

Flood risk analysis for metropolitan areas – a case study for Shanghai

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To my parents: Mingchang Ke and Mingmei Su

献给我的父亲和母亲

Summary

In Shanghai, the main threat to the city's safety is a typhoon induced storm surge in combination with a high astronomic tide in the Huangpu River. Historical flood events have shown that the weakness of the floodwall, with potential overtopping and breaching along the Huangpu River and its branches, has caused great economic damage and loss of life. In order to better understand flood risk in the city, flood risk analysis at the local city level is strongly required. With climate change, land subsidence and the rapid socio-economic development, flood risk is inevitably increasing if no measures are taken. Not only the current flood risk but also the flood risk in the future needs to be understood. Moreover, it is necessary to recommend effective risk-reduction measures to mitigate future flood risk. Therefore, the objective of this thesis is to quantify the current and future flood risk and to make recommendations on risk-reduction measures in a case study of Shanghai. It also aims to show and develop general methods for flood risk analysis in rapidly growing metropolitan areas.

As a first step the Shanghai water system has been analysed. In terms of flood threats to the river, the water level is dominated by the storm tide at the mouth of the Huangpu River. The heavy precipitation mainly induces waterlogging due to an insufficient drainage capacity in the city, while not significantly increasing river runoff in the Huangpu River. Moreover, a control gate (between Tai Lake and the Huangpu River) is regulated to reduce drainage water from Tai Lake when a storm surge occurs. Therefore, a combination of a storm surge and a high astronomic tide will be the main flood threat. It is noticed that the current protection level of the floodwall is only based on the exceedance of the crest height of the floodwall by the water level and does not directly take other failure mechanisms into account. Failure mechanisms such as breaching of floodwalls and failure of the closure of floodgates would induce potential floods in Shanghai.

In order to identify flood hazard in extreme events, a frequency analysis of annual maximum water levels was performed; the new frequency curves represent the relationships of water levels at three typical gauge stations along the Huangpu River with different return periods. The Generalized Extreme Value (GEV) distribution was suggested as a most suitable probability distribution for the datasets of annual maximum water levels at Wusongkou and Huangpu Park instead of a Pearson Type III distribution. With the aid of the 1D hydraulic model, water levels in each cross section of the Huangpu River were derived. The potential overtopping points were systematically identified by a comparison of the crest height of the floodwall and the water levels under different return periods (50yr, 100yr, 200yr, 500yr, 1,000yr and 10,000yr). It turned out that the current estimation of overtopping probability is 1/200 p.y. in the Huangpu River. In addition, potential breaching points and failure of floodgates were also hypothesized on both sides of the floodwall. Subsequently, inundation maps were produced by 1D2D hydrodynamic modelling (SOBEK) under different flood scenarios along the Huangpu River. The results can be visualized on a map with information on maximum inundation depth and the extent of inundation. Firstly, a scenario without protection demonstrates the important role of the floodwall and the infrastructures (e.g. floodgate) along the Huangpu River to protect Shanghai against river flooding. Secondly, various overtopping events at certain points along the floodwall were simulated. It was found that the inundation would merely occur adjacent to the riverine area due to a limited flood volume under overtopping scenarios, since it only occurs during a limited period (e.g. 1 hour). Thirdly, as breach scenarios were developed to explore the worst-case flooding in Shanghai; it turned out that breaching would cause the most serious flooding along the Huangpu River, as parts of the city centre would get inundated with a maximum inundation depth of more than 3m. Lastly, the simulations of a failure of the floodgates were conducted at three selected

locations. It showed that the inundation depth was a few decimetres in each scenario (40cm-80cm on average), which would pose threats to the buildings and the infrastructures adjacent to the floodgates. Ex-ante flood damage assessment plays an increasingly important role in flood risk management. Potential flood damage in cities like Shanghai can be massive due to the high rate of socio-economic development and the rapid urbanization in the near-future. Different flood scenarios result in different degrees of damage. New damage functions for various building categories were suggested in Shanghai; with the application of these functions, it was calculated that the potential damage under various breaching scenarios ranged from 88 to 440 million \$USD in part of downtown area, which accounts for 1.5% - 7.6% of the maximum potential damage (5.77 billion \$USD). In the estimation of indirect flood damage on the service interruption of the subway system, two typical subway stations were selected to estimate the revenue loss due to flooding. It was calculated that the service interruption at one subway station for one week would cause approximately 1 million \$USD of revenue losses in Shanghai, which implied that it would cause a huge practical inconvenience for the inhabitants during such unexpected events. Furthermore, in the discussion of the effects of components on the flood damage, the damage function has the greatest influence on the final results, and this deserves priority for future study to reduce the uncertainty of flood damage estimation.

Flood risk is calculated by the occurrence/exceedance probability and its associated potential damage. In this thesis, the total risk, which accounts for expected value and standard deviation of damages on the basis of risk aversion, represents the results of flood risk analysis. The results are represented below. The probability of flooding exists in events of overtopping, breaching and failure of floodgates. 26 scenarios were simulated along the Huangpu River based on various boundary conditions of the water level as a function of return periods of 200yr., 500yr., 1,000yr., and 10,000yr. at Wusongkou, in which 8 breaching points and 3 floodgates points were selected on the west and east side of the floodwall. The total (flood) risk is calculated between 40 million \$USD/yr. and 112 million \$USD/yr. along the Huangpu River of Shanghai, in which the point at ~45km away from the mouth is most likely to be overtopped, and the breaching point, ~26km away from the mouth at the west side of the Huangpu River in the city centre, leads to largest potential flood damage among all the scenarios. Furthermore, it is noticed that the economic damage due to breaching is a factor of 10 higher than the damage caused by overtopping scenarios. However, in terms of the contribution to the flood risk, the failure of floodgates accounts for ~41% of the overall flood risk due to its higher probability of failure than breaching and parts of overtopping scenarios. Economic development appears to have the greatest effect on future flood risk, which could triple flood risk in 2030 and increase six fold in 2050 if no further measures are taken. Land subsidence is the second driver of future risk, and the 'absolute' sea level rise has the least effect on the future flood risk. The combination of all these affected factors would raise flood risk 4 times and 16 times in total in 2030 and 2050 respectively if no further measures are taken.

In order to evaluate and recommend an effective (combination of) risk-reduction measure(s) to mitigate flood risk, a comparative study between Shanghai and Rotterdam was conducted to propose potential risk-reduction measures under the threats of future climate change and economic growth. It also showed that the metropolitan cities, under similar challenging flood threats, can learn from each other. Regarding the risk-reduction measures, the potential (structural and non-structural) measures have been proposed and evaluated by the methods of cost-benefit analysis and economic optimization. Preliminary results of the cost-benefit analysis show that the construction of a storm surge barrier has a somewhat larger benefit/cost ratio than the upgrading of the floodwall. Besides, since the Shanghai Municipal Government desires to upgrade the city to the level of an international metropolis with a high quality of life, the upgrading of the floodwall will largely hinder the view of rivers and lower the attractiveness of the city. Therefore, it is expected that the construction of the storm

surge barrier is a better solution to protect Shanghai in the long run. Economic optimization led to a preliminary result of a safety level of 1/4,500p.y. for the Huangpu River in Shanghai due to fast economic growth in the future (2050). It is additionally noted that, given the current relatively low protection level the flood barrier boards (to protect buildings for small floods) have advantages and it is also recommended to apply this measure at the entrance of all types of buildings in case of unexpected flood events. These results show how flood risk analysis can provide rational information to support decisions for risk reduction for rapidly growing mega-cities, like Shanghai.

Qian Ke, July, 2014

Samenvatting

De grootste bedreiging voor de veiligheid van de stad Shanghai is een combinatie van een door een tyfoon veroorzaakte stormvloed in de Huangpu Rivier en een hoog astronomisch getijde. Historische overstromingsgebeurtenissen langs de Huangpu rivier en haar zijtakken hebben aangetoond dat grote economische schade en verlies van leven veroorzaakt is door een verzwakte vloedmuur, potentiële overtopping en breuken. Om het overstromingsrisico in de stad beter te begrijpen, zijn overstroming risicoanalyses op het lokale stadsniveau noodzakelijk. Klimaatverandering, grondverzakking en de snelle sociaaleconomische ontwikkeling, vormen een onvermijdelijke verhoging van het overstromingsrisico indien er geen maatregelen worden genomen. Niet alleen het huidige overstromingsrisico, maar ook de toekomstige overstromingsrisico's moet begrepen worden en is het noodzakelijk om doeltreffende en risico beperkende maatregelen ter vermindering van toekomstige overstromingsrisico's aan te bevelen. Het doel van deze thesis is om het huidige en het toekomstige overstromingsrisico te kwantificeren en om aanbevelingen te doen over risico beperkende maatregelen in een casestudy van Shanghai. De thesis beoogt eveneens algemene methoden voor risicoanalyse van de overstroming in snel groeiende stedelijke gebieden aan te tonen en te ontwikkelen.

Als een eerste stap is het watersysteem van Shanghai geanalyseerd. In termen van overstromingsbedreigingen van de rivier, wordt duidelijk dat het water niveau aan de monding van de rivier Huangpu gedomineerd door de stormvloed. Zware neerslag veroorzaakt wateroverlast die te wijten is aan een onvoldoende draineringscapaciteit in de stad, terwijl de rivier afvoer in de Huangpu rivier niet aanzienlijk toeneemt. Bovendien, reguleert een controle doorgang (tussen Tai Lake en de Huangpu rivier) de vermindering van afvoerwater van Lake Tai, wanneer een stormvloed optreedt. Een combinatie van een stormvloed en een hoog astronomische getij zal dus de grootste dreiging van overstroming zijn. Het huidige beschermingsniveau van de vloedmuur is slechts gebaseerd op een water niveau dat alleen als het extreem hoog is, de top van de vloedmuur overschrijdt en niet direct rekening houdt met andere faalmechanismen. Faalmechanismen, zoals het overtreden van vloedmuren en het falen van de sluiting van sluizen, kunnen potentiële overstromingen in Shanghai tot gevolg hebben.

Teneinde overstromingsgevaar in extreme gebeurtenissen te herkennen, werd een frequentieanalyse van het jaarlijkse maximum water niveau uitgevoerd; de nieuwe frequentie curves vertegenwoordigen de relaties van het water niveau bij de drie typische test stations langs de Huangpu rivier met verschillende terugkeer perioden. De “Generalized Extreme Value” (GEV) distributie werd voorgesteld als de meest geschikte kansverdeling voor de datasets van jaarlijkse maximum waterniveaus in Wusongkou en Huangpu Park in plaats van een Pearson Type III distributie. Met behulp van het 1D hydraulische model, werden waterstanden in elke doorsnede van de Huangpu rivier afgeleid. De potentiële overtoppingspunten werden systematisch geïdentificeerd door een vergelijking te maken van de hoogte van de top van de vloedmuur en de waterstanden onder verschillende terugkeer perioden (50 jaar, 100 jaar, 200 jaar, 500 jaar, 1.000 jaar en 10, 000 jaar). Het bleek dat de huidige schatting van de waarschijnlijkheid van overtopping in de Huangpu rivier 1/200 jaar is. Potentiële breuk punten en het falen van sluizen aan de beide zijden van de vloedmuur werden als hypothese gesteld. Vervolgens werden overstromingskaarten geproduceerd door 1D2D hydrodynamische modellering (SOBEK) onder verschillende overstroming scenario's langs de Huangpu rivier. De resultaten kunnen worden gevisualiseerd op een kaart met informatie over maximale overstromingsdiepte en de omvang van overstroming. In de eerste plaats bewijst een

scenario zonder bescherming langs de Huangpu rivier de belangrijke rol van de vloedmuur en van infrastructuur (zoals bijvoorbeeld sluisdeuren) in de bescherming van Shanghai tegen overstromingen van de rivier. Ten tweede, werden verschillende overstromingen op bepaalde punten langs de vloedmuur gesimuleerd. De conclusie was dat overstroming vooral zou optreden in het gebied grenzend aan de rivier, ten gevolge van het beperkte overstroming volume onder overstromingsscenario's aangezien het slechts gedurende een beperkte periode (bijvoorbeeld 1 uur) gebeurt. In de derde plaats, terwijl overstromingsscenario's werden ontwikkeld om de ergste overstromingsgevallen in Shanghai te onderzoeken, bleek dat breuk in de vloedmuur de ernstigste overstromingen langs de Huangpu rivier zou veroorzaken, en dat delen van het centrum van de stad overspoeld zouden worden met een overstroming van een diepte van meer dan 3m. Tot slot, werden simulaties van het falen van de sluizen uitgevoerd op drie geselecteerde locaties. Er werd aangetoond dat de overstromingsdiepte in elk scenario gemiddeld 40cm - 80cm was, wat een bedreiging zou vormen voor de gebouwen en de infrastructuur grenzend aan de sluizen.

Ex-ante schadebeoordeling van overstromingen speelt een steeds belangrijkere rol in overstromingsrisicobeheer. Potentiële overstromingsschade in steden als Shanghai kan massaal worden als gevolg van de hoge mate van sociaaleconomische ontwikkelingen en het hoge tempo van urbanisatie in de nabije toekomst. Verschillende vloed scenario's resulteren in verschillende mates van schade. Nieuwe schade functies voor verschillende categorieën van gebouwen werden in Shanghai voorgesteld. Met de toepassing van deze functies, werd berekend dat de potentiële schade onder de verschillende scenario in een deel van de binnenstad, varieerden van 88 tot 440 miljoen \$USD, goed voor 1,5% - 7,6% van de maximale potentiële schade (5,77 miljard \$USD). In de schatting van door indirecte overstromingen veroorzaakte schade op de onderbreking van de diensten van het metrosysteem, werden twee typische metrostations geselecteerd om het verlies van inkomsten als gevolg van overstromingen in te schatten. Er werd berekend dat de onderbreking van de dienst voor een week bij een metrostation in Shanghai zou leiden tot ongeveer 1 miljoen \$USD inkomstenverlies, implicerend dat het een enorm praktisch ongemak veroorzaakt voor de bewoners tijdens dergelijke onverwachte gebeurtenissen. Daarbij komt dat, bij de bespreking van de effecten van de bestanddelen van door overstromingen veroorzaakte schade, de schade functie de grootste invloed heeft op de eindresultaten. Dit verdient prioriteit in toekomstige studie om de onzekerheid van schattingen van overstromingsschade te verminderen.

Overstromingsrisico wordt berekend door de kans op gebeurtenis / overschrijding en de bijbehorende potentiële schade. In dit proefschrift geeft het totale risico, dat bestaat uit de verwachte waarde en de standaarddeviatie van schade op basis van risico-aversie, de resultaten weer van de risicoanalyse van overstroming, zoals hieronder beschreven. De kans op overstroming bestaat in gebeurtenissen zoals overtopping, dijkbreuk en het falen van sluizen. Op basis van verschillende randvoorwaarden van de waterstand werden 26 scenario's gesimuleerd bij Wusongkou, langs de Huangpu rivier, met een functie van terugkeer perioden van 200, 500, 1,000 en 10.000 jaar. Een selectie werd gemaakt van 8 breukpunten en 3 sluizen aan de west- en aan de oostkant van de vloedmuur. Het totale (overstroming) risico van de Huangpu rivier bij Shanghai wordt berekend tussen 40 en 112 miljoen \$USD/jaar. Overtopping is het meest waarschijnlijk op 45 km afstand van de monding van de rivier; het breekpunt op 26 km afstand van de monding, in het centrum van de stad aan de westkant van de Huangpu rivier, resulteert onder alle scenario's tot de grootste potentiële overstromingsschade. Bovendien moet opgemerkt worden dat de economische schade als gevolg van breuken 10 maal hoger is dan de schade die veroorzaakt wordt door overtopping. Echter, in termen van het aandeel aan het overstromingsrisico, draagt het falen van de sluizen voor 41% bij aan het algehele overstromingsrisico, als gevolg van de hogere kans op falen, dan breuken en delen van overtoppings-scenario's. Economische ontwikkeling lijkt het grootste effect te hebben op

toekomstige overstromingsrisico's, welke zou kunnen verdrievoudigen in 2030 en zelfs zes keer zo hoog in 2050, als er geen verdere maatregelen worden genomen. Bodemdaling is de tweede oorzaak van toekomstig risico, en de 'absolute' zeespiegelstijging heeft het minste effect op de toekomstige overstromingsrisico's. De combinatie van al deze factoren zou in totaal het overstromingsrisico tot 4 maal in 2030 en tot 16 maal in 2050 verhogen als geen verdere maatregelen worden getroffen.

Om een effectieve (en een combinatie van) risicoreductie maatregel(en) en een verminderd overstromingsrisico te evalueren en te adviseren, werd een vergelijkende studie tussen Shanghai en Rotterdam uitgevoerd, teneinde potentiële risico beperkende maatregelen onder de dreiging van klimaatverandering en economische groei voor te stellen. Het onderzoek toonde aan dat grote steden, onder vergelijkbare overstromingsdreigingen, veel van elkaar kunnen leren. Met betrekking tot de risico beperkende maatregelen, zijn de potentiële (structurele en niet-structurele) maatregelen voorgesteld en geëvalueerd aan de hand van een de methoden van kosten-batenanalyse en een economische optimalisatie. Voorlopige resultaten van de kosten-batenanalyse laten zien dat de bouw van een stormvloedkering een iets grotere kosten-baten verhouding heeft dan een opwaardering van de vloedmuur. Bovendien, aangezien de gemeentelijke overheid van Shanghai het verlangen heeft om de stad te moderniseren naar het niveau van een internationale metropool met een hoge levensstandaard, zal de opwaardering van de vloedmuur grotendeels een belemmering vormen voor het uitzicht op de rivieren en daarmee de aantrekkelijkheid van de stad verminderen. Het is te verwachten dat de bouw van de stormvloedkering een betere oplossing is om op de lange termijn Shanghai te beschermen. Economische optimalisatie leidde tot een voorlopige resultaat van een veiligheidsniveau van 1/4500 per jaar voor de Huangpu rivier in Shanghai, als gevolg van snelle economische groei in de toekomst (2050). Eveneens kan opgemerkt worden dat, gezien het huidige relatief lage beschermingsniveau, afsluitingsplaten (ter bescherming van gebouwen tegen kleine overstromingen) hun voordeel behouden en het is dan ook aanbevolen om deze maatregel bij de ingang van alle soorten van gebouwen te blijven handhaven in geval van onverwachte overstromingen. Deze resultaten laten zien hoe een overstroming risicoanalyse rationele informatie kan bieden ter ondersteuning van besluiten voor risicobeperking voor snel groeiende mega-steden, zoals Shanghai.

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Chapter 1

Introduction

This chapter describes the rationale for the research, its scope and research objectives. It also formulates the research contributions and the structure of the thesis.

1.1 Background

1.1.1 Floods in metropolitan areas

According to the EMDAT Disaster Database, floods remain the most common natural disaster, which account for ~36% of all natural disasters worldwide in the period of 1990-2013 (EMDAT 2013). Flooding is also a global phenomenon which causes widespread devastation, economic damages and loss of lives (GFDRR 2012). For example, Pakistan suffered 20% of its GDP loss due to flooding in August 2010 (Hyder 2010). Besides economic damage, the earthquake-induced tsunami on the north-east coast of Japan led to the disappearance and deaths of more than 18,000 persons in March 2011 (NPA 2014); and floods in large areas of Thailand in October and November 2011, affected global production networks and caused great social disruptions; Hurricane Sandy in Greater New York City in October 2012 was the second costliest (more than 68 billion \$USD) hurricane in United States history (Blake, Kimberlain et al, 2013). It is noted that major cities and metropolitan areas, like Karachi, Sendai, New York and Bangkok, were all affected by recent floods. On one hand, the concentration of property assets, infrastructures and populations led to large economic losses and casualties in

these areas; on the other hand, climate change with sea level rising and extreme events caused floods more likely to happen.

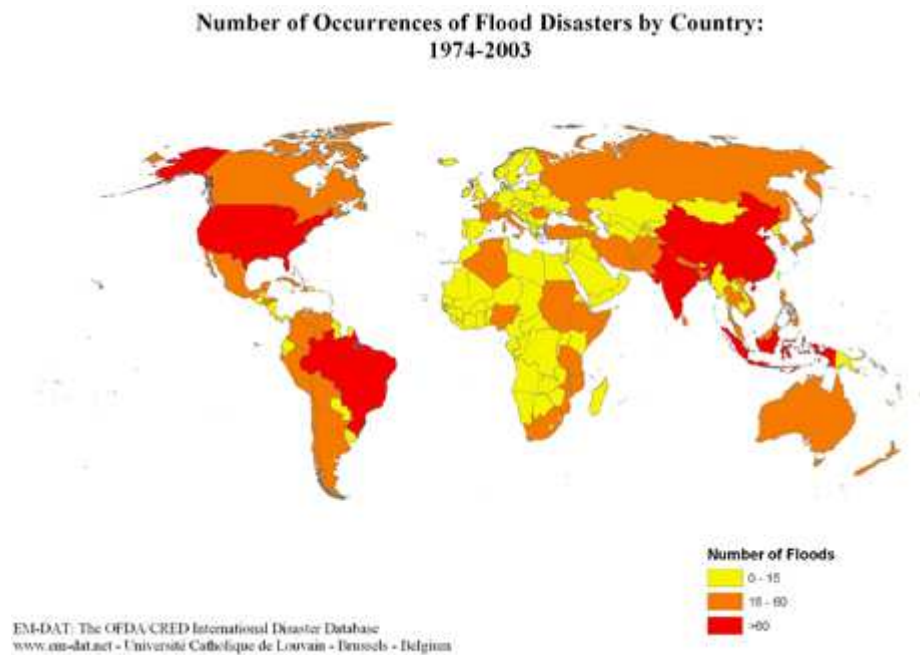


Fig.1. 1 Number of occurrence of flood disaster by country in the world in 1974-2003 (EMDAT 2009)

As seen from the worldwide map on the number of occurrences of flood disasters in Fig.1. 1, floods occurred mostly in Asia and North and South America. 40% of floods worldwide occurred in Asia in the past two decades (1990-2013) (EMDAT 2013). The vulnerable countries in terms of floods are more often located in Eastern and South-Eastern Asia, like China, Japan, South Korea, Thailand, Vietnam, Indonesia and the Philippines. Floods caused 56% of the overall losses in Eastern and South-Eastern Asia and the number is expected to increase further in the coming decades (Munich Re 2013). The reasons for the high increase in flood losses are primarily socio-economic factors such as continued strong economic growth and the resultant increase in values. In addition, these countries are also frequently hit by typhoons every year, with storm surges, torrential rainfall and strong wind, which together causes and increases the probabilities of flood.

A metropolitan area is a region consisting of a densely populated urban core and its less populated surrounding territories, sharing industry, infrastructure and housing (Squires 2002). In Eastern and South-Eastern Asia, there are many metropolitan areas, for instance, Tokyo, Jakarta, Seoul, Shanghai, Manila, Osaka, Bangkok, Hong Kong, Ho Chi Minh City, etc.. These areas commonly face potential flooding problems. 1). Most of these cities are located in the coastal or deltaic area, which is more likely to be affected by typhoon weather; 2). and these cities have a tendency to be located in a low lying area and experience (natural and anthropogenic) subsidence. Flooding in these metropolitan areas causes tremendous economic damage and social disruption due to aggregated assets value, intricate infrastructure networks and a dense population. Therefore, adequate flood management for metropolitan areas is a high requirement in order to safeguard the metropolitan residents including the property assets.

1.1.2 Floods in China

China suffers from serious flood disasters due to its varied topography and its diverse climate. In China, 8% of the land area which is located in the mid- and downstream parts of the seven major rivers is prone to floods; 50% of the total population is living in these flood-prone areas, contributing over 2/3 of the total agricultural and industrial product value. Besides, cities located in the coastal area

of China, such as Shanghai, Wenzhou and Guangzhou etc., are frequently affected by typhoons. The yearly direct economic damage caused by floods accounted for roughly 1.35% of GDP in China (1990-2012) (MWR 2012) and the average loss of life due to floods in the past 60 years was estimated at approximately 4424/year (MWR 2012), although the casualties due to flood has been reduced in recent years by the improvement of flood defence system and the better management with government's great attention. These figures are also illustrated in Fig.1. 2 and Fig.1. 3. They show that the average relative loss (loss/GDP) reduced from 2.49% (1990-1999) to 0.48% (2000-2012), and the average annual loss of life reduced from 5,548 casualties (1950-1989) to 3,909 (1990-1999) and to 1,362 (2000-2012).

However, owing to global climate change the extreme events related to typhoons would cause even greater economic damage and social disruption in the coastal area of China. The Central Government has paid great attention to the important cities, and especially to Shanghai, which is an economic centre of China while it is affected by one or more typhoons almost every year. Besides, Shanghai has been planned as a priority of flood prevention in the 'Flood Prevention Planning of Yangtze River Basin and Tai Lake Basin' (MWR 1999; MWR 2008), which has the highest protection level in these regions.

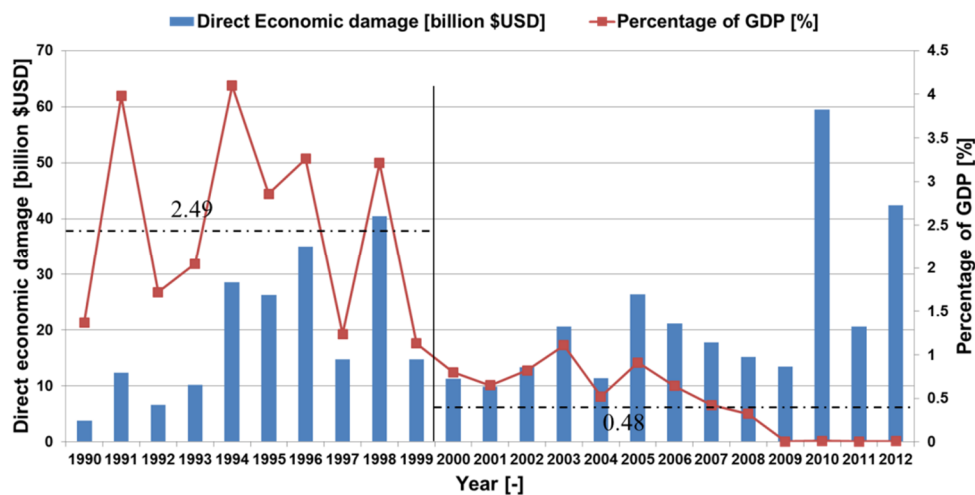


Fig.1. 2 Direct economic damage due to flooding between 1990 and 2012 in the mainland of China (Data source: MWR 2012)

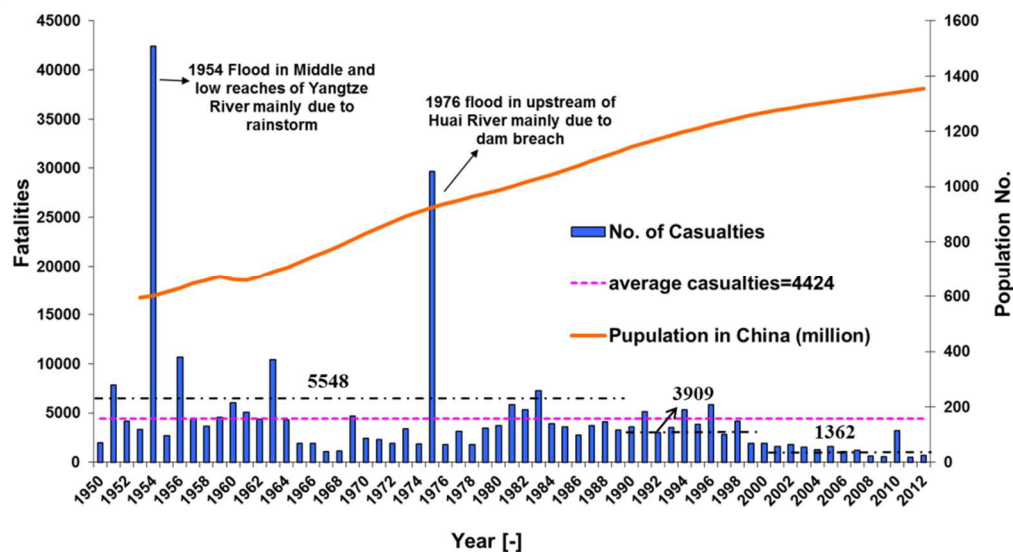


Fig.1. 3 Historical records of loss of life due to flooding between 1950 and 2012 in the mainland of China (Data source: MWR 2012)

1.1.3 Floods in Shanghai

In China, the flood risk in Shanghai has already drawn great attention. Shanghai is vulnerable to flooding owing to its geographic location, flat and low-lying terrain and the growing socio-economic development as well as climate change and land subsidence. Since Shanghai suffers from serious land subsidence for a long time, numerous geological researchers (Gong, 2008; Shen et al., 2005) have questioned the long-term function of a flood defence system (e.g. floodwalls) as flood prevention; they also pointed out that current situation of floodwalls and sea dikes does not meet the regulated safety standards anymore. In recent studies (Nicholls et al., 2007a), Shanghai ranked as one of the top 20 cities in the world in terms of population exposure and economic assets value exposure to the floods, (i.e. 2.4 million people and 73 billion \$USD in total). The expected annual risk is estimated as 2,000 persons/year in terms of loss of life and 73 million \$USD/year in terms of economic damage. Hallegatte et al. (2013) also estimated flood risk in Shanghai at 63 million \$USD/year under an optimistic scenario of a maximum protection level of 1/1,000p.y..

Based on the most recent observations in the period of 1997-2012, the flood damage averages 72 million \$USD/year with a standard deviation of 82 million \$USD/yr in Shanghai (SWA 2013) (see Fig.1. 4). The causes of flooding are mainly caused by storm surge events resulting from typhoons, for instance in 1997, 2005 and 2012. The 1999 flood event mainly resulted from long term rainfall in the whole Tai Lake Basin, which caused farmland inundation in large areas of the suburbs of Shanghai city. In the year of 1998, 2000, 2001, 2002, 2004 and 2007, economic damage was caused by a combination of typhoons and rainstorms during summer time.

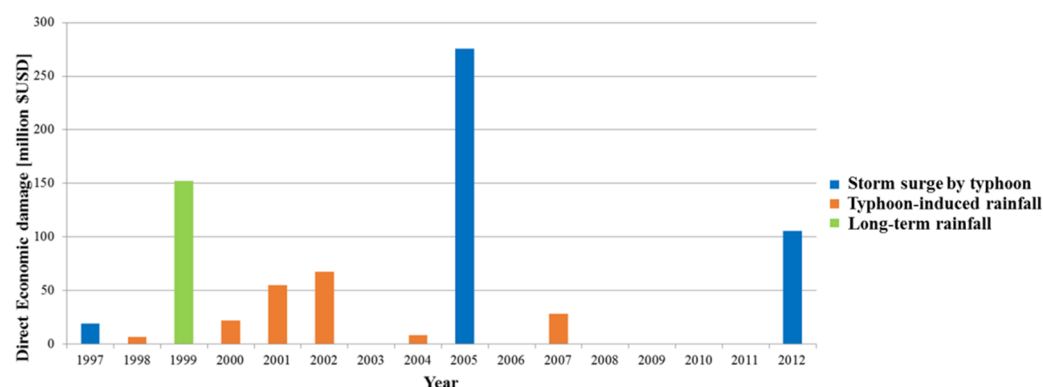


Fig.1. 4 Recent floods in terms of direct economic damage during 1997-2012 in Shanghai

1.1.4 Flood risk

Risk is a combination of the probability of an event and its negative consequences (UN/ISDR 2009). Risk has two distinctive connotations: in popular usage the emphasis is usually placed on the concept of chance or possibility, such as in the risk of an accident; whereas in technical settings the emphasis is usually placed on the consequences, in terms of potential losses for some particular causes, places and periods. It can be noted that people do not necessarily share the same perceptions of the significance and the underlying causes of different risks. In Chinese, ‘risk (风险)’ literally means “the negative consequence (danger) caused by the wind”, which originates from the fishermen working in the coastal areas in ancient China. During the long time of fishing experience, they found that “wind” brought huge uncertainty to their safety; that is to say, ‘wind results danger’ means ‘risk’. Here for ‘wind’ can be represented as one of hazardous factors, in which the probability of the occurrence and its characteristics need to be determined; and ‘danger’ can be represented as a negative consequence which can also be estimated in a quantitative way.

In the European Floods Directive, flood risk is defined as the “combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural

heritage and economic activity associated with a flood event” (Samuels and Gouldby 2009). Probability can be described as the frequency of occurrence of hazards which are shown by means of a return period. On the other hand, flood damage is an important factor to determine the flood risk as well. The flooding area without damages is not considered as flood disaster, or researchers would pay less attention to such areas.

Nowadays, risk has been applied in many related fields to address economic, engineering, social and environmental issues. These different issues often reflect the demands or needs of particular decision makers and, as a result, there is no overall definition of risk and any attempt to develop one would inevitably satisfy only a small proportion of risk managers. In general, risk can be simply defined as the product of probability and its negative consequence, but the meaning behind this function is far more complicated.

$$F_r = \text{function} (P_f, C) \quad (1.1)$$

Where: F_r - flood risk; P_f - Probability of flooding; C - Consequence;

Probability is usually represented by the probability density function (PDF) which describes the probability of value of a stochastic variable around a certain value under a given uncertainty; or the distribution function of probability (i.e. the exceedance probability).

$$P(X \geq x_p) = \int_{x_p}^{\infty} f(x)dx = 1 - P(X < x_p) = 1 - F(x) \quad (1.2)$$

Where: $f(x)$ - probability density distribution; $F(x)$ - cumulative probability distribution.

The probability of flooding is the probability that an area of interest is unintentionally flooded with an unmanageable quantity of water because a water defence fails in one or more places (Rijkswaterstaat 2008). The hydraulic load and the height and strength of a water defence are factored in when calculating the probability. In this sense, flood probability is the probability of a water defence failing, not the probability that the critical load occurs. The consequence of flood events represents an impact such as loss of life, economic, social or environmental damage, in different dimensions. Consequence may be expressed quantitatively by e.g. a number of fatalities and monetary value by a ranking of high, medium and low estimates.

The so-called risk curve, which graphically shows the probability of exceedance of a certain level of consequence, may represent flood risk. A well-known example of such a risk curve is the FN curve (see Fig.1. 5 (i)). It displays the probability of exceedance of N fatalities and is mostly shown on a double logarithmic scale. It could also be applied to the economic damage that results from a disaster like a flood or an explosion, if the horizontal axis is measured in monetary units, named the FD curve (Fig.1. 5(ii)). The classical measures of expected value and standard deviation will appear to be very useful numbers to classify the risk (Vrijling et al, 1998). Vrijling and van Gelder (1997) proposed a linear combination of the statistic moments of the FN curve (see Eq.(1.3)), namely the expected value of the number of deaths $E(N)$ and the standard deviation $\sigma(N)$, in which k is the risk aversion index and which has been tested based on 3 in different activities in the Netherlands (Vrijling, van Hengel et al. 1995).

$$TR = E(N) + k \cdot \sigma(N) \quad (1.3)$$

Where: TR - total risk; $E(N)$ - expected number of loss of life; $\sigma(N)$ standard deviation of number of loss of life; k - risk aversion index.

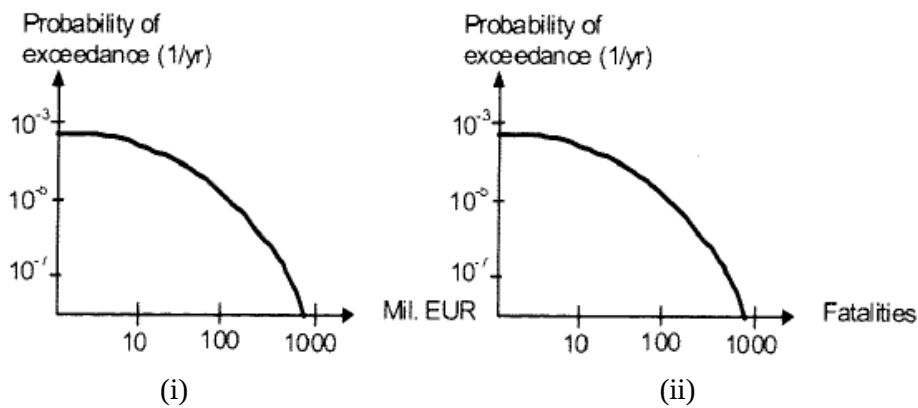


Fig.1. 5 Examples of FD curve (i) and FN curve (ii) (Cong 2010)

1.1.5 Flood risk analysis

Flood risk analysis is a chain of investigation on flood disaster from the triggering event to all its consequences: hydraulic load/ resistance - potential failure of flood defence - flood routing - inundation – flood damage/loss of life (see Fig.1. 6). The hydraulic load and resistance can determine the failure probability of a flood defence; flood simulation shows the flood routing and derives inundation characteristics under the correspondent flood scenario; the negative consequence (e.g. flood damage and loss of life) can then be assessed accordingly.

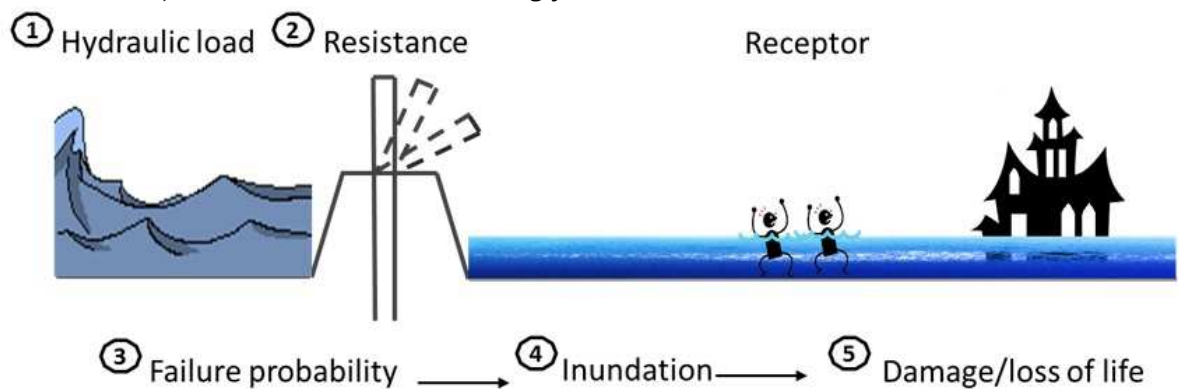


Fig.1. 6 Conceptual model of flood risk analysis from the triggering event (failure of defence) to its consequences (e.g. economic damage/loss of life)

The probability of flooding and its inundation characteristics are combined to show the potential flood hazard in an area of interest. Flood damage can then be estimated based on the inundation characteristics. Ideally, a flood risk analysis should take all relevant flood scenarios, their associated probabilities and potential damages into account, as well as a thorough investigation of the uncertainties associated with the risk analysis. Flood scenarios should include several failure mechanisms of flood defence systems to determine the associated failure probabilities. The flood simulation based on the failure information of a flood defence can further determine the characteristics of inundation in an area of interest. The associated negative consequence can then be estimated based on inundation information. In the end, flood risk can be quantified by an expression of expected annual damage in monetary terms (e.g. \$USD/yr) or FD curves. In summary, the complete distribution of flood risk can be calculated in two steps: 1). estimation of flood damage under a full distribution of probabilistic flood events are used to establish risk curve, which gives the information on the different return periods or the exceedance of the flood probability with the corresponding flood damage. 2). the flood risk can then be calculated by estimating the area under the risk curve. The results of flood risk are of particular importance for the insurance companies to derive premiums and for the policy makers who plan to invest in flood management measures to assess current risk levels and to calculate the benefits (expressed as “the reduced (flood) risk”) of risk-reduction measures.

1.2 Overview of this thesis

1.2.1 Research problem

Flood risk analyses at a global level and at a local level have been studied by many researchers. Nicholls et al. (2007a; 2007b) explored the global port cities to examine the exposure to coastal flooding. Their study focuses on 136 port cities around the world that have more than one million inhabitants and the results showed the city rankings which indicated those cities were most worthy of further more detailed investigation. Followed by these studies, Hallegatte et al. (2013) provided a quantification of present and future flood losses in these 136 coastal cities based on a new database of urban protection and the different assumptions on adaptation. Apart from the broad-scale analysis in a global world, numerous studies about flood risk analysis have also put stresses in the local cities such as in Cologne, Copenhagen and New York, (Grünthal, et al.2006; Hallegatte, et al. 2009; Aerts, et al. 2013). However, in order to better understand flood risk at a local level it needs to be more specific and to be linked to the metropolitan area, especially in a rapidly growing area. With climate change, land subsidence and the fast-growing socio-economic development, flood risk is inevitably increasing if no measures are taken. It is not only required to understand the current flood risk but also the flood risk in the future. Moreover, it also needed to recommend the effective risk-reduction measures to mitigate future flood risk.

1.2.2 Scope of this thesis

The geographical focus of this thesis will be Shanghai city in China which is representative of metropolitan areas. First, Shanghai has a long history of flooding and is currently ranked as one of the top cities in terms of flood vulnerability worldwide (Nicholls et al., 2007a). Second, due to its fast growing socio-economic development, preventing flood has a high priority in Shanghai. The safety standard of the Huangpu River in Shanghai is 1/1,000p.y., which is higher than some other developed cities already (e.g. New York with 1/100p.y.). While faced with future climate change and ongoing land subsidence, the potential flooding could also occur any time due to the failure of flood defence. As an economic centre of the mainland of China, Shanghai deserves critical attention to be studied in the field of flood risk analysis. Moreover, flood risk analysis at a local city level can provide more accurate information and results, which can support the understanding of the potential flood risk in a growing city to better prevent flood.

This research will focus on typhoon induced flooding in the river, resulting from storm surges coinciding with a high astronomic tide. Since the coastal area of Shanghai currently has relatively few buildings and infrastructures, it can hardly be compared to the economic damage in the city centre along the Huangpu River; therefore, coastal flooding will not be included in this thesis. Water logging (or pluvial floods) is more related to the drainage and pumping system problems, which therefore is also beyond the scope of this thesis. Among the possible failure mechanisms of flood defence system, overtopping, breaching and failure of floodgates will be taken as the main failure modes to represent the flood scenarios. The detailed geotechnical issues were not addressed. And, the estimation of the negative consequence of flood will focus on economic damage while the estimation of the loss of life will not be included.

1.2.3 Research objectives

The objective of this research is to quantify the current and future flood risk and to make recommendations on risk reduction measures in a case study of Shanghai. This research mainly focuses on scenario-based flood risk analysis including the determination of flood probabilities, the derivation of its inundation characteristics and on the estimation of flood damage under different flood scenarios. It will also show and develop methods for flood risk analysis in rapidly growing metropolitan area. The

evaluation of the potential risk-reduction measures will be performed by a cost-benefit analysis and an economic optimization in the end. Therefore, five steps can be taken.

1. To examine flood threats and flood defence system in Shanghai (**Chapter 2**)
2. To produce inundation maps due to different failures of the flood defence system (**Chapter 3**)
 - a. To derive frequency curves for the water levels in typical stations
 - b. To identify potential weak points along the floodwall
 - c. To estimate inundation characteristics under different flood scenarios by 1D2D hydraulic model
3. To estimate the direct and indirect potential economic damage based on flood scenarios (**Chapter 4**)
4. To quantify current flood risk based on flood probabilities and the associated flood damage under different scenarios and to estimate future flood risk due to the effects of climate change, land subsidence and economic development (**Chapter 5**)
5. To evaluate and recommend the risk-reduction measures by cost-benefit analysis and economic optimization (**Chapter 6**)

1.2.4 Contributions of this thesis

The contributions of this thesis are related to 1). derive a new frequency curve for the water levels based on three typical hydrological stations in the Huangpu River; 2). produce inundation maps based on scenario analysis, in which the breach scenarios and failure of floodgates are the new potential failure modes concerned in the floodwall of Shanghai; 3). develop a damage model to estimate flood damage at an individual building scale and to examine the indirect damage in Shanghai; 4). quantify the expected annual damage based on a probabilistic method and also to calculate the future flood risk due to climate change, land subsidence and economic development in Shanghai; 5). evaluate the potential risk-reduction measures by cost-benefit analysis and economic optimization.

These contributions will provide insights not only on the framework of flood risk analysis but also on the understanding of the current and future flood risk in a representative city, i.e. Shanghai, which will be able to support flood risk management in an effective and sustainable way in other metropolitan areas.

1.3 Outline of this thesis

The outline of the thesis is presented as below in Fig.1. 7. Chapter 1 is the introduction; Chapter 2 is the system analysis of Shanghai city; Chapter 3 contains a flood hazard analysis including a frequency analysis and the determination of inundation characteristics under flood scenarios; Chapter 4 is a flood damage estimation with a case study in a selected area of downtown Shanghai, also indirect damage will be discussed; In Chapter 5, flood risk analysis will quantify the expected annual damage and also future flood risk; Chapter 6 is evaluation and recommendation of risk-reduction measures by cost-benefit analysis and economic optimization; Chapter 7 is the conclusion and recommendation in the future work.

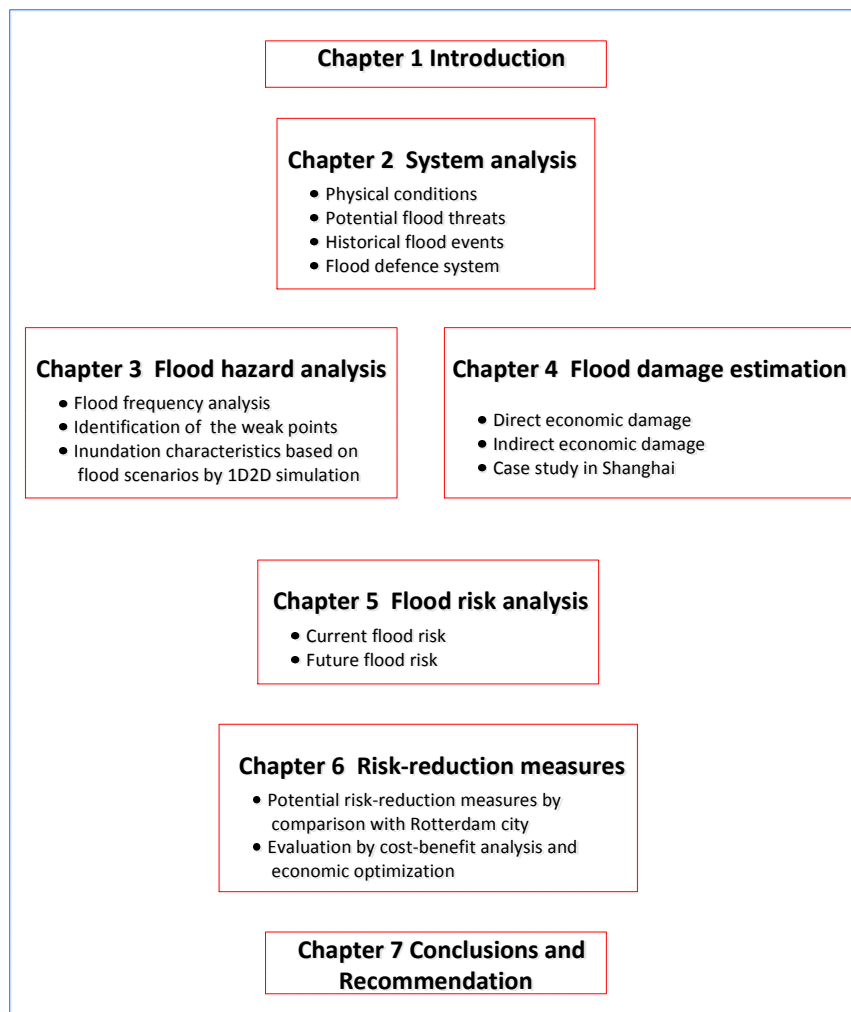


Fig.1. 7 Layout of this thesis

Chapter 2

Shanghai: System analysis

The main threat to the river flood of Shanghai is the occurrence of a typhoon induced storm surge in combination with a high astronomic tide in the Huangpu River, which has threatened the city's safety for a long time. Historical flood events have shown the weakness of the floodwall with potential overtopping and breaching along the Huangpu River and its branches, which caused great economic damage and loss of life in Shanghai. The objective of this chapter is to examine flood threats and flood defence system in Shanghai, which provides information for the determination of flood probabilities and flood risk analysis in next step. In terms of flood threats to the river, the joint probability of the occurrence of torrential rainfall and high storm tide is limited. The heavy precipitation mainly induces water logging in the urban city while not significantly increase river runoff in the Huangpu River. Moreover, a control gate (between Tai Lake and the Huangpu River) is regulated to reduce drainage water from Tai Lake when a storm surge occurs in the Huangpu River. Therefore, the storm surge and high astronomic tide will be the focus of flood threat in the next step. In terms of flood defence system, it is noticed that the current protection level of floodwall is only based on the exceedance of the crest height of the floodwall by the water level and does not directly take into account the other failure mechanisms. Failure mechanisms such as breaching of floodwalls and failure of floodgate would induce potential floods in Shanghai.

2.1 Introduction

Shanghai is the biggest metropolis and economic centre in mainland of China. Due to its flat-low elevation and frequent typhoon weather it suffered floods for a long time. Chinese researchers (Yuan et al. 1999) have looked back over the floods before 1999 in Shanghai city based on historical records and empirical judgement. This book literally described flood events on the consequences of damage and fatalities dated back to 2,000 years ago; and the spatial and temporal distribution of flood disasters were specifically visualized based on typical events. It thus can be regarded as a resourceful descriptive database regarding floods in Shanghai city. However, the information is only updated to 1999; new information after 1999 could be supplemented and the projections of different scenarios of flood events could also be useful in future planning. In recent studies, Dutch researchers pointed out that Shanghai city ranked as top one vulnerable city of flooding among nine coastal cities worldwide (Balica et al., 2012), which were based on their coastal city flood vulnerability index (CCFVI) in terms of hydro-geological, socio-economic and political-administrative components under different scenarios. Nevertheless, flood defence system has not been taken into account in this paper. As flood defence system is a critical component in flood risk analysis, non-failure of flood defence system would not result in floods in a modern city; thus, flood vulnerability cannot solely determine the severity of flood risk. It then needs to study the flood defence system to identify weak points and further analyse the potential failure mechanisms. The objective of this chapter is to examine flood threats and flood defence system in Shanghai, which can provide information for the determination of flood probabilities and flood risk analysis in next step. Firstly, the general physical situation, such as geography, climate and socio-economic development, will be descriptively explored; secondly, the water system and historical events will be investigated; thirdly, flood threats will be identified based on previous work in a qualitative way; lastly, the flood defence system will be examined and the potential failure mechanisms will be analysed accordingly. A list of research questions will be addressed as below:

- Why is Shanghai vulnerable to flooding?
- What are the potential flood threats in Shanghai?
- What is the current situation of flood defence system in Shanghai?

The structure of this chapter will be organized as below. Section 2.2 will describe the general situation of Shanghai in terms of geography, climate and socio-economic development. Section 2.3 will give an impression of Shanghai water system at a macro-scale generally and Section 2.4 will go back to the historical events. Section 2.5 will answer the second question in terms of flood drivers in the river. The current flood defence system will be investigated in Section 2.6. In the end, a discussion on flood threats and potential failure mechanisms of floodwall will be given in Section 2.7.

2.2 City profile

Shanghai city is located in the East of China. The whole city situates on the eastern fringe of the Yangtze River Delta, which is in the centre of the coastline from North to South of China. It is surrounded by the waters (see Fig.2. 1). The estuary of the Yangtze River is situated to the north, the East China Sea to the east, the Hangzhou Bay to the south and Tai Lake to the west. The Huangpu River meanders through the whole city from West to East in the upstream and changes its direction from South to North in the middle and downstream, which splits Shanghai into West and East part. Besides, two neighbour provinces, namely Jiangsu and Zhejiang, are located to the northwest and southwest, respectively. Shanghai city has a total area of 6,340.5 km² extending about 120 km from North to South and nearly 100 km from West to East, which accounts for 0.06% of China's total territory. The whole city consists of 17 districts and 1 county (Chongming Island) (SSB 2011), of which 9 downtown districts are located in the city centre called “Puxi”, which means the West of the Huangpu River

(see Fig.2. 1). Pudong area which is on the East of the Huangpu River developed very fast and part of it has become the city centre of Shanghai.

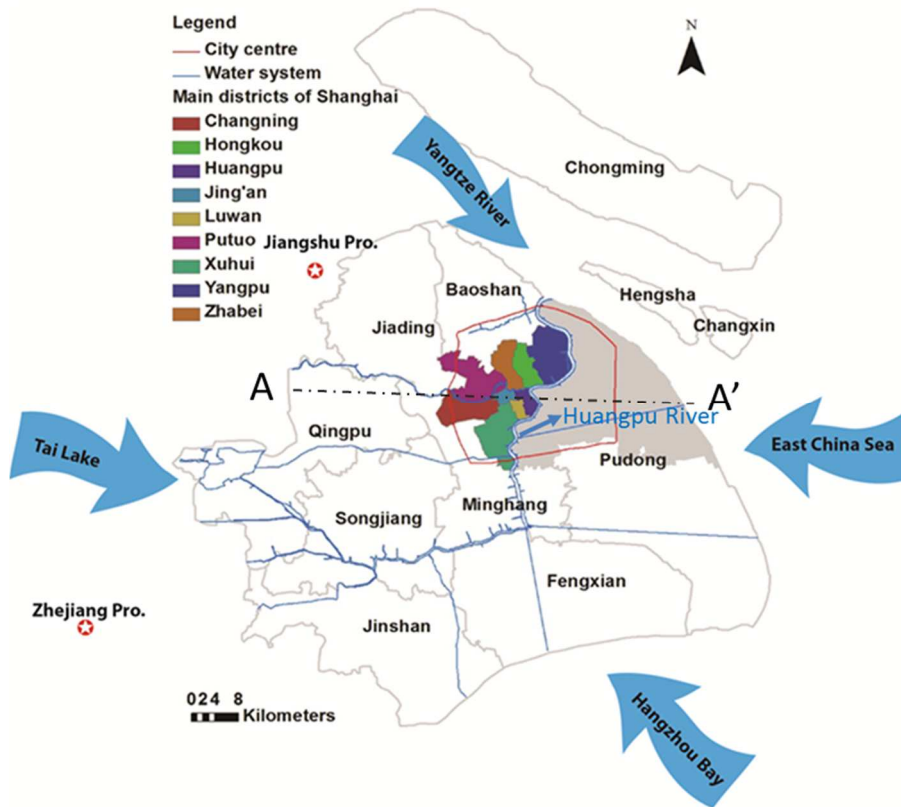


Fig.2. 1 Shanghai municipality including downtown districts (with colour) and suburb districts (grey and white); the red line graphically indicates city centre area

Shanghai is a flat and low-lying region with an average elevation of WD¹ 3m-5m, with an exception of small hills in the west regions. Shanghai can be divided into four regions in terms of terrain, namely the Lake plain region in the West with ~2.2-3.5m, the coastal plain region in the East and South with ~4-5m, the Estuary islands region in the North with 3.3-4.2m and the downtown region with ~3-3.5m (Gong 2008). Generally, the East part of Shanghai (~4-5m) is relatively higher than the West part (~3-3.5m). A cross section of Shanghai from West to East (A-A' in Fig.2. 1) is shown in Fig.2. 2. It illustrates that the inland terrain is relatively lower than the coast side.

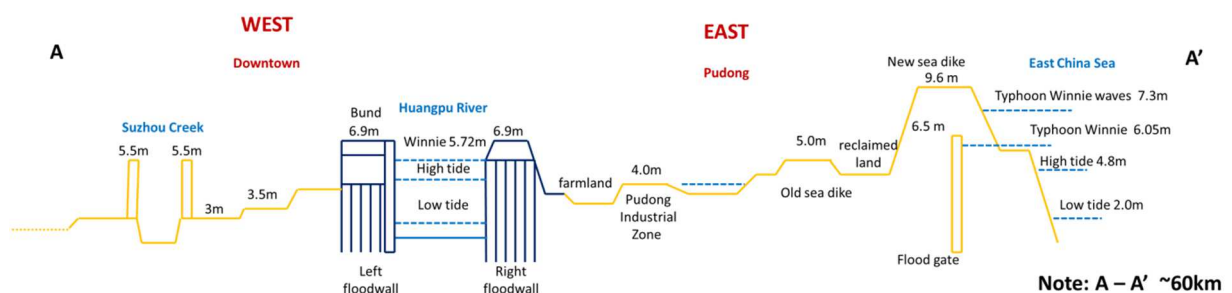


Fig.2. 2 Schematization of cross section of Shanghai city from West (3-3.5m) to East (4-5m), including crest height of floodwall/dikes along Suzhou Creek (5.5m), the Huangpu River (6.9m) and East China Sea (9.6m)

¹ Hereafter, geographic elevation and water levels in the river and Sea are referred to Wusong Datum(WD) overall in this thesis. WD is 1.924m lower than mean sea level of China Yellow sea; the mean sea level of Yellow Sea is a reference datum for China in general, while local datum is applied widely in China, e.g. WD.

In Shanghai, land subsidence has been experienced for a long time especially since 1921 (Yan 1998; Sun 2002), which is caused by the tectonic subsidence and compaction of sediments due to extraction of groundwater and urban construction (Gong 2008; Tang, Cui et al. 2008; Wu, Shi et al. 2008; Yin, Yin et al. 2011). The subsidence rate was 39.1mm/year during the period of 1921-1965 owing to the increasingly utilization of groundwater for industries development; while since the government began to control extraction and to recharge the groundwater after 1965, the rate of land subsidence decreased to 6.2mm/year on average until 2007 (Gong 2008). According to Gong (2008), the primary cause of land subsidence in downtown is construction of high-rise buildings (60%) after 1990 while in suburbs 70% is attributed to withdrawal of groundwater. The prediction of land subsidence after 2010 along the Huangpu River is 8.1-8.8mm/year, which might contribute 60% to the ‘relative’ sea level rising in this century (Gong 2008; Wang et al., 2013).

Shanghai is frequently threatened by Typhoon² during June to September. It was affected by typhoon almost every year between 1949 and 2005, with a frequency of 1.5 times per year (see Fig.2. 3). The typhoon induces storm surge, wind and torrential rainfall simultaneously. In Shanghai, the annual average rainfall is 1111mm (dataset: 1960-1990) (HKO 2004) with 112 rainy days per year. Almost 50% of the rainfall is between June and September. Every year there is a ‘plum rainy’ season normally from April to June lasting 15-30 days successively, which can cause a sustained high water level in the rivers.

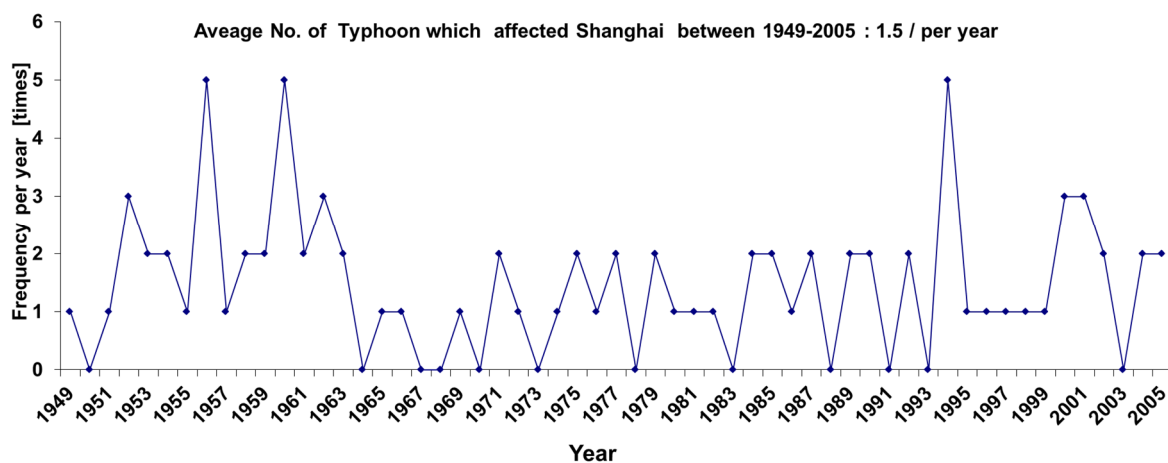


Fig.2. 3 Annual typhoon frequency from 1949 to 2005 in Shanghai (Adapted from (Meng et al., 2007))

Shanghai is considered as the most crowded city in mainland China with a population density of 3,632/km² on average by the end of 2010. The population of long-term residents reached 23 million, including 9 million from other parts of China, mainly from Anhui, Jiangshu and Henan provinces (SSB 2011). The city's permanent residents account for nearly 1% (14 million) of China's population. In addition, population growth is expected to increase mainly due to the expected net immigration (SSB 2011). Regarding the population distribution, more than 44% of long-term residents live in the downtown area (Puxi Area), 31% of them live in the near suburbs (e.g. Baoshan, Minghang and part of Pudong) and 25% live in the outer suburbs (e.g. Chongming, Fengxian, Jinshan, Qingpu and Songjiang) (SSB 2011). Moreover, almost half of the immigration population is living in the suburbs (SSB 2011). Fig.2. 4 shows a spatial distribution of population density in each district of Shanghai by 2010, which indicates that the population density in downtown area (25,000/km²) is significantly higher than in the suburbs (3,000/km²), with highest district of Hongkou (36,307/km²).

² The typhoon weather in Shanghai will be elaborated in section 2.5.

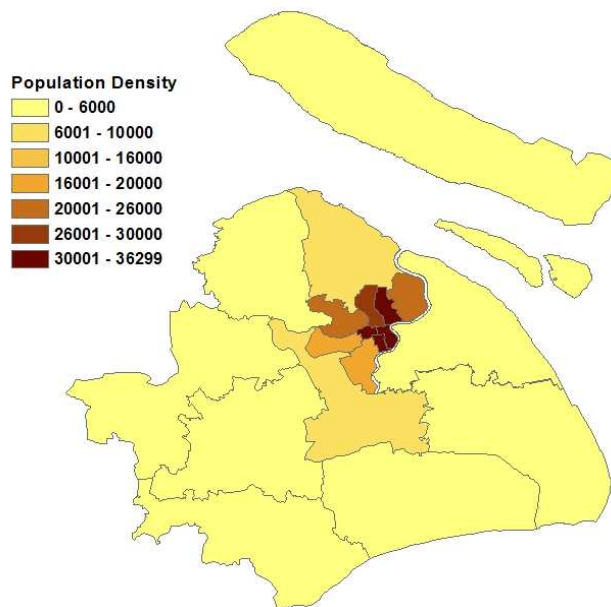


Fig.2. 4 Population density (/km²) of each district in Shanghai in 2010 (Data Source: SSB 2011)

The economy developed rapidly in Shanghai. The GDP has increased to 44 billion \$USD (270 billion RMB) by the end of 2010 with an average growth rate of 12% per year during the past 34 years. Shanghai accounts for 4% share of total GDP of China and GDP per capita is 12,024 \$USD by the end of 2010 with average growth rate of 5.3% (1978-2010). Fig.2. 5 and Fig.2. 6 represent downtown districts were much richer than other suburbs in terms of GDP per km² and GDP per capita in 2010, which deserves more attention if flood really occurs in these rich districts. The rapid economic development drives the accelerated urbanization process as well. Urbanization rate reached to 89% (a proportion of urban citizen) by the end of 2010, which increases 14% during the past 10 years; and compared to the average urbanization rate of 50% in China, Shanghai is the top one city in terms of urbanization (SSB 2011). However, on one hand, urbanization stands for great economic value and high densely population; on the other hand, urbanization would lead to enormous potential flood damage due to the decrease of water area and the increase of impervious ground area. The disappearance of water area in recent years is mainly attributed to municipal construction (51%) and building of residential area (31%) in Shanghai (Yang, Cheng et al. 2007).

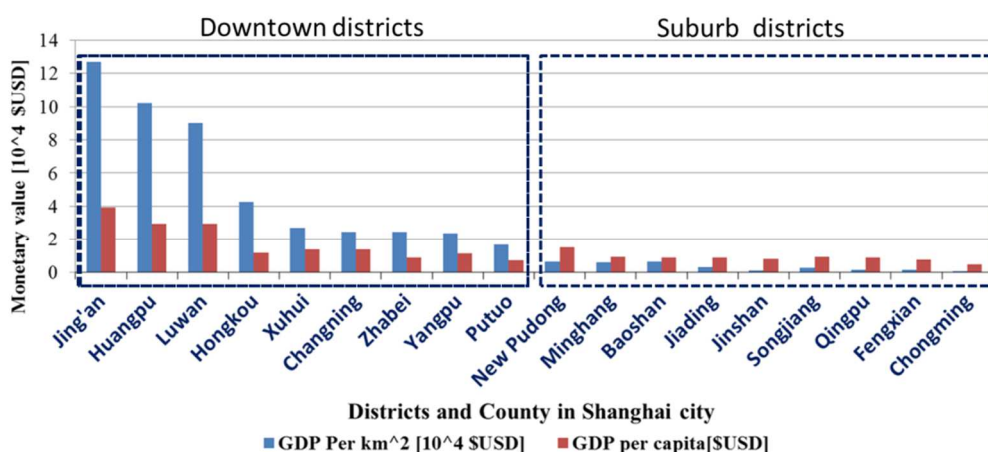


Fig.2. 5 GDP information in each district and county of Shanghai city in 2010 (Data Source: SSB 2011)

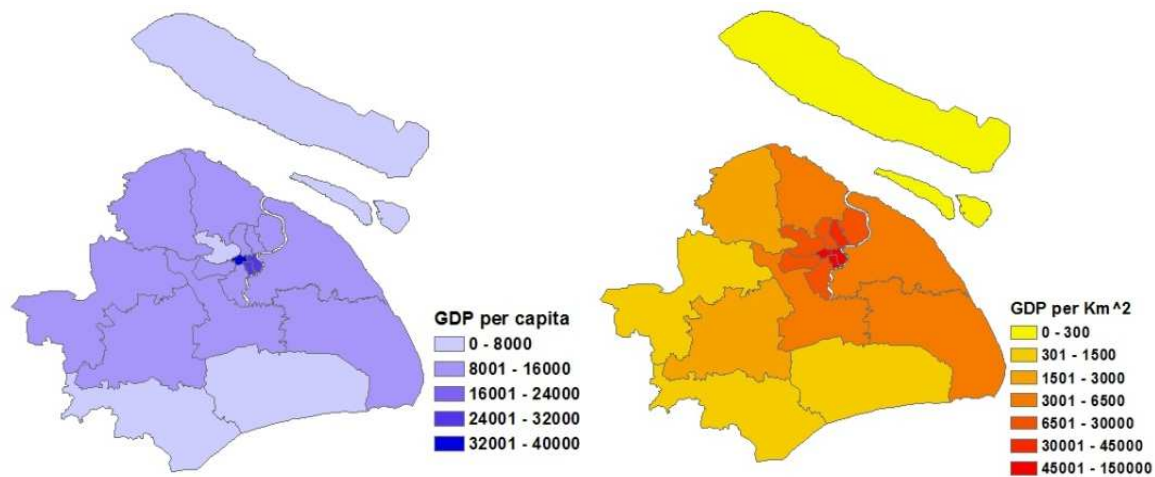


Fig.2. 6 Spatial distribution of GDP information (\$USD) in Shanghai city in terms of districts in 2010 (Data Source: SSB 2011)

2.3 Water system

Water system at a macro-scale of Shanghai is shown in Fig.2. 7 and Fig.2. 8, which provides the information on the river names and their flow directions. It shows that the waters in Shanghai are all connected to the Huangpu River, which connects the Tai Lake and the Yangtze River then flows into the East China Sea. The upstream tributaries of the Huangpu River originate from Tai Lake, which is located around 200km to the West of Shanghai city, and some tributaries such as Jinghui Gang (f), in the districts of Fengxian and Jinshan, converge into Hangzhou Bay to the South. The biggest branch of the Huangpu River is Suzhou Creek (b), which also partly crosses through the downtown city. Other information about the branches of the Huangpu River in terms of length, width and depth are indicated in Tab.2. 1. Information in a more detail about the Yangtze River, Tai Lake, the Huangpu River and Suzhou Creek will introduce as followed.

Tab.2. 1 River length, width and depth of the main branches of the Huangpu River in Shanghai (Data source: Zhang 1997; SWR 2010)

River name	Letters in Fig.2. 7	Length [km]	Width[m]	Depth[m]
Suzhou Creek	b	54	58.6	3.4
Yunzao Bang	c	34.2	92.0	5.0
Chuangyang Gang	d	28.7	47-140	---
Dazhi Canal	e	39.2	95-120	---
Jinghui Gang	f	22	75-132	---
Dianpu River	g	45.6	40-183	---
Xie Tang	h	23.2	170.0	6.0
Taipu River	i	14.8	150-180	3.5
Yuangxie Jing	j	16.5	178	7.8

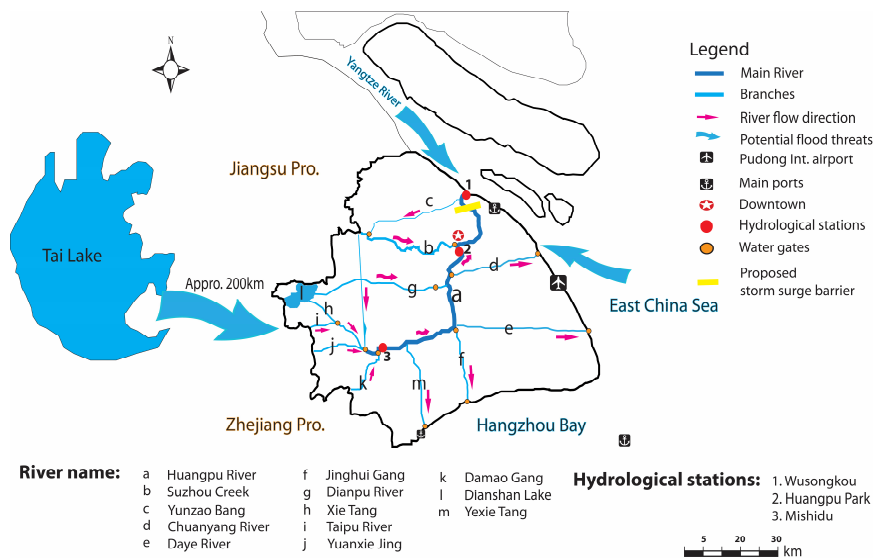


Fig.2. 7 Macro-scale map of water system in Shanghai

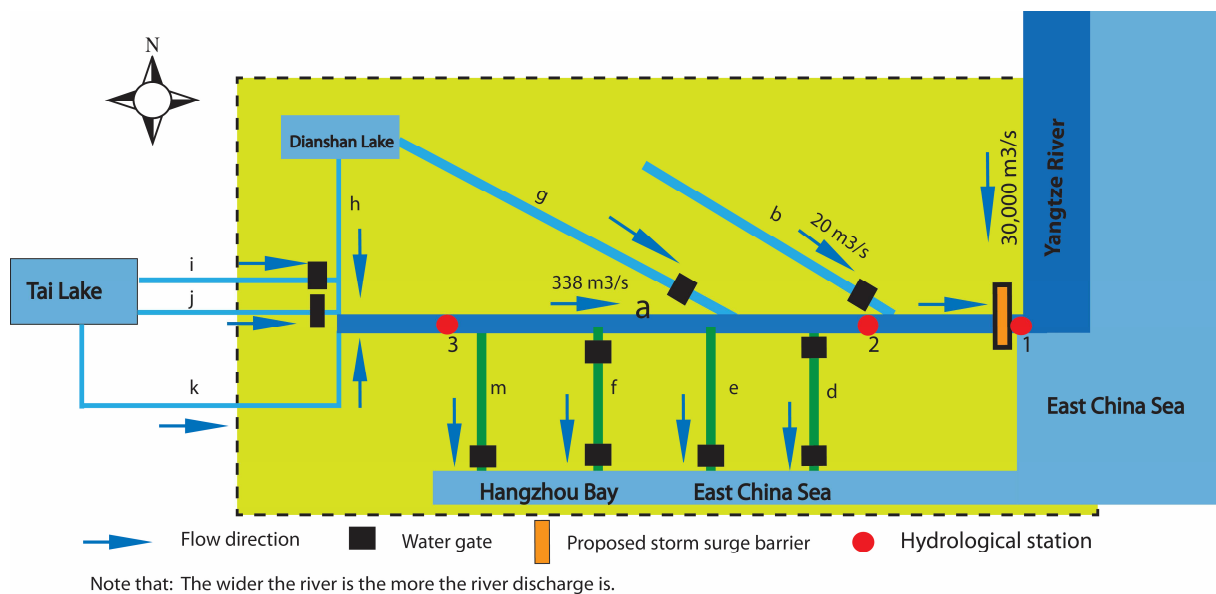


Fig.2. 8 Schematization of macro-scale water system in Shanghai city

2.3.1 Yangtze River

Yangtze River is the third largest river in the world with a length of 6,300 km (close to the Mississippi River) running from West to East. This extensive waterway cuts through the heart of China, and is regarded as a mark of a division of the country into north and south, both geographically and culturally. Huangpu River is the last tributary of Yangtze River. The annual average discharge of Yangtze River is around 29,000 m³/s (See Fig.2. 9). About 70% of discharge is produced during rain seasons between May and October, with an average discharge of 40,844 m³/s during this period.

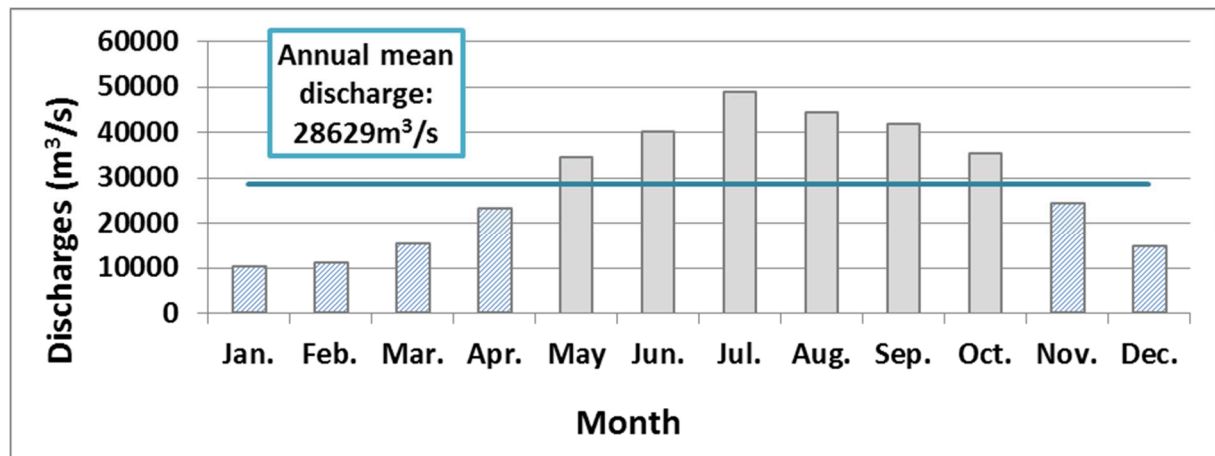


Fig.2. 9 Yangtze River Discharge at Datong station (time-series: 1922-2004) (Data source: (GRDC 2009))

2.3.2 Tai Lake

Located in the delta region of the Yangtze River in East of China, Tai Lake is the third largest water body with an area of $\sim 2,250 \text{ km}^2$ in China. Rivers flow into the lake and drain a catchment of $36,895 \text{ km}^2$ that encompasses parts of three administrative provinces (municipality): Jiangsu to the North, Zhejiang to the South and Shanghai to the East. Tai Lake Basin is one of the most developed regions in China, including mega cities of Shanghai, Wuxi, Hangzhou and Suzhou, etc. Although its population only accounts for 3.8% of Chinese population, its GDP takes 11% of national share (exclusive of Hong Kong and Macaw).

The annual average water level is WD 3.3m and the warning level in Tai Lake is regulated as 3.8m (TBA 2013). Primarily, there are two outlets of Tai Lake: namely Wangyu River, which discharges Lake's water to the Yangtze river eventually; and Taipu River (the upstream of Huangpu River (i)), which has a drainage capacity of half of Tai Lake's water collections. A water gate (i.e. Taipu Gate) was constructed around 2km away from Tai Lake on the Taipu River to operate water levels as well as water quality in Tai Lake and the Huangpu River. On one hand, Taipu Gate functions as flood control infrastructure to release extra water from Tai Lake to the Huangpu River during flood season when water level exceeds WD 3.8m in Tai Lake, but if storm surge events affects the Huangpu River or the water level is predicted at WD 3.7m at Mishidu (the upstream of the Huangpu River) the drainage water would be reduced by manual operation (MWR 1999 pp.2). On the other hand, water from Tai Lake through Taipu Gate can provide a dynamic environment to improve the water quality for the Huangpu River, as well as can supply sufficient water for daily usage and navigation during dry seasons in the Huangpu River.

2.3.3 Huangpu River

Huangpu River is a tidal river located to the South of the Yangtze Estuary. There are three main tributaries in the upstream (See Fig.2. 7) —Xie Tang (h) that connects Taipu River (i) and Dianshan Lake (l), Yuanxie Jing (j) and Damao Gang (k). They converge at Mishidu Station (3) of upstream in Huangpu River, where is roughly 80 km away from Wusongkou (1), and then flow through the urban area and finally to the Yangtze Estuary. The width of the Huangpu River is $\sim 800 \text{ m}$ close to the estuary and average $\sim 360 \text{ m}$ in general, with its bottom elevation around WD -5 to -15m. The deepest location could be of WD -18m. The annual average discharge in the upstream (Songpu Bridge) is $\sim 439 \text{ m}^3/\text{s}$ with a standard deviation of $\sim 67 \text{ m}^3/\text{s}$ (1998-2012).

2.3.4 Suzhou Creek

Suzhou creek (**b**) is the largest tributary of Huangpu River, which originates from Tai Lake and runs through Jiangsu Province to the Huangpu River, passing through a city of Suzhou. It has 125 km length including 54km in Shanghai city. Suzhou creek is a narrow (average width 58.6m) and shallow (average depth 3.4m) river with an annual average discharge of 10-25m³/s; the discharge is not significant and mainly depends on the downstream tide levels.

Suzhou creek runs for 17km through the downtown of Shanghai and converges to Huangpu River near a hydrological station named Huangpu Park in city centre. A water gate (see Section 2.6.3), which is close to the mouth of Suzhou creek, prevents storm surge from entering Suzhou Creek during Typhoon.

2.4 Historical flood events

Fig.2. 10 provides information (e.g. inundation extent) on typical floods in city centre of Shanghai (in 1962) and failure points along floodwalls of the Huangpu River and its branches in the year of 1974, 1981 and other years. The tremendous flood disaster ever happened after the liberation of R.P. China (1949) is 1962 flood event which caused 1/6 loss of total GDP. When the tropical cyclone affected Shanghai city on 2nd, August, in 1962, water level at Huangpu Park station rise up to 4.76m (increased by 83cm) and half of the downtown city was inundated for nearly 10 days due to 46 failures (breach and overflowing) points along floodwalls of the Huangpu River and its branches. The inundation depth was 0.5-1.0m on average as a whole while reached to 1.5-2m in some low-lying areas. 375 industries were suspended, of which the cotton industries were hit most severely (nearly half of them) and 17 transportation (Bus & Train) routes were interrupted. Moreover, 25 people were killed mainly because of electrical shock in the water during this event. The primary reasons of this disaster are low topography due to land subsidence and the weakness of the flood defence system in Shanghai city. Firstly, the land subsidence occurred most seriously between 1921-1965, which resulted in 1.76m subsidence accumulatively on average in downtown and in some place even up to 2.63m. The elevation along the Huangpu River in city centre was ~1.5m lower than the highest tide level at that time. Secondly, the floodwalls along the rivers were not strong enough to withstand the high storm tide during typhoon.

In 1981, several points of floodwall and floodgates were failed on the West and East side of the Huangpu River in downstream and middle stream. Part of the city centre was flooded. The average inundation depth was 0.5m with maximum depth of 1m. According to the historical records (Yuan et al. 1999), 63 industries (partly) suspended production due to the inundation. For example, one industry was inundated due to earthen dike breach and it recovered completely in more than one month; another ship construction industry was completely flooded due to a failure of floodgate and it recovered in 3 days. Other warehouses with grains, paper and cloth, etc. were damped to some extent. Besides, 6,790 households got inundated in the whole city, which mainly distribute around Xiepu Road, South Railway station and Liuli town in city centre.

In recent years, there were a number of tremendous typhoon disaster happened in Shanghai (see Tab.2. 2). In 1997, Shanghai city was affected by Typhoon Winnie, which led to 100 million USD of economic damage. The water level in Huangpu Park (city centre) rose to 5.72 m, which was equivalent to the water level of 200 years return period. The 2005 Typhoon Matsa induced torrential rainfall with the accumulative rainfall intensity of 138-350mm, which led to 238 roads under 20-30cm inundation with direct economic damage of over 216 million USD.

Last year, it was reported that the floodwalls in the upstream of the Huangpu River were collapse on 8th, October, 2013 with a breach width of ~15m during Typhoon Fitow, which led to an inundation in

adjacent farmland and residential buildings (see Fig.2. 11). The water level at breaching was 4.9m against the floodwall. Besides, several points in the floodwall along the upstream of the Huangpu River were overtopped, which caused inundation in Songjiang, Qingpu, Jinshan and Minghang districts. The maximum inundation depth was estimated at more than 2.5 m. More than 300 soldiers were involved in rescue and emergency management. No casualties were reported (Li 2013). The temporary flood defence system was built after breaching in 8 hours to prevent further flooding. It was also reported that one industry lost 10 million \$USD during this flooding and it needs 45 days to completely recover production (Liu 2013). Moreover, Shanghai insurance administration reported the direct damage to the farmland reached to approximately 10 million \$USD during Typhoon Fitow in Shanghai.

In a summary, the historical flood events were mainly due to a high hydrological load from the river (e.g. storm surge) and the failure of defence system (e.g. overtopping and breaching) along the Huangpu River and its branches. In the next section, the flood threats in terms of hydrological loads and flood defence system is going to be examined and investigated in Section 2.5 and Section 2.6, respectively.

Tab.2. 2 Recent floods caused by storm tide in 1997-2005 in Shanghai city (Data source: (Hu, 2007))

Flood event	Hydrological station	Highest water level [m]	Economic damage [million \$USD]	No. of Casualties	No. of Collapsed houses	Inundated farmland [hm ²]
19, Aug., 1997 (Typhoon Winnie)	Wusongkou	5.99	100	7	#540	49,570
	Huangpu Park	5.72				
	Mishidu	4.27				
31st, Aug., 2000 (Typhoon Papi)	Wusongkou	5.87	19.4	1	#200	17,880
	Huangpu Park	5.7				
	Mishidu	4.15				
13-15, Sep., 2000 (Typhoon Samie)	Wusongkou	5.45	2.4	---	---	747
	Huangpu Park	5.22				
	Mishidu	4				
6-7, Aug., 2005 (Typhoon Masha)	Wusongkou	5.04	216	7	#15,600	55,840
	Huangpu Park	4.94				
	Mishidu	4.38				

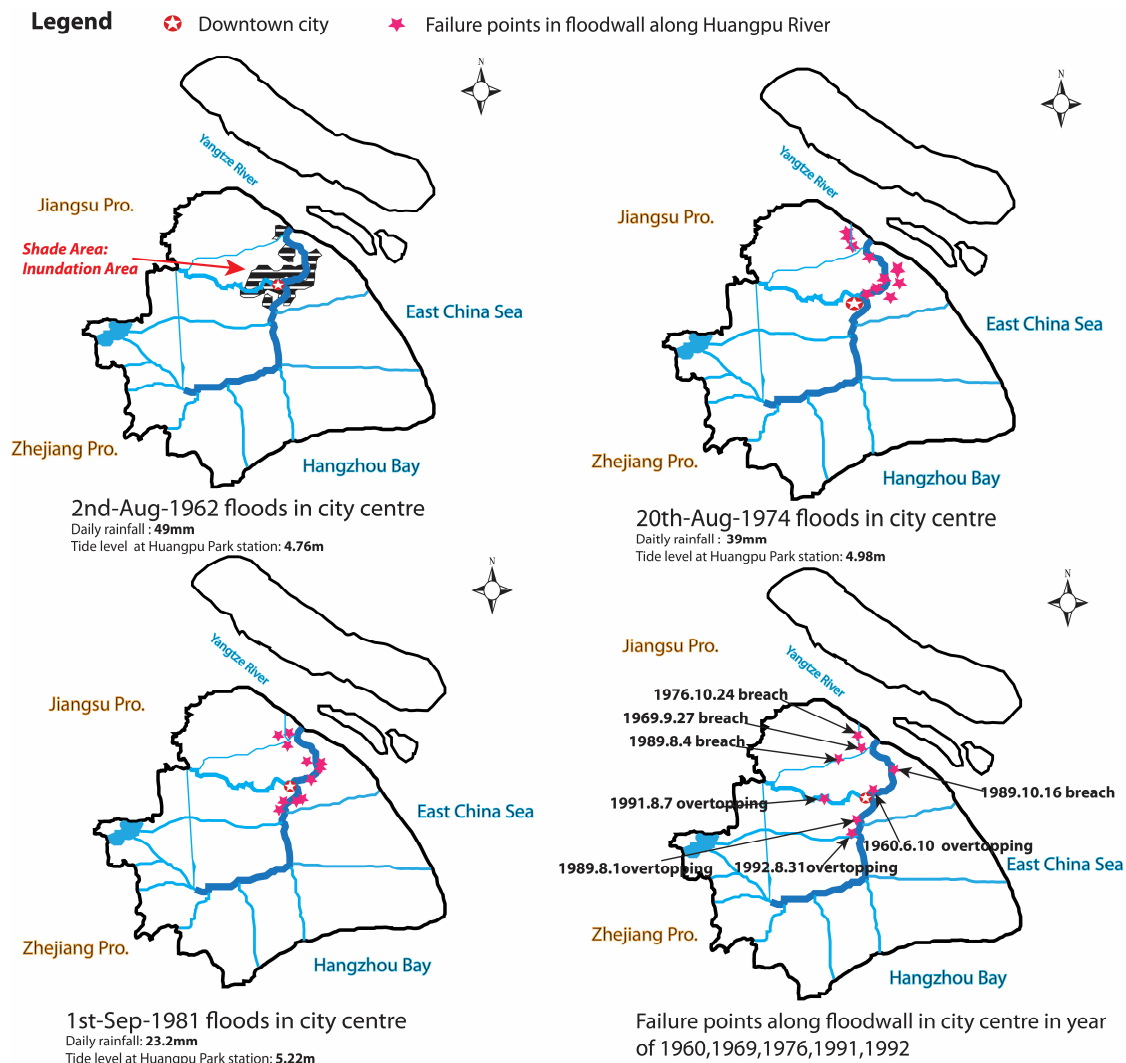


Fig.2. 10 Historical flood events in Shanghai city between 1960-1991, in which the red star represents the failure of floodwall, e.g. overtopping, breaching and the failure of floodgates (Data source: (Yuan et.al. 1999))



Fig.2. 11 Floodwall breach in the upstream of the Huangpu River in October of 2013, which led to inundation in adjacent farmland and residential buildings³

³ Pictures are adopted online live.kankanews.com/tufa/2013-10-08/0013599808_5.shtml; http://www.news365.com.cn/xwzx/gd/gdsh/201310/t20131009_1620822.html.

2.5 Flood threats

Several papers have studied the flood drivers in Shanghai. A few researchers (Nai, J, 2003; Lin, R and Li, 2000; Zhu, 2002) have pointed out that the high water level in the Huangpu River is dominated by the high storm tide which is an addition of storm surge and astronomic tide at the mouth of the river (Wusongkou). The water level at Wusongkou runs back to the upstream, which affect the water level of every cross section in the Huangpu River successively. The regional runoff and upstream discharge from Tai Lake are of secondary importance compared to the factors of storm surge and high astronomic tide. Another study (Kerssens, P, et al., 2003) showed that the high discharge of the Yangtze River could be neglected as only ~15cm of water level could be raised from the influence of the Yangtze river. They also concluded that it is almost impossible that high flood peak of Yangtze River and storm surge can coincide together. Therefore, the discharge of Yangtze River is not taken into account in the flood threats of the Huangpu River in this thesis.

In a summary, there are mainly four interrelated factors which can increase water level in the Huangpu River of Shanghai (see Fig.2. 12): namely astronomic tide, storm surge, river runoff from Tai Lake and torrential rainfall accompanied with Typhoon. First, as the Huangpu River is a tide-dominated river, storm surge considerably influences the water levels in the downstream and middle stream. The coincidence of astronomic tide and storm surge could induce high storm tide; second, in order to release flood pressure for Tai Lake Basin, drainage water coming from Tai Lake due to torrential rainfall during Typhoon can increase river runoff in the Huangpu River, especially in the upstream; third, the urban drainage water during torrential rainfall is also considered as a potential flood driver in the Huangpu River. While these flood drivers contribute to different degrees to the high water levels in the Huangpu River.

The following sub-sections are going to elaborate these factors qualitatively in a sequence of storm tide (astronomic tide and storm surge) and accompanying torrential rainfall and wind during Typhoon.

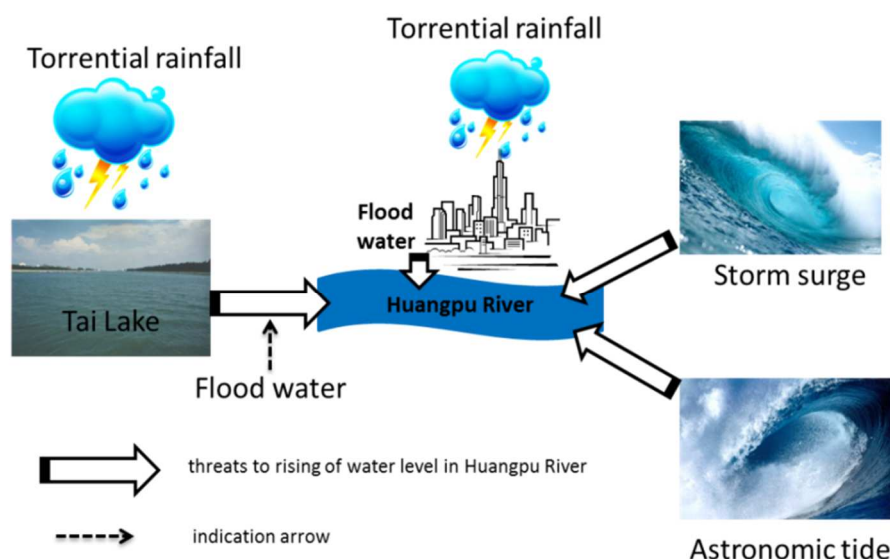


Fig.2. 12 Potential flood threats to the Huangpu River

2.5.1 Astronomic tide

Astronomic tide represents periodic rise and fall of sea level due to differential attraction of sun and moon, which is influenced further by gravity and centrifugal forces. When storm surge coincides with high astronomic tide, the storm tide will be tremendous. That's why the height of astronomic tide is critical to water levels in the Huangpu River as a whole. Vertical difference between the high water

and the low water is the tidal range (e.g. $\sim 2.3\text{m}$ on average at Wusongkou), which changes from cycle to cycle because of continuous shifts in the positions of the earth, sun and moon; and the period of tide is usually 12 hours (semi-diurnal tide). The historical highest astronomic tide and its average value at Wusongkou are WD 4.63m and WD 3.51m, respectively.

2.5.2 Storm surge

Storm surge is defined as the ‘dome’ of ocean water propelled by the winds and low barometric pressure of a hurricane (NYCOEM, 2011). The highest surge level ever-recorded at Wusongkou is WD 1.81m in 1956 in the Huangpu River. Hohai University (1999) has analysed the historical surge levels at Wusongkou of 71 typhoon induced floods of the Huangpu River from 1921 to 1997. The mean surge level in the period of interest at Wusongkou is 0.61m with standard deviation of 0.41m. It was estimated that the surge level with 1/1,000p.y would be 2.4m at Wusongkou. An example to show the storm surge and astronomic tide is show in Fig.2. 13.

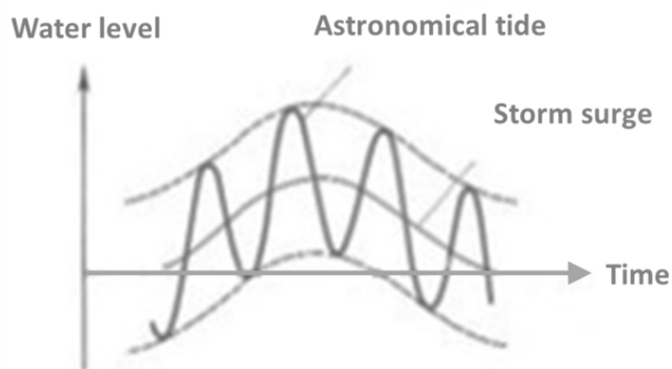


Fig.2. 13 Astronomic tide and storm surge

2.5.3 Storm tide

A storm tide is defined as the water level which is a combination of storm surge and astronomical tide (Boon, 2007). In recent years, storm tide was rising year by year with an increasing trend due to not only physical situation but also human activities, such as reclamation and construction activities along the river side, which reduce the storage capacity in the river. During Typhoon Wennie in 1997 the storm surge met the high astronomical tide, which increases the water levels intensely. The highest tidal level at Huangpu Park station reached to 5.72m^4 , which is equivalent to the water level as a function of 200yr return periods. Hereafter, water level means storm tide in this thesis in general. The characteristics of water level at typical stations of the Huangpu River will be statistically analysed in Chapter 3.

2.5.4 Tropical cyclone - Typhoon

Tropical cyclone is a storm system characterized by a large low-pressure centre and numerous thunderstorms that produce strong winds and heavy rain. It is strengthened when water evaporated from the ocean is released as the saturated air rises, which results in condensation of water vapour contained in the moist air. The tropical cyclones can produce extremely powerful winds and torrential rainfall. They are also able to produce high waves and damaging storm surge as well as spawning tornadoes. Depending on the wind force around the centre of it, a tropical cyclone is referred by names in terms of wind speed in 2 minutes as below in Tab.2. 3 (CMA 2006)

⁴ The tidal level is 5.66m after ground setting correction.

Tab.2. 3 Category of tropical cyclone in terms of 2-minutes wind speed in China

Tropical cyclone	Wind speed
Typhoon	above 32.7m/s
Severe tropical storm	24.5-32.6 m/s
Tropical storm	17.2-24.4 m/s
Tropical depression	10.8-17.1 m/s

As seen from Table Tab.2. 3, typhoon is the severest tropical cyclone, which brings storm surge, torrential rainfall as well as gale wind usually at the same time. It can additionally increase water level at the mouth of the Huangpu River and destroys property and buildings subsequently. The strength of a typhoon determines a large part of the magnitude of storm surge, which depends on the moving direction of the typhoon, atmospheric pressure, distance and angle of landfall and wind strength. Dorst (2003) indicated that the stronger the intensity of the typhoon, the stronger torrential rainfall as well as the higher the storm surge. Other studies (Zong and Chen, 1999) emphasized three aspects of the destructive effects of tropical cyclone in Shanghai city. First, gale-force winds can damage buildings and service facilities (e.g. electrical lines and telecommunicated lines). The wind can also cause waves in the river. Second, the low-pressure centre of a typhoon can raise the water level temporarily to 0.5 - 1.5m; the magnitude of the surge can be amplified up to 2 to 3m as it moves into the shallow waters within Yangtze estuary and the Huangpu River. The water level at the mouth of the Huangpu river will be pushed up if typhoon-induced storm surges coincide with high astronomic tides, which could lead to flooding in urban and rural areas of Shanghai; Thirdly, typhoon-induced torrential rainfall could cause high discharge from the river network and also water-logging in urban area, particularly in the low-lying area. On one hand, torrential rainfall could cause high river discharge temporarily in the Huangpu River; on the other hand, the water-logging due to torrential rainfall has been exacerbated by land subsidence and insufficient drainage capacity in Shanghai (Lu et al., 2010). However, based on a statistical analysis on the joint probability of storm tide, torrential rainfall and upstream runoff in the Huangpu River (Lin and Li, 2000), it is found that the torrential rainfall and upstream runoff is of secondary importance in comparison to storm tide in the Huangpu River. The joint probability of the occurrence of torrential rainfall in Tai Lake and high storm tide is limited. The regional torrential rainfall mainly induces water logging in the urban city while not significantly increase water level in the Huangpu River.

To sum up, typhoon caused storm surge; and if storm surge meets with high astronomic tide, the water level can be pushed up considerably, especially in the downstream and middle stream of the Huangpu River. Torrential rainfall and strong wind are the additional negative effects of Typhoon in Shanghai in terms of water logging and building/infrastructure destruction, respectively. Therefore, the focus of hydrological load in the Huangpu River will be on storm surge and high astronomic tide; torrential rainfall and upstream river runoff will not be included in the forward analysis.

2.6 Flood defence system

Four main flood defence systems were built in Shanghai city. The first is sea dike as primary flood defence to protect the coastal area. Floodwall with its sluices and gates along the Huangpu River is considered as the second defence system. Some small floodwalls along the remaining of waterways in Shanghai form the third defence. The fourth one is the drainage pipes and pumps in the urban area of Shanghai city, which are required to prevent water-logging during rainstorm weather. Since the focus of this research is on river flood in the Huangpu River, floodwall along the Huangpu River will be elaborated in the next section.

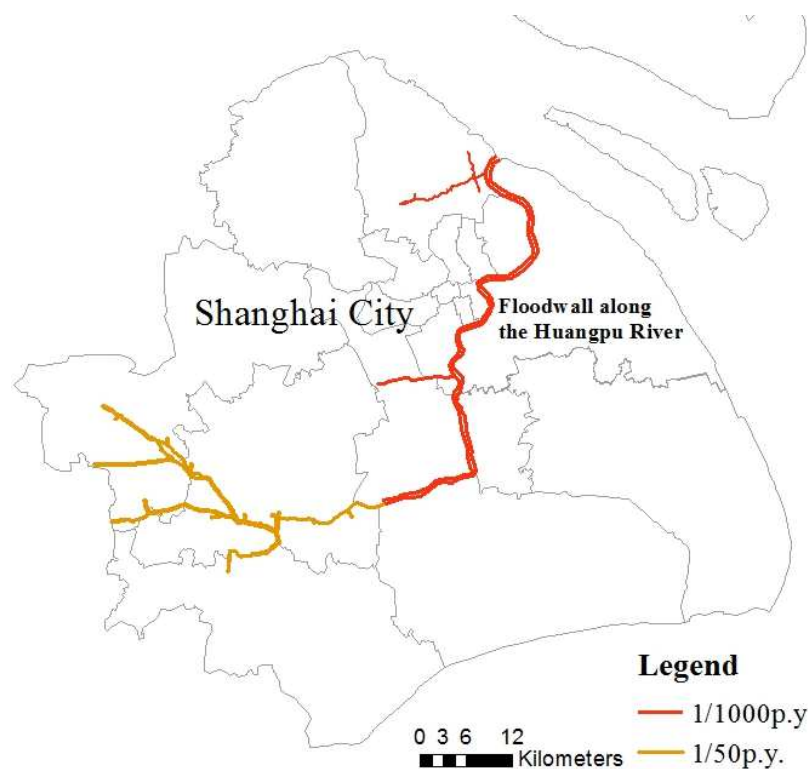


Fig.2. 14 Floodwall related to the safety standards in the Huangpu River: 1/1000p.y in the middle and downstream and 1/50p.y in the upstream

2.6.1 Floodwall along the Huangpu River⁵

A floodwall is a permanent primarily vertical barrier designed to temporarily contain the waters of a river or other waterway which may rise to unusual levels during seasonal or extreme weather events. Floodwalls are mainly used on locations where space is scarce, such as cities or where building levees or dikes would interfere with other interests, such as existing buildings, historical architecture or commercial use of embankments. There are many flood prone areas that are protected by systems that partly consist of floodwalls. Examples are New Orleans in the USA and Ayutthaya in Thailand. The next section will introduce the history of the floodwall construction in Shanghai as well as the current situation.

2.6.1.1 History of floodwall construction

After the floods in 1962, 1974 and 1981, the floodwall was raised and reinforced by the municipal government step by step (see Fig.2. 15). At first, the embankment, which is made from rubble stones along the downstream of the Huangpu River, is emerged in 18 century. In 1956, the reinforcement of embankment was executed with masonry and stone in downtown area along the Huangpu River, Suzhou Creek and the tributaries, which are now called floodwall. In 1959, the first concrete flood defence was completed with its level at 4.6m-4.8m. After Shanghai was suffering from the combination of violent typhoon and high tides in 1962, the local authority promulgated the first flood protection standards in 1963 with 1/100p.y. and the design water level at Huangpu Park station is 4.94m, which led to the construction and reinforcement of the floodwall further. In the summer of 1974, when water level at Huangpu Park broke the history record to 4.98m the floodwall in urban district was in great danger. This forced the local authority to further construct and raise the floodwall to 5.8m in city centre. However, a typhoon raised the water level to 5.22m at Huangpu Park in 1981; at that time, 5.86m

⁵ The pictures of this section are taken from a field investigation in the summer of 2013

at Huangpu Park was calculated as 1/1,000 p/y protection level in 1984, which is approved by the Ministry of Water Resources and Shanghai Municipal People's Government (Jia 1984). Since 1988, a massive reinforcement and heighten of floodwall has been performed along 208km of the Huangpu River and its branches for 13 years. In 1997, a violent typhoon raised water level to 5.72m at Huangpu Park as a highest record till now, which is equivalent to 1/200 p.y. design level. Fig.2. 15 shows the development of crest height of floodwall at Huangpu Park from 1959 to 2010. The current flood wall at Huangpu Park is 6.9m under the protection level of 1/1,000p.y.

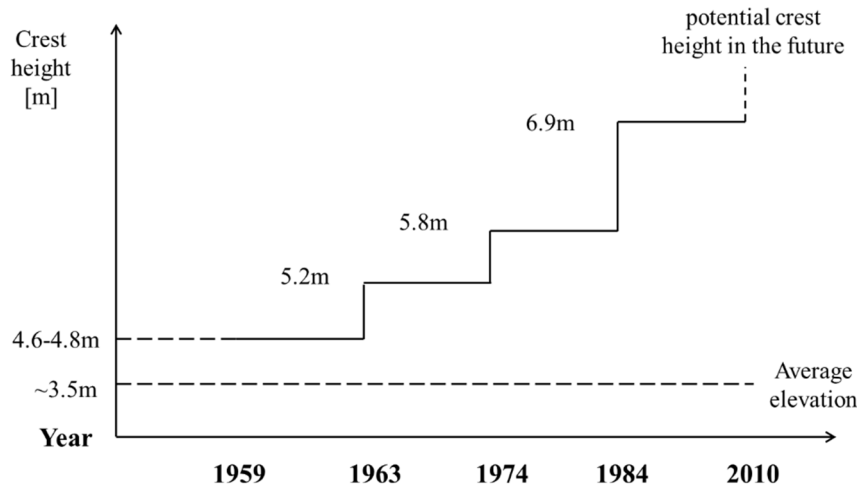


Fig.2. 15 Development of the crest height of floodwall at Huangpu Park from 1959 to 2010, in which the current crest height of 6.9m was followed by the design water level of 1/1,000p.y in 1984

2.6.1.2 Current situation

Fig.2. 16 shows current information about the crest height, design water level, warning water level and highest records at Wusongkou, Huangpu Park and Mishidu in the Huangpu River. The floodwall along the Huangpu River starts from Wusongkou to Xihejing on the west side and to Qianbujing (Zhagang) on the east side (Shanghai Municipal Government, 1996). The small floodwall of the branches starts from the mouth of the tributaries till the first sluices. Besides as flood prevention, the floodwall can function as recreational and tourist area, e.g. in the Bund (see Fig.2. 18 (ii)). The crest height of floodwall is designed based on design water level which is calculated by frequency analysis under pre-defined exceedance probabilities, plus wind set-up and safety board (i.e. uncertainties).

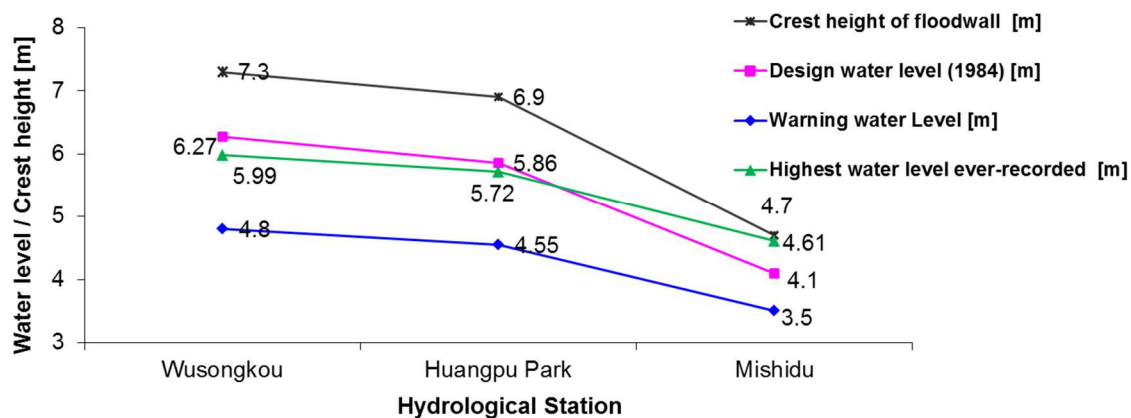


Fig.2. 16 Updated information about the crest height, design water level, warning water level and highest records at Wusongkou, Huangpu Park and Mishidu in the Huangpu River, respectively

Floodwalls are a specific form of flood defences as they are usually a combination of an earth structure with (often vertical) steel and concrete elements. The vertical shape is used to retain high water level; the basement of floodwall is usually the revetment of wharf or the protection part of river bank (see Fig.2. 18 (i)). Most of the floodwall in the Huangpu River is vertical concrete wall combined with revetment basement; while some are followed the inclined shape similar to a cross section of sea dike. Fig.2. 17 shows the selected cross section of floodwalls along the Huangpu River in the East side. The design water levels are followed by the safety standard of 1/1,000p.y which was calculated in 1984. The related crest height is decreased from 7.2 to 6.2m from downstream to middle stream.

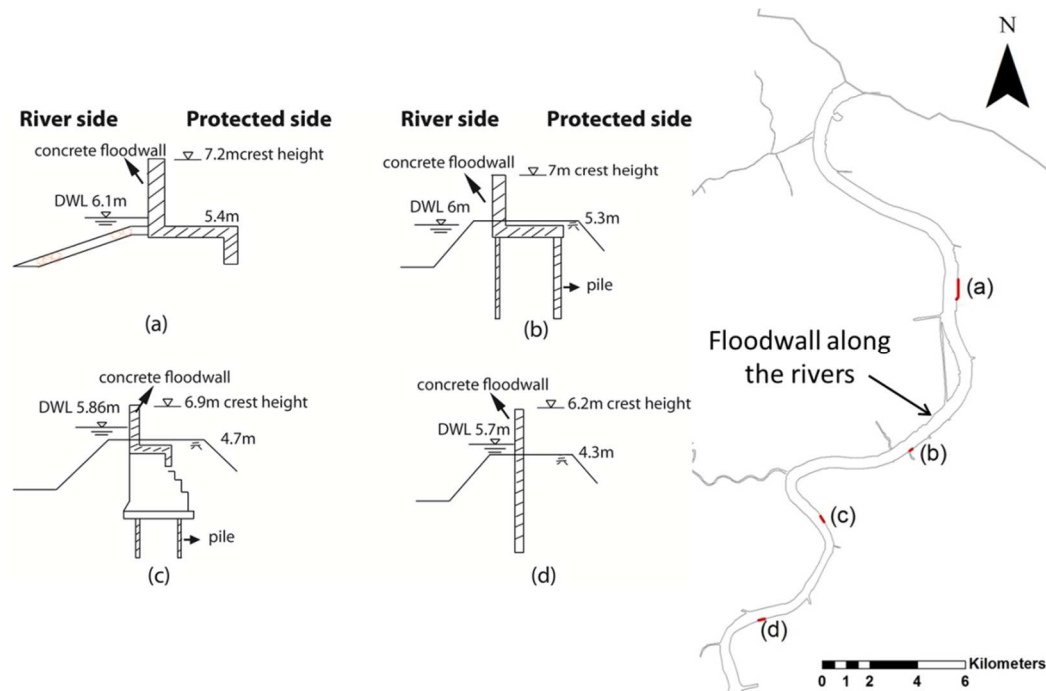


Fig.2. 17 Cross section of floodwall along the Huangpu River in selected parts

Typical floodwall in the west part of Huangpu River is Bund, which lasts 1,697m from Waibaidu Bridge to Xinkai River station. The width of Bund floodwall is ~17.5m. This floodwall is functioned as sight-seeing platform and parking area besides flood prevention. From the cross section (see Fig.2. 19), it can be seen that the ramp way connects greenland and sightseeing platform, which are 1-2m higher than the average elevation in the city (~3.5m). Pedestrian path and carriage way are located to inner side of the river without elevation heightening.



Fig.2. 18 Field observation of floodwall along the Huangpu River in 2013 (i) floodwall with revetment (ii) Bund sight-seeing floodwall (iii) small flood gate in glass

The material of floodwall varies based on different functions. Most of the floodwall are constructed in steel and concrete, while parts of them (around 100m) along south Bund are built in glass with thickness of 18mm and height of 1m above 75cm concrete wall in order to improve sight view of the Huangpu River (see Fig.2. 18 (iii)); and other flip-up floodwall in steel are designed for traffic flow (for pedestrian and vehicles) while they can be closed off when the water levels exceeds the warning water levels (People's daily, 2012).

The Huangpu Park locates at the beginning of the Bund in the west side of the Huangpu River, which also includes a hydrological gauge station there, namely Huangpu park hydrological station. The water level of this station is a reference as a design basis for the crest height of floodwall in the middle stream of the Huangpu River.



Fig.2. 19 Cross section of waterfront area in Bund of Shanghai (Xi and Xu, 2011)

2.6.2 Typical floodwall failures

As limited information on the structure failure of floodwall in Shanghai is available, a representative case of New Orleans during Hurricane Katrina in 2005 will be introduced to show the typical flood-wall failures. A large part of the flood defences in New Orleans are floodwalls, of which a number failed and consequently breached during this disaster.

In the flood defence system of New Orleans, three dike ring areas are there: Central Orleans, Orleans East, and St. Bernard. Four areas with failures in the system of dike rings are circled as: 17th Street Canal, London Avenue Canal, Lower Ninth Ward, and the earthen embankments of St. Bernard. The failure in 17th Street Canal and London Avenue Canal might have caused up 80% of flooding in the Central Orleans dike ring (ILIT 2006). The floodwall failed although the water level did not reach the design level, which showed that the geotechnical failures have contributed to a large degree to the flooding. The failure mechanisms of New Orleans were mainly overflow/overtopping and a combination of overflow and insufficient stability of the structure and its foundation in St. Bernard dike ring; and overflow/overtopping, transition around structures and failures of floodwall in Orleans East; and piping, sliding, uplift and instability of floodwall foundation and non-closure of structure in Central Orleans (more details in (Kanning, 2012)). These observations in New Orleans also implies that the floodwall may fail in other cities, e.g. in Shanghai, with similar failure mechanisms under an extreme event like Hurricane Katrina.

During a site visit in Shanghai, leakage from the underground was observed under the floodwall, which is regarded as a potential threat of geotechnical failure (see Fig.2. 20(i)). And it was also noticed that the buildings and other infrastructures are closely connected to/behind the floodwall (see Fig.2. 20(ii)), which poses a potential threat to the local people and property assets if flood defence fails.



Fig.2. 20 Field observations on the vulnerability of floodwall along the Huangpu River in 2013: (i) leakage and (ii) the close connection between flood defence system and buildings

2.6.3 Water gates

The Suzhou Creek gate (see Fig.2. 21 (i)) is the largest tide gate along the Huangpu River, which was built to prevent storm surge after the flood in 1984. This gate closes when the water level in front of the gate exceeds 4.55m (SIDRI 2011). During the typhoon season, the barrier will be closed once or twice a month for maintenance and to flush silt depositions from the sill. During Typhoon Wennie in 1997, this water gate successfully prevented storm tides entering Suzhou Creek.



Fig.2. 21 (i) Suzhou Creek gate and (ii) typical floodgates in Shanghai

A large number of gates are present in the flood defence system along the Huangpu River (see Fig.2. 21 (ii)), which is floodgate. All these floodgates are required to be closed when water level reaches to warning level during the flood events. They are separately controlled by the nearby private industries; hence the performance of these floodgates during flooding is a big concern. Moreover, it was also noticed that many buildings and infrastructures are present behind the floodgates. The failure of these floodgates, either by human error or structural failure, could pose threats to the adjacent buildings and infrastructures.

In Shanghai, there are 18 ferry lines across the Huangpu River, which is regarded as a public transportation system. It commutes the people every day. Since these floodgates are usually related to the ferry lines, it is concerned that the suspended of the ferry system due to flooding can lead to huge inconvenience to the people.

2.7 Discussion

The main flood threat is the occurrence of a typhoon induced storm surge in combination with a high astronomic tide in the Huangpu River. Based on previous study on the correlation analysis of storm tide in the Huangpu River and torrential rainfall in Tai Lake and in Shanghai (Lin and Li 2000), the joint probability of the simultaneous occurrence of torrential rainfall and high storm tide is limited. It means the water level in the upstream (Mishidu) is dominated by the storm tide at the mouth of the Huangpu River. The heavy precipitation mainly induces water logging in the urban city while not significantly increase river runoff in the Huangpu River. This might be argued that the high runoff will also be caused by the drainage from Tai Lake. However, according to 'Flood Control Plan in Tai Lake Basin', flood water in Tai Lake can be released to the Yangtze River to the North and the Hangzhou Bay to the South through the new canals and pumps as well, which can reduce the drainage pressure in the Huangpu River especially during storm surge events. In addition, it has been regulated that the drainage runoff need to be reduced when the water level is predicated to reach at WD 3.7m at Mishidu in the upstream of the Huangpu River in order to ensure safety of Shanghai (MWR 1999). Shanghai as one of the important cities in Tai Lake Basin definitely has higher priority to ensure safety than other cities.

Historical flood events have already shown that the floodwall may fail due to potential overtopping and breaching along the Huangpu River and its branches. Furthermore, the current protection level of floodwall is only based on the exceedance of the crest height of the floodwall by the water level and does not directly take into account the other mechanisms. First, the floodwall might not be high enough due to land subsidence, which could easily induce overtopping at the weak points; second, it is hard to assess the soil characteristics of the floodwall only by the observations and the foundation of the floodwall is critical for the safety of the system. One of the lessons from New Orleans is that floodwall systems can fail before water levels exceed the crest height; third, the floodwalls are mainly vertical concrete wall; on the inside of the floodwall some of them are with armouring infrastructure while some are not. Such kind of structure could also cause potential failure due to geotechnical problems (see also Section 2.6.2) when hydrological loads sustain a long period. Lastly, all the floodgates need to be closed on time when water level reaches to the pre-defined warning level or during an emergency. On one hand, the failure to close down the floodgates could directly induce floods in adjacent area; on the other hand, the structural failure of floodgate could lead to floods as well.

In the next chapter, the flood hazards caused by different failure mechanisms of the floodwall and its infrastructures will be examined by scenarios analysis.

Chapter 3

Shanghai: Flood hazard analysis for the Huangpu River

Flood hazard is related to the exceedance probability of design level of hydraulic load and the extent of inundation characteristics. In order to identify flood hazard in the extreme events, a frequency analysis of annual maximum water level was performed to produce different return periods of water levels at three typical gauge stations along the Huangpu River. With the aid of the 1D hydraulic model, water levels in each cross section of the Huangpu River were derived; the potential overtopping points were systematically identified by a comparison to the crest height of floodwall. In addition, potential breaching points and failure of floodgates were also hypothesized on the both sides of the floodwall based on synthetic judgement. Subsequently, inundation maps were produced by 1D2D hydrodynamic modelling (SOBEK) under different flood scenarios along the Huangpu River. The results can be visualized on the map with information on maximum inundation depth and the inundation extent. It firstly demonstrates the significant necessary of the floodwall and infrastructures (e.g. floodgate) along the Huangpu River to protect Shanghai against river flooding. Secondly, it is found that the inundation would occur merely adjacent to the riverine area due to limited flood volume under overtopping scenarios. Thirdly, as breach scenarios were developed to explore the worst-case flooding in Shanghai it turned out that breaching would be the most serious flooding along the Huangpu River as parts of the city centre would get inundated with maximum inundation depth of more than 3m. Lastly, the simulations of failure of floodgates were conducted at three selected locations. It showed the inundation depth was averagely 39cm-82cm in each scenario, which would pose threat to the buildings and infrastructures adjacent to the floodgates. These results could provide as a basis for ex-ante assessment of flood risk and serve as rational information for the decision makers in urban planning or emergency management.

3.1 Introduction

3.1.1 Background

In China, central government pays great attention on addressing flood disasters, such as adjustment of safety standards for the important cities (MWR 1995), the improvements on early-warning system and enhancement of emergency management in times of floods (Liu and Li 2003; SCIO 2009). The Chinese Ministry of Water Resource regards flood risk mapping as an important project in order to make rational decisions regarding evacuation plans, urban planning and emergency management, etc. (MWR 2010). One of the important steps is to produce flood hazard maps based on various scenarios (different occurrences of flood with related probabilities), in order to assess potential flood damage or optimize traffic routes during floods in the next step, with information on inundation characteristics.

3.1.2 Inundation modelling

Basically, there are two methods to develop the inundation characteristics due to different flood patterns, namely prediction and observation. Investigation on site, the analysis of remote sensing by satellite or aerial images and hydrodynamic modelling, etc. can provide inundation information with various accuracy requirements and objectives. Hydrodynamic modelling is a widely used method, which can simulate flood process by 2D overflow model coupled with 1D flow model imposed with geo-information system. The flood process can be visualized dynamically in a set flood period, and also in a projection of a flood scenario (e.g. the hypothesized breaching location or the low probability of extreme event). The EU Directive project gave a guidance on proper application of multiple inundation models with 1D2D SOBEK, SV2D, RFSM, SVID, etc. in the Netherlands, UK and Italy based on various input data and topography of study areas (Asselman, Bates et al. 2009). Vanderkimpfen et al. (2009) compared MIKE FLOOD and 1D2D SOBEK package on flood simulation in eastern part of Belgian coast plain, and stated that the choice of the modelling package is in no way predominant in flood risk evaluation. In this study, 1D2D SOBEK is selected as this package software has been used and tested in many cases in various countries (MVW 2005; Shaviraachin 2005; Asselman, Bates et al. 2009; Li 2011). In Shanghai, MIKE21 has been used to evaluate the overtopping risk to identify the risky seawalls and floodwalls along Huangpu River in projection of future years (2030&2050) (Wang, Xu et al. 2012). Yin et. al (2012) applied an inundation model (FloodMap) along the Huangpu River with multiple scenarios to produce flood hazard maps corresponding to different return periods, but the flood hazard in this model is limited in results from overtopping of floodwall along the Huangpu, the potential breaching locations were excluded in the study and this may lead to incomplete results. As limited data is available regarding topography and hydrological/hydraulic boundary conditions in Shanghai, the results remain limited from scenario-based inundation modelling along the Huangpu River. Therefore, the study of the inundation modelling in Shanghai deserves more attention for various objectives of decision making on flood risk management.

3.1.3 Objective and structure

The objective of this chapter is to produce flood hazard maps due to different scenarios of the floodwalls along the Huangpu River. The information on the flood hazard map includes maximum inundation depth and inundation extent under scenarios of overtopping, breaching at weak points and failure of floodgates. These results can provide as a basis not only for flood risk analysis, but also for the optimization of traffic routes during floods and urban planning in the future. Three main questions will be answered in this chapter:

- What are the water levels with extreme return periods in the river?

- What are the inundation characteristics with scenarios of overtopping and breaching and failure of floodgates?
- What are the inundation characteristics under different flood scenarios?

The structure of the remaining sections will be organized as below. The answer of the first question is in Section 3.2, which will plot water level-frequency curves for three typical gauge stations in the Huangpu River. Section 3.3 will answer the second and third questions with 1D2D SOBEK modelling. A brief discussion on inundation characteristics in Shanghai due to different scenarios will be given in Section 3.4 in the end.

3.2 Flood frequency analysis

The magnitude of flood event is inversely related to its frequency of occurrence, very severe events occurring less frequently than more moderate events. The objective of frequency analysis of hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Westen, Alkema et al. 2011). The long term hydrological data should be independent and identically distributed. A series of frequency–water level curves would be derived by the hypothesized PDF or CDF is fitted to the data. The standard procedure is first to determine the homogeneity of datasets, and then estimate the probability distribution of the datasets according to criteria selection; subsequently, the parameter(s) in the specific probability distribution are estimated by the mathematical procedure.

3.2.1 Data requirement – Hydrological condition

There are three hydrological stations located along the Huangpu River in upstream, midstream and downstream, respectively (See Fig. 3. 1 in red triangle): Mishidu, Huangpu Park and Wusongkou. The annual maxima long-term water levels are used in this frequency analysis. The general data information including the names of gauge stations and data periods are shown in Tab. 3. 1:

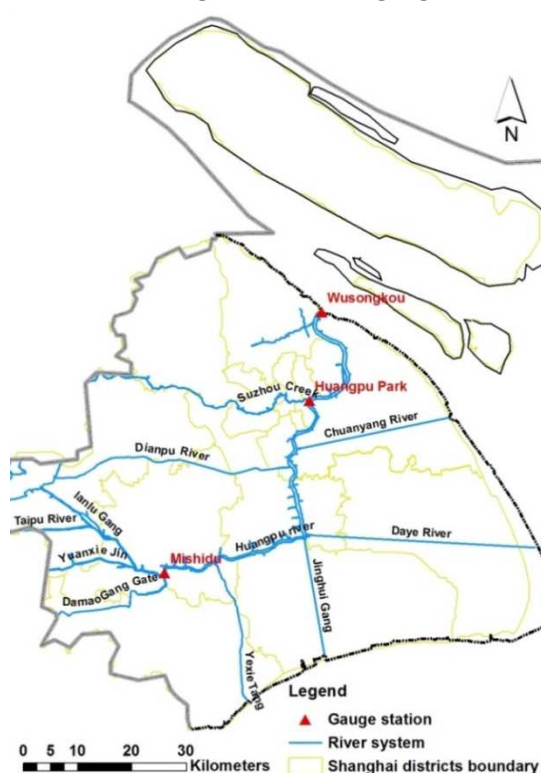


Fig. 3. 1 Locations of hydrological stations in the Huangpu River: Wusongkou, Huangpu park and Mishidu

Tab. 3. 1 Data description in flood frequency analysis

Gauging station	Datasets periods	Length	Type
Wusong	1921-2012	101 years	Annual maxima water level
Huangpu Park	1913-2012	100 years	
Mishidu	1948-2012	65 years	

Due to land subsidence and human activities, the measured water levels before 1981 are revised to reach consistency by a method of correlation analysis by Hohai University (2001). According to the results of correlation analysis, it is concluded that gauge stations along the Huangpu River are influenced mainly by storm tide from East China Sea, the influence from Yangtze River and Tai Lake are comparatively insignificant. The differences of annual maxima water levels between revised and original data are between 19cm-64cm. The annual average maximum water level are 5.01m, 4.75m and 4.14m at downstream, middle stream and upstream of the Huangpu River, respectively. For the water levels after 1981 the observed data were used without revision.

3.2.2 Probability distribution functions

Since the occurrence of high water levels is a stochastic phenomenon it is the engineering practice to describe them with a statistical analysis. This means it is not possible to say exactly when which high water level will occur but it is described in terms of the high water level with a return period of so many years. As an example the high water level with a return period of 1,000 year is the water level that in average once in thousand years will be exceeded. The relation between the return periods and the corresponding water levels is a statistic description of high water level. Based on the systematic and reliable years of historical observed data, the characteristics of distribution of stochastic variables, e.g. extreme water level, can be determined in a mathematical way. Probabilistic distribution functions and the correspondent parameters can describe stochastic variables well. Usually the form is adopted as below:

$$P(X \geq x_p) = 1 - F(x) = \int_{x_p}^{\infty} f(x) dx \quad (3.1)$$

Where: $F(x)$ - cumulative distribution function; $f(x)$ - probability density function.

When making a flood frequency analysis, it is necessary to compare the assumed population with the sample data. Generally, the sample values are plotted in a figure by assigning each of them an exceed probability based on the plotting position formula. Since the concept of probability was introduced by Hazen (1913), many discussions on plotting positions have been given by statistics and hydrologists. Most of these researches can be described by a general formula as below (Gringorten 1963):

$$P_m = \frac{m - a}{n + 1 - 2a} \quad (3.2)$$

Where: P_m are ordered probability values $P_1 < P_2 < \dots < P_n$, m denotes the m_{th} value of n ordered records, n denotes the sample length, and a is defined as a constant depends upon the distribution. Normally, a ranges from 0 to 0.5; In this chapter, a is adopted as 0.44, which is determined when $n \geq 20$ (Gringorten 1963).

Different region or countries adopt an appropriate probability distribution differently. For instance, the log Pearson type III distribution is commonly used in the United States (Water Resources Council, 1981), the general extreme value (GEV) distribution is recommended by the United Kingdom (Natural Environment Research Council, 1975), while the Pearson type III distribution with a curve fitting method is widely applied in China (Ministry of water resources, 1980). Based on the characteristics of the datasets, two probability distributions were selected to analyse the frequency of maxima water levels in the Huangpu River, namely Pearson-III and GEV distribution.

3.2.2.1 Pearson-III Distribution

Followed by the “Chinese standards of design flood calculation in hydraulic engineering” (MWR 2002), the frequency distributions of hydrological stochastic variables are adopted as Pearson Type III in general. The Pearson Type III distribution is also called three-parameter gamma distribution, since it can be obtained from the two-parameter gamma distribution by introducing so-called location parameter a_0 . The density of Pearson Type III distribution is shown as below:

$$f(x | a_0, \alpha, \frac{1}{\beta}) = \frac{\beta^\alpha}{\Gamma(\alpha)} (x - a_0)^{\alpha-1} e^{-\beta(x-a_0)} \quad x > a_0 \quad (3.3)$$

Where: constant variable $a_0, \alpha, \beta > 0$; $\Gamma(\alpha)$ is gamma function.

The PDF of the gamma distribution is shown as below:

$$f(x | a, b) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{-\frac{x}{b}} \quad (3.4)$$

Where: the gamma parameter a , b equals to P-III parameters $\alpha, \frac{1}{\beta}$. Parameter a_0 is the lower bound for this distribution ($x > a_0$). The Pearson type III distribution is very flexible since it has three parameters which can produce a wide variety of shapes of density function. Parameter α is governing the skewness of the distribution, and when it tends to infinity, the Pearson type III distribution becomes normal distribution.

The relations of original parameters to the basic parameters are as below:

$$\begin{aligned} a_0 &= E(X) \left(1 - \frac{2C_v}{C_s}\right) \\ \alpha &= \frac{4}{C_s^2} \\ \beta &= \frac{2}{E(X)C_v C_s} \end{aligned} \quad (3.5)$$

Where: $E(X)$ is mean value; C_v is kurtosis⁶; C_s is skewness⁷.

⁶ Kurtosis is a measure of how outlier-prone a distribution is. The larger the kurtosis, the more outlier prone the distribution is.

The Pearson III distribution of X is:

$$F(x) = P(X \geq x_p) = \frac{\beta^a}{\Gamma(\alpha)} \int_{x_p}^{\infty} (x - a_0)^{\alpha-1} e^{-\beta(x-a_0)} dx \quad (3.6)$$

If we can determine the parameters of $E(X)$, C_v , C_s in Pearson type III distribution, the water level-frequency in the Huangpu River could be deduced and being represented in a form of water levels as a function of return periods (T) in years.

$$T = \frac{1}{P} \quad (3.7)$$

Where: P is probability of flooding per year [-].

Probability density distribution of P-III at Wusongkou, Huangpu Park and Mishidu is shown in (i), (ii) and (iii) in Fig. 3. 2.

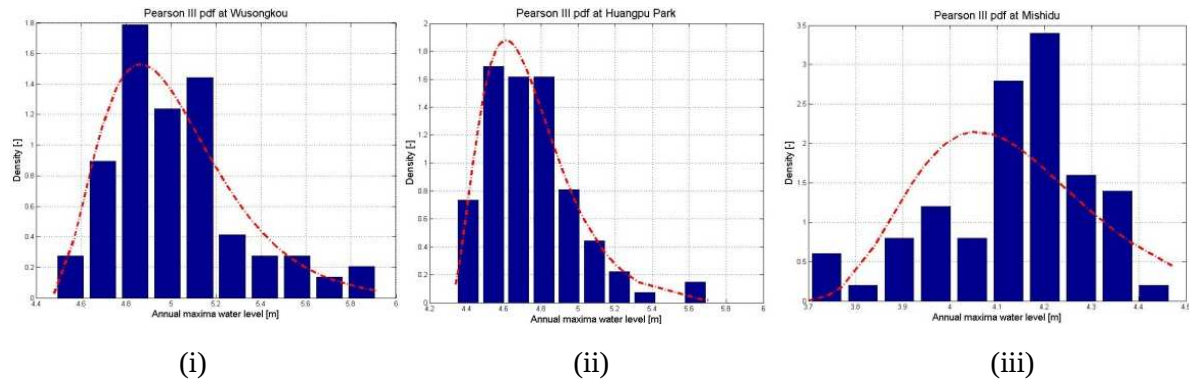


Fig. 3. 2 PDF of P-III at Wusongkou (i), Huangpu Park (ii) and Mishidu (iii)

3.2.2.2 GEV distribution

Generalized extreme value (GEV) distribution is used as an approximation to model the maxima of long sequences of random variables. In this paper, the available datasets are annual maxima water levels in each gauge stations; therefore, it is recommended to use GEV distribution to calculate the water levels as a function of return period. The density function and cumulative function of GEV distribution is shown as below:

$$f(x|k, \mu, \sigma) = \left(\frac{1}{\sigma} \right) \exp \left[- \left(1 + k \frac{(x - \mu)}{\sigma} \right)^{\frac{1}{k}} \right] \left(1 + k \frac{(x - \mu)}{\sigma} \right)^{-1 - \frac{1}{k}} \quad (3.8)$$

for $1 + k \frac{(x - \mu)}{\sigma} > 0$

The CDF (cumulative distribution function) for GEV distribution is given by Jenkinson (1969) as

⁷ Skewness is a measure of the asymmetry of the data around the sample mean. If skewness is negative, the data are spread out more to the left of the mean than to the right. If skewness is positive, the data are spread out more to the right.

$$F(x|k, \mu, \sigma) = \begin{cases} \exp \left\{ - \left[1 + k \left(\frac{x - \mu}{\sigma} \right) \right]^{-\frac{1}{k}} \right\} & \text{for } k \neq 0 \\ \exp \left[- \exp \left(- \frac{x - \mu}{\sigma} \right) \right] & \text{for } k = 0 \end{cases} \quad (3.9)$$

The generalized extreme value combines three simpler distributions into a single form, allowing a continuous range of possible shapes that includes all three of the simpler distributions. Types I, II, and III are sometimes also referred to as the Gumbel, Frechet, and Weibull types, though this terminology can be slightly confusing. $k > 0$ corresponds to the Type II case, while $k < 0$ corresponds to the Type III case; for $k = 0$, it's corresponding to the Type I case. Here, k is shape parameter, μ is location parameter and σ is scale parameter.

Probability density distribution of GEV at Wusongkou, Huangpu Park and Mishidu is shown in (i), (ii) and (iii) in Fig. 3. 3.

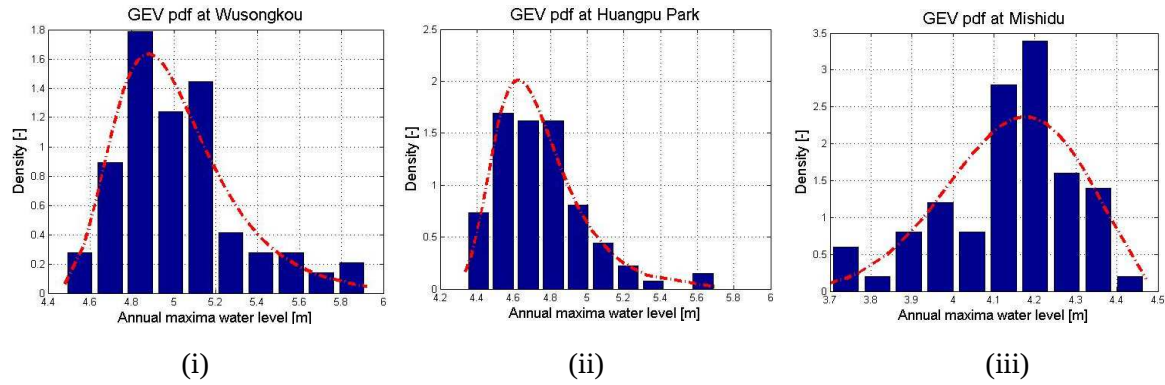


Fig. 3. 3 PDF of GEV at Wusongkou (i), Huangpu Park (ii) and Mishidu (iii)

3.2.3 Parameter estimation

Each probability distribution contains a number of parameters that must be determined to make future analysis. These parameters are generally from one to five, with the most common distributions having two to three free parameters. Several approaches of estimating the best values of these parameters are in circulation, including, most frequently, the methods of least-square estimation (LSE), maximum likelihood method (MLM), and linear moments (L-M). The methods discussed here are limited to point-site estimates. The three parameter estimation methods for P-III and GEV are described in Appendix 3-2. The results of fitting curves in GEV and P-III distribution at three typical gauge stations (Wusongkou, Huangpu Park and Mishidu) are shown in Fig. 3. 4, Fig. 3. 5, Fig. 3. 6, respectively.

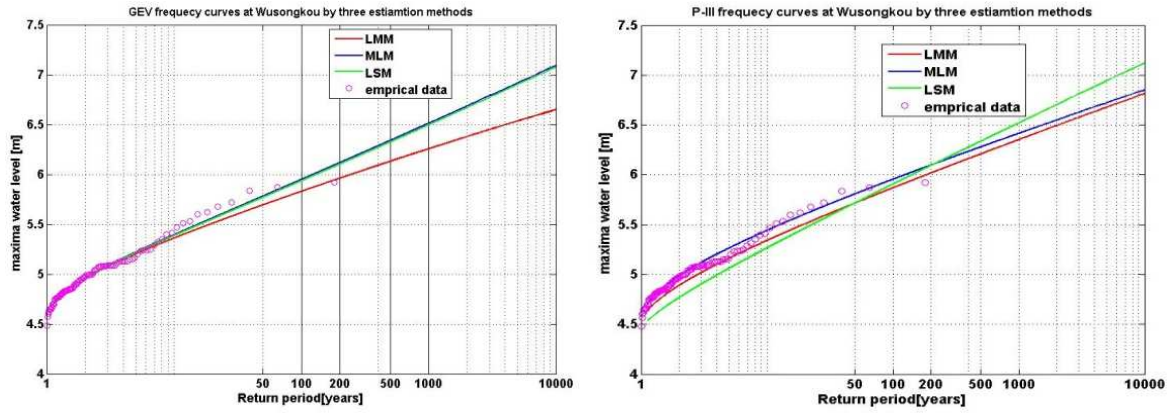


Fig. 3. 4 Fitting curves by three parameter estimation methods (LSE, MLM and L-M) in GEV (*left*) and P-III distribution (*right*) at Wusongkou

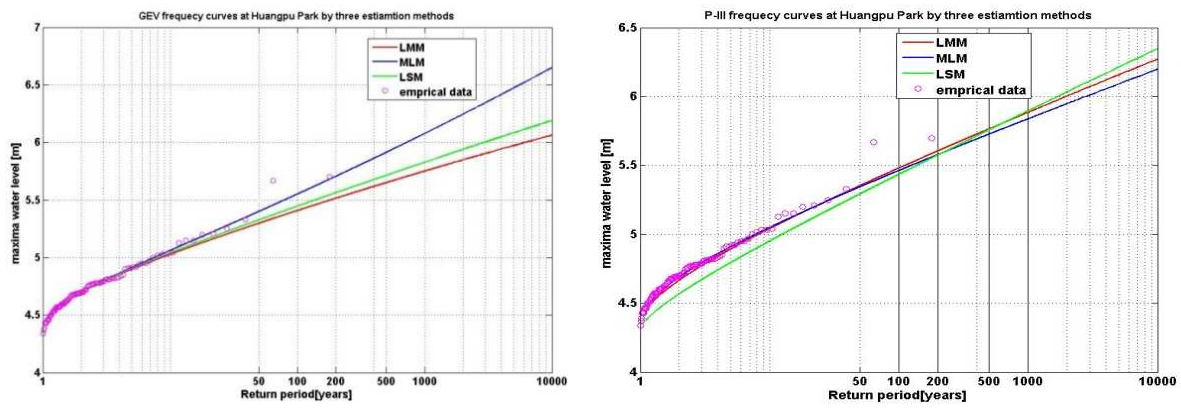


Fig. 3. 5 Fitting curves by three parameter estimation methods (LSE, MLM and L-M) in GEV (*left*) and P-III distribution (*right*) at Huangpu Park

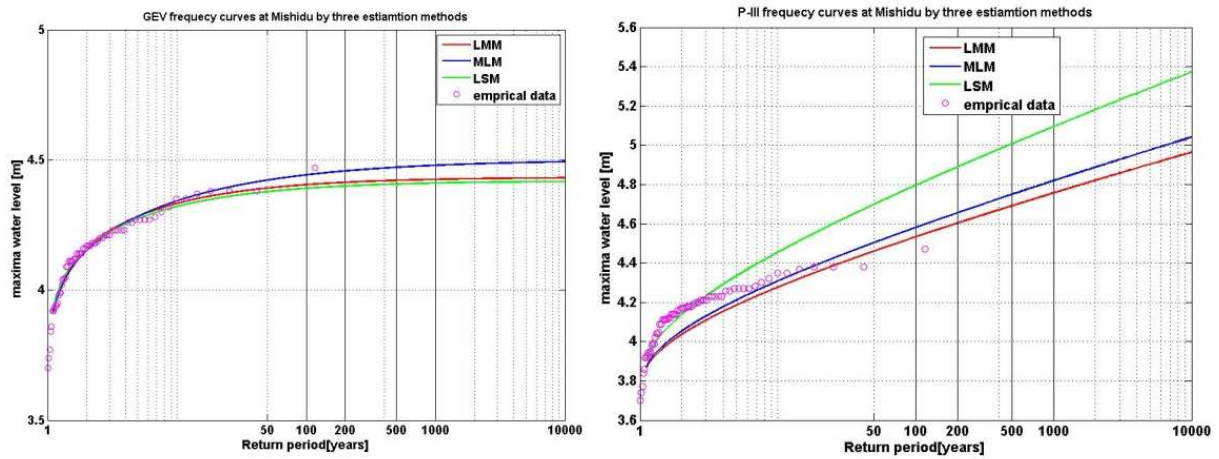


Fig. 3. 6 Fit curves by three parameter estimation methods (LSE, MLM and L-M) in GEV (*left*) and P-III distribution (*right*) at Mishidu

3.2.4 Statistical performance indicator

In order to specify the distribution, an appropriate form of the distribution must be selected from among the large number of candidate forms found in wide use. For comparison estimation methods with empirical data sets, the correlation coefficient (R), Kolmogorov-Smirnov (K-S) test, Mean square deviation (MSD) are taken into account.

a) Correlation coefficient

The correlation coefficient (R) is used to determine whether there is a significant difference between the expected frequency and theoretic frequency.

$$R = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (3.10)$$

Where: x_i is the theoretic frequency for each observation, y_i is the prediction frequency in the corresponding observation.

b) K-S test

The K-S test performs a Kolmogorov-Smirnov test to compare the expected frequency to theoretic frequency.

$$D = \max |P(x) - S(x)| \quad (3.11)$$

Where: $P(x)$ is the empirical cumulative frequency and $S(x)$ is the prediction cumulative frequency.

Dagnelie (1968) indicated that the critical value can be approximated numerically. The critical value $C = (N, \alpha)$ can be obtained as a function of level of significance α and the sample size N with an expression of the form:

$$C(N, \alpha) = \frac{a(\alpha)}{\sqrt{N + 1.5}} \quad (3.12)$$

Where: $a(\alpha)$ is a function of α ; for the usual alpha levels of $a(0.05) = 0.886$.

The hypothesis regarding to the distributional form would be rejected if the test statistic is greater than the critical value obtained.

c) Mean square deviation

The Mean square deviation (MSD) or Mean square error (MSE) of an estimator is a way to quantify the difference between values implied by the density estimator and the true value of the quantity being estimated. The MSD of an estimator with respect to the estimated parameter x_i is usually defined as:

$$MSD = E[(x_i - \hat{x}_i)^2] = \left[\frac{\sum (x_i - \hat{x}_i)^2}{n-1} \right]^{1/2} \quad (3.13)$$

Where: x_i is the theoretical frequency for the observation and $\hat{x}_i$ is the corresponding empirical frequency.

In a summary, the larger the correlation coefficient (R) is, and the smaller the KS and MSD are, the distribution is statistically better fit. In Tab 3.2, the criteria for GEV distribution shows better fit results than P-III distribution. The R are all more than 0.99 in GEV distribution at three stations by three estimation methods, while the R in P-III distribution are only more than 0.99 at Wusongkou by methods of LMM and MLM. The KS and MSD are all smaller in GEV than in P-III. Moreover, the critical values of K-S test are calculated as 0.0875, 0.0879 and 0.109 at Wusongkou, Huangpu Park and

Mishidu, respectively. Compared with the test statistics at each station by three methods, it shows the P-III distribution is rejected at three stations only except for P-III distribution by MLM at Huangpu Park. Therefore, GEV is recommended as the probability distribution for datasets at gauge stations in the Huangpu River at the first step.

However, the fit curves in GEV distribution at Mishidu remain flat compares to the curves in P-III (see Fig. 3. 6). It shows the water levels as a function of return periods in GEV distribution at Wusongkou have no big difference (no more than 5cm) after return period of 100 years; the water level at 10,000 years return period is only no more than 4.5m by the three parameter estimation methods. While during Typhoon Fitow in October 2013, the maximum water level at Mishidu was measured as 4.61m, which directly rejected the GEV results. Therefore, as a conservative estimation, P-III distribution is taken as probability distribution at Mishidu.

Tab. 3. 2 Results of statistical performance indicator (R, K-S test and MSD) with three parameter estimation methods (LMM, MLM, LSM) for GEV and P-III distributions at Wusongkou, Huangpu Park and Mishidu

Probability distribution		GEV			P-III		
Gauge stations	Estimation methods	R	K-S	MSD	R	K-S	MSD
Wusongkou	LMM	0.9976	0.0493	0.0442	0.9918	0.1493	4.5059
	MLM	0.9975	0.051	0.0348	0.9959	0.0906	4.4145
	LSM	0.9976	0.0462	0.0357	0.9664	0.3396	4.6066
Huangpu park	LMM	0.9985	0.0484	0.0436	0.995	0.1086	4.3303
	MLM	0.9983	0.0465	0.0253	0.9976	0.0676	4.3114
	LSM	0.9985	0.0461	0.0373	0.9705	0.2800	4.4100
Mishidu	LMM	0.9945	0.0732	0.0186	0.9236	0.3536	3.7254
	MLM	0.993	0.0925	0.0207	0.937	0.3116	3.7071
	LSM	0.9954	0.0657	0.0221	0.9761	0.1335	3.6170

Critical value of KS: 0.0875, 0.0879 and 0.109 at Wusongkou, Huangpu Park and Mishidu

3.2.5 Results and discussion

New frequency curves of water level as a function of return periods were derived at three gauge stations of Wusongkou, Huangpu Park and Mishidu along the Huangpu River, which is shown in Fig. 3. 7, respectively. Tab. 3. 3 summarized the water levels correspond to the frequency of 1/10000, 1/1000, 1/500, 1/200, 1/100 and 1/50 at each gauging station. The water level between return periods with 10 factors differences (e.g. 1,000&100 and 500&50) at Wusongkou and Huangpu Park are 52.5cm and 54.5 cm, respectively, while only 23 cm differences at Mishidu. Furthermore, Fig. 3. 7 also shows the gradient of frequency curve at Mishidu is much slower than the previous two stations.

GEV was selected as a suggested probability distribution for the datasets of annual maximum water level at Wusongkou and Huangpu Park instead of P-III. The new results produced higher water levels under different return periods than the previous study in 1984; while lower results than the research in 2004 (~6cm and ~15cm lower at Wusongkou and Huangpu Park at different return periods, respectively). The main reason of the different results was attributed to the different datasets. The new result employed the most updated data (till 2012) on annual maximum water level at each gauge station than the other two studies. Based on the additional datasets (the year of 2003-2012), it is noted that the annual maximum water level after 2002 (see red dots in Fig. 3. 8) are relatively lower compared with the previous datasets before 2002.

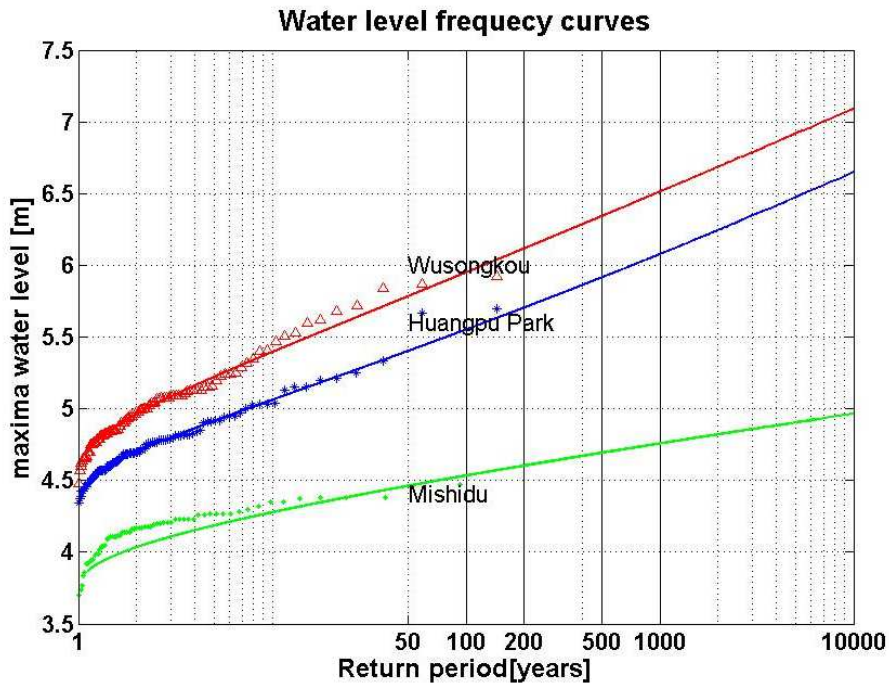


Fig. 3. 7 Results of water level-frequency curve at three gauge stations

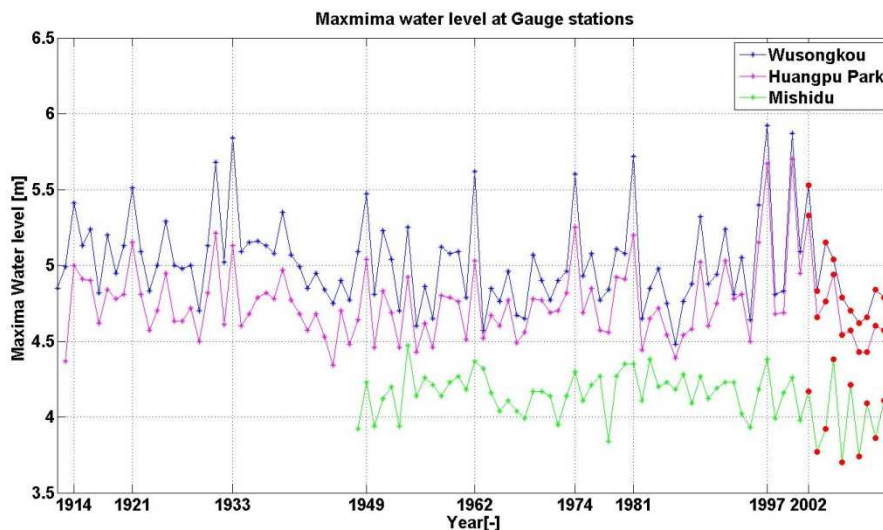


Fig. 3. 8 Annual maximum water level at gauge stations of the Huangpu River till 2012

Furthermore, it can be seen that the water levels at Huangpu Park station are significantly influenced by storm surge, which thus represents the identical frequency curve to the Wusongkou in the figure; and apparently the water level at Huangpu Park is lower than the one at Wusongkou. While the water level at upstream of the Huangpu River (i.e. Mishidu) shows different curve from the other two since the runoff in the upstream coming from the Tai Lake control more than storm surge to the water volume in the upstream.

A comparison with the official reports in years of 1984 and 2004 was conducted, see Fig. 3. 9. New results are averagely 24cm higher than 1984 while 15cm lower than 2004, while at Mishidu station the current results is ~20cm higher than 2004 results and ~65cm than 1984 results. Firstly, the results from 1984 and 2004 are both retrieved from Person-III distribution according to Chinese hydraulic engineering standards (MWR 2002). Secondly, the original data till 1981 in report of 1984 were not homogeneously revised, which led to lower result than 2004 and also new results. Thirdly, the new results are followed by GEV distribution, which is a first application in the Huangpu River and the up-

dated water levels at three gauge stations from 2005-2012 are averagely 18cm lower than the data before 2004.

Tab. 3. 3 Results of water level frequency analysis at Wusongkou, Huangpu Park and Mishidu

Water level [m]	Gauge station	No.	Parameters in GEV/P-III			Return Period [Years]					
			k	sigma	mu	10,000	1,000	500	200	100	50
Water level [m]	Wusongkou (1912-2012)	A	0.0136	0.2254	4.8810	7.09	6.51	6.34	6.12	5.95	5.78
	Huangpu Park (1913-2012)	B	0.0377	0.1832	4.6326	6.65	6.08	5.92	5.71	5.55	5.40
	Mishidu (1948-2012)	C	Cs 5.0138	Cv 0.0063	4.1378	4.96	4.76	4.69	4.60	4.53	4.46

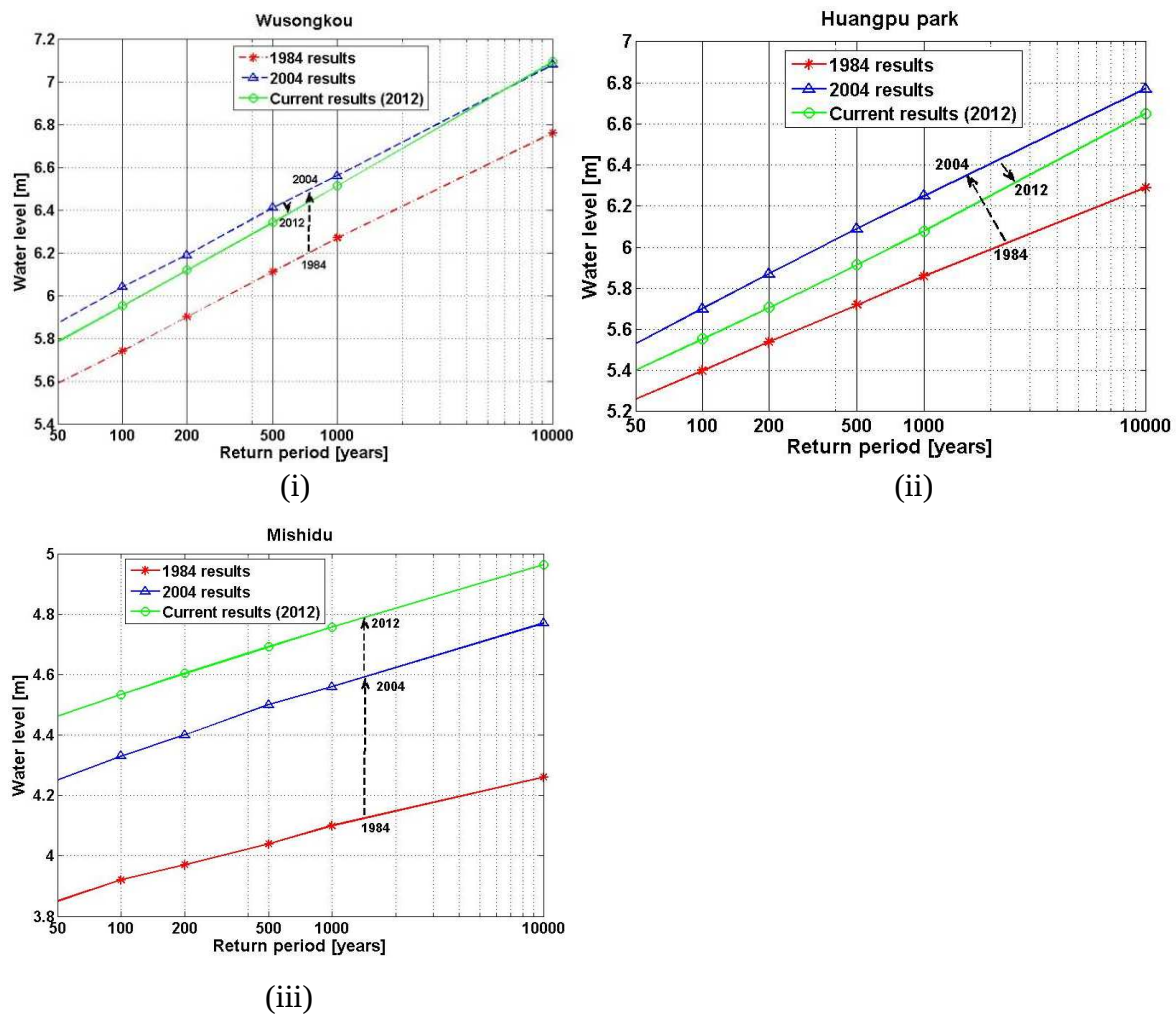


Fig. 3. 9 Water levels at Wusongkou (i), Huangpu Park (ii) and Mishidu (iii) in the results of 1984, 2004 and current research (data updated to 2012) The arrow means shift direction of the results.

3.3 Hydrodynamic modelling: using the 1D2D SOBEK model

In SOBEK, there are seven program modules⁸ work together to give a comprehensive view of water system. 1DFlow and Overland Flow (2D) are selected as computation modules in this study. 1DFlow is equipped with the user shell and which is capable of solving the equations that describe unsteady water movement, salt intrusion, sediment transport, and morphology and water quality. In this case, only the water movement module will be used. The Overland Flow (2D) module is designed to calculate two-dimensional flooding scenarios. The module is fully integrated with the 1DFLOW module for accurate flooding simulation. It is especially designed to simulate breaching of flood defence system. The hydrodynamic simulation engine underneath is based upon the complete Saint Venant Equations. It can simulate steep fronts, wetting and drying processes and sub critical and supercritical flow.

3.3.1 1D Flow modelling

3.3.1.1 Principle of 1D Flow

The water flow is described with the Saint Venant Equations for open channel flow. SOBEK use finite difference method (FDM) solves these equations numerically.

Continuity equation:

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \quad (3.14)$$

Where: A_t - total cross section area; [m²]

q_{lat} - lateral discharge per unit length; [m²/s]

Q - discharge; [m³/s]

Momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A_f} \right) + g A_f \frac{\partial h}{\partial x} + \frac{g Q |Q|}{C^2 R A_f} - w_f \frac{\tau_{wi}}{\rho_w} = 0 \quad (3.15)$$

Where: the first term describes the inertia; the second term describes the convection; the third term describes the water level gradient; the fourth term describes the bed friction; the fifth term describes the wind friction.

Q - discharge [m³/s]; t -time [s]; x -distance[m]; B -boussineeq constant [-]; A_f -cross section flow area [m²]; g -gravity acceleration [m²/s]; h -water level [m] (with respect to the reference level); C - chezy coefficient [m^{1/2}/s]; R -hydraulic radius[-]; w_f -flow width[m]; τ_{wi} -wind shear stress [m^{1/2}/s]; ρ_w - water density [kg/m³].

In SOBEK, 1DFlow is related to open-channel dynamic water networks, consisting of reaches, cross sections and structures. The boundary conditions are defined in the upstream and downstream of the Huangpu River in terms of time series of water level and river discharge, respectively. As the river networks can be superimposed over a map of the study area by geo-information system, the river net-

⁸ 1DFLOW (Rural, Urban, River), Overland flow-2D, RR (Rainfall-runoff), 1DWAQ (Water quality), RTC (Real- time Control)

works are visualized at a glance by drawing and adjusting in 1DFlow. In reality, the schematization is fairly complicated, including all creeks and small drainage canals. In this case, only the macro water management system is considered, which consists of the Huangpu River, Suzhou Creek and Yunzao Bang. The model schematization is presented in Fig. 3. 10. The model datum is Wusong Datum (WSD) and all the levels are related to this reference datum.

In this study, 1DFlow of the Huangpu River is to simulate the water levels (in different return periods) in each cross section, and then coupled with 2D Overland Flow due to the failure of the floodwall along the river.

Boundary conditions

- **Upstream boundary:** time series of discharges are set at this location, which represent the runoff from the upper part and the water volume of related creeks;
- **Downstream boundary (Wusongkou):** time series of water level are set at this location, which represent the effect of the storm surge and the tidal fluctuation
- **Suzhou Creek:** it is a narrow (averagely width 58.6m) and shallow (averagely depth 3.4m) river with an annual average discharge of 10-25m³/s; the discharge is not significant and mainly depends on the downstream tide levels. Hence, a constant discharge of 20m³/s is set in this model.
- **Yunzhao Bang:** constant discharge of 20m³/s

Upstream regulation

- To improve this model, a storage area is set (see Fig. 3. 10) at the upstream of Huangpu River in order to control the water volume of Mishidu and also represent the extension of upstream branches of the Huangpu River. By numerous trial and error, the storage area is set as 1.19E+09 m² with lateral flow of 750m³/s

Cross section and friction

- According to the official survey of river channel in Shanghai, 80% of cross sections are in shape of trapezium or approximate trapezium; and the ratio of slope is 1:1.5 to 1:2 (Li 2011). Hence, in 1DFlow the overall cross sections are adopted as trapezium (See Fig. 3. 11), with slope of 1:1.5 in branches and 1:2 in the Huangpu River. The bed level of river channel in this model is set as 0m widely refers to the datum. The surface level (the embankment of cross section) conforms to the crest height of floodwall with safety standards of 1,000 return periods currently in Shanghai.
- The friction of manning coefficient is set between 0.015-0.035 for different reaches in this model.

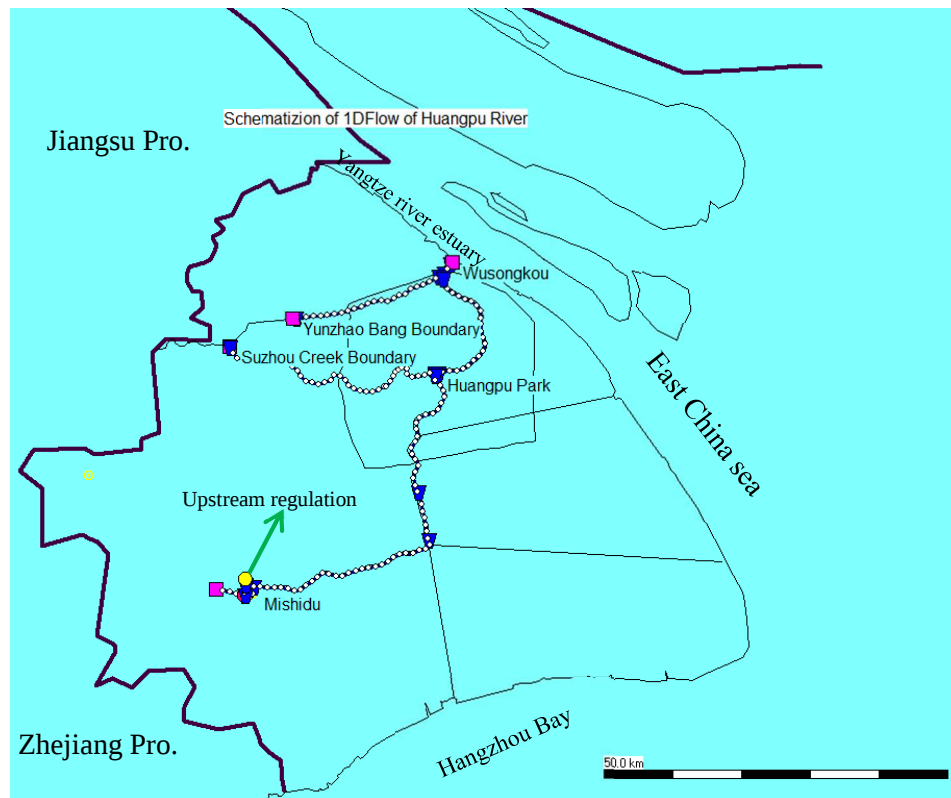


Fig. 3. 10 Schematization of 1DFlow of macro water system of Huangpu River

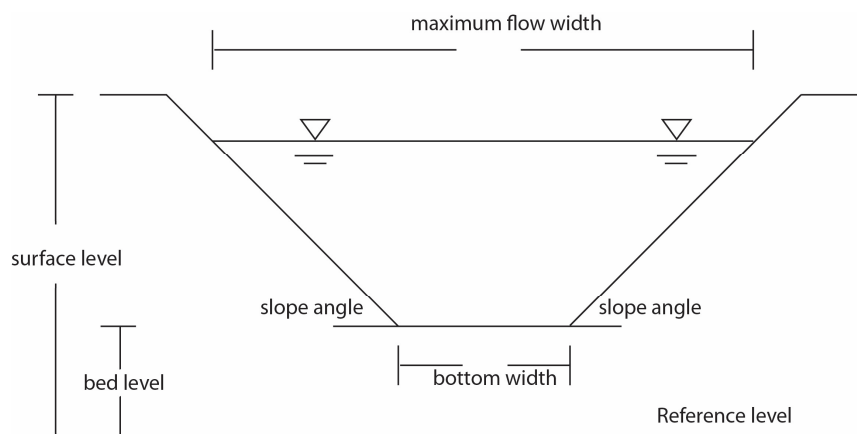


Fig. 3. 11 Trapezoidal cross section in the channel of the Huangpu River

3.3.1.2 Calibration & Validation

Two typhoon periods were selected to calibrate and validate the 1D model in the Huangpu River. The first period of typhoon Winnie during 15th-22nd August, 1997 is chosen as calibration, which lasts 7 days in total. The second period is Typhoon Masha during 5th-9th, August, 2005 lasting 4 days. In a summary, nearly 2/3 of the available data were used in the calibration and around 1/3 data were used in the validation.

- **Calibration**

The parameters of the calibration in the 1DFlow model are shown in Tab. 3. 4.

Tab. 3. 4 Parameters of calibration in 1DFlow model

Parameters	Value
Simulation period	15 th -22 nd , August, 1997
Time step in computation	1 hour
Simulation mode	unsteady calculation
Initial channel depth	2.98 m
Bed resistance	Variable(0.015-0.035)
“Node” distance	1000m
Output parameter	water level[m];volume[m ³];discharge[m ³ /s];

Typhoon Winnie (1997-August-18th)

• Results

- 1) The MAE^9 between the measured and simulated water level at Huangpu Park gauge station is 41.62cm. As the simulation period is during Typhoon Winnie, the flood tide level is supposed to be more fit to the measured data. Hence, the ebb water levels are the main contributor of the discrepancy, which also can be explained that the roughness of the river bed in inflow and out-flow direction should be used differently. If we only compare the flood levels, MAE is merely ~ 1.6 cm, which shows the flood levels are much better fitting the measured ones.
- 2) The highest water level in record at Huangpu Park is 5.72m observed on 19th, August, 1997, which is simulated at 5.78m at 8:00am, 19th, August, 1997 in this model.
- 3) This flood event is determined as 100-return period flood event (Chen 2000), which is also in line with the calibration results.
- 4) In SOBEK, the negative discharge means the opposite flow direction set in the channel. Since the negative discharge Huangpu Park are more influential than the positive discharges, which reflects that the effect of the downstream boundary conditions are more important and dominant than the upstream one.

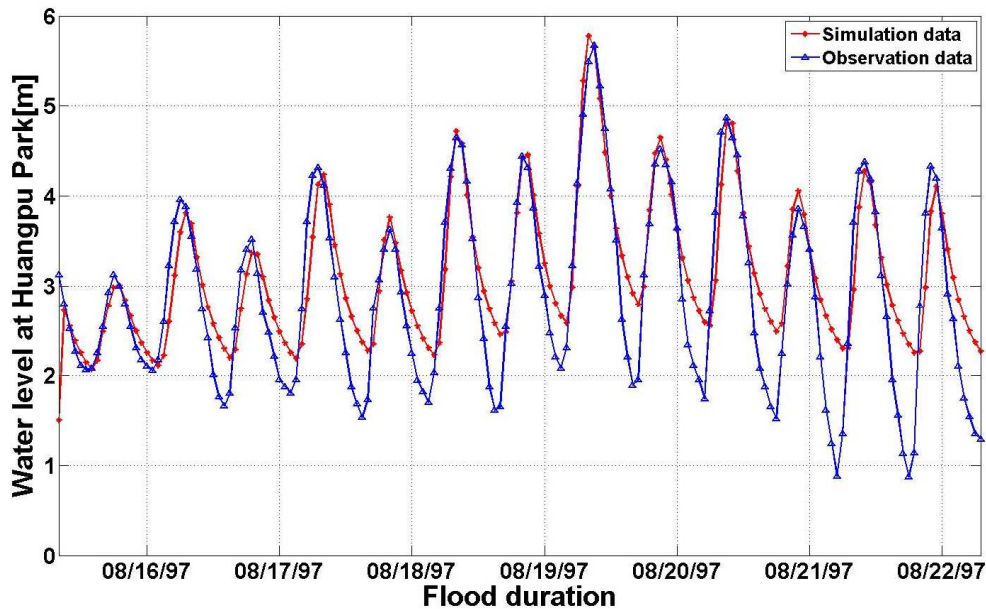


Fig. 3. 12 Simulated water levels at Huangpu park in calibration period (Overall $MAE = 41.62$ cm and MAE for flood level ~ 1.6 cm)

⁹ Mean Absolute Error: $MAE = E(|x_i - \hat{x}_i|)$ where: x_i is the observation data; $\hat{x}_i$ is the simulation value;

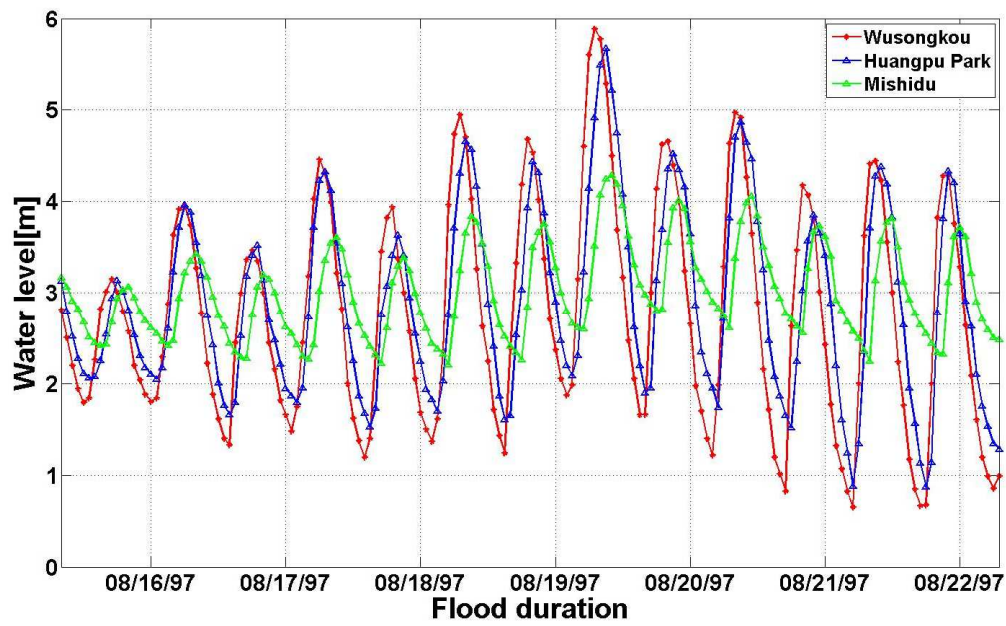


Fig. 3. 13 Simulated water level at Wusong, Huangpu Park and Mishidu during Typhoon Winnie, 1997

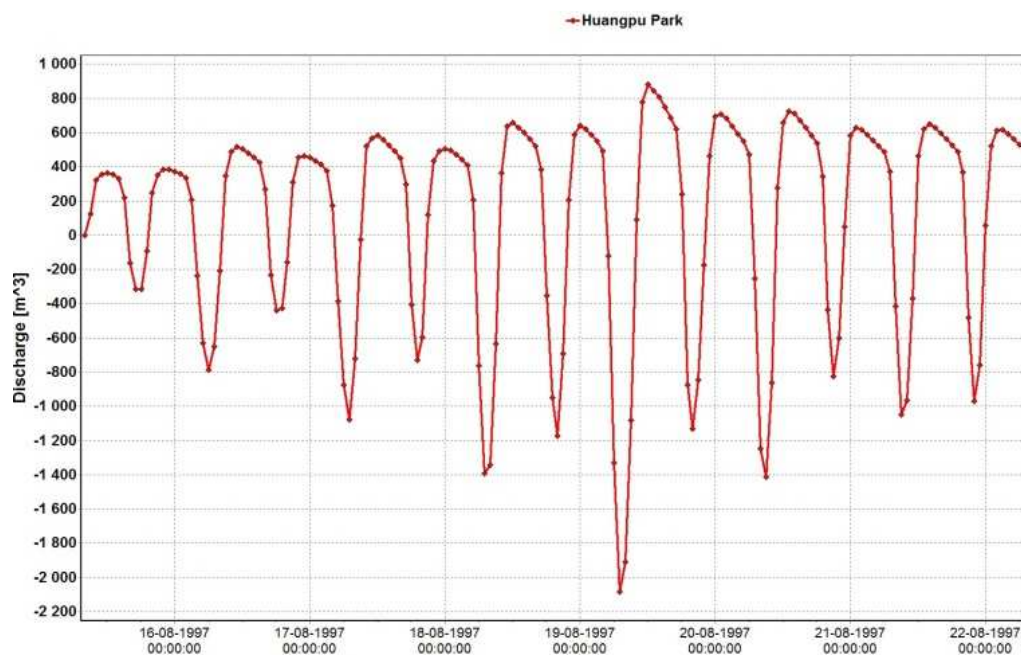


Fig. 3. 14 Simulated discharges at Huangpu Park in Typhoon Winnie

- **Validation Results**

The period of Typhoon Masha in 2005 (5th-9th, Aug.) is selected based on the data availability and typical typhoon weather in August of Shanghai.

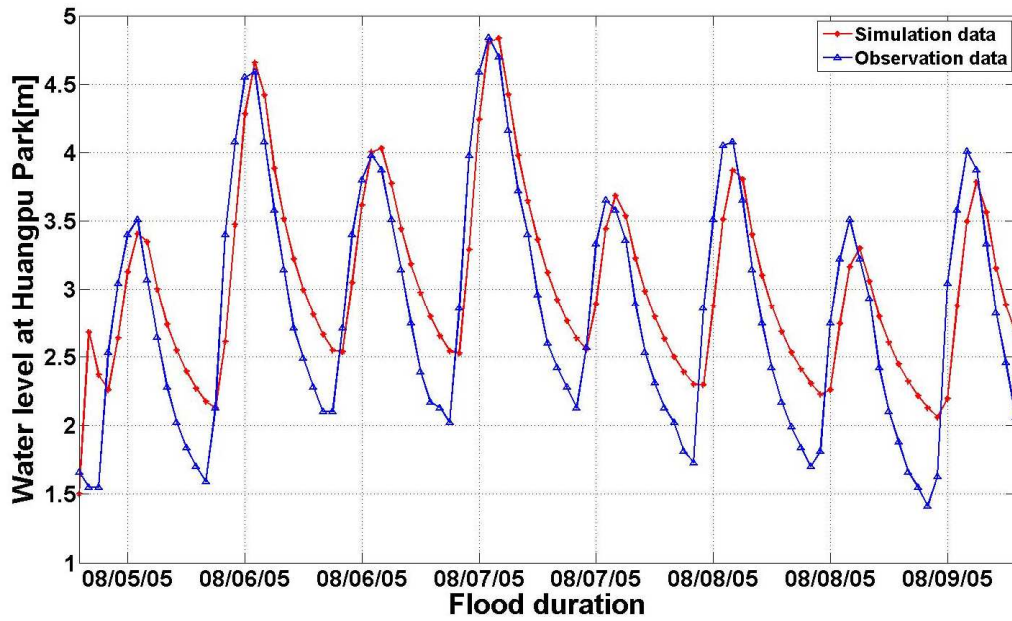


Fig. 3. 15 Simulated water levels at Huangpu park in period of 5th-9th, Aug., 2005 (Overall $MAE=41.29\text{cm}$ and MAE for flood points $=5\text{cm}$)

- 1) The difference could be due to the different roughness in inflow and outflow direction which should be used. By lowering the roughness factor in the inflow direction, the peak discharge will be increased.
- 2) As the biggest concern in this case is Huangpu Park station, there are no more improvements on the upstream part of Huangpu River.
- 3) Considering the scale and scant/limited data available, this 1D flow model can reasonably represent the water-flowing process in the Huangpu River.

3.3.1.3 Identification of weak points of the floodwall

The overtopping scenarios were built up by upscale and downscale of the boundary condition at the mouth of Huangpu River in August 1997 (see Fig. 3. 16). 1997 is set as a base year as a historical highest water level (5.72m) at Huangpu Park was reached in August 1997 due to the coincidence of high astronomical tide with storm surge caused by Typhoon Winnie.

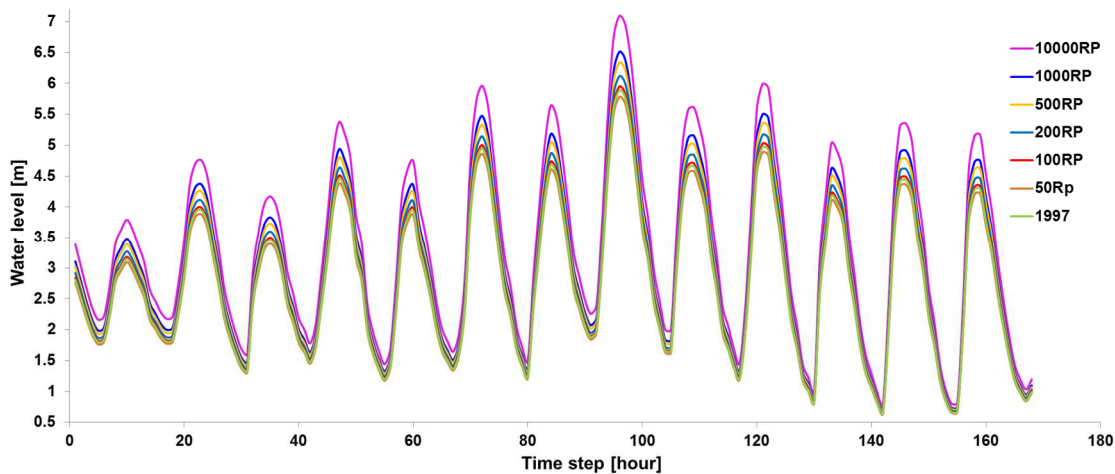


Fig. 3. 16 Amplification and abbreviation of boundary condition of water level at Wusongkou based on August 1997

The water levels along the Huangpu River were derived by 1D flow model as a function of return period, which are compared to the crest height of floodwalls¹⁰ (Li, Wang et al. 2011) on the both side of the Huangpu River. The surface level in the model is set at the low point of floodwall. As the high-economic exposure in the downtown than the new developing area, the crest height of floodwall in the east side (developing area) is lower than the west side (downtown area). These crest height information were updated to 2008.

The potential overtopping points of floodwall are marked in Fig. 3. 17 in alphabetical order based on the occurrence possibilities of overtopping. It shows that the current floodwall cannot protect from flood event with 200 return periods already; overtopping (A) would happen in a distance of around 45km to the mouth of Huangpu River. Besides, more overtopping points would occur if flood events with return period of 500yr (B, C, D) and 1000yr (E, F, G, H) happen in the Huangpu River. Lastly, floodwall would be out of function almost completely under the return period of 10,000yr flood. Therefore, overtopping scenarios of floodwall along the Huangpu River will be set as 200yr, 500yr, 1000yr and 10,000yr return periods of flooding. These results are in line with the previous work by (Li, Wang et al. 2011), they plot water level of the Huangpu River with return period of 1,000yr based on Typhoon Winnie (1997) and Typhoon Papain (2000). Similar results were retrieved with comparison of crest height of floodwall and water levels in their studies.

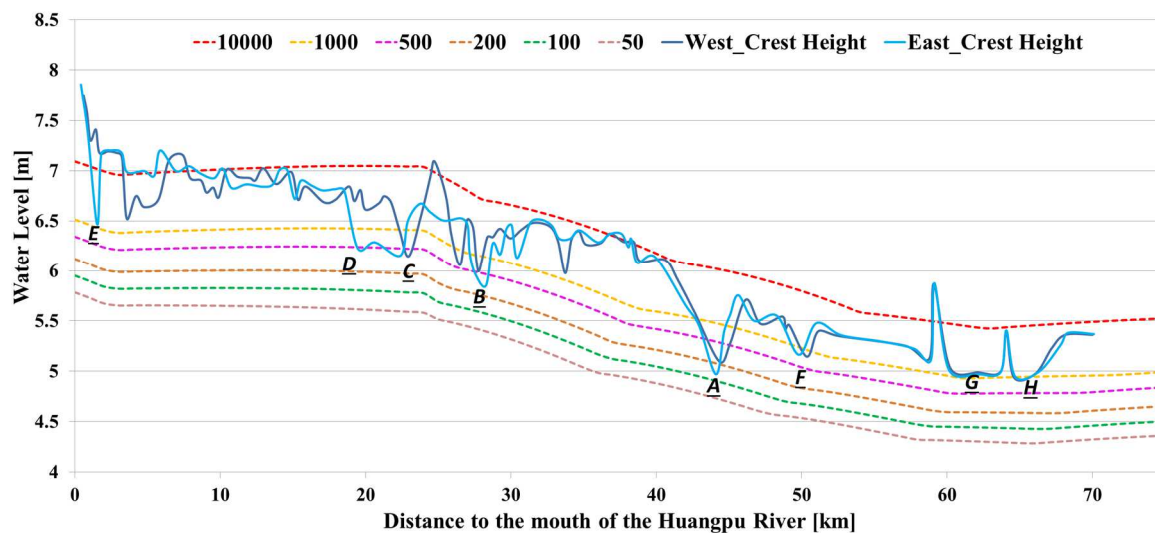


Fig. 3. 17 Crest height of floodwall on both sides along the Huangpu River compares to the water levels as a function of return period of 10000,1000,500,200,100 and 50 years

3.3.2 Flood scenario analysis - 2D flood simulation

Four types of scenarios were identified in terms of different types of flooding. The no-embankment were just a hypothesized scenario to show if there is no floodwall system along the river what would happen, which can also imply the significance of the flood defence system for Shanghai city; the overtopping scenarios were setup to testify the current height of the floodwall would fulfil the safety standards or not; since the floodwall could fail even if the water levels have not exceed the crest height due to the structural reasons (e.g. piping, erosion, sliding etc.), breaching scenarios were proposed based on the potential weak points along the river as well; lastly, based on the observations from the floodwall system along the Huangpu River (see Section 2.4.2), the scenarios of the failure of the selected floodgates along the river were also considered in the section.

¹⁰ Data source: IWHR (Institute of Water Resources and Hydropower Research), Beijing, China

3.3.2.1 Digital Elevation Model

The so-called Digital Elevation Model (DEM) was retrieved from (INTERMAP 2012) with floating value in the grid size of 30m. It can be easily noted that the high value in the downtown and southeast of Shanghai (yellow cluster 10-20m) could be the results of high-rise buildings and other high infra-structures (flyover or crossover, etc.) in the city, which implies the data has not fully filtered. Hence, a modification needs to be done before importing into the 2D model. Firstly, based on a general exploration on elevations of Shanghai (See details in Chapter 2 Section 2.2.1), the average value is 3-5m (Wusong Datum: red dot in (ii) Fig. 3. 18) in the whole city; considering the land subsidence, it is recommend to adopt generally 3.5m. Due to lack of information on the height of the buildings, the ground elevations were manually adjusted on a condition if the value is higher than 8m it is set as 3.5m instead; and the values less than 8m remain the source value in Intermap2012. The manual adjustment was performed by ‘Raster Calculator’ in ArcGIS. Secondly, since Shanghai is a relatively flat area without much differences of elevation generally in the city, the grid value was resampled to 300m by a command of ‘Aggregate’ in ArcGIS in order to achieve a more manageable data system (see (ii) in Fig. 3. 18). In addition, less resolution is required when only water depth is to be predicted in flood characteristics.

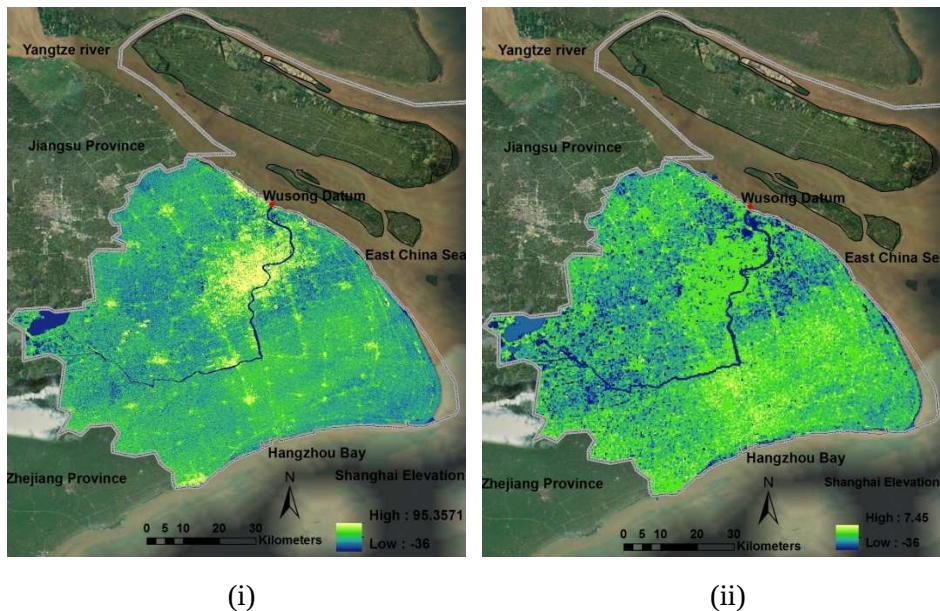


Fig. 3. 18 (i) Digital Elevation Model (DEM) of Shanghai city (INTERMAP 2012) and (ii) new DEM after aggregation

3.3.2.2 Surface roughness

Land use map could be supported as geo-data to determine the surface roughness for each land use type in the model. However, due to lack of information Shanghai is taken as an urban area being full of industry and commercial units with manning value of 0.06 widely.

3.3.2.3 Scenarios set-up

- **No protection scenario**

First, 1D2D hydrodynamic model was undertaken in SOBEK under the no protection (no embankments) scenario in Shanghai. The boundary conditions at Wusongkou are based on Fig. 3. 16. The overflowing period was taken between 8:00am, August 15, 1997 to 7:00am, August 22, 1997. The results of inundation maps were shown in Appendix 3-3. The inundation results under the scenarios of no embankments are shown in Tab. 3. 5. The inundation percentages in the mainland Shanghai (except

three islands) are 9.55%, 9.92%, 10.35%, 11.07%, 11.71%, 13.43% under the return periods of 50yr, 100yr, 200yr, 500yr, 1,000yr, 10,000yr. The inundation is mostly occurred at the mouth and in the upstream of the Huangpu River. Since the storm tide is descending from the mouth to the upstream, the area closed to the mouth would be the most possibly affected. The upstream area would be the lowest area in Shanghai. Due to the low elevation (2-2.5m), it would be easily inundated with average depth of 1.29m with standard deviation of 0.84m. The simulations do not show much difference of average depths under different return periods; only represent the increment of the inundation area in the results. Due to the relief of the water volume in the upstream and downstream of the Huangpu River, the city centre which is located in the middle stream was not affected too much by the inundation. The results shows the riverine area in Baoshan and Pudong district in the downstream and in Qingpu and Jinshan district in the upstream are being inundated most. The maximum inundation depth is more than 2.6m in each return period, which could cause serious economic damage and also threaten people's lives.

Tab. 3. 5 Results of inundation extent under no-embankments scenarios along the Huangpu River

Return Period [Years]	50	100	200	500	1,000	10,000
Inundation Area (km ²)	494.63	514.02	535.84	573.36	606.4	695.40
Inundation Percentage*	9.55%	9.92%	10.35%	11.07%	11.71%	13.43%

*: The area of Shanghai except the three islands is taken as 5179.23km²

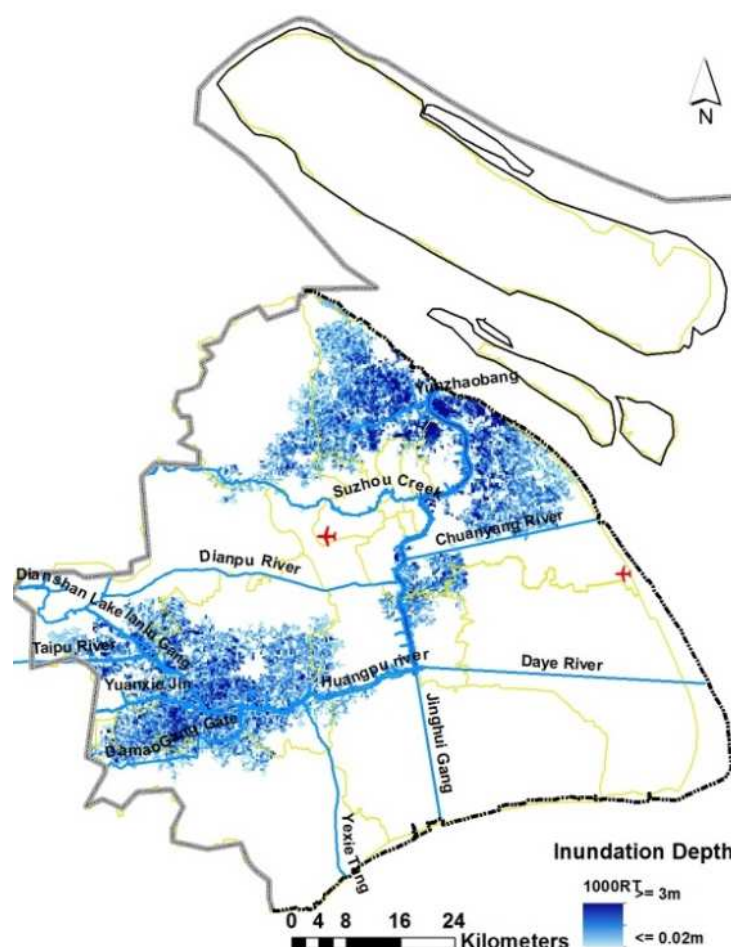


Fig. 3. 19 Simulated flood inundation under no protection scenario in 1/1,000yr probability of flooding in the Huangpu River of Shanghai

• Overtopping

The overtopping occurs when the water level surpasses the floodwall crest at a certain point. Fig. 3. 20 shows six potential overtopping points were identified based on the information in Fig. 3. 17. As seen from Fig. 3. 17, the potential overtopping points were identified along the floodwall of the Huangpu River. These weak points were identified by comparing the occurred highest water level with floodwall crest.

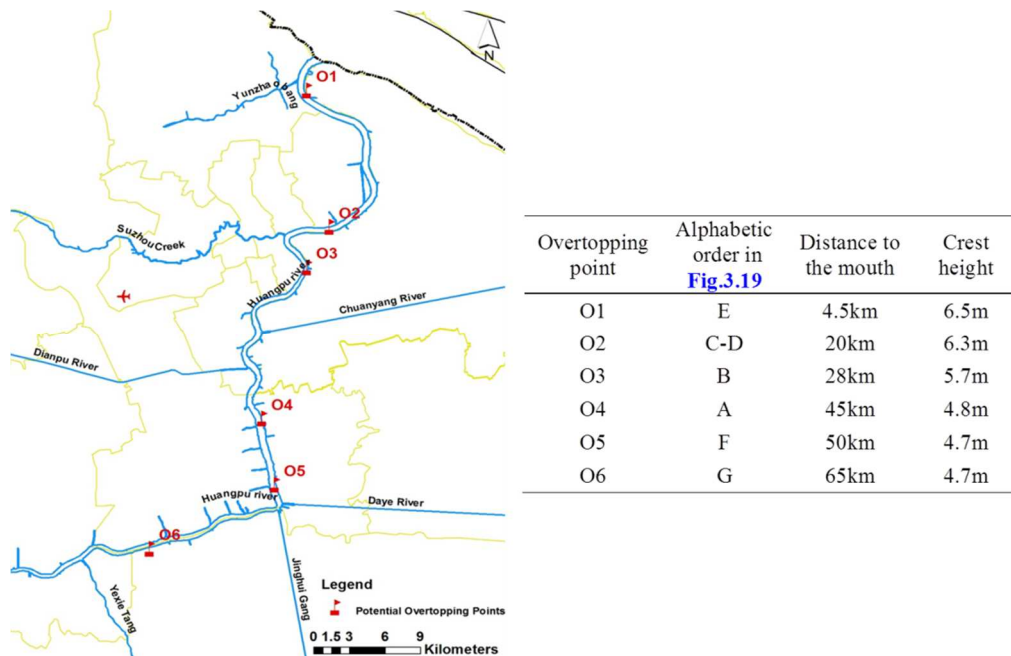


Fig. 3. 20 General information on potential overtopping points along the floodwall of the Huangpu River

The overtopping scenarios were simulated at each location under the water levels as a function of different return periods. The inundation is largely dependent upon the water volume overtopped from the crest level. In this model, the flooding was happened between 7:00-13:00 19-August, 1997, which only lasts a few hours. Under the scenarios of 1/500yr and 1/1,000yr at O2, the flooding only lasts one hour; and the other scenarios last 2-6 hours. In general, the inundation mainly distributes within 1km of the riverine. As seen from Tab. 3. 6, the overtopping point O1, O2, O3 generally have higher maximum inundation depth ($\geq 2\text{m}$) than O4, O5, O6 ($\leq 1.87\text{m}$) at different return periods.

There are several results from the flood simulation scenarios:

- 1) The adjacent area to the floodwall would be suffered from the flooding.
- 2) At O1, the inundation depth is averagely 1.76m with area of 16.7km^2 as a function of 10,000yr return period, which is also the worst-case scenario among all in this case.
- 3) The overtopping at O2, O4, O5, O6 under the different return periods (200yr, 500yr, 1,000yr, 10,000yr) gradually expanded in north-south direction; the inundation are mainly limited on the both sides of the river.
- 4) At O3, the inundation area increased up to 1.5 km (at return period of 10,000 yr) away from the river side with inundation depth larger than 3m.
- 5) An example of inundation maps at different return periods (200yr, 500yr, 1000yr and 1000yr) at overtopping point O4 were shown in Fig. 3. 21. As increased of the return period of the flooding, the inundation area increased as well accordingly. The mean value of inundation depth increased 14cm as return period increased from 200yr to 500yr and from 500yr to 1000yr;

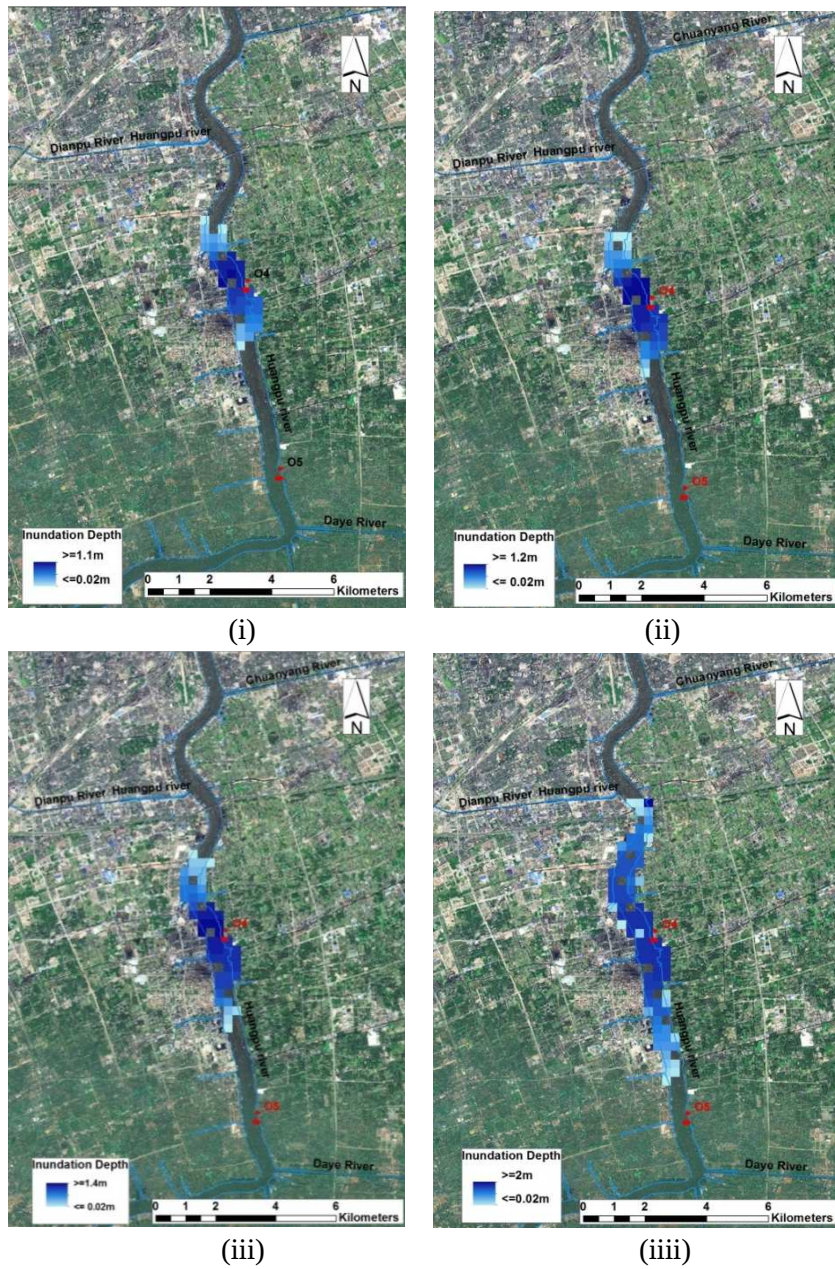


Fig. 3. 21 Inundation map of overtopping at O4 (45km away from the mouth) due to water levels as a function of return period of 200yr (i), 500yr (ii), 1,000yr (iii) and 10,000yr (iiii)

Tab. 3. 6 The percentile of maximum inundation depths under different scenarios of overtopping in the Huangpu River

Overtopping	Return Period [Years]	Mean depth [m]	Max. depth [m]	Maximum inundation depth in percentile* [m]					Inundation area [km ²]
				15%	25%	50%	75%	85%	
O1	10000	1.76	3	0.4	1	1.8	2.6	3	16.7
	500	1.07	2	0.14	0.4	0.85	1.7	2	3.86
O2	1,000	1.1	2	0.155	0.4	1	1.8	2	3.94
	10,000	1.31	2.4	0.1	0.45	1.3	2	2.4	7.72
O3	500	1.36	2.6	0.02	0.2	1.4	2.6	2.6	2.01
	1,000	1.08	3	0.02	0.1	0.3	2.8	3	4.03
	10,000	0.83	3	0.02	0.1	0.3	1.2	3	7.13
O4	200	0.65	1	0.3	0.4	0.7	0.9	1	3.27
	500	0.79	1.2	0.3	0.5	0.9	1.1	1.2	3.53
	1,000	0.93	1.3	0.4	0.63	1.1	1.28	1.3	4.28
	10,000	1.17	1.7	0.3	0.8	1.4	1.7	1.7	7.21
O5	1,000	1.03	1.6	0.1	0.4	1.3	1.5	1.6	3.44
	10,000	1.05	1.6	0.3	0.5	1.2	1.6	1.6	5.46
O6	1,000	0.89	1.87	0.2	0.3	0.85	1.5	1.87	2.69
	10,000	0.94	1.64	0.26	0.5	0.9	1.3	1.64	3.53

*: Note that the maximum inundation depth is under a spatial distribution of the affected area; For example, the value in percentile of 85% means 85% of grid cells are smaller or equal to this value

• Breaching

- Determination of potential breaching locations

The potential breaching locations in the east side of the Huangpu river are identified based on an investigation of floodwall examined by the Shanghai Investigation, Design and Research Institute (Li, Wang et al. 2011). 48 weak points were identified along the Huangpu River based on the information on the building year, fundamental and geometry structure and historical records, etc. Unfortunately, not all of these potential breaching locations are available. Only 4 weak points were determined on the map which can potentially affect New Pudong district; they are marked as BE1, BE2, BE3, and BE4 and shown in Fig. 3. 22. These sections are all identified as structure-fragile due to weathering, cracking and washing-out by the front water wave, etc. (Li, Wang et al. 2011).

- BE1- Embankment of East China Sea Branch of State Oceanic Administration
- BE2- Embankment of Shanghai Offshore Petroleum Geophysical Corporation
- BE3- Embankment of 4805 Factory
- BE4- Embankment of Xinhua Harbour Company

On the other hand, the potential breaching points in the west side of the Huangpu River are all assumed in the city centre of Shanghai, specifically in Baoshan district, Hongkou district, Huangpu district and Xuhui district (also see Fig. 3. 22).

The assumed breach locations are selected based on:

- 1- Low terrain around (e.g. BW1)
- 2- Lower crest height of floodwall (e.g. BW3 and BW4)
- 3- Historical failure location(e.g. BW2, BW3)

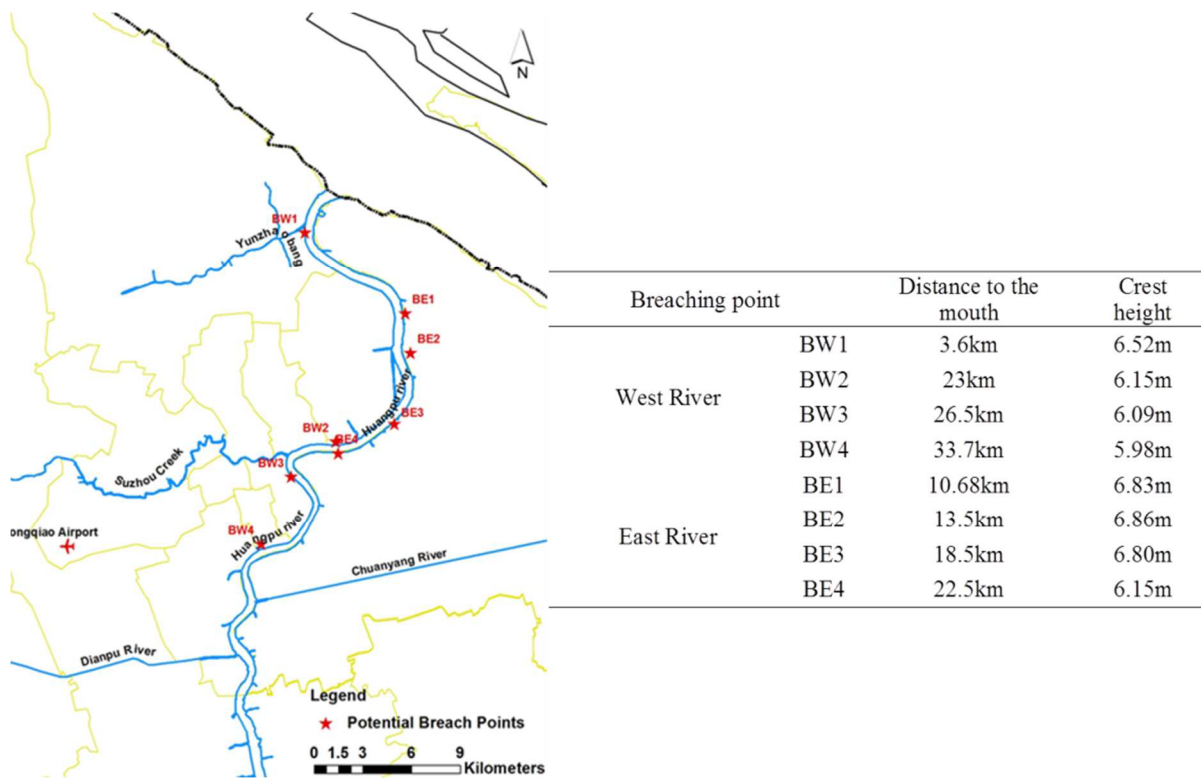


Fig. 3. 22 General information on potential breaching points on the both sides of the Huangpu River

- Breach growth

In 2D flood-simulation model, the geo-data, such as topography and roughness of the terrain are coupled with 1D model. SOBEK can compute the development of a flood in time in each breach location. It gives a direct overview of what could go wrong and how a flood develops. In 1D2D SOBEK, the results of dynamic flood process can be visualized by animations, which can provide as discussions on dealing with the danger of floods and the preparation for an unexpected flood afterwards.

The breaching initiation and growth rate determine a large extent to the volume of water into the flood area. Due to the complex mechanisms involved and the difficulties to retrieve data, the breaching was simplified to a sudden collapse on a condition of water level at a certain level, lasting 24 hours. Based on the information on the schematic of typical cross section of floodwall in the downstream and middle stream of the Huangpu River, the pre-defined warning water level is around ~5m. Hence, it is assumed that when the water level reached at ~5m or more the breach occurred. This engineering technique was applied in (Apel et al, 2004), in which a breach condition is defined as the exceedance of a load factor over a resistance factor (e.g. maximum discharge > critical discharge). The spatial variability of the floodwall geometry and the length effect of different long river stretches on the failure probability are not considered in this research. The boundary condition in the downstream of river was set as return period of 1,000yr during 15-22 August, 1997. An example of breaching on the condition of water level reaching to the warning level is shown in Fig. 3. 23. This example shows that the breach immediately occurs based on a condition of water level reached to the warning level; the starting time and time series of water levels at BE3 is shown in Fig. 3. 24. The water level exceeds ~5m at 8:00am on 18-Aug-1997, which initiates a breaching and lasts 24 hours. The breach volume is then determined as approximately ~26 million m³ in total.

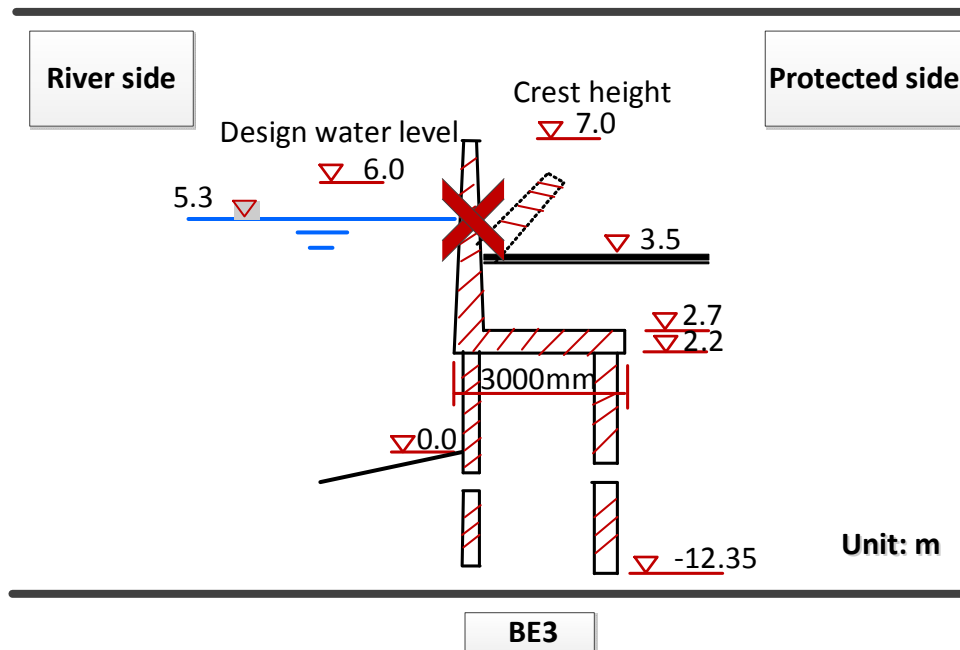


Fig. 3. 23 Schematic cross section of a typical floodwall under breaching when water level exceeds the warning level of 5m (location: BE3)

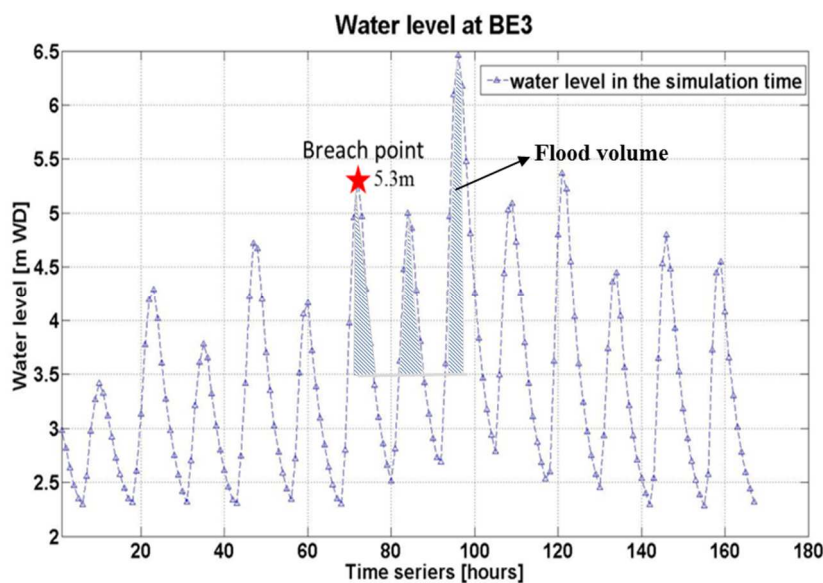


Fig. 3. 24 An example of the flood water (shade area) at location of BE3 after breaching under a flood with 1/1,000p.y

In SOBEK, the breach growth can be specified, in vertical and horizontal direction, as a function of time based on formula of vdKnaap (2000) or Verheij-vdKnaap (2002). The breach is simulated in two phases. First, the gap crest level is going down with a constant gap width (see Fig. 3. 25 phase 1-3). When a certain maximum depth of the gap is reached, second, the width of the gap starts increasing horizontally (see Fig. 3. 25 phase 4-5). A number of parameters are required to input in the breach model, such as initial breach width, maximum breach depth, start time of breach and maximum breach width, etc.

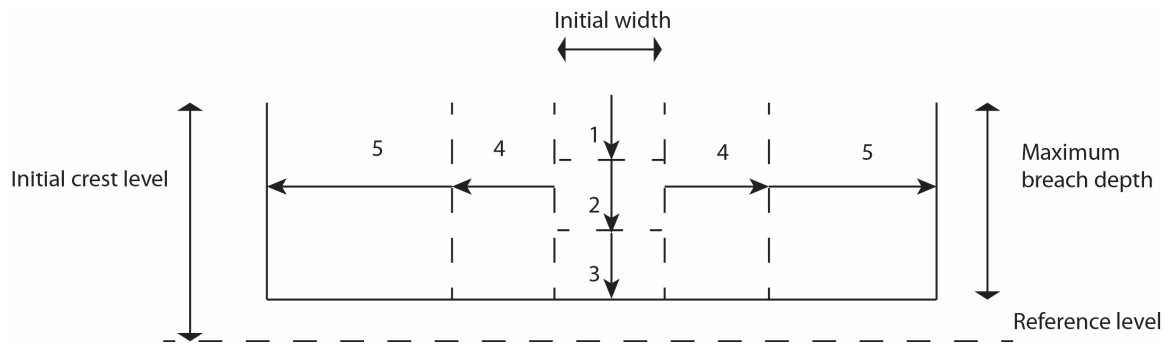


Fig. 3. 25 Different stages of breach growth in vertical profile for earth embankment (SOBEK 2001)

As limited data is available on breaching process in the floodwall of the Huangpu River, the parameter value of breach growth is based on the assumptions from the similar cases. In New Orleans during 2005 of Hurricane Katrina, several sections of the embankment failed (e.g. 17th Street Canal, London Avenue Canal and Lower Ninth Ward, etc.). In New Orleans, the typical breach width were observed at between 70m-150m due to geotechnical failures (e.g. under-seepage, erosion, sliding or piping) and between 150-250m due to overtopping/overflow in different locations (Grossi and Muir-Wood 2006). Besides, an empirical formula to determine the breach width based on the river width was recommended in 'Guideline of Flood Risk Mapping' in China (MWR 2006): $B_b = 1.9(\log B_r)^{4.8} + 20$, in which B_b is final breach width; B_r is river width. Since the river width of the Huangpu River in the downstream and middle stream is approximately ~600m (B_r), it is then calculated that the possible breach width B_b could be ~276m. Based on the above information, the breach width was thus set as 300m uniformly in the model to explore the worst-case scenario along the Huangpu River.

Overall, the parameters in the breach model of SOBEK are summarized in Tab. 3. 7. They are all taken as the deterministic parameters in the model.

Tab. 3. 7 Summary of parameters in the breach model

Parameters in breach model	Value
initial breach width	10m
maximum breach depth	depends on floodwall crest at potential breaching locations
start time of breach	a time of water level ≥ 5 m WD
time to reach maximum breach depth	1s
maximum breach width	300m

- Breaching results

The results of maximum inundation depths under breaching scenarios on the east and west side were generally shown in Tab. 3. 8. Regarding to inundation area and average inundation depth, the breaching at west side of the floodwall caused larger inundation area than the east side, while the average inundation depth is lower than the east side. It could be explained that the relatively higher elevation (~4m-4.5m) in the east side could blocked the flooding, hence the water volume fill up the inundation area with deeper water. The largest inundation area is caused by breach location at west side 23km away from the mouth (BW3), which leads to 40.7km² inundation area with average depth at BW3 is 0.63m in city centre. An example of inundation map at breaching location of BW3 is shown in Fig. 3. 27. While all the breach scenarios in the east side reach more than 1m inundation depth averagely. In the west side, BW2, BW3 and BW4 all affect the city centre area, which will be used as input to esti-

mate flood damage further in the next step. The other inundation maps of the breaching scenarios are shown in Appendix 3-5.

Tab. 3. 8 Results of maximum inundation depths, mean value of inundation depth and inundation area under breaching scenarios on the east and west side of the Huangpu River

Breach point	Inundation depth Mean value [m]	Maximum inundation depth in percentile* [m]					Inundation area [km ²]
		15%	25%	50%	75%	85%	
BE1	1.09	0.1	0.3	0.8	1.8	2.3	7.22
BE2	1.09	0.2	0.4	0.7	1.6	2	6.13
BE3	1.25	0.2	0.3	0.9	2	3	11.33
BE4	1.28	0.1	0.3	1	2	3	6.55
BW1	1.07	0.1	0.3	0.8	1.7	2	10.49
BW2	0.73	0.02	0.02	0.3	1.3	1.7	20.73
BW3	0.63	0.1	0.2	0.4	0.7	1	40.71
BW4	0.44	0.02	0.1	0.2	0.5	0.7	26.02

*: Note that the maximum inundation depth is under a spatial distribution of the affected area; For example, the value in percentile of 85% means 85% of grid cells are smaller or equal to this value

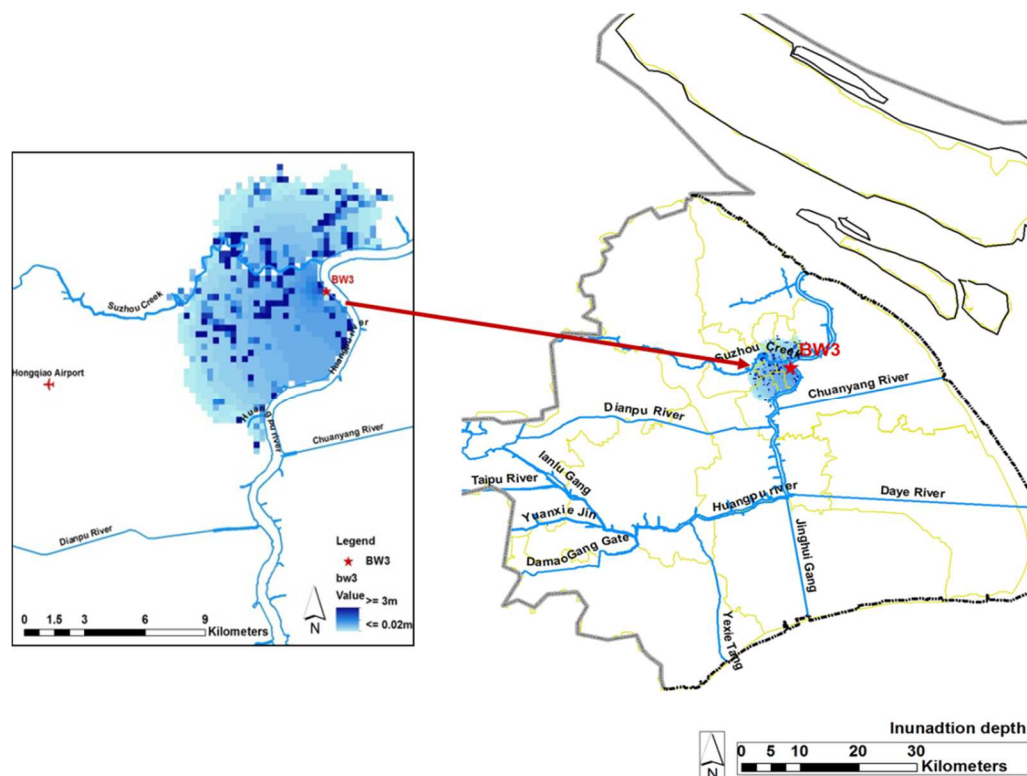


Fig. 3. 26 An example of inundation map due to breaching at BW3 on the east side of the Huangpu River

• Failure of floodgate

As observed from the flood defence system of the Huangpu River, the performance of the floodgate is essential in the flooding since the failure of floodgate (e.g. non-closure and structural failure) may lead to flooding as well. It could be regarded as a special case of the instantaneous breaching with

breach width of $\sim 10\text{m}$ (the width of the floodgate) when the water level reaches at 4.7m or more¹¹. A historical failure of floodgate occurred in September 1981, which led to an inundation and a subsequent 3-days close of a shipment factory (Yuan et al. 1999). Since numerous floodgates function as a section of flood defence along the Huangpu River, any failure of floodgate could lead to a flood. Based on the observations in the fieldwork, three locations of floodgates along the Huangpu River were selected to explore the flood simulation (see Floodgate_01 (Fg1), Floodgate_02 (Fg2) and Floodgate_03 (Fg3) in Fig. 3. 27). The simulations were based on 1/ 1,000p.y flood which was up-scaled by 1997 Typhoon Winnie. The last period is controlled as 24 hours, which is also in line with the breaching scenarios. The time of water level at $\geq 4.7\text{m}$ at Fg1, Fg2 and Fg3 were determined in the 1D model.

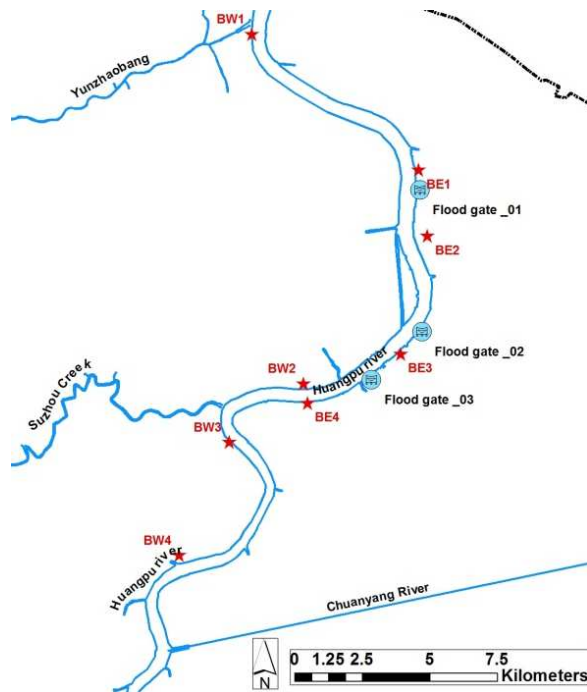


Fig. 3. 27 Location of the selected floodgates on the East side of the Huangpu River (Floodgate locations are Blue circle; Breach locations are red star)

The final results of the failure of floodgate simulation are shown in Tab. 3. 9. It is noted that the inundation area are limited with size of 4.78 km^2 , 6.8 km^2 and 10.41 km^2 under scenarios of Fg1, Fg2 and Fg3, respectively, which is also shown on the map of Fig. 3. 28. The expected mean values of inundation depth are 0.82m , 0.39m and 0.42m , respectively.

Tab. 3. 9 Results of maximum inundation depths under the selected scenarios of the failures of floodgates on the east side of the Huangpu River

Floodgate	Inundation depth [m]	Maximum inundation depth in percentile* [m]					Inundation area [km ²]
	Mean value	15%	25%	50%	75%	85%	
Fg1	0.82	0.02	0.02	0.2	1.25	2.38	4.78
Fg2	0.39	0.02	0.02	0.1	0.43	0.74	6.80
Fg3	0.42	0.02	0.02	0.2	0.45	0.8	10.41

*: Note that the maximum inundation depth is under a spatial distribution of the affected area; For example, the value in percentile of 85% means 85% of grid cells are smaller or equal to this value

¹¹According to 'Emergency Plan for Flood Prevention in Shanghai' (www.shanghaiwater.gov.cn), it is regulated that the floodgates should be close down when the water level reaches at warning level (4.7m) or more in the downstream of the Huangpu River.

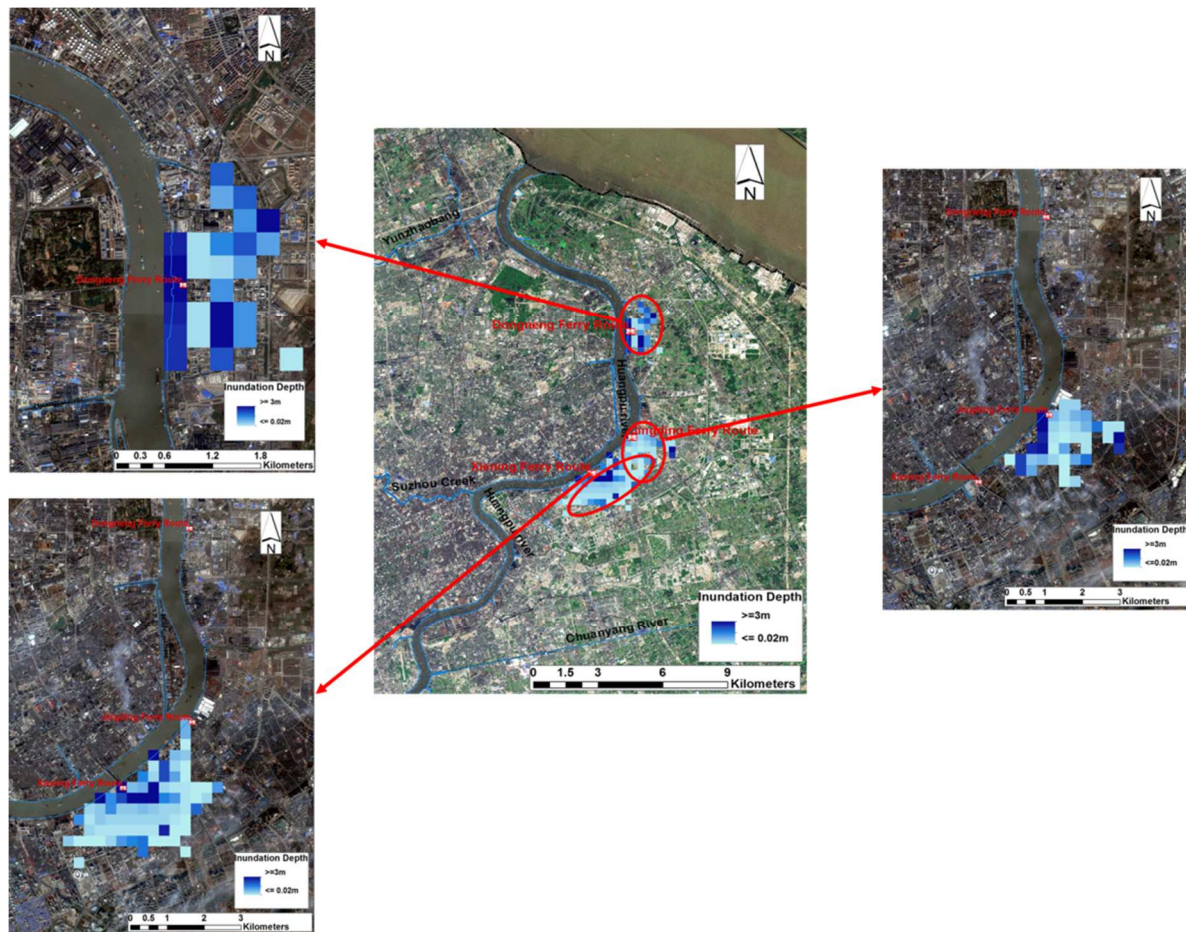


Fig. 3. 28 Inundation map due to the failure of floodgate on the East side the Huangpu River under three selected scenarios (the red ellipses show the inundation area)

3.4 Discussion

In this chapter, three steps were followed to produce inundation map along the Huangpu River. First, water levels as a function of different return periods (50yr, 100yr, 200yr, 500yr, 1000yr, 10000yr) at gauge stations of the Huangpu River were derived based on probabilistic methods, which were also represented as water level-frequency curves. The aim of the water level-frequency analysis was to provide the water levels as changed with different return periods at Wusongkou as a boundary condition in 1D hydraulic modelling. Second, 1D river hydraulic modelling was built to compute water levels at each cross section of the Huangpu River under different return periods. The results of water level were used to compare with the corresponding floodwall crest in order to identify the potential overtopping points along the river. Third, 2D hydraulic modelling coupled with 1D model was developed by SOBEK to simulate flood scenarios. Besides overtopping, scenarios with no protection along the river were analysed to show the significance of the floodwall in Shanghai. In addition, the hypothetical breaching scenarios and the failure of floodgates scenarios were developed to explore worst case of river flood in Shanghai. The results were also provided as an input for next step of flood risk analysis.

3.4.1 Frequency analysis

New frequency curves of water level as a function of return periods were derived at Wusongkou, Huangpu Park and Mishidu along the Huangpu River. GEV was adopted as probabilistic distribution at Wusongkou and Huangpu Park, which is different from previous work in the Huangpu River. The updated datasets to the year of 2012 (10 more observation data than the analysis in 2004) led to lower

estimation on the water levels as a function of return periods, which means either the 10 more historical records or the new probabilistic distribution (GEV) influenced the final results or both did.

3.4.2 1D Hydraulic modelling of the Huangpu River

In 1D hydraulic model, two factors are crucial to the final results, namely boundary condition and hydraulic roughness. The boundary conditions in the model are usually either time series of water level or water discharge, or constant value. The input data need to be collected based on the actual flood period. It is inevitably effort-consuming, which is regarded as a high requirement in the hydraulic model. Another critical factor is hydraulic roughness in the river bed; since limited data and information collected in the river, the roughness was set differently range from 0.015-0.035 after numerous tries and errors in the calibration. As seen from the calibration and validation results, the water levels during floods were more closed to the observation data than the ones during ebb period. It is noticed that the differences of roughness in the inflow and outflow direction should be used, which could reduce the discrepancy between the ebb water levels and the observations in this case. Thus, further detailed investigation on the river bed should be performed in the future.

3.4.3 2D Hydraulic modelling of overland flood

In 2D hydraulic model, the elevation data is the most critical factor to determine the inundation depth and inundation extent. Since the raw data source was not fully filtered by the building height in the city, a modification of ground elevation has been done in a GIS Environment. Since Shanghai is a flat region with average elevation of 3.5m, it manually changed the elevation above 8m into 3.5m in the city of Shanghai. Since the inundation depth is the main output in the inundation map in this research, 300m resolution of the ground elevation as grid cell in the GIS environment could be enough. If the velocity is also required as the flood characteristics, finer resolution should be taken into account to compute more accurate results. Therefore, it is highly recommend collecting high quality of elevation data in the future. Regarding surface roughness, considering Shanghai is a highly developing city with various industrial and commercial buildings, the surface roughness was widely taken as the manning value of 0.06. It is equivalent to the value of urban area being full with industrial and commercial buildings. In reality, the intricate network of the roads and streets in the city could block the water in the flooding, so the inundation extent would be over-estimated.

A number of assumptions were made during the scenarios analysis especially the breach scenarios; it was assumed that the breaching were all sudden collapses with a large breach width in the model. This is aimed to explore the worst-case scenarios of flooding in the Huangpu River. Further study on the breach modelling in a probabilistic method is strongly recommended in order to identify the flood risk of the Huangpu River. Therefore, the current results of the flood hazards analysis in Shanghai could be regarded as a preliminary analysis or the first approximation of the inundation depth due to different scenarios.

Appendix 3-1: Ranking of probability distribution at gauge stations in best-fit software

Tab. 3- 1 Ranking of selected probability distribution at Wusongkou

Distribution	Kolmogorov Smirnov (Critical value=0.109)		Anderson Darling		Chi-Squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gen. Extreme Value	0.0543	1	0.27357	1	0.74808	1
Gamma (3P)	0.0706	4	0.39937	4	5.9599	4
Gumbel Max	0.06057	2	0.30003	2	1.1559	3
Log-Pearson 3	0.0647	3	0.34152	3	1.0962	2
Weibull (3P)	0.09106	5	0.80614	5	7.7683	5

Tab. 3- 2 Ranking of selected probability distribution at Huangpu Park

Distribution	Kolmogorov Smirnov (Critical value = 0.0879)		Anderson Darling		Chi-Squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gen. Extreme Value	0.05251	1	0.1723	1	3.633	1
Gumbel	0.05755	2	0.21167	2	5.0524	4
Peason Type 3	0.06077	3	0.24001	3	4.9164	3
Log-Pearson 3	0.06254	4	0.3361	4	4.0715	2
Weibull (3P)	0.07684	5	0.50072	5	5.7829	5

Tab. 3- 3 Ranking of selected probability distribution at Mishidu

Distribution	Kolmogorov Smirnov (Critical value =0.0875)		Anderson Darling		Chi-Squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gamma (3P)	0.13679	4	0.9743	3	8.9959	3
Gen. Extreme Value	0.08142	1	4.2615	5	N/A	
Gumbel Max	0.18956	5	3.9023	4	15.778	4
Log-Pearson 3	0.08664	3	0.33172	2	2.3868	1
Weibull (3P)	0.08143	2	0.29913	1	2.4001	2

Appendix 3-2: Parameters Estimation Method

1 Maximum likelihood method (MLM)

The Maximum Likelihood Estimation (MLM) is a general and typical statistical principle for fitting a mathematical model to the observed data. MLM is famous for its sufficiency, consistency, efficiency and parameterization invariance (Myung, 2003).

MLM starts with the likelihood function. Consider a set of random values $\{x_1, x_2, x_3, \dots, x_n\}$, the corresponding probability density function is denote as $f(x_i | \theta_i)$. $f(x_i | \theta_i)$ is parameterized by unknown parameters $\{\theta_i\}$. The likelihood function in terms of $\{\theta_i\}$ with $x_1, x_2, x_3, \dots, x_n$ is expressed as (Akaike, 1971):

$$L(\theta) = \prod_{i=1}^n f(\theta | x_i)$$

MLM estimates θ by seeking the parameter value of θ that maximizes the $L(\theta)$. In conclusion, MLM is a principle to find the probability distribution that makes the observational data occurs in maximum possible.

- **GEV distribution**

If the set $\{x_i\}$ are independent and identically distributed from a GEV distribution, then the log-likelihood function for a sample of n observations $\{x_1, x_2, x_3, \dots, x_n\}$ is

$$\ln[L(\theta | x)] = -n \ln(\mu) + \sum_{i=1}^n \left[\left(\frac{1}{\sigma} - 1 \right) \ln(y_i) - (y_i)^{1/\sigma} \right]$$

Where $\theta = (k, \mu, \sigma)$ and $y_i = [1 - (\sigma / \mu)(x - k)]$ (Hosking et al 1985a). The MLE of k, μ, σ can be identified by solving the following system of equations, which correspond to setting to zero the first derivations of $\ln[L(\theta | x)]$ with respect to each parameter (Hosking, 1985). Thus

$$\begin{aligned} \frac{1}{\mu} \sum_{i=1}^n \left[\frac{1 - \sigma - (y_i)^{1/k}}{y_i} \right] &= 0 \\ -\frac{n}{\mu} + \frac{1}{\mu} \sum_{i=1}^n \left[\frac{1 - \sigma - (y_i)^{1/\sigma}}{y_i} \left(\frac{x_i - k}{\mu} \right) \right] &= 0 \\ -\frac{1}{\sigma^2} \sum_{i=1}^n \left\{ \ln(y_i) [1 - \sigma - (y_i)^{1/\sigma}] + \frac{1 - \sigma - (y_i)^{1/\sigma}}{y_i} \sigma \left(\frac{x_i - k}{\mu} \right) \right\} &= 0 \end{aligned}$$

The Newton-Raphson method was used to solve the likelihood equations above following Hosking 1985 and Macleod 1989. The *gevfit* in Matlab is used to produce the results in this thesis.

- **P-III distribution**

If the set $\{x_i\}$ are independent and identically distributed from a P-III distribution, then the log-likelihood function for a sample of n observations $\{x_1, x_2, x_3, \dots, x_n\}$ is

$$\ln[L(\theta | x)] = \frac{\beta^\alpha}{\Gamma(\alpha)} \prod_{i=1}^n (x_i - a_0)^{\alpha-1}$$

Since P-III distribution is also a three-parameter gamma distribution, the sample dataset can be converted to gamma distribution, the parameter can be estimated by the maximum likelihood method by *gamfit* function in Matlab.

2 Least square method (LSM)

The method of least squares assumes that the best-fit curve of a given type is the curve that has the minimal sum of the deviations squared (least square error) from a given set of data. Suppose that the data points are $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$. Where x is the independent variable and y is the dependent variable. The fitting curve $f(\theta_i | x)$ has the deviation (error) d from each data point, i.e., $d_1 = y_1 - f(\theta_i | x_1)$, $d_2 = y_2 - f(\theta_i | x_2)$, ..., $d_n = y_n - f(\theta_i | x_n)$. According to the method of least squares, the best fitting curve has the property that:

$$\prod = d_1^2 + d_2^2 + \dots + d_n^2 = \sum_{i=1}^n d_i^2 = \sum_{i=1}^n [y_i - f(\theta | x_i)]^2 = \min$$

Where θ_i is the parameter in the objective function $i = 1, 2, \dots, n$.

The objective function in LSM for GEV and P-III distribution are their CDF cumulative distribution function see Equation 3.4 and Equation 3.6.

The main disadvantage of least-squares fitting is its sensitivity to outliers. Outliers have a large influence on the fit because squaring the residuals magnifies the effects of these extreme data points. To minimize the influence of outliers, you can fit your data using robust least-squares regression.

The *lsqcurvefit* function in Matlab is used to produce the results.

3 Linear moments method (LMM)

L-moments method (LMM) are certain linear combinations of probability weighted moments (Hosking 1990). The L-moment estimators are desired because of their notable advantage, including fast, small biases, easy to understand, and always derived feasible estimators. LMM can often be used when MLM is unavailable, is difficult to compute, or has undesirable properties.

Let X be a random ordered sample $X_{1n} \leq X_{2n} \leq X_{3n} \leq \dots \leq X_{nn}$ follows the cumulative distribution function $F(x)$. The L-moments of a population, $\lambda_r(F)$, $r = 1, 2, 3, \dots$, are emphasized as certain linear combinations of the expected order statistics.

Definition of Linear moment:

$$\lambda_r(F) = r^{-1} \sum_{j=0}^{r-1} (-1)^j \binom{r-1}{j} EX_{r-j:r} \quad r=1,2,3,\dots$$

The first L-moment is a measure of location; the second L-moment is a measure of spread. Other shape features can be obtained by dividing higher order L-moments by λ_2 , which is also called higher order L-moment ratios. τ_r are dimensionless analogies of L-moment. In particular, τ_3 and τ_4 are plausible measures of skewness and kurtosis, respectively.

$$\text{L-Cv: } \tau = \frac{\lambda_2}{\lambda_1}$$

$$\text{High-order L-moment ratios: } \tau_r = \frac{\lambda_r}{\lambda_2} \quad r=3, 4, \dots$$

It has been proved that the L-moments has connection to the probability weighted moments which was put forward in 1979 by (Greenwood, Landwehr et al.).

$$\lambda_{r+1} = \sum_{j=0}^r \frac{(-1)^{r-j} (r+j)!}{(j!)^2 (r-j)!} M_{1,j,0} \quad r=0,1,2,3,\dots$$

Probability weighted Moments can be estimated by a random sample with descend order.

$$\hat{M}_{1,0,0} = \frac{1}{n} \sum_{i=1}^n x_i$$

$$\hat{M}_{1,1,0} = \frac{1}{n} \sum_{i=1}^n \frac{n-i}{n-1} x_i$$

$$\hat{M}_{1,2,0} = \frac{1}{n} \sum_{i=1}^n \frac{(n-i)(n-i-1)}{(n-1)(n-2)} x_i$$

• GEV distribution

According to (Hosking and Wallis 1997), the parameters of **GEV**, k (shape parameter), μ (location parameter) and σ (scale parameter) can be estimated with the following L-moments equations:

$$\lambda_1 = \mu + \sigma[1 - \Gamma(1+k)]/k$$

$$\lambda_2 = \sigma(1 - 2^{-k})\Gamma(1+k)/k$$

$$\tau_3 = 2(1 - 3^{-k})/(1 - 2^{-k}) - 3$$

$$\tau_4 = [5(1 - 4^{-k}) - 10(1 - 3^{-k}) + 6(1 - 2^{-k})]/(1 - 2^{-k})$$

Since there is no obvious solution for the parameters, if $-0.5 \leq \tau_3 \leq 0.5$, the location parameter can be estimated as below:

$$k \approx 7.8590c + 2.9554c^2$$

$$c = \frac{2}{3 + \tau_3} - \frac{\log 2}{\log 3}$$

Then, the other two parameters can be estimated in the following equations:

$$\mu = \lambda_1 - \sigma\{1 - \Gamma(1+k)\}/k$$

$$\sigma = \frac{\lambda_2 k}{(1 - 2^{-k})\Gamma(1 + k)}$$

• **P-III distribution**

In the probability distribution of P-III, E_x , C_v , and C_s can be estimated with the following L-moments equations:

$$E_x = \lambda_1$$

$$C_v = \frac{\sqrt{\pi\alpha}\Gamma(\alpha)\lambda_2}{\Gamma(\alpha + \frac{1}{2})\lambda_1}$$

$$C_s = \frac{2}{\sqrt{\alpha}} \text{sign}(\tau_3)$$

$$\alpha \approx \begin{cases} \frac{1 + 0.2906z}{z + 0.1882z^2 + 0.0442z^3}, 0 < |\tau_3| < \frac{1}{3}, z = 3\pi\tau_3^2 \\ \frac{0.36067z - 0.59567z^2 + 0.2536z^3}{1 - 2.78861z + 2.56096z^2 - 0.77045z^3}, \frac{1}{3} \leq |\tau_3| < 1, z = 1 - |\tau_3| \end{cases}$$

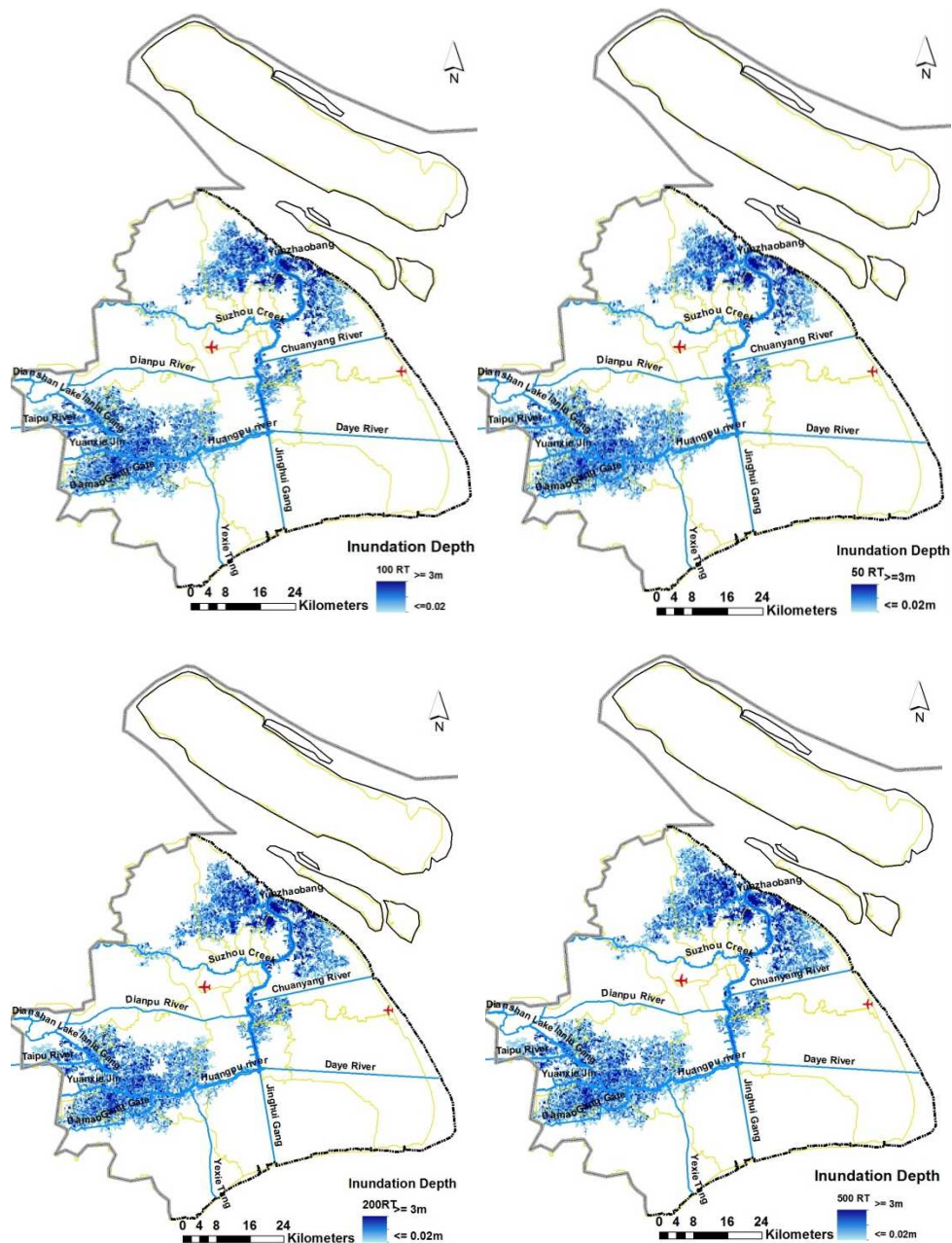
Then the parameter of P-III can be derived by the following equations:

$$a_0 = E_x \left(1 - \frac{2C_v}{C_s}\right)$$

$$\alpha = \frac{4}{C_s^2}$$

$$\beta = \frac{2}{E_x C_v C_s}$$

Appendix 3-3: Results of inundation maps due to no embankments under different return periods



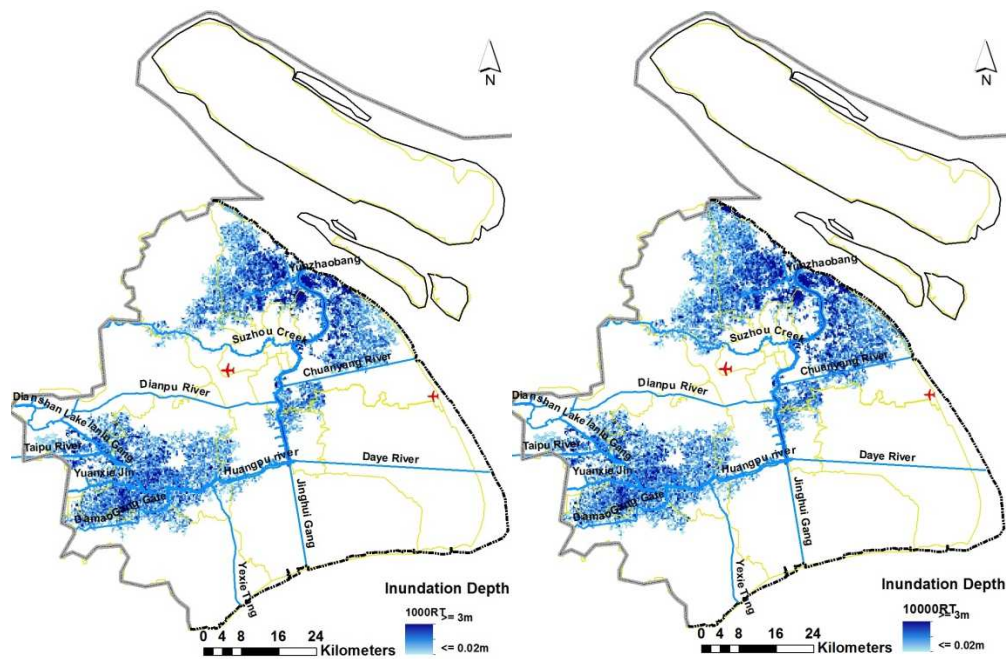
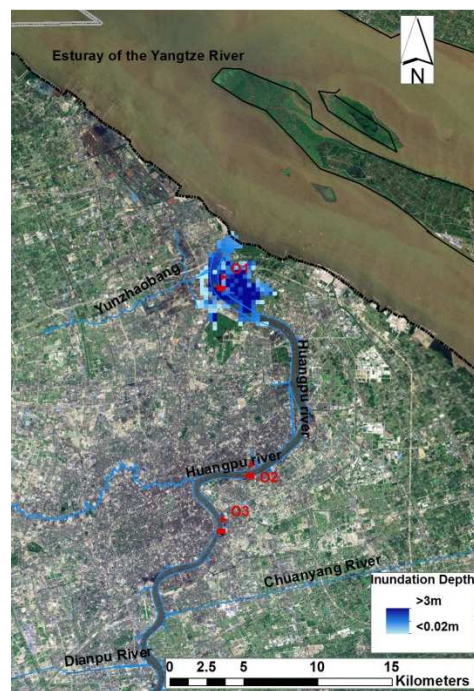


Fig.3- 1 Inundation map under the scenarios of no embankment along the river in Shanghai as a function of return periods of 50yr, 100yr, 200yr,500yr,1,000yr and 10,000yr at Wusongkou boundary condition

Appendix 3-4: Results of inundation maps at potential overtopping points



(RT=10,000yr)

Fig.3- 2 Maximum inundation depth on the overtopping scenarios of 4.5km away from the mouth

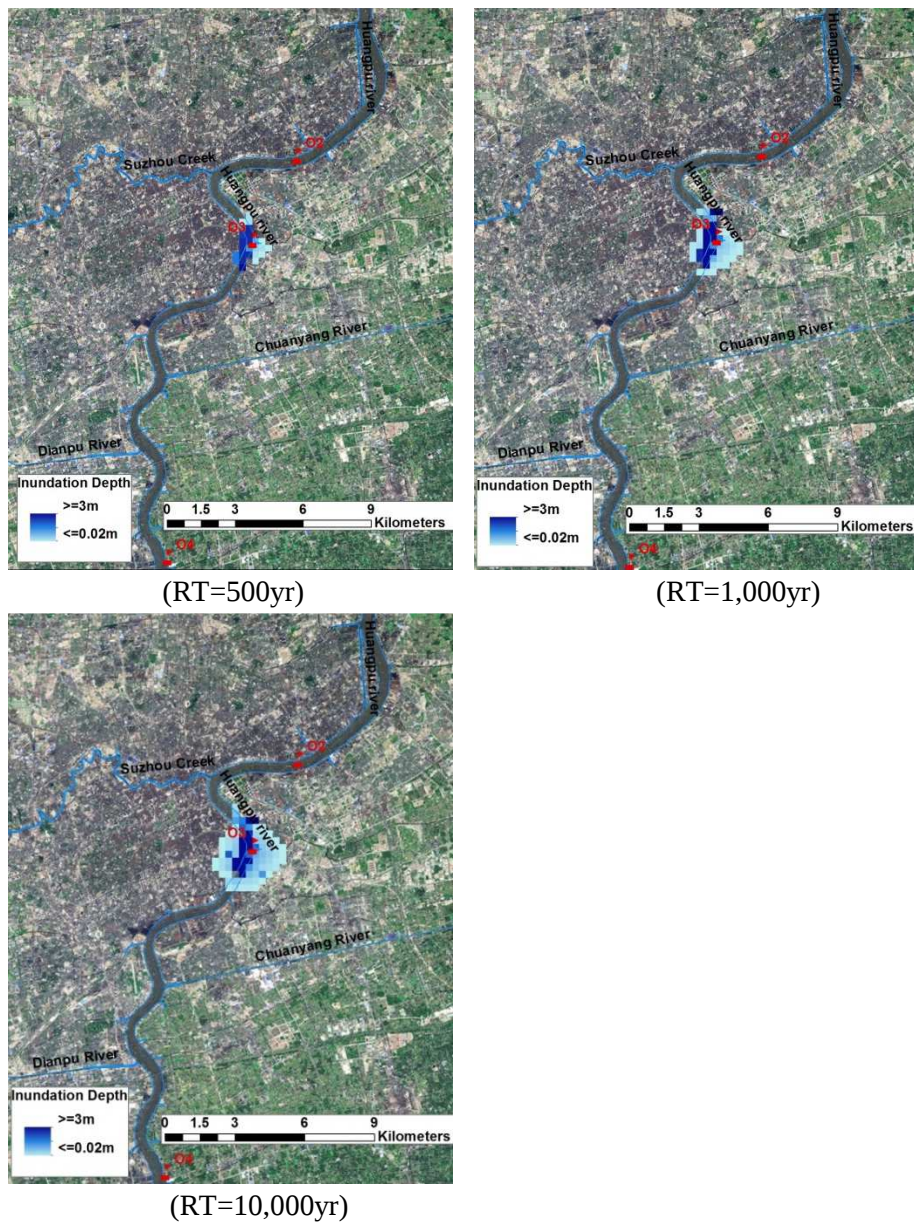


Fig.3- 3 Maximum inundation depth on the overtopping scenarios of 28km away from the mouth due to return periods of 500yr, 1,000 yr and 10,000yr

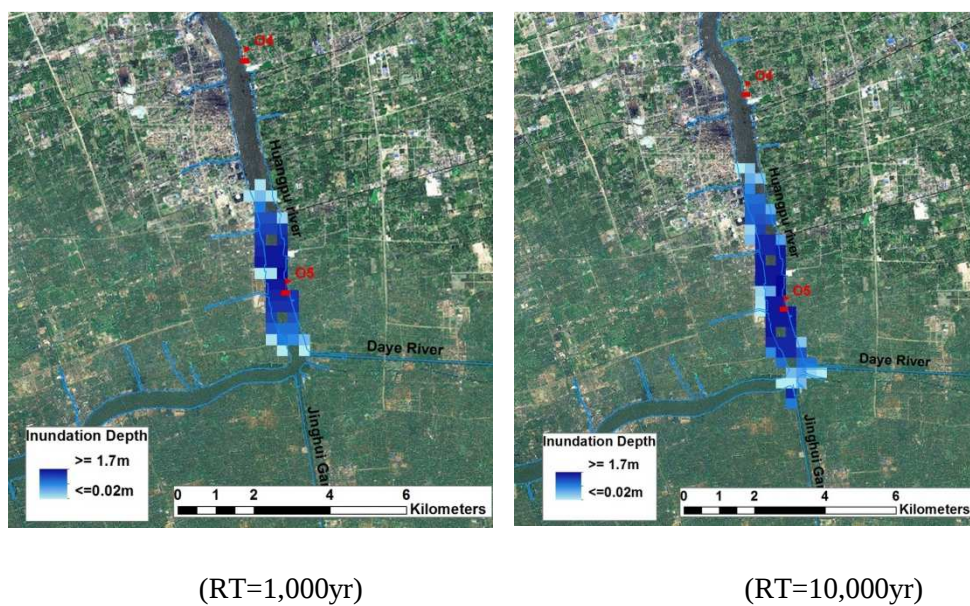
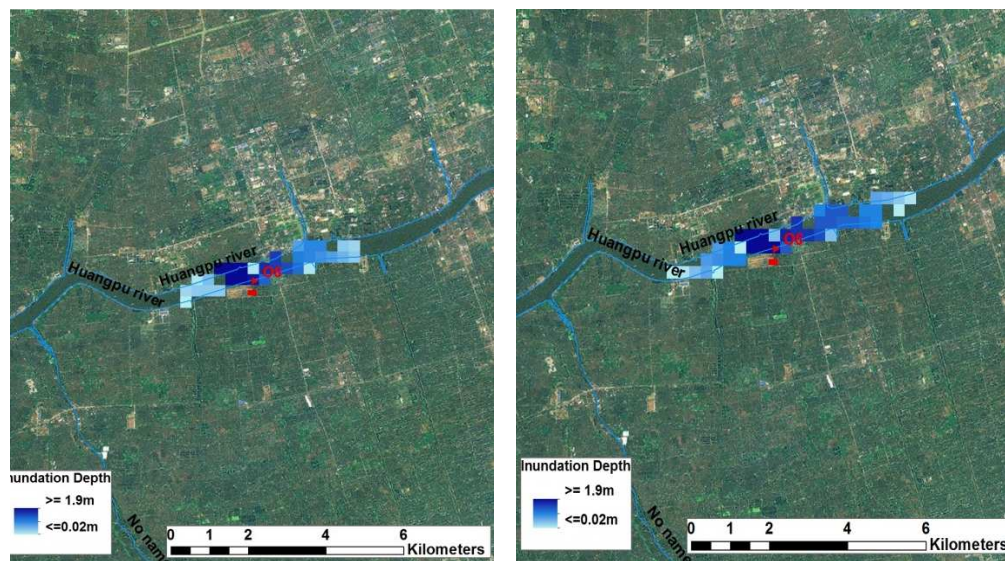


Fig.3- 4 Maximum inundation depth on the overtopping scenarios of 50km away from the mouth as a function of return periods of 1,000yr and 10,000yr

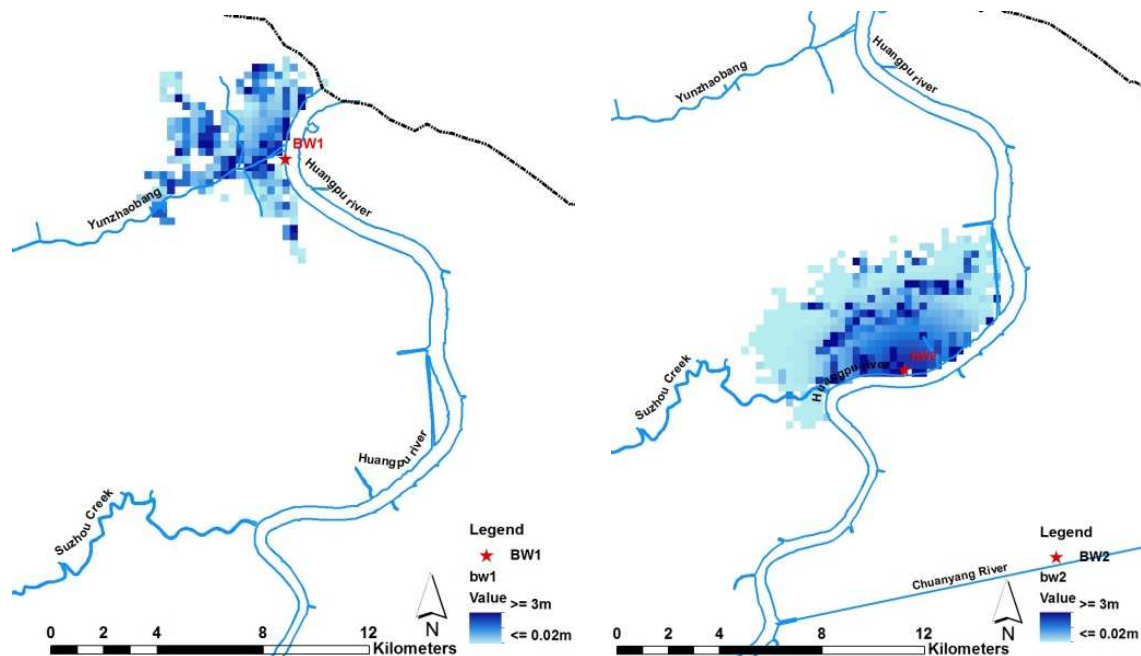


(RT=1,000yr)

(RT=10,000yr)

Fig.3- 5 Maximum inundation depth on the overtopping scenarios of 65km away from the mouth as a function of return periods of 1,000yr and 10,000yr

Appendix 3-5: Results of inundation maps due to potential breaching in east and west side of the Huangpu River



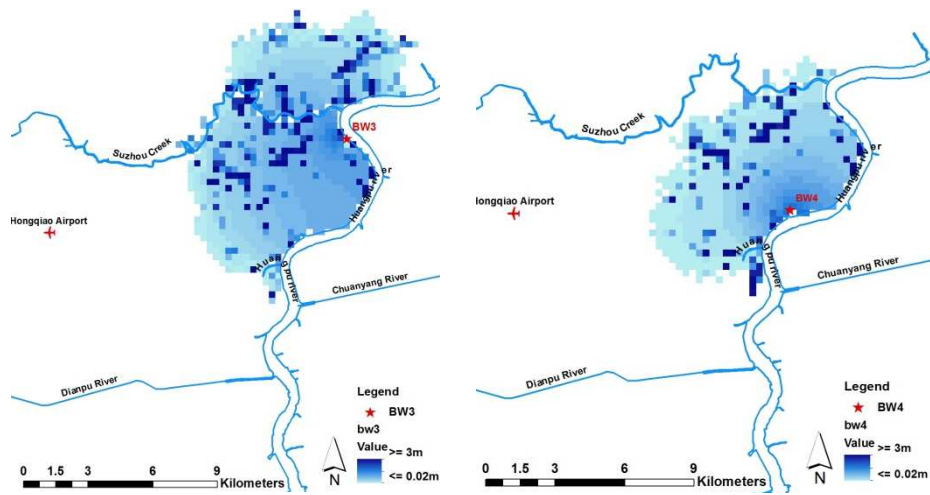


Fig.3- 6 Maximum inundation depth due to breaching scenarios on the west side of the Huangpu River at BW1, BW2, BW3 and BW4

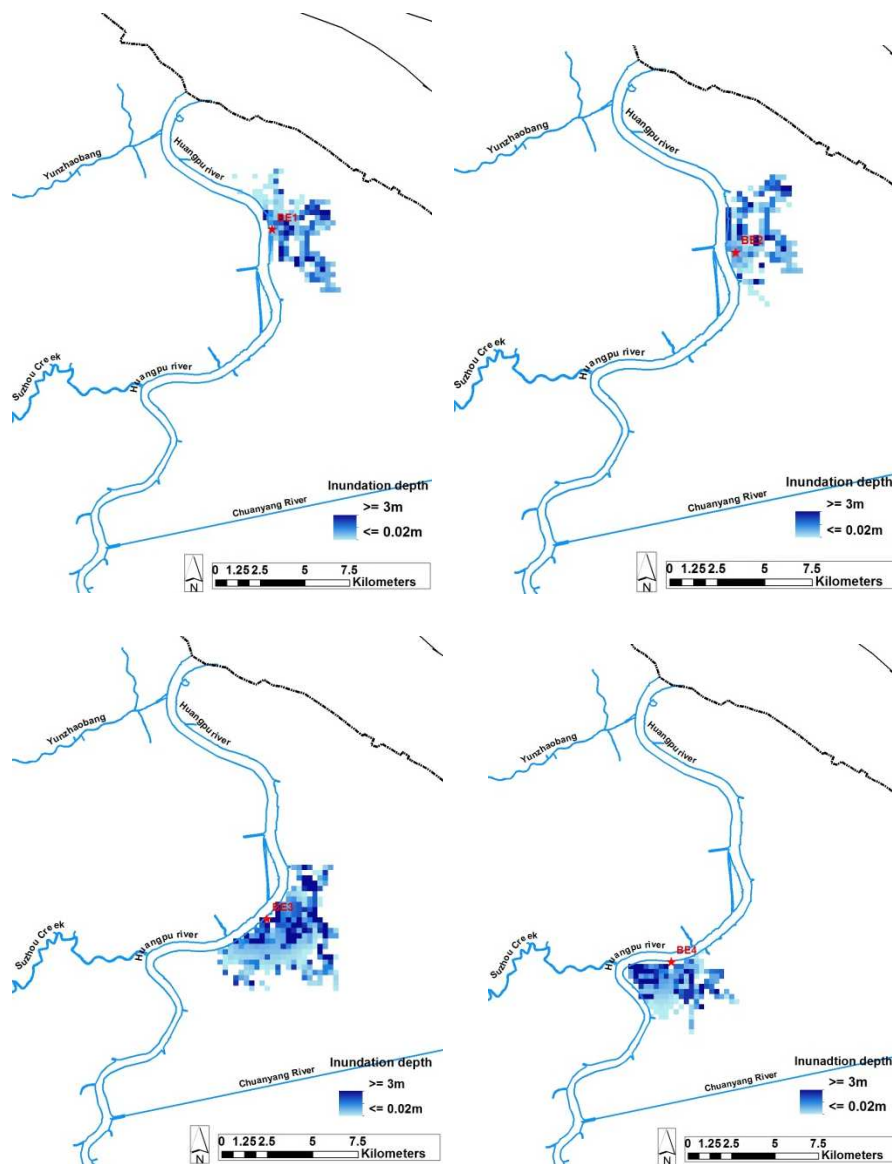


Fig.3- 7 Maximum inundation depth due to breaching under scenarios on the East side of the Huangpu River at BE1, BE2, BE3 and BE4

Chapter 4

Shanghai: Flood damage estimation

Flood damage assessment plays an increasingly important role in flood risk management. Potential flood damage in metropolitan cities like Shanghai can be massive due to large extent of flooding and the high rate of socio-economic development and the rapid urbanization in the future. Different flood scenarios result in the associated damage to different degrees. In Shanghai, the damage estimation for a series of building-categories at an individual building level under different flood scenarios has not been studied yet. In addition, an estimation of service interruption of subway system and other critical infrastructures could supplement the estimation of flood damage in a complete way although numerous researches have emphasized the vulnerability of underground space to floods in Shanghai. Therefore, the objective of this chapter is to estimate the direct and indirect potential economic damage, and to highlight the inconvenience of service interruption during flood events in a selected area of Shanghai city. In the estimation of maximum potential damage to the buildings, floor area ratio (FAR) was used to estimate market value of buildings, which avoided the lack of data on the number of stories at an individual level of buildings in an urban area. Subsequently, the new damage functions to the damage categories were suggested in Shanghai; with the application of these functions, it was calculated that the potential damage under three scenarios were 114, 560 and 328 million \$USD, which account for 1.98%, 10.39% and 5.68% of the maximum potential damage (5.77 billion \$USD), respectively. On the other hand, flood would also cause service disruption in the subway, schools and hospitals, etc., which is regarded as a great loss on the tourism reputation and revenue. Furthermore, in the discussion of the effects of components on the flood damage, damage function has greatest influence on the final results, which deserves priority of study to reduce the uncertainty of flood damage estimation in the future.

4.1 Introduction

Flood damage draws increasingly attentions in recent years in the field of flood risk management (Wind et al., 1999; Kreibich et al. 2004; Thielen et al., 2005; Jonkman, Kok et al. 2008; Merz Bubeck, de Moel et al. 2011). A widely accepted method of flood damage estimation is the assessment based on stage-damage function, which considers the relationships of flood characteristics (such as water depth, flow velocity, flood duration, etc.) and damage extent (either by the absolute damage values or the relative damage rates) in the elements at risk. The absolute damage value could be regarded as the cost to recover the originality of the elements at risk; the relative damage rate refers to the fraction of the amount of damage (i.e. repair cost) to the maximum economic damage of the elements at risk. The stage-damage function can be derived based on historical empirical data or expert judgement, as a fundamental element in the estimation of flood damage. Besides, the maximum economic damage is also crucial in flood damage estimation, which is usually calculated on a basis of market value of the elements at risk. All the information related to the damage can be represented on ground grid cell via geo-information system and the results of flood damage can be shown on the map under a specific flood event/scenario. This approach is regarded as a standard method in the Netherlands, which has been represented in a software tool of HIS-SSM to calculate physical, economic, and social impacts of disasters (Kok, Huizinga et al. 2004; CDC 2005). It has been widely applied in south and west part of the Netherlands. Likewise, Hazus[®]MH is a U.S standardized methodology to calculate the potential loss in terms of economic losses, structural damage, etc. from multi-hazards (e.g. flood, earthquake and storm surge) based on GIS environment, which also relates the hazard and exposure in the form of damage curves to calculate the losses (Scawthorn, Blais et al. 2006; Wagemaker, Leenders et al. 2008; Cummings, Todhunter et al. 2012; Dierauer, Pinter et al. 2012). The approach of stage-damage function mainly estimates tangible direct damage, while there are numbers of models which can be used to estimate intangible (environmental impacts, loss of life) or indirect damage (business interruption), e.g. contingent valuation method and input-output model (Hasegawa, Tamura et al. 2009). The contingent valuation method depends on the people's willingness to pay specific environmental services, which has been applicable in the developing counties, such as Vietnam, Brazil, and Nigeria (Fuks and Chatterjee 2008). Bočkarjova (2007) applied input-output models to assess the indirect loss by using the interconnectedness of economic sectors (like agriculture, manufacturing and construction), and to determine the amount of production loss after the flood. Besides, Vilier (2013) applied ARIO (Adaptive Regional Input-Output) model to estimate the cost of business interruption due to hypothetical breach scenarios in the Netherlands. It showed the results were in line with the actual figures of floods and the losses due to business interruption are non-linear with material damage. Another intangible flood damage is loss of life, Jonkman (2007) estimated the (expected) casualties under the consideration of evacuation schemes in New Orleans and in South Holland. Since flood damage includes economic, social, cultural and environmental impacts, the aforementioned methods in ex-ante and ex-post flood events could provide valuable information on the flood damage estimation in the field of flood risk management for the policy makers or decision makers.

In addition, the estimation of flood damage varies from different spatial scales, which can be classified into micro-scale, meso-scale and macro-scale. In the micro-scale estimation, the specific objects, such as buildings and infrastructures, would be taken into account in the estimation of economic value that is represented as replacement value or depreciated value, in which the latter is recommended as the maximum damage value in the process of flood damage estimation (Merz, Kreibich et al. 2010); In the meso-scale estimation, land use data is employed as the exposure of economic assets in a region or a city; larger units would be adopted in the macro-scale to estimate flood damage, such as in a country or the worldwide range. Furthermore, flood damage may also vary in different temporal scales in terms of economic development and climate change, which affect the ultimate results of flood risk. The projection of flood damage may provide more valuable information for decision-makers in risk-

based approach of flood risk management, which is applicable in cost-benefit analysis of a flood prevention project, an evaluation of risk-reduction measures or the determination of insurance premium.

In Shanghai, limited work has been done in the estimation of flood damage. Wang et al. (2001) developed the depth-damage functions for the buildings and infrastructures under water depth varied from $<0.5\text{m}$ to $>3\text{m}$ at an interval of 0.5m based on insurance records, which is also an initiative of damage estimation in Shanghai. Chen (2002) estimated the flood damage by depth-damage function method in different industry sectors under the assumed water depth of 0.5m , 1m , 1.5m and 2m in downtown of Shanghai to weigh the cost and the benefit of the construction of a storm surge barrier at the mouth of the Huangpu River, whereas the stage-damage functions were all taken from other coastal cities in China. Shi (2010) assessed the flood damage on the floors, decorations and inventories in the residential buildings based on three income groups in a selected area of Shanghai during Typhoon Matsa in 2005. It pointed out the damage rates for each category of contents in the buildings are more or less the same under the corresponding inundation depths for different income groups. However, these damage estimations were limited either in a rough way or in a particular sector; the damage estimation at an individual building-level under different flood scenarios have not been studied yet. In addition, a qualitative analysis of service interruption of subway system and other critical infrastructures could supplement flood damage estimation in a complete way in Shanghai although numerous researches have been emphasized the vulnerability of underground space to flood events. Therefore, the objective of this chapter is to estimate the direct and indirect potential economic damage, and to highlight the inconvenience of service interruption during flood events in a selected area of Shanghai city. A list of research questions will be addressed as below:

- What can be the impacts by river flood in Shanghai?
- What factors can affect the results? Which one affects most? How to determine damage?
- How much damage could result under different scenarios of flooding? What are the uncertainties of results?
- What could be the impacts of service interruption after floods in Shanghai?

The structure of the remaining sections will be organized as below. Section 4.2 is going to study the damage model of tangible direct damage, especially in stage damage function method, and to analyse the impacts of tangible indirect damage after floods. Section 4.3 is a case study in part of downtown area of Shanghai in terms of direct and indirect damage estimation. In the end, Section 4.4 is a discussion of the results on flood damage in Shanghai.

4.2 Economic damage modelling

Regarding to the flood damage, it is necessary to clarify the flood damage types, especially the scope of damage being used in this research. Flood damage is primarily categorized into two types by addressing two questions: 1) whether the loss is caused by (direct) contact of flood water and 2) whether the damage items can be expressed in a monetary term. The answer 'Yes' to the first question is direct damage, such as structural damage to buildings, contents, transportation infrastructures (e.g. road and railways), lifeline systems (e.g. gasoline pipes, telecommunications and electricity infrastructures, etc.) and vehicles, or damage to crops and livestock in rural area and the answer of "No" is indirect damage, which mainly reflects on disruption of transport network and then results in service and business interruption. The second question is principally addressed on monetary representation, which is expressed on tangible and intangible damage, respectively, by either hardly expressed (e.g. loss of lives) or quantified (e.g. psychological trauma) by marketed value. A summary of types of loss from flood in this research is shown in Tab.4. 1. In this section, the main focus is on the tangible direct damage and indirect damage; other categories of flood damage will not be discussed and addressed.

Tab.4. 1 Types of flood damage (Handmer 2002; Jonkman, Bockarjova et al. 2008; Merz, Kreibich et al. 2010)

Whether the damage items can be expressed in a monetary term?	Whether the damage is caused by (direct) contact of flood water?	
	Direct (Yes)	Indirect (No)
Tangible (Yes)	damage to building, contents, transportation infrastructures, lifeline systems, vehicles, crops, livestock, etc.	service interruption, business interruption, temporary evacuation, clean cost, etc.
Intangible (No)	injuries, loss of lives, damage to cultural heritage, ecological damage, etc.	inconvenience of social life, psychological trauma, etc.

Note: The bold text of damage category would be addressed in this section

4.2.1 Tangible direct damage

Direct economic damage is the largest component of damages in floods. The standardized method to assess the direct economic damage can be divided into three steps. First, the elements at risk should be classified into different categories based on expert judgement. For example, in Dutch flood damage model, the potential damage assets are consist of agriculture and recreation, roads and railway, electricity and communication, cars, industry, and different types of buildings, which are either represented by land use categories (Klijn, Baan et al. 2007) or at an individual object level (Kok, Huizinga et al. 2004). In China, the categories of direct damage objects include agriculture, engineering structures, residential inventories, industrial and commercial assets, lifelines, medical cost and relocation cost, etc. (WRM 1998). Second, the maximum economic damage needs to be evaluated based on the damage categories and their (market) values. It could be viewed as an exposure assessment to the flooding. In the Netherlands, the maximum damage value is considered before damage calculation, which is based on the 'Financial Numbers Damage caused by Floods' (NEI 2002) in \$USD/m² or \$USD/units. Third, the stage-damage functions for the elements at risk need to be developed and applied to produce the flood damage.

4.2.1.1 Damage model

In this research, a simple model can describe how to calculate the tangible direct damage due to flood:

$$F_d = S_i \times f(d, t, v, r, \dots) \quad (4.1)$$

Where: F_d - flood damage in monetary terms [\$ USD]; S_i - maximum potential values of elements-at-risk i [\$ USD]; d - inundation depth [m]; t - flood duration [h]; v - flow velocity [m s⁻¹]; r - rising rate [m s⁻¹]; $f(d, t, v, r \dots)$ - damage function [0, 1], in other words which could be regarded as damage rate [0,1] related to flood characteristics.

This model is a widely accepted way of flood damage estimation. A crucial component in this model is stage-damage function $f(d, t, v, r, \dots)$, which is concerned with a relationship between the severity of the flood hazard and the extent of damage that is represented either by absolute damage in monetary unit (\$ USD) or by relative damage in proportional to maximum damage (%). Maximum potential value of elements at risk (S_i) is an estimation of economic value for exposed objects in the study area, i stands for the number of the categories of the elements at risk. Flood hazard, which are mostly represented by hydrological characteristics under an exceedance probability of flooding, such as inundation

depth (d), flood duration (t), flow velocity (v) and rising rate (r), etc., reflects the severity of flood event, which is explicitly or implicitly connected to damage degree. Fig. 4. 1 shows the method of the economic estimation of tangible direct damage in a spatial distribution on the map. Flooded area can be represented with information of inundation depth and maximum damage value in ground grid cells; the application of stage-damage function on the damage categories can compute the end results; in the results, each grid cell is assigned a value of flood damage and shown on the map accordingly.

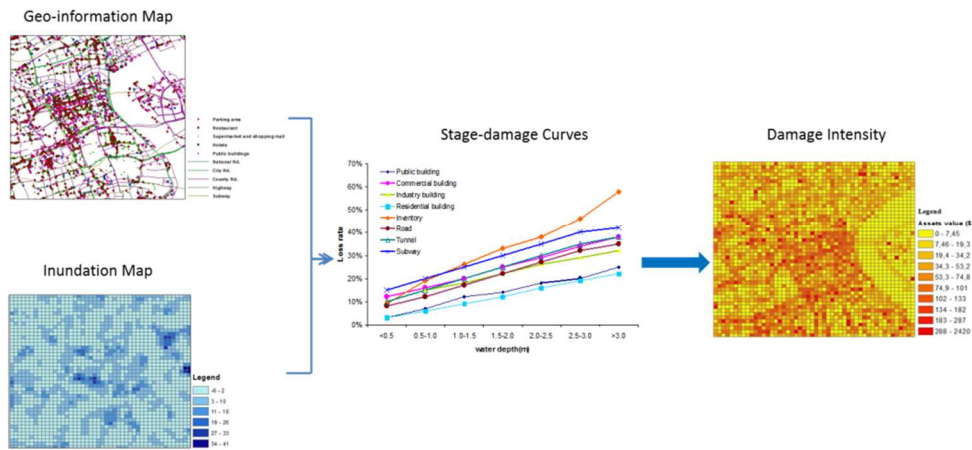


Fig. 4. 1 Tangible direct damage model in this section

4.2.1.2 Depth-damage functions

Depth-damage functions relate flood characteristics and damage extent in the flood events. ‘Depth’ refers to water depth or inundation depth in an area by a flood event, which incurred the associated damage to the buildings or infrastructures, etc. While other flood characteristics, such as flow velocity, rising rate of the water, flood duration and contamination in the water, etc., are also the critical factors to the flood damage in specific regions or on specific objects. Hence, ‘depth’ in depth damage function should not be limited to the inundation depth. Flow velocity and rising rate of the water would be considered as the most critical factors to the damage/loss of life in steep catchments or near breaches. Flood duration matters largely in the damage/loss of transportation infrastructure or business interruption. Flood induced contamination with heating oil may lead to the completely damage to the inundated buildings (Merz, Thielen et al. 2007). Nevertheless, the inundation depth is commonly selected as a main indicator to determine the flood damage in many cases (Wind, Nierop et al. 1999; Merz, Thielen et al. 2007; de Moel and Aerts 2011). First, inundation depth is an obvious indicator, which has the biggest influence on flood damage. Second, it can be computed by either 1D or 2D hydraulic model, less efforts (e.g. data and CPU time) are required in the computation of hydrodynamic model compared to other characterises. For example, the ground roughness, breaching growth and drainage capacity would be the added information for the computation of flow velocity, rising rate of the water and flood duration in the model, respectively.

In general, depth-damage functions can be produced by two methods. The empirical function is based on the data and information from one or more historical events in an area, which can be used to estimate flood damage for the subsequent flood event(s) in the same area or applied in other similar area. Synthetic depth-damage function is largely based on expert judgment on the flood surveys from insurance companies or loss adjuster. Synthetic functions are hypothetical curves developed independently from historical flood data for a specific area (Middelmann-Fernandes 2010). The empirical curves usually conveys rich information on flood characteristics including inundation depth, flow velocity, flood duration, water quality, rising rate of water, etc., as a result the surveys require large efforts and are usually time-consuming. Synthetic functions could be extrapolated in other areas due to its integrated consideration on the relationship of flood characteristics and flooded objects from differ-

ent perspectives of experts. For example in UK, the hypothetical damage for buildings and contents at different water depths was appraised by What-If-Survey executed by flood damage experts and experts in other disciplines (e.g. architects). Examples of empirical function could be found in the applications of German HOWAS damage database (Merz, Kreibich et al. 2004), urban flood loss in Bangkok (Dutta and Tingsanchali 2003) and a Brazilian case (Nascimento, Baptista et al. 2006). The synthetic functions, on the other hand, are widely employed in UK (Penning-Rowsell et al., 2005), the Netherlands (Kok, Huizinga et al. 2004) and other countries (Smith 1994).

In China, depth-damage functions were developed differently based on the data availability in areas or cities. Wang et al. (2001) generated depth-damage functions based on the historical data of flood events to estimate urban flood damage in Guangzhou city (See Fig. 4. 2). The depth-damage curves in coastal area of Tianjin city and Tan district of the Yellow river basin were derived by (Feng and Cui 2001). Kang et al. (2006) showed inventories are more vulnerable to flooding than the structural damage of buildings (Fig. 4. 3). These are all valuable data for flood damage assessment in Chinese cities. Shi et al. (2009) investigated the flood damage by an urban flood in summer 2008 on residential buildings and inventories. She formulated the empirical depth-damage functions in Shenzhen city (see right figure in Fig. 4. 2). It is noted that the scatter dots show large uncertainties of the depth-damage functions on the buildings and inventories in the study area. The logarithm fit curves need to be further calibrated to enable the application in the subsequent floods in Shenzhen or other cities. In a summary, the Chinese depth-damage functions are commonly related to inundation depth, which also shows inundation depth is the most influential indicator in the estimation of flood damage. Based on these existing functions, it is noticed that the flood damage occurs when the inundation depth is no more than 0.5m and the maximum damage could be reached with damage rate of 40%-60% under 3-3.5m or more.

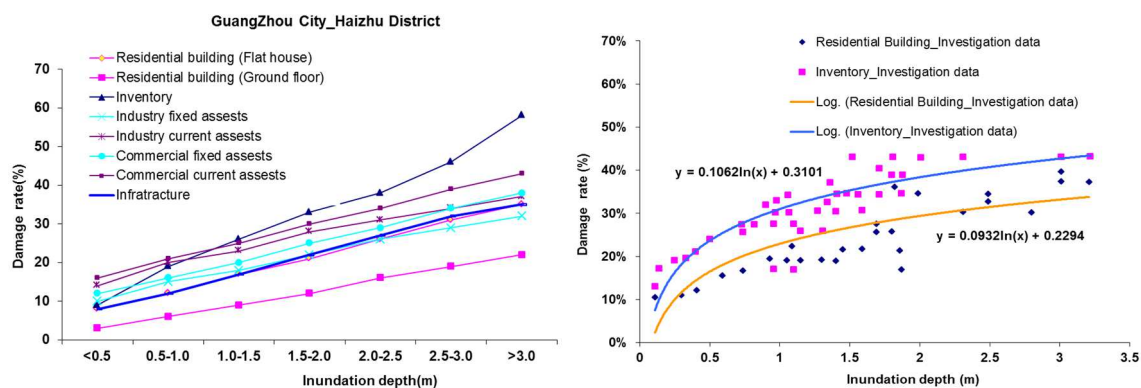


Fig. 4. 2 Relationship of water depth and property loss rate in Haizhu district of Guangzhou City(left) based on (Wang 2002) and Shenzhen City (right) based on (Shi, Shi et al. 2009)

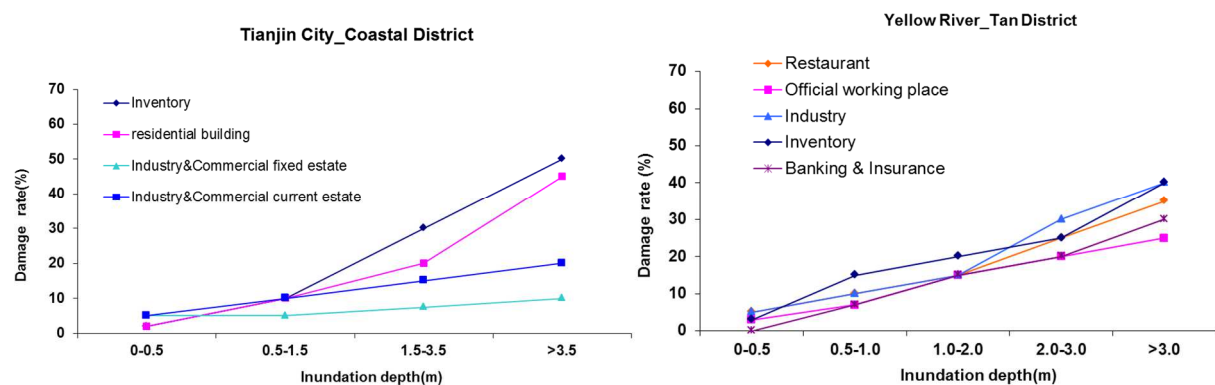


Fig. 4. 3 Relationship of water depth and property loss rate in coastal district of Tianjin City (left) based on (Feng, Cui et al. 2001) and Tan district of Yellow river (right) based on (Kang, Wu et al. 2006)

4.2.2 Tangible indirect damage

Indirect flood damage can cause substantial economic and social disruptions that may last over long periods of time. An illustration is the interruption of lifeline utilities and infrastructure, which could potentially lead to widespread economic and social repercussions due to the damage to critical links within their networks (Veerbeek 2007). The same can be said for business interruption of production facilities that provide vital goods or services. To concretely point out, the interruption of energy lifelines (electricity, gas and water, etc.), transportation infrastructures, urban facilities, and communication facilities (landlines, cell phone, radio and internet, etc.) significantly impair the economic development (e.g. production and service), and people's social lives. For example, Hurricane Sandy in 2012 raised a great impact on US and also other affected countries. The total damage in US is estimated at over 63 billion \$USD. Hurricane Sandy not only flooded streets, tunnels and subway lines, but also indirectly pushed the shops, schools and hospitals closed, several flights cancelled, and even New York stock exchange closed for two days. The severest impact of Sandy is electricity power outages for two days, leaving 8.7 million customers without power (Kunz and Gunturi 2012), which also resulted in the industry lost two business days affecting averagely 27% of the U.S. manufacturing sectors. Moreover, the evacuation & relocating activities, health services and repair, etc. would cost overwhelmingly large as well due to huge storm surge, heavy rainfall and strong wind brought together by Sandy. In the end, it should keep in mind that urban failures due to the hit of disasters has interactions of each element in the system (e.g. lifeline - economy) besides direct (physical) damage.

To reach a rough estimate, the **indirect damage** is usually taken as a constant percentage of direct loss in many countries (see Tab.4. 2). In Chinese regulation of calculation of economic benefit of flood-control projects (WRM 1998), it is recommend to apply empirical percentage of direct loss for indirect economic loss. And previous Chinese researchers also pointed out 15%~28% and 16%~35% of direct loss in agriculture and industrial field, respectively. In Pakistan, the indirect loss is, in general, 12.7% of direct loss when the inundation depth reached to 1m (Tariq 2011); in Australia AN-UFLOOD model (NR&M 2002), 55% and 15% of direct loss is indirect loss in commercial and residential area, respectively, such as clean-up cost; in rural and urban area, the indirect loss is 20% and 45% of direct loss in Australia (DRE 2000).

Tab.4. 2 Empirical ratio of indirect to direct flood damage in some counties

Country		Indirect/direct	Source
China	Agriculture	15%~28%	(Chen 2002; Xiao, Chen et al. 2009)
	Industrial	16%~35%	
Pakistan		12.7% (1m Depth)	(Tariq 2011)
Australia	Commercial	55%	(NR&M 2002)
	Residence	15%	
	Rural area	20%	(DRE 2000)
	Urban area	45%	

Business interruption would be a main aspect of indirect economic damage during flood events. Basically, there are two sources for business interruption due to flooding. One is industries themselves get flooded, which causes production sector being out of order and then not able to meet the suppliers and customers' requirements; another one is the suppliers or the customers cannot easily get access to the industries due to traffic network interruption, which affect the production capacity of the industries indirectly. If a producer is affected during a flood (See Fig. 4. 4) then both those who supply that producer and those who consume the products from that producer will be affected. The ripple effect led to huge loss in a region if the economic boundary is limited within in an area. That's because there are other options for suppliers and customers to seek equilibrium on their productions, they may quit or

defer the original choice and divert resources from other users. In Figure 4, the suppliers have two options: to defer production until the flooded business bounce back to buy their production; or seek another outlet for their product. The consumers of the flooded business of production have three options. The first is to defer their purchases until the business is back in production. The second is to buy an identical product from another producer; and the third is to buy a near substitute product from another producer. In the latter two cases, the consumers experience some loss and there is a national loss if they shift their purchases to a company abroad. The behaviours of varying adaptations for suppliers and customers show that if any single firm is flooded, the effects to all its suppliers and customers need to be followed forwards and backwards, where the adjustments they make will mean that their consumers and suppliers, respectively, will have to make adjustments. This is extremely difficult and very data-intensive (Messner, Penning-Rowsell et al. 2006). A real case of flooding in Thailand in 2011 can demonstrate the business interruption plays a crucial role in flood losses. In 2011, the flood occurred due to dam failures in Chao Prapa River during a heavy rainfall period. The flood starts from late July in north of Thailand and gradually spread to the south. In mid-November, large parts of Bangkok got inundation. The flooding persists until mid-January of 2012. Owing to the long period of the flooding in the area, business interruption is larger than the property damage, which accounts for ~125% of the latter one. Among the 1,43 billion baht (46.5 billion \$ USD) in economic damages and losses due to flooding, most was attribute to the manufacturing industry, as six major industrial estates were inundated by as much as 3 meters (10 feet) during the floods (World bank 2012). Disruptions to manufacturing supply chains affected regional automobile production and caused a global shortage of hard disk drives which lasted throughout 2012. It takes nearly one year for the supply to recover. Business interruption in Thailand is the largest contributor to the total loss of the floods, mainly because the flood lasts for a long time (a couple of months) (AON 2012).

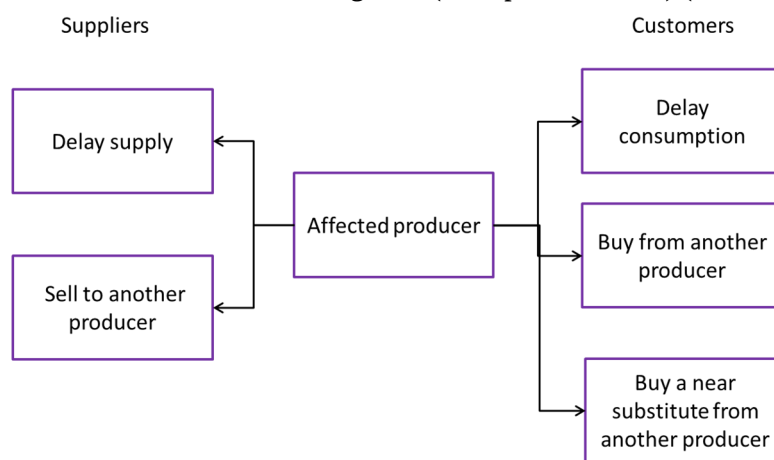


Fig. 4. 4 Options for suppliers and customers to affected producer during business interruption (Messner, Penning-Rowsell et al. 2006)

Another significant effect of indirect damage is the **service interruption** due to breakdown of the subway stations or other underground space under the cities. In recent years, many cases of subway inundation were reported in the world due to flooding from the river or due to the heavy rainfall. On 15 April 2012 at around 13:00, a heavy rainfall poured down in Tehran; and then a break in the channel wall of Kan River caused a flash flood in the Tehran metro tunnels. Consequently, line 4 of the metro went out of operation for about two weeks. This flash flood caused property damage of about \$21 million to the metro especially in the electrical system (Taghizadeh, Soleimani et al. 2013). The damaged stations were repaired and got back to operation in 12 days with the efforts of 2,500 people worked every day. Likewise, during Hurricane Sandy in October of 2012 in New York, the subway service was disrupted for days due to flooding. The flooding water flowed through the streets of lower Manhattan and poured into the subway entrances, cascading into ventilation grates and pooling inside

tunnels. Seven tunnels were flooded, subway stations were battered and switches and signal system were mostly likely damaged. It is reported¹² that the entire system, all 660 miles (1,050 km) and 468 stations of it, is shut down, much of it is inundated with corrosive salt water.

In last decades, a number of cases on the flooding in subway system in the cities of Prague, Taipei, Seoul and Boston were discussed in the report (Compton, Faber et al. 2009). It was summarized that most direct losses in subways were caused by damage to power supply systems, signalling equipment, communication system, ventilation system, tracks and escalators that were out of operation for weeks to months after a flood in the subway. The common cause of the flooding was the overflow/ breaching water from the river; or was heavy rainfall cascading into the tunnel or the stations. In the case of Taipei in 2001, the floodwater partly flowed through from a 6 m² hole in a basement of station to another station nearby. The attempts to close the hole with sandbags were unsuccessful. The subway flooding lasted several days and weeks to get back to the operation. These cases of the flooding caused subway system cease from several days to months, being out of operation or at reduced capacity with temporary measures like manual control singling system. In the case of Seoul in 1998, the metro line suffered large decline in ridership of approximately 40% as a result of the reduced capacity of the line system, which lasts 35 days. These real cases revealed the negative consequence to the subway system in cities in terms of direct damage and the subsequent service interruption has a great impact on people's social life.

4.3 Case study

4.3.1 Study area

The study area (see the red box in Fig. 4. 5) is located in the “Puxi” area, which is the most prosperous economic centre in Shanghai city with famous tourist spots of “Nanjing Road”, “People’s Square”, “Bund” and “Yuyuan Garden” etc. This is a fairly densely-populated area (>15000/km²) with different functions of buildings: commercial buildings, public buildings, residential buildings and industrial buildings, and (underground) infrastructures. The area is approximately 17.2 km² including parts of six districts: Huangpu district, Jing’an district, Zhabei district, Hongkou district, Luwan district, New Pudong district; and water bodies of Huangpu River and Suzhou Creek. The average elevation in this area is WD ~3.0m. The flood threats are largely coming from typhoon weather. The storm surge and high astronomic tides pushes up the water level at the mouth of Huangpu River, which increase the water levels subsequently in the Huangpu River; when high discharges comes from the upstream of the Huangpu River coincidently, water level can rise up to 5.72m during Typhoon Winnie in 1997 at Huangpu Park gauge station, which is equivalent to 200-return periods of a flood event. The main reason to select this part of area as study case is data availability of geo-information on all the buildings, which facilitates the individual level of flood damage estimation on the buildings in urban area, and also makes spatial distribution of damage results possible. In later studies, it is highly recommended to expand or scaled the research to larger areas at a micro level.

¹² <http://science.time.com/2012/10/30/the-lessons-from-new-yorks-flooded-subways/#ixzz2pzKjuzbE>



Fig. 4. 5 Map of Shanghai city (left) and study area with red box (right)

4.3.2 Estimation of tangible direct damage

In the case study, the method of stage-damage function is applied in the estimation of tangible direct economic damage. Eight hypothetical breaching scenarios along the floodwall of the Huangpu River were simulated by 1D2D SOBEK (see more details in Chapter 3), among which three scenarios (BW2, BW3 and BW4) which are adjacent to or within in the study area were selected. They are located at the west side of the Huangpu River to the estuary of 23km, 26.6km and 33.7km, respectively. These scenarios can potentially affect the downtown Shanghai. The breaching are the hypothetical scenarios with a condition that when the water level reaches 5m or more the sudden collapse of floodwall occur at the certain points. In order to pursue worst-case scenarios, the assumed breaching width of floodwall is set as 300m with flood duration of 24 hours. For the study area, the mean value, 5% and 95% percentile of inundation depth under the distribution of grid cell area at scenarios of Bw2, Bw3 and Bw4 are shown in Tab.4. 3. The breaching location (Bw3) in the study area led to inundation depth of 1m averagely with deepest depth of more than 3m, even 95% percent of the inundated grid cells were more than 35cm. It could be a flood disaster for the study area under this scenario. In scenario of Bw2, no more than 1/3 of area were inundated; while in Bw3 and Bw4, more than 2/3 and 1/2 area were flooded according to the map Fig. 4. 6.

Tab.4. 3 Mean value, 5% and 95% percentile of inundation depth under the distribution of inundated grid cell area at scenarios of BW2, BW3, BW4 in the study area

Scenarios	Inundation depth [m]			Inundation extent [-]
	5% percentile	mean value	95% percentile	
Bw2	0.02	0.43	2.00	29.5%
Bw3	0.35	1.00	3.00	76.2%
Bw4	0.02	0.52	3.00	56.7%

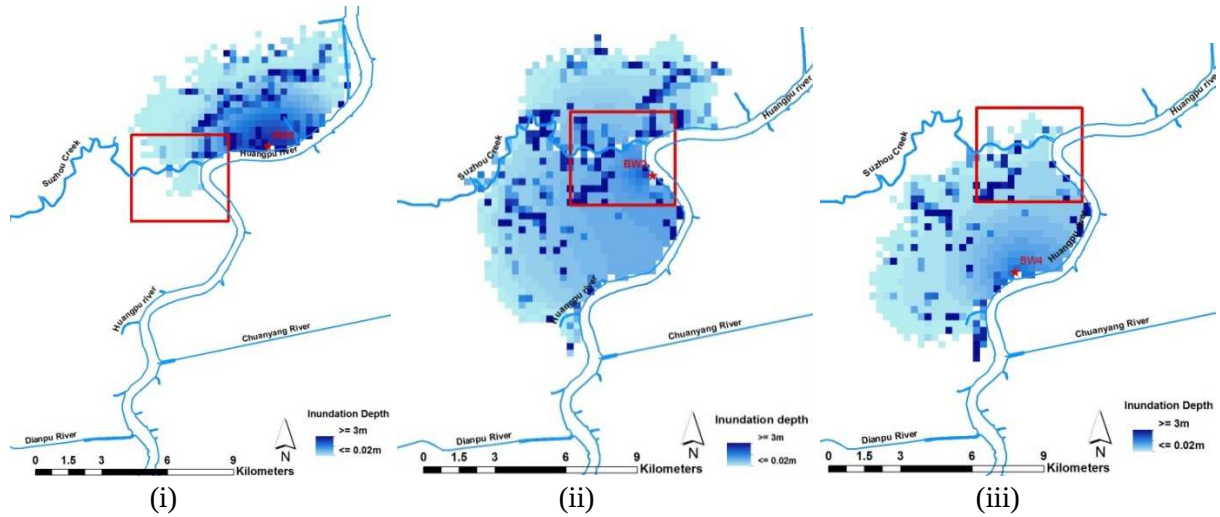


Fig. 4. 6 Inundation map of breaching scenario at BW2 (i), BW3 (ii) and BW4 (iii) (grid cell size: 300m×300m)

4.3.2.1 Classification of elements at risk

The raw data of buildings in the study area is shown in Appendix 4-1. All the buildings were further classified into residential building, industrial building, commercial building, and public building and inventory in the residential building, which is shown in Tab.4. 4.

Tab.4. 4 Classification of buildings in study case

Category	
Building	Residential building
	Industrial building
	Commercial building
	Public building
	Inventory

4.3.2.2 Maximum potential damage

Of the physical assets to be found in an area, only some proportion will be exposed to the risk of flooding. It could be regarded that the exposed value of assets under extreme events (worst case) is the maximum potential damage in the estimation of flood damage. In study area, large portion of buildings are high-rise constructions. Due to limited information on the vertical distribution of these buildings (e.g. stories), the estimation of the values of buildings will be based on the floor area times construction cost [\$USD/m²], the result of which is market value of the buildings. The floor area is a result of floor area ratio (FAR) times total area of a site. Based on Pan, Zhao et al. (2008) research on FAR of typical sites in Shanghai city by high resolution satellite imagery, the FAR in Huangpu and Pudong districts are 2.96 and 3.27, respectively; the other FARs in districts are adopted as 2.0 in general. As a result, the floor area in each district is calculated according to Eq. (4.4). The economic value for the buildings in each district is calculated based on 1) construction cost [\$USD/m²], 2) the percentage of each category in each district and 3) floor area in each district, which is shown Eq. (4.3). The total economic value of elements at risk is then calculated based on Eq. (4.2). The calculation of market value for the buildings in the study area is shown in Appendix 4-2 in detail.

$$S = \sum_i^n \sum_j^m S_{ij} \quad (4.2)$$

Where: S - market value of all the categories at risk [USD]; S_{ij} - market value of category i in district j [USD]; n - number of categories at risk [-]; m - number of districts in study area [-].

$$S_{ij} = C_i \times P_{ij} \times F_j \quad (4.3)$$

Where: C_i - Construction cost for each category i [USD/m²];

P_{ij} - Percentage of category i in district j [-];

F_j - Floor area in district j [m²].

$$F_j = A_j \times FAR_j \quad (4.4)$$

Where: A_j - Site area in district j [m²];

FAR_j - Floor area ratio in district j [-].

Since only proportion of economic assets are exposed to floods, especially in the high-rise building area, it's necessary to take an exposure assessment subsequently. In order to find out the proportion of assets value at risk, there is a recommended assumption based on population density in a developed urban area (Green 2010). Green (2010) identified a relationship between population density and development intensity in terms of high rise building area, and recommended 1/6 of assets is taken as the exposed value if the population density is above 15,000/km² (see Tab.4. 5). Overall, the summarized results are listed in Tab.4. 6. The total exposed value of buildings and residential inventories are 5.77 billion USD, which approximately equals to 341 million USD/km² in the study area. In addition, it is noted that commercial, public, industrial and residential (including inventory) buildings account for 30.3%, 28.6%, 18.7% and 22.4% of the total value in the study area, respectively.

Tab.4. 5 Recommended assumptions for proportion of net assets at risk by population density in a developed area

	Urban population density			
	<1000/km ²	1000-8000/km ²	8000-15,000/km ²	>15,000/km ²
Ratio of assets at risk to net assets	1:1	1:2	1:4	1:6

Tab.4. 6 Summary of market value and exposed value of buildings at risk in the study area

Category	Market Value [billion USD]	Exposed value (1/6 of MV) [billion USD]	Share of the total value [-]
Commercial building	10.5	1.75	30.3%
Public building	9.9	1.65	28.6%
Industrial building	6.5	1.08	18.7%
Residential building	7.7	1.28	22.2%
Inventory	0.063 [#]	0.0105	0.2%
Total	34.66	5.77	100%

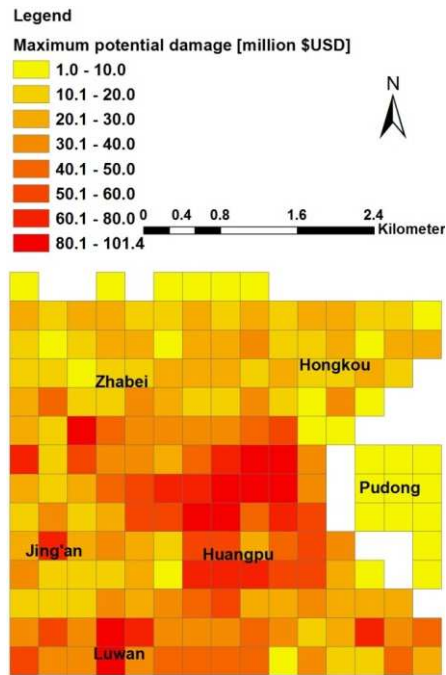


Fig. 4. 7 Spatial distribution of potential maximum damage in part of the downtown area of Shanghai city (grid cell 300m ×300m)

The spatial distribution of maximum potential damage of buildings in the study area is shown in Fig. 4. 7. It shows the Huangpu district concentrate nearly 64% of value of buildings in the study area. People square, Yuyuan and Nanjing Road are in Huangpu district. These are popular tourist sites in Shanghai; hence, numerous hotels, restaurants, shops, etc. are located. Due to relatively low elevation (~3.5m WD) and high economic assets value in the downtown area, the potential damage would be huge if the area would get inundated.

4.3.2.3 Depth-damage functions in Shanghai

The potential flood damage is calculated based on the depth-damage curves, which represents the relationship between flood characteristics and damage rate. There are two alternatives of depth-damage functions for Shanghai (See Fig. 4. 8). One was developed by (Wang 2001), which were largely based on the observations of historical flood events collected by insurance company in Shanghai; another one was developed based on investigation of the insurance records and survey data after 1999 flood event in Tai Lake Basin (Yua, Cheng et al. 2011; Penning-Rowsell, Wang et al. 2013). It is noted that both of the depth-damage functions were formulated in a synthetic way. These data reflect the relationship between inundation depth below 0.5m to above 3.0m at an interval of 50cm (<0.5m, 0.5-1.0m, 1.0m-1.5m, 1.5m-2.0m, 2.0m-2.5m, 2.5m-3.0m, >3.0m) and damage rates on public, residential, industry and commercial buildings, inventories and infrastructures. The expected damage rate under the same inundation class under the functions of Shanghai is much higher than the corresponding rate in Tai Lake Basin. Since Tai Lake Basin includes not only Shanghai city but also other cities of China, it would underestimate the flood damage if we directly applied the depth-damage functions for Shanghai. On the other hand, Yu, Hall et al. (2013) applied the depth-damage functions to validate the tangible direct flood damage in 1999 flood event in Tai Lake Basin, which is equivalent to a 150-200yr return periods of flood event with a cause of long term heavy rainfall. They made a close estimation of 11.97 billion Yuan (~1.9 billion \$USD) compares to the reported damage of 14.1 billion Yuan (~2.24 billion \$USD). It further demonstrated the reliability of these depth-damage functions in Tai Lake Basin.

Therefore, in order to generate a new depth-damage functions for Shanghai, two function sources (see Fig. 4. 8: **(i) previous Shanghai functions (ii) Tai Lake Basin functions**) were compared and discussed specifically on the buildings (public, industry, commercial and residential) and inventories. First, the damage rate of **inventory** in (i) is much higher than in (ii). It is mainly because the investigation in the flood of Tai Lake Basin was in both urban and rural area. The inventory goods in urban area are more diverse than in rural area, so is the associated economic value; and in urban area, there should be higher popularity of electrical equipment than in rural area. Hence, the damage rate of inventory is considered to taken as the higher one from (i) in Fig. 4. 8 and so does the **residential building**. Second, the damage rates of **industry and commercial building** in the two function sources are far more in line with each other. In (i), the damage rates of industry and commercial building are even six times higher than the rates of (ii), especially at the shallow depth (<0.5m). The difference is largely reduced as the inundation depth increases. It could be explained that the local characteristics of industry and commercial buildings in Shanghai attribute to a large damage due to flooding than in other cities of Tai Lake Basin, or the insured in industrial and commercial sector claimed higher value than the actual damage after floods. Moreover, compared the damage rates of industry and commercial buildings to other cities in China (see Fig. 4. 3 of Tianjin city and Tan district of Yellow River Basin), the damage rates of industrial and commercial building in Tai Lake basin is relatively lower than the value in other cities. Therefore, as a conservative estimate, the new damage rates for commercial building at different inundation depths are generally taken as the values between in (i) and in (ii), which are 7% less than (i) and 2%-6% higher than (ii). The new depth-damage function for industrial building is 2% less than the new one of commercial building at each inundation depth class, which is also in line with the study in (i) in these two sectors. Third, the damage rate of **public building** was directly used from (i) since there is no category of public building in (ii). As a result, the new depth-damage functions for Shanghai were developed, which is shown in Tab.4. 7.

In the suggested depth-damage functions for buildings and inventory in Shanghai (see Tab.4. 7), the primary damage at inundation depth of <0.5m are mainly attributed to the floor damage; thanks to people's relatively easier mobility (move contents to the higher places) general damage at this level can be avoided to a large degree. Second, the damage on contents and properties increases largely when inundation depth increases to 1.0m to 3.0m, especially in industry and commercial sectors; the damage rates are higher than other sectors (except inventory) owing to large proportion of immovable assets at these levels; third, when the water rises up above 3.0m, contents such as air-conditioners, fans and hanging-light (chandelier) would be damaged, which contributes to the damage of this level substantially. Because strong and water-proof construction materials (such as brick and concrete steel) are widely used in urban Shanghai, physical damage to building itself would not be large (low probability of collapse); therefore, the damage rate would stay no more than 58% as a whole, which is also the highest damage rate of inventory.

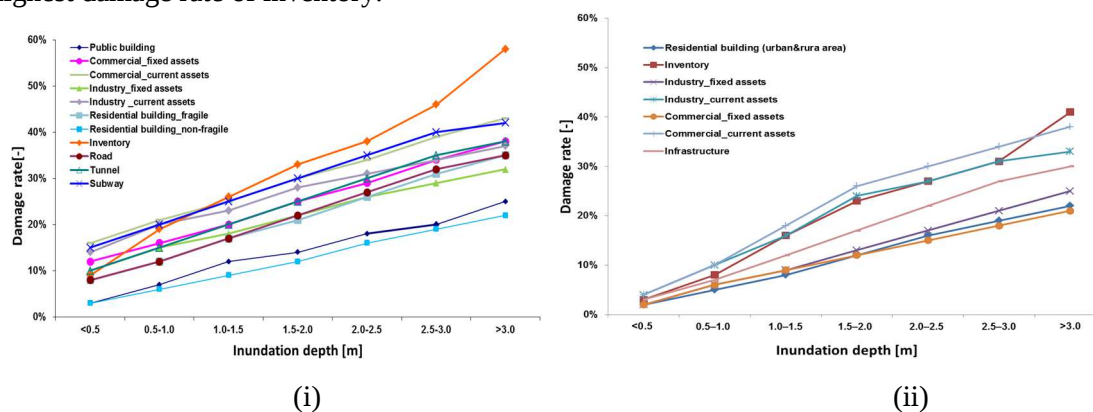


Fig. 4. 8 Stage-damage functions for elements at risk in Shanghai city (i) by Wang et. al (2001) and in Tai Lake Basin (ii) by Yu, Cheng et.al (2011)

Tab.4. 7 Suggested stage-damage functions for buildings and inventory in Shanghai

Category	Inundation depth [m]						
	<0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	>3.0
Public building	3%	7%	12%	14%	18%	20%	25%
Commercial building	5%	9%	13%	18%	22%	27%	31%
Industry building	3%	8%	11%	15%	19%	22%	25%
Residential building	3%	6%	9%	12%	16%	19%	22%
Inventory	9%	19%	26%	33%	38%	46%	58%

4.3.2.4 Damage results

With the application of the Eq. 4.1, the flood damage due to inundation of Bw2, Bw3 and Bw4 scenarios in the study area were calculated. The total damage of a scenario amounts to the sum of the damages of all inundated grid cells. The maximum potential damage S_{ij} for each category (i) in each district (j) multiply the damage rate of a specific category (i) under a certain inundation depth produces the flood damage of a category in a district. We can derive either the flood damage for each category or in each district. In a summary, the potential damage under three scenarios were 114, 560 and 328 million \$USD, which account for 1.98%, 10.39% and 5.68% of the maximum potential damage (5.77 billion \$USD) (see in Tab.4. 8). The spatial distribution of potential damage to buildings and residential inventories in the study area were produced by ArcGIS and shown in Fig. 4. 9. It is observed that the damage is mainly concentrated in Hongkou, Huangpu and Luwan districts, which are also adjacent to the breach location BW2, BW3 and BW4, respectively. Huangpu district which is in the centre of the study area could be mostly affected by the potential flood events. In terms of damage categories, as seen from of Fig. 4. 10, the shares of building damage in each category under the scenarios represent similar dividends. Among this, the commercial buildings take great share (35.5%, 38.4% and 43.4 % in scenario BW2, BW3 and BW4, respectively) of the total damage compared to other buildings, while the residential buildings merely account for 15%-16% of the total damage in all the scenarios. The industrial buildings take the share of 25%-27% in the damage results. The public buildings (24.5%) account for nearly the same share as the industrial buildings (25%) in scenario BW2, while in scenario BW3 the share of damage in this category drops down to no more than 20% and even less than the share of residential building in BW4. In a summary, the commercial and industrial buildings are attributed to a large degree of the direct damage under the breaching scenarios in the study area. It is noted that the building damage is highly related to the depth-damage functions as the suggested function in commercial and industrial buildings has higher damage rates under the same inundation condition compares to other buildings.

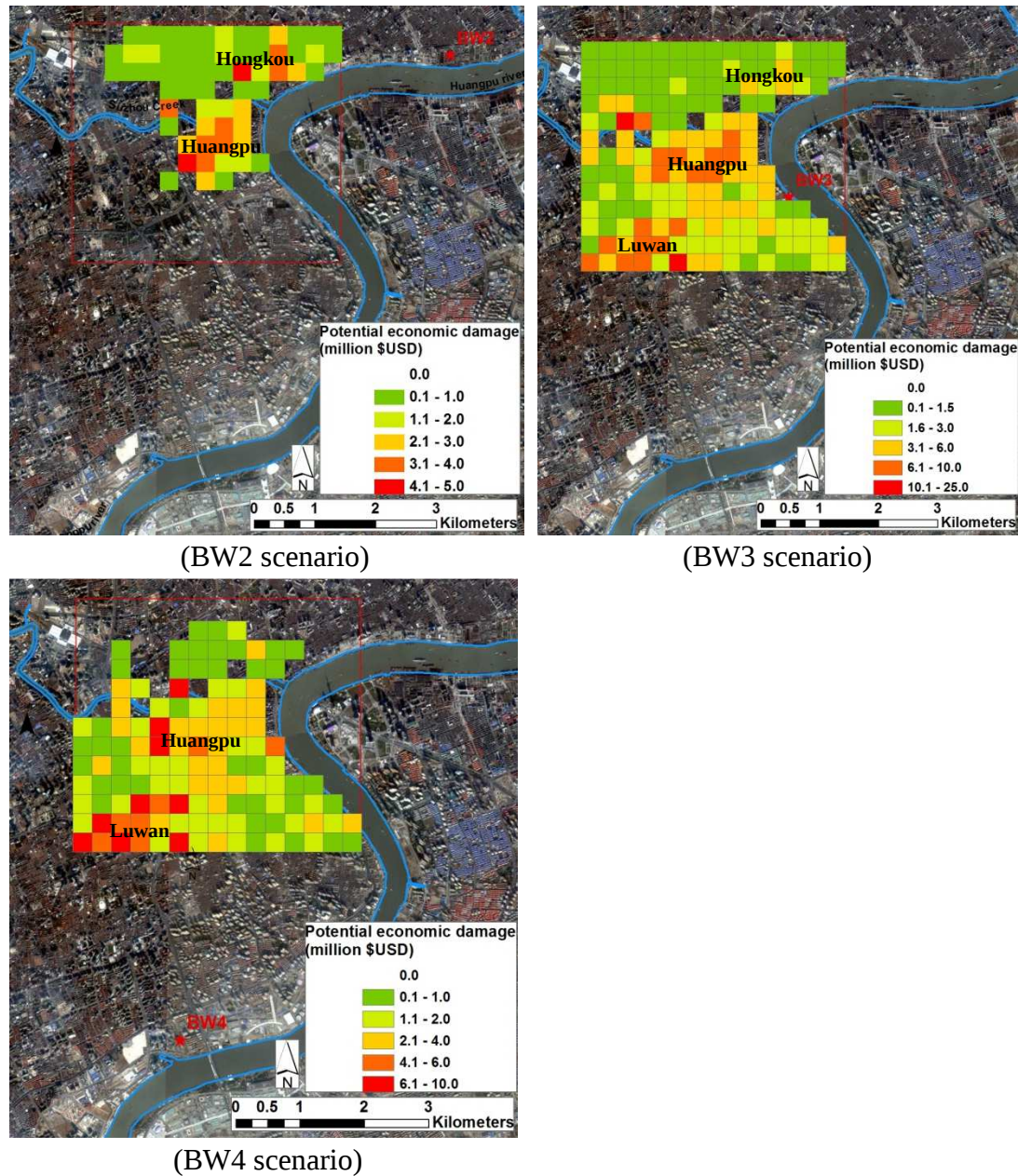


Fig. 4. 9 Potential economic damage to public building, industrial building, commercial building, residential building and its inventory due to breaching at BW2, BW3 and BW4 in part of downtown Shanghai (grid cell: 300m x300m)

Tab.4. 8 Summary of potential damage under BW2, BW3, BW4 flood scenarios

Scenarios	Total Potential damage [million \$USD]	Percentage of the maximum damage [-]
Bw2	114.3	1.98%
Bw3	559.77	10.39%
Bw4	327.71	5.68%

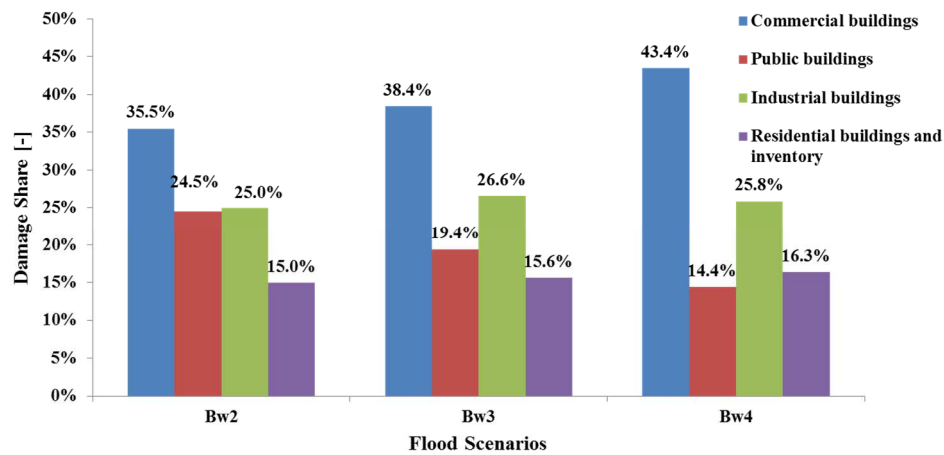


Fig. 4. 10 Share of damage categories in terms of buildings under three flood scenarios in the study area

4.3.3 Service interruption

It can be imagined that Shanghai would be suffered a lot if super storm slashed it one day, but the indirect loss is hardly estimated since complex multi-dimensions (economy, social aspect, healthcare, environment, etc.) need to be considered. In this study, service interruption due to flood inundation to nodal points of traffic network and public facilities (schools and hospitals) will be discussed.

Shanghai subway is a speedy transit system, which accounts for 35% of total public transportation utilities till 2011 (Quan, Liu et al. 2011). It is reported there are 12 lines with 285 stations in total of 444km length till the end of 2012, which mainly distributes in city centre (SSW 2013). As Shanghai is a tide-effected estuary city with flood threats of sea level rise, land subsidence and frequently hits of typhoon weather, if flooding occurs the subway system may not easily spared. Historical flood events indicate that the subway system in Shanghai is indeed vulnerable. In August of 2005, heavy rainstorm led to flood water flow back into Station Rd. Changshu of line 1, which results in out of function for a long time (Zheng 2007); in September of 2005, Typhoon Kanu hit Shanghai which led to St. Zhongshan Park get inundated (Lou, Liu et al. 2010); in June of 2011, several stations of line 10 suffered from leakage due to lower elevation at ground and insufficient drainage and pumping capacities during rainstorm weather, which led to further leakage in carriages as well (Shi 2011). Moreover, a preliminarily research (Quan, Liu et al. 2011) on vulnerability of subway system (based on selected line of 1,2,4,7,8,9,11) in Shanghai indicated that line 8 and 4 are mostly need to be safeguarded in the future. In conclusion, Shanghai subway system could be inundated during flooding. For instance, the streets in Shanghai may get flooded by river flood, and water level continues to rise above the sidewalks; flood water then directly flows into subway station if the entrance is without protection measures. Hence, the inundation and leakage may occur subsequently.

In Shanghai, the indirect damage to subways can be attributed to extra cost of emergency on leakage or inundation and service interruption. A simple method to calculate damage to subway system is to presume a relationship between the lengths of track inundated and direct damage, which is carried out by Neukirchen (1993). In order to obtain rough order of magnitude estimate of indirect effect on subways, Compton et al. (2009) assumed service interruption is also a function of length of track inundated, in which 2 million euro/km flooded is taken as revenue loss in a case study of Vienna, in which 2 euro per ridership and 5 days per km of track flooded is assumed based upon empirical data. In Shanghai, service interruption is taken as 1 day per km of track being inundation by flood; hence, it can come out the loss of revenue could be approximated at 300 million euro/km of track, based on 4 RMB per ride (0.63 \$USD per ride) and 600mln daily ridership on average (Zhu 2012) as a whole.

This is a worst case of Shanghai subway being out of function as a whole, which considers all the tracks being inundated in 5 days and all the passengers being disrupted in a daily life. Statistical data directly shows passengers intensity per km in subway line 1,2,3,4,5 of Shanghai in Tab.4. 9, which can be further taken into account in revenue loss due to flood inundation for each line.

Tab.4. 9 Passengers intensity per km per day in subway line 1,2,3,4,5 of Shanghai city in 2007 (Wang, Li et al. 2007)

Line	#Passengers/km	Fare/ride [RMB]	Revenue loss [RMB/km]	Revenue loss [\$USD/km]
1	24,000	4	96,000	15,238
2	26,400	4	105,600	16,762
3	11,000	4	44,000	6,984
4	14,670	4	58,680	9,314
5	4,100	3	12,300	1,952

Note: currency rate of RMB to \$USD equals to 6.3:1.0

In the EU FLOODsite study (FHRC, 2008), a recommended algorithm for rail disruption suggests calculating the number of people traveling through the floodplain, and then divides losses per passenger into costs for either delays (40–45% of total disruption costs) or cancellations (55–60% of total disruption costs). This calculation is an average of £0.037 per hour, per passenger for commuter train services, which equals 0.37 RMB per hour, per passenger, or 8.88 RMB per day, per passenger in the application of Shanghai. This method assumed all the passengers are affected during a flood event, which could estimate the indirect damage to subway in a period of flood events (e.g. a few hours or a few days). There are two typical stations in line 1 and 2 being selected in this research. First, they are located close to Huangpu River. St. People square and St. Lujiazui is within 1.8km and 500m distance to the River, respectively, which means if river flood occurs; these stations are likely to be affected due to short distance to the river. Second, based on an investigation of subways stations in Shanghai (Lou, Liu et al. 2010), only limited number of the entrance and exit has flood barrier although most of them have drainage system. In People square St., only 5 out of 20 entrances were installed portable flood barrier as emergency equipment. St. People square (see in Fig. 4. 11) and St. Lujiazui (see Fig. 4. 11) are both located in a prosperous commercial circle and a popular tourist site, which have daily passenger intensity of 82,000/day and 78,000/day, respectively (Zan and Shi 2012). The passenger intensity during rush hour (7:00-9:00 and 17:00-19:00) is estimated at 14-15% (Wang, Li et al. 2007) more than average value, so the indirect loss due to out of function of St. People square and St. Lujiazui can be approximated with results shown in Tab.4. 10. At St. People square, the minimum and maximum ticket loss is 118,800 \$USD and 136,620 \$USD, respectively if the station is closed for one day; at St. Lujiazui, which is located in the Pudong, the minimum and maximum ticket loss is estimated as 113,004 \$USD and 129,955 \$USD during one day close of this station. A conservative assumption of the flooding in these subway stations was any point of the track line would be inundated.

Tab.4. 10 Indirect loss of service interruption at St. People Square and St. Lujiazui in Shanghai subway

Stations	People square(#1)		Lujiazui(#2)	
	Minimum [\$USD]	Maximum [\$USD]	Minimum [\$USD]	Maximum [\$USD]
#Rides	110,700	127,305	105,300	121,095
1 day	118,800	136,620	113,004	129,955
7 days	831,600	956,340	791,034	909,689

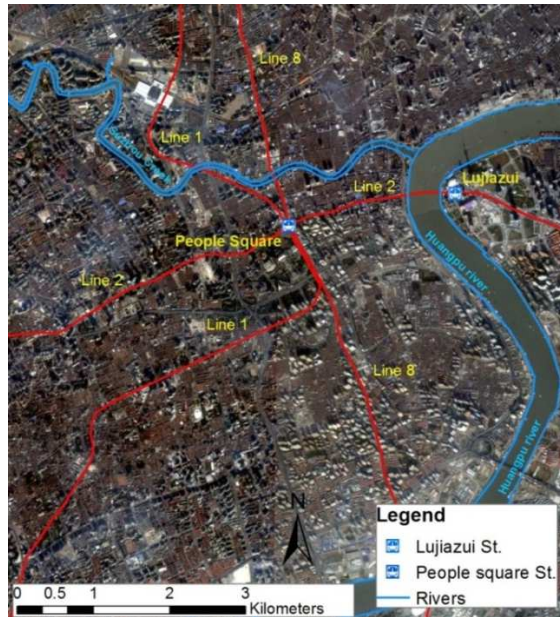


Fig. 4. 11 Map of subway stations at People square connecting Line 1, 2 and 8 and Lujiazui at Line 2 in Shanghai subway system

The service interruption is taken into account in indirect damage, while the extra cost of emergency, which can be significantly determined to the overall indirect loss, is not addressed in this study. Therefore, the estimation on indirect damage to Shanghai subway in this case is assumed at the lowest bound of estimated value.

Moreover, based on the geo-information analysis, quite a few POI (e.g. schools, healthcare centre and shops) are close (<500m) to the Huangpu River (see Fig. 4. 12). In total, there are 58 shops, 87 schools and 50 healthcare sites. The schools include various schools, namely kindergartens, primary schools, middle schools, high schools and universities, etc. The healthcare sites are hospitals, emergency rooms, dentist rooms and general healthcare centre, etc. The shops mainly include 24-hours grocery shops and supermarkets. They would be highly likely to be affected when the river flood occurs in the city centre. In that case, schools, shops and healthcare centre are forced to be suspended during a period, which may cause huge inconvenience and significantly affect people's social lives then. Besides, they are mainly clustered in the Bund area of west side of the Huangpu River according to Fig. 4. 12, the occurrence of river flood may result in huge loss of tourism reputation and revenue.

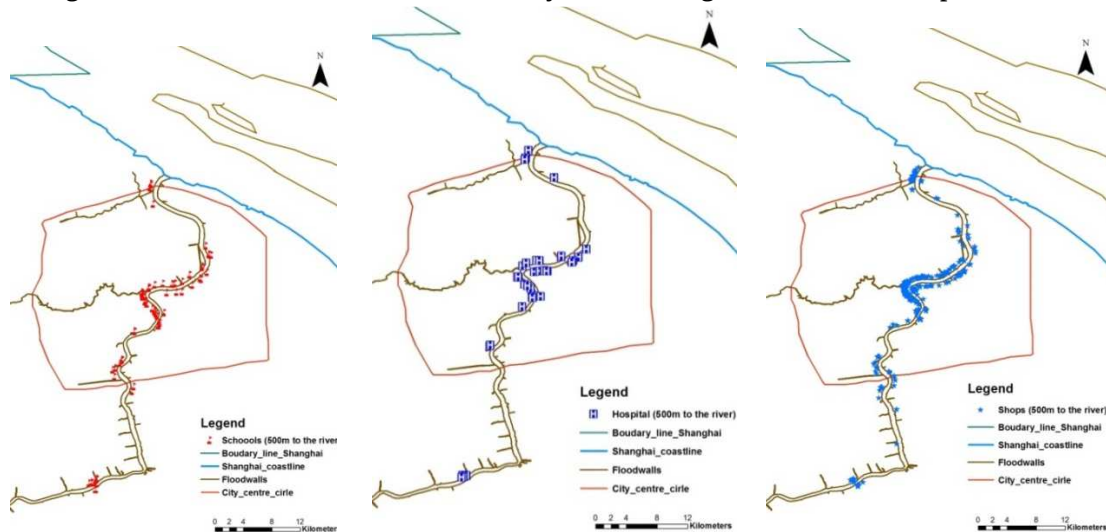


Fig. 4. 12 POI (Schools, healthcare centre and shops) within 500m distance to the Huangpu River

4.4 Uncertainty analysis

In the case study, as seen from the inundation map in Fig. 4. 6, the study area is not fully flooded under BW2, BW3 and BW4 scenario, especially in BW2 only north part of the area is flooded. A question of how much flood damage would be if the whole area is flooded is brought up. The associated uncertainty of flood damage is also a big concern in the process of flood damage estimation. In this section, the flood damage with associated uncertainty will be estimated based on an assumption that the study area would be widely inundated with the value of water depth induced by breaching scenario of BW2, BW3 and BW4.

Uncertainties in decision and risk analysis are usually divided into two categories (van Gelder 1999): inherent uncertainties stems from the natural variability of a system under study. The maximum water level in a river at a certain cross section cannot be deterministically estimated in the next year as this is a property of water pattern itself. This kind of the uncertainty is irreducible, which means even with long period of historical records the uncertainty cannot be removed. Another category is epistemic uncertainty, which results from incomplete knowledge or insufficient data in a system, such as the errors in the collected samples. It can be improved as knowledge increases. A way to show the uncertainty in a system is applying probabilistic distribution for the variants based on the statistics principles. The results can also be represented in a probabilistic way to show the uncertainties. In flood damage estimation, uncertainties arise from several sources (Beard 1997; Merz, Kreibich et al. 2004; Egorova, van Noortwijk et al. 2008; de Moel and Aerts 2011).

1). Inundation depth

The inundation depth is estimated based on the flood (hypothetic breaching) scenarios in the hydrodynamic model. The results vary depend on the reliability of the hydraulic model and the quality of input data. Moreover, the inherent uncertainty of hydrological data as boundary conditions in the hydrodynamic model led to uncertainty of the end result as well.

2). Valuation of maximum potential damage

The estimation of maximum potential damage entails uncertainty due to the estimation methods and data availability. It usually represents the maximum economic damage in \$USD/m² or \$USD/units. In the Netherlands, the Dutch finance department provides a mean value for the maximum damage per unit object with 90% of confidence interval in flood damage estimation (Briene, Koppert et al. 2002); and Egorova, van Noortwijk et al. (2008) applied triangular distribution to describe the uncertainty of the maximum damage amount per object under flooding.

3). Depth-damage function

The primary source of uncertainty in flood damage estimation stems from depth-damage function as it depends on empirical data or expert judgment, which is challengeable to exactly estimate the flood damage in the next flood events. de Moel and Aerts (2011) also highlighted depth-damage functions need higher priority in the process of flood damage estimation. Various factors could lead to flood damage to different degrees. For example, the different structures of the buildings (e.g. wood & concrete) to the same type of building may result in different damage; the buildings under the same inundation but more adjacent to the breaches may suffer from more damage. Different categories of elements at risk would result in different flood damage due to their different endurance capacities.

Since these factors in the damage model were represented in uncertain forms with probability distributions, a Monte Carlo analysis could be employed to address the uncertainty in the procedure of the direct damage estimation in this section. The Monte Carlo analysis was conducted as the following steps: 1) identify probability distribution and its parameters for each variable; 2) generation of the

samples base on PDF information and model itself for execution; 3) statistical analysis on model output, which is also shown in Fig. 4. 13.

Inundation depth d and maximum potential damage per each category of buildings S_i are independent variables. S_i was set as a triangular distribution followed by Egorova, et al. (2008). In order to avoid negative value, triangular distribution is also chosen to describe the inundation depth instead of normal distribution. Moreover, the advantage of triangular distribution is its simple form. It is assumed that the study area is fully inundated with the probability distribution of inundation depth in scenarios of BW2, BW3 and BW4. The minimum and maximum depth were taken as 5% percentile and 95% percentile of inundation depth in a spatial distribution of grid cell area at each scenario (BW2, BW3 and BW4) with mean value of 0.43m, 1.0m, 0.52m, respectively. Hence, the triangular form for the inundation depth is then shown as $T \square (0.02, 0.43, 2.0)$, $T \square (0.35, 1.0, 3.0)$, $T \square (0.02, 0.52, 3.0)$. Subsequently, the mean values of maximum potential damage for each category of buildings and inventory were taken as the calculated exposed value shown in Tab.4. 6. And 50% and 200% of the maximum potential damage were taken as the lowest bound and highest bound in triangular distribution, respectively. So the triangular form of maximum potential damage for each category could be shown as $T \square (0.5S_i, S_i, 2S_i)$.

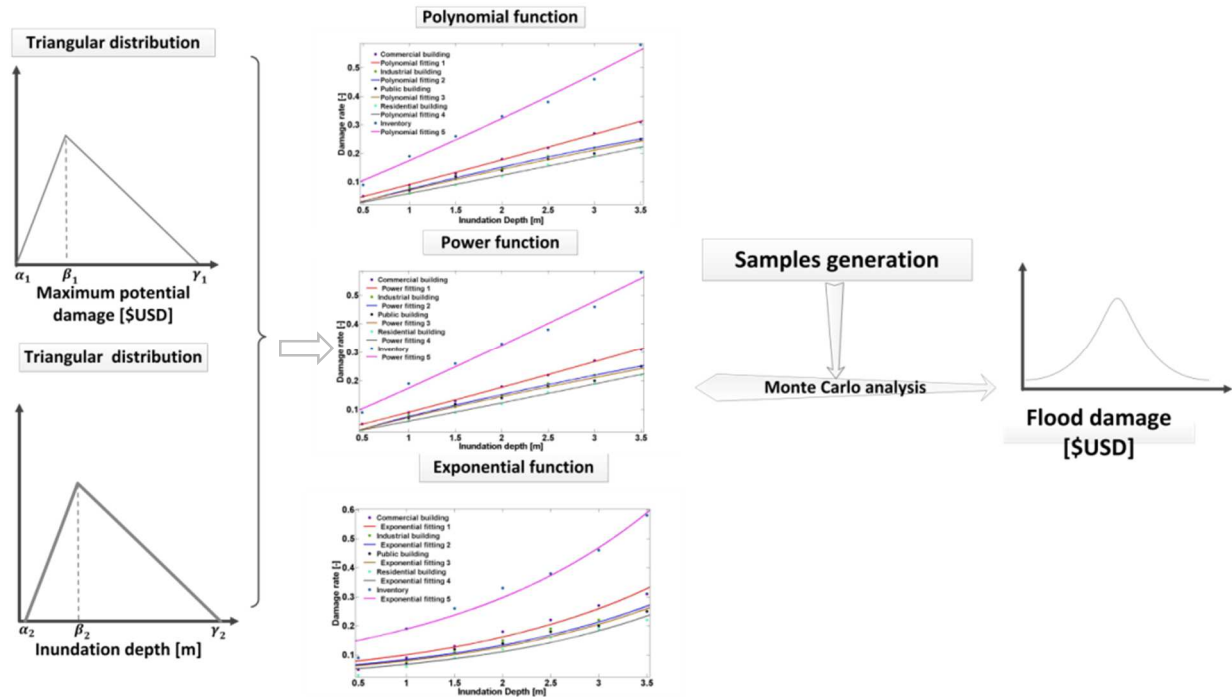


Fig. 4. 13 Monte Carlo analysis of flood damage estimation

Based on the depth-damage function for each category of building and inventory in Shanghai (see Tab.4. 7), three alternatives of algorithm were selected to fit. First, polynomial function allows a simple adaptation to individual damage symptoms of different types of objects. Second, power function has represented desirable results with an application to the HOWAS database in Germany (Buchele, Kreibich et al. 2006) from a practical point of view. Third, the exponential function was chosen as it avoided the negative result of damage rate under inundation depth. They are shown as below in Equation (4.5), (4.6) and (4.7)

Polynomial function

$$Dr = a_1 \cdot d^2 + b_1 \cdot d + c_1 \quad (4.5)$$

Power function

$$Dr = a_2 \cdot d^{b_2} + c_2 \quad (4.6)$$

Exponential function

$$Dr = a_3 \cdot \exp(b_3 \cdot d) \quad (4.7)$$

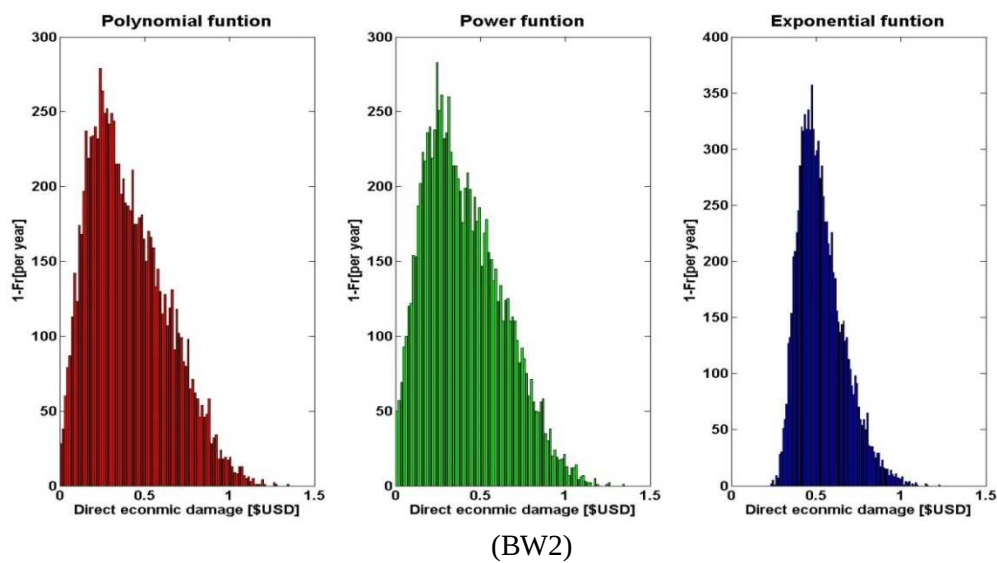
Where: d - inundation depth [m]; Dr - damage rate [-]; a_i, b_i, c_i - the parameters in the equations, which depend on the fitting functions, $i=1, 2, 3$.

By using of the curve fitting tool, the Shanghai depth-damage functions of the buildings and inventory were fit in three functions (see Eq. (4.5), Eq. (4.6), Eq. (4.7)) to produce the fitting curve for each category, which is shown in Fig. 4. 13. All of the fitting curves are good to fit with R-square value above 0.93.

After 10,000 sampling in the Monte Carlo analysis, flood damage results were derived under three different functions, which is shown in Tab.4. 11. It shows the expected direct damage to buildings and inventory ranges from 411-536 million \$USD under inundation depth in scenario BW2, 733-738 million \$USD under inundation depth in scenario BW3 and 594-655 million \$USD under inundation depth in scenario BW4, respectively, which account for 7.11% ~13.6% of maximum potential damage in the study area. Power function led to smallest results compares to other functions in this case. The histograms of direct economic damage by Monte Carlo analysis under three damage functions are shown in Fig. 4. 14.

Tab.4. 11 Damage results with expected value (μ) and standard deviation (σ) under three alternative functions: polynomial, power and exponential

Scenarios	Damage Function [billion \$USD]		
	Polynomial	Power	Exponential
	(μ, σ)	(μ, σ)	(μ, σ)
BW2	(0.41,0.23)	(0.41,0.23)	(0.54,0.14)
BW3	(0.74,0.31)	(0.73,0.30)	(0.73,0.23)
BW4	(0.60,0.35)	(0.59,0.34)	(0.66,0.24)



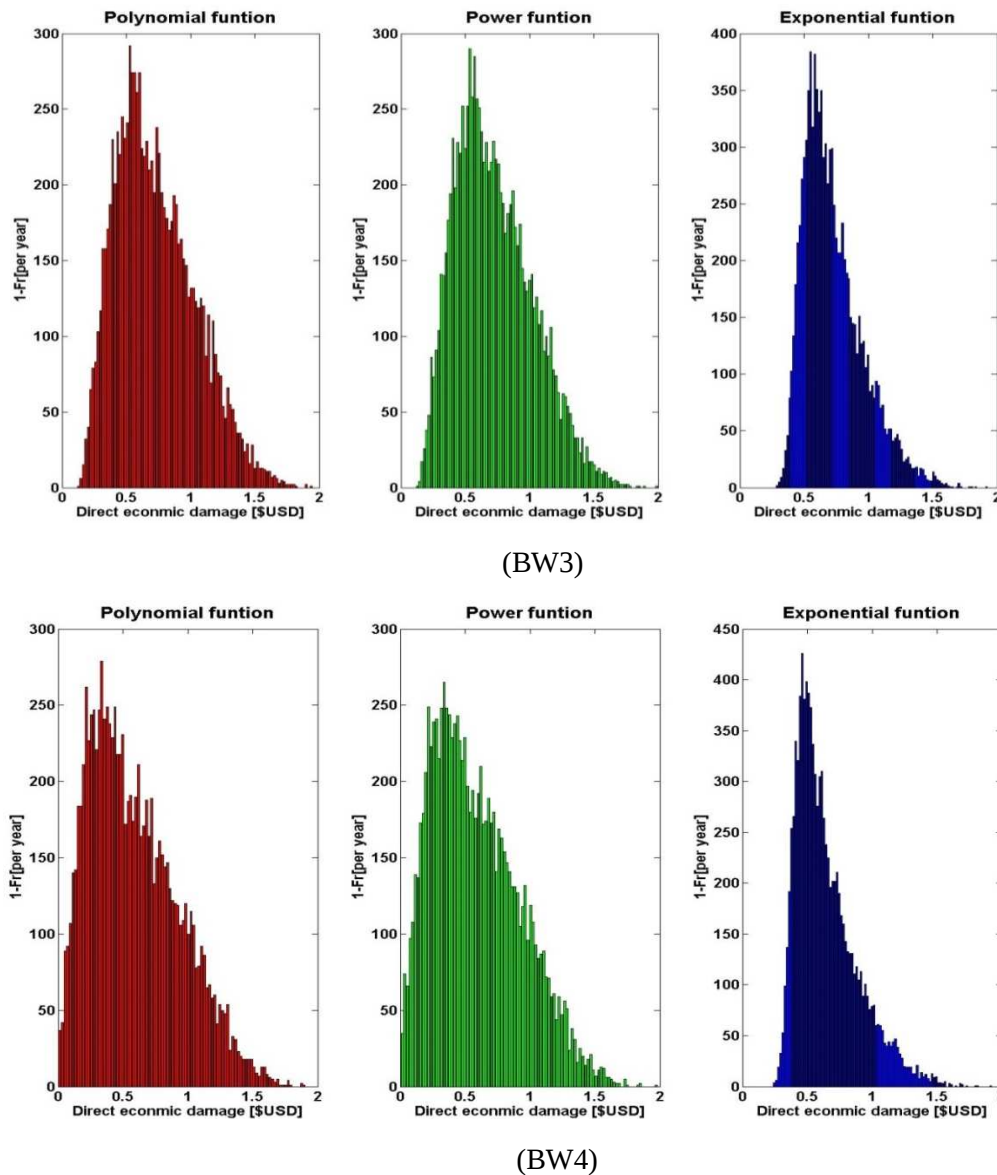


Fig. 4. 14 Histogram of the direct economic damage under scenarios BW2, BW3 and BW4, in which depth damage functions were represented by polynomial function, power function and exponential function

The results show the direct flood damage represents slightly right-skewed non-Gaussian distribution in Fig. 4. 14. The right tails shows the potential large flood damage could be caused by various uncertainties. In addition, the exponential function generates larger damage results in all scenarios, especially under scenario BW2. It is attributed to unrealistic (i.e. higher) results at the shallow water depth produced by the exponential function.

4.5 Effects of components on flood damage

The basic model to calculate the flood damage is based on damage functions which relate the inundation depth in a grid cell to a fraction of the maximum potential damage value of the damage category at risk. Then the fraction is multiplied with the maximum potential damage to derive a flood damage estimate. Three components determine the damage, namely the maximum potential damage, the inundation depth and damage functions. In this section, it will be specifically focus on the effects of components which determine the estimation of potential flood damage.

The parameters of the maximum potential damage and inundation depth would be $\alpha_1, \beta_1, \gamma_1$ and $\alpha_2, \beta_2, \gamma_2$ respectively in triangular distribution. Additionally, the parameters in three damage functions, namely a_1, b_1, c_1 in the polynomial function, a_2, b_2, c_2 in the power function and a_3, b_3 in the exponential function will also be taken into account to observe the effects on the results of flood damage. This was done by manually varying one parameter in a component at a time with value of $\pm 10\%$. The effect of each parameter on the damage estimation is presented as a factor, which is calculated by dividing the high (with variance of $+10\%$) by the low (with variance of -10%) damage estimate, while keeping the others equal. The effects of components on flood damage are then derived from the average value of the parameter factors in each component.

The reference case is flood scenarios of BW3 with inundation depth of $T \square (0.35, 1.0, 3.0)$, and the maximum potential damage would be taken as the overall economic value in the study area $T \square (2.885, 5.77, 11.54)$. The damage function would take the median rates in the damage categories under the same inundation depth in general with three functions, in which the parameters of the polynomial, power and exponential function are then shown in Tab.4. 12.

Tab.4. 12 Parameters in the components of the flood damage estimation

Components	Parameters	Value
Maximum potential damage	$(\alpha_1, \beta_1, \gamma_1)$	(2.885, 5.77, 11.54)
Inundation depth	$(\alpha_2, \beta_2, \gamma_2)$	(0.35, 1.0, 3.0)
Polynomial function	a_1, b_1, c_1	9.5E-4, 8.5E-2, 0.01
Power function	a_2, b_2, c_2	8.5E-2, 1.025, 1.052E-1
Exponential function	a_3, b_3	0.066, 0.46

Fig. 4. 15 shows the effects of the three components on the results of flood damage. It indicates that the damage function has greatest influence on the results of flood damage among the three components, and the maximum potential damage is the second one; the inundation depth has the least effect on the flood damage. Damage function has critical effect on damage estimation; it thus deserves more attention in the further study. This can be obtained by, for example an updated field survey, for vulnerability investigation of flood damage categories. And, a detailed classification of properties, such as the ages of buildings or the construction material of buildings, is also required.

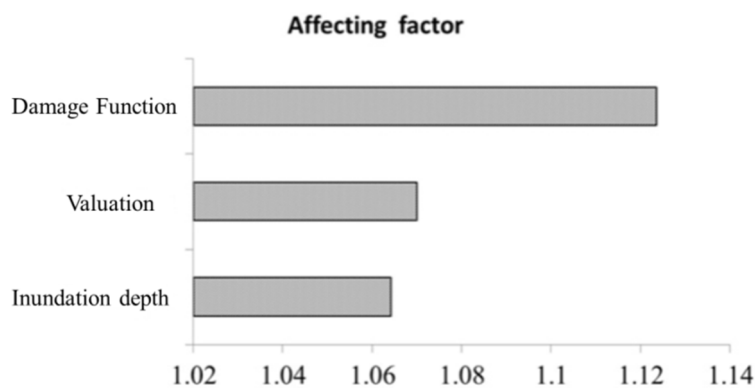


Fig. 4. 15 Effects of three components on the flood damage with variation of $\pm 10\%$, the factor is calculated by dividing the high (with variance of $+10\%$) by the low (with variance of -10%) damage estimate, while keeping others equal.

4.6 Discussion

This section will discuss the uncertainties of the components which determine the damage results in ex-ante flood events in this study. The DEM data and ground roughness would affect the inundation extent and inundation depth to a large degree, which has been discussed in 2D hydraulic modelling of overland flood along the Huangpu River (See Section 3.4.3). Hence, the uncertainties of the inundation depth and inundation extent can also affect the flood damage results. Besides, the classification of damage categories, the determination of potential maximum damage for each category, the suggested depth-damage functions are significant for flood damage estimation in Shanghai. A small area in downtown as a case study on potential flood damage estimation was conducted, yet it still gives indications for larger scale estimation in metropolitan city in the future. In indirect damage estimation, although service interruption due to the halt of subway system was taken into account in Shanghai, business interruption by flooding will also be examined by other real cases occurred worldwide as an implication. However, our method on flood damage estimation is relatively simple with several assumptions, which needs to be discussed as below.

4.6.1 Tangible direct damage estimation

- **Damage category**

The classification of the potential damage category is critical to the process of damage estimation. In this case, the buildings were classified based on the functions in general. Different function of the buildings has different potential damage degrees. In Shanghai city, commercial building has highest damage percentage among all the building categories. 59% of total amounts of the buildings are commercial building in the study area, which also accounts for large portion of damage percentage in the final results. Even though the material of buildings is significant to the damage percentage, the concrete buildings are widely built in Shanghai. Hence, no further classification of the materials of building was conducted. But the detailed construction years of each category of buildings are necessary to further collected as it is influential to the damage (rates). The direct damage to the buildings and its contents are only a limited share of the variability that is observed in damage data. Other categories such as transportation infrastructures were not included in this study. Nevertheless, these results can provide as a basis for insurance companies which are interested in the building damage. In light of this, it seems the more detailed classification of damage categories the more accurate the results are; while a comprehensive classification of the damage categories are time-consuming and effortful, especially in a large city. Hence, problem-oriented damage estimation is recommended for the ex-ante flood events.

- **Potential maximum damage**

In the estimation of maximum potential damage to the buildings, floor area ratio (FAR) was used to estimate market value of buildings, which avoided the lack of data on the number of stories at an individual level of buildings in an urban area, especially in Shanghai which has hundreds of high-rise buildings widely. The FAR can produce flood area of the buildings; hence, the market value of the buildings can be estimated by multiplying the flood area (m^2) and construction cost (\$USD/ m^2). Based on a relationship of population density and development intensity, the exposed value of the buildings to floods was calculated as 1/6 of the market value in downtown of Shanghai. It could be questioned that the stage damage function has already taken maximum potential damage into account, which is regarded as 100% of the market value. While in a densely developed area with numbers of high-rise buildings, a large proportion of high-rise buildings are simply above the foreseeable inundation depth. Regarding to the high rise constructions, the exposed value of damage should not be the total value of the whole buildings. That's why based on the population density in a developed area (no slums being

considered), the values of buildings at risk were only a proportion of market value. Besides, the assumption of one residential area has 8 buildings and one building has 24 households is only based on general information on the internet of real estate agents (<http://shanghai.anjuke.com/>) in the estimation of the maximum potential damage. It could underestimate the number of households in a residential area with such rapid development in Shanghai, which needs to be determined further.

- **Depth-damage function**

A series of new depth-damage functions were constructed for different category of buildings and inventory, which was based on pervious works in Shanghai and other cities. Although it is hard to validate the final results, which is a common challenge in the field of flood damage estimation currently, the application of Monte Carlo analysis can help to address uncertainties in depth-damage function during the estimation of flood damage. Therefore, the probabilistic analysis could provide the rational results for the decision maker. The damage results range from millions of dollars even if the study area gets fully inundated with mean value of no more than 1m depth. Considering the study area is 17.2km² (only 6% of downtown area) with limited number of the buildings as compared to the whole Shanghai, the damage results are reasonable; moreover, if we apply the damage results in the study area to the overall downtown of Shanghai (exclude Pudong district), then the damage ranges from 6.85 (411 million \$USD / 6%) -12.3 (738 million \$USD / 6%) billion \$USD averagely, which is comparable to the results in south Holland of the Netherlands due to hypothetic breaches of flooding. However, it should be noted that the depth-damage functions used in this research is only regional appropriate in Shanghai; it is still difficult to transfer these functions to other cities due to different situations. Moreover, due to the fast growing pace in Shanghai the current functions cannot represent the future potential vulnerabilities of the property assets; there is absence of a method scaling the depth-damage functions to represent future scenarios (Penning-Rowsell, Wang et al. 2013).

- **Study area**

The study area which is located in the downtown Shanghai was chosen mainly because of data availability. As it is part of the most prosperous area in Shanghai, it has instructive information for the further overall damage estimation under different flood scenarios. The results in the study area could provide a basis for rapid damage estimation and then flood risk analysis in the next step. Based on the regionalization of social-economic status in different districts of Shanghai, direct damage to buildings under flood scenarios could be roughly estimated afterwards (see in Chapter 5).

4.6.2 Tangible indirect damage estimation

In recent years, the metropolitan cities like Shanghai drastically expand underground space for public infrastructures and utilize more urbanized area in order to save surface ground in the city. Increasingly more underground systems were developed, while these underground systems are susceptible to flooding. In Shanghai, the municipal government has already paid great attention on these vulnerable ground facilities, which includes subway system, tunnels, underground shopping centres, parking garages and other underground infrastructures. In the estimation of indirect flood damage on service interruption, two typical subway stations were selected under the hypothetical inundation case for one day and one week, mainly on revenue loss, which implied that huge practical inconvenience would be induced for the inhabitants during such unexpected events. The estimated indirect loss was based on passenger volume at a specific subway station, which is only the lower bound of indirect loss in case of flooding. In addition to the repair cost to the electrical equipment, signal controls and escalators, etc., the cleaning cost for removing debris and mud from tracks and stations and additional emergency cost would be added up as indirect damage as well.

Besides the service interruption, it should be noticed that the business interruption would be inevitable in such an economically developing city. The disruption of transportation infrastructures and other lifeline systems (e.g. electricity and water) would induce business suspending and cause substantial indirect economic loss. A few examples on indirect damage due to business interruption in recent flood disasters indicates 1) the indirect flood damage due to business interruption ranges to a large degree; 2) the amount of loss mainly depends on the flood duration and its recovery time; 3) urban area has larger impact on business sectors. During Hurricane Katrina in New Orleans, the indirect damage was estimated at around 39% of the direct damage (Hallegate 2008). In 2011 Japanese Great Northeast Earthquake and Tsunami, the business loss was approximately 50% of the direct damage caused by flood. During Thailand 2011 flood, the indirect loss due to business interruption was roughly 125% of direct damage. During 2012 Sandy in New York and New Jersey, the total losses due to business interruption were approximately between 20.6 and 25.3 billion \$USD, or between 33% and 42% of the direct damage. In a summary, Tab.4. 13 gives examples of flood disasters worldwide on the share of the direct and indirect damage. It shows that the indirect damage could range from 28% to 55% of total damage in the flood events. In New Orleans, Japan and New York (and New Jersey), the indirect damage accounts for more or less one third of total damage in general; while in Thailand the indirect damage took over more than half of the total damage. The costly indirect damage in Thailand could be explained that 1) averagely 19% of the manufacturing firms (e.g. memory chips, hard disk drives and automobile components) in Thailand are involved in global production networks (Chongvilaivan 2012); 2). the halt of the global production network intensified the indirect damage. 3). long period of flood, lasting several weeks even months in some regions, impacted the manufactory sectors to a large degree.

Tab.4. 13 Share of direct and indirect damage in recent large-scale floods worldwide [-] based on (Villier 2013)

Disasters	Affected Region	Share of Flood Damage [-]		Ratio of Indirect/Direct
		Direct	Indirect	
2005 Hurricane Katrina	New Orleans	72%	28%	~39%
2011 Japanese Tsunami	Northeast Japan	67%	33%	~50%
2011 Thailand flood	Massive Thailand	45%	55%	~125%
2012 Hurricane Sandy	New York and New Jersey	70%-75%	25%-30%	~33%~42%

Furthermore, other sources of indirect loss in terms of intangible damage in an urban city could be the loss of city attractiveness or government trust. For example, a number of people chose to abandon their houses in New Orleans after Katrina even after 8 years, due to either be unwilling or unable to return (Aljazeera Amwerica 2013). Likewise, tourists would be reluctant to travel for and fewer residents would choose to settle down if the same situation happened in Shanghai. Much more uncertainties need to be addressed in terms of indirect damage, especially in intangible indirect loss. It might be better to prevent the city dry and never to be flooded.

4.6.3 Uncertainty analysis

In addition to flood damage estimation, we also discussed the uncertainties of the estimates. It shows that the results of tangible direct damage would be in a range with representation of expected value and standard deviation. The uncertainty would be roughly $\pm 50\%$ around the expected value under 95%

confidence interval. While tangible indirect damage, as shown in Tab.4. 13, could be 33%-125% of the tangible direct damage in different cases. The uncertainty of indirect damage due to service disruption and business interruption is much larger than the estimation of direct damage. Thus, it is not recommended to take a constant percentage of direct damage for indirect damage estimation, which will propagate uncertainties significantly. Furthermore, although the intangible indirect damage after floods such as psychological trauma or loss of trust on government are not discussed in detail in this section it is estimated that the uncertainty of intangible indirect damage could be within much larger uncertainties in different cases due to various local situations, such as flood experience or social status of the residents. Besides, the (tangible and intangible) indirect damage would probably increase to a large degree in a long run.

Appendix 4-1 : Spatial distribution of different categories of buildings in the study area

Tab.4- 1 Different category of buildings in the study area

Category	Amount	Percentage
#Commercial point	776	25.94%
#Company	561	18.75%
#Community neighbourhoods	248	8.29%
#finance & insurance	181	6.05%
#Integrated Building	176	5.88%
#School	156	5.21%
#Restaurant	125	4.18%
#Official working place	124	4.14%
#Entertainment	99	3.31%
#Hotel	93	3.11%
#Healthcare	92	3.07%
#Industry	80	2.67%
#Legal affair point	42	1.40%
#Residential area	42	1.40%
#Others	37	1.24%
#Post office	35	1.17%
#Academic	23	0.77%
#Tourist place	19	0.64%
#Ticket point	15	0.50%
#Press	11	0.37%
#Residential street	11	0.37%
#Harbour & airport	9	0.30%
#Sports centre	9	0.30%
#Subway station	9	0.30%
#Long journey Bus station	5	0.17%
#Parking	5	0.17%
#District level government	4	0.13%
#Toilet	2	0.07%
#Bridge	1	0.03%
#City Hall	1	0.03%
#Gas station	1	0.03%

In the study area, there are different functions of Buildings, which is shown in Tab.4- 1. In general, they were classified into four categories, namely commercial, industrial, public and residential building. A summary of each category of buildings is shown in Tab.4- 2.

- **Commercial building:** Company, hotel, restaurant, etc.
 - Commercial points including the shops, beauty salon, fast food restaurant (e.g. KFC, McDonald) and sales department of industry, etc.
- **Public building:** Research institute, city hall, community neighbourhood, integrated building, governmental offices, school, post office, tourist place, etc.

- **Industrial building:** Wood plant, Doll plant, Printing plant, Food plant, Medical plant, clothes, Clothes, Plastic production plant, Furniture production plant. etc.
- **Residential area:** assume 8 buildings in one residential area and one building contains 24 apartments, then 336 (8*24*42) buildings in the study area.

The spatial distribution of different categories of building in the study area is shown in Fig.4- 1.

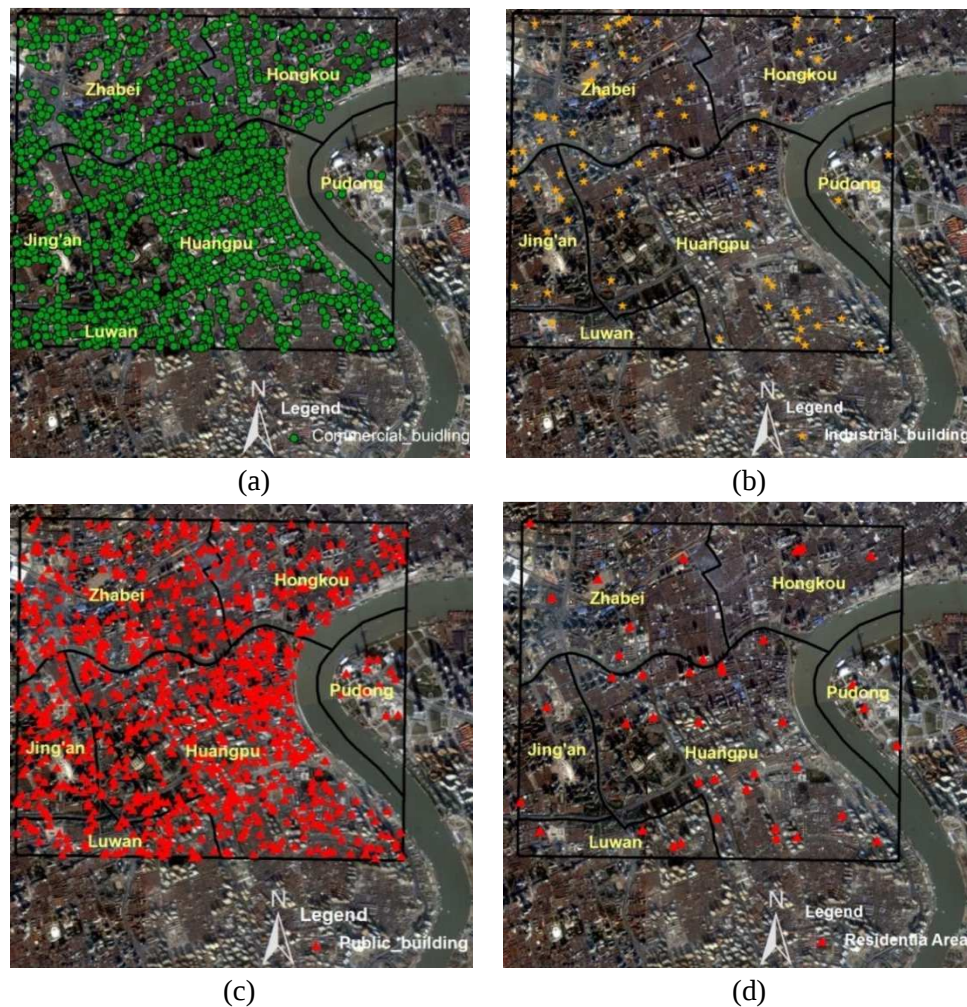


Fig.4- 1 Spatial distribution of different categories of Buildings in the study area: (a) Commercial building, (b) Industrial building, (c) Public building, (d) Residential area

Tab.4- 2 A summary of four categories of buildings in the study area

Category	Amount (Percentage %)
Buildings	3286
#Public building	930 (28.3%)
#Commercial building	1,940 (59%)
#Industrial building	80 (2.4%)
#Residential area	42
#Residential building	336 (10.2%)
Total	3,286 (100%)

Appendix 4-2 : Exposure assessment - Maximum potential damage

The site area of each district and the percentage of buildings in each district in the study area were calculated in ArcGIS10.0. According to Pan, Zhao et al. (2008) research on FAR of typical sites in Shanghai city by high resolution satellite imagery, the FAR in Huangpu and Pudong districts are 2.96 and 3.27, respectively; the other FARs in districts are adopted as 2.0 in general. Based on Eq.(4.4), which shows the floor area is a result of floor area ratio (FAR) times total area of a site floor, the results of floor area in each district are shown in Tab.4- 3.

In order to calculate the market value of each building categories in each district, based on Equation (4.2), it requires to calculate the percentages of four categories of buildings in the districts and the results are shown in Tab.4- 4. According to Shanghai annual official statistics (SSB 2010), the construction cost of different categories of buildings in the study area in 2010 are shown in Fig.4- 2. In 2010, the construction cost of commercial building, industrial building, public building and residential building are 784, 596, 782 610 \$USD/m², respectively. Consequently, the market values of four buildings in each district are shown in Tab.4- 5. The total value of the buildings in the study area is estimated at 34.62 billion \$USD (3,286 buildings). Thus, one building equals approximately 10.5 million \$USD in general.

$$F_j = A_j \times FAR_j$$

Where: A_j - site area in district j [m²]; (In this case, $j = 6$);

FAR_j - floor area ratio in district j [-].

F_j - floor area in district j [m²].

Tab.4- 3 The site area, FAR and floor area of each district in the study area (F_j)

District	Site area (km ²)	Floor area ratio	Floor area (km ²)
Huangpu	6.8	2.96	17.76
Zhabei	3.74	2	7.48
Hongkou	2.729	2	4.86
Jing'an	1.50	2	3.00
Luwan	1.10	2	2.20
Pudong (Lujiazui Area)	1.4	3.27	2.62
Total			37.92

$$S_{ij} = C_i \times P_{ij} \times F_j$$

Where: C_i - construction cost for each category i [\$USD/m²]; (In this case, $i = 4$)

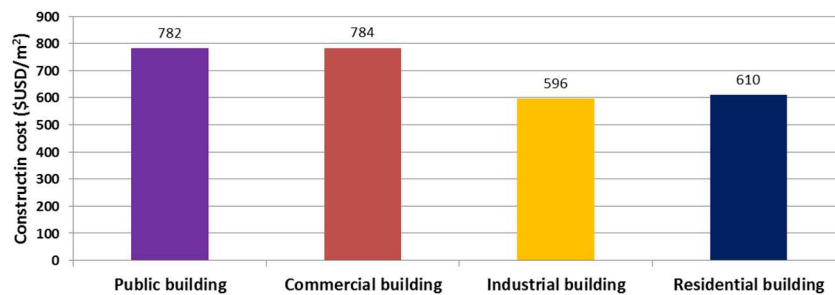
P_{ij} - percentage of category i in district j [-];

S_{ij} - market value of category i in district j [\$USD];

Tab.4- 4 Percentages of four categories of buildings in the districts (P_{ij})

Districts	Category of buildings			
	Commercial	Public	Industrial	Residential
Huangpu	55.72%	49.46%	35.00%	50.00%
Pudong	0.36%	1.40%	3.75%	7.14%
Zhaipei	16.70%	20.86%	35.00%	16.67%
Luwan	13.04%	7.31%	1.25%	9.52%
Jing'an	5.62%	10.11%	12.50%	4.76%
Hongkou	8.56%	10.86%	12.50%	11.90%

Based on an assumption that the buildings are distributed completely in the study area and different categories of the buildings are assumed to have the same stories in the same districts.

Fig.4- 2 Construction cost for each categories of buildings in Shanghai in 2009 (C_i)Tab.4- 5 Results of exposure assessment of buildings in study area in 2009 [million \$USD] (S_{ij})

Districts	Category of buildings				Total
	Commercial	Public	Industrial	Residential	
Huangpu	8793.7	7784.8	4200.5	6141.7	26920.7
Pudong	12.9	50.1	102.4	199.5	365.0
Zhabei	979.3	1220.0	1560.9	760.9	4521.1
Luwan	224.9	125.7	16.4	127.8	494.9
Jing'an	132.2	237.2	223.6	87.1	680.0
Hongkou	366.4	463.6	406.9	396.5	1633.4
Total	10509.5	9881.5	6510.7	7713.5	34615.1

Regarding the value of inventory in each household, Fig.4- 3 shows a list of popular household items in Shanghai with estimated values; the reasons to select them are, firstly, they are fragile to be inundated, which could induce large damage consequently; and secondly, these data are available from official report (SSB 2010). In a summary, the estimation of inventory value is 7,909\$USD/household. Based on the assumption of amount of apartments and residential buildings (in Appendix 4-1), the total inventory value is 63 million \$USD.

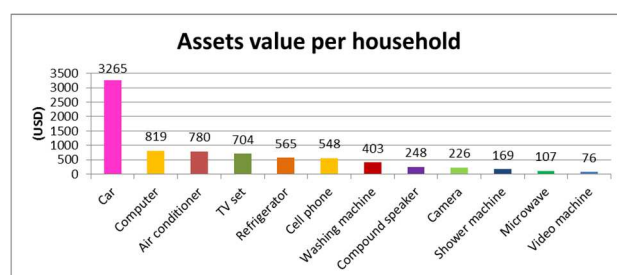


Fig.4- 3 Assets value per household in Shanghai city in 2009

Chapter 5

Shanghai: Flood risk analysis

Flood risk is calculated by the occurrence/exceedance probability and its associated potential damage. In theory, flood risk analysis is a full probabilistic analysis, which should consider a set of scenarios with all possible loads and the resistance, and the failure mechanisms in the system to compute the predicted frequency of occurrence and their associated consequences. The objective of this chapter is to quantify the (river) flood risk based on possible flood scenarios along the Huangpu River of Shanghai, and to identify the potential risk factors which can affect the future flood risk. The probability of flooding is consisting of overtopping, breaching and failure of floodgates. 26 scenarios were simulated along the Huangpu River based on various boundary conditions of the water level as a function of return periods of 200yr, 500yr, 1,000yr, 10,000yr at Wusongkou, in which 8 breaching points and 3 floodgates points were selected on the west and east side of the floodwall. The total flood risk is calculated between 40 million \$USD/yr and 112 million \$USD/yr along the Huangpu River of Shanghai, in which the O4 (~45km away from the mouth) is most likely to be overtopped and the breaching point at BW3 (~26km away from the mouth in west side of the Huangpu River in the city centre) leads to largest potential flood damage among all the scenarios. Furthermore, it is noticed that the economic damage due to breaching is much higher with a factor of 10 than those caused by overtopping scenarios. However, in terms of the contribution to the flood risk, the failure of floodgates accounts for ~41% of the overall flood risk due to its higher probability of failure than breaching and parts of overtopping scenarios. In terms of factors affecting on the future flood risk, the economic development has greatest effect on future flood risk, which could triple flood risk in 2030 and increase six folds of risk in 2050 solely if no further measures are taken. Land subsidence is the second driver of future risk and the 'absolute' sea level rising has the least effect on the future flood risk. The combination of affected factors would raise the total flood risk 4 times and 16 times in 2030 and 2050 respectively. These results provide rational insights into the potential local emergency response and cost-benefit of risk-reduction measures in the future.

5.1 Introduction

Flood risk is calculated by a combination of occurrence/exceedance probability and its associated potential damage. For example, a flood in the river results in €1,000,000 of economic losses. If that flood has a probability of occurrence of 4% per year, the risk contribution of that specific flood in terms of expected annual damage is €40,000/year. This kind of calculation is useful to compare different floods. If another flood in adjacent area has a flood risk value of €100,000 /yr. It can be regarded that the latter flood is 2.5 times worse than the first one. In theory, the flood risk analysis is a full probabilistic analysis, which should be calculated based on all possible loads, the resistances of the system, the potential flood scenarios and their associated consequences including uncertainty analysis. Therefore, the result of the flood risk analysis should be represented as a risk (damage-probability) curve in the end, which shows the full distribution function of flood consequence in an area; the (overall) flood risk can then be calculated by integrating the area under the risk curve. The flood risk shows an estimated damage per year in a specific area.

A number of researchers have studied the flood risk in specific areas worldwide. In South Holland of the Netherlands, the flood risk was determined under different breaching scenarios and a multiple combinations in terms of dike rings (Jonkman, Kok et al. 2008). The procedure was first to determine the probability of floods, which was undertaken by a statistical calculation of failure probability in a dike stretch of a dike ring under various failure mechanisms; the summation of the failure probabilities of all dike stretches or a combination of breaching probability were taken as the overall probability of flood in the whole system; second, the inundation characteristics are further determined for all the flood scenarios as an input for the determination of consequence. Finally, the economic damage was calculated based on the inundation characteristics and the spatial distribution of property assets; the number of loss of life was estimated based on population density and evacuation schemes under different scenarios. To sum up, every scenario has a corresponding result on economic damage or the loss of life; and by considering the occurrence probability of each scenario the total flood risk was derived. The probability of flooding in the South Holland was calculated as 3.99×10^{-4} / year in total, which approximately equalled to once in 2,500 years. The associated damage was estimated at around €99.8 billion in the first ten large contributed flood scenarios. Hence, the flood risk in the South Holland was calculated as €39.32 million /year (53 million \$USD/year¹³). These results were regarded as an indicative and realistic estimation of risk level in the Netherlands. In New York city, the flood damage to buildings was estimated at between 59 and 129 million \$USD/year by considering more than 200 low-probability storm-surge events (Aerts, Lin et al. 2013). It was regarded as a more accurate estimation of direct flood risk in NYC than earlier studies. In Shanghai, the expected annual damage was previously estimated at 70 million \$USD/year (Nicholls, Hanson et al. 2007) and 63 million \$USD/year (Hallegatte et al. 2013) under an optimistic scenario of maximum protection of 1/1,000/yr, which were not very informative as only one flood scenario cannot stand for the overall flood risk. Therefore, the objective of this chapter is to quantify the flood risk based on possible flood scenarios along the Huangpu River, and to identify the potential factors which can affect the future flood risk in Shanghai. The results could provide as a basis for the evaluation of risk-reduction measures, specifically for the cost-benefit analysis in the next step. The corresponding research questions will be addressed as below:

- How to determine flood risk based on the local information on flood defence system and flood scenarios?
- What is the current and future flood risk in Shanghai?
- Which risk factor(s) influence future flood risk most significantly?

¹³ Currency rate: Euro : USD = 1:1.35

The structure of the remaining sections will be organized as below. Section 5.2 is going to show the methodology of flood risk analysis. Section 5.3 is presenting the results of risk quantification under different scenarios. Section 5.4 is going to address the future challenge of flood risk in terms of sea level rise, land subsidence and economic development and to identify the most influential factor. Lastly, it ends with discuss in Section 5.5.

5.2 Methodology

The flood risk can be determined by integrating the area under risk curve, which could be seen as expected annual damage (EAD) in monetary term in a system. Risk curve can be shown as a curve with relationship of different return periods of the floods and the associated damage, or called as F-D curves; FD curve is graphical presentation of information on the frequency of a negative accident (e.g. flood) in a system and the distribution of economic damage in such accident, in which F narrowly means the cumulative frequency namely $F(D)$ of the flood events and D means the associated damage. It gives information on the exceedance probability of flood event as a function of economic damage and could be derived from the p.d.f of the economic damage $f_D(x)$ (Jonkman, van Gelder et al. 2003; Cong 2010).

$$1 - F_D(x) = F(D > x) = \int_x^{\infty} f_D(x) dx \quad (5.1)$$

$$E(D) = \int_0^{\infty} x \cdot f_D(x) dx \quad (5.2)$$

Where: $f_D(x)$ is the probability density function of the economic damage; $F_D(x)$ is the cumulative distribution function of the economic damage; $E(D)$ is the expected value of the economic damage.

In the analysis of the FD curve, various hypothetical events shall be assessed. Each of these events will have a predicted frequency of occurrence f and an expected number of economic damage D . D in this discussion will be the expected amount of the direct economic damage in the flood event. The associated frequency of occurrence f will be expressed in events per year. FD curve is regarded as a cumulative frequency basis, which plots the cumulative probability F in the frequencies of the all the events where the expected economic damage is D or more in y-axis. Since the amount of economic damage and the occurrence frequency can span multiple orders of magnitude, FD curve is usually shown in log-log scale on the axis.

An estimated probabilistic model could be assumed to fit the results of economic damage at the given flood events (e.g. exponential distribution, lognormal distribution, etc.). Vrijling and van Gelder (1997) proposed a linear combination of the statistic moments of the FN curve, namely the expected value of the number of deaths $E(N)$ and the standard deviation $\sigma(N)$ in the form of $E(N) + k \cdot \sigma(N)$. The determination of the total risk starts from the assumption that the accidents statistics reflect the result of a social process of cost-benefit appraisal and a standard can also be derived from them (Vrijling, van Hengel et al. 1998). Likewise, the number of death could be substitute by the economic damage in a monetary term at a given flood; then the total risk of the economic damage could be re-written as:

$$TR = E(D) + k \cdot \sigma(D) \quad (5.3)$$

The total risk (TR) accounts for risk aversion, which reflects the acceptance of risk in a community or in a society. Relatively frequent flood with small consequence may has an equal expected value of damage as a rare flood with big consequence. The standard deviation can reflect the difference. Hence, the total risk can be regarded as the result of flood risk with risk aversion. Hereafter, flood risk is represented by total risk calculated by Eq. (5.3).

An example of the FN curve and FD curve due to historical floods in China is shown in Fig.5. 1. The $E(N)$ of loss of life between 1950 and 2010 was calculated as 4,508/yr with standard deviation $\sigma(N)$ of 6273/yr. The total flood risk in terms of loss of life can be estimated as 23,327/yr in China. In terms of economic damage, a lognormal fit curve with $E(D)$ of 20.65 billion \$USD/yr and standard deviation $\sigma(D)$ of 15.25 billion \$USD/yr was found to best fit the empirical data. The total risk could be calculated as 66.4 billion \$USD/yr when risk index k is taken as 3. This result is comparable with the 1.5% of GDP averagely every year in China due to flooding in the past 19 years (1990-2008) by (Chen 2011). The FD curve shows the flooding in China is expected to lead to massive economic damage.

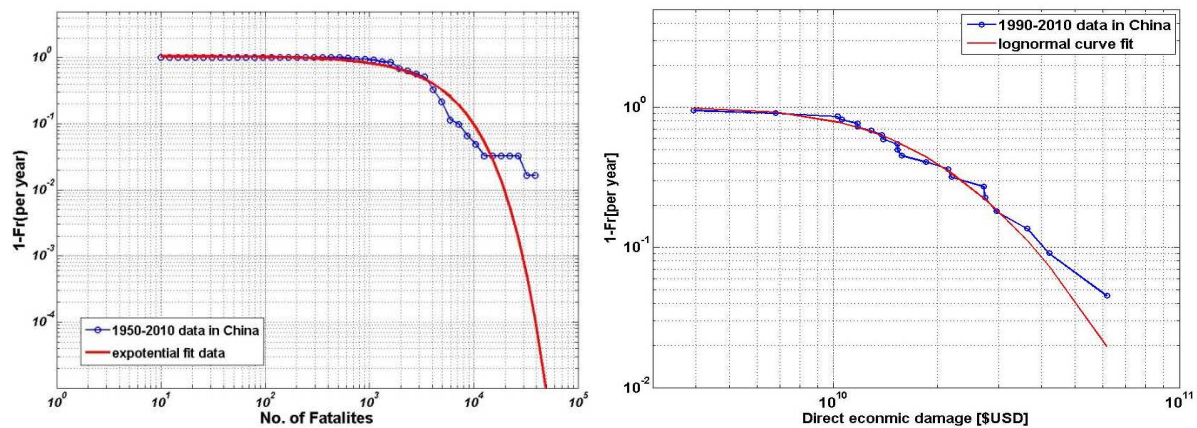


Fig.5. 1 Empirical FN curve (1950-2010) and FD curve (1990-2010) due to historical floods in mainland of China (Data source: MWR 2010)

In order to establish FD curve and compute the (river) flood risk (expected annual damage) along the Huangpu River, a set of scenarios were taken into account with predicted probability of flooding and the associated damage. A table shows a list of flood scenarios will be arranged in a descending order in terms of flood damage, each of them with a predicted probability of flooding. Cumulative probability for each scenario will then be derived. Finally, a FD curve for Shanghai case could be established and flood risk can be calculated further based on statistical principles. Because $f(D)$ is non-negative, so that FD curves never rise from left to right, but are always falling or flat. The lower an FD-curve is located on the FD-graph, the safer is the system it represents, because lower FD-curves represent lower frequencies of negative events (e.g. flood) than higher curves. Moreover, as seen from Tab.5. 1, it is easily to deduce the $f(D)$ from the $F(D)$ and conversely, it is possible to calculate the $F(D)$ by summing up the $f(D)$ upward from D .

Tab.5. 1 List of flood scenarios in a descending order with predictable failure probability, the associated damage and the cumulative probability

Scenarios	Failure Probability of flooding $f(D)$	Associated damage D	Exceedance probability $1-F(D)$
1	P_{f1}	D_1 (maximum)	P_{f1}
2	P_{f2}	D_2	$P_{f1} + P_{f2}$
3	P_{f3}	D_3	$P_{f1} + P_{f2} + P_{f3}$
.....			
N	P_{fn}	D_n (minimum)	$P_{f1} + P_{f2} + P_{f3} + \dots + P_{fn}$

In order to establish FD curve and compute the flood risk of river flood along the Huangpu River, the following steps should be followed:

Step 1: Scenarios set-up

Based on flood hazard analysis in Shanghai, three potential flooding events along the Huangpu River could be identified 1) by overtopping of the floodwall without structural failure, 2) structural failure due to larger hydraulic load than the defensive resistance, i.e. breaching and 3) failure closure of the floodgates. Subsequently, a series of flood scenarios were set-up. The summary of the potential failure points of flooding along the Huangpu River were illustrated in Fig.5. 2. The orange flag sign represents the overtopping points with a sequential order of O1-O6, which are identified as weak points based on the comparison of the water level with crest floodwall at a certain point. The potential breach locations were marked as red stars on the both of west and east side of the Huangpu River. Each side was assigned 4 points respectively, namely BE1, BE2, BE3, BE4 and BW1, BW2, BW3, BW4. The locations of failure close-down of floodgates were shown as blue circle on the east side with name of Fg1, Fg2 and Fg3 on the map (more details in Chapter 3). It should be noted that these scenarios are not representing the overall failure possibilities of flooding along the river; but they are representative flood scenarios in this schematized flood risk analysis for Shanghai.

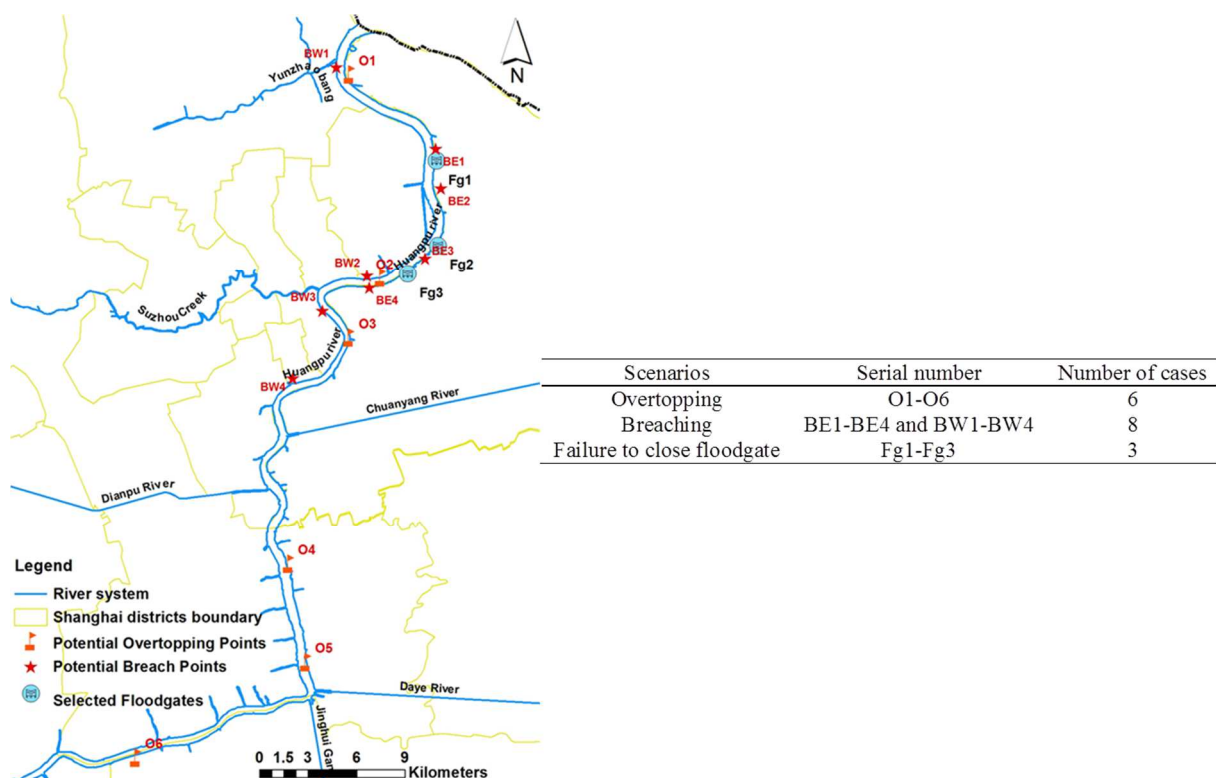
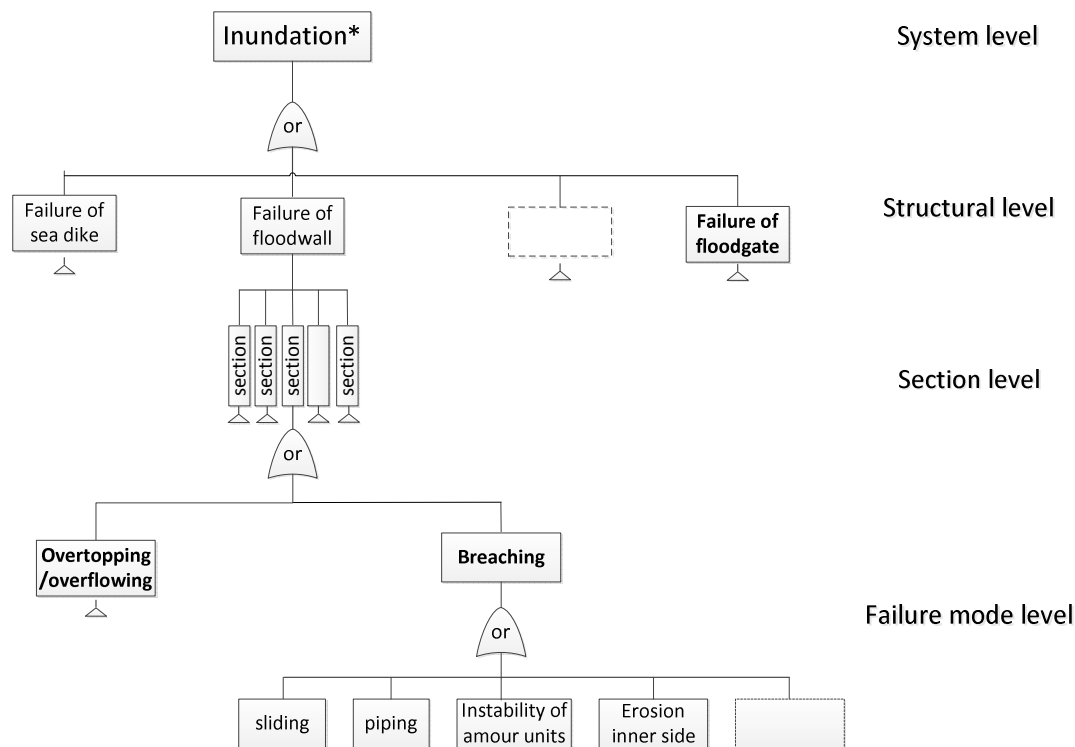


Fig.5. 2 Potential failure points of flooding along the Huangpu River on both sides (i.e. overtopping, breaching and failure of floodgates)

Step 2: Determination of failure probability

The overall failure probability of flood defence should take all the failure mechanisms into account (see Fig.5. 3). Commonly, the fault tree is used to analyse the failure modes and failure probability in the system. It can be seen that besides the overtopping and overflowing, the structural failures (i.e. breaching) like sliding, piping, instability and erosion of flood defence structures, etc. are the significant failure mechanisms, in which the failure probability can be calculated by the method of Bayesian probability theory and already be applied in the Netherlands, e.g. PC-RING model in the each dike ring system (Allsop, Kortenhaus et al. 2007). In the Bayesian probability theory (van Gelder 2000), the resistance and load characteristics were modelled by the stochastic variables with the associated probability distributions; the uncertainties of the variables, namely the inherent uncertainty (e.g. water levels at a given time) and empirical uncertainty, were taken into account in the distribution of proba-

bility and its estimated parameters. However, since the data related to the geometry of floodwall and its fundamental conditions (e.g. soil characteristics) were lacking, the probability of the flooding based on scenarios was 1). the exceedance probability of the water level in the river compared to the crest of the floodwall at a certain point for overtopping; 2). the probability of breaching at a certain water level in the floodwall 3). the failure probability of close-down the floodgates. Ideally, the fragility curves, which express the failure probability of a defence as a function of the hydraulic load, e.g. water level, can show the failure probability at a given hydrological load (i.e. water level). Since this is not the focus of this research, a number of assumptions were made for the calculation of failure probability in the floodwall of the Huangpu River:



*: Note that 'inundation' means a fact of flooding due to the failure of flood defence

Fig.5. 3 Fault tree with basic failure mechanisms (adapted from Cong 2010)

- 1) Overtopping occurred when the water level exceeds the crest height of floodwall;
- 2) In order to explore the worst-case scenario, breaching occurred simultaneously when water level reaches at the warning water level adjacent to the floodwall (around 5m or more); the conditional failure probability at 5m or more was assumed as 0.01% uniformly for the overall breach points (see Fig.5. 4). This is largely based on the local situation of the floodwall in the downstream of the Huangpu River, in which the floodwall is mainly in concrete material with either pile foundation or armouring support system. On the other hand, local engineers (Gu and Yu, 2008) have pointed out the potential geotechnical failure probability of floodwall with the failure modes of sliding, collapse of revetment, piping and subsidence, etc. Ideally, it needs to calculate the failure probability of each failure mechanism and to sum up to get the breaching probability. Since this is not the focus of this research, the conditional failure probability of floodwall at water level of 5m or more is based on expert judgement.
- 3) Failure to close the floodgate could be caused by a manual performance error; the conditional failure probability of floodgate at water level of 4.7m or more was assumed as typical failure probability due to human error in a routine operation where care is required, namely 1% (Kirwan 1994).

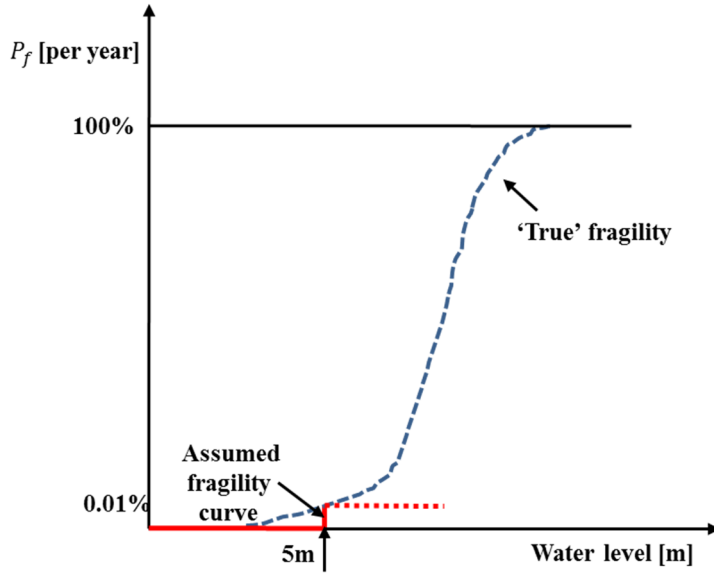


Fig.5. 4 The simplified fragility curve of breach scenario as a function of the water level at 5m or more in this research compared with a more realistic fragility curve

As a result, the assumed failure probability for overtopping, breaching and failure closure of flood-gates could be written as below:

$$P_{f.o} = p_{(wl > crest.h)} \quad (5.4)$$

$$P_{f.b} = p_{(wl \geq 5m)} \cdot p_{(failure|wl \geq 5m)} \quad (5.5)$$

$$P_{f.fg} = p_{(wl \geq 4.7m)} \cdot p_{(failure|wl \geq 4.7m)} \quad (5.6)$$

Where: $P_{f.o}$ - failure probability of overtopping; $p_{(wl > crest.h)}$ - occurrence probability of water level exceeding the crest height of floodwall; $P_{f.b}$ - failure probability of breaching; $p_{(wl \geq 5m)}$ - occurrence probability of water level at 5m; $p_{(failure|wl \geq 5m)}$ - conditional probability of floodwall when the water level reaches at 5m; $p_{(wl \geq 4.7m)}$ - occurrence probability of water level $\geq 4.7m$; $p_{(failure|wl \geq 4.7m)}$ - conditional probability of close-down floodgate when the water level reaches at $\geq 4.7m$; $P_{f.fg}$ - failure probability of floodgate.

Note that, the flood scenarios are assumed as independent with each other, which means the failure of one scenario would not cause negative effect on other sections of the floodwall system. The overtopping scenarios would not cause further breaching based on the assumptions.

Step 3: Calculation of maximum inundation depth

Flood characteristics determine the severity of the adverse impacts on the elements at risk. Commonly, the inundation depth is a vital determinant on the direct economic damage in an urban area. Flood simulations under the aforementioned selected scenarios were subsequently conducted in the 1D2DSobek model (also see details in Chapter 3). The results of inundation depth for each scenario were shown on the map with grid size of 300m*300m. An example of inundation maps under different scenarios at around ~20km East side away from the mouth of the river were shown in Fig.5. 5, which shows an increasing order of inundation extent followed by overtopping, failure of floodgate and breaching scenarios successively.

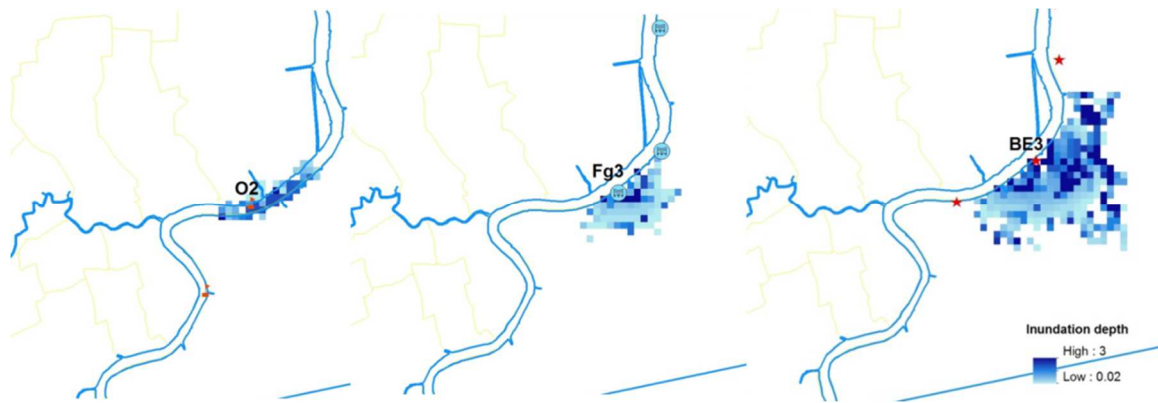


Fig.5. 5 Inundation maps under different scenarios in an adjacent area around ~20km East side away from the mouth of the river, which shows an increasing order of inundation extent followed by over-topping, failure of floodgate and breaching scenarios

Step 4: Estimation of economic damage

Ideally, the flood damage under each flood scenario can be estimated based on the inundation depth and spatial distribution of economic assets by the method of stage–damage function in GIS environment. This method has been already applied in part of downtown Shanghai in Chapter 4, which estimated the flood damage at an individual building level in the study area. As the information on spatial distribution of buildings or other infrastructures are lacking in whole area of Shanghai, it is explicitly challengeable to assess potential maximum damage for the elements at risk in a quantitative way. In order to estimate potential flood damage in the flood scenarios, an aggregated macro-level damage model was developed, which could be seen as a semi-quantification of flood risk analysis in terms of flood damage estimation. The aggregated macro level damage model includes two parts: exposure assessment which estimates the potential maximum damage in the districts of Shanghai and stage-damage function which shows the relationship of damage rates of elements at risk as a function of inundation depth.

Maximum damage assessment

1. Six criteria were selected with an aim to assess the economic vulnerability in the districts of Shanghai (see Appendix 5-1). The result is a ranking of risk areas (=municipal district) with degrees of their economic vulnerabilities. The more vulnerable the area is the more potential flood damage it could be resulted. By using of the GIS tool, the rankings and categorization of the areas in terms of economic vulnerability can be shown on the map. In the end, three groups of districts in terms of economic vulnerability were classified, which was shown in Appendix 5-1.
2. Based on the previous results of the valuation of the economic assets (mainly on the buildings and residential inventories) in a small part of downtown Shanghai (see the red box in (i) of Fig.5. 6), the potential maximum damage to buildings was estimated at 5.77 billion \$USD in the study area (~17.2km²). Followed by the size of grid cell in inundation depth produced by the flood simulation of hydrodynamic model, the red box can be divided as 210 (15 column and 14 rows) of grid cells with size of 300m*300m, in which only 188 grid cells contains economic assets and the others are water bodies or out of the boundary. It is calculated the potential maximum damage is 30.6 million \$USD per grid cell (5.77×10^9 \$USD/188 grid cells) averagely in this study area.
3. The study area represents a group of highly economic districts in the city centre with each grid cell of 30.6 million \$USD, such as Huangpu, Jing'an, Luwan, Hongkou and the commercial Pudong area. These areas usually include fancy hotels, restaurants and shopping malls etc.. Based on the eco-

conomic vulnerability assessment, Yangpu, Zhabei, Xuhui, Putuo, Changning and the non-commercial Pudong districts were categorized as the second group, namely less vulnerable districts to flooding in terms of economy, the economic assets were then estimated at half of 30.6 million \$USD per grid cell. In the third group of suburb districts, Songjiang, Baoshan, Chongming, Qingpu, Jiading, Jinshan, Fengxian, the economic assets were estimated at 1/4 of 30.6 million \$USD per grid cell. As a result, the potential maximum damage were estimated at **30.6, 15.3 and 7.65 million \$USD** per grid cell in three groups of the districts in Shanghai, which equals to **335.5, 167.7, 83.8 million \$USD /km²**.

4. In a summary, the spatial distribution of the estimated potential maximum damage per grid cell in the municipal districts of Shanghai was illustrated in (ii) of Fig.5. 6. In these districts, the darker the colour is the more potential maximum damage per grid cell is assigned.

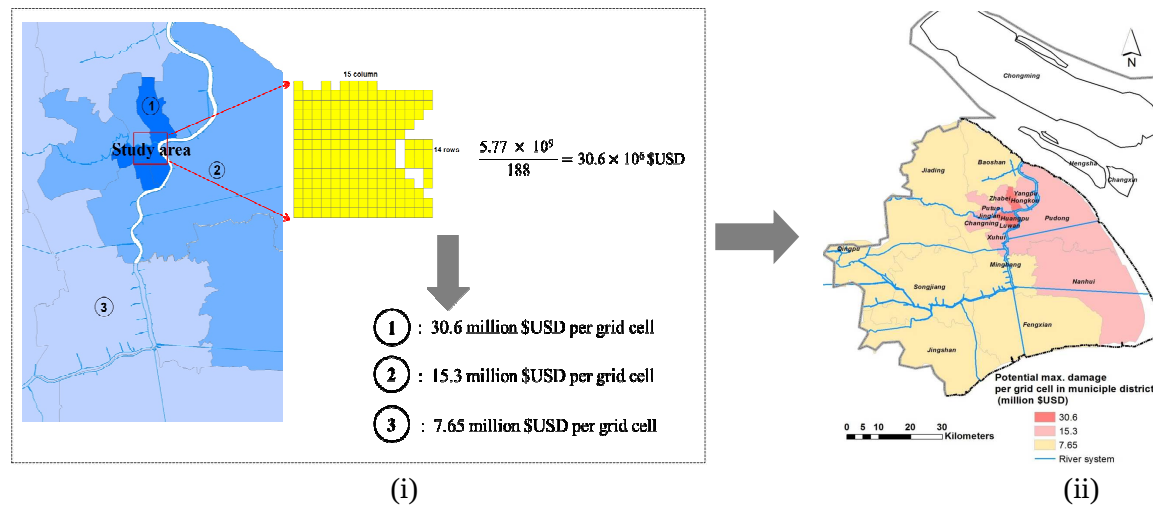


Fig.5. 6 Distribution of potential maximum damage per grid cell in municipal districts of Shanghai city (the darker the colour, the more potential maximum damage contains) First group: Huangpu, Jiang'an, Luwan, Hongkou, with 30.6 million \$USD potential maximum damage per grid cell; second group: Yangpu, Zhabei, Xuhui, Putuo, Changning, Pudong, with 15.3 million \$USD potential maximum damage per grid cell; third group: Songjiang, Baoshan, Chongming, Qingpu, Jiading, Jinshan, Fengxian, with 7.65 million \$USD potential maximum damage per grid cell. [grid cell: 300m*300m]

Aggregated depth-damage function

In order to generate depth-damage function to overall buildings in Shanghai, the damage rate in the category of buildings was averaged as a medium estimation under the same inundation depth; the highest/lowest rate under a certain inundation depth in the category of buildings were taken as the high/low estimation. In general, an aggregated stage-damage function including low, medium and high estimation were derived and represented in Tab.5. 2., which could be applied in a rapid ex-ante estimation of flood damage. Consequently, flood damage under each flood scenario could be produced in a GIS environment by the method of depth-damage function.

Tab.5. 2 Suggested aggregated depth-damage function for buildings in urban Shanghai

	Inundation depth [m]						
	<0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	>3.0
Low estimate	3%	6%	9%	12%	16%	19%	22%
Medium estimate	5%	10%	14%	18%	23%	27%	32%
High estimate	9%	19%	26%	33%	38%	46%	58%

Step 5: Construction of FD-curve

Similar to the FN curve (cumulative frequencies–fatalities), FD-curve can be established by the consideration of the flood probability under a flood scenarios with associated economic damage. In practice, there are two methods to establish FD curve. The first is to calculate FD curve directly from empirical frequency data in the historical events; the second is to develop and use a probability model to estimate the frequencies. The most practical method is involved a mixture of empirical data and statistical modelling. Maaskant, Jonkman et al. (2009) has developed a FN curve due to flooding with exponential distribution in a dike ring of South Holland in the Netherlands. Likewise, FD curve could be developed in a country, a region or a city by a vast number of scenario simulations. The overall flood risk could be computed by integrating the area under the FD curve (Vrijling and Van Gelder 1997). Based on the results of the probability of flooding and the associated economic damage for the selected scenarios, FD curve could be established and a probabilistic model can be developed to calculate the total risk in the end. The expected value and standard deviation of the flood damage could be calculated based on the Eq. (5.7) and (5.8) as below:

$$E(D) = \sum_{i=1}^N (P_i \cdot D_i) \quad (5.7)$$

$$\sigma(D) = \sqrt{\sum_{i=1}^N P_i \cdot (D_i - E(D))^2} \quad (5.8)$$

Where: $E(D)$ - Expected value of flood damage; $\sigma(D)$ - standard deviation of flood damage; P_i - the estimated probability of flooding under a specific scenario i ; D_i - the estimated flood damage under a specific scenario i ; N - number of scenarios, in this case $N = 26$;

5.3 Results of flood risk analysis

26 scenarios were simulated along the Huangpu River based on the various boundary conditions of the water level as a function of return periods of 200yr, 500yr, 1,000yr, 10,000yr at Wusongkou, in which 15 overtopping points, 8 breaching points and 3 floodgates points were selected on the West and East side of the floodwall, respectively. The results of these flood scenarios in terms of failure probabilities and the associated damages were represented as follows.

5.3.1 Overtopping scenario

The overtopping locations were identified by the comparison of water level in the river and crest height of floodwall alongside. Fig.5.7 shows a list of overtopping scenarios at 6 points of floodwall, in which the grey box stands for flood simulation of overtopping. It means each points of overtopping has different failure probabilities from 1/200, 1/500, 1/1,000 to 1/10,000p.y based on the occurrence of water levels as a function of return periods. For the overtopping point O4 with failure probability of 1/200, we also simulated the failure probability of 1/500, 1/1,000 and 1/10,000. Analogously, the other points were all simulated from the failure probability 1/500, 1/1,000 to 1/10,000 as flood scenarios. Hence, based on Eq. (5.1), the overtopping probabilities are regarded as exceedance probability of a certain water level at a given cross section of the river.

The corresponding inundation extent and inundation depth under each scenario was calculated by the SOBEK model and shown on the map in Chapter 3 (see Appendix 3-4); the flood damage was then calculated based on the aggregated macro-level damage model which has been described in the methodology section on the estimation of flood damage. The estimated results of damage to buildings in each scenario are shown in Tab.5. 3; it shows the lower the probability of flooding the more damage would be incurred. The highest damage would be occurred under 1/10,000p.y at O1 with a distance of

4km to the estuary, which would range from 369.2 million \$USD to 950 million \$USD. The most likely overtopping point at O4 which is 45km away from the estuary would incur 30-93 million \$USD economic damage under 1/200p.y.. The potential damage under the predefined standards of 1/1,000yr would range from 32-200 million \$USD at different overtopping points. Compares to the overall potential maximum damage of 52- 206 billion \$USD¹⁴ if Shanghai (excluding islands) was flooded without floodwall and other infrastructure under 1/1,000p.y, the damage was substantially smaller; which indicates the overtopping scenarios are only expected to flood small part of the whole area. In total, the ‘residual’ overtopping flood risk is then calculated at 0.79-2.25 million \$USD/yr in the Huangpu River of Shanghai.

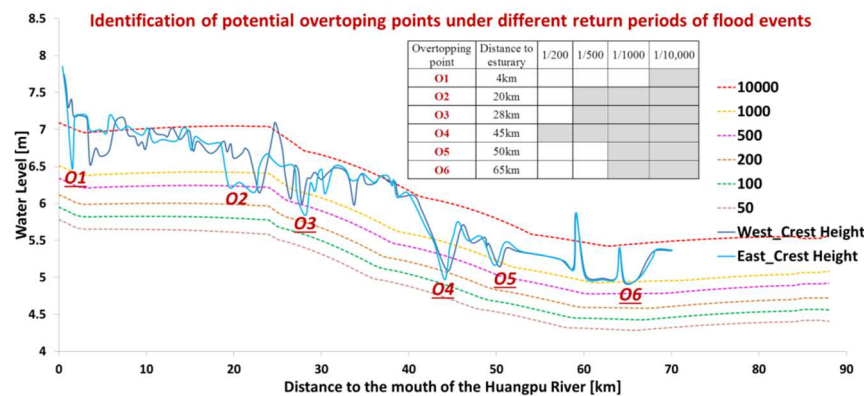


Fig.5.7 Potential overtopping scenarios at 6 points of floodwall with failure probabilities of 1/200p.y, 1/500p.y, 1/1,000p.y, 1/10,000p.y (grey box in the table stands for flood simulation of overtopping)

Tab.5. 3 Failure probabilities and the associated economic damage to buildings under overtopping scenarios at 6 potential points along the floodwall of the Huangpu River

Overtopping points	Damage [million \$USD]			
	Failure Probability [-]	Low estimation	Medium estimation	High estimation
O1	0.0001	370	545	950
O2	0.0020	55	85	155
	0.0010	56	87	160
	0.0001	135	200	360
O3	0.0020	50	75	130
	0.0010	78	116	200
	0.0001	112	170	300
O4	0.0050	30	50	93
	0.0020	40	64	120
	0.0010	55	87	160
	0.0001	110	170	320
O5	0.0010	48	75	138
	0.0001	77	120	220
O6	0.0010	32	51	93
	0.0001	45	71	132

¹⁴ Based on the inundation map under no-protection scenario with probability of 1/1,000yr (see Section 3.3.2.3), the inundation area would be 606.4km², which was calculated and shown in Tab.3. 5.

5.3.2 Breaching scenario

Breaching includes all the structural failure mechanisms when the water levels haven't reached the crest height of the floodwall; it needs fully analyse the loads and resistances of the flood defence in the system. As the fully reliability analysis of floodwall is beyond the scope of this research, the breaching is assumed simultaneously when the water level reached at 5m with a breach width of 300m in the scenarios. Hence, the probability of breaching could be a conditional probability of the occurrence probability of 5m or more at each point. Based on the previous frequency analysis, GEV distribution was recommended as the first option for annual maximum water level at Wusongkou and Huangpu park station. Hence, the occurrence probabilities of water level at 5m were calculated as 0.5/yr and 0.14/yr at Wusongkou and Huangpu Park, respectively. Subsequently, the occurrence probability of 5m water level at each breach point is taken as an exponential relation as a function of the distance to the estuary, which were calculated and shown in Fig.5. 8. In addition, the failure probability of breaching at water level of 5m is, in general, assumed as 0.01%. Based on Eq. (5.3), a summary of failure probabilities at potential breach points in the floodwall was shown in Tab.5. 4. The total breaching probability is a summation of 8 potential breaching scenarios with failure probability of 1.59×10^{-4} /yr. The highest and lowest probability of breaching is 4.0×10^{-5} at BW1 and 8.0×10^{-6} at BW4, respectively.

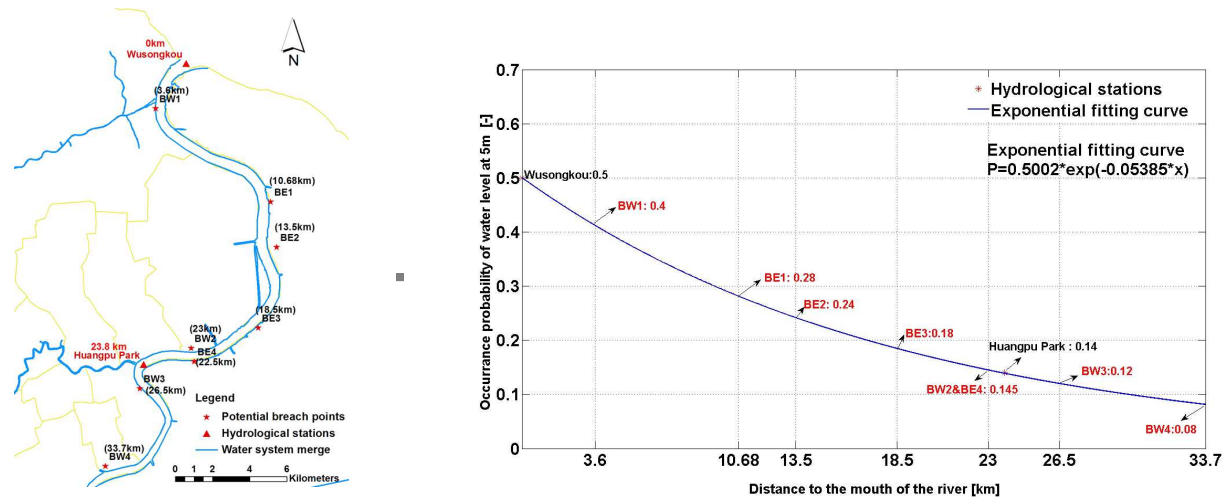


Fig.5. 8 Occurrence probability of water level at 5m based on an exponential relation as a function of distance to the mouth of the river for each breach point by means of interpolation method (East side: BE1, BE2, BE3 and BE4 and West side: BW1, BW2, BW3 and BW4)

Tab.5. 4 A summary of breaching probabilities at potential points on the East side (BE1, BE2, BE3 and BE4) and West side (BW1, BW2, BW3 and BW4) of the Huangpu river

	Potential breaching point	Distance to Wusongkou [km]	Occurrence Probability [1/yr]	Conditional probability [1/yr]	Failure probability [1/yr]
East side	BE1	10.68	0.28	0.0001	2.80E-05
	BE2	13.5	0.24	0.0001	2.40E-05
	BE3	18.5	0.18	0.0001	1.80E-05
	BE4	22.5	0.145	0.0001	1.45E-05
West side	BW1	3.6	0.4	0.0001	4.00E-05
	BW2	23	0.145	0.0001	1.45E-05
	BW3	26.5	0.12	0.0001	1.20E-05
	BW4	33.7	0.08	0.0001	8.00E-06

Tab.5. 5 Results of flood damage due to breaching along the Huangpu River

Breaching	#	Probability [1/year]	Damage [million \$USD]		
			Low	Medium	High
East side	BE1	2.80E-05	193	297	533
	BE2	2.40E-05	175	268	484
	BE3	1.80E-05	350	530	943
	BE4	1.45E-05	209	315	560
West side	BW1	4.00E-05	284	436	783
	BW2	1.45E-05	612	956	1,792
	BW3	1.20E-05	1,186	1,888	3,440
	BW4	8.00E-06	627	1,005	1,812

Next, the flood damage to buildings due to breaching scenarios along the Huangpu River is also calculated by the aggregated macro level damage model. The results are show in Tab.5. 5. The flood damage to buildings under different breaching scenarios ranges from 0.17 billion \$USD to 3.4 billion \$USD. It is noted that the failure probability is not related to the amount of economic damage, which means it is not expected that the smaller the failure probability is the more economic damage would be incurred. Since the simulation of breaching was limited within 24 hours¹⁵, which might lead to conservative results on economic damage.

The breaching results indicated that the flooding in the Huangpu River would induce large amount of economic damage to buildings. The worst-case scenario was at BW3 (28km away from the mouth the river on the west side of the river). It could cause economic damage at 1.19-3.44 billion \$USD in part of the city centre, which is more or less the same as the total economic damage in 1999 flood in Taihu Basin (~2.24 billion \$USD). Since only the damage to buildings and residential inventories are taken into account in these scenarios, the total economic damage would be double or triple of these figures due to adverse effect on business interruption and service interruption in the urban area. It also shows the river flooding due to breaching along the Huangpu River could lead to massive damage in Shanghai. Furthermore, compared with overtopping and breaching scenarios, it is noticed that the economic damage due to breaching is much higher with a factor of 10 than those caused by overtopping scenarios.

5.3.3 Scenarios of failure of floodgates

Based on the ‘Emergency Plan for Flood Prevention in Shanghai’ (www.shanghaiwater.gov.cn), it is regulated that the floodgates should close down when the water level reaches at 4.7m or more along the downstream of the Huangpu River. The failure to close down floodgates along the Huangpu River could be regarded as a special case of the instantaneous breaching with breach width of ~ 10m (the width of the floodgate) when the water level reaches 4.7m or more. Similar to the breaching scenarios, the occurrence probabilities of water level at 4.7m were calculated as 0.89/yr, 0.5/yr and 0.00001/yr at Wusongkou, Huangpu Park and Mishidu, respectively. A polynomial relation as a function of the distance to the estuary was proposed to calculate the occurrence probabilities of water level at 4.7m at Fg1, Fg2 and Fg3, which is also shown in Fig.5. 9. And the failure probability of close-down floodgate at water level of 4.7m or more was assumed as 1% due to human errors based on Dutch experiences. In the end, by multiplying the occurrence probability and failure probability, the conditional failure probability at Fg1, Fg2 and Fg3 were calculated as 1.38×10^{-4} , 1.21×10^{-4} and 1.13×10^{-4} , respectively.

¹⁵ An assumption of quick response on flood control within 24 hours for local government in Shanghai

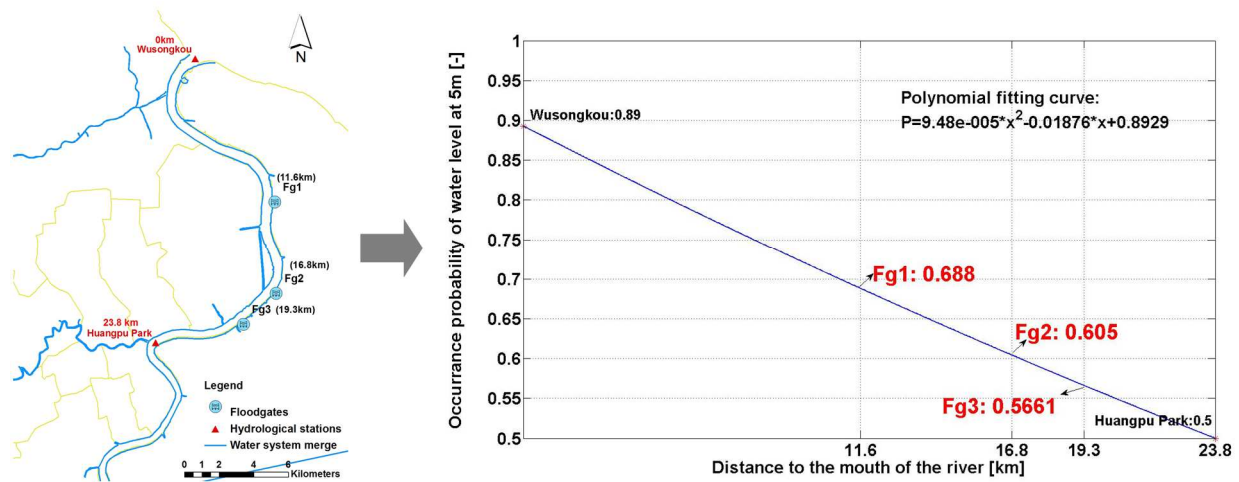


Fig.5. 9 Occurrence probability of water level at 4.7m based on polynomial relation as a function of distance to the mouth of the river for each floodgate point by means of interpolation method (Fg1, Fg2 and Fg3)

Tab.5. 6 Failure probability of floodgates and the associated flood damage at three selected locations

Floodgate	Occurrence Probability [1/yr]	Conditional Probability [1/yr]	Failure probability [1/yr]	Damage [million \$USD]		
				Low	Medium	High
Fg1	0.688	0.01	6.88E-03	59	90	159
Fg2	0.605	0.01	6.05E-03	51	83	149
Fg3	0.566	0.01	5.66E-03	85	135	243

Based on the damage model, the associated flood damage were estimated and shown in Tab.5. 6 accordingly. It is noticed that the economic damage ranges from 51-243 million \$USD under these scenarios.

5.3.4 Flood risk in Shanghai

The scenario-based flood risk is shown by means of a FD curve and the expected annual value of flood damage. It shows the probability of exceedance in one year of a certain amount of flood damage due to one event. Both axes are generally displayed in logarithmic scale. The FD curve provides information on the probability of a flood disaster with a certain magnitude of consequences and is used to display the risk. The intersection with the vertical axis equals the flooding probability of the Huangpu river, which is $3.68 \times 10^{-2}/\text{yr}$ (i.e. around once in 27 years). The total damage of the selected scenarios was calculated as 5.12 billion \$USD, 7.97 billion \$USD and 14.4 billion \$USD under low, medium and high estimation, respectively.

Based on the probability and the damage value for the selected scenarios, the expected value of flood damage can be determined. It was mathematically proven that the area under the FD curve equals the expected damage value by Vrijling and van Gelder (1997). This yields the expected value $E(D)$ ranges from 2.05 million \$USD/yr, 3.21 million \$USD/yr and 5.79 million \$USD/yr and the standard deviation $\sigma(D)$ ranges from 12.6 million \$USD/yr, 19.7 million \$USD/yr and 35.4 million \$USD/yr under low, medium and high estimation, respectively. Hence, the total flood risk can be calculated based on the Eq. (5.1) with results of **39.8 million/yr**, **62.2 million/yr** and **112 million/yr** with risk aversion index of 3 under low, medium and high estimation, respectively.

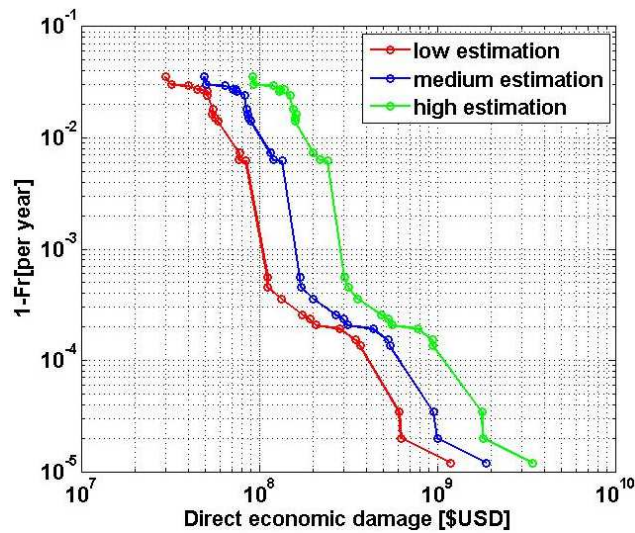


Fig.5. 10 FD curve in the selected scenarios of flooding along the Huangpu River in Shanghai with low, medium and high estimation of the associated damage

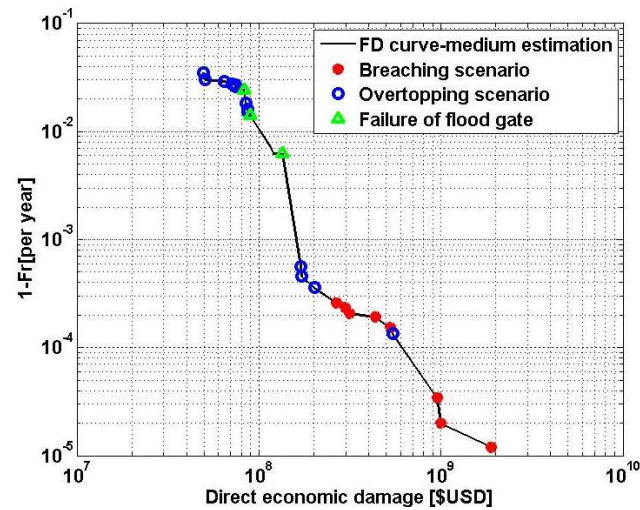


Fig.5. 11 Distribution of three types of flood scenarios in FD curve with medium estimation

Fig.5. 11 shows breaching scenarios have larger damage compares to overtopping and failure of floodgate, except for the overtopping scenarios at O1 (~4km away from the mouth of river) under 1/10,000p.y. Due to its adjacent location to the mouth of the river and low elevation around, the high storm surge and astronomic tide lead to high water level under extreme events could lead to massive damage, which is even higher than other breaching scenarios. Furthermore, it is noticed that the economic damage due to breaching is much higher with a factor of ~10 than those caused by overtopping and the failure of floodgate. However, in terms of the contribution to the flood risk, the overtopping and breaching scenarios account for ~33% and ~26% to the total flood risk respectively while the failure of floodgates accounts for ~41% of the overall flood risk due to its higher failure probability (with a factor of ~100 even ~1,000) than breaching and parts of overtopping scenarios(also can be seen from Fig.5. 11) .

The EAD in our study was estimated at 2-6 million/yr, which is 10 factors lower than earlier studies in Nicholls et al. (2007a) and Hallegatte et al. (2013) (also shown in Tab.5. 7). This can be explained that 1). current research is focus on the river flooding based on the simulated flood events by 2D hydraulic model, which considers 26 scenario-based floods by different failures. It shows floods would not cover the overall area of Shanghai, while only a limited area adjacent to the failure points could be flooded. This thus led to limited damage; 2). other flood patterns, such as waterlogging due to insufficient drainage capacity in the city, were not considered; 3). current flood damage estimates were direct

economic damage to buildings. The damage would be significantly increase if other damage categories were included, such as transportation infrastructures. However, our current research considered many flood events at a local city level, which is indicative for a sophisticated flood risk analysis (Jonkman 2013). Hence, EAD in this research can be regarded as the preliminary results in Shanghai and more investigations would be needed for a more complete assessment.

Tab.5. 7 A comparison of the current result of EAD in Shanghai with earlier studies

Different studies	EAD in Shanghai [million \$USD]
Current research	2-6
Nicholls et al. (2007a)	73
Hallegatte et al. (2013)	63

5.4 Future challenges and flood risk

Since the current protection level of the floodwall along the Huangpu River is no more than 1/200p.y in Shanghai. Flood risk would be further increased to a large degree with sea level rising and land subsidence if no further risk reduction measures are initiated. On the other hand, the potential flood risk would be significantly increased as well with rapid economic development in an urban developed city. In order to find out the most influential factor which determines flood risk in the Huangpu River, three scenarios were proposed to investigate the future flood risk. The projection years are 2030 and 2050 with a reference year of 2010. 1) the potential risk under sea level rising and land subsidence would be identified with a comparison of flood risk at 1/200p.y in the river; 2) it is projected to identify potential flood risk due to economic development; 3) the combination of the factors of sea level rising, land subsidence and economic growth to the future flood risk along the river is evaluated. The results can raise awareness of future challenges of flood-risk in Shanghai. In addition, it should be noted that the flood risk in the section is also represented by total risk calculated in section 5.3.

5.4.1 Change of extreme events

With climate change, sea level rising is an inevitable phenomenon worldwide, which is seen as ‘absolute’ sea level rising purely due to global warming. While with local land subsidence, it is usually regarded the sea level rising as a summation of ‘absolute’ sea level rising and land subsidence together, which is also called at ‘relative’ sea level rising. This section is going to project the flood risk under the scenarios of ‘relative’ sea level rising as boundary conditions of water level as a function of return periods from 200yr, 500yr and 1,000yr, respectively. It should be noted that the flood risk in this section is based on the calculation of total flood risk at present (reference year is 2010).

Boundary conditions

Due to climate change, the average sea level rising rate along East China Sea is **2.1mm/yr** from 1991-2010, and the predicted rising rate between 2011-2030 and 2030-2050 would be **2.5mm/yr** and **5mm/yr**, respectively (Li, Qin et al. 1998; Yin, Yin et al. 2011). Regarding land subsidence, it is reported that the compaction subsidence since 2011 is predicted as **6mm/yr** along with **1mm/yr** of tectonic subsidence (Yin, Yin et al. 2011). In general, the land subsidence is predicted as **8-9mm/yr** in Shanghai after 2010 (Gong 2008). Therefore, with such estimated increasing rate, the ‘relative’ sea level rising since 2011 is projected to be **21-23cm by 2030** and **47-51cm by 2050**, respectively. As a result, the projection of water level at the estuary could be estimated at 6.33-6.35m (200yr) and 6.72-6.74m (1,000yr) as a function of return period in the year of 2030, and 6.59-6.65m (200yr) and 6.98-7.04m (1,000yr) in the year of 2050 (see Tab.5. 7). The boundary condition of a series of water level at

the estuary can be up-scaled based on the projection of annual maximum level in 2030 and 2050 under return periods of 200yr and 1,000yr.

Tab.5. 7 Boundary conditions of annual maximum water level at the estuary of the Huangpu River under return periods of 200yr and 1,000yr in 2030 and 2050, respectively

Return period	Reference year	Projection of annual maximum water level at Wusongkou	
	2010	2030	2050
200yr	6.12m	6.35m	6.65m
1000yr	6.51m	6.74m	7.02m

Increase of flood probability

Based on the 1D hydraulic model in SOBEK, the results of the projected water levels in the Huangpu River are illustrated in Fig.5. 12 with a comparison to the crest height of the floodwall. It is noted that the floodwall would be largely out of function under the return period of 1,000 years in 2050 if there are no further measures being taken. Potential huge flood event would occur if most of the floodwall would be overtopped, which also increased the breaching possibilities of the floodwall in the river. These scenarios in the projections simply highlight the current safety standards of 1/1,000p.y would not fulfil the requirements in the future. Further measures should be taken to safe-guard Shanghai apparently. Moreover, the water levels as a function of 200yr of return periods in 2030 and in 2050 are clearly close to the water level of 500yr and 1,000yr return periods in 2010 (see Fig.5. 12). Simply speaking, the possibilities of flooding would increase roughly **~2.4 times** and **~5.2 times** with sea level rising and land subsidence in terms of overtopping in 2030 and 2050, respectively.

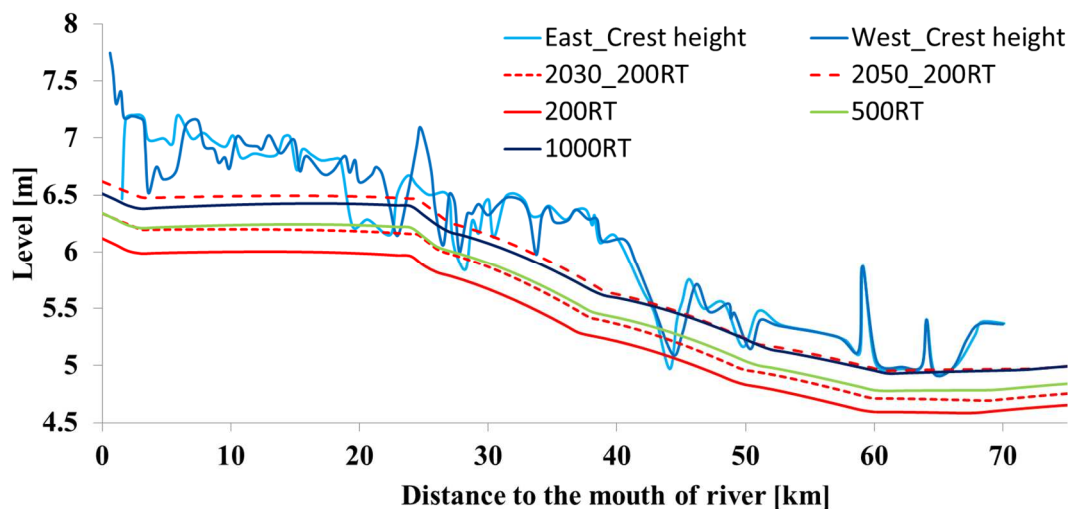


Fig.5. 12 Water levels as a function of return periods 200yr with the projection of sea level rising and land subsidence in the Huangpu River in the year of 2030 and 2050, with a comparison of the water level as a function of return periods of 500yr and 1,000yr in 2010

Increase of flood damage

On the other hand, the potential maximum inundation depth in the flood would increase by 23cm and 51cm under the current flood scenarios in 2030 and 2050, respectively due to 'relative' sea level rising. The potential flood risk would increase **~1.2 times** and **~1.5 times** on average in 2030 and 2050 compares to current situation (2010), with the correspondent flood risk increased to 48-135 million \$USD/yr in 2030 and 60-168 million \$USD/yr in 2050.

Tab.5. 8 The projection of flood risk (with increase of flood damage) under the factor of ‘relative’ sea level rising in the year of 2030 and 2050 compares to the potential flood risk in reference year of 2010

	Flood risk [million \$USD/yr]		
	2010 reference year	2030 ‘relative’ sea level rising ~ 23cm	2050 ‘relative’ sea level rising ~ 51cm
Low estimation	40	48	60
Medium estimation	62	74	92
High estimation	112	135	168

Increase of flood risk

The ‘relative’ sea level rising increases not only the occurrence probability of flooding in the future, but also the flood damage in the flood area due to lower inundation depth by land subsidence under the same flood conditions. On average, the maximum inundation depth in the potential flood area would be lowered down 23cm and 51cm under the current flood scenarios in 2030 and 2050, respectively. By calculating the flood risk under ‘relative’ sea level rising, the potential flood risk would increase **~1.9 times and ~3.5 times** on average in 2030 and 2050 compares to current situation (2010), with the correspondent flood risk increased to 66-189 million \$USD/yr in 2030 and 132-372million \$USD/yr in 2050 (see Tab.5. 9).

Tab.5. 9 The projection of flood risk (with increase of flood probability and increase of flood damage) under the factor of ‘relative’ sea level rising in the year of 2030 and 2050 compares to the potential flood risk in reference year of 2010

	Flood risk [million \$USD/yr]		
	2010 reference year	2030 ‘relative’ sea level rising ~ 23cm	2050 ‘relative’ sea level rising ~ 51cm
Low estimation	40	66	132
Medium estimation	62	104	203
High estimation	112	189	372

5.4.2 Economic development

Flood risk will increase as the economic grows rapidly, especially in an urban developed area. If we follow the GDP rising rate of ~7.7% with inflation rate of ~2.6% in Shanghai meanwhile remain other condition constant (e.g. flood defence and vulnerability) since 2010, the potential flood risk would increase to 108-304 million \$USD/yr and 291-822 million \$USD/yr in 2030 and 2050, respectively. The real economic growth rate is taken as 5.1% (GDP rising rate minus inflation rate), which is line with the expected damage rising rate (5%) which is defined by Water Resources Ministry of China (WRM 1998; Wang, Lu et al. 2001; Chen 2002). However, the rapid economic development doesn’t imply the same increasing rate on flood risk; conversely, the economic development may trigger the investment on the flood defence system or reduce the flood vulnerability, flood risk then decreases accordingly. But according to this purely economic development scenario on flood risk, it simply turns out the economic development led to more potential flood risk than extreme event does. The potential flood risk would increase **~2.7 times and ~7.3 times** on average in 2030 and 2050 compares to current situation (2010).

Tab.5. 10 The projection of flood risk under the factor of economic growth in the year of 2030 and 2050 compares to the potential flood risk in reference year of 2010

	Flood risk [million \$USD/yr]		
	2010 reference year	2030 growth rate 5.1%	2050 growth rate 5.1%
Low estimation	40	108	291
Medium estimation	62	168	456
High estimation	112	304	822

5.4.3 Combination of extreme events and economic development

In a summary, the present value of future flood risk is calculated as **~4.2 times** and **~16 times** of the current flood risk (reference year 2010) due to ‘relative’ sea level rising and economic development both in the future (the year of 2030 and 2050) (see Fig.5. 13). The future flood risk would increase to 169, 265 and 478 million \$USD/yr and 642, 1000 and 1810 million \$USD/yr in 2030 and 2050, respectively, if there are no further measures being taken.

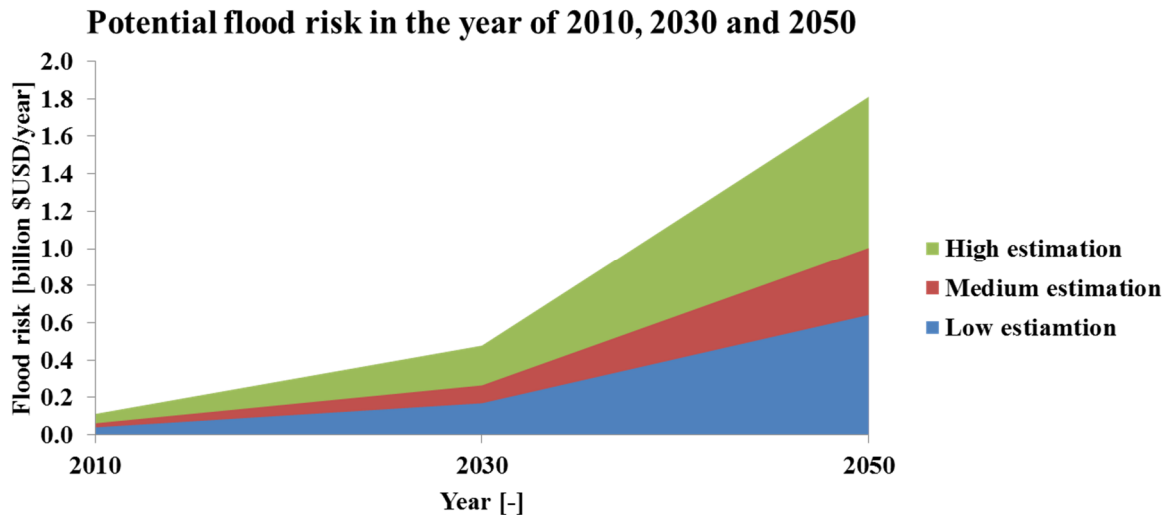


Fig.5. 13 Potential flood risk under the combination scenarios of ‘relative’ sea level rising and economic development in the year of 2010, 2030 and 2050

5.4.4 Contribution of the affected factors to future flood risk

The ‘absolute’ sea level rising, land subsidence and economic development are all contributing to the increase of future flood risk to some extent (see Fig.5. 14). As analysed before, the rising of the sea level and land subsidence would increase flood risk **~1.9 times** and **~3.5 times** on average in 2030 and 2050 compares to current situation (2010), respectively. And since land subsidence accounts for 78% and 70% in the increase of the ‘relative’ sea level rising in 2030 and 2050, it then comes out the land subsidence would increase flood risk 1.7 times and 2.5 times in 2030 and 2050, respectively. The ‘absolute’ sea level rising would contribute 0.4 times and 1.1 times to the future flood risk in 2030 and 2050, and economic development has highest influence on the future flood risk, which would increase 2.5 times and 7.3 times in the future (the year of 2030 and 2050).

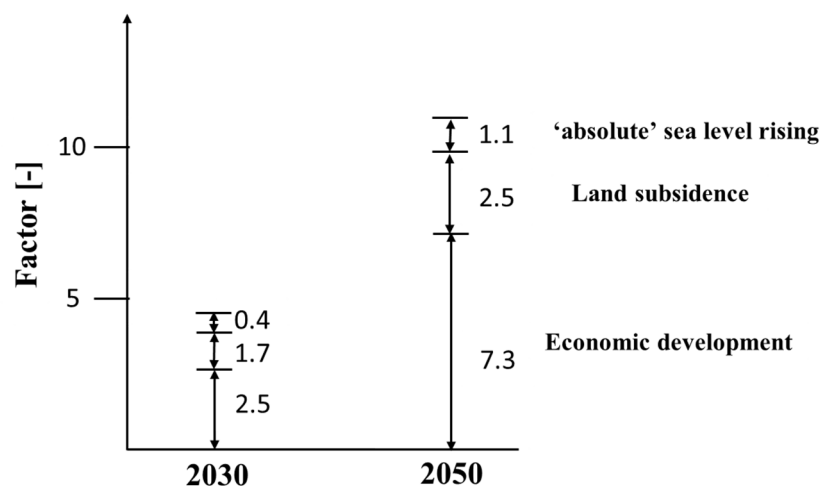


Fig.5. 14 Contributions of the effected factors to the future flood risk in year of 2030 and 2050 with a descending order: economic development, land subsidence and 'absolute' sea level rising

5.5 Discussion

The results of these scenario-based risk analysis indicate the current estimated flood risk of the Huangpu River ranges from 40-112 million \$USD/yr. Since the flood risk is calculated after implementing the protection system under overtopping, structural and operation failure of floodwall and its infrastructures, it could be regarded as 'residual' flood risk of the Huangpu River as well. Due to large uncertainties on the limited number of scenarios, the estimation of flood probabilities and flood damage, it is difficult to precisely quantify the flood risk. Possible uncertainties which determine the flood risk will be discussed in this section.

5.5.1 Flood scenarios

First, limited number of scenarios would underestimate the flood risk. Due to limited information, potential breaching points along the floodwall of the Huangpu River were identified by assumptions based on historical failure records, the crest of floodwall and economic situation of potential affected area. Only 8 breaching scenarios were simulated to explore the potential flood risk; and these breaching points were mainly located in the middle and upstream of the river due to higher economic value. Since large part of rural area (lower economic situation) and water bodies were distributed in the upstream of the Huangpu River, no breaching simulation in the upstream was performed in this study. However, according to a recent breaching case of floodwall in the upstream of the Huangpu River in the summer of 2013 (see Section 2.4), it is further demonstrated that the weak points in the upstream of the river deserve great attentions. Therefore, a further reliability analysis on floodwall is strongly recommended in the future. Second, the breaching and failure of floodgates were assumed as a sudden collapse or an instantaneous failure, in which the failure of floodgate is seen as a special case of breaching. The input parameters of breach process were deterministic where the breach width is set as 300m and breach period is 24 hours. By applied with these figures, it might over- or under-estimate the flood extent and inundation depth in the end. The expected flood damage will definitely increase to a large degree if the breaching lasts longer. Since there is limited work on reliability analysis of floodwall along the Huangpu River, the analysis of breaching scenarios is indicative in this research. It could be considered as a first estimate of flood risk along with other scenarios in the Huangpu River. Besides, the overtopping scenario was analysed based on a 1D hydraulic modelling, which identified a general possibilities of the (overtopping) flooding. These analyses provide a preliminary result of the flooding probability and inundation characteristics along the Huangpu River.

5.5.2 Flood probability

Ideally, the overall flood probability should take into account based on reliability analysis on the whole flood defence system. Since this is not the focus of this research, the failure probability was simplified as the probability of a failure on a condition of a certain hydraulic load. And the spatial variability of the floodwall geometry and the length effect of different long river stretches on the failure probability are not considered in this research.

First, one section of the floodwall is assumed independent of every other one, the lower bound of the failure probability of floodwall is then determined by the weakest section. Thus, a series of representative weak points were selected to estimate the potential failure probabilities. Apart from the overtopping scenarios, the breaching scenarios and the failure of floodgate were mainly located in the downstream and middle stream of the Huangpu river; the occurrence probability of the warning level ($\sim 5\text{m}$) at these potential locations were based on frequency analysis of the water level in the river, which shows the closer to the mouth of the river (downstream) the more likely the occurrence probability is. However, it should be noted that this is not properly applied in the upstream of the floodwall since water pattern and the resistance capacity of the floodwall are different from the sections in the middle and downstream. (Structural) failure probabilities of floodwall in the upstream should be separately considered in the future research. Hence, it is reasonable to compare the occurrence probability of $\sim 5\text{m}$ as the warning level in the middle and downstream of the Huangpu River. Second, since the conditional probability of breaching is largely dependent on the expert judgement, a sensitivity analysis of variation of the conditional probabilities to the results of flood risk in Shanghai is performed. In Tab.5.4, the conditional probability of breaching is assumed as 0.01% (i.e. 10^{-4}). It is noticed that the flood risk results are not sensitive to the decrease of conditional probability in 10 and 100 factors (10^{-5} and 10^{-6}) while the increase of 10 and 100 factors of the conditional probability (10^{-3} and 10^{-2}) led to 2-5 factor of increase of flood risk in Shanghai (also see Fig.5.15). Moreover, the sensitivity results are also shown in the form of FD curves. As we can see in Fig.5.16, the FD curve shifts up and down with the increase and decrease of the conditional probability of breaching. It also implies that the conditional probability of breaching affects the final results of flood risk. Thus further reliability analysis including the consideration of geometry, construction material and soil characteristics of the flood defence system is highly recommended.

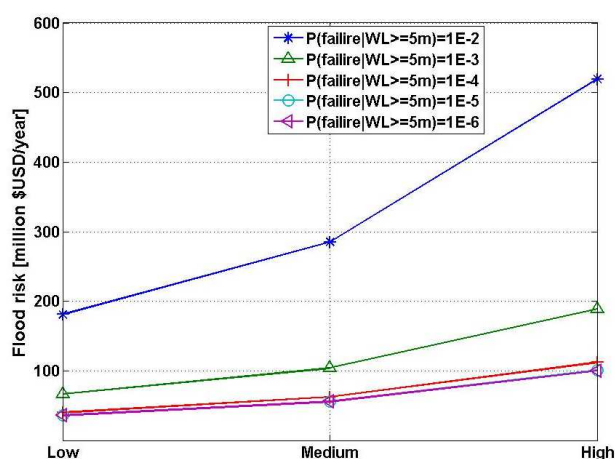


Fig.5.15 Sensitivity analysis of variation of the conditional probabilities of breaching to the final results (low, medium and high estimation) of flood risk in Shanghai

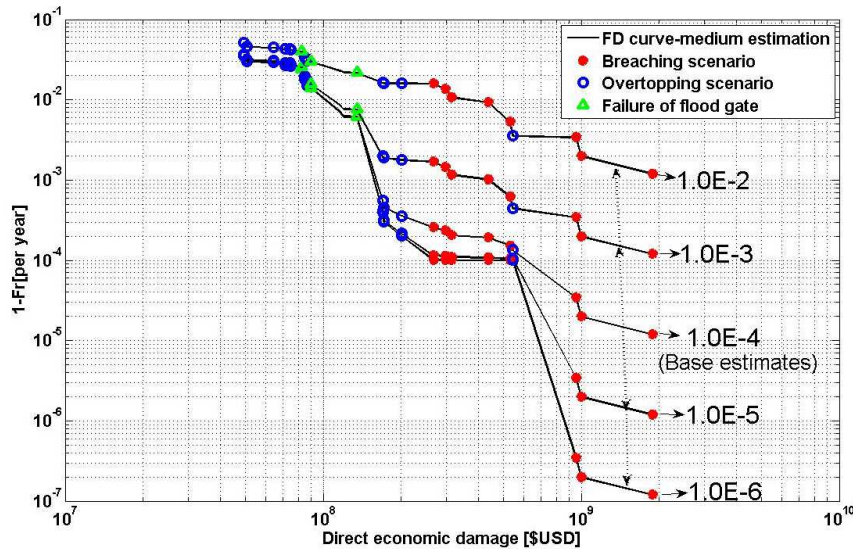


Fig.5. 16 Sensitivity analysis of variation of the conditional probabilities of breaching (varies from 10^{-6} , 10^{-5} , 10^{-4} , 10^{-3} to 10^{-2}) to the FD curve (medium estimation) in Shanghai

5.5.3 Flood damage

Large uncertainties of flood risk were caused by the estimation of flood damage. In this study, the associated flood damage under each scenario was calculated based on a macro-scale aggregated model. The quantification of potential maximum damage in a monetary term and the suggested general stage-damage functions were both performed in a macro-scale due to large credible information on the potential exposed values and vulnerability of elements at risk is unknown. Since the estimated damage is limited to buildings and residential contents, other damage categories such as infrastructures and lifeline systems were not taken into account, which may underestimate the potential flood damage then flood risk. Thus, a comprehensive category of the ex-ante flood damage estimation in an individual scale is recommended in the future study, which requires very detailed investigations. Since the indirect damage due to business interruption and service disruption could be account for around 30% in the total damage based on empirical study in flood damage estimation (see Section 4.5.2), especially in an urban city, it is thus recommended to take at least ~30% of indirect loss in the total damage estimation in urban cities in further studies. Furthermore, the intangible loss, like loss of life and social disruption, due to flood disaster should not be neglected and need to take into account in the future study.

5.5.4 Flood risk

In this research, the proposed mathematical model to calculate the flood risk is highly dependent on the standard deviation of the expected economic damage on the basis of risk aversion, in which the risk aversion index is taken as 3. Fig.5. 17 shows the total flood risk under different risk attitudes with results of 15-41 million \$USD/yr (slightly risk aversion $k=1$), 27-77 million \$USD/yr (medium risk aversion $k=2$) and 40-112 million \$USD/yr (strongly risk aversion $k=3$) in Shanghai. If the risk aversion index equals to zero, the flood risk then equals to the expected value 2-6 million \$USD/yr. These results give insights into the further risk-reduction measure in the future but it is highly recommend to take strongly risk aversion on flood risk in Shanghai city due to its critical financial status in China.

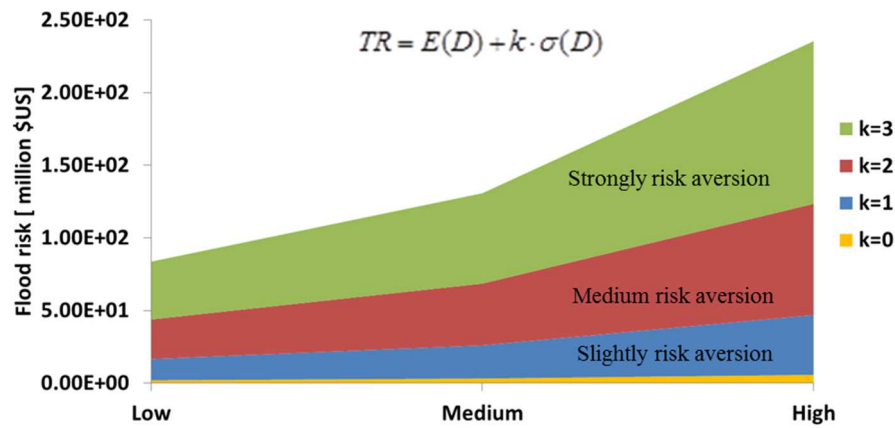


Fig.5. 17 The results of flood risk based on different risk aversion index: $k = 0, 1, 2, 3$

The standard deviation of expected economic damage plays an important role in the final results of flood risk, in which the flood damage under each scenario has one order higher effect than failure probability (see Eq. (5.8)). It could be also explained that the economic development has substantial influence on the future flood risk due to purely significant growth of potential flood damage.

Besides, the ongoing sea level rising, land subsidence and economic development lead to drastically increment of future flood risk in Shanghai. The increase rates of these affected factors were all deterministic based on the assumptions. Large uncertainties under these increasing rates should be further taken into account. For example, the increasing rate of land subsidence was uniformly taken as a 9mm/yr in Shanghai since 2011 while the increase rate of land subsidence could reached up to 20mm/yr in parts of city centre due to massive construction of high-rise buildings and groundwater extraction. Likely, if the flood damage increases as the economic growth rate, larger flood risk would be resulted in such a conservative estimation.

Appendix 5-1: Vulnerability assessment in municipal districts of Shanghai

In order to identify the magnitude and spatial distribution of the flood vulnerability, different areas are compared and evaluated with regard to different criteria by a multi-criteria approach. The general model is shown as below:

$$\bar{B} = \bar{A} \bullet \bar{\omega}$$

$$\bar{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & \dots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \dots & \dots & a_{3n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & a_{m3} & \dots & \dots & a_{mn} \end{bmatrix} \text{ and } \bar{\omega} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \dots \\ \dots \\ \omega_n \end{bmatrix}$$

Where: $\bar{B}$ is the vulnerability utility between 0-1. $\bar{A}$ is the normalized value of the criteria in different area; $\bar{\omega}$ is the weights of the criteria; m - number of the areas; n - number of criteria;

The results of vulnerability utility range between 0-1; 0 implies least vulnerable, 1 implies most vulnerable.

• Criteria selection

Floods cause massive damage to the economic properties and infrastructures, for instance the damage to the floor on the ground, rotten wallpaper, malfunction of machine in the industrial area and the collapse of fragile house, etc. in urban area, which is usually measured in a monetary term (e.g. \$USD). Tab.5- 1 shows the Evaluation criteria of flood vulnerability in Shanghai in economic dimension. Firstly, GDP/km² and GDP per capita imply the economic capacity in the municipal district; Secondly, the unsafe residential buildings (including old-style lanes and valleys, and crude shacks) may collapse or greatly be affected in an event of flood; the industrial and commercial buildings stand for the aggregation of economic assets; Thirdly, local government income represent the investment capacity for the flood defence infrastructures in a municipal district.

Tab.5- 1 Evaluation criteria of flood vulnerability in Shanghai in economic dimension

Flood vulnerability dimension	Evaluated criteria	Utility	Unit	Description
Economic	Industrial buildings (+)	u1	#	Potential economic damage
	Commercial buildings (+)	u2	#	Potential economic damage
	(unsafe) Residential buildings (+)	u3	#	Potential collapsed house
	GDP/km ² (+)	u4	\$/km ²	Aggregation of economic assets value
	GDP per capita (+)	u5	\$/person	Aggregation of economic assets value
	Local government income (-)	u6	\$	Investment of risk reduction measures

• Criteria normalization

In order to show the criteria in a more informative way, the standardisation method is adopted to implicitly assume a linear relationship between the criteria score and its utility. The results of criteria score would be range between 0-1, in which 0 implies less vulnerable while 1 implies the most vulnerable. The criteria score is transformed by dividing the difference of each score to the minimum score by the score range for that criterion, which is also called as 'score range approach'. There are two kinds of criteria to represent positive (+) and negative (-) correlation to the vulnerability, which can be transformed in following way:

$$a_{ij}' = \frac{a_{ij} - a_j^{\max}}{a_j^{\max} - a_j^{\min}}$$

or

$$a_{ij}' = \frac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}}$$

Where: a_{ij}' - normalized value; a_{ij} - criteria value; $a_j^{\max}$ - maximum value in the criteria j ; $a_j^{\min}$ - minimum value in the criteria j .

The results of the normalization are shown in Tab.5- 2.

Tab.5- 2 Results of the normalized social-economic criteria in the districts of Shanghai city

Districts	u1	u2	u3	u4	u5	u6
New Pudong	0.49	1.00	1.00	0.03	0.24	0.00
Huangpu	0.00	0.10	0.72	1.00	0.83	0.91
Luwan	0.00	0.04	0.48	0.78	0.83	0.95
Xuhui	0.10	0.11	0.14	0.25	0.46	0.86
Changning	0.06	0.05	0.13	0.23	0.44	0.88
Jing'an	0.01	0.04	0.25	0.89	1.00	0.91
Putuo	0.19	0.14	0.45	0.15	0.17	0.94
Zhabei	0.14	0.12	0.88	0.19	0.17	0.95
Hongkou	0.11	0.09	0.98	0.47	0.45	0.96
Yangpu	0.27	0.06	0.98	0.20	0.29	0.94
Minghang	0.60	0.22	0.59	0.03	0.12	0.89
Baoshan	0.40	0.13	0.24	0.02	0.07	0.78
Jiading	0.85	0.18	0.19	0.01	0.00	0.84
Jinshan	0.18	0.07	0.24	0.00	0.09	0.97
Songjiang	1.00	0.19	0.83	0.01	0.02	0.89
Qingpu	0.52	0.07	0.30	0.01	0.12	0.93
Fengxian	0.10	0.07	0.00	0.00	0.03	0.96
Chongming	0.02	0.00	0.21	0.00	0.03	1.00

• Criteria weights

The weight given to a criterion indicates its relative importance compared to other criteria or, more precisely, the relative importance of a change of a criterion from lowest to highest possible score compared to a similar change of the other criteria (Malczewski 1999). The weight assigned to a criterion determines the degree of influence of that criterion in the overall evaluation – the criterion weights are therefore something like the key to the aggregation procedure. Consequently, the weighting is perhaps one of the most crucial and sensitive parts of the whole MCA process, concerning its outcomes. Hence, it is also described as the most time-consuming and controversial part of MCA, especially when several decision makers are involved (RPA 2004).

The Pairwise Comparison Method is another one in determining the weights for the criteria. This method involves the comparison of the criteria and allows the comparison of only two criteria at once. This method can convert subjective assessments of relative importance into a linear set of weights (Heywood et al., 1993). It was developed by Saaty (1980) in the context of a decision making process known as the Analytical Hierarchy Process (AHP) (Malczewski, 1999a; Eastman et al., 1995; Malczewski, 1996). The criterion pairwise comparison matrix takes the pairwise comparisons as an input and produces the relative weights as output, and the AHP provides a mathematical method of translating this matrix into a vector of relative weights for the criteria. Malczewski (1996) and Eastman et al. (1995) have evaluated this procedure very clearly. The advantage of the pairwise comparison approach is that it makes it quite easy for the decision makers to express their preference structure. On the other hand the effort increases significantly with the number of criteria to be considered. WEB-HIPRE (<http://hipre.aalto.fi/>) was selected to conduct the AHP for weights assignment. The results of vulnerability criteria weights is shown in Fig.5- 1, in which GDP per capita and GDP/km² were assigned the highest score (0.21).

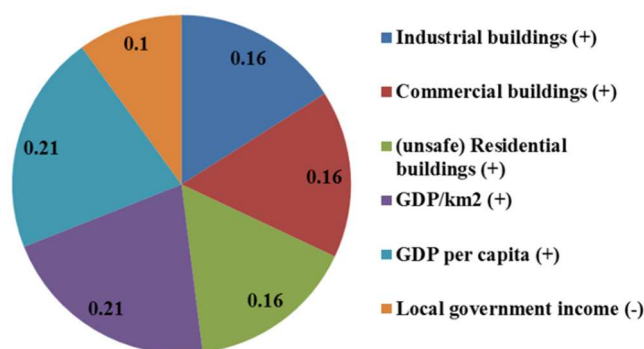


Fig.5- 1 The distribution of vulnerability criteria weights in socio and economic dimension

• Results

The results of vulnerability ranking are shown in Fig.5- 2. Huangpu, Jing'an, Luwan and Hongkou were grouped into the first class of vulnerable districts; the followed districts are Yangpu, Zhabei, and Xuhui. Putuo, Changning, Pudong, which are less vulnerable in terms of economic situation compares to the first group; the districts of Minghang, Songjiang, Chongming, Baoshan, Qingpu, Jiading and Jingshan were in the third group due to the developing economic situation. The spatial distribution of the classification of the vulnerability rating is shown in Fig.5- 2.

Districts	Vulnerability Normalization Value	Ranking
Huangpu	0.743	1
Jing'an	0.716	2
Luwan	0.679	3
Hongkou	0.573	4
Yangpu	0.421	5
Zhabei	0.414	6
Xuhui	0.383	7
Putuo	0.339	8
Changning	0.339	9
Pudong	0.303	10
Minghang	0.257	11
Songjiang	0.228	12
Baoshan	0.194	13
Chongming	0.174	14
Qingpu	0.174	15
Jiading	0.171	16
Jingshan	0.169	17



Fig.5- 2 Spatial distribution of classification of vulnerability rating in Shanghai city, specifically for natural hazards (e.g. flooding) the darker the colour the more vulnerable of the districts

Chapter 6

Shanghai: Evaluation of risk-reduction measures

Flood risk analysis has shown that the extreme events and economic development would substantially increase flood risk in Shanghai, which initiated the discussions on how to effectively manage the future flood risk. The objective of this chapter is to evaluate and recommend an (or a combination of) effective risk-reduction measure(s) to mitigate flood risk along the Huangpu River of Shanghai. By a comparison study with Rotterdam and Shanghai, potential flood risk-reduction measures were proposed and also showed that the metropolitan cities can learn from each other under similar challenging flood threats. Regarding the cost-effective measures, the potential (structural and non-structural) measures have been compared by the method of cost-benefit analysis and economic optimization. The cost-benefit analysis shows that the construction of a storm surge barrier has larger benefit/cost ratio than the upgrading of floodwall. Economic optimization led to a preliminary result of optimal safety level of 1/4,500p.y for the Huangpu River in Shanghai due to fast economic growth in the future (2050). It is additionally noted that the flood barrier boards also have advantages and it is recommended to apply this measure at the entrance of all types of buildings in case of unexpected flood events. Regarding the flood insurance, the less developed area with farmland in the upstream of the Huangpu River is suggested to select flood insurance as a damage-reduction measure to address flood risk. These results can provide a better understanding of the modern safety systems. It also shows that the economic optimization and cost-benefit analysis can rationally support the decision making from economic point of view.

6.1 Introduction

As flood risk will increase significantly in the near future due to climate change and economic development, it undoubtedly requires further risk-reduction measures to reduce to an acceptable level, which is prevailing and challengeable in the context of flood risk management. Since different countries or areas have different values to be weighted, an area-tailored recommendation on the effective solutions of risk-reduction measures would be supportive and valuable for the decision makers. Since 2009 Dutch government (Rijksoverheid 2009) proposed an application of ‘Multi-layered Safety’ aims to ensure the safety of dike rings or to minimize the damage/loss of lives in the affected areas. Multi-layered Safety integrates different types of measures into Dutch flood management: reducing the probability and the consequences of floods both. It is consisting of ‘prevention’ based on flood defence system and ‘mitigation’ based on spatial planning and emergency management, which is subject to expectation and challenge. According to the definition of flood risk, risk-reduction measures should be literally thinking from two directions: reducing the probability of a flood or mitigating a flood related to the consequence. But Vrijling (2013) observed that the effectiveness of resources spend in prevention is most probably higher than on mitigation of damage with several examples in the Netherlands; he further pointed out mitigation becomes only effective after the disaster has occurred and at least the economic damage has become a fact. This is fairly understandable since damage could be totally avoided if the flood defence is strong enough. In practice, the decisions on the flood risk reduction measures are based on the compromise of technical, economic and political considerations. Economic assessment method, especially cost-benefit analysis, has been largely influenced the flood protection measures for years in the Netherlands, UK and Germany (Interwies, Görlach et al. 2005). Jonkman, Jak et al. (2004) discussed a historical development in flood protection in the Netherlands and presented the method of cost-benefit analysis is a useful instrument in decision making, and he also pointed out economic analysis, when applied correctly, can provide important rational information in the decision-making process. Although there are some limitations on the methodology of cost-benefit analysis, such as availability of data, difficulties of expressing all the impacts into monetary terms and limited openness to the public participation. etc., it is still regarded as a sufficiently developed method to provide rational information for the decision makers.

In Shanghai, the current flood risk was estimated at 40-112 million \$USD/yr. along the Huangpu River of Shanghai. On the basis of the previous work on future flood risk due to climate change, land subsidence and economic development, the potential flood risk will increase approximately 4 times and 16 times in 2030 and 2050 respectively if there are no further measures being taken. In order to reduce future flood risk and maintain the protection level as 1/1,000p.y, Shanghai has initiated plans on the construction of storm surge barrier at the mouth the Huangpu River, reinforcement of floodwall system, implementing early-warning system and building other infrastructures, etc. (MWR 2008). However, limited work has been discussed on the effectiveness of flood risk-reduction measures in Shanghai. Therefore, the objective of this chapter is to evaluate and recommend a (combination of) risk-reduction measure(s) from risk point of view by the methods of cost-benefit analysis and economic optimization. The research questions are shown as below:

- What would be the potential risk-reduction measures for Shanghai by a comparison study with Rotterdam?
- How to evaluate the effectiveness of the risk-reduction measures?
- What can be the recommendations on (cost) effective measure(s) to address flood risk in Shanghai?

The structure of the remaining sections will be organized as below. Section 6.2 is a comparison study with Rotterdam area in terms of flood risk management in order to propose potential risk-reduction measures. Section 6.3 is going to evaluate the risk-reduction measures based on cost-benefit

analysis and economic optimisation with a case study of Shanghai. Lastly, it ends with discussion in Section 6.4.

6.2 Comparison study with Rotterdam

In this section, a comparison study between Shanghai and Rotterdam is conducted in terms of flood risk management in order to propose potential risk-reduction measures under the threats of future climate change and economic growth. It also aims to show that the metropolitan cities can learn from each other under the similar challenging flood threats. First, a general comparison in terms of geography, demographics, economics and climate between Shanghai and South-Holland Province (including Rotterdam area) is shown in Tab.6. 1.

Flood risk endangers Shanghai and Rotterdam both. The general information about historical flood events and flood threats in Shanghai has been described in Section 2.4 and Section 2.5 in detail, which has showed Shanghai is confronted with the potential flood risk currently and also in the future.

Rotterdam area is located where the Rhine and Meuse enter into the North Sea at the South end of the Randstad which is the western metropolitan area of the Netherlands (see Fig.6. 1). Rotterdam is the second largest city in the Netherlands with around 600,000 inhabitants. The province of South Holland inhabits around 3.52 million people. Besides, the Rotterdam is a large city with a well-equipped port infrastructure, favourable accessibility and considerable volumes of goods in the Netherlands. Since it is located in close proximity to the North Sea, it is often referred to as the ‘Gateway’ to Europe.



Fig.6. 1 Location of Randstad and the important cities in the Netherlands: Amsterdam, Rotterdam, Utrecht and Den Haag (Jonkhoff 2009)

Besides the low-elevation below the sea level, the storm surge ($\sim 3\text{m}-5\text{m}$) coming from the North Sea and the high river discharge in the Rhine river ($\sim 16,000\text{m}^3/\text{s}$) from another direction are the dominant flood pressures in Rotterdam. In the Netherlands, the flood disaster in 1953 stimulated the most sophisticated flood protection system in the world, with the protection level between 1/2,000 p.y. and 1/10,000 p.y. in various dike ring systems. Yet, flood risk remains under the climate change and socio-economic development in Rotterdam. KNMI'06 scenarios (KNMI 2006) estimated a broad range of possible future on sea level rising in Rotterdam, which is around 50-85cm by 2100. In a summary, Shanghai and Rotterdam are faced with common threats in terms of floods: storm surge from the sea, high river discharge and possible rainfall either in a long term or intensively occurred in a short term.

Tab.6. 1 Comparison of Shanghai and South-Holland (including Rotterdam area) in terms of geography, demographics, economics, climate and expected annual damage (data source: (CBS 2010; City of Rotterdam Regional Steering Committee 2009; Li 2010; MLR 2010; SSB 2011; Jongejan 2010))

		Shanghai City		South-Holland	
Geography					
Area [km²]		6,340		2,818 (Rotterdam 319)	
Elevation[m] (relative to m.s.l.)	Average	3-3.5 (WD)		-4-0 (NAP)	
Lowest point [m]		2.2(WD)		-6.7 (NAP)	
Demographics and Economics					
Population [million]		23.02 (Shanghai city)		3.52 (South Holland)	
		Downtown Shanghai	6.98	Rotterdam city	0.60
Population Growth Rate		3.24%		0.65% (Rotterdam 0.8%)	
Population Density [/km²]		3,632		1,252 (Rotterdam 2,963)	
GDP Growth Rate (2010)		~7.7%		~0.8%	
GDP per capita		12,024 \$USD		45,332 \$USD	
Ports (2009) [Million Ton]	Cargo throughput	590		387	
	Container throughput	25		9.74	
Climate and Hydrology					
Average Precipitation [mm/yr]		1,164		790	
Sea level rising	Average sea level rise(current)	3-5mm/a		2 mm/a	
	Land subsidence	4-16mm/a		10 mm/year	
	Projected sea level in 2100	80-210cm		65-130cm (50-85cm in Rotterdam)	
Storm surge level [m]	1/10,000p.y	2.93		~4.00	
	1/10p.y	1.18		~2.00	
Highest recorded water level [m]		5.99 (Wusongkou)		3.8 (Hoek van Holland)	
	Observation Period	1916-2009		1880-2009	
Protection level for flooding per year	Floodwall	1/50p.y (upstream)		1/10,000p.y. (Dike-ring 14)	
		1/1,000p.y. (mid-&downstream)			
	Sea dike	1/100p.y.-1/200p.y.			
Flood risk					
Expected Annual Damage (EAD)		2 - 6million/yr. \$USD		0.4 million/yr. \$USD	

Apart from increasing flood probability, both cities also face land subsidence and advancing economic development, which increases possible flood damage. With long history fighting with flood, Dutch and Chinese both have valuable experiences on fighting with floods, while Dutch did more successful in the eye of the world in terms of flood prevention. Rotterdam with a great ambition is intend to climate proof itself with some innovated adaption measures, such as floating pavilion and water plazas, to collect extra rainfall and also with the new moveable dam and barrier projects in Rhine deltas around Rotterdam area (see Fig.6. 2).



Fig.6. 2 Concept of protection with moveable barrier projects in Rotterdam area, the Netherlands (RCI 2009)

In the Netherlands, Delta works defend the storm surge from North Sea and the embankments such as dikes and defensive structures protect low-lying areas from high peak discharge of river flood. On the other hand, the friendly water is diverted via canals into cities (or dike rings) through the operation and regulation of sluices to control water level in the Netherlands. In recent years, Dutch government proposed ‘Multi-layered Safety’ (MLS) measures in order to ensure a high-level safety in the considerations of probability-reduction and damage-reduction. Based on a comprehensive assessment by cost-effective analysis on MLS (Hoss, Jonkman et al. 2011) in a case study of Dordrecht in the Netherlands, it showed flood defences stay the most cost-efficient strategy due to the well-developed flood defence system in the case study; MLS could serve as a supplement to the dominant strategy. Shanghai has also sensed flood pressure due to climate change and land subsidence, which requires efforts to put on flood prevention and damage mitigation both. But not all the potential measures are suitable to be implemented in the area of interest by just copying other’s experience. For example, the National Flood Insurance Program has been identified as responsible for increasing risk in the US while in the Netherlands there is no insurance program because none can afford to take the risk. Therefore, it is necessary to conduct an analysis in a cost-effective way to recommend the customized risk-reduction measures.

6.2.1 Risk-reduction measures in the two cities

A comparison of the current (planning) flood risk measures between Shanghai and Rotterdam were listed in Tab.6. 2. It shows both Shanghai and Rotterdam are attempting to reduce risk level on the aspects of flood prevention and damage mitigation, especially to reduce the magnitude and probability of flooding.

In Shanghai, to enlarge the water area and to reduce the sediment in the river were a similar concept to the ‘Room for river’ in the Netherlands, which indicates to decrease water levels or river discharges under a certain hydraulic load for flood control. In the field of engineering, strengthen and reinforcement of the flood defence system is a traditional and effective way to prevent flood in the first place in both cities. Yet, Kerssens, Jong et al. (2003) pointed that solely heighten the floodwall in the Huangpu River would hinder the sight view and also substantially increased the investment cost; every 1m of increment on the floodwall requires extra 4m width of the construction cost. Construction of storm surge barrier in the Netherlands has already been testified as a successful strategy to prevent flood and

Tab.6. 2 List of flood risk reduction measures in Shanghai and Rotterdam city

Measures	Shanghai	Rotterdam
Natural environment	Enlarge water area Reduce sediment (enlarge river room)	‘Room for river’ Water retention areas
Engineering	Construction/ Reinforcement of dikes and storm surge barrier Digital hydrological- metrological monitoring system	Construction/ Reinforcement of dikes and storm surge barrier
Collection of rainfall	Increment of Greenland	Green roof, water plaza
Architecture	---	Floating house/park/ buildings
Flood risk map	Scenario-based flood risk map (New Pudong district)	Flood risk map (Dike ring area)
Flood insurance	in the planning	---
Flood warning and evacuation	Early-warning system	Early warning Evacuation not an option

safeguard the Netherlands. Chinese researchers (Chen 2001; Chen 2002) have also technically analysed the feasibility of the construction of storm surge barrier in the Huangpu River from the risk perspective. Other measures such as increment of green land in Shanghai and green roof /water plaza in the Netherlands were designed to address the high intensity of rainfall in case of incapacity of drainage system in the urban area. Flood risk mapping and flood insurance are regarded as the additional measures to supplement ‘hard’ measures if the flood defence fails and the floods do occur. It’s qualitatively hard to judge which measures are more effective to address potential risk in Shanghai in the list, which needs cost-benefit analysis to weigh the trade-off further.

Based on these current risk-reduction measures, two types of risk-reduction measures in terms of probability reduction and damage reduction were proposed and shown in Tab.6. 3, namely ‘hard’ and ‘soft’ measures. First, the improvement of floodwall or the construction of storm surge barrier would be the first option for Shanghai to address flood risk; defences reduce probability of flooding but do not reduce losses in case of failure of defensive system (e.g. overtopping or breaching). Second, heightening the entrance of the buildings can also be regarded as a ‘hard’ measure to reduce flood probabilities and flood damages. Third, flood insurance as a ‘soft’ measure to reduce individual loss will be evaluated and discussed later.

Tab.6. 3 Potential flood risk reduction measures in terms of probability and damage in Shanghai

	‘Hard’ measures	‘Soft’ measures
Reduce probability	Reinforcement/strengthen flood wall Construction of storm surge barrier	
Reduce damage	Heighten entrance of building	Flood insurance

6.2.2 Costs of measures

Two types of cost on the measures were identified, namely direct and indirect cost. The direct cost is the expenditures on the construction and operation, which is generally regarded as intrinsic cost; the indirect cost is, for instance the maintenance expenditure, which is extrinsic cost. When calculating the cost of the measures, it is intended to include all the cost on the considerations, which might be different from the figure in practice. Besides, the cost is heavily depending on the study case (i.e. local eco-

conomic factors) and the implementation of the measures. Therefore, it only can approximately estimate the cost before implementing the project.

6.2.3 Benefits of measures

Flood measures all target to the ultimate benefit, i.e. the reduction of the potential damage. Therefore, in most cases the benefits based on the implemented measures are quantified as a yearly avoided damage (\$USD/yr) in a monetary term, as the net present value (NPV) of the expected amount of damage avoided in a certain temporal frame. However, the benefit includes various aspects on economic, societal and environmental, etc., dealing with different dimensions, different groups of people and potential benefit lying far in the future, such as fertility improvement on the soil of farmland, revitalization of wetland, raising of public awareness and stimulation of local (flood risk) research, etc. In practice, the benefit (=risk reduction) is commonly represented in a monetary term. Intangible aspects would not be taken into account or normally be simplified as an estimated fraction of tangible monetary effects instead.

6.3 Evaluation of risk-reduction measures

In the evaluating of risk-reduction measures, the first step is to assess the feasibility of the potential measures by cost-benefit analysis. If the benefit outweighs the cost the potential candidates of measures are attractive; otherwise, it will not be considered as cost-effective. The second step is to determine how much economic investment is optimistic compares to the reduction of the potential damage, which is economic optimization.

6.3.1 Cost-benefit analysis

The basic principle of cost-benefit analysis requires the benefit of an implementing measures exceed the cost, which usually utilizes a benefit/cost ratio (*BCR*) to weigh the potential measures. If the *BCR* is large than 1, the measure is feasible and attractive; if the *BCR* is smaller than 1, the measure is not satisfactory and desirable. Ideally, this method needs to estimate the effect of the potential implementing measure in a monetary value. The model of cost benefit analysis can be written as below:

$$\left\{ \begin{array}{l} \text{Cost} = I(P_f) + PV(M) \\ \text{Benefit} = \frac{P_{f,0} \cdot D_0 - P_f \cdot D}{r'} \end{array} \right. \quad (6.1)$$

$$r' = g - r \quad (6.2)$$

Where: $I(P_f)$ - investment to upgrade or maintain the probability of flooding to P_f ; $PV(M)$ - present value of maintenance and operational cost; $P_{f,0}$ - probability of flooding in initial state; P_f - probability of flooding after completion of the project; D_0 - flood damage at a failure probability of $P_{f,0}$; D - flood damage at a failure probability of ; g - economic growth rate; r - interest rate; r' - discount rate, the expected damage is discounted to the present value.

From this model, it can be seen that the cost benefit analysis is economically evaluating the effectiveness of a potential project. A favourable project is recommended if the cost is lowest while the benefit is largest. Although the alternative of the risk-reduction measures were also decided from other (e.g. societal and political) perspectives, the cost benefit analysis can technically support the decision making from economic cost-effectiveness point of view.

On the other hand, a criteria to trade off an upgraded (or new) project could be taken as the investment of the project plus the residual risk (R_r) after implementation should be lower than the existing risk (R_e), which has been used to assess periodic safety level in (Vrijling, Kanning et al. 2009). It is written as below:

$$I(P_f) + PV(M) + R_r \leq R_e \quad (6.3)$$

alternatively,

$$I(P_f) + PV(M) + \frac{P_f \cdot D}{r'} \leq \frac{P_{f,0} \cdot D_0}{r'} \quad (6.4)$$

Where: R_r - residual risk; R_e - existing risk.

In this model, it can be evaluated when the project is worthy to invest or it needs to be postponed.

6.3.2 Economic optimisation

In the economic optimization theory, the total cost is the summation of expenditure of a safe system and the total risk, i.e. the expected value of economic damage. An optimistic point will be derived to reach the minimization of the total cost. This method has been widely applied in the field of engineering in the Netherlands and other counties (Jonkman, Kok et al. 2003). The total risk is equal to the probability of flooding times the associated damage. The equation is shown as below:

$$\text{Total cost (TC)} = \text{Investment (I(P}_f\text{))} + PV(M) + \text{Total risk (PV(P}_f \cdot D\text{))} \quad (6.5)$$

Where: TC - total cost; D - flood damage at a given failure; $PV(P_f \cdot D)$ - present value of the total risk.

In order to minimize the total cost,

$$\min(TC) = \min(I(P_f) + PV(M) + PV(P_f \cdot D)) \quad (6.6)$$

The annual probability of exceedance of the crest level of the floodwall is given by the exponential distribution of the water level:

$$1 - F(h) = P_f = e^{-\frac{h-A}{B}} \quad (6.7)$$

In which, h is water level, A and B are the parameters for the exponential distribution. Take an example of increase the crest height of the floodwall, the investment ($I(P_f)$) could be defined as $I(P_f) = I_{h_0} + I_h \cdot X$, in which I_{h_0} is the initial cost, I_h is the marginal cost per unit of floodwall (\$USD/m), X is the height increment ($h - h_0$). So the total investment is calculated as :

$$I(P_f) = I_0 + I'(-\ln(P_f)) \quad (6.8)$$

where: $I_0 = I_{h_0} + I_h(A - h_0)$; $I' = I_h \cdot B$.

Since the risk exists every year the present value of the risk over an infinite period has to be taken into account, assuming the damage are growing over time at the same rate as economic growth:

$$PV(P_f \cdot D) = \sum_{n=0}^{+\infty} P_f \cdot \frac{D}{(1+r)^n} \cdot (1+g)^n \approx \frac{P_f \cdot D}{r'} \quad (6.9)$$

Where: r - interest rate; g - economic growth rate; r' - discount rate, the expected damage is discount to the present value; n - utility year, taken 'infinite' here.

$$\text{Therefore: } TC = I_0 + I'(-\ln(P_f)) + PV(M) + \frac{P_f \cdot D}{r'} \quad (6.10)$$

$$\text{Minimization of the total cost: } \frac{\partial(TC)}{\partial(P_f)} = 0 \rightarrow P_{f,opt} = \frac{I' \cdot r'}{D} = \frac{I_h \cdot B \cdot r'}{D} \quad (6.11)$$

Eq. (6.11) shows that an economically optimum point will be reached in a positive relationship with marginal cost of increment of floodwall (I_h), standard deviation of the water level (B) and the discount rate r' , and in a negative relation to the flood damage (D). In the Dutch case, Delta Committee calculated an acceptable probability of flooding in central Holland in 1960 of $8 \cdot 10^{-6}$ per year. Based on the same method, an approximation of optimal level in New Orleans is proposed as $2 \cdot 10^{-4}$ per year by Dutch engineers (Jonkman et al. 2009).

6.3.3 Case study – Shanghai city

In this section, specific risk-reduction measures will be discussed by cost-benefit analysis and economic optimization in order to propose a cost-effective measure to address future risk. In cost-benefit analysis, the cost of the measures will be roughly estimated based on the local economic factors and the benefit will be regarded as the reduced risk by the potential measures. The reference year is taken as 2050, which means the benefit/cost ratio will be calculated based on the change of climate and the economic development after 2010. And the factors of safety level, the investment of measures and the protected value will be also projected in 2050 in the approach of economic optimization.

6.3.3.1 'Hard' measures

1) . Heighten the floodwall

A cost-benefit analysis on the proposed measure of upgrading floodwall is performed as below:

o Cost

It was estimated that in order to maintain the safety level of 1/1,000p.y in 2050, the estimated investment to strengthen and heighten the floodwall was 1 billion \$USD for 315km of floodwall with increment of 1.5m in city centre during the expected construction period of 15 years since 2001 by local engineers (Chen 2002). The 2011 present value of cost is 1.63 billion \$USD. Therefore, the unit cost of the floodwall is roughly estimated as 3.4 million \$USD/m/km. But it should be noticed that as such rapid economic growth the marginal cost of increment of floodwall could be under-estimated when compared to the estimated unit cost of concrete floodwall construction in New Orleans of USA as 4.9-11.8 million \$USD/m/km (Jonkman, Hillen et al. 2013).

In order to find out how high the crest floodwall should be built to maintain the protection level of 1/1,000p.y, it is necessary to combine the design water level, the required crest freeboard height and safety board, which is regulated for defining the crest of flood protection system (e.g. floodwall, levees and dikes) in China (CCD 1998 pp.13):

$$H_{cre.} = h_{design} + h_{wave} + \text{free board} \quad (6.12)$$

Where: $H_{cre.}$ - crest height of the floodwall; h_{design} - design water level under a defined safety standard; h_{wave} - the required crest freeboard height, which is determined by wave overtopping condition; free board is an additional height for a safety margin.

The water level under occurrence probability of 1/1,000p.y at the mouth of the river (Wusongkou) was estimated at 6.98m-7.02m in 2050 due to 'relative' sea level rising (See Section 5.4.1). It is assumed that the crest freeboard height and safety board for floodwall shall be up to 2m, in which the safety board was regulated as 1m for Shanghai floodwall (CCD 1998 pp.7). Therefore, the crest height of floodwall in 2050 with safety standard of 1/1,000p.y. would increase to 9.02m at Wusongkou, which is 1.74m (9.02m-7.3m=1.72m) higher than the present situation (7.3m). The investment for heightening and strengthening of floodwall is then calculated at ~2.65 billion \$USD with 15 years construction period. If we take 2% as the maintenance cost, the total cost is approximately ~2.7 billion \$USD.

It should be noted that the cost of upgrading of floodwall only takes construction cost into account, other cost, such as the relocation cost, was not considered. Therefore, this is only a lower bound of cost for upgrading of floodwall.

o Benefit (=risk reduction)

Based on the author's pervious calculation, the future flood risk due to a combination of sea level rising, land subsidence and economic development would increase to 642, 1,000 and 1,810 million \$USD/yr under low, medium and high estimation respectively in 2050, in which 132, 203 and 372 million \$USD/yr were contributed by 'relative' sea level rising (see Section 5.4) if there are no additional measures being taken. Based on a simple model shown in Eq.(6.13), the future flood risk in 2050 could be regarded as existing risk (R_e), which can be partly reduced by upgrading of floodwall. The residual risk (R_r) is assumed as the risk solely increased by economic development in 2050.

$$benefit = R_{red.} = \frac{P_{f,0} \cdot D_0 - P_f \cdot D}{r'} = \frac{R_e - R_r}{r'} \quad (6.13)$$

Where: $R_{red.}$ - reduction of risk; R_r - residual risk; R_e - existing risk.

Hence, flood risk which is increased by 'relative' sea level rising could be reduced by improving the floodwall, which were estimated at 132, 203 and 372 million \$USD/yr under low, medium and high estimation in 2050. These value can be converted to present values by dividing the discount rate of 5.1%, leading to present values of ~2.6 – ~7.3 billion \$USD. This is regarded as the benefit. The benefit/cost ratio is then calculated at 0.96– 2.7.

o Economic optimal level

In this section, we're going to evaluate the optimal safety level of the floodwall in 2050 by economic optimization. The result of optimal safety level is corresponded to the optimal design water level of the floodwall. In order to calculate the result, the information on 1). the safety level for the system expressed by means of failure probability of flooding; 2). discount rate; 3). investment costs required for the upgrade of the floodwall; 4). flood damage due to flooding as a function of the safety level should be approximately estimated.

1) Safety level

It is assumed that the annual probability of exceedance of the design water level at Wusongkou is given by the exponential distribution.

- The current design water level under 1/1,000p.y is 6.6m at Wusongkou.
- Based on the historical records (observation period: 1901-2012), the lowest annual maximum water level at Wusongkou is observed at 4.85m. Thus, it is assumed that when the design water level is only 4.85m the flooding occurs with 100%.

Then the parameters (A, B) in the exponential behaviour of failure probability could be calculated based on Eq. (6.7), with results of $A=4.85$ and $B=0.2533$. Fig. 6. 3 (see the solid line) shows the relationship between design water level and return period at Wusongkou. It can be seen that 10 factors in a change of return periods from 100 years to 1,000 years is corresponding to an increase of water level by ~55cm.

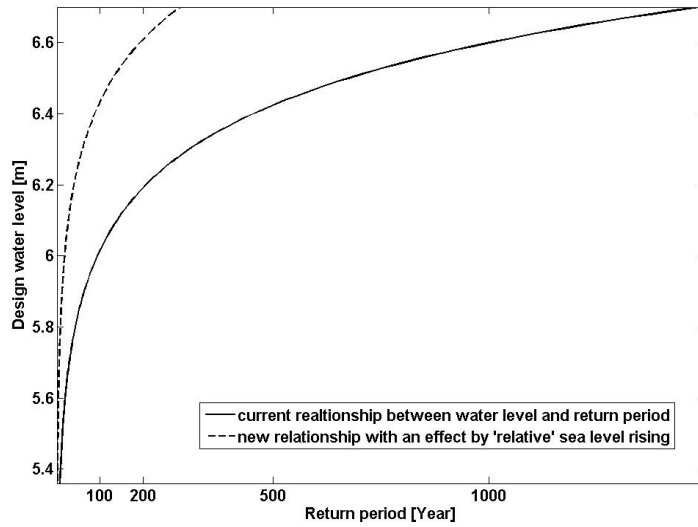


Fig.6. 3 Relationship between return period and design water level at Wusongkou by exponential distribution and this curve shifts upward by an effect of ‘relative’ sea level rising at Wusongkou in 2050

In 2050, due to ‘relative’ sea level rising the flood probability would increase roughly ~5.2 times, which means the 1/1,000p.y. would increase to approximately 1/200p.y. (see the dashed line in Fig.6. 3). This can also be modelled by assuming an exponentially distributed flooding probability that will increase over time due to sea level rise¹⁶ (Vrijling and van Beurden 1990).

2) Discount rate

The economic growth rate in recent years is ~7.7% with inflation rate of ~2.6% in Shanghai; so the discount rate is calculated as 5.1% (7.7%-2.6%=5.1%). It should be noted that the economic growth rate is optimistically assumed to keep a constant value in the next 40 years.

3) Investment in the floodwall system

Based on the previous discussion of the cost of improving floodwall, the unit cost of the floodwall is estimated at 3.4 million USD/m/km in 2010. The unit cost will increase with the economic development every year and the proposed construction period of upgrading floodwall in 315km is estimated at 15 years. The unit cost is then averaged at 4.9 million USD/m/km.

4) Flood damage

In this approach, the flood damage is the potential damage protected by the floodwall system. The damage value can be represented by an average value caused by different flood scenarios along the Huangpu River. But different flood scenarios led to different magnitudes of floods due to various

¹⁶ $P_f(t) = e^{-\frac{h-\eta t-A}{B}} = P_{f,0} \cdot e^{-\frac{\eta \cdot t}{B}}$ $P_{f,0}$ - flood probability chosen at $t=0$; η - sea level rise [m/year].

flood intensities and different failure points (e.g. breaching and overtopping). The associated flood damage would be significantly different due to variant inundation extent and discrepant economic situation in the inundation area. In our previous scenario-based flood risk analysis, the breaching scenarios led to 10 factor higher flood damage than overtopping and the failure of floodgates since we intended to pursue the worst-case breach scenario along the Huangpu River. The highest flood damage due to breaching is 1.89 billion \$USD at the west side of the Huangpu River in the city centre. In the economic optimization, the higher of potential protected damage lead to higher level of protection. Therefore, under a conservative estimation the largest potential flood damage (1.89 billion \$USD) can be regarded as the protected value (flood damage) in this approach.

In 2050, the flood damage would increase ~ 1.5 times due to ‘relative’ sea level rising (See ‘Increase of flood damage’ of Section 5.4.1.) and ~ 7.3 times due to economic development in 2050 (See Section 5.4.2). As a result, the protected value (flood damage) would increase to 16.6 billion \$USD in 2050.

5) Results

The input data to calculate the optimal safety level is summarized in Tab.6. 4.

Tab.6. 4 Input data to calculate the optimal safety level in 2050 in Shanghai

Parameter	I_h [10^6 \$USD/m]	B [-]	r' [-]	D [10^9 \$USD]
Value	1543*	0.2533	5.1%	16.6

*: 4.9 million \$USD/m/km * 315 km

The optimal level of failure probability in 2050 is calculated at 2.3×10^{-4} , which is approximately equivalent to 1/4,500 p.y.. The corresponding design water level is 7.4 m (see Fig.6. 4). With a comparison to the current design level of 6.6m under 1/1,000p.y., it is supposed to increase 0.8m.

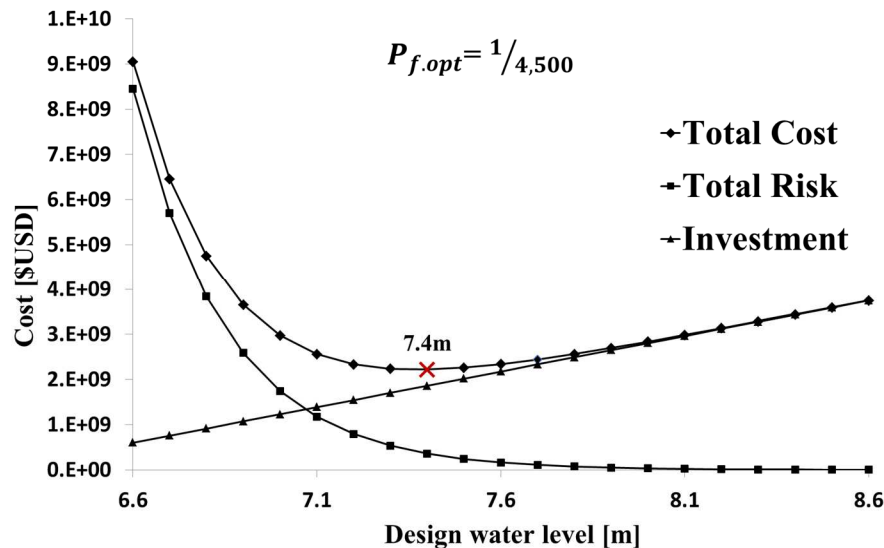


Fig.6. 4 An example of the estimation of economical optimum level of design water level at 7.4 m, under medium estimation of potential flood damage at Wusongkou of the Huangpu River

As the estimates of the information on the flood damage, discount rate and investment cost are rough estimates, a sensitivity analysis has been carried out to show the optimal safety level with variations of these parameters. First, the flood damage under low, medium and high estimation lead to optimal safety level ranges from 1/3,000p.y. – 1/7,000p.y (See Tab.6. 5). Second, the results of variation of 50% lower of the investment cost and discount rate lead to optimal safety level 1/7,000p.y. and 100% higher of these parameters lead optimal safety level to 1/3,000p.y. (See Tab.6. 6).

Tab.6. 5 Results of optimal safety level and design water level under low, medium and high estimation of flood damage in 2050

	Low	Medium	high
Flood damage [billion \$USD]	10.6	16.6	30.3
Optimal design water level [m]	7.3	7.4	7.5
Optimal safety level	1/3,000	1/4,500	1/7,000

Tab.6. 6 Sensitivity analysis of variation of the parameters of investment cost and discount rate (under medium estimation of flood damage) in economic optimization

	Investment cost		Discount rate	
	50% lower	100% higher	50% lower	100% higher
Optimal safety level	1/7,000	1/3,000	1/7,000	1/3,000

2). Construction of storm surge barrier

Storm surge barriers are floodgate systems that allow water to pass under normal circumstances but can be closed when a storm surge is expected (Vrijling 2001). It has been widely constructed worldwide as part of the coastal defence system, especially in developed countries (Linham, Green et al. 2010). Famous examples are the storm surge barriers in Zeeland (Southwest) of the Netherlands, namely Maeslant and Eastern Scheldt storm surge barrier. In New Orleans, several storm surge barriers have been built after Katrina to protect the city (Jonkman, Hillen et al. 2013). The construction of storm surge barrier can reduce the length of the exposed system in the estuary; thus it can reduce the length of the dike heightening behind the barrier. Another advantage of some storm surge barrier for port areas is that they allow free navigation under normal conditions when they are open. The cost of a storm surge barrier depends on many factors, including the types of barrier and gates, the local soil characteristics, the desired height and the hydraulic head. Jonkman, et al. (2013) estimated the unit cost of storm surge barrier per unit width from available data around the world, which ranges between 0.5 and 2.7 million /m width. The management and maintenance costs of complex storm surge barriers are relatively high, and these cost have been estimated at 5%-10% of the construction costs (Nicholls, Cooper et al. 2007).

As storm surge from East China Sea during typhoon is the biggest flood threat for the Huangpu River, a new storm surge barrier is proposed at the mouth of the Huangpu River, which is supposed to resist storm surge induced by typhoon to prevent flood in Shanghai. Therefore, it can be regarded that the construction of the storm surge barrier is another alternative to maintain the protection level of 1/1,000 p.y. in Shanghai. It will be designed to prevent a storm surge with probability of exceedance 1/1,000p.y. (P_f). Three potential locations of the storm surge barrier were identified by local engineers (Chen 2001; Hu 2006) based on a comprehensive analysis on the geological condition, the effects on the future navigation, the morphology of the river, urban planning and the relocation cost of the harbours, etc. These locations are show in Fig.6. 5 with alphabetic order of A, B, C at a distance to the mouth of the Huangpu River of 8.75km, 5.8km and 1.4km, respectively. The widths of the river at these locations are around 550-650m in general. They are Wusongkou (A), Changhang anchorage (B) and - Fishery Yard (C), respectively.

o Cost

The investment of construction storm surge barrier was estimated at 4 billion RMB in 2001 by local engineers and the construction period is estimated at 5 years. Thus, the present value of the investment cost would be 1.1 billion \$USD. It is estimated that the maintenance cost and other indirect cost (e.g.

labour and logistics) are 5% of construction cost every year. Then, the total investment would be ~2.2 billion \$USD.

Based on the estimated unit cost per unit width of storm surge barrier worldwide, the construction cost of storm surge barrier at the mouth of the Huangpu river is between ~0.3~1.5 billion \$USD if it is assumed the width of the barrier is 550m. The total investment would be ~0.6~3.0 billion \$USD with infinite utility. It can be noticed that the local estimation is close to the high bound of the world-wide general estimation.

o Benefit

As we discussed before, the reduced flood risk by ‘hard’ measures to prevent flood would be ~2.6 – 7.3 billion \$USD in 2050. While an adverse effect of the storm surge barrier could be the hinder of the shipment in the harbour along the river. If it is assumed the storm surge barrier closes one day per year to safeguard the river, the economic loss in the harbour was estimated at averagely 0.43 million \$USD/yr (2.6 million RMB/yr) in 2005 by Chen (2002). The present value of hindering of the shipment would be calculated at 8.43 million \$USD with discount rate of 5.1%. Compares to the direct economic avoided damage, the adverse effect is very small. In a summary, the potential benefit of the construction of the storm surge barrier is still larger than the cost of the construction of the storm surge barrier. The benefit/cost ratio is then calculated at 1.2 – 3.3.

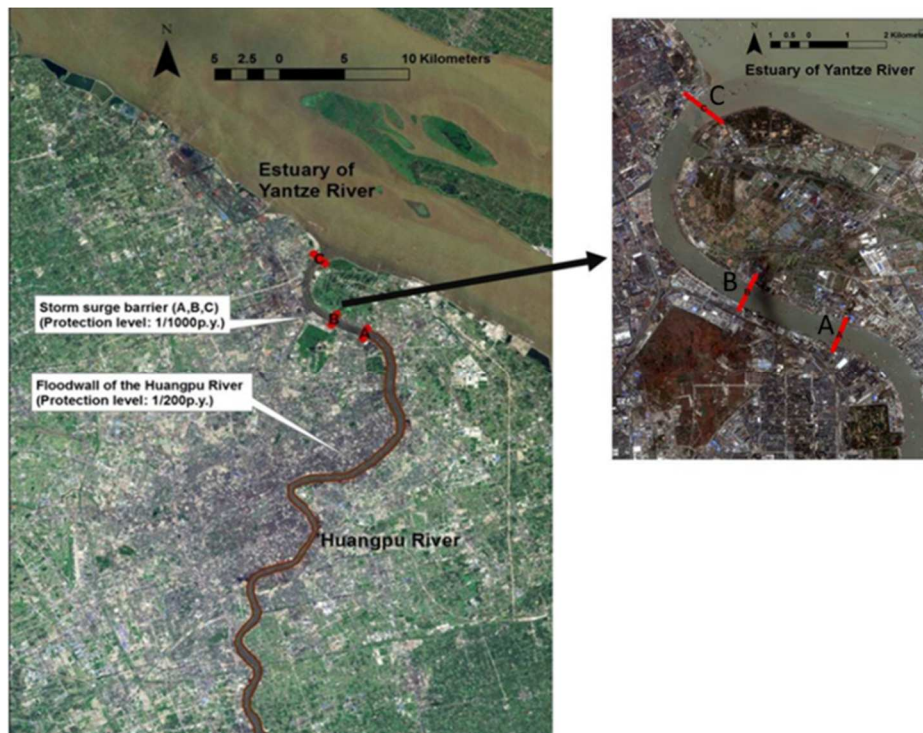


Fig.6. 5 Potential locations for storm surge barrier in the Huangpu River of Shanghai, namely A- Wusongkou, B - Changhang anchorage and C - Fishery Yard

3). Flood barrier board

It was noticed that moveable flood barrier is widely applied at the entrance of the subway stations to prevent flood water during flood seasons in Shanghai. The moveable flood barrier can also apply to the entrance of the (industry, commercial and residential) buildings. Although flood water cannot be fully prevented by such a simple measure, it can temporarily keep the contents safe inside. But it should be noted that this measure would only be effective in shallow water due to its limited height (~50cm).

o Cost

In the cost-benefit analysis, the investment of application of flood barrier board is the market price of the unit cost, which mainly depends on the construction material (e.g. wood, plastic or steel). The market price of flood barrier board in aluminium alloy (see Fig.6. 6) is roughly ~150 \$USD/m (SWZ 2013). Suppose the cost of flood barrier board for one entrance of the buildings is ~500 \$USD; one building with 2 entrances would cost 1,000 \$USD.

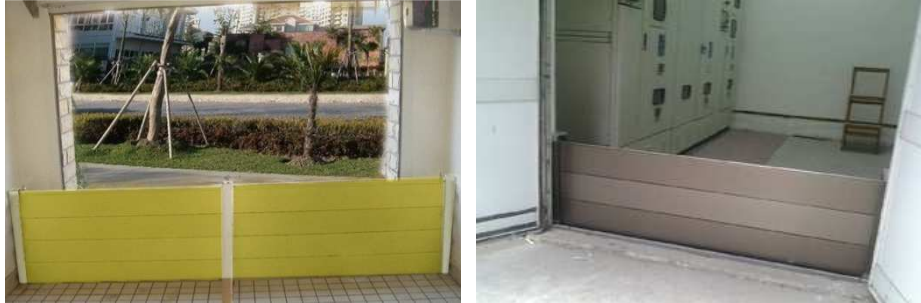


Fig.6. 6 Example of flood barrier board in aluminium alloy in Shanghai (SWZ 2013)

o Benefit

The reduction of risk (benefit) will be calculated based on Eq. (6.1). First, suppose the flood probability in the initial situation is 1/200p.y., which is the current protection level calculated previously. If the flood barrier board is implemented, it is assumed that the flood would occur by four types of failure: 1). human failure to implement board during floods; 2). structural failure due to insufficient strength; 3). flood water can go along other paths (e.g. piping); 4). overtopping when inundation depth is more than 0.5m (higher than the board). The human failure probability is taken as 1%. The structural failure could be caused by e.g. piping, or the flood water can go through sewer system. It is assumed that the structural failure probability is 1% and the probability of other sources of leakage is 10%, respectively. Based on 2D flood simulation in Chapter 3, it was estimated that roughly 50% flood area was with more than 0.5m of inundation depth in an event of river flood under 1/200p.y. in Shanghai. A simple fault tree analysis of the failure of flood barrier board is illustrated in Fig.6. 7. Therefore, the failure probability can be calculated at 3.1×10^{-3} per year.

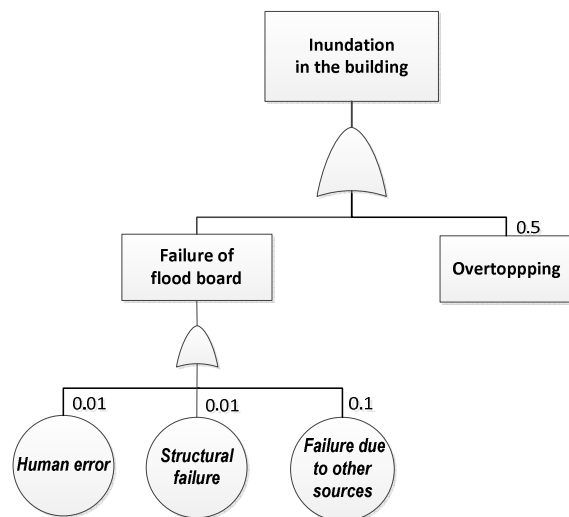


Fig.6. 7 A simple fault tree of the inundation in the building due to overtopping or the failure of flood barrier board under a flood probability of 1/200p.y. in Shanghai

The damage which can be saved by flood barrier board is only the inside contents of the building. The structural damage of the buildings, infrastructural damages and indirect damages (e.g. interruption

of economic activity) would not be protected by this measure. Hence, we only assume 1/10 of flood damage could be saved in the end.

Thus, Eq. (6.1) would be shown as below:

$$Benefit = \frac{P_{f,0} \cdot D_0 - P_f \cdot D}{r'} = \frac{5.0 \cdot 10^{-3} \times D_0 - 3.1 \cdot 10^{-3} \times (\frac{9}{10} D_0)}{r'} = \frac{2.21 \cdot 10^{-3} D_0}{5.1\%}$$

The suggested damage function for buildings in Shanghai showed that the damage percentage is 3%-5% under inundation depth of no more than 0.5m; hence, it is assumed that the flood damage with an inundation depth of no more than 0.5m would be ~500,000 \$USD¹⁷ (D_0) in a building. Therefore, the benefit is roughly ~22,000 \$USD, which leads to a benefit/cost ratio of 22.

From a cost-effective point of view, it is recommended to use flood barrier board in flood prone areas with flat elevation as the flooding water has a slow velocity during inundation which can avoid the potential failures of flood barrier boards. For the industrial and commercial buildings in flood prone areas, it is strongly recommend to employ flood barrier board in strong material (e.g. steel or aluminium alloy) with anchoring system in case of the failure of boards. However, it should be noted that the benefit/cost ratio of flood barrier board in this section is limited under a flood with failure probability of 1/200p.y., in which approximately 50% of inundation depths are under the crest height of the flood barrier board (~0.5m). While less benefit would be resulted under the floods with higher inundation depth under extreme events, e.g. flooding with 1/1,000p.y. or 1/10,000p.y.. since flood water can easily exceed the crest height of board. In addition, the more to apply the flood barrier boards the more likely of the human error could be resulted.

6.3.3.2 'Soft' measures

- **Flood insurance**

Flood insurance is one of the methods to reduce the individual loss due to an unexpected flood event. The insured purchased the insurance premium every year from the flood insurer. Flood insurer is liable to cover most part of the damage in the flood-prone area if the flood occurred. The flood insurance premium is based on the potential expected flood damage, and additional cost like operation fee and profit. Hence, the premium is a factor δ higher than the present value of expected economic damage. The mathematical expression would be written as below:

$$Premium = P_f \cdot (\delta \cdot D) / r' \quad (6.14)$$

Where: $\delta > 1$, the factor higher than the expected damage;

In order to calculate the total cost of the damage-reduction measure of flood insurance, it is assumed that all the insured would be affected by a same flood event and the insurer is willing to completely compensate the economic damage. The total cost in the case of flooding with a flood insurance measure would be shown as below:

$$TC = I_0 + I_h(-\ln(P_f)) + \frac{P_f \cdot (\delta \cdot D)}{r'} \quad (6.15)$$

Based on the economic optimum method, the economic optimum level of probability is:

¹⁷ In general, the exposed value during a flood was estimated at 1.75 million \$USD for a building (including all types of buildings). Hence, 1.75 million \$USD * 3% = 525,000 \$USD.

$$P_{f.opt} = \frac{I_h \cdot B \cdot r'}{\delta \cdot D} \quad (6.16)$$

This expression indicates that the safety level of the flood defence would increase with the increase of the insurance factor δ . It implies the flood insurance would definitely increase the cost in this measure. Vrijling (2009) has also stressed that in the case of The Netherlands, the occurrence of flood would be a national disaster and the governmental could help the affected people and property owner. The expenditure could be borrowed from other countries. Flood insurance in the Netherlands would be no clear advantage. But for a case of small community which needs recovery by itself and further external help in an event of flooding, it is recommended to take flood insurance as an additional measure to supplement of the 'hard' measure in a case of failure.

In Shanghai city, the occurrence of flooding in the whole city would cause a catastrophic damage in terms of economic, societal and environmental aspects. Regardless of direct economic damage, the indirect damage in the disruption of the transportation system (e.g. subway system) and the lifeline utilities (e.g. electricity, gas and drinking-water system, etc.) would be tremendous, and deserves great attention in the quantification of flood damage. Flood insurance would not be effectively helpful to reduce the individual loss in the hard-quantification aspect. While, the less developed area with some farmland in the upstream of the Huangpu River could select flood insurance as a loss-reduction measure to address the flood risk. Moreover, the application of the flood insurance is more suitable for a city (community) which is individually responsible other than (local) government intervention.

6.4 Discussion

6.4.1 Cost-benefit analysis

Cost benefit analysis requires to trade off the cost of the measure(s) and the benefit after implementing the measure(s). On one hand, assessing the cost of an upgrade of the protection system is not complicated, even though it requires a precise definition of the system and an assessment of its construction, operation and maintenance costs. The engineers can approximately evaluate the cost based on the local conditions (e.g. labours, the cost of construction equipment's and material, etc.). In this chapter, the cost of upgrade the floodwall and the construction of the storm surge barrier were both evaluated based on local engineer's estimation. On the other hand, evaluating expected benefit is much more problematic as it needs to take potential impacts in various dimensions (direct economic damage and loss, injuries and casualties, psychological trauma, etc.) into account. In this research, the direct economic damage to the buildings and inventories were taken as proxy for overall avoided damage in a flood event, which may under-estimate the benefit after implementing the risk-reduction measures. Hallegatte (2006) pointed out the direct benefit can be amplified by 1) spatial or sectoral propagation into the rest of the economic system over the short term (e.g. through disruption of lifeline services) and over long term; 2) by response to the shock (e.g. loss of confidence, indirect consequence of inequality deepening); 3) by financial constricts impairing reconstruction; 4) by technical constricts slowing down reconstruction. The flood of Shanghai could not only cause direct damage but also huge indirect loss in sectors of transportation, lifeline system, business and tourism, etc., especially the impacts lying in a long run. For instance, if flood disaster happened in Shanghai ever once, investors may be reluctant to invest large amount of money into new business in the affected area and the tourists may choose 'safer' sites to spend their vacations. In this research, the reduction of future flood risk only concerns the potential direct flood damage on the buildings and inventories in Shanghai. Various negative consequences are also expected when the flood is a fact and will definitely increase the value of potential benefit.

6.4.2 Economic optimization

Economic optimization is a technical approach to define the risk at an economic optimal level, which can support the decision making in a political decision process. This concept has been applied to dike rings in the Netherlands. Due to the densely populated areas with high economic value, the present protection level is very high, e.g. 1/10,000p.y. (Deltares 2011), in the dike ring system of South and North Holland. In Shanghai, economic risk analysis shows that safety standard of 1/4,500p.y should be applied to the floodwall of the Huangpu River in 2050. This result is based on rough estimates of flood damage, discount rate and investment cost. In the sensitivity analysis, it shows that the results based on the variation of these parameters ranges from 1/3,000p.y. to 1/7,000p.y.. The results indicate it is justified for Shanghai to take higher safety level than current safety level (1/1,000p.y) to cope with future change (i.e. ‘relative’ sea level rising and economic development) in the near future. However, it is recommended to perform the uncertainty analysis on the parameters of the potential flood damage, discount rate and investment cost in Shanghai to provide rational and technical support for policy making on optimal safety level in the future.

6.4.3 Recommended measures for Shanghai

Due to sea level rising and land subsidence, the crest height of floodwall cannot be sufficient to withstand the protection level of 1/1,000p.y. In order to maintain the protection level of 1/1,000p.y. in 2050, the improvement of the floodwall and the construction of a new storm surge barrier were discussed from cost-effective point of view.

From the viewpoint of simplicity, the improvement of floodwall might be preferred as such structure has been built and maintained in China for thousands of years. It is a traditional and straightforward way to fight against flood. However, the heighten of the floodwall (up to 9.04m) would hinder the sight-view of the Huangpu River, which produces a negative effect on the citizen’s social life and tourist attractiveness (e.g. in the Bund). Furthermore, with the ongoing land subsidence and sea level rising, the improvement of floodwall might not be a sustainable way to safeguard the increasing economic value. As seen from Tab.6. 7, the benefit/cost ratio of construction of storm surge barrier is 1.2-3.3, which is larger than the benefit/cost ratio of upgrading of floodwall (0.96-2.7). It means the storm surge barrier is more cost-effective than upgrading of floodwall in Shanghai.

Tab.6. 7 Results of cost-benefit analysis for the recommended measures in Shanghai: 1) upgrade of floodwall, 2) construction of storm surge barrier.

Recommended measures	Cost [billion \$USD]	Benefit [billion \$USD]	benefit/cost ratio [-]
Upgrade of floodwall	2.7	2.6-7.3	0.96– 2.7
Construction of storm surge barrier	2.2	2.6-7.4	1.2-3.3

Besides, it is noted that the difference of water levels in the Huangpu River as a function of return periods in 10 factors (e.g. 10,000yr and 1,000yr) is only around 50cm, which means the increase of 50cm is 10 factor’s improvement of safety. Thus, it is recommend to take maximum 1m as additional height to the design water level of 1/1,000p.y in 2050 if it really needs to upgrade the floodwall. Another additional solution to address potential overtopping is the application of an extra drainage system along the Huangpu River. Since overtopping only occurs a few hours during storm surge events, drainage system could drain off the water into the river if the capacity is sufficient. Further study on the expenditure of the extra implementation of the drainage system is recommended.

In addition, from a socio-economic point of view, there would be a strong preference for the storm surge barrier since it would need much less relocation of households and enterprises than the floodwall upgrading solution. Moreover, it will shorten the length of protection area needed. Although it is an attractive measure, the cost-benefit analysis cannot comprehensively address the overall effects espe-

cially the intangible effects in the social, environmental and ecological dimensions. The construction of storm surge barrier involves other potential negative environmental or morphological consequences for the rivers. These concerns cannot easily be transformed into monetary terms.

Since Shanghai Municipal Government desires to upgrade the city to an international metropolis with high quality of life, the heightening and strengthening of the floodwall will largely prohibit the sight view of rivers and lower the attractiveness of the city. Considering a bigger future of Shanghai, it is believed that the construction of the storm surge barrier is a better solution to protect Shanghai in a long run.

Since there are many industrial and commercial sites in Shanghai especially in the city centre, it is recommended taking flood prevention as the dominant solution to protection Shanghai. It also recommends to prepare the flood barrier boards at the entrance of all types of buildings in case of unexpected flood events. Regarding the flood insurance, the less developed area with farmland in the upstream of the Huangpu River is suggested to select flood insurance as a damage-reduction measure to address flood risk. These results can provide a better understanding of the modern safety systems. It also showed the economic optimization and cost-benefit analysis can rationally support the decision making on risk-reduction measures and protection levels from economic consideration.

6.4.4 Implications for other metropolitan cities

The construction of storm surge barrier at the mouth of the Huangpu River is recommended to reduce future flood risk in Shanghai, which is based on the experiences of the Delta works in the Netherlands. It should be noted that the common flood threats in Shanghai and in Rotterdam are mainly storm surge from the Sea. In Shanghai, the torrential rainfall with a coincidence of the high storm tide is limitedly correlated (Lin and Li 2000). Moreover, the drainage water from Tail Lake is regulated by a control gate (Taipu River) in the upstream of the Huangpu River. Therefore, it is assumed that the closure of storm surge barrier would not cause flooding in the river due to storage incapacity. However, the closure duration and river discharge during the closure of storm surge barrier need to be further studied. For other metropolitan cities under the flood threat of storm surge, it is recommended to evaluate the measures based on local meteorological conditions and socio-economic factors to support rational decision making.

Chapter 7

Conclusions and Recommendations

The aim of this research was to quantify the flood risk and make recommendations on risk reduction measures in a case study of Shanghai. It mainly concerns scenario-based analysis of flood hazards model in SOBEK, flood damage estimation, flood risk analysis and the evaluation of risk reduction measures. The objectives of this research were formulated as:

1. To examine flood threats and flood defence system in Shanghai
2. To produce inundation maps due to different failures of the flood defence system
 - a. To derive frequency curves for the water levels in typical stations
 - b. To identify potential weak points along the floodwall
 - c. To estimate inundation characteristics under different flood scenarios by 1D2D hydraulic model
3. To estimate the direct and indirect potential economic damage based on flood scenarios
4. To quantify current flood risk based on flood probabilities and the associated flood damage under different scenarios and to estimate future flood risk due to the effects of climate change, land subsidence and economic development
5. To evaluate and recommend the risk-reduction measures by cost-benefit analysis and economic optimization

On the basis of the study results, a number of conclusions have been made below.

7.1 Conclusions

Flood risk analysis investigates the flood process chain from the flood routing in the river network, the potential weak points of the flood defence system, inundation due to failures of the flood defence system and the associated economic damage. The result of flood risk analysis in a region, an area or a community within a temporal frame gives insights into the policy making of the recommendations on risk-reduction measures. In this research, Shanghai is selected as a representative study case to quantify the current and future potential flood risk due to its fast economic growth, land subsidence and the

change of climate. The methodology of flood risk analysis could also be applied in other metropolitan cities provided the input data and information are available.

7.1.1 General

- **Storm surge is the biggest threat to the flooding of the Huangpu River.**

Shanghai is an important city located in the East-coast area of China. It is physically exposed to floods due to flat low topography and frequent typhoon weather. Moreover, due to a highly developing pace of the potential economic damage and social impacts, the property-assets-concentrated downtown area deserves more attention in terms of flood prevention in Shanghai. Storm surge events will be the biggest threat to the flooding of the Huangpu River, especially during the typhoon. A high water level which is pushed up by the storm surge and a high astronomic tide can lead to potential flooding due to overtopping, breaching and failure of floodgates. Large economic damage in Shanghai will be caused subsequently.

- **Floodwall may fail due to various failure mechanisms in Shanghai.**

Historical flood events have already shown that the floodwall may fail due to potential overtopping and breaching along the Huangpu River and its branches. Furthermore, the current protection level of floodwall is only based on the exceedance of the crest height of the floodwall by the water level and does not directly take other mechanisms into account. In this research, the structural failure of a floodwall with small probabilities was taken into account, although it was based on hypothetical breaching. The associated flood damage under each scenario was assessed accordingly.

7.1.2 Frequency analysis

- **New frequency curves of water levels as a function of return period are derived.**

The objective of frequency analysis in this research is to establish the hydrological boundary conditions as a function of return periods in the Huangpu River. Three hydrological stations were selected to represent the upstream, middle stream and downstream of the Huangpu River. Two suggested probabilistic distributions were taken into account to represent the magnitude of the water level related to the frequency of occurrence. In contrast to previous studies, GEV distribution was adopted as a suggested probabilistic distribution for Wusongkou (downstream) and Huangpu Park station (middle stream), while P-III distribution was more fit for the datasets at Mishidu (upstream). The results show that the water levels with return periods of a factor 10 apart (e.g. 1,000yr & 100yr and 500yr & 50yr) at Wusongkou and Huangpu Park both have approximately 50cm difference while roughly 20 cm difference is shown at Mishidu. Moreover, it demonstrated that the Huangpu River is a tide-effected river, which leads to similar water patterns in the downstream and middle stream, and comparatively less tide effect in the upstream.

7.1.3 Hydraulic model

- **The current protection level is expected to be less than to 1/1,000p.y..**

Based on a 1D hydraulic model, the water levels as a function of different return periods can be derived by changing the boundary conditions in the downstream of the river. In this research, the changes in the boundary condition at Wusongkou represent different return periods of storm surge events; the results of the water levels in the Huangpu River with a comparison to the crest height of floodwall show that the current protection level is approximately 1/200p.y.. Several potential weak points can be identified along the upstream, middle stream and downstream of the river. A point which is located at around 45km away from the mouth of the river has the greatest overtopping probability (1/200p.y.)

due to its lowest crest height along the floodwall. Other points, e.g. 4km, 28km, 50km and 65km away from the mouth, are likely to be overtopped under flood probability of 1/1,000p.y..

- **Inundation maps are produced by a 2D hydrodynamic model based on overtopping scenarios, breaching scenarios and the failure of floodgates.**

In the 2D hydrodynamic model, four types of scenarios were simulated in terms of different failure mechanisms of the floodwall. The no-protection scenarios directly implied that the significant requirement of the flood defence system for Shanghai city. Breach scenarios potentially have a larger inundation extent than overtopping and the failure of floodgates; overtopping scenarios at different points along the floodwall suggest that the flood routing starts from a horizontal into a vertical direction in a limited inundated area, normally no more than 1.5 km away from the river since it only occurs within a limited period (e.g. 1 hour). In addition, breaching on the West side of the Huangpu River has a much larger inundation extent and a deeper inundation depth than on the East side, mainly due to its lower terrain in the West area. Furthermore, all the scenarios have on average more than 0.4m inundation depth, which poses potential threats to the property assets, the suspension of the transportation system or other infrastructures. In 2D flood simulations, it should be noted that the inundation results are dependent on the quality of DEM.

7.1.4 Flood damage estimation

- **Large economic damage could be caused by a flooding of Huangpu River in the downtown area of Shanghai.**

The damage function method is a basic model to effectively estimate ex-ante flood damage in an area of interest. In this research, the damage function method was applied to estimate the potential flood damage at an individual building level in a selected area of Shanghai. It was noted that the ex-ante damage estimation greatly depends on the classification of potential damage categories, the associated damage functions and the maximum damage value of property assets, in which the damage function contributes most to the flood damage estimation. Although it is hard to validate the results, which is currently a common challenge in the field of flood damage estimation, the application of Monte Carlo analysis can assist to address uncertainties during the estimation of flood damage. It shows that large potential flood damage (7%-14% of maximum damage value) could be caused in the downtown area under the breach scenarios for the West side of the Huangpu River.

- **Service interruption and business interruption due to floods require great attention in Shanghai.**

The service interruption at one subway station for one week would cause approximately 1 million \$USD in revenue losses in Shanghai, which implies that huge practical inconvenience would be induced for the inhabitants during such unexpected events. Considering the large number of subway stations and other indirect cost (e.g. extra emergency cost, cleaning cost and repair cost), it could be regarded as the lowest bound of the indirect damage estimation. In addition, the potential service interruption and business interruption due to flooding could contribute 30%-50% of the total damage based on the study on previous studies of real cases of flooding in other cities. Furthermore, in a developing urban city, the long term effect on the tourist-industry and business investments would be far-reaching. Therefore, it is better to prevent flooding in Shanghai.

7.1.5 Flood risk

- **Total (flood) risk was estimated at between 40-112 million \$USD/yr. in Shanghai.**

In this research, the flood risk is calculated based on 26 flood scenario analyses, in which the potential economic damage due to breaching is 10 factors higher than those caused by overtopping and the failure of floodgates. The results of flood risk are represented by a total risk which is calculated by a mathematical model. This model is dependent on the expected value and the standard deviation of the economic damage on a basis of risk aversion, in which the risk aversion index was taken as 3. Thus, the total (flood) risk was estimated at between 40-112 million \$USD/yr. in Shanghai, which is of particular importance for insurance companies to determine the insurance premium, and for policy makers to trade off risk reduction projects by a cost-benefit analysis.

- **Future flood risk could increase 16 fold in 2050 due to sea level rise, land subsidence and economic development.**

Regarding flood risk in the near future, the ‘absolute’ sea level rise, land subsidence and economic development, these factors all contribute to some extent to the increase of future flood risk. In terms of the affecting factors, economic development would contribute most to the future flood risk, followed by land subsidence and then ‘absolute’ sea level rise. The present value of future flood risk is calculated as ~4.2 and ~16 times the value of the current flood risk (reference year is 2010) as a result of a combination of the affecting factors in the year of 2030 and 2050, respectively. The future flood risk could increase to as high as 1.8 billion \$USD/yr. in 2050 if no further measures are taken in Shanghai.

7.1.6 Flood risk-reduction measures

- **Construction of a storm surge barrier is a better solution than an upgrading of the floodwall to protect Shanghai in a long run.**

The cost-benefit analysis shows that the storm surge barrier has a somewhat higher benefit/cost ratio than upgrading the floodwall in Shanghai. Besides, the relocation cost of households and enterprises along the Huangpu River due to upgrading the floodwall would be much higher than the construction of a storm surge barrier. Moreover, the upgrading of the floodwall would hinder the view of the river and lower the attractiveness of the city and, with the ongoing land subsidence and sea level rising, the improvement of the floodwall might not be a sustainable way to safeguard the increasing economic value. From a socio-economic point of view, the construction of the storm surge barrier is a better solution to protect Shanghai in the long run.

- **Damage reduction measures can be provided as additional measures to the probability reduction measures in Shanghai.**

Flood prevention measures seems more cost-effective from an economic point of view than the damage reduction measures, because damage reduction measures are only effective when a flood really occurs and flood damage becomes a fact. Even though we put flood prevention as the first priority to protect Shanghai, the additional measures, like preparation of flood barrier boards, can reduce flood damage to some extent when flooding occurs. The application of flood insurance can also reduce individual loss as floods occurs in a small community. Given the current protection level it is recommended to widely prepare the flood barrier boards at the entrance of all types of buildings in case of unexpected flood events. Moreover, it is suggested to select flood insurance in the less developed farmland area in the upstream of the Huangpu River to address the potential flood risk.

- **It is recommended to apply a higher safety level to the floodwall of the Huangpu River.**

By method of economic optimization, a preliminary result of a safety level of 1/4,500p.y. is recommended for the floodwall of the Huangpu River to cope with future flood risk in 2050, which is based on rough estimates of flood damage, discount rates and investment costs, to retrieve an optimal level

from an economic point of view. The corresponding design water level at Wusongkou is proposed at 7.4m, which is 0.8m higher than the current design water level (6.6m).

7.2 Recommendations

Due to the limitations discussed in this thesis, the following recommendations are made as below:

1. The focus of this thesis is on the quantification of flood risk caused by failure of the flood defence system along the Huangpu River in Shanghai. Even though the coincidence of a storm surge and a high astronomical tide is the biggest driver to flooding, causing potential flood damage, other types of floods can also lead to severe economic damage and social disturbance. For instance, pluvial flooding due to insufficient drainage capacity in the system can cause inundation under extreme precipitation. However, such type of flooding is less catastrophic due to its lower inundation depth and lower social disturbance. The coastal flood is another flood type, which could cause economic damage and loss of life. The safety standards of the sea dikes of Shanghai are defined between 1/200p.y. and 1/100p.y. in different coastal areas. Although coastal areas, like the districts of Fengxian and Jinshan, are relatively less developed area with less buildings and infrastructures, the economic damage there would mainly affect the farmland, which cannot be compared to the economic damage in the city centre. Thus, due to fast urbanization in China, a quantitative study of coastal flooding in Shanghai is recommended in the future.
2. The flood damage in this thesis focuses on tangible economic damage. Other consequences, such as loss of life (direct and intangible damage) or physiological effects (indirect and intangible damage) are not considered. For some purpose, such as the compensation scheme in the insurance companies, the direct damage estimation is sufficient since they only cover the direct damage. Although the intangible damage is difficult to value in monetary terms, it is our recommendation to include all the effects of floods in the ex-ante flood risk analysis to better understand the system and to provide more completed results of flood risk for decision making.
3. In this thesis, the water levels as a function of return periods were extrapolated to 10,000yr. and 1,000yr. with around 100yr. historical observation data. Under a changing climate environment, future effects of sea level rise and land subsidence on the water levels in the river are recommended to be considered to predict the water level as a function of return periods.
4. Existing defence standards generally refer to failure probability due to overtopping or overflow. Other geotechnical failure mechanisms, such as piping and sliding, which can lead to failure when water levels are below the crest of the defences, are recommended to be studied in more detail based on available information. It is suggested to pay equal attention to the various failure mechanisms of flooding.
5. Better knowledge on the breach growth process and more data on the foundation and structure of the flood defence system would most likely reduce the uncertainty in the risk assessment. Sophisticated field investigation on the flood defence system is recommended in the future.
6. Improved input data in the 2D flood simulations, e.g. Digital Elevation Model (DEM) and roughness data, could provide more accurate results in the further study.
7. Detailed investigations on the vulnerability of potential damage categories could assist to better understand the potential flood damage in an ex-ante estimation.
8. Since this research is based on an assumption of desirable performance of control gates in the upstream of the Huangpu River during storm surge events in case of additional drainage water from Tai Lake, a storm surge barrier can function very well to prevent a storm surge at the mouth of the river. In order to prevent flooding due to limited storage capacity of river, extra water storage area is recommended if storm surge barrier is constructed at the mouth of the

Huangpu River. Failure of the control gates and rapid changes of the complex river (canal) systems between Tai lake and the upstream of the Huangpu river should also be taken into account in future research.

9. A more comprehensive evaluation of various risk-reduction measures is highly recommended in the future.

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List of Symbols

Symbol	Description	Units
$F(x)$	cumulative distribution function	[-]
F_r	flood risk	[\$USD/yr]
C	consequence	[\$USD]
$F(x)$	cumulative probability distribution	[-]
$f(x)$	probability density function	[-]
$E(X)$	mean value	[-]
C_v	kurtosis	[-]
C_s	skewness	[-]
P	probability of flooding	[/yr]
T	return periods	[yr]
x_i	the theoretic frequency for each observation,	[-]
y_i	the prediction frequency in the corresponding observation	[-]
x_i	the corresponding empirical frequency	[-]
A_t	total cross section area	[m ²]
q_{lat}	lateral discharge per unit length	[m ² /s]
Q	discharge	[m ³ /s]
x	distance	[m]
t	time	[s]
B	boussineeq constant	[-]
A_f	cross section flow area	[m ²]
g	gravity acceleration	[m ² /s]
h	water level	[m]
C	chez coefficient	[m ^{1/2} /s]
R	hydraulic radius	[-]
w_f	flow width	[m]
τ_{wi}	wind shear stress	[m ^{1/2} /s]
ρ_w	water density	[kg/m ³]
B_r	river width	[m]
B_b	breach width	[m]
F_d	flood damage in monetary terms	[\$ USD]
S_i	maximum potential values of elements-at-risk i	[\$ USD]
d	inundation depth	[m]
t	flood duration	[h]
v	flow velocity	[m s ⁻¹]
r	rising rate	[m s ⁻¹]

$f(d, t, v, r \dots)$	damage function	[-]
S	market value of all the categories at risk	[\$USD]
S_{ij}	market value of category i in district j	[\$USD]
n	number of categories at risk	[-]
m	number of districts in study area	[-]
C_i	construction cost for each category i	[\$USD/m ²]
P_{ij}	percentage of category i in district j	[-]
F_j	floor area in district j	[m ²]
A_j	site area in district j	[m ²]
FAR_j	floor area ratio in district j	[-]
d	inundation depth	[m]
Dr	damage rate	[-]
a_i, b_i, c_i	the parameters in the equations, which depend on the fitting functions, $i=1, 2, 3$	[-]
$P_{f.o}$	failure probability of overtopping	[/yr]
$P_{(wl>crest.h)}$	occurrence probability of water level exceeding the crest height of floodwall	[/yr]
$P_{f.b}$	failure probability of breaching	[/yr]
$P_{(wl \geq 5m)}$	occurrence probability of water level at 5m	[/yr]
$P_{(failure (wl \geq 5m))}$	conditional probability of floodwall when the water level reaches at 5m	[/yr]
$P_{(wl \geq 4.7m)}$	occurrence probability of water level $\geq 4.7m$	[/yr]
$P_{(failure (wl \geq 4.7m))}$	conditional probability of close-down floodgate when the water level reaches at $\geq 4.7m$	[/yr]
$P_{f.fg}$	failure probability of floodgate	[/yr]
$E(D)$	expected value of flood damage	[\$USD/yr]
$\sigma(D)$	standard deviation of flood damage	[\$USD /yr]
P_i	the estimated probability of flooding under a specific scenario i	[-]
D_i	the estimated flood damage under a specific scenario i	[\$USD]
N	number of scenarios, in this case $N = 26$	[-]
$I(P_f)$	investment to upgrade or maintain the probability of flooding to P_f	[\$USD]
$PV(M)$	present value of maintenance and operational cost	[\$USD]
$P_{f,0}$	probability of flooding in initial state	[/yr]
P_f	probability of flooding after completion of the project	[/yr]
D_0	flood damage at a failure probability of $P_{f,0}$	[\$USD]
D	flood damage at a failure probability of P_f	[\$USD]
g	economic growth rate;	[-]
r	interest rate	[-]
r'	discount rate	[-]
R_r	residual risk	[\$USD/yr]

R_e	existing risk	[\$USD/yr]
TC	total cost	[\$USD]
D	flood damage at a given failure	[\$USD]
$PV(P_f \cdot D)$	present value of the total risk	[\$USD]
n	utility year, taken 'infinite' here	[-]
$H_{cre.}$	crest height of the floodwall	[m]
h_{design}	design water level under a defined safety standard	[m]
h_{wave}	the required crest freeboard height, which is determined by wave overtopping condition; safety board is an additional height for a safety margin	[m]

List of Abbreviation

CDF	Cumulative Density Function
D.W.L	Design water level
DEM	Digital Elevation Model
EAD	Expected Annual Damage
FAR	Floor Area Ratio
GEV	Generalized extreme value
K-S test	Kolmogorov-Smirnov test
L-MM	Linear Moment Method
LSM	Least Square Method
MAE	Mean Absolute Error
MLM	Maximum Likelihood Method
MSD	Mean Square Deviation
MSE	Mean Square Error
PDF	Probability Density Function
POI	Point of interest
R	Correlation coefficient
WD	Wusong Datum

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