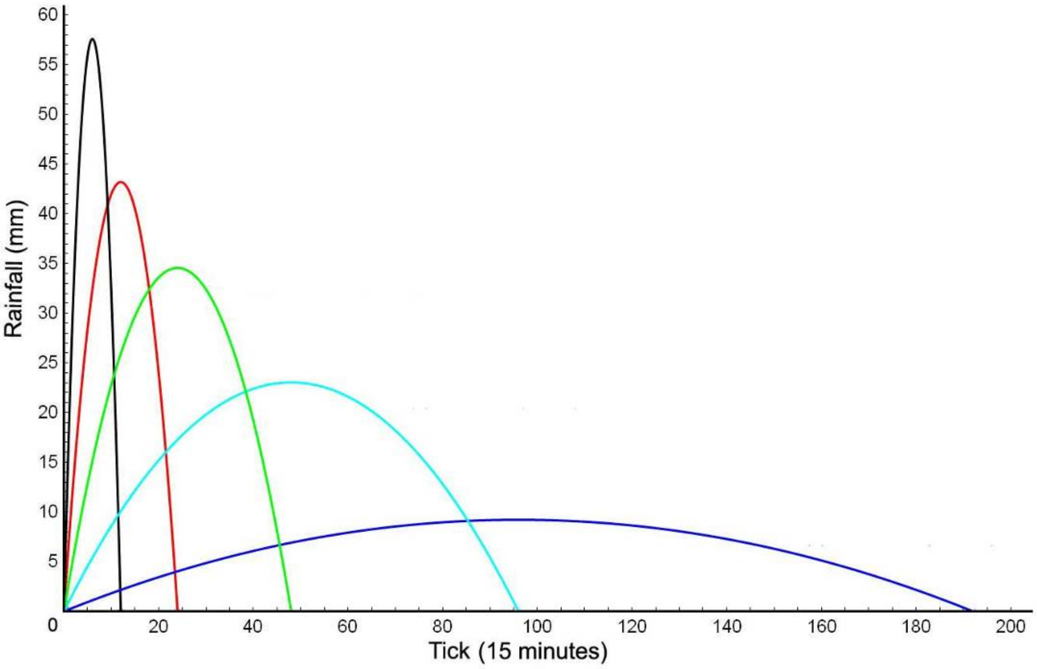


Figure 5-4 Regular rainfall scenario curves adopted in the ABM model

The flood inundation process

Once there is a rainfall scenario, there is an inundation scenario that corresponds to it, because the land surface was initially set by the DEM and other factors are not considered. Rainfall accumulates and forms a certain water height on the ground, and flooding happens if the water does not flow away.

The water flow is computed from the higher elevation cells to lower ones, but the computation will ignore the cells that have no water (water depth is 0). The water in one cell will flow to one of its eight neighbors if the neighbor's peak water is lower than its own (Figure 5-5). The neighbor is thus labeled as target neighbor in this *ith* step. Peak water means the sum of water depth and the elevation of the cell. In the case that all the neighbors have a higher water peak, the current cell will act as a sink and neighbor water flows in. The peak water of both the current cell and its target neighbor will be the same after this flow calculation (Equation 4). Exceptions exist if the elevation of one cell is far higher than the peak water level of its target neighbor, or in the inverse way. In these cases the equation 4 is not applicable, so the model will do an alternative computation which lets the higher cell give all its water to the other (Equation 5).

Then the procedure goes to the cell with the lower elevation and the water flow is calculated in the same way.

$$WD_{i+1} = \frac{1}{2}(E + WD_i + E_{TN} + WD_{TN,i}) - E \qquad 4$$

or

$$WD_{i+1} = 0, WD_{TN,i+1} = WD_{TN,i} + WD_i \quad when\, E > (E_{TN} + WD_{TN,i}) + WD_i \qquad 5$$

where WD_{i+1} is the water depth of current cell, in time step $i+1$
E is the elevation of the current cell
i is time step
E_{TN} is the elevation of the target neighbor where water flows to
WD_{TN} is the water depth of the target neighbor

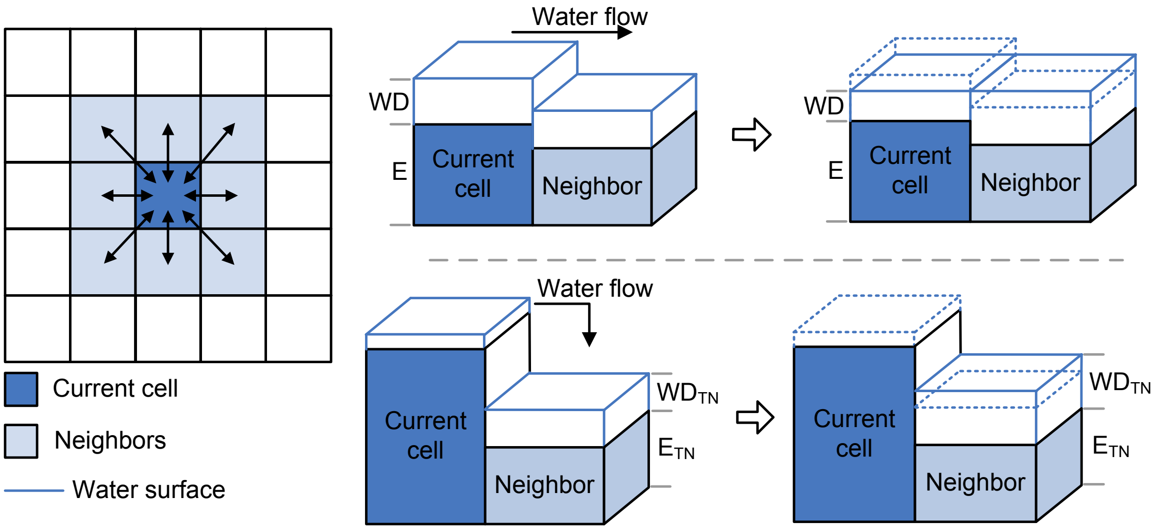


Figure 5-5 Sketch of water flow between raster cells.

Own presentation based on (Dawson et al., 2011)

Due to infiltration, reservoir storage and evaporation, not all precipitation turns to runoff or flood water. The model uses interception to represent these phenomena and to simplify the water flow process. When all the cells have done the water flow procedure, they are required to lose some water, as the effect of the interception, until its water height is 0.

After the water flow and interception computing, the remaining water depth on one cell is considered as flood inundation. If there is a household living in this cell, it will suffer flood damages and respond in certain ways.

Rain warning and flood prediction

Despite the varied existing flood experience of each individual, the flood responding behaviors depend significantly on rainstorm/flood warnings released mostly by government authorities (Priest et al., 2011). Although communication between neighbors and communities may also help in taking actions in advance of flooding, it can also be considered as receiving warning information. People's reaction to becoming informed of a potential flood event varies according to such factors as experience, communication and warning (Dawson et al., 2011).

Nevertheless, the question of how to enable the agents to predict their potential flood risk with a certain accuracy is really challenging. To solve this problem in principle, it is stressed the fact that official warnings play a dominant role in individual flood prediction and decision making. If agents receive a rainfall warning, they will approximately know the future rain/flood trend and the extent of the predicted rainfall. Another fact in hydrology is, if we consider an ideal and simple situation, that the flood inundation process of a place (cell in the model) highly correlates to the local topography and the process of a rainstorm event occurs in the upstream areas (Hunter et al., 2007). In other words, a certain rainfall scenario (represented by precipitation curve vs time) will direct a certain inundation scenario for an affected place if the local topology is fixed and no other intervention is considered. With this knowledge it is assumed that, in the same rainfall scenario, the flood inundation process for a cell in the model is always the same. This shifts the problem of predicting inundation to the problem of predicting rainfall, and rainfall prediction is fairly easy according to official rainfall warnings.

The widely known theory of unit hydrograph (UH) shares a similar approach to my assumption and thus supports a sound theoretical foundation and quantitative computation for the model. UH is the hypothetical temporal runoff response of a watershed to a unit input of effective rainfall, applicable to a given basin and for a given duration (Sherman, 1932). UH indicates the relation function of flow to time in a certain basin (Nash, 1957), which is still widely cited to date (López et al., 2012; Che et al., 2014) and generally presented as the Equation 6 below.

$$h = \frac{1}{k(n-1)!}\left(\frac{t}{k}\right)^{n-1} e^{-t/k} \qquad 6$$

where: *h* is unit hydrograph, *t* is time, *k* is the reservoir constant, *n* is the number of reservoirs. The *k* and *n* together indicate the topographical features of the basin area, e.g. elevation and slope. In practice, a set of *k* and *n* are chosen based on hydrological gauge records or model training, such that the runoff storage-diffusion properties of the basin are properly represented (Ponce, 1989).

UH gives the link between flow amount and flow time, and is thus a very practical tool in runoff prediction which has been used for decades and which to date remains useful. The principle of UH fits exactly to the model presented in this paper, of which the flood inundation of a cell varies depending on its upstream basin features (elevation and slope), along with model running ticks. The model was trained in each of the above mentioned five rainfall scenarios, with running only the rain and flood parts, so that each cell records and remembers their inundation process. The remembered inundation process will be used for agents' prediction but with variable accuracy due to individual capacities. This series of computational experiments output rational inundation scenarios for all the cells in all the five rainfall scenarios. Figure 5-6 shows examples of the inundation curves for 10 selected cells under rainfall scenario 3.

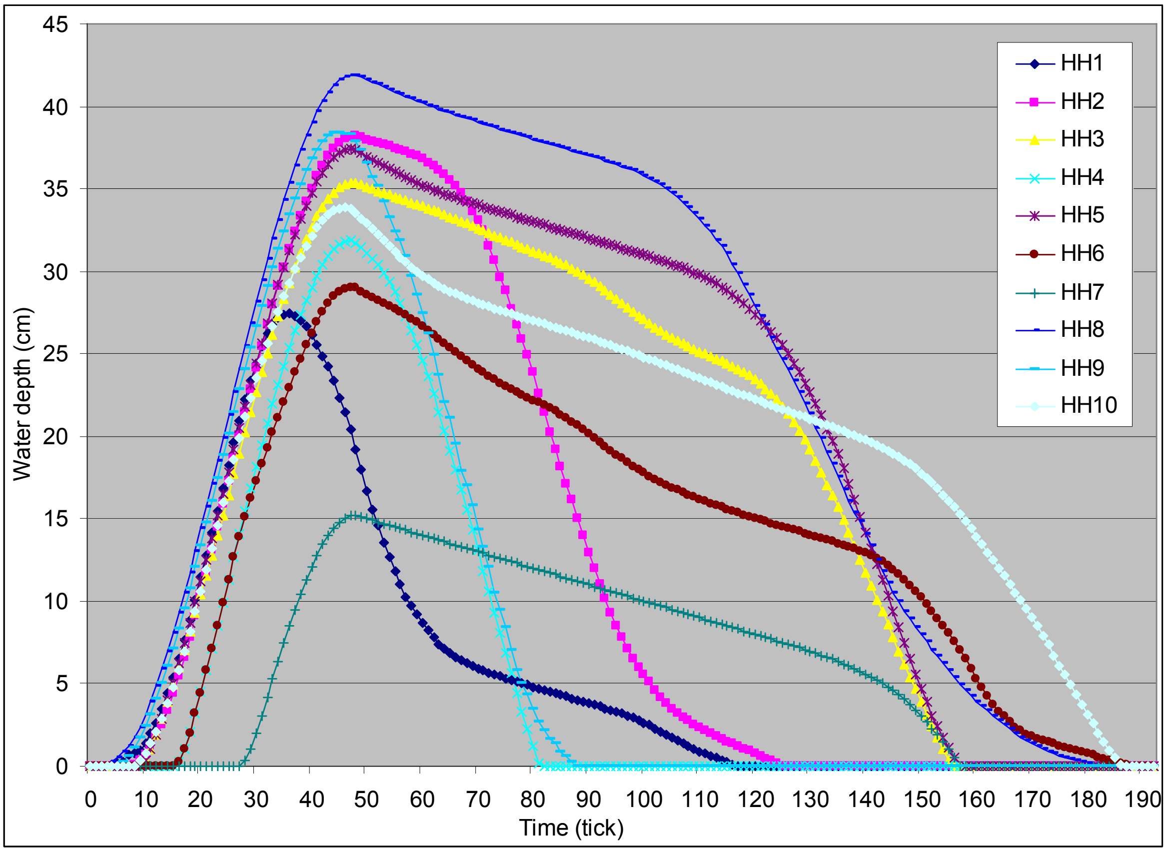


Figure 5-6 Inundation processes of the 10 selected cells of the model in action, in rainfall scenario 3.

Note: The 10 selected cells are the locations for the sample households which will be introduced later in section 5.4.1

In case there is no flood warning or the household does not receive any warning, the agent will predict randomly a fluctuation around its current inundation.

5.3.4 Various flood responding measures

Managing flood events as they occur has the potential to reduce the probability of flooding through controlling flood pathways, and can significantly reduce the damage that is caused by managing losses and influencing the behavior of individuals and organizations (Dawson et al., 2011). General flood responses are classified in four types according to flood phases (Table 5-2 (Yang et al., 2014)): (1) farsighted precaution, (2) close-to-event measures based on forecasting and warning, (3) flood fighting actions and (4) recovery actions after an event.

All flood responding measures require investments, including labor, power, time, capital etc., which are all capitalized and considered as flood loss. Responses listed in Table 5-2 are ranked by its approximate cost based on literature and experience. While, the costs for farsighted precaution measures are not included in the final loss of a specific flood incident, because they are generally long-term investments for preventing all floods. So there are no cost rates for them. However, these precaution measures are seen as properties that can suffer damages in the flood, which is thus involved in the flood damage evaluation later. What response costs should be invested in depends on the magnitude of flood impacts and a coefficient which measures the ratio of house vulnerability to flood impacts and the adaptive capacity of a household.

Underestimation of an inundation level can result in fewer response investments and excessive damages. For this reason, the more specific the warning is, the more effective the remedial measure taken is. As previously noted, the information available from the warning-based inundation prediction addresses this point directly.

The investments for long-term flood prevention are not included in loss estimation of one specific flood event. However, the impacted parts are considered, being calculated by damage function and depreciation function.

Table 5-2 General flood response measures for individual agents and the approximate costs

Flood response phase	Specified measures / actions	Cost rate*
Farsighted precaution prior to a flood event (for long-term flood control)	Education and awareness-raising	-
	Placement pattern of in-house assets	-
	Relief material preparation and storage	-
	Build/buy house that is away from potential flood impacts	-
	Flood adapted configuration & interior fitting of house	-
	Insurance for flood impacts	-
Close-to-event measures based on forecasting and warning (especially for the predicted coming flood)	Consciousness and devices for receiving rainstorm warning	0
	Monitoring and repairing existing flood protection schemes/facilities	0-0.01%
	Seal walls with waterproofing compounds to avoid seepage	0-0.01%
	Move people to safer places	0.01-0.05%
	Move valuable assets away from flood prone places	0.01-0.05%
Flood fighting actions (efforts to reduce flood loss during event)	Stop travelling (to or from work/shopping/meeting, etc.)	0.01-0.1%
	Emergency repairing and reinforcing of defense facilities	0.1-0.5%
	Floodwater diverting by pumping system, canal desilting, etc.	0.1-0.5%
	Evacuating to safe area/shelters	0.5-1%
	Moving assets to safe places	0.5-1%
Recovery actions after flood	Claiming insurance to compensate the damages	0
	Repairing roads, houses and other infrastructures	=depreciation
	Resetting damaged furniture and other in-house assets	=damage
	Clean and disinfect everything that got wet to reduce health impacts	0.01-0.1%

*Note: The cost rate of one responding measure for an agent indicates the proportion it accounts to the agent's total capitalized properties, which is approximately estimated based on literature data (Kreibich *et al.*, 2005; Naess *et al.*, 2005; Dawson *et al.*, 2011).

5.3.5 Flood loss estimation

The total lost value of an agent in a flood event is composed by the inundation damages, responding investments and post-event recovery costs.

Damage and loss by inundation

Flood loss is usually estimated in terms of economic losses, which can be calculated as the amount of money lost (Merz *et al.*, 2010b; Hallegatte *et al.*, 2013). For the convenience of simulation, this study only concerns with the direct economic losses caused by inundation damages. In quantitative expression, the damage loss is the product of a loss rate and the pre-flood value of the property (Dutta et al., 2003), as the Equation 7:

$$L_D = \sum_{i=1}^{n} \alpha_i \cdot V_i \tag{7}$$

Where L_D is the lost value by inundation damages, α_i is the damage loss rate for the i_{th} property and V_i is the pre-flood value of the i_{th} property.

Quantifying α_i is a challenging task as it varies depending on the characteristics of the damaged property as well as the inundation depth and duration. However, abundant research has found some rules of flood loss rate of general properties, which are expressed in the depth-damage curve (Figure 5-7) (Dutta et al., 2003; Moel and Aerts, 2011).

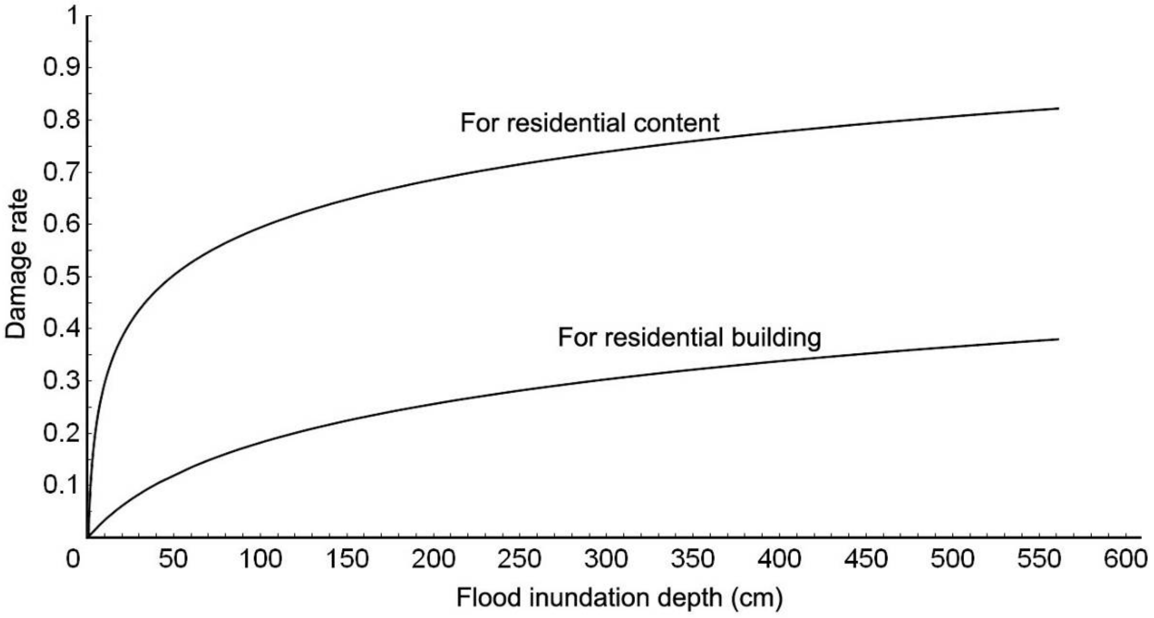


Figure 5-7 Sketch of inundation-damage curves for urban damage estimation

Reedited from (Dutta et al., 2003)

According to the depth-damage curve for urban damages (Dutta et al., 2003), the model presented in this paper calculates the loss rate of residence building and in-house assets as the function of mean inundation in a flood event (equation 8 and 9).

$$\alpha_B = B_c \cdot \ln(I_{mean} + 1) \qquad 8$$

$$\alpha_P = P_c \cdot \ln(I_{mean} + 1) \qquad 9$$

where α_B is the building loss rate and α_P is that for in-house properties. I_{mean} is the mean inundation depth during the flood period. B_c is the parameter that implies characteristic of the residence buildings, while P_c is for in-house properties.

Investments and costs of flood responses

What kinds of response measures are taken during a flood and how much do they cost will depend on the current flood situation and future flood prediction. The principle is that a stronger measure will be able to deal with deeper inundation threats but it costs more. Thus, how much should the households invest in taking measures is related to the inundation depth. In addition, the agents would usually like to invest certain capital to protect their properties from being damaged by flood inundation, but they would stop investing once it costs too much or the inundation is too deep to be prevented. So a threshold of a household's response rate exists. In this case study, the threshold is set to be the household's adaptive capacity. The cost of taking response measures is the function of maximum inundation depth (both current and predicted), elevation and exposure. The equation is expressed as:

$$Rc = \begin{cases} a \cdot P \cdot Ex \cdot I, & when\, Rc \le Ac \\ Ac, & when\, Rc > Ac \end{cases} \qquad 10$$

Rc: Rate of responding cost to the Household's property
P: Property of the agent
Ex: Exposure
I: Inundation depth
Ac: Adaptive capacity

The parameter *a* in the equation is a constant to harmonize the scales of the factors' values. For example, the value of property *P* may range from a thousand to a million HK$, *Ex* ranges from 0 to 1, and *I* ranges from 0 to about 300 centimeters. The function $P \cdot Ex \cdot I$ would give a million level number but *Rc* should range from 0 to 1 which is adjusted with the scale converter *a*.

Once the model is set and initiated, the elevation of a household is unchangeable and exposure is calculated in the precaution phase (0 to 1). So the proportion of the household investment in flood protection will depend on how deep it is inundated (the inundation depth *I*, generally 0 to 300cm). Value of the parameter *a* is set to reach an approximate trend according to inundation-damage curves in existing publications (e.g. Dutta *et al.*, 2003; Li, 2003). The parameter value can be adjusted once the real value in the case area is available or when the model is applied in other areas.

Costs in recovery after flood

It is worthy of discussion whether the recovery cost should be included in the final flood loss. In existing research on flood loss assessment, recovery cost is often involved, although not quantified (Dutta *et al.*, 2003; Cutter and Finch, 2008; Crawford-Brown *et al.*, 2013; Felsenstein and Lichter, 2013). This study takes recovery to mean the restoration of all the construction and in-house assets to their situations as before the flood event. So the cost of recovery is set to regenerate the damaged and lost properties to the status before the flood. However, any investments for recovery will add the same amount of value to the investor, which is thus a zero-sum trade-off and not necessary to be put into the final flood loss calculation.

Total flood loss

Finally, the total loss of a household in a flood event is the sum of the two types of losses: damaged property loss and responding costs. Using the above approaches, the final total flood loss of an agent can be calculated (Equation 11). In a certain research area, the total loss is a function of different rainfall scenarios and flood response measures. The model can be designed with adjustable precipitation scenarios and agents' response measures can vary as well, in order to compare the total loss caused by the different scenarios.

$$H_{loss} = L_D + R_c \tag{11}$$

The model will represent the flood losses of all household agents. It is therefore possible to classify the households by their responding rate and responding costs in the flood event. Then it is possible to find out which group of households suffers more and which suffers less.

5.4 Model output: flood loss and response measures

5.4.1 Data Processing

The basic data for the NTR basin is based on the Digital Elevation Model (DEM) with spatial resolution of 30 meters and altitude resolution of 1 meter. The Ng River system adopted in this model is also extracted from the DEM, using the Hydrology Module in ArcGIS. The river net is thus a little different from the real channels which have been significantly regulated. A map of buildings in the case area is adopted to approximately represent household locations (identifying individual residential buildings is difficult). The building map was converted to ASCII form and imported to the model. The map generates 3294 households in the basin with the same resolution of the elevation data, which does not indicate the real household number in the area. In this model, elevation of the NTR basin range from 0 to 595 m, and households' elevation range from 2 to 212 m. The slope of a cell in the model is defined as the result of its elevation subtracting that of its lowest neighbor. In this model, slope values of all the cells range from 0 to 38. The distance of a household to the nearest river was calculated when the model was initialized, which ranges from 0 to 19 cell-units. Exposure is calculated based on the location and the distance to river, ranging between 0 and 1 using the method in section 4.3.4 of Chapter 4. The extreme values 0 and 1 are not reached because it's highly unlikely that one household has the minimum/maximum value in both location and distance to river.

In the absence of detailed census data, the model initially sets building values and in-house property values of all households randomly. Though, the range of the random building values is based on the real prices of residence apartments in the case area, which ranges from 1 to 10 million HK$ (http://www.hkproperty.com/, retrieved on May 4, 2014). The in-house properties was set between 1 and 10 million HK$ as well, which is a general capital range of Hong Kong households' assets with fluctuation around 2 million HK$ (RVD Hong Kong, 2013). The adaptive capacity of a household is then initialized based on its total properties, also using the method in section 4.3.4. The extreme values 0 and 1 are not reached as well because it's highly unlikely that one household has the minimum/maximum value in both building value and in-house property.

For tracking the households' running process, 10 households are randomly selected and labeled with their ID numbers (Table 5-3). Households in a certain place (model cell) and their attributes will change when the model is reset.

Table 5-3 Characteristics and attributes of the 10 randomly selected households in the NTR basin

Label	Location (coordinate x,y)	Elevation	Slope	Exposure	Adaptive capacity	Building (HK$)	In-house property (HK$)	Total property (HK$)
1	42, 227	7	0	0.767	0.243	3136155	3245481	6381636
2	72, 203	7	1	0.580	0.095	2600253	1106181	3706434
3	58, 129	12	3	0.595	0.463	1383948	8961083	10345031
4	107, 266	13	4	0.460	0.623	7521377	5696612	13217989
5	132, 200	9	3	0.542	0.462	6999475	3313360	10312835
6	181, 146	23	5	0.686	0.334	1493278	6523497	8016775
7	183, 199	30	6	0.625	0.464	4974238	5377416	10351654
8	234, 229	4	0	0.725	0.223	4445075	1576518	6021593
9	238, 295	6	1	0.691	0.286	2856933	4284147	7141080
10	301, 215	17	2	0.523	0.609	6417497	6545851	12963348

Five rainfall scenarios are set in the model and they can be manually chosen by the person who runs the model. The Hong Kong Observatory releases rainstorm warnings in three levels: Yellow warning with hourly rainfall over 30mm, Red warning with hourly rainfall over 50mm and Black warning with hourly rainfall over 70mm (HKO, 2014)。Given that a flood-triggered rainstorm is usually stronger than normal and the highest hourly rainfall in Hong Kong has been 145 mm recorded on June 7, 2008 (Hong Kong DSD, 2014), the model assumes five rainfall scenarios with the maximum rainfalls range from 20mm/h to 120mm/h.

- Rainfall scenario 1 (RS1) indicates an extremely intensive rainfall scenario. It rains for 3h (12ticks, a tick in the model represents 15 minutes of real time) with maximum 30mm/tick. The equation is *y=-0.83x(x-12).* When the time goes beyond 12 ticks, the rainfall is set keeping at 0.
- Rainfall scenario 2 (RS2) indicates a very intensive rainfall scenario. It rains for 6h (24ticks) with maximum 20mm/tick. The equation is *y=-0.14x(x-24)*. When the time goes beyond 24 ticks, the rainfall is set keeping at 0.
- Rainfall scenario 3 (RS3) indicates an intensive rainfall scenario. It rains for 12h (48ticks) with maximum 15mm/tick. The equation is *y=-0.026x(x-48)*. When the time goes beyond 48 ticks, the rainfall is set keeping at 0.
- Rainfall scenario 4 (RS4) indicates a medium rainfall scenario. It rains for 24h (96ticks) with maximum 10mm/tick. The equation is *y=-0.0043x(x-96)*. When the time goes beyond 96 ticks, the rainfall is set keeping at 0.
- Rainfall scenario 5 (RS5) indicates a long-duration rainfall scenario. It rains for 48h (192ticks) with maximum 5mm/tick. The equation is *y=-0.0005x(x-192)*. When the time goes beyond 192 ticks, the rainfall is set keeping at 0.

It should be noted that the extreme rainfall scenario does not necessarily mean a deeper or severer flood inundation. Time also plays a role, and location has effects on the flood inundation process as well. Although the peak rainfalls of RS3 and RS4 are moderate, they can still cause high inundation level for the sample households due to the relatively long raining period. In the opposite, the RS1 with extremely high peak rainfall but short duration and RS5 with extremely long raining duration but low peak rainfall bring lower inundation level Figure 5-8.

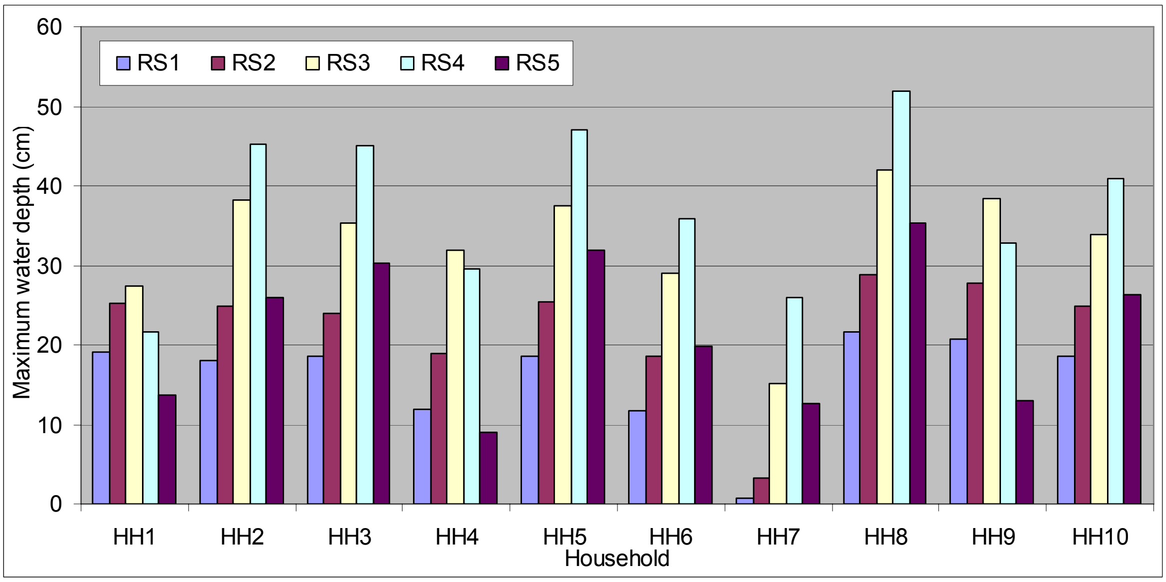


Figure 5-8 The maximum water depth of the sample households in different rainfall scenarios.

To simulate the water infiltration and evaporation process, an interception function is adopted in the model, which is set with a value of 1mm/tick for all cells. Thus the cells all have interception as an attribute to make water reduce in every step. As in real word, the evaporation is ~0.1mm per 15 min (tick) and infiltration reduces about 50% runoff (Ren and Guo, 2006), the model artificially initializes an interception value of 1mm per tick, which is a bit large to save model running time.

If there is a flood warning, the households have an 80% chance to receive the warning. Once received, the household can determine the near future rainfall trend and intensity (rainfall scenario), and therefore can estimate its inundation depth. Options for warning lead time and interval are available on the model interface and can be set manually before running the model. When flooding occurs, households will change their color from white to red, and then to black, to show visually how deep they are inundated.

In the flood damage section, all residence buildings have the same standard to flood damage. Therefore, the parameter in the loss rate function (Equation 8) is set as $B_{c1} = 0.06$. Variant in-house properties of each household are packed as one property, and the loss rate parameter (equation 9) is set as $P_{c1} = 0.1$. In the flood response section (equation 10), parameter a has the value of $1/(5\times10^9)$, which is adjusted to the goal of making the Rc curve fitting with existing publications (e.g. Dutta *et al.*, 2003; Li, 2003). These parameter values can be adjusted once the real value in the case area is available or when the model is applied in other areas.

While it is desirable to have a model that represents the reality to a large degree, currently there is generally insufficient information on the behaviors and responses of individuals and organizations during flood events to parameterize the agent behavior rules (Dawson et al., 2011). Moreover, many of the river channels have been regulated and artificial drainage pipes have been fixed in the research area during the last decades, however information on this has not been available for this research. Thus the flood water flow in this model is not able to exactly reflect the real world flooding event. The purpose of this case study is to experimentally demonstrate the utility and potential of an agent-based model to be used in a flood loss analysis and flood incident management. Once better data become available, the model can be evolved more realistic. At this stage, the model supports exploring the process of flood loss along with various household responses and compares the effectiveness of different flood response strategies and measures.

5.4.2 Differences of the flood losses among households

The model executes a precaution function first if the flood warning option is checked on. 90% of all households in the NTR basin receive the warning information and take some precaution measures, which require investments. In case precautionary measures have been taken, the adaptive capacity of households will be enforced and thus their exposure will be reduced.

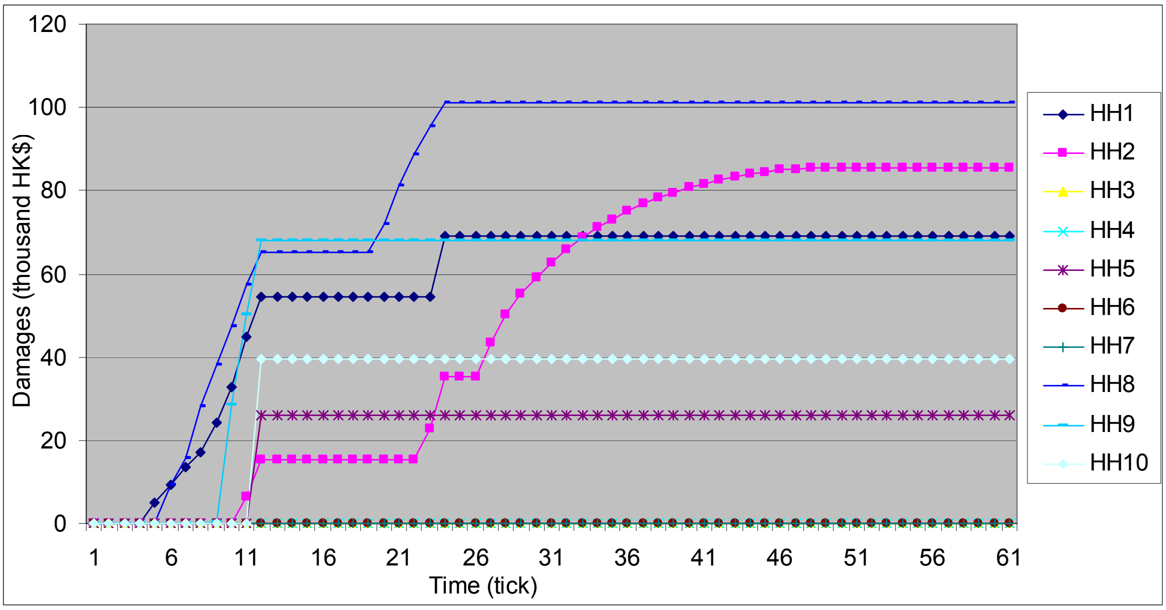


Figure 5-9 Flood Damages of the sample households in RS3 with rain warning of 12h lead time and 3h warning interval.

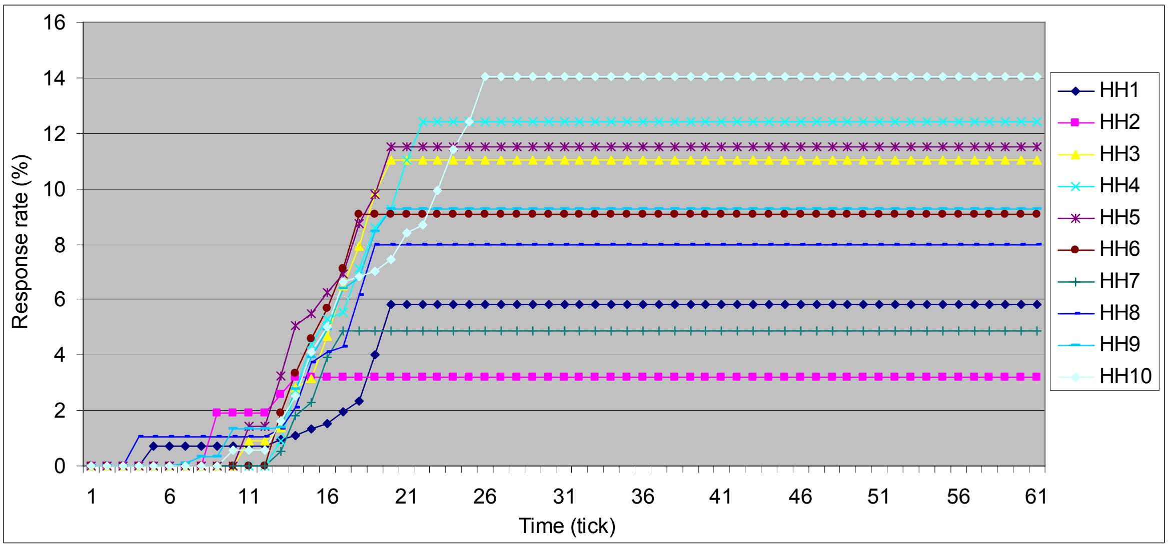


Figure 5-10 The proportion of responding investments to total capitals, for the sample households in RS3 with rain warning of 12h lead time and 3 h warning interval.

HH1, HH2, HH8 and HH9 suffer the most damages among the sample households (Figure 5-9), incurred by fairly less investments in response measures (Figure 5-10). This is mainly because the four households are the poorest out of the ten, in terms of their total properties. Limited by their scarce economic resources, they have low adaptive capacity, which in turn limits their response investments. This indicates that the lack of economic resources significantly contributes to the absolutely larger extent of flood damages. This is an evidence that, comparing with the riches, the disadvantaged communities and their people are in a higher risk of flood impacts.

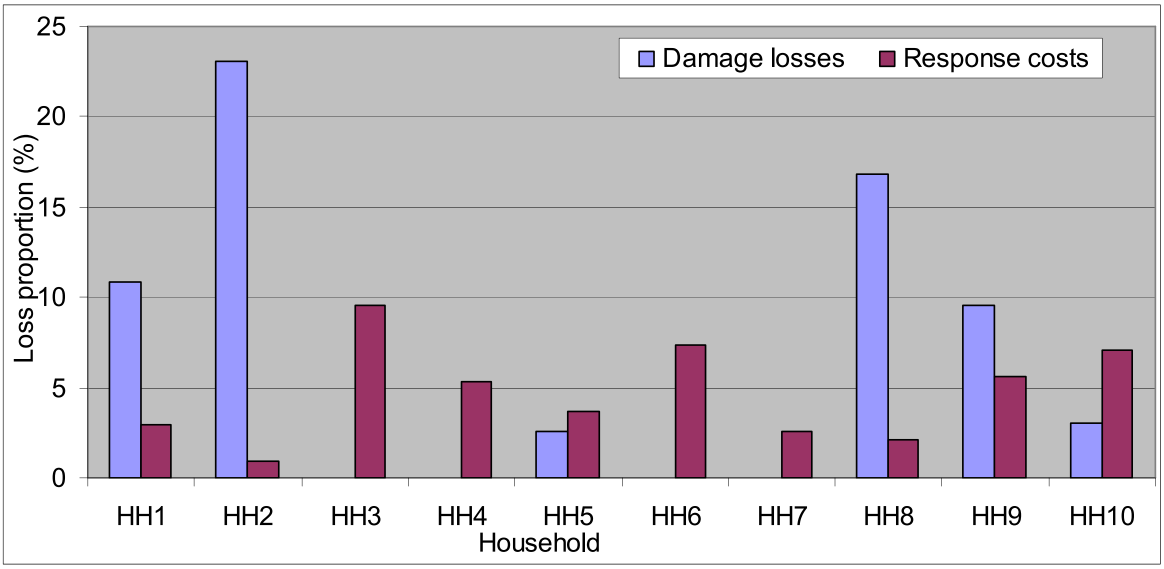


Figure 5-11 The proportion of responding costs and damage losses, for the sample households in RS3 with rain warning of 12h lead time and 3h warning interval.

Figure 5-11 clearly shows that households who invest more in flood response measures suffer less flood damage. Some households (HH3, HH4, HH6 and HH7) even respond so effectively that they don't suffer damages at all. This indicates that responding measures are quite helpful for reducing flood inundation damages.

5.4.3 Flood loss in different response strategies

Under a certain rainfall scenario, there will be different damages for households receiving different warning information. The model uses the term lead time (LT) to represent the time period from the time of warning release to the time of flood start. And warning interval (WI) is used to denote the time period from one warning release to the next one. The model has run several times under RS3 with different lead time of warning but the same warning interval (3h). The results are shown in Figure 5-12. It manifests that generally warnings with shorter lead time contribute to higher flood damage whereas longer lead time helps reduce damages. While comparing to the cases with various warnings, the damages are always the highest in the absence of warning release. It is noted that changes of lead time do not always lead to changes of damage for some households (e.g. HH8 and HH10). This indicates that there may be other decisive factors in function as well, which leads to further tests on warning intervals.

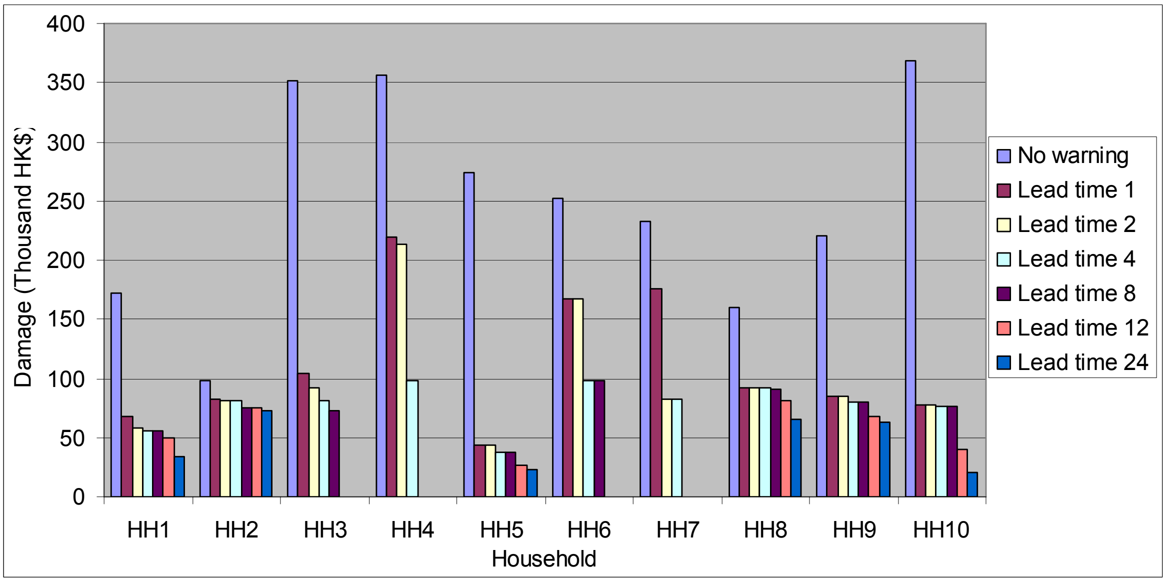


Figure 5-12 The difference of damages, for the sample households in RS3 with 3h warning interval but different lead time of warning.

In these tests the warning has been set with lead time of 12h and with various warning intervals ranging from 2h to 12h. A test on the situation of no warning has also been included. Figure 5-13 shows the result of higher damage accompanied by longer warning interval. Further investigations focus on the combined effect of lead time and warning interval changes. The findings, as shown in Figure 5-14, mean that without warning the flood loss rates of households are prone to reach the highest level, comparing with other conditions with warnings. In addition, a longer lead time and shorter interval can obviously alleviate the loss rate. However, this significant impact is not applied to the case of HH2, largely due to its features of poor and very low adaptive capacity. Therefore, I argue that the effectiveness of warning system on alleviating flood loss is strongly correlated with the household's economic situation.

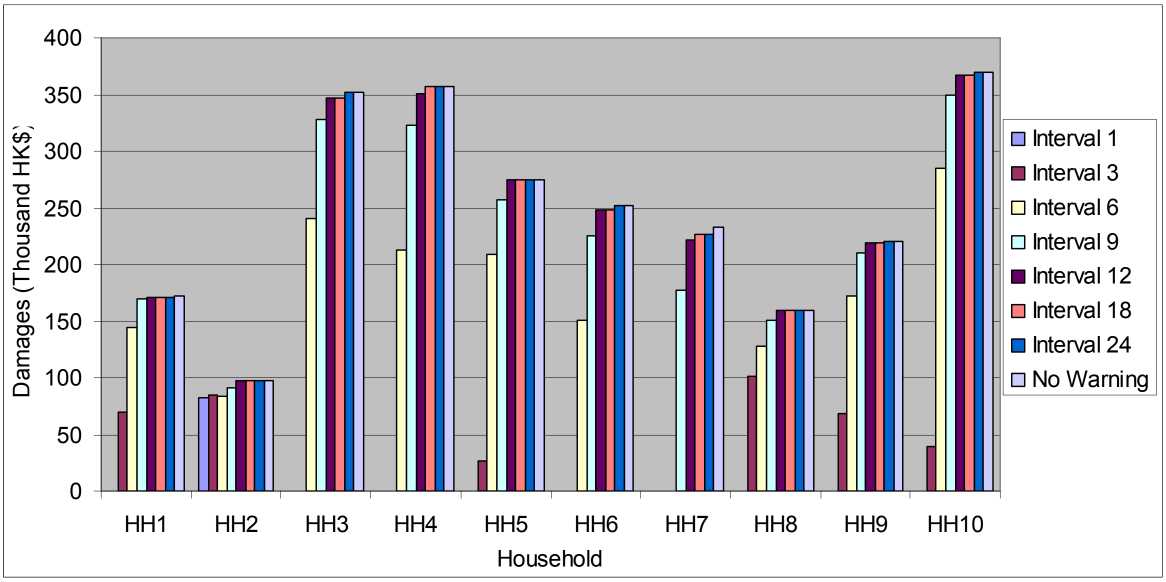


Figure 5-13 The difference of damages, for the sample households in RS3 with 12h warning lead time but different warning intervals.

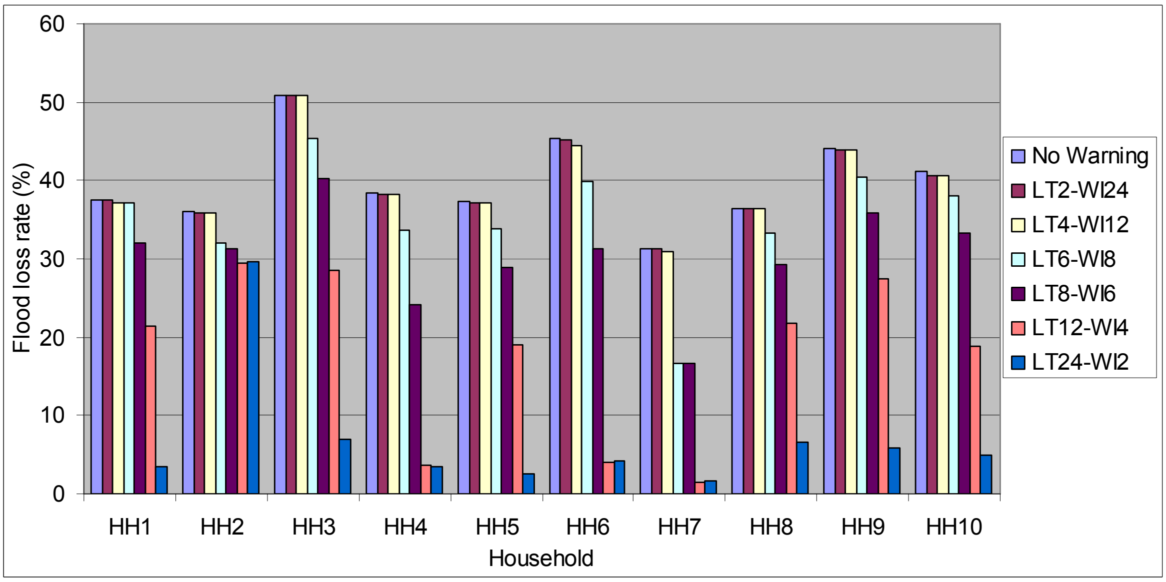


Figure 5-14 The difference of flood loss rate, for the sample households in RS3 with different warning information.

LT: lead time; WI: warning interval.

Comparing the results from Figure 5-12 and Figure 5-13, HH3, HH4 and HH10 are the households whose damages perform much different in both the situations of changing warning lead time and warning interval. Given that HH3, HH4 and HH10 are the richest households in the 10 samples, it indicates that the amount of exposed properties is sensitive to response strategies, such as whether warning information is received.

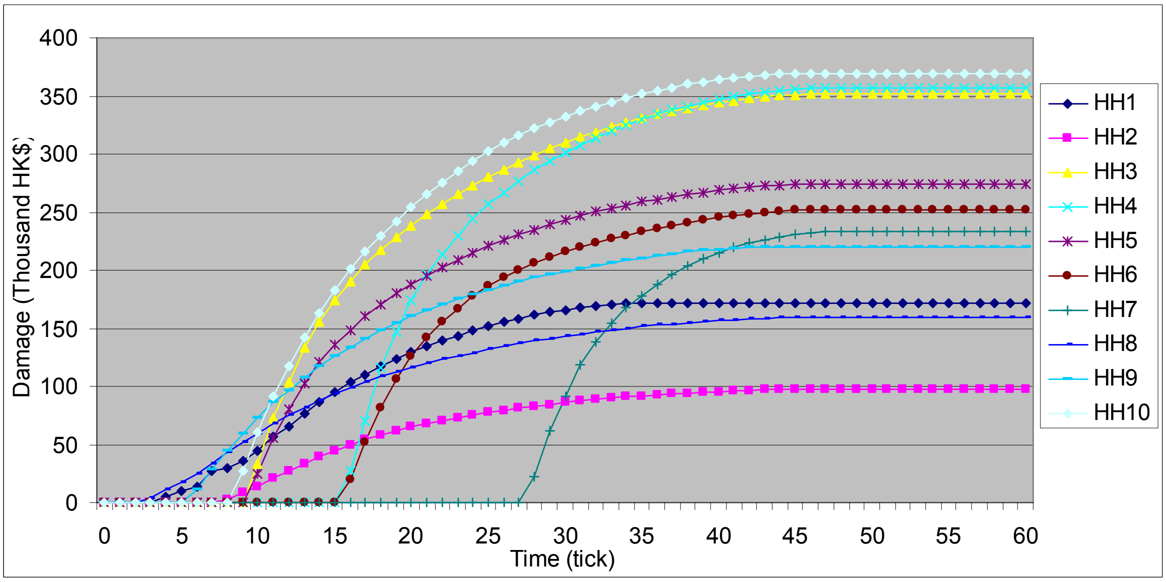


Figure 5-15 The damages for the sample households in RS3 with no warning information released.

In the situation of no warning, households suffer flood damages without taking any response measures and the damages increase along with the growing of the flood water level until the flood recedes (Figure 5-15). Furthermore, the final flood loss rate of all households is lower in the condition of a flood warning (lead time 12h and interval 3h) than that in the condition of no warning at all (Figure 5-16). It's also very clear that the poor households, HH2 and HH8, have small differences in the two warning scenarios, which further proves that flood warning does not help much if the adaptive capacity of a household is too low.

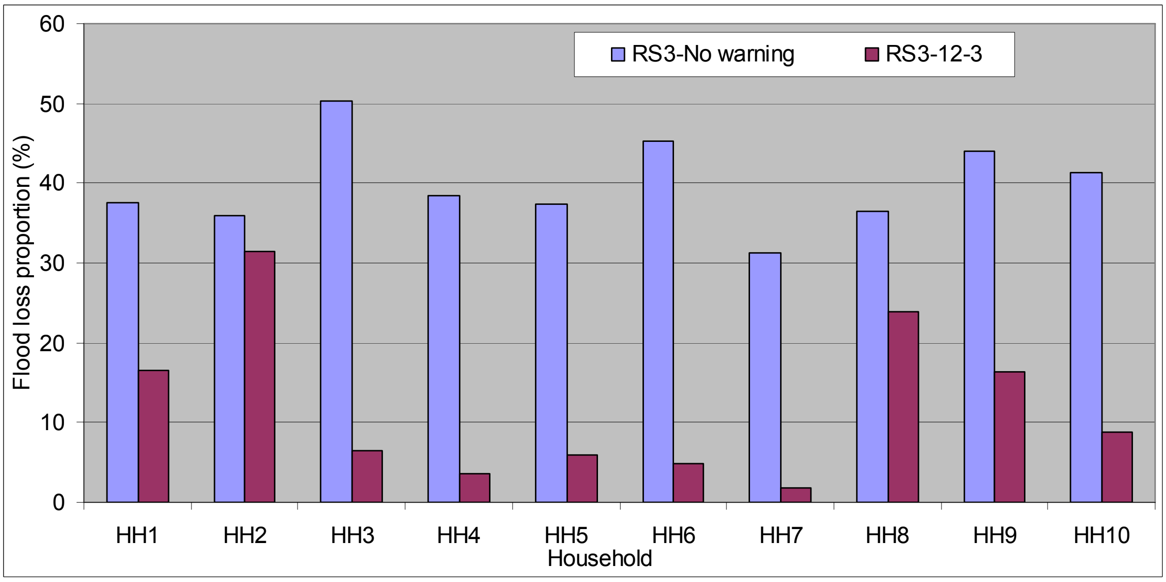


Figure 5-16 Comparison of the flood loss proportions of the sample households between RS3 and no warning scenarios.

5.4.4 Flood loss in different rainfall scenarios

Following the discussion on warning information and response strategies above, the effects of rainfall scenarios were also tested in the model. As shown in Figure 5-17, rainfall scenarios with high hourly rainfall (RS1 and RS2) generally cause more serious flood damages to all of the households, as they cause floods very soon and leave less time for responding. The moderate scenarios (RS3 and RS4) cause relatively moderate damages for all. While in a long period rainfall scenario with low peak rainfall, damages do not occur for most households as they can arrange some response measures, except the poor HH2. This finding suggests that more attention should be paid to extreme rainfall events when flood management decisions are made, although their occurrence probability is low.

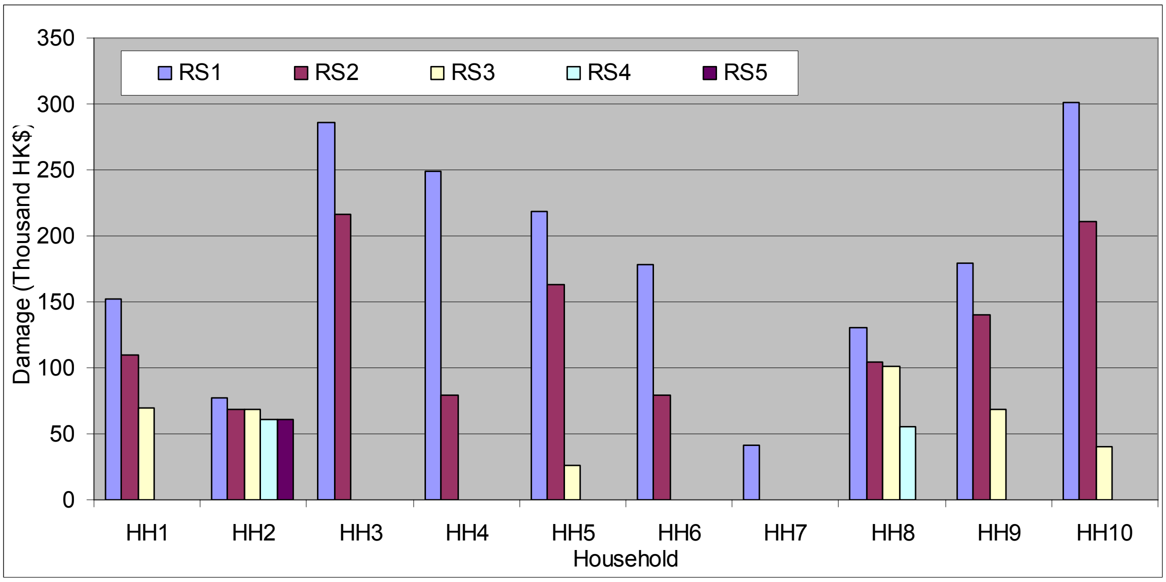


Figure 5-17 The damages for the sample households in different rainfall scenarios with same warning information (lead time 12h and interval 3h).

Figure 5-18 reveals a similar phenomenon to that in figure 17. Moreover, the comparison of the two reveals that damages can be totally avoided with small investments in responding measures, e.g. HH7 has little flood loss (responding costs) but no damages. This means that an effective response strategy will play a great role in flooding control.

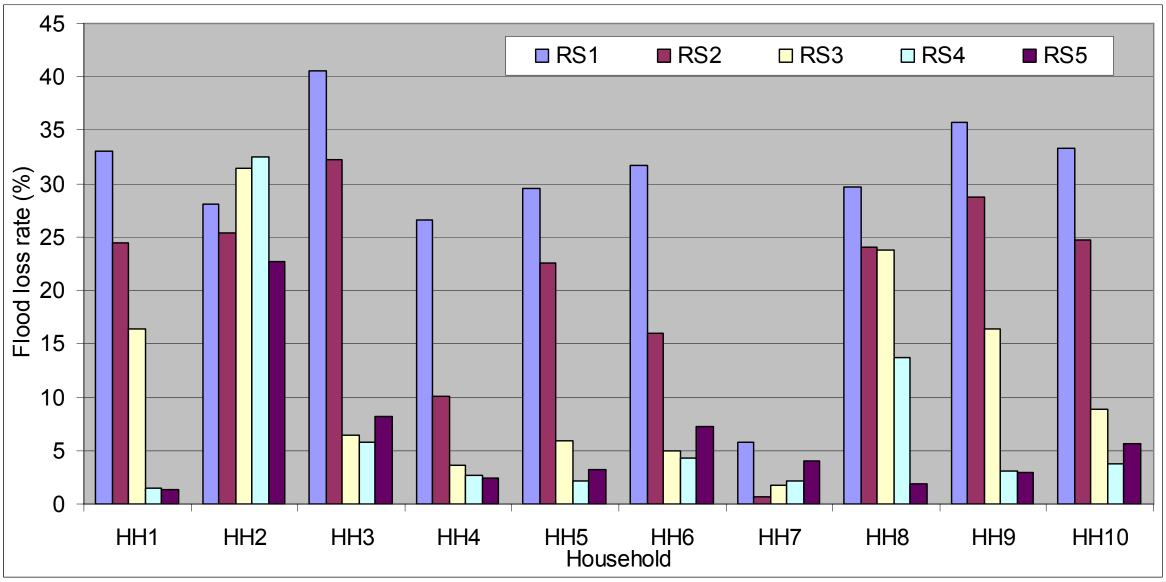


Figure 5-18 The loss proportion for the sample households in different rainfall scenarios with same warning information (lead time 12h and interval 3h).

5.5 Improving flood response strategies

Based on a number of model simulations in the NTR basin in Northern Hong Kong, this study has examined the effects of households' flood prevention measures when facing various rainstorm scenarios and warning information. The results show that exposed property amounts, flood warning information and rainstorm conditions all contribute to households flood losses.

When facing a rain triggered flood, poor households with low adaptive capacity to flood threats have the potential to suffer more flood losses than the rich ones. And the individual adaptive capacity is very important to the actual responses. It implies a case that poor households may receive warnings and be willing to respond but they are not able to or have no resource to. This suggests stronger flood prevention and mitigation especially for the poor, for instance lifting up the ground of residence buildings, connecting to timely weather forecasts, checking the conditions of the surrounding drainage facilities frequently, etc.

Findings from this study reveal that in general warning lead time affects flood loss significantly, while the effects are not great in case of a short warning interval. Short warning interval means a high frequency of warning, which give the households more opportunities to receive warning and take actions in a long raining duration. Receiving warnings with a short time interval can partly compensate the shortcomings in warning lead-time. Further results indicate that the damages go higher when warning interval was set longer, and a longer lead time with shorter interval can lower the loss rate greatly. To improve the warning system with more frequent information release should be a priority in flood control planning and management.

The model results suggest that extreme rainfall scenarios generally cause more serious flood damages to all households, as they cause floods very soon and leave less time for responding. Although moderate rainfall scenarios with low peak rainfall may cause deeper flood water depth in a long raining period, the damaged can be effectively and timely avoid because flood warnings were released, which ensures successful execution of certain response measures.

5.6 Policy implications for decision making

The results of this study have several potential policy implications. First, flood warning plays the overwhelming role in coping with a coming flood incident. The model simulations in the present paper show further evidence for this point. Changes in warning information, including lead time and warning interval, significantly contribute to the changes in total flood loss. It is therefore extremely important to keep improving the flood warning system with more accurate prediction, longer lead time and more frequent information release. To achieve this, further research on the mechanisms of rain triggered flood and appropriate channels for the release of warning information are highly recommended.

The exploratory analysis have found in particular that random response actions with no warning guidance do not help to reduce total flood losses, which suggests that some individuals who are not covered by warning systems are unable to effectively cope with flood impacts. Due to the lack of capacity of prevention and resilience, their adaptation to flood incidents relies on past experiences of dealing with similar risks. Thus much adaptation is autonomous and facilitated by the social capital and resources of households. However, individual experiences are very limited and unorganized. This makes it complicated and difficult to operate a successful flood management. The current system of treating flooding as a public problem does not stress the increased individual role in responding to flooding risks and damages. The resulting mismatch in policy potentially exacerbates regional vulnerability in face of rising flood losses. Further analysis indicates that supportive government policies related to flood resistance can play a positive role in helping people to implement adaptation measures. Improving individual capacity is a way to help them adopt adaptation measures during floods, and the government should pay particular attention to the marginal communities, and people within the community who have a low level of access to public information. Enhancing adaptive capacity in this context requires a new vision on the populations and communities of the region as an integrated system, supported by institutions that facilitate cross-scale and inter-sectoral planning. Governmental institutions, in their bid to find solutions to cope with flood incidents, need to invest in modeling how floods affect city factors and what the role of human is in response.

Although different individuals suffer differently due to flood impacts, there are some general measures to reduce overall risk to floods. These measures are mainly engineering constructions, such as river regulation, advanced drainage system, and adequate relief materials. The experience in Hong Kong has demonstrated that adopting a higher level of flood control engineering system has significantly reduced the flood risk and potential loss of the people living in flood prone areas. However, it is also worth noting that this study focuses only on rainfall triggered floods in a natural environment. The impacts of improving flood control engineering on their damages and losses have not been examined. The effectiveness and impact of engineering measures are important research issues for future studies.

Furthermore, the results of this study also have implications for adaptation plans for floods under climate change in other regions and countries. Directly providing early disaster warning and prevention information to local communities, particularly marginalized people, in many urbanizing regions is still not common. Given the rapid development of communication technology, the widespread individual use of cell phones, and the cost effectiveness of text messages to individuals, transparency disaster information and prevention services should be explored in more detail.

5.7 Limitations of the study and model

This modeling study makes a shift from a simplistic flood loss assessment, to simulating the effects of the interaction of rainfall, flood inundation and human responses using an agent-based model. It has to be pointed out that this study does not only aim to simulate a real flood event and households behaviors, but more importantly to examine the effects of various flood response options according to rainstorm/flood warnings. It is an experimental model based on the natural environment in the case area, but the data on water flows and household behaviors do not fully reflect the real world. The model reveals some interesting phenomena in the flooding process and responding strategies, though limitations exists in these aspects:

- The model was initially set with only five rainfall scenarios and the precipitation cannot be regulated during the model running process, which is needed for better and easier prediction.
- Due to the absence of data, the model environment does not include human engineering constructions for flood control.
- Only flood warning is considered as a basis for response measures in the model. The interactions among agents help in emergency as well in the real world, but which is not considered yet in this model.
- Adaptive capacity is set as the maximum threshold of agents' responding rate. But the adaptive capacity reflects only the amount of properties owned by the household. Other factors that have impacts on adaptive capacity are not considered.
- The model runs on basic rules that once agents receive warning information they take certain response actions. To generalize more and accurate behavior rules, the response part of the model would need to be re-evaluated on a case-by-case basis.
- Only households are considered in the model, while community, enterprises and government are not included, although they also take active measures

in responding to floods and which in some cases significantly help households.

- Experience plays no role in this model. Since the model runs only one flood event, this gives the households no opportunity to learn and improve their response strategies.

Altogether, a lack of reliable data in the specified case area and limited time/funding jointly limit the reflection of the model to real world situations and determine it as a pilot simulation. It therefore represents a first step towards the development of an operational tool for guiding the design of more adequate flood response strategies and management plans. The simulation would approach the reality once it concerns one or more of the above mentioned limitations. Despite this, this is a reasonable representation, easy to envisage and use, and effective as a first-level approach to modeling flooding and its impact process. It represents a unique tool for scientists and scholars looking for a practical framework to explore the complex flood control system by focusing on the bottom up individual actions and self-organization mechanisms of a real world application. For full dynamic simulations of the process of adaptation, the model will be extended with realistic environment conditions and a more advanced flood responding behavior module.

6 Summary and conclusions

This thesis presents integrated analysis on both water shortage risks and flood threats of the Pearl River Delta in China, in the context of climate change. It explores and further develops assessment methods for climate impacts and response simulations to flood threats. In this chapter (6.1 to 6.4) I will answer the four research questions presented in Chapter 1, by summarizing the key findings of the previous chapters. Then in section 6.5 I will draw overall conclusions to inform decision making and indicate further research.

6.1 Climate change and its impacts on water system in PRD

- *Q1: What are the climate change characteristics, trends and associated impacts on the water system of the PRD area?*

The trend of increasing annual mean temperatures and precipitation which has been observed for the second half of the 20th century in PRD is likely to continue and cause wetter conditions. According to the predictions, the temperature is likely to rise by around 3°C and precipitation increases slightly by 2100, while the sea level is likely to rise with an annual rate of 0.33cm to 1cm in the near future. The inter-annual variability of precipitation is much more notable relative to its trend variability, which means that extreme precipitation events occur frequently. Although projections of future climate change exhibit considerable uncertainties, both the frequency and the duration of floods are likely to increase in the PRD area.

Climate impacts on water systems are mainly reflected in water quantity, quality and their spatial-temporal distribution. These impacts can be briefly put in three categories: water shortage, flood, and pollution that eventually contributes to water shortage as well.

In many areas, a warmer climate is likely to increase water demand while shrinking water supplies. This shifting balance would challenge water managers to simultaneously meet the needs of growing communities and sensitive ecosystems. This thesis illustrated that precipitation change or fluctuation is the major factor that dominates the amount of available water resources. Rising temperatures will cause more intense hydrological circulation, due to increased evaporation and thus decreased runoff. Due to changes in precipitation and temperature, soil water content and surface runoff are also likely to reduce, which therefore have indirect impacts on gross water availability. Climate change will bring more frequent extreme dry weather and the chance of continuing drought will also increase. These could affect the cities by reducing their local rainwater collection. Even a moderate drought would have a ripple effect in the human-environment system, whereby less flowing water will be more vulnerable to pollutants and will result in an increase in pollutant density. In addition, as more freshwater is removed from rivers for human use, saltwater will have the chance to move farther upstream. Drought can cause coastal water resources to become more saline as freshwater supplies from rivers are reduced, which therefore would further exacerbate the severity of water shortage. Considering that the probable characteristics of hydrological droughts in the PRD area are closely related to the variability and availability of water resources of the basin, water resources should be managed by integrating climate change information in order to sustain regional socio-economic development.

Flood implications of the climate change trends are pronounced in most of the cities in PRD. Climate change and its associated impacts are changing the hydrological distributions and cycles. This would probably increase flood occurrence, with more variability and uncertainty. As annual precipitation and extreme rainstorms are both projected to continue to rise over the next century, floods are expected to increase, posing a continuing problem for some low-lying and poorly drained areas. The frequency and intensity of extreme weather and climate events have assumed significant change, together with continuing development in flood-prone areas and natural riverbed siltation, will strengthen both the scale and degree of urban flood risk. Sea level rise may contribute to flooding by inundation, storm surge, erosion caused dike system failure, and drainage difficulties due to backwater flow at river estuaries. At the same time, the return period of a certain high water level will be shortened, which will hence increase the probability of suffering tidal inundation.

Moreover, climate change potentially influences water resources by enlarged hydrological variation, which means an increasing frequency of drought and flood. The significant challenges increase the importance of adaptation in the PRD metropolitan area.

6.2 Risks of and adaptation to water shortage in PRD cities

- *Q2: What are the water shortage risks in the PRD cities, what responses were carried out, and what responses are still needed?*

In the context of climate change, the natural basis of water resources is changing and is most likely leading to a further deterioration of the water shortage. The most severe impact of water shortage and drought is its disaster-chain effect, which implies not only a lack of water but also many indirect consequences, such as pests, diseases, forest fires, ground subsidence, crop reduction and even social instability (Chapter 3).

Local governments in the PRD area have implemented a series of measures to address water shortages, achieving remarkable success. For instance, the DSWS Project serves the two big cities Shenzhen and Hong Kong greatly for more than half a century with fresh water from the East River. Currently this water supply system appears to be balanced. But it faces many significant challenges due to social and economic differences between the cities in the river basin. And this balance could easily be broken by a drought or pollution that reduces the available source water. Thus, should climate change affect the water supply either in terms of quality or quantity then this will affect the relationships between stakeholders.

Other response measures include rainwater harvest, seawater desalination and utilization, wastewater treatment and reuse and water demand management. Actually, Hong Kong has done very good work in rainwater collection and seawater utilization, which can be a model for the other cities.

While based on the existing water securing system, further actions should be considered to meet the potential challenges which accompany natural, social and economic changes. A long-term response strategy may be done in two ways. One is to improve the self-sufficiency rate of water supply, which is possible by extending the reservoirs' capacity or seawater desalination. The other is to diversify water source options, for example, water treatment and reuse. These will reduce overreliance on rainwater or river water, which are big potential risks. Apart from these, possible strategies to increase resilience include options of demand management technology and crisis response measures. Also, public awareness campaigns on climate change impacts and response strategies need to be undertaken so that people can prepare for climate change impacts.

6.3 Flood risks in the PRD cities

- *Q3: How vulnerable to the flood risk are the PRD cities, and for what reasons?*

Chapter 4 focused on flood risk and vulnerability of the PRD cities. The results suggest that the exposure and sensitivity of central cities (Hong Kong, Macao, Shenzhen and Guangzhou) are very high because of highly exposed populations and assets located in lowland areas. The high-density population and production are particularly sensitive to impacts, and disadvantaged sections of society (e.g. old people, unemployed labor, small business) should be the core concern in addressing flood threats. However, the potential vulnerability and risk are low due to high adaptive capacities (both by hard and soft flood-control measures).

Findings indicate that flood risk emerges from the interaction of flood hazard and vulnerability. Flood risks in urban area could be understood as a combination of the probability of occurrence of a flood and the vulnerability of the urban system. As a river delta, the PRD has frequently suffered from flooding in the past. Urban settlements in the PRD are typically located and developed along shorelines and the river estuary, putting them at particularly high risk from flooding and an expansion of the water's edge. A changing global climate is causing rising sea levels and more extreme rainfall events thus would increase the probability of flood occurrence with high variability. Flood vulnerability of the PRD cities is seen as high, based on the evaluation. The two parts together indicate a reliable increase of flood risk in the PRD cities, in particular vulnerable cities such as Zhongshang and Dongguan. From the large-scale point of view, the PRD areas has a higher frequency of floods and more severe flood risks in general because it is highly impacted by the combination of urbanization effects and climate-related changes in the future.

Furthermore, the extraordinary changes due to urbanization and economic development also increase the likelihood of flooding due to human-induced hydrological changes, which include: 1, urbanization that changes land surface characteristics; 2, excessive exploitation of groundwater that leads to land subsidence; 3, significant riverbed dredging that exacerbates river bank erosion;

and 4, land reclamation which seriously narrows the river channel and reduces the river’s natural capacity for draining and regulating flood water.

6.4 Responses to reduce flood damages and improve flood management

- *Q4: What are the local dynamics in responding to flood risk, and what are the implications for better adaptation?*

The dynamics of flood responding is explored at household level, focusing on their response behaviors in various rainfall scenarios and flood warning scenarios (Chapter 5). Households make decisions based on their actual flooding situation and perspectives of potential flood severity. Along with the raining, flooding and warning, the households thus respond dynamically by investing in flood control.

Model simulation on flood loss and response gives more information on individual adaptation to floods. The results show that economic resources owned, flood warning information and rainstorm conditions all contribute to households flood loss. Poor households with less economic resources are not sensitive to flood warning information due to the lack of capacity to respond, which suggests stronger flood prevention and mitigation strategies for the poor. For instance, permanently lifting up the ground of residential buildings, connecting to weather forecasts in a timely manner, and checking the conditions of the surrounding drainage facilities frequently are some of the options.

Findings further reveal that the coupled warning lead time and warning interval affect flood loss fairly strongly and the flood loss rates of households are generally greater in the case of no warning or lagged warnings than with timely, effective warnings. In addition, flood warning, in general, helps reduce damages during the flood process, which means a more moderate and even no damage. The study also reveals that, although extreme rainstorm does not necessarily bring extreme inundation, it causes more serious flood damages because the flood water raises very soon which leaves less time for responding. To avoid potential increase in flood risk and loss, an adaptive management policy needs to concern more on the prediction of extreme events with longer lead time.

6.5 Concluding remarks

Several overarching conclusions can be drawn from the summary. First, climate in the PRD area changes significantly in both the past and projected future, of which the trend is continuing with increasing mean temperature, fluctuating precipitation, rising sea level and increasing typhoon intensity as well as the frequency of extreme weather events.

Second, climate change is adding risks of water shortage in the PRD area, along with population growth, economic development and difficulties in response/management, making the water supply situation more complicated. Taking Hong Kong as a case study, six interrelated risks within the context of climate change are highlighted, namely: drought, rainstorm/flood events, sea-level rise, water pollution, and social management and policy gaps. It suggests that for a sustainable future, the PRD cities needs to invest in improving water self-sufficiency, diversify water sources and conduct aggressive public awareness to increase individual adaptation to predicted climate change impacts.

Third, the frequency and intensity of extreme weather and climate events have changed significantly, together with continuing development in flood-prone areas, increase both the scale and degree of urban flood risk in the PRD area. However, the potential vulnerability and risk can be low due to high adaptive capacities (both by hard and soft flood-control measures). Therefore, suggestions are made to develop an integrated climate response strategy, to release accurate early warning and action guidance, to share flood related information to the public and to apply the advantages of social networking.

Last but not least, as demonstrated in chapter 5, in-time, accurate and wide-covered flood warning plays a significant role in reducing flood loss. And earlier investments in responding measures are more efficient than late activities. It is increasingly recognized that the nature of coupled social-environmental problems such as flooding require innovative institutional arrangements to address the complex biophysical processes occurring at local, regional and global scales, while fitting within the economic, socio-cultural and political constraints of decision making. In doing so, the following recommendations can be considered as "no-regret" measures: (1) improving the flood warning system with more accurate prediction, longer lead time and more frequent information releasing; (2) improving individual adaptive capacity by education, information sharing, in particular to the marginal communities and people within; and (3) regulating flood-prone areas with construction and engineering measures.

6.6 Research limitations and outlook

However, uncertainty exists in this study. Uncertainty in analysis processes reflects the incomplete knowledge of the system or limited capacity of available hardware (e.g. computing capacity). Furthermore, many uncertainties exist in the flood formation process, which relate to the combined effects of human behaviors at all aspects of the process and specific regional characteristics among cities. The research was done on city level, with the context of a river basin. Once the study goes to sub-city level (e.g. district, if data available) the results may vary slightly. It is worth mentioning that the indicator system depends highly on the indicators chosen and the data used. Especially when the eleven cities are compared in one indicator system, uncertainty rises from input data due to different statistical criteria of these cities. The research findings are still plausible because the study is interested in the change in the mean climate conditions and deals with relative risks among the cities, not absolutely.

Moreover, the flood responding model in chapter 5 correlates a large amount of information about human behavior in emergency situations which are rarely quantified. The model has to run some parameters with literature referred values or even artificial ones. Since the model is based on a relatively simplified conditions, additional research is needed to lead the artificial system to self-adapt towards the adequate model by importing the real data to it, thus ensuring that the resulting model represents reality.

Not withstanding its limitations, this thesis does demonstrate its insights in the complexity of the research matter by applying a multitude of methods at different geographic locations and across disciplines. Overall findings of this study help with understanding the level of climate change impacts and vulnerability, which are vital to gauge the cities' risks and corresponding responses and therefore inform decisions about how best to deal with emerging climate-related water risks like drought and flood. Particularly with respect to future research on the climate change impacts and disaster nexus it is promising, as done in this thesis, to combine in-depth qualitative field research with quantitative data analysis and modeling approaches.

Based on the findings of this thesis my specific recommendations for further research relate to: (a) how to simulate the hydrological drought event and its impacts under different climate scenarios with consideration of social responding strategies such as water allocation schemes, (b) how does the flood vulnerability/risk relate to various uncertainties such as scales and governance, (c) how efficient are engineering measures in addressing flood impacts, in comparison to temporary, emergency and targeted actions, (d) what are the representative flood response behaviors at the individual or the community level and how are their cost-benefit balances, and (e) how and how much do education, personal experience, information communication and their combinations contribute to flood impact mitigation (as exhibited in the case studies / literature).

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8 Appendix

8.1 Field investigation routes and sites

A field investigation was carried out during the period November 19 to December 18, 2011, which focused mainly in Shenzhen and Hong Kong with a few visits to other cities in the PRD area. The field work significantly supported the thesis in four aspects:

- data collection, including open resources, maps, books and other information materials.
- better understanding climate features and natural environment elements in this area, such as sea level, river flooding and drinking water resources.
- getting personal experience on climate-related water issues and interviewing researchers, stakeholders and practitioners about the environment status, climate feature, and socio-economics situation of the urban systems in PRD.
- research cooperation established with local academic institutions/researchers.

Figure 8-1 and Figure 8-2 illustrate the key visited sites during the journey, and Table 8-1 further show the specified locations.

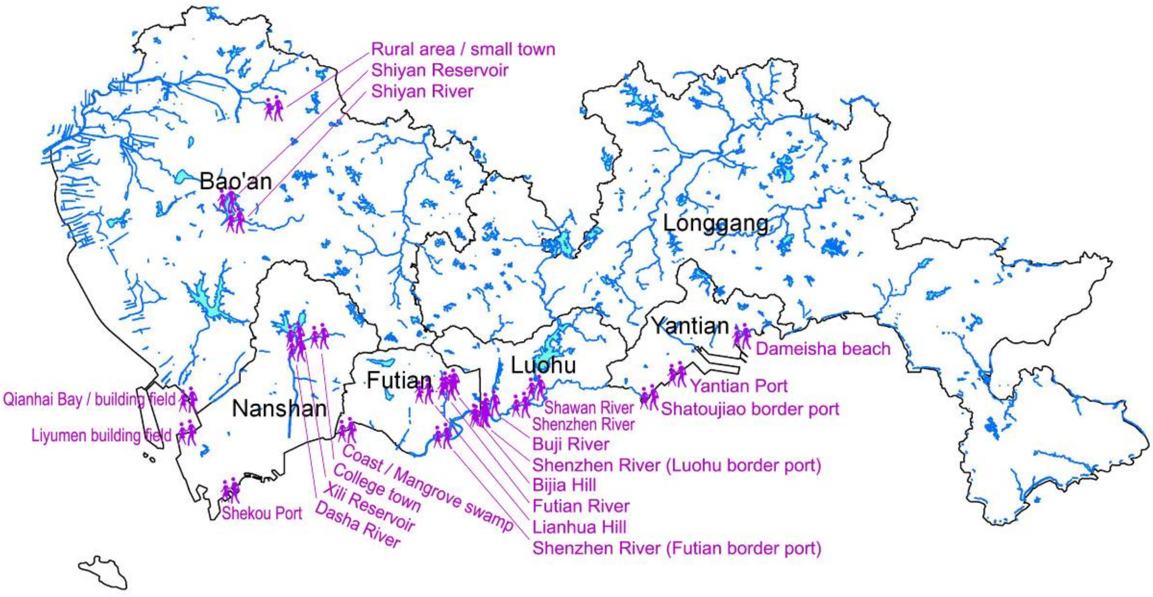


Figure 8-1 Site visits in Shenzhen.

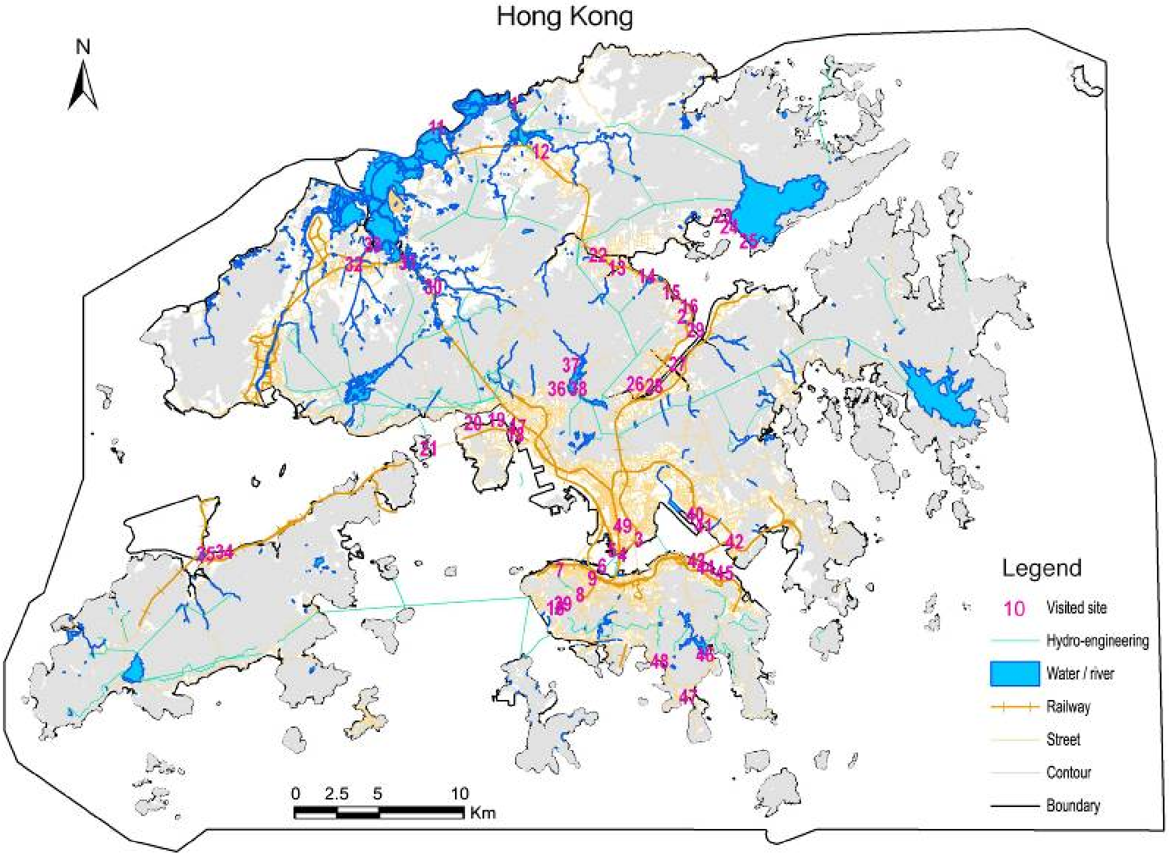


Figure 8-2 Site visits in Hong Kong.

Table 8-1 Detailed sites location that are visited during the field investigation.

	Category	Sites	Site label
Shenzhen	Reservoir	2	Shiyan; Xili;
	Coast	4	Qianhai Bay; Liyumen; Mangrove swamp; Dameisha beach
	Harbor/Port	3	Shekou port; Yantian port; Shatoujiao border port
	Town	4	Guangming district; College town; Huaqiangbei & Yannan;
	Road/bridge	3	Luohu border port; Liyumen building feld; Qianhai Bay
	River	6	Shiyan; Dasha; Shenzhen; Futian; Buji; Shawan;
	Other	2	Bijia hill; Lianhua hill
Hong Kong	Reservoir	4	Pok Fu Lam reservoir; Plover Cove reservoir; Upper Shing Mun reservoir; Tai Tam Tuk reservoir
	Coast	10	Tolu Harbor; Sha Tin; Fo Tan; Sha Tin Hoi; Tung Chung Bay; International Airport; Ngau Tau Kok / Kai Tak Airport; Quarry Bay coast park; Stanley Promenade; Repulse Bay
	Harbor/Port	6	Tsim Sha Tsui; Star ferry pier; Central ferry pier; Rambler channel; Kwun Tong typhoon shelter; Shau Kei Wan typhoon shelter
	Town	15	Chinese Uni. of HK; Hung Hom; Uni. of HK; Central; Sheung Shui; Tai Po Market; Lai King; Tsing Yi; Tai Wo; Tai Mai Tuk; Kam Sheung Road Station; Long Ping; Wo Yi Hop; Yau Tong; Quarry Bay
	Road/bridge	3	Ting Kau Bridge; Tingyi-Mawan Bridge; Sha Tin Lek Yuen Bridge
	River	3	Shenzhen River; Kam Tin River; Shan Pui Ho River
	Other	2	Victoria Peak; HK observatory

8.2 Guideline for interviews with experts

Climate change and impacts

1. Generally speaking, how do you think the characteristics and trend of the climate in Hong Kong (precipitation, temperature, sea level…)?
2. What do you think are the main impacts of climate change to HK?
3. Is there some place or some people who are especially vulnerable to climate impacts? Why and is there a case?
4. Do climate impacts cause certain social conflicts (benefit among stakeholders)?

Water resource

1. What's the characteristic of HK's water resource? What's the key problem?
2. What's the impact of climate change to water resource? How serious is this impact?
3. Do you know any water-related disasters in HK, When and where did it happen? Can HK handle these kinds of threat?
4. How do you evaluate HK's work on water management?
5. Is there any conflicts related to water issues?
6. What's the problem with Shenzhen River? What measures and strategy does HK take to address it?

Climate adaptation

1. Which measures has HK taken to addressing climate impacts? How do they work?
2. As a well developed city, HK has enough power/capability to protect and help citizens in case of disasters, right? What are the measures?
3. What's the strategy of HK in addressing climate change? Need any revision?
4. How is HK's capability in addressing climate change? What's the advantage and what's the short?
5. What do you think should be considered firstly in adapting and responding climate impacts?
6. How can general citizens address climate change and its impacts? What measures can they take?

Urban planning and development

1. What does urban development suffer from climate impacts?
2. Does water issue affect urban planning and development? Is there any engineering measures planned to prevent flood / water shortage in HK?
3. Is there long-time urban planning program in HK? Any special planning on climate/environment/water?
4. Are climate impacts considered in HK's urban perspective planning?
5. Concerning the above questions, which places do you recommend for visiting?

The end

1. Is there anything important that I ignored? Do you have any comments about my work?
2. Could you please recommend some papers, books or other data for my work?

8.3 Questionnaire: Chinese and English

氣候變化對珠三角城市發展的影響 – 香港公眾調查問卷

Climate Change and Urban Development in the Pearl River Delta, China --- A Public Survey

調查執行人 Investigator：楊亮（Liang YANG） **調查地點 Location：**香港（Hong Kong）
調查時間 Time：2011 年 11 月 - 12 月（November – December, 2011）
主辦方 Organizer：德國漢堡大學地理系，氣候變化與安全項目 Research Group Climate Change and Security, Institute of Geography, University of Hamburg, Germany
合作方 Partner：香港中文大學，太空與地球資訊科學研究所 Institute of Space and Earth Information Science, Chinese University of Hong Kong
北京大學深圳研究生院，環境與能源學院 School of Environment and Energy, Peking University Shenzhen Graduate School

珠江三角洲作為中國人口最密集、經濟最發達的大都市區正在經歷著城市發展與氣候變化的影響之間的衝突。我們當前正在開展“珠江三角洲氣候變化與水資源對城市發展的影響”科研課題，為了進一步瞭解公眾對氣候變化及其影響的認識，研究應對氣候變化的需求並提出應對措施，特設計如下調查問卷。請您花幾分鐘時間回答以下問題（本次調查不記名，所得資訊將僅應用於科學研究）。The Pearl River Delta metropolitan, as China's most densely populated and economically developed area, is experiencing conflict of urban development and climate change impacts. We are currently carrying out the research project "*Adaptation and Response of Urban Cluster to Climate Change in Pearl River Delta*". In order to further understand the public's awareness of climate change and its effects, as well as to meet the needs to address climate change and put forward countermeasures, a special questionnaire is designed by this project. Please take a few minutes to answer the following questions. (Your responses will be anonymous and the information obtained will be used only in scientific research).

一、選擇題（可多選，最多選三項）Multiple-Choice Questions (Maximum 3 choices)

1、您覺得本港的氣候是不是有變化呢？Have you personally noticed some climate change in your local area?
A 沒有，完全沒感覺到 No, no change at all B 有較小的變化 Changed a little
C 是的，變化挺大的 Yes, changed a lot D 很難說 Don’t know / hard to say

2、您在本港是否感受到了氣候變化的不利後果？Do you feel the adverse impacts of climate change?
A 是，問題非常嚴重Yes, it’s a very serious problem B 是，但是相對還能承受Yes, but it’s still affordable
C 我感覺到影響非常小 No, I feel little impacts D 說不清楚 I have no obvious sense. It’s not clear.

3、氣候變化對本港可能的影響主要有哪些？The main climate impacts on the city might be?
A 暴雨Rainstorm B 颱風Typhoon C 高溫酷熱Hot weather
D 海水潮汐影響 Sea tidal E 乾旱缺水 Drought / water shortage F 沒有影響 No impact

4、您有沒有參加過應對氣候變化的行動？ Have you ever participated in actions to address climate change?
A 我參加了挺多這樣的活動I took part in such activities many times
B 很願意參加，但是不知從何做起 I’d like to participate, but I don’t know where to start
C 偶爾，視情況而定 Occasionally; it depends. D 沒有，我不關注 No, I am not concerned about it

5、您是否認爲，每個人生活方式的選擇都能爲節能減排、應對氣候變暖而發揮作用？(選 1-2 項) Do you think personal lifestyle plays a role for energy conservation and climate warming mitigation?(1-2 choices)
A 我個人已經在努力了，每個人都努力就能改變現狀 I have worked for this; if everyone starts, we can change the situation
B 是的，從生活細節開始著手，每個人都能做到 Yes, start with the details of life, everyone can do it
C 我不這麼認爲，個人的努力太弱小了 I don’t think so, individual efforts are too weak
D 我不這麼認爲，因爲生活方式和習慣是很難改變的 No. It’s hard to change personal lifestyle
E 這樣做會犧牲現代生活品質與效率，我不願意 To do so will loss quality and efficiency of modern life, I don’t like to
F 我想努力，但是不知道如何努力 I’d like to, but I don’t know how to do it

6、如果有人號召，您是否願意加入到應對全球變化的實際努力中來？If someone calls, would you like to join the activities response to global change?

A 願意Yes, I will B 不願意No, I won't C 說不好，看情況It depends

7、有人認爲，應對氣候變化的措施將影響經濟增長，您如何看待？ To address climate change will affect economic growth, what do you think?
A 應對氣候變化是所有地區的責任，必須採取措施 All regions have the responsibility to address climate change; measures must be taken
B 可能會對當前有影響，但未來經濟增長的品質會更高 It may affect the current economy, but benefits the quality of future economic growth
C 不同國家和地區應根據情況採取不同政策 Different countries and regions can adopt different policies based on their conditions
D 還是應該首先保持經濟增長 Maintaining economic growth is more important

8、在應對氣候變化中，誰最應該採取積極行動？Who should take the most positive action in response to climate change?
A 每一個個人Each individual B 公司和企業Companies and enterprises C 政府部門Government
D 專業人士Professionals / experts E 其他Other

9、怎麼樣您才會更積極地參加應對氣候變化行動呢？What would encourage you to take action, or more actions on climate change?
A 單位組織集體活動If my club or organization were taking action
B 有志同道合的人們一起行動 Act together with like-minded people, not acting alone
C 能夠得到經濟或物質上的利益 Get financial or material interest from the actions
D 得到社會的認可和尊重 Get recognition and respect from the community
E 能夠肯定活動確實會有實際效果 Be sure that the activities have practical effect

10、本港哪些市民最容易受到氣候變化的影響？Which people in the city are most vulnerable to climate change and its impacts?
A 臨時住所、棚戶區居民Temporary residents / shanty towns
B 老城舊城區居民 Local residents of the old town C 現代化繁華中心城區的居民 Modern downtown residents
D 山坡、河流沿岸的居民 Residents at hillside and nearby river
E 郊區小鎮、農村居民 Outskirts and rural residents F 海岸帶、近海邊的居民 Coastal residents

11、您覺得本港水資源存在的主要問題是？What do you think are the main water problems in this city?
A 飲用水缺乏Lack of drinking water B 暴雨多/洪水多Heavy rain & flood
C 供水/排水不順暢 Poor water supply and drainage system D 水價高 High water price
E 水污染嚴重 Water pollution F 用水浪費/不合理 Water waste & unreasonable use

12、導致本港水資源問題的原因主要是？Main reasons that cause the water problems are?
A 氣候變化和極端天氣導致水資源驟增驟減Climate change and extreme weather
B 工業、商業和人民生活需水用水量太大 High water consumption
C 水資源保護不夠、污染嚴重 Not enough protection of water resources
D 供水、排水基礎設施規劃落後、建設不足 Poor water supply and drainage infrastructure

13、本港已經採取哪些行動應對氣候變化了呢？What actions has the city taken to address climate change?
A 沒有採取行動No action B 政府有災害應急措施和機制Emergency measures to deal with disasters
C 提高了基礎設施抗災害能力 Improve the anti-disaster capacity of the infrastructure
D 實施了節能減排，降低能耗 Implementation of energy conservation and energy consumption reduction
E 幫助市民提高應對氣候影響的能力 Help people improve their adaptation ability

14、哪些極端天氣在本港發生最頻繁或最使您擔心？Which extreme weather events occur most frequently or make you worry about most?
A 超級颱風 Super typhoon B 嚴重乾旱/缺水 Drought / water shortage
C 特大暴雨/洪水 Heavy rain / flooding D 海平面上升/海嘯 Sea level rise / tsunami
E 寒冬 Terrible cold winter F 高溫/酷熱 Heat wave / hot weather

15、城市發展受到氣候變化的影響表現在？What are the effects of climate change on urban development?
A 公共基礎設施被破壞Destruction of the infrastructure
B 造成企業或個人財產損失 Damage to private property C 生命安全受威脅 Human lives at risk
D 城市發展的成本更高 Higher cost for urban development E 生活環境條件變差 Deterioration of environment

16、本港受洪水威脅最嚴重的地區主要是？The most serious flood-threatened area(s) in this city?

A 港口碼頭區Port terminal area
B 沿海 1 公里海岸帶（不含港口碼頭）1km wide zone along the coast (excl. ports)
C 中心城區 Downtown / central area D 河流、山谷、溪流沿岸 Areas along rivers, valleys, streams
E 水庫周邊及排水口下游 5 公里內 Around reservoir & 5km downstream from it

17、您所在社區/街道經常面臨的水問題是？What's the main water problem in your community / neighborhood?
A 來水量大/洪水Flood by too much water B 排水不暢/洪水Flood by poor drainage
C 缺水 Water shortage D 水污染 Water pollution
E 水價高 High water-price F 沒有水問題 No water problem

18、為什麼本港水價越來越高？(選 1-2 項) Why does the water price keep increase?
A 可利用的水資源減少 Reduced availability of water resources
B 水處理和輸送成本增加Water treatment and distribution costs increase
C 水質更好、水量更有保證了 Better water quality and ensured availability
D 水資源管理風險增加 Increasing risks in water resources management
E 沒有明顯升高 No significant increase

19、您是否認為當前政府已有足夠措拖應對氣候變化帶來的影響？ Do you think currently the government has sufficient measures to address climate impacts?
A 是 Yes B 不是 No
C 如果政府下決心去應對，就能夠應對 If the government determines to do, they can
D 不清楚，很難說 I don't know; it is hard to say

20、您覺得本港周邊海洋有什麼變化？ What do you think are the changes of the sea around the city?
A 海水污染 Marine pollution B 海水平面升高 Sea level rise
C 海水潮汐帶來的問題加劇 Water problems caused by increased tide
D 沒有明顯變化 No significant change

21、本港受缺水影響最大的是？ Which of the below suffers most by water shortage?
A 居民生活用水 Domestic use B 園林綠化用水 Green space / landscaping
C 工業企業用水 Industrial enterprises D 農田菜地用水 Crop & animal

22、如果您所在社區/街道可能遭到洪水威脅，您和您的家人會採取什麼措施應對？What measures will you take if your community / neighborhood may be under the threat of flooding?
A 暫時轉移貴重物品，呆在安全地區，災後回來Temporarily transfer valuables and stay at safe areas, come back after the disaster
B 積極採取措施，疏導和排泄洪水 Take active measures to evacuate and discharge water
C 維修加固房屋和防洪設施，防止洪水灌入或滲入 Maintain and reinforce house and flood-control facilities to prevent flooding water
D 參加洪水災害保險 Buy the flood insurance
E 搬家，放棄在那裏居住和生活 Give up the flooding place and move to safe area
F 等待政府部門統一救援和幫助恢復生活 Wait for government's measures and helps

23、您覺得應對氣候變化的首要問題是？What do you think is the key issue for coping with climate change and impacts?
A 在意識上和認識上重視Strong awareness and understanding on it
B 有足夠的經濟能力 Available economic capacity C 改變生活習慣 Changes in lifestyle
D 科學認知和技術能力的提高 Scientific knowing and technological capabilities
E 健全法律、制度的約束力 Sound legal and institutional binding
F 高效有力的組織、領導和管理 Strong and effective organization, leadership and management

24、哪類市民最容易受到水問題的影響？What kind of people are most vulnerable to the threat of water issues?
A 窮人 The poor B 兒童 Children C 老人 The elderly D 婦女 Women E 農民 Farmers

25、本港缺水的主要原因是？What's the main reason for water shortage in the city?
A 降水太少Less rain B 水資源分配和管理不當Bad allocation and mismanagement of water resources
C 水利設施和工程的規劃與建設不夠 Planning and construction of water conservancy facilities are not enough
D 水污染太重，有水不可用 Too much water pollution; lack of usable water
E 沒有經濟實力購買水資源 No money to buy water

26、本港洪水災害的主要特徵是？What's the main feature of the city's flood?

A 河流水位迅速猛漲形成洪災River floods by heavy rain in the catchments
B 城市排水不暢形成街道洪水 Street floods by poor urban drainage system
C 水庫水位超標，形成洪水風險 Flood risk of exceeded reservoir water level
D 海水潮汐上漲形成的洪水 Increasing tidal flood
E 颱風帶來強降水、並破壞水利設施 Typhoon, heavy rain and destroyed irrigation facilities

27、在氣候變化影響下，本港的發展將會如何？How will the city develops under climate impacts?
A 減速、緩慢發展Develop slower and slowly
B 付出高成本應對氣候變化以維持發展 Pay a high cost to maintain the development
C 向安全地區轉移發展重心 Shift development focus to safe areas
D 廢棄一些高風險的受影響區域及其設施 Abandon the areas and facilities that are in high risks
E 環境惡化，生活品質降低，城市吸引力減弱 The city is less attractive because of environment degradation and reduced life-quality

28、本港水資源管理和利用，主要的不足還有哪些？What's the main weakness concerning the management and utilization of water resources?
A 宣傳不夠、市民意識不足Lack of publicity and public awareness
B 管理不規範、效率低 Poor management with low efficiency
C 政策法規本身不夠合理，且執行不力 Policies and regulations are not reasonable, as well as weak enforcement
D 技術水準有限，需要更多的科技力量 Limited technology available / huge need for more scientific and technological strength
E 風險評估和預測能力不足，甚至不知道風險在哪里 Lack of capacity on risk assessment and prediction

二，打分題，五分制 The Scoring Questions (five-point scale)

根據您的經驗和看法，請對下列各種說法打分 According to your experience and views, please mark a score for the following statements

氣候變化及其影響 Climate change and the impacts	1=非常反對；2=不同意；3=不好說；4=同意；5=非常贊成 1 = strongly disagree; 2 = disagree; 3 = hard to say; 4 = agree; 5 = strongly agree				
氣候變化將會帶來非常嚴重的後果Climate change will have very serious consequences	1	2	3	4	5
本港有能力很好地應對氣候變化的影響The city has the ability to well address the climate change impact	1	2	3	4	5
我非常關心氣候變化問題及其帶來的影響I'm very concerned about climate change and its impacts	1	2	3	4	5
本地區氣候變化問題還沒有定論，不清楚怎麼變化的There's no clear conclusion about climate change and impacts in this region yet	1	2	3	4	5
應對氣候變化需要提前行動、及早行動Addressing climate change calls for advance and early action	1	2	3	4	5
我們仍有足夠的時間爲應對氣候變化做準備We still have enough time to prepare for addressing climate change	1	2	3	4	5
本港的城市發展受氣候變化影響很小 HK's development suffers little from climate change	1	2	3	4	5
我希望社會能認可我爲應對氣候變化所做的貢獻Personal contribution in addressing climate change should be commended	1	2	3	4	5
應教育和引導居民個體提高其自身應對氣候變化的能力People should be educated and guided to improve their own ability to address climate change	1	2	3	4	5
受到氣候變化災害影響之後，我會積極做出改變，防範于未然Learning from climate disasters, I will prepare actively some preventive measures	1	2	3	4	5
本港水資源問題和措施Water resource issue of the city					
本港經常發生洪水及相關的洪澇災害The city is often associated with floods disasters	1	2	3	4	5
氣候變化深刻影響本港的水資源管理和利用Water resource suffers from a profound impact of climate change	1	2	3	4	5
本港給排水設施能夠滿足需要The city's water supply/drainage facilities can meet the needs	1	2	3	4	5
本港水資源數量和品質都很可靠Our water quantity and quality are reliable	1	2	3	4	5
海平面上升和潮汐的影響並**沒有**給本港帶來麻煩The impact of sea level rise and	1	2	3	4	5

tidal cause NO trouble to the city					
本港缺水問題非常嚴重Water shortage is very serious in this city	1	2	3	4	5
我曾經親身經歷過本港的嚴重洪災（或缺水）I have experienced severe floods in the city (or water shortage)	1	2	3	4	5
本港家庭生活用水價格合理The city’s domestic water price is reasonable	1	2	3	4	5
水資源相關問題不是本地城市發展的障礙The water-related issues are NOT obstacle to urban development	1	2	3	4	5
需要更多的科學研究來認識氣候變化及其對水資源的影響We need more researches to understand climate change and its impacts on water resources	1	2	3	4	5
城市發展和應對氣候變化Urban development and addressing climate change					
受到氣候變化影響的家庭或個人應該得到幫助或資助Families or individuals affected by climate change should be helped or funded	1	2	3	4	5
本港已經採取了應對氣候變化的行動The city has taken actions to address climate change	1	2	3	4	5
本港居民能夠得到足夠的水災資訊和應對知識Adequate information is available for citizens on flood disaster and coping measures	1	2	3	4	5
每個個人的積極行動是應對氣候變化的基礎Each person's positive action is the basis of addressing climate change	1	2	3	4	5
我個人和我家庭有能力應對氣候變化帶來的負面影響My family and I have the ability to respond to negative climate effects	1	2	3	4	5
應對氣候變化需要付出昂貴的代價Addressing climate change is costly	1	2	3	4	5
政府部門應該在應對氣候變化中發揮主要作用The government should play a major role in responding climate change	1	2	3	4	5
本港還應該採取更多的行動以應對氣候變化The city must take more actions to tackle climate change	1	2	3	4	5
新規劃和建設的交通、樓房等設施應考慮可能的氣候變化影響Planning and construction of new facilities should consider the possible impacts of climate change	1	2	3	4	5
氣候變化是緩慢發生的，其負面影響可以被逐漸解決Climate changes slowly, and its negative effects can be gradually resolved	1	2	3	4	5
其他Other:	1	2	3	4	5

三，簡答題 The Short Answer Questions

1、氣候變化帶來的問題中，您覺得什麼問題是最應該最迫切需要被解決的？Concerning any of the climate change problems, what do you think should be the most urgent one?

2、如果需要應對氣候變化的影響，您覺得什麼措施是最應該首先被採取的？If it’s necessary to address climate change, what measures do you think should be taken first?

3、您知道本地區已經或正在執行哪些應對氣候變化的措施？What measures do you know have been or are being implemented to address climate change in HK?

4、您所在的社區/街道遭受的最近一次缺水是什麼時候，什麼原因造成的，影響如何？Do you know when the last water shortage was at you community / neighborhood? Why and how?

5、您所在的社區/街道遭受的最近一次洪水是什麼時候，什麼原因造成的，影響如何？Do you know when the last flood was at you community / neighborhood? Why and how?

6、您認爲政府部門的水資源管理和利用工作做得怎麼樣？有哪些經驗值得推廣、哪些教訓值得反思？What do you think about the government’s management, allocation and other works on water resources? What experience should be promoted and what lessons should be learned?

7、影響城市發展的因素中，您認爲跟氣候變化、自然環境相關的有哪些？請列舉三個。What do you think are the main factors, concerning about climate change and natural environment, that affect urban development most? Please list three.

8、除了上述問題之外，您還有其他什麼想法和建議？Do you have any further comments / proposals?

四、個人資訊 Personal data

1、您的性別? Your gender?
A 男 Male
B 女 Female

2、您的年齡? Your age?
A 18歲以下 (≤18 years old)
B 19-30
C 31-45
D 46-60
E 61 歲以上 (≥61 years old)

3、您的學歷? Your education?
A 初中及以下Junior high school or below
B 高中或中專 High school / associate degree
C 大專或本科 Bachelor
D 碩士 Master
E 博士及以上 Doctor / Post-doc

4、您在本港居住了多長時間? How long have you lived in the city?
A 1 年以內 (< 1 year)
B 1 到 3 年 (1 to 3 years)
C 3 到 5 年 (3 to 5 years)
D 5 到 10 年 (5 to 10 years)
E 10 年以上 (>10 years)

5、您的職業是什麼? What's your occupation?
A 學者、知識份子，研究人員Scholar, intellectual, researcher
B 企業管理人員 Business management
C 公務員、政府職員 Government employee
D 企業一線生產者 Business line producer
E 傳媒工作者、公益人士 Media workers, public-interest service
F 自由職業者 Freelancers
G 學生 Students
H 失業/離、退休人員 Unemployed/retired
I 其他 Other

6、您的個人月均總收入是?
Your personal monthly gross income is:
A 不到2000元 (Less than 2,000 HK$)
B 2000 到 5000 元 (2,000 to 5,000 HK$)
C 5000 到 1 萬元 (5,000 to 10,000 HK$)
D 1 萬到 2 萬元 (10,000 to 20,000 HK$)
E 2 萬到 5 萬元 (20,000 to 50,000 HK$)
F 5 萬元以上 (50,000 HK$ or more)

7、您居住在什麼地方? Where do you live in?
A 中心城區Downtown / city center
B 城區邊緣/近郊區 Urban edge / near city
C 工業園/開發區 Industrial park / developing Zone
D 遠郊/農村 Outer suburban / rural area

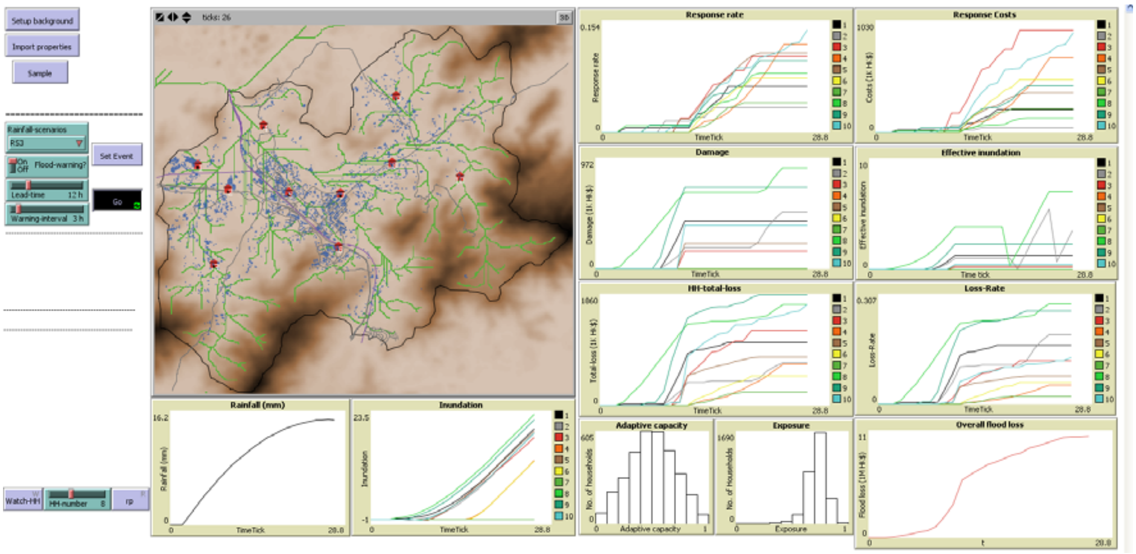
Your contact (voluntarily)

最後，歡迎討論與此次調查相關的任何問題，您可以聯絡本次調查的負責人: 楊亮 liang.yang@zmaw.de

At the end, welcome to discuss more about this survey, you can contact the person in charge of this investigation Mr. Liang YANG: liang.yang@zmaw.de

謝謝您的參與！ ☺ **Thank you for your contribution!** ☺

8.4 Codes of the agent-based model



Rainfall-scenarios RS3

On Off Flood-warning?

Lead-time 12 h

Warning-interval 3 h

HH-number 8

Figure 8-3 Screenshot of the agent-based model in action, with Netlogo platform.

Below are the codes of the model:

```
extensions [gis]

globals [ rainfall sec-rainfall            min-rainfall         hour-rainfall        day-rainfall
          sec-rainfall-list                min-rainfall-list   hour-rainfall-list
          inundation-duration-lista      inundation-duration-listb                    warning-rain
          dem-data    basin    river-data ntriver    watershed    build-area    mainstreet    railway
          max-slope min-slope max-elev min-elev max-hh-e min-hh-e
          color-min    color-max    old-show-water?      ;; how many feet tall one unit of water is
          overall-costs
        ]
breed [households household]
households-own [ river-dist exposure adap-capacity prevent-depth
                 vulnerability vulnerability0 self-risk    self-prediction
                 i-list
                 act-response-rate goal-response-rate self-response-rate warning-response-rate
                 goal-response-rate-list self-response-rate-list
                 buildingvalue property property-loss cost-c cost-d cost-p
                 warn-rainfall;set factors that impsct response measurs
                 inundation predict-inundation drain
                 flood-process flood-process-list cost-d-list hhloss-list response-rate-list
                 duration inundation-duration effective-inundation
                 a b ; a is buildingloss-rate coefficient; b is propertyloss-rate
                 hhloss total-loss loss-rate ]
patches-own [ elevation water-height slope residence in-basin river evaporation]
```

```
to Setup
   clear-all
   set dem-data gis:load-dataset "NTRiver/ntrdemascll.asc" ; no coordinate information; Each cell represents 15*15 square meters.
   set build-area gis:load-dataset "NTRiver/ntrbldasc252.asc" ; Origional value 0 was replaced by 2 to avoid edge error. dont know why.
   set river-data gis:load-dataset "NTRiver/NTRascii1.asc"
   set basin gis:load-dataset "NTRiver/basin30.asc"
   set watershed gis:load-dataset "NTRiver/watershedpolyg.shp"
   set mainstreet gis:load-dataset "NTRiver/MainStreet.shp"
   set railway gis:load-dataset "NTRiver/railway.shp"

   gis:set-world-envelope (gis:envelope-of dem-data)    ;can also use (gis:envelope-union-of gis:envelope-of ntriver gis:envelope-of watershed)
   gis:apply-raster dem-data elevation
   let min-elevation gis:minimum-of dem-data - 150    ;; put a little padding on the lower bound so we don't get too much
   let max-elevation gis:maximum-of dem-data      ;; white and lower elevations have more variation for better visualization. ;; learned from "Grand Canyon" in the model library
   ask patches[ set pcolor scale-color brown elevation max-elevation min-elevation]
   gis:apply-raster build-area residence
   gis:apply-raster basin in-basin
   gis:apply-raster river-data river
   gis:set-drawing-color black
   gis:draw watershed 1
   gis:set-drawing-color gray - 1
   gis:draw mainstreet 1
   gis:set-drawing-color violet
   gis:draw railway 1

   set-default-shape households "house" ;create households
   ask patches with [residence = 2] [sprout-households 1 [set color blue set size 1]] ; Origional value 0 was replaced by 2.
   ask patches with [river = 0] [set pcolor green]
   ask patches [set evaporation 0.1 ] ; real-word evaporation is ~0.1mm per tick (15 min), which is 0.01cm. Enlarger it to 0.1 as to include leakage/infiltration as well.
   ask patches [set slope elevation - min [elevation] of neighbors]
   ask patches with [slope = -1] [set elevation elevation + 1]
   ask patches [set slope elevation - min [elevation] of neighbors] ; fill all hollows to make the minimum slope to be 0
   reset-ticks
end

to import-property
```

```
  clear-turtles
  set-default-shape households "house" ;create households
  file-open "NTRiver/HHproperties.txt"
  while [not file-at-end?]
   [let items read-from-string (word "[" file-read-line "]")
     create-households 1 [
        set color blue set size 1
        set xcor      item 1 items
        set ycor      item 2 items
        set buildingvalue     item 3 items
        set property     item 4 items
        set exposure     item 5 items
        set adap-capacity     item 6 items
        ]]
  file-close

  ask households [set duration 1 ;
                        set vulnerability0 random-float 1
                        set self-risk random-float 1 ]
  reset-ticks
end

;;Due to many agents (3294), the model runs very slow.
;;Sample 10 agents to run the core funtions so that the model can run faster
to sample
   ask households [if xcor = 42 and ycor = 227 [set size 10 set color red set label 1 ]
                         if xcor = 72 and ycor = 203 [set size 10 set color red set label 2 ]
                         if xcor = 58 and ycor = 129 [set size 10 set color red set label 3 ]
                         if xcor = 107 and ycor = 266 [set size 10 set color red set label 4 ]
                         if xcor = 132 and ycor = 200 [set size 10 set color red set label 5 ]
                         if xcor = 181 and ycor = 146 [set size 10 set color red set label 6 ]
                         if xcor = 183 and ycor = 199 [set size 10 set color red set label 7 ]
                         if xcor = 234 and ycor = 229 [set size 10 set color red set label 8 ]
                         if xcor = 238 and ycor = 295 [set size 10 set color red set label 9 ]
                         if xcor = 301 and ycor = 215 [set size 10 set color red set label 10 ]
                        ]
end

;;reset flood event but keep the initially set model environment and agent attributions
to set-event   ;set a flood event
  set rainfall 0
  ask patches [set water-height 0]
  ask households [set vulnerability vulnerability0
                        set act-response-rate 0 set goal-response-rate 0 set self-prediction 0
```

```
                        set property-loss 0 set cost-c 0 set cost-d 0 set cost-p 0
                        set warn-rainfall 0 ;set factors that impsct response measurs
                        set inundation 0 set drain 0 set duration 1 set inundation-duration 0
                        set a 0 set b 0 set hhloss 0 set total-loss 0 set loss-rate 0
                        set cost-d-list []
                        set hhloss-list [0]
                        set response-rate-list []
                        set flood-process-list []
                        set goal-response-rate-list [0]
                        set self-response-rate-list [0]
                        ]
  set sec-rainfall-list [] ;;initianize an empty list
  set min-rainfall-list []
  set hour-rainfall-list []
  set inundation-duration-lista []
  set inundation-duration-listb []

  clear-all-plots
  if flood-warning? [ask households with [size = 10]
                              [if random 100 <= 80
                              [set cost-c random (0.001 * property) set prevent-depth (cost-c + cost-d) * 0.0004
                              set exposure exposure - 10 * cost-c / property] ;80% of 3294 households receive
warning and take measures
                               if exposure < 0 [set exposure 0]]]

  read-flood
  reset-ticks
end

to go
  go-rain
  go-flood
  go-response
  go-damage
  go-recover
  go-total-loss
  tick
end

to go-rain
  if rainfall-scenarios = "RS1" [;RS1 indicates an extremely intensive rainfall scenario.
                                    ifelse ticks < 12 [set rainfall (- 0.83 * ticks * (ticks - 12))];
                                                 [set rainfall 0]] ; when ticks >= 12, rainfall keeps 0
  if rainfall-scenarios = "RS2" [;RS3 indicates an intensive rainfall scenario.
```

```
                                        ifelse ticks < 24 [set rainfall ( - 0.14 * ticks * (ticks - 24) ) ];
                                                        [set rainfall 0]] ; when ticks >= 24, rainfall keeps 0
  if rainfall-scenarios = "RS3" [;RS1 indicates an intensive rainfall scenario.
                                        ifelse ticks < 48 [set rainfall ( - 0.026 * ticks * (ticks - 48) ) ];
                                                       [set rainfall 0]] ; when ticks >= 48, rainfall keeps 0
  if rainfall-scenarios = "RS4" [;RS2 indicates a midium rainfall scenario.
                                        ifelse ticks < 96 [set rainfall ( - 0.0043 * ticks * (ticks - 96) ) ];
                                                       [set rainfall 0]] ; when ticks >= 96, rainfall keeps 0
  if rainfall-scenarios = "RS5" [;RS3 indicates a long-duration rainfall scenario.
                                        ifelse ticks < 192 [set rainfall ( - 0.0005 * ticks * (ticks - 192) ) ];
                                                      [set rainfall 0]] ; when ticks >= 192, rainfall keeps 0
end

to go-flood
  ask patches with [in-basin = 1 ][set water-height water-height + 0.1 * rainfall] ;rainfall is in mm, convert it to cm.
  ;ask patches with [in-basin != 1] [set water-height 0]
  foreach sort-on [ (- elevation)] patches ;; patches do something in descending order by elevation
      [ask ? [ let target min-one-of neighbors [ elevation + water-height]
                  let target-water [water-height] of target
                  if water-height > 0
                     [if (elevation + water-height) > [elevation + water-height] of target
                         [ifelse (elevation + water-height) - ([elevation + water-height] of target) >= (2 * water-height)
                             [set target-water target-water + water-height set water-height 0 ]
                             [set target-water 0.5 * ([elevation + water-height] of target + (elevation + water-height)) - [elevation] of target
                              set water-height 0.5 * ([elevation + water-height] of target + (elevation + water-height)) - elevation ]]
                      if (elevation + water-height) < [elevation + water-height] of target
                         [ifelse ([elevation + water-height] of target) - (elevation + water-height) >= (2 * target-water)
                             [set water-height target-water + water-height set target-water 0 ]
                             [set target-water 0.5 * ([elevation + water-height] of target + (elevation + water-height)) - [elevation] of target
                              set water-height 0.5 * ([elevation + water-height] of target + (elevation + water-height)) - elevation ]]
                     ]]]
ask patches [ifelse water-height > 0 [set water-height water-height - evaporation] [set water-height 0]]

  ask households [set inundation precision water-height 1 ;water-height is in cm, so is inundation. make the values to be integer.
                     set color scale-color red inundation 100 0]
end
```

```
to go-response
    ask households ;with [size = 10 ]
        [ifelse remainder (ticks + 1) (warning-interval * 4 ) = 0 and flood-warning? ;and random 100 < 80 ;
ticks+1 makes the computing starting at 0 tick. the codes are excuted every "warning-interval hours"
(warning-interval * 4 ticks). HHs have 80% chance to accept a warning
                    ;;if successful to get warning, do these:
                    [if (ticks + lead-time * 4) <= (length flood-process-list) [set predict-inundation max sublist
flood-process-list ticks (ticks + lead-time * 4)]
                     if (ticks + lead-time * 4) > (length flood-process-list) and ticks < (length
flood-process-list) [set predict-inundation item ticks flood-process-list]
                     if ticks >= (length flood-process-list) [set predict-inundation 0]
                     set goal-response-rate (1 / 3000000000 ) * (buildingvalue + property ) * exposure * max
(list inundation predict-inundation )
                     if goal-response-rate > adap-capacity [set goal-response-rate adap-capacity]
                     set goal-response-rate-list lput goal-response-rate goal-response-rate-list
                    ]
                    ;;if fail to get warning, do these:
                    [
                     set self-response-rate (1 / 3000000000 ) * (buildingvalue + property ) * exposure *
inundation
                     if self-response-rate > adap-capacity [set self-response-rate adap-capacity]
                     set self-response-rate-list lput self-response-rate self-response-rate-list
                    ]
               let rr1 act-response-rate
               set i-list list (max goal-response-rate-list ) (max self-response-rate-list )
               if act-response-rate < (max i-list) [set act-response-rate act-response-rate + random-float 0.02 ]
               if act-response-rate > rr1 [set exposure exposure - 3 * (act-response-rate - rr1); increased response
rate help reducing exposure.
                                                  if exposure < 0 [set exposure 0 ]];
              set response-rate-list lput act-response-rate response-rate-list
              set cost-d property * max response-rate-list
              set cost-d-list lput cost-d cost-d-list ;; add the number of cost-d to the end of the list
             ]
;set cost-d max cost-d-list
end

to go-damage ; NOT necessary to run all households, just chose sevral typical ones to show their responses
and loss


  ask households
      [ifelse remainder (ticks + 1) (warning-interval * 4 ) = 0 and flood-warning? ;and random 100 < 80
        [set prevent-depth (cost-c + cost-d) * 0.0004 ; 1 HK$ help prevent 0.01cm flood water depth
         if inundation > prevent-depth [set effective-inundation inundation - prevent-depth ]]
        [if inundation > prevent-depth [set effective-inundation inundation - prevent-depth ]]
```

```
            set a 0.06 * ln (effective-inundation + 1 ); + duration / 96;
            set b 0.1 * ln (effective-inundation + 1 ) ;+ duration / 960;    a&b are damage rate.
            set hhloss buildingvalue * a + property * b
            set hhloss-list lput hhloss hhloss-list ];;This is the case that response can not prevent the too high
predicted inundation, thus damage still occures.

end

to go-recover

    ask households with [size = 10 ] [if inundation < 5 [set cost-p max hhloss-list]]

end

to go-total-loss
  ask households with [size = 10 ] [set total-loss max hhloss-list + cost-c + max cost-d-list + cost-p
                                              set loss-rate total-loss / (buildingvalue + property)]

end

to read-flood
  read-flood ;; The contents here includes a 30 pages long file, which is for the ten selected households
            ;; in running about 300 ticks. The file is not added here. If needed, please contact
      ;; the author by liang.yang@zmaw.de
end
```

8.5 Short resume

I graduated from the Southwest University in Chongqing, China, majoring in Environmental Resources Management and Urban-rural Area Planning. I got my Master’s degree in the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences in Beijing. In my Master's thesis I discussed measures to evaluate the urban land carrying capacity. Since October 2010 I was a PhD student at the Research Group Climate Change and Security (CLISEC) at the Institute of Geography, University of Hamburg, focusing especially on climate change impacts and adaptation on the water issues in urban area.

RESEARCH INTERESTS

- Natural resources management
- Climate change impacts and adaptation
- Agent-based modeling (ABM)

REPRESENTATIVE WORKS

2014 **Liang Yang**, Jürgen Scheffran, Diana Süsser, Yongqing David Chen. Assessment of Flood Losses with Household Responses: Agent-based Simulation in an Urban Watershed. (First draft ready for further improvements)

2014 Grace. W. Ngaruiya, Jürgen Scheffran, **Liang Lang**. Social Networks in Water Governance and Climate Adaptation in Kenya. (accepted for publishing in the book “Handbook of Sustainable Water Use and Management”, Cambridge University Press)

2014 **Liang Yang**, Jürgen Scheffran, Huapeng Qin, Qinglong You. Climate-related Flood Risks and Urban Responses in the Pearl River Delta, China. (Accepted for publishing in *Regional Environmental Change*)

2014 Chunxiao Zhang, Hui Lin, Min Chen, **Liang Yang**. Scale Matching of Multiscale Digital Elevation Model (DEM) Data and the Weather Research and Forecasting (WRF) Model: A Case Study of Meteorological Simulation in Hong Kong. *Arabian Journal of Geosciences*, February 2014 DOI: 10.1007/s12517-014-1273-6

2013 **Liang Yang,** Chunxiao Zhang, Grace Ngaruiya, 2013. Water Supply Risks and Urban Responses under a Changing Climate: A Case Study of Hong Kong, *Pacific Geographies*, 39: 9-15.

2010 **Liang Yang**, Yao Lv, Huayu Zheng, 2010. Review and Analysis of the Studies of Urban Land Carrying Capacity. *Progress in Geography*, 29(5):523-530 (Chinese text with English abstract)

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Danke für Alles. Es ist schön, daß es euch gibt.

Liang Yang
Hamburg
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