A study on flood hazard and GDP exposure for the Foshan-Zhongshan region in the Pearl River Delta, China

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2020

Zhang, M. (2020). A study on flood hazard and GDP exposure for the Foshan-Zhongshan region in the Pearl River Delta, China. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/143277>

<https://doi.org/10.32657/10356/143277>

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**A Study on Flood Hazard and GDP Exposure for the
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**ZHANG QI
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**

2020

**A Study on Flood Hazard and GDP Exposure for the
Foshan-Zhongshan Region in the
Pearl River Delta, China**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Master of Engineering

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

13 August 2020

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Date

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Zhang Qi

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

13 August 2020

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Date

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Associate Professor Lo Yat Man Edmond

Authorship Attribution Statement

*(B) This thesis contains material from [1] paper published in the following peer-reviewed journal in which I am listed as first author.

Key results from Chapter 4 and Chapter 5 are published as Zhang, Q., Jian, W., and Lo, E. Y. M. (2020). “Assessment of flood risk exposure for the Foshan-Zhongshan region in Guangdong Province, China.” *Water (Switzerland)*, MDPI AG, 12(4), 1159. (2020). DOI: 10.3390/W12041159

The contributions of the co-authors are as follows:

- I collected and processed of the original data, constructed the HMS model, and performed the analysis.
- Dr Jian collected historical water level and discharge data for Makou and Sanshui, provided the hourly water level and discharge for the 2018 Event.
- I wrote the original draft and guided by Prof Lo and Dr Jian together edited and rewrote the draft.
- I prepared the initial tables and figures, and Dr Jian enhanced on some of the figures.

13 August 2020

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Date

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Zhang Qi

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Acknowledgment

This master's degree was inspired by Professor Pan Tso-Chien, Executive Director of the Institute of Catastrophe Risk Management (ICRM), NTU. I sincerely thank my supervisor Assoc. Professor Lo Yat-Man, Edmond for his constant guidance and support, as well as several researchers from ICRM, specifically Dr. Jian Wei for the kind help, guidance and sharing.

Abstract

Flood has caused 20% of the worldwide economic loss arising from catastrophe events over 2008 to 2018. It ranks as the most frequent peril in China. These observations inspired the MEng project to study the flood risk of China's Pearl River Delta region with its high asset concentration, and specifically for a basin within. A hydrological model was constructed using HEC-HMS for this basin using only publicly accessible data sources as data availability is often restricted. The HEC-HMS simulation model was built based on two recent historical flood events occurring in 2017, a high river inflow event and 2018, a high local precipitation event. Needed river rating curves for mid to downstream stations have further been developed to provide relationships between observed water level and the river discharge as data for the latter is often unavailable. A more severe flood event was synthesized by having the high 2017 upstream river inflows and the high 2018 local precipitation occurring simultaneously. Climate change impact has also been included by having the precipitation intensity increased. An empirical approach was developed to estimate the flood extent as resulting from river overflows. This enabled the area flooded to be assessed in extent and depth, particularly for the more severe synthetic events, along with the GDP at risk from the flooding.

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Chapter 1 Introduction

Asia is expected to become the world's largest gross domestic product (GDP) contributor in 2020 as highlighted by the 2019 World Economic Forum Annual Meeting¹. However, Asia is most vulnerable to catastrophic disasters. The region is directly exposed to the Ring of Fire that is responsible for around 90% of the world's earthquakes². Frequent major floods occur in Asia including the devastating 2005 Mumbai, 2007 Jakarta, and 2011 Thailand floods. Around one-third of tropical cyclones generated in the West Pacific Ocean cut through East Asia (Elsner and Liu 2003), making countries such as China, Korea, Philippines and Vietnam highly prone to typhoons. Moreover, many Asia (mega)cities are located in these high hazard areas, as driven by socio-economic growth. A particular catastrophic event is the 2004 Indian Ocean earthquake and tsunami. This 9.1 moment magnitude earthquake occurring off the north west coast Sumatra resulted in a massive tsunami that swept through the Indian Ocean leading to over 220,000 loss of lives in coastal communities across 14 countries³.

Asia has suffered USD 83 billion economic loss in 2016 due to catastrophe events, while only 11% (USD 8.8 billion) was insured. This 11% insured loss penetration ranked as the lowest among continents in the world. Among catastrophe perils worldwide, flood contributes relatively high economic loss, while ranked low in terms of insurance cover. From a longer perspective, over 2008 to 2018, flood loss cumulatively accounted for 20% of overall economic loss world-wide (Figure 1.1) with 82% of the loss non-recoverable by financial instruments (Table 1.1), as according to Munich Re NatCatSERVICE catastrophe database⁴. Similar results showing the low loss recovery for flood events have been reported

¹ World Economic Forum, <https://www.weforum.org/agenda/2019/12/asia-economic-growth/>, [accessed in Dec 2019].

² U.S. Geological Survey, Earthquake Glossary, Ring of Fire, <https://earthquake.usgs.gov/learn/glossary/?termID=150>, [accessed in Jul 2020].

³ U.S. Geological Survey, Earthquakes with 50,000 or More Deaths https://web.archive.org/web/20120910022455/http://earthquake.usgs.gov/earthquakes/world/most_destructive.php, [accessed in Jul 2020].

⁴ Munich Re NatCatSERVICE, <https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html>, [accessed in Dec 2019].

in various works done by Center for Hazards and Risk Research (CHRR) and Center for International Earth Science Information Network (CIESIN)⁵.

Although the 2016 worldwide flood loss insurance penetration is 18%, if broken down by large economic regions, China flood coverage is as low as 2% while Europe highest at 33% (Figure 1.2). As the top GDP producing country in Asia, China has a long history of flood disasters. During the past two-thousand-year period, 1011 flood events were recorded, equivalent to once every two years (Wei and Hong 2012). Compared with other recorded perils, flood is ranked as the most frequent during all major dynasties from the Qin Dynasty (started at 221 BC) to the Qing Dynasty (ended at 1912) (Ge et al. 2008; Wei and Hong 2012). This motivated the current Master of Engineering project on flood risk in China.

Figure 1.1 Munich Re NatCatSERVICE, 2008-2018 worldwide natural disaster losses split by perils.

⁵ Global Flood Total Economic Loss Risk Deciles, <https://sedac.ciesin.columbia.edu/data/set/ndh-flood-total-economic-loss-risk-deciles/metadata>, [accessed in Dec 2019].

Table 1.1 Munich Re NatCatSERVICE, 2016 worldwide natural disaster summary.

Peril	Overall loss 2008-2018	Insured loss 2008-2018	Insured %	Uninsured %
Flood/flash flood	394	69	18%	82%
Earthquake/tsunami	478	84	18%	82%
Convective storm	349	213	61%	39%
Tropical Cyclone	582	214	37%	63%
Heatwave/wildfire	70	46	66%	34%
Winter storm	127	56	44%	56%
Total	2,000	682	34%	66%

* Value amounts are in billion USD.

Figure 1.2 Munich Re NatCatSERVICE, flood loss insurance cover percentage in 2016 by regions.

In general, there are three main flood types: riverine flood (fluvial), surface flood or urban flood (pluvial) and coastal flood (due to storm surge, sea water backflow, tsunamis, etc.). The flood studied in this thesis is the fluvial type, but with impact from local precipitation. A flood model generally consists of hydrologic and hydraulic models and this study focuses on hydrologic modeling with a simple method to estimate the flood extent.

It is noted that such physically-based hydrologic model for China is relatively less used as compared to more developed countries like US and Japan. This has historically been related to the limited data availability in the public domain. Hence this project aims to construct such a model with global datasets

for topographic features and openly available precipitation and discharge data as released publicly by the local governmental agencies.

A growing number of studies also indicate changing characteristics of precipitation due to climate change. Strong precipitation is generally one of the most common factors in causing flood events, and typhoons are such a major source of intense precipitation. As climate change would most likely increase the intensity of typhoons and the resulting precipitation (Easterling et al. 2017; Knutson et al. 2010), threat from flooding events would increase. This effect of increased precipitation is also studied in this thesis. Wing et al. (2018) shows that the population and GDP growth are likely to be negatively affected by climate change. Hence this study also assesses the economic loss potential from the impact of increased rainfall from climate change.

The Pearl River Delta (PRD) region has experienced major flood events in 1915, 1968, 1994, 1998, 2005, especially from the West and North River. The maximum calculated peak flow among Pearl River control stations is 21,000 m³/s at Wuzhou Station in 1915 super flood event, which has impacted more than 3.7 million people and inundated 4,320 km² farmlands in the PRD⁶. Based on the collected data, two flood events that occurred in the PRD region in 2017 and 2018 are studied here. It is notable that the 2017 flood resulted from extremely high upstream river flow, while the 2018 event was associated with regional heavy precipitation. Hence this study aims to construct a hydrologic model to represent the relationship between rainfall and runoff and to model a synthetic situation where high upstream flow and high localised precipitation occurs concurrently. Consideration of impact on climate change is through an increase in the modeled precipitation.

The modelling approach taken here is to estimate the flood extent as resulting from river overflows. This enabled the area flooded to be assessed in extent and depth, particularly for the more severe synthetic events, along with the GDP at risk from the flooding. While the GDP at risk does not represent actual loss, a rigorous estimate of actual loss, particularly direct losses to the built structures, requires detailed knowledge of the exposure covering spatial distribution, economic function and vulnerability

⁶ Pearl River Water Resources, 'Historical Flood disasters', http://www.pearlwater.gov.cn/zjgk/lshz/200411/t20041104_1297.htm, [accessed in Dec 2018].

(i.e. damage curves). Alternatively, there are reported works (Carrera et al. 2015; Jongman et al. 2012) which associate land-use with economic sectors and with the reduction in economic output for each sector dependent on the flood depth. This then readily produces an estimate of the economic loss for the flooded region, and via economic models (e.g. Input-Output models) the losses beyond the region. Both approaches require detailed data which is unavailable for the research work reported here. Thus the work is limited to reporting the GDP at risk as an indicator of the actual flood loss and impact.

The remainder of the thesis is organized as follows. Chapter 2 provides a review of the research topic, existing hydrologic models and their limitations, as well as the climate change impact on precipitation. Chapter 3 describes the approach taken for constructing the hydrologic model and inundation estimation. Results and modeling outputs are presented in Chapter 4. Finally, Chapter 5 concludes the study and discusses the future work.

Chapter 2 Literature review

2.1 Hydrologic model

The historical development of hydrologic models had been in three major stages. The initial stage was regarded as black-box modeling, which is based on empiricism such as the unit hydrograph as initially suggested by Sherman (Sherman 1932). This is defined as the hydrograph of the direct runoff resulting from one-unit depth of rainfall. Since the 1960s, the development moved to the second stage of having conceptual and lumped parameter models, regarded as grey-box models. Representative models are Stanford Watershed Model, developed in 1966 (Crawford and Burges 2004), TOPMODEL, Sacramento model, Tank model and the Xinanjiang model. The Xinanjiang model was developed by Hohai University in 1973 and have been widely used in China since the 1980s (Rui et al. 2012; Zhao 1992). The third stage is physically-based model, or the white-box model. This includes the Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS), and the Europe hydrological system Systeme Hydrologique Europeen (SHE) model. These models take advantage of Geographic Information System (GIS), remote sensed and gaged/telemetered data, as well as the vastly improved computational power. The need for such models arose in the middle of 1970s, with SHE being the first of these models (Abbott et al. 1986). They can better model the actual mechanism of water cycle, such as evapotranspiration, infiltration, groundwater, flow direction, surface runoff pattern, etc.

2.2 Climate change impact

The Intergovernmental Panel on Climate Change (IPCC) has reported strong evidences showing that the climate change is occurring and affecting wide aspects of the human life and society, not only environmentally but also economically (IPCC 2007, 2012, 2014). The US National Weather Service

has reported ten extreme rainfall events worldwide over May 2015 to August 2016, all with precipitation intensity return periods of 1-in-500 year. One heavily researched area is on the impact of climate on the frequency and severity of extreme precipitation. Even with different definitions of extreme precipitation, many of these studies indicate a conclusion that more extreme and intense events are more likely to happen in many parts of the world (Easterling et al. 2017; Walsh, J. et al. 2014; Wuebbles 2016).

China has different regional and seasonal patterns of precipitation as highlighted by Zhai, et al (2005). Most parts of China have rainfall intensity increased, especially in some of the southwest and south China coastal regions. Yao et al. (2008) have found positive trend of daily precipitation over south-eastern and north-western China in periods of 1978 to 2002, as attributed to the strengthened monsoon precipitation. Even in regions where the seasonal or annual precipitation trend is negative, there is a significant increase in rainfall intensity. Researchers have concluded significant increase of ratios of heavy rainfall to total annual precipitation by 1.8% to 3.8% in South China and greatly increased potential of flood risk under all three IPCC scenarios (scenario A2, A1B and B1) by the end of 21st century (Chen et al. 2012). For the PRD region located along the southern coast, the climate change impact is therefore significant.

The impact to the PRD region is believed to be largely consistent with the global impact projection (Chau and Jiang 2001; Tracy et al. 2007; Y. Ding et al. 2007). The regional annual mean temperature is projected to increase by 3.5 °C (from 1.7 °C to 5.6 °C), the annual rainfall in Hong Kong or Guangdong province would increase about 1% every 10 year towards the end of 21st century (Leung et al. 2006). Most of the PRD population and assets concentration lie below half a meter relative to the mean sea level (MSL), making these coastal low-lying areas even more susceptible to flooding and sea level rise. The official Chinese Third National Communication report published in 2018 states that the current Sea Level Rise (SLR) in the South China Sea (most relevant to the PRD region) is at a rate of 3.4 mm/year based on data from 1980 to 2017 (Ministry of Ecology and Environment of China 2018). The rate is very likely to range over 2.3 mm/year to 5.3 mm/year, or 70-160 mm cumulatively in the coming 30 years. Earlier study by Huang et al. (2004) suggests that the SLR around Guangdong

province would be 300 mm by 2030. These regional estimates are all higher than the global SLR rate of 1.7 mm/year or 0.19 m cumulated increase from 1901 to 2010 (IPCC 2014).

Currently, there are no conclusive studies on the causal effect of climate change on tropical storm (typhoon, hurricane, cyclone) frequency or severity (Chan 2006; Knutson et al. 2010; Webster et al. 2005). Some studies suggest the recent more intense hurricane or typhoons are due to global warming while others attributing it to variabilities in the climate system. However, more individual weather-events, especially natural catastrophes, are highlighted and potentially linked to climate change impact (Union of Concerned Scientists 2018). The 2018 Typhoon Mangkhut occurred in West Pacific, which made landfall on Guangdong province. The maximum daily rainfall has exceeded 700 mm in the Philippine Sea and with large area rainfall exceeding 300 mm along the track towards Guangdong province as reported by National Aeronautics and Space Administration (NASA)⁷. This event is regarded as related to El Nino phenomenon, regarding its high typhoon intensity (Tarmizi et al. 2019). Moreover, the 2019 Typhoon Hagibis brought a maximum daily precipitation of 992.5 mm in Kanagawa Prefecture, being the wettest typhoon in Japan since available records⁸. These extremely powerful and long-lasting storm-induced rainfall events, which led to devastating inland flooding are often linked with climate change or global warming (Van Oldenborgh et al. 2017). It highlights the necessity to examine recent extreme events and to perform scenario analysis for better understanding of the potential and impact of future extreme events. Moreover, it suggests that the historical data alone does not fully describe the precipitation characteristics under the impact of climate change on the future intensity and frequency of rainfall events (Giorgi et al. 2018). The resulting flood hazard map if generated without consideration of climate change would thereby result in an underestimation of the hazard level with consequence of insufficient protection planning and risk awareness.

⁷ NASA blog, <https://blogs.nasa.gov/hurricanes/2018/09/10/mangkhut-nw-pacific-ocean-2018/>, [accessed in Dec 2019].

⁸ RMS - Typhoon Hagibis: Japan's Wettest Typhoon on Record, <https://www.rms.com/blog/2019/10/15/typhoon-hagibis-japans-wettest-typhoon-on-record/>, [accessed in Dec 2019].

2.3 PRD study area

The PRD region in south China lies mainly between latitude 22°N to 25°N, and longitude 112°E to 115°E. The PRD consists of 11 cities, i.e. 9 cities from Guangdong province, which are Guangzhou, Shenzhen, Dongguan, Zhuhai, Foshan, Zhongshan, Jiangmen, Zhaoqing and Huizhou, and the two Special Administrative Regions (SAR) of Hong Kong and Macau (Figure 2.1). Amongst them are two megacities⁹ (Guangzhou and Shenzhen) and three metropolitan cities with more than 5 million population. The region is ranked as the largest urban area worldwide by World Bank 2015¹⁰. The region contributes 13% of China GDP (as of 2017) with an extreme concentration of population and socioeconomical exposures. A summary the PRD's GDP, population and land area as at 2017 is presented in Table 2.1. The GDP data of Hong Kong and Macau were collected from World Bank Open Data¹¹, and the rest from Guangdong Statistical Yearbook 2018¹².

The rainy season for the PRD region is between April and September during which 80% of the annual total precipitation occurs. The weather system is affected by the rainy (locally known as Meiyu) season between April and June. The coastal areas are also subjected to tropical cyclones which may bring heavy precipitation and/or storm surges during the typhoon season over July to September.

The river network running through the PRD region consists of three major tributaries, the West River (Xijiang, 西江), the North River (Beijiang, 北江), and the East River (Dongjiang, 东江).

Table 2.2 summarises the river length, drainage area for the three main tributaries. Amongst them the longest and largest branch is the West River, originating from the Maxiong Mountain on Yunnan-Guizhou Plateau. The North River is the second largest tributary, originated from Jiangxi province and entering the delta region through Sanshui station. For this MEng work, the downstream reaches of the

⁹ According to United Nation, a megacity refers to a very large city, with at least 10 million population.

¹⁰ The World Bank, 'World Bank Report Provides New Data to Help Ensure Urban Growth Benefits the Poor', 2015, <http://www.worldbank.org/en/news/press-release/2015/01/26/world-bank-report-provides-new-data-to-help-ensure-urban-growth-benefits-the-poor>, [accessed in Dec 2019].

¹¹ World Bank Open Data, GDP, <https://data.worldbank.org/country>, [accessed in Jan 2019].

¹² Guangdong Statistical Yearbook 2018, <https://www.chinayearbooks.com/guangdong-statistical-yearbook-2018.html>, [accessed in Jan 2019].

West and North Rivers comprise the main study. It is noted that the criss-crossing PRD water network encompasses a drainage area of 26,800 km², accounting for 5.9% of the whole Pearl River drainage area.

Figure 2.1 Map of Guangdong Province (green area) and the PRD region (red area).

Table 2.1 PRD 11 cities GDP, population, area, GDP per capita and population density, in CNY.

City	Name in Chinese	GDP (million CNY)	Population (million)	Area (km ²)	GDP per capita (CNY/person)	Population density (person/km ²)
Hong Kong	香港	2,287,711	7.4	2,754	309,485	2,684
Shenzhen	深圳	2,249,006	12.5	1,997	179,514	6,274
Guangzhou	广州	2,150,315	14.5	7,249	148,314	2,000
Foshan	佛山	939,852	7.7	3,798	122,749	2,016
Dongguan	东莞	758,209	8.3	2,460	90,885	3,391
Huizhou	惠州	383,058	4.8	11,346	80,188	421
Zhongshan	中山	343,031	3.3	1,784	105,224	1,827
Macau	澳门	337,420	0.6	33	541,953	18,867
Jiangmen	江门	269,025	4.6	9,505	58,975	480
Zhuhai	珠海	267,518	1.8	1,732	151,534	1,019
Zhaoqing	肇庆	211,001	4.1	14,891	51,271	276

Table 2.2 General information of Pearl River basin.

River	Length (km)	Drainage area (km ²)	Drainage %
West River	2,075	353,100	77.8%
North River	468	46,700	10.3%
East River	520	27,000	6.0%

Chapter 3 Methodology

The methodology described in this section includes building a rainfall-runoff hydrological model using the HEC-HMS based on data reported for two major recent flood events in the PRD region. The first event occurring in July, 2017 represents a scenarios of high river flow into the study area and the second event in June, 2018 represents a scenario of high localised rainfall within the study area. The model is then used to construct a synthetic scenario based on the two actual events to simulate a more severe flooding situation of high river inflow with heavy local precipitation simultaneously, and to assess the potential inundation impact. The final step is to increase precipitation to reflect a future changed climate situation of increased rainfall with other parameters and conditions remain unchanged.

Section 3.1 describes the data sources for precipitation, river discharge and water level, and ground surface elevation used in this study. Conversion between the different vertical datums used for water level and ground surface elevation datasets is presented. Within the constraints of the data availability, the study area was selected, and watershed delineated as presented in Section 3.2. Section 3.3 details the setup of the HEC-HMS model for simulating the rainfall-runoff process. Finally, Section 3.4 provides the methodology for estimating the inundation extent based on the overflow volume calculated in Section 3.3.

3.1 Field data

3.1.1 Rain gage and river stage data

River flow is typically quantified by water level (level) and flow rate (discharge) which are measured by gage stations placed near or over the rivers. In the river network in the PRD region, water level data is more commonly available than discharge data which is only continuously

measured at a few main monitoring stations. Hence in this study, the river flow is analysed with water level data when discharge data is unavailable.

Both hourly rainfall and river water level data were downloaded from the Water Resources Department of Guangdong Province (广东省水利厅) rainfall report¹³ and water report¹⁴ for the two case study events in July 2017 and June 2018, respectively.

The locations of the rain gage station and river stage station are listed in Table 3.1 and Table 3.2, and shown in Figure 3.1. There are 25 rainfall gage stations and 10 river stage or water level stations in total used in this study. Seven stations have both rainfall and water level data, which are Sanshui, Sanshanjiao, Makou, Ganzhu, Nanhua, Xiaolan, Banshawei. One of the stations, the Tianhe station (a downstream station on the West River), only has daily water level (measured at 8am each day) available. The warning levels for stations shown in Table 3.2 are taken from the above mentioned water report.

¹³ Rainfall report, <http://www.gd3f.gov.cn:9001/Report/RainReport.aspx>, [accessed in Dec 2018].

¹⁴ Water report, <http://www.gd3f.gov.cn:9001/Report/WaterReport.aspx>, [accessed in Dec 2018].

Table 3.1 Rain gage station list.

Rainfall Station ID	Rain gage station	Name in Chinese	City
1	Baishuidai	白水带	Jiangmen
2	Banshawei	板沙尾	Foshan
3	Changjiangshuiku	长江水库	Zhongshan
4	Daao	大敖	Jiangmen
5	Dashi	大石	Guangzhou
6	Ganzhu	甘竹	Foshan
7	Lezhu	勒竹	Foshan
8	Makou	马口	Zhaoqing
9	Nanhua	南华	Foshan
10	Nansha	南沙	Guangzhou
11	Nijiao	尼教	Foshan
12	Pingsha	平沙	Zhuhai
13	Rongqi	容奇	Foshan
14	Sanshakou	三沙口	Guangzhou
15	Sanshanjiao	三善滘	Guangzhou
16	Sanshui	三水	Foshan
17	Shaping	沙坪	Jiangmen
18	Shifudayuan	市府大院	Foshan
19	Tangxia	棠下	Jiangmen
20	Wanqinshaxi	万顷沙西	Guangzhou
21	Xiqiao	西樵	Foshan
22	Xiaolan	小榄	Zhongshan
23	Zhengkeng	正坑	Zhongshan
24	Zhuyin	竹银	Zhuhai
25	Zidong	紫洞	Foshan

Table 3.2 Water level station list.

Water level Station ID	Water level station	Name in Chinese	River	City	Warning level (m)
1	Sanshui	三水	North River	Foshan	7.5
2	Sanduo	三多	North River	Foshan	4.9
3	Lanshi	澜石	North River	Foshan	4
4	Sanshanjiao	三善滘	North River	Guangzhou	1.8
5	Makou	马口	West River	Foshan	7.5
6	Ganzhu	甘竹	West River	Foshan	4.8
7	Tianhe	天河	West River	Jiangmen	5.8
8	Nanhua	南华	West River	Foshan	4.5
9	Xiaolan	小榄	West River	Zhongshan	3.8
10	Banshawei	板沙尾	West River	Foshan	n.a.

Figure 3.1 Rainfall and water level stations. Red circles represent rain gage stations (25 in total) as listed in Table 3.1. Blue triangles represent water level stations (10 in total) as listed in Table 3.2. The red triangles are stations with both rainfall and water level.

3.1.2 Discharge data

The discharge data was collected from various sources as detailed in Table 3.3. The Makou and Sanshui stations, locating in the upstream of the river network in the study area, serves as the upstream input stations for river discharge flowing into the study area. The Tianhe station is used for model benchmarking. Lastly, some discharge data was also collected from newspaper and local reports for the historical events and used in qualitative benchmarking.

Table 3.3 Discharge data source summary.

Data source	Stations	Resolution	Duration
Hydrological Bureau of Guangdong Province (广东省水文局)	Makou, Sanshui	Hourly discharge	7th-10th June, 2018
Pearl River Hydrological Bureau of Water Resources Committee of Pearl River, Ministry of Water Resources (水利部珠江水利委员会水文局)	Makou, Sanshui	Daily discharge (at 8 am)	July 2017, June 2018
Pearl River Navigation Administration, Ministry of Transport (交通运输部珠江航务管理局)	Makou, Sanshui, Tianhe	Daily discharge and water level (at 8 am)	Jun-Aug 2014 -2017, June 2018

3.1.3 Digital Elevation Model (DEM)

A good Digital Elevation Model (DEM) provides the foundation for any physically-based flood model. It describes the topographic variation which is processed via GIS tools to generate watersheds and water flow direction for a hydrological model such as HEC-HMS. With advances in remote sensing and photogrammetry, a DEM can be produced from stereo optical satellite images, LIDAR data and radar data (Makineci and Karabörk 2016). Nowadays global DEMs are publicly available from several official data centers. Two popular DEM are the Shuttle Radar Topography

Mission (SRTM) DEM and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). Both can be downloaded from the US Geological Survey (USGS) EarthExplorer website¹⁵.

Researchers have studied the accuracy of DEMs, especially for the low-lying coastal regions which are often densely populated and sensitive to coastal flooding, storm surge and sea-level rise (Du et al. 2015). Vertical accuracies of SRTM and ASTER are examined and compared, based on the Ice, Cloud, and land Elevation Satellite, Geoscience Laser Altimeter System (ICESat/GLAS) and Global Positioning System (GPS) field survey data. Both the ICESat/GLAS and field survey data have higher vertical accuracy and lower error as compared to DEMs; therefore they have been used as a benchmark dataset (Carabajal 2011; Carabajal and Harding 2005). For PRD regions, the root mean square error from SRTM was reported to less than that of ASTER GDEM (Du et al. 2015). A similar comparison for the Philippines produced similar conclusions (Santillan and Makinano-Santillan 2016). In general, the more complex the terrain is, or the higher and steeper the area is, the lower the DEM accuracy. As the SRTM DEM is widely used and considered sufficient in accuracy and resolution, it was the DEM used in the MEng project. For the PRD region the SRTM horizontal resolution is at 1 arc-second, approximately 30 m. The vertical resolution is at one meter, representing the minimum difference between two elevation values.

The SRTM DEM was downloaded from the 1 arc-second global database as GeoTIFF (Georeferenced Tagged Image File Format), with void filled elevation data from latitude 22.0°N to 24.0°N and longitude 112.0°E to 114.0°E. The downloaded DEM mosaicked together is shown in Figure 3.2.

¹⁵ USGS EarthExplorer, EarthExplorer Home, <https://earthexplorer.usgs.gov/>, [accessed in Dec 2018].

Figure 3.2 The SRTM DEM downloaded from USGS showing ground elevation from 22°N to 24°N, 112°E to 116°E.

3.1.4 Horizontal and vertical datum

A datum describes the reference system used in surface elevation measurements. A horizontal datum refers to the location or position on the Earth, while vertical datum is used for elevation measurements such as for terrain, water level, etc.

The horizontal datum of the SRTM DEM is EPSG: 4326, latitude and longitude coordinates of World Geodetic System WGS84, which is widely used in satellite navigation including the GPS. EPSG:4326 is one type of Geographic Coordinate System (GCS) based on an ellipsoidal Earth surface model. For geospatial calculation, it is projected to 1980 Grid System (HK 1980 Grid, EPSG:2326), a Projected Coordinate System (PCS), through the Transverse Mercator projection

via a built-in function in the ArcGIS. Note that when converting the projection, vertical elevation data is unaffected.

Vertical datum refers to the zero-surface elevation which varies by region. The SRTM DEM elevation is known as orthometric height, based on vertical datum EGM96 (Earth Gravitational Model 1996), which is a geoid commonly used in satellite observations, a geoid is an irregular imaginary Earth surface based on gravitational equilibrium calculation. As it cannot be directly observed or measured, it is usually approximated by MSL, especially for coastal regions where the difference is less as compared to more inland areas. MSL is generally defined as the arithmetic mean of hourly sea level over a certain period of time, which reflects the gravitational equilibrium through water. As the MSL is an orthometric vertical datum, different from the GPS datum of theoretic ellipsoid surface model, the two readings can vary depending on location.

The water level data from the PRD governmental sources is based on a separate datum, PRD Datum, with transformation shown in Figure 3.3 as based on the Explanatory Notes on Geodetic Datums in Hong Kong report (Environmental Protection Department 2008; Hong Kong Survey and Mapping Office, Land Department 1995). The Hong Kong Principle Datum (HKPD) is widely used as the Hong Kong land height reference and WSG 84 Datum refers to the ellipsoidal height used in GPS. As the EGM96 is essentially equivalent to the MSL of Hong Kong, the elevation based on EGM96 is 0.236 m higher than the elevation based on Pearl River Datum. Lastly the vertical resolution of the SRTM DEM is at 1 m, it is therefore within accuracy bounds to treat PRD datum as that of the SRTM DEM elevation.

Figure 3.3 Relative vertical reference level for different datum system.

3.2 Watershed delineation

Watershed, or drainage basin, is a natural segregation of land based on physical laws, where all the water within the watershed is channelled to a single point, known as outlet. A DEM containing detailed topographical information, is one of the best ways for delineating watersheds. Here the SRTM DEM data has been processed in ArcMap software for watershed delineation as described below.

In the delineation, the waterbody (river channel, lake, sea, etc.) has elevation of zero and the land area in the PRD regions has low elevation, even less than 1 m. This together with the complex crisscrossing river network makes it challenging to determine the river flow direction and accumulation based on the standard tools in ArcMap. Hence, the major river corridors were burned into the DEM, producing a hydro-corrected DEM for ArcMap to calculate river flow more readily.

The following steps in the ArcHydro toolbox were used to delineate the watershed.

1. Get flow direction, which gives the direction of water for each cell.
2. Calculate Flow accumulation, i.e. aggregate the total flow value for each cell.
3. Define watershed outlet for each subbasin.
4. Use the “Watershed” function to delineate watershed.

The delineated watershed is shown in Figure 3.4. The watershed area is dominated by Foshan, Zhongshan and Zhuhai, with some areas in Jiangmen, Guangzhou and Zhaoqing. As shown in Figure 3.4, 64% of the watershed area is at 5 m or below.

Figure 3.4 Delineated watershed with 28 subbasins (in black lines), overlay with administration boundary and the DEM elevation.

3.3 HEC-HMS model

The HEC-HMS or HMS, as developed by the US Army Corps of Engineers Hydrologic Engineering Center¹⁶, is a widely used open-source model to solve a range of rainfall-runoff problems. The HMS model can reflect the real-world situation with physical based model and parameters, while also allowing for lumped or averaged parameters to represent spatially variable features. Thus, it is possible to build each component at grid-level resolution; hence it can be regarded as semi-distributed model.

HMS version 4.2.1 was used for this project. The following sections describe the procedure for setting up the model with two main components, i.e. basin model and meteorological model, together with the necessary parameters and output.

3.3.1 Basin model

The Basin model converts the physical river and watershed into a relatively simplified dendritic hydrological network, consisting of physically meaningful components of subbasin, river reach, outlet, junction, diversion, source, sink, etc. Each of these components is then defined by a set of characteristics and parameters. Geographic properties such as river length, land slope and area are calculated from the ArcGIS with respective tools.

Subbasin

For each subbasin, the Soil Conservation Service (SCS) curve number method was used in the loss model to calculate infiltration which is then subtracted from precipitation before simulating the surface runoff, i.e. in the quantity of excessive precipitation that can be effectively converted into

¹⁶ US Army Corps of Engineers Hydrologic Engineering Center, <https://www.hec.usace.army.mil/>, [accessed in Dec 2018].

runoff. CN number 98 was used for impervious land (Plan 1) and 60 for pervious land (Plan 2) as based on CN tables from the HMS technical manual. Recession method is assumed where the flow decreases exponentially after the rainfall event and used to represent the baseflow. The study area as modeled in the HMS consisted of 28 subbasin, with a total drainage area of 6,682 km². This represents 1.6% of the total Pearl River Basin drainage area, or 12% of PRD area. Table 3.4 presents the list of key parameters for the 28 subbasin model set up as shown in Figure 3.5.

Table 3.4 Subbasin model parameter summary.

WS_ID	Area (km ²)	Plan1 - impervious			Plan 2 - pervious			Channel			
		slope (M/M)	Roughness	Area (%)	slope (M/M)	Roughness	Area (%)	River name	slope (M/M)	Manning's n	Bottom Width (m)
1	1,303	0.1348	0.15	5	0.1348	0.1	95	West River	0.0004500	0.023	1,370
2	163	0.0477	0.15	13	0.0477	0.1	87	North River	0.0000534	0.023	470
3	119	0.0845	0.15	11	0.0845	0.1	89	West River	0.0004500	0.023	1,370
4	582	0.0837	0.15	12	0.0837	0.1	88	West River	0.0004500	0.023	1,380
5	36	0.0285	0.15	8	0.0285	0.1	92	West River	0.0004500	0.023	550
6	430	0.0450	0.15	17	0.0450	0.1	83	West River	0.0004500	0.023	200
7	286	0.1125	0.15	9	0.1125	0.1	91	West River	0.0004500	0.023	750
8	196	0.0187	0.15	7	0.0187	0.1	93	West River	0.0004500	0.023	1,200
9	125	0.0386	0.15	13	0.0386	0.1	87	West River	0.0004500	0.023	300
10	34	0.0293	0.15	9	0.0293	0.1	91	West River	0.0004500	0.023	650
11	355	0.0412	0.15	17	0.0412	0.1	83	North River	0.0000534	0.023	480
12	136	0.0513	0.15	36	0.0513	0.1	64	North River	0.0000534	0.023	280
13	186	0.0497	0.15	8	0.0497	0.1	92	North River	0.0000534	0.023	330
14	97	0.0371	0.15	20	0.0371	0.1	80	North River	0.0000534	0.023	300
15	330	0.0420	0.15	22	0.0420	0.1	78	North River	0.0000534	0.023	650
16	109	0.0415	0.15	22	0.0415	0.1	78	North River	0.0000534	0.023	150
17	85	0.0253	0.15	10	0.0253	0.1	90	West River	0.0004500	0.023	600
18	172	0.0287	0.15	9	0.0287	0.1	91	North River	0.0000534	0.023	500
19	52	0.0258	0.15	6	0.0258	0.1	94	West River	0.0004500	0.023	1,000
20	86	0.0335	0.15	28	0.0335	0.1	72	West River	0.0004500	0.023	250
21	77	0.0282	0.15	15	0.0282	0.1	85	West River	0.0004500	0.023	360
22	291	0.0358	0.15	7	0.0358	0.1	93	West River	0.0004500	0.023	1,380
23	312	0.1113	0.15	17	0.1113	0.1	83	West River	0.0004500	0.023	740
24	329	0.1464	0.15	5	0.1464	0.1	95	West River	0.0004500	0.023	1,490
25	414	0.0873	0.15	10	0.0873	0.1	90	West River	0.0004500	0.023	360
26	87	0.0582	0.15	8	0.0582	0.1	92	West River	0.0004500	0.023	540
27	166	0.0435	0.15	63	0.0435	0.1	38	North River	0.0000534	0.023	260
28	124	0.0569	0.15	23	0.0569	0.1	77	North River	0.0000534	0.023	490

Figure 3.5 Watershed delineation for the study area.

The more numerically stable kinematic wave as compared to dynamic wave was used as the flow model. It is a conceptual model, reflecting the physical property of basin and the response to precipitation events. This is typically suitable for urban area or undeveloped open channel with regards to gradually varied unsteady flow. Its main parameters are set as in the subbasin model. Even though this model simplifies the surface runoff mechanism with limited parameters and reduced-dimension of watershed representation, its performance is robust and credible.

The kinematic wave model contains three parts: overland flow, channel flow and collector channel flow. For overland flow, it is usually split into pervious (e.g. vegetation, fields, parks) and impervious (e.g. paved surface, parking lots, built-up area). The percentage of impervious land cover is calculated based on the artificial surface type in the Global Land Cover-SHARE (GLC-SHARE)¹⁷ database, provided by the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO). There are 11 land cover types identified in the GLC-SHARE project. Except for artificial surfaces type, the rest are considered as pervious, hence the percentage of artificial land cover area to the total area was assumed to be equivalent to the impervious percentage. The artificial land percentage for each 30 arc-second grid (approximately 1 km by 1 km) is shown in Figure 3.6. The majority of the watershed region has impervious land cover at less than 50%. Although encompassing high population and urbanization area, this artificial land percentage per subbasin is not particularly high. The red zone between subbasin Zones 12 and 27 is the Chancheng district of Foshan city. Without subbasin 27 which is part of Guangzhou city having artificial land cover > 60%, the average impervious percentage is 14% for the study basin. The study area is not majority urban area, covered as artificial land, but it contains large area of suburban or rural area, like farmlands and forests.

¹⁷ Global Land Cover - SHARE, FAO, <http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1036355/>, [accessed in Dec 2018].

Figure 3.6 GLC-SHARE artificial surface in percentage form of the study area.

Reach

Reach represents river streams and branches, and it is defined to have at least one inflow and only one outflow. It is used in the routing methodology, i.e. simulates the propagation or attenuation of river flow within the individual reach segments. For flat or small slope reaches, the Muskingum-Cunge Routing method is suitable. It is a time-dependent variable coefficient method, i.e. the routing parameters get recalculated from continuity equation after each time and distance step at the various channel properties and flow depths. The method uses conservation of mass and the diffusion form of the momentum conservation. As such it cannot account for backwater effects or downstream impact to the upstream.

River cross-sections are assumed to be trapezoidal, as commonly used for unknown river bed situations. Two key parameters are Manning's n and river slope. From the literature review for the PRD region, the average Manning's n is generally recommended as 0.023, with several ranges from 0.014 – 0.03 (Long and Li 2007), or 0.02 (Wang et al. 1992), or 0.015 to 0.03 (Wei et al. 2012). The average slope of the West River is 0.045%, and the North River as 0.0053% as extracted from government information (Guangdong Province Database). Furthermore, there is no specific reported information on river slopes at the subbasin level, thus it is assumed to follow the general slope of the respective river. In total, there are 31 reach components of which 12 are from the North River and 19 from the West River.

Source, Junction and Diversion

Source defines the upstream flow, which can be considered as the flow origin for that subbasin. Junction and diversions are representations of the subbasin outlet. The difference is that downstream of a junction is linked to only one reach, while a diversion can link to two reaches with a split ratio to be defined. The split ratio then forms one of key factors for model calibration. The split ratio for 2 of 11 diversions in the PRD HMS model is based on Liu (2015), and the rest based on the observations of the width ratio between the diverted reaches from the Google Maps. The boundary outlets were represented by junctions but with no downstream component specified. Figure 3.7 shows the HMS basin model with the study basin as background image.

Figure 3.7 HEC-HMS Basin model set up output.

Using the HMS model and input rainfall, historical events could be simulated with predicted flows compared with historically available water level data. From this, rating curves (i.e. stage-discharge relationship curve) for several key stations are generated, which allows the estimations of water level and subsequently potential inundation.

3.3.2 Meteorological model

The precipitation for each watershed is based on an area-dependent weighted average value using the Thiessen polygon (also known as Voronoi polygon) method. This method is particularly suitable as the

rainfall gage stations are unevenly distributed spatially. Through proximity and neighborhood analysis, a Thiessen polygon is constructed for each gage station, and collectively they encompass the entire basin area. The gage weight is calculated as based on the percentage of the rain gage Thiessen polygon falling into the targeted subbasin area. As mentioned, there are 25 rain gage stations used. The 25 Thiessen polygons overlaid with 28 subbasins in the study basin are shown in Figure 3.8.

The HMS model after construction is run for the rainfall-runoff simulation and to generate runoff data for each component including subbasins, reaches, junctions, diversions. These are then used in the inundation calculation described next.

Figure 3.8 Thiessen polygon separation on study basin with 25 rainfall gage stations.

3.4 Inundation methodology

Inundation is not directly calculated from the physically distributed model such as the HMS. Hence the potential inundation extent and the flood depth was estimated based on the river warning level, the DEM elevation and a side-weir overflow equation, along with appropriate assumptions. This was

deemed appropriate as there is no publicly available river geometry data such as river bed dimension nor high-resolution floodplain elevation map needed for a regional flood extent calculation.

The warning level as published for key river stations is assumed to be that at the bankfull level. Through further derived rating curves (i.e. stage or water level to discharge curves), the river bankfull discharge are then calculated using the warning level. Flow level above this warning level as representing the overbank flow is then used in inundation calculation as described below.

3.4.1 Inundation length estimation

The overbank flow situation is modeled as a side weir open-channel overflow, with the embankment crest parallel to the open-channel flow direction. When the water level exceeds the bankfull or warning level, it drains through the side weir so that the downstream of the weir remains below a maximum permissible level.

Referring to Figure 3.9, where the discharge $Q(x)$ with side weir overflow starting is denoted as Q_1 , and ending as Q_2 . The discharge $Q(x)$ then decreases along the stream direction x . $Q(x)$ is described using eq. (3.1) (Delkash and Bakhshayesh 2014),

$$\frac{dQ}{dx} = -\frac{4}{3}C_m\sqrt{2g}(y-w)^{1.5} \quad (3.1)$$

where dx is the incremental distance along the weir, C_m is the known weir discharge coefficient, g is gravitational acceleration, y is the depth of water, and w is the given height of side weir (i.e. the warning level in this study). For the double-side weir situation in this application, the coefficient used in eq. (3.1) has been doubled to a value of $4/3$. The negative sign represents the physical meaning of decreasing Q with incremental of dx .

Figure 3.9 Side-weir inundation schema plot.

Based on a derived rating curve, the discharge $Q(x)$ varies with water level $y(x)$ as eq. (3.2), where C_1 and C_2 are known constants from the rating curve.

$$Q(x) = C_1 y(x) + C_2 \quad (3.2)$$

Eq. (3.2) can be converted into the following eq. (3.3).

$$y(x) = \frac{Q(x)}{C_1} - \frac{C_2}{C_1} \quad (3.3)$$

Using eq. (3.3), eq. (3.1) can be rewritten as eq. (3.4) below, where the derivative function becomes a function of Q only.

$$\frac{dQ}{dx} = m_1(m_2 Q + m_3)^{1.5}, m_1 = -\frac{4}{3} C_m \sqrt{2g}, m_2 = \frac{1}{C_1}, m_3 = -\frac{C_2}{C_1} - w \quad (3.4)$$

Solving this ordinary differential equation, Q can be expressed as a function of x , as in eq. (3.5). With boundary and special cases, L , the length between Q_1 and Q_2 , i.e. the length of the side weir, or the length between the start and end of the inundation can be calculated.

$$Q(x) = \frac{9C_1^3}{8C_m^2 g(x+C_0)^2} + C_2 + C_1 w, \text{ where } C_0 = \sqrt{\frac{9C_1^3}{8C_m^2 g[Q_1 - (C_1 w + C_2)]}} \quad (3.5)$$

At $x = 0$, the discharge represents that at the starting point of side-weir inundation, i.e. Q_1 . This allows C_0 to be solved as shown in eq. (3.5) in terms of Q_1 . As w is the warning level, and regarded as the bankfull height, the bankfull discharge $Q_{BF} = C_1 w + C_2$. Eq. (3.5) can be inverted such that for a given value of $Q(x)$, x can be solved as eq. (3.6).

$$x = \sqrt{\frac{9C_1^3}{8C_m^2 g(Q - Q_{BF})}} - \sqrt{\frac{9C_1^3}{8C_m^2 g(Q_1 - Q_{BF})}} \quad (3.6)$$

Substituting Q in eq. (3.6) with Q_2 the end point of inundation (Figure 3.9), the length of inundation, L can be calculated by eq. (3.7). An observation is that Q_2 should be greater than Q_{BF} , otherwise there is no valid solution for L .

$$L = \sqrt{\frac{9C_1^3}{8C_m^2 g(Q_2 - Q_{BF})}} - \sqrt{\frac{9C_1^3}{8C_m^2 g(Q_1 - Q_{BF})}} \quad (3.7)$$

To have a consistent boundary condition for the end-point discharge Q_2 , two methods are assessed. The first is to assume Q_2 as a fixed percentage of Q_{BF} , i.e. $Q_2 = q \times Q_{BF}$, where $q < 100\%$. Upon substituting Q_2 with this relationship with Q_{BF} , L then becomes positively correlated with Q_1 , the initial discharge, which means higher initial Q_1 gives larger L .

The second method assumes that Q_2 also depends on the initial Q_1 , as $Q_2 = Q_1 - p \times (Q_1 - Q_{BF})$, where p represents a percentage, close to but not exceeding one. With this dependency, L becomes negatively correlated with Q_1 , i.e. higher Q_1 gives the shorter L .

In actual calculation, Q_1 is defined as the HMS simulated discharge when the value is greater than bankfull discharge and thus having overflow. For each hour when overflow occurs, the Q_2 value varies as based on different Q_1 , and as well as L . A set of Q_2 and L is thus calculated for each hour when overflow occurs. An averaged value is taken as the final choice of L , based on the different hours and the two methods. The value for p is selected as 90% and q as 1% based on trial and error so that both methods derive similar L values. The side weir discharge coefficient, C_m , depends on the geometry of the weir, curvature of reaches, and surface condition, of the weir (Caroline and R Afshar 2014). It can be calculated in various methods as presented in Delkash and Bakhshayesh (2014). The formula used in this study is $0.24 + 0.54 \times WL/y_1$, where y_1 is the water level corresponding to Q_1 (Singh et al. 1994),

so that it can be calculated as a function of discharge and water level, given the limited information of side weir geometry.

The side weir calculation developed above allows the determination of the length of bank where the discharge exceeds the warning level and where overflow with subsequent inundation is likely to occur. The next step is to model the inundation into the floodplain.

3.4.2 Flood extent estimation

We assumed that when the HMS simulated discharge exceeds the warning level, there is a potential for flooding. The overflow volume, V , is calculated as per eq. (3.8),

$$V = \sum_i [(Q_{i, sim} - Q_{BF}) * \Delta t], \Delta t = 1 \text{ hour} \quad (3.8)$$

where $Q_{i, sim}$ represent the HMS simulated discharge for the i^{th} hour during which it is higher than bankfull or warning level. It is further assumed the water flows over the bank to the nearest and lowest elevation areas, and that a circular inundation shape with the center at stage station results, defined as a Potential Inundation Circle (PIC) in this study. Based on the conservation of flood volume, the flooded area and flood depth within the PIC can be calculated using the GIS tools. The radius of the PIC has an initial value as the side-weir length, L as calculated in Section 3.4.1, and is then gradually increased until the flood depth at the periphery of the PIC is less than 0.3 m. Note that in this analysis, the PIC flood extent is determined by ground elevation values within the PIC.

Figure 3.10 shows a schematic for calculating maximum flood depth, d , starting from the lowest ground elevation. Each area A_i represents the collective area within the PIC with an elevation of i . As the DEM vertical resolution is 1 m, i represents integers starting from zero, with all height or depth expressed in meters. The flood depth at any location within the PIC depends on its own elevation level, i.e. when the location DEM (ground elevation) is zero, the total area is denoted as A_0 , and the flood depth for A_0 is d ; when the location DEM is n , the area is represented by A_n , where the flood depth equals to $d-n$.

Figure 3.10 Flood depth calculation schema diagram.

As the green shaded area in Figure 3.10 symbolizes inundation zone, the total flooded volume can be calculated as eq. (3.9). The constraint for this equation is the choice of n , where A_n corresponds to the highest ground elevation with flooding at flood depth of $d-n$ meter (d is the maximum flood depth as corresponding to the lowest ground). It is noted that the elevation values from the DEM are integers, while d is a floating point number. The constraint condition can be expressed as $n < d \leq n+1$, hence there would never be flooding for A_{n+1} .

$$V = A_0(d) + A_1(d - 1) + \dots + A_{n-1}(d - n + 1) + A_n(d - n) \quad (3.9)$$

When only locations with DEM value of zero ($n = 0$) is flooded, the maximum depth d is V/A_0 . Similarly, when the flood only impacted locations less than 2 m, i.e. at 1 m elevation or lower, the above equation can be written as $V = A_0(d) + A_1(d - 1)$. Hence, the maximum flood depth d can be solved as $(V+V_1)/(A_0+A_1)$ where V_1 in the numerator is A_1 multiplied by depth of 1 m. In general, if the highest ground gets inundated has elevation of n , then the maximum flood depth d at zero elevation is calculated via eq. (3.10), where V/A representing the average depth.

$$d = \frac{V + \sum_{i=0}^n iA_i}{\sum_{i=0}^n A_i} = \frac{V}{A} + \frac{\sum_{i=0}^n iA_i}{A} \quad (3.10)$$

The boundary condition at the periphery of flooding is set as flood depth to be less than 0.3 m, hence the desired PIC should satisfy that its periphery is not flooded with more than 0.3 m depth.

Chapter 4 Result & discussion

4.1 Historical case studies

Two major historical events were selected as case studies, with both resulted in flooding to the basin within the study area. The first event happened in July 2017, which was the first numbered flood event for the West River during that year¹⁸. As the control station of the West River, Gaoyao station, located upstream of the study area recorded 9.95 m maximum water level (warning level is at 10 m), with a peak flow of 43,500 m³/s, close to a 20-year return period. There was enormous incoming river flow to the downstream area, which increased water levels, and affected the PRD region. The second event was a heavy rainfall event in June 2018, largely influenced by Typhoon Ewiniar, bringing strong precipitation to the study area. The upstream water level was below warning level at the time of heavy downpours. The 2017 event then represents a high upstream inflow but low precipitation scenario, while the 2018 event represents a low inflow but high local precipitation scenario. The following sections presents the calibration and validation of the HMS model for simulating the rainfall and runoff situation for the two case studies.

4.1.1 2017 Event

- Event description

The 2017 event was triggered by long-lasting heavy precipitation associated with subtropical high pressure system in the middle reaches of the West River in the Pearl River Basin. This had led to continuously increased water level recorded between 28th and 30th, June 2017. On 2nd July, the water level had reached the warning level (18.5 m) of Wuzhou Station in Guangxi Province, one of the

¹⁸ Flood numbering: when the hydrological control station Wuxuan exceeds its warning water level (55.7 m) or Wuzhou exceeds its warning water level (18.5 m), the flood event will be numbered, according to the Hydrological Bureau, Ministry of Water Resources.

key water level stage stations of the West River further upstream of the PRD region. Hence according to official flood control guideline, this event was officially declared as a flood event, which was the first event for 2017. Wuzhou reached the peak flow on 4th July, i.e. 4.6 m higher than the warning level, which was close to a 10-year return period. The immediate next downstream station is Jiangkou Station in Zhaoqing city, which reached its peak flow at a 20-year return period level, i.e. 4.4 m above warning level (17.0 m) during the same day. The peak flow water level also exceeded warning level 2.94 m for Ducheng Station and 2.15 m for Deqing Station, along the West River flow direction.

A few days later, the North River was also affected by heavy precipitation, and one of its key control stations, Shijiao, located upstream of the delta region, recorded a peak water level of 8.34 m, with a discharge of 10,200 m³/s on 4th July. This did not exceed its warning level of 11 m. Moreover, its downstream station, Sanshui (see Figure 3.1) also recorded a high water level, exceeding 10-year return period on the same day.

Moving more downstream into the delta area, Sanshanjiao Station (Figure 3.1) on the Shunde waterway (part of the North River) had its peak flow with level of 2.46 m exceeding warning level (1.8 m) on 5th July, resulting in severe flooding locally. On the same day, Yinggezui station on Xiaolan waterway (part of the West River) had a peak water level of 3.89 m, only slightly below the warning level of 4.0 m. The water level gradually ceased rising after 5th July.

- HMS output

The developed HMS model was used to simulate this event from 00:00 2nd July to 23:59 8th July, a total of 168 hours with a time step of 1 hour. The input precipitation is summarized in Figure 4.1, which shows daily accumulated rainfall as averaged over the 25 input gages. It is obvious that the rainfall was concentrated in the first 3 days when most water levels started to rise and reached their peaks. The second day (3rd July) experienced the most accumulated average rainfall of 60 mm, with most rain gages recording between 50 mm to 100 mm. The duration of strong precipitation lasted for 2 days.

Figure 4.1 2017 event daily rainfall as averaged over 25 gage stations.

The discharge at two source stations, Makou and Sanshui (Figure 3.1), is presented in Figure 4.2, together with hourly rainfall intensity at Makou and Sanshui stations. Both source flows at Makou and Sanshui were largely influenced by the received heavy precipitation and accumulated inflow from upstream. There are two sets of discharge information presented. The scattered points (circles) denoted as Obs. Q value was the daily 8am observation or from government flooding alert reports. The other discharge denoted as Cal. Q (line) is calculated based on statistical analysis on the historical discharge and water level data at these two stations (see section 4.2 for details). If an hourly water level data is missing, it was calculated as the average of its immediate before and after water level.

The Cal. Q is about 5-10% higher than the Obs. Q for both Makou and Sanshui stations. For Makou station, the peak of Cal. Q is 40,238 m³/s based on peak water level of 6.74 m (warning level is at 7.5 m) on 4pm 4th July (or 64th hour into the simulation), while the highest reported discharge is

38,200 m³/s at the same hour. Both are higher than the 10-year return period flow rate of 34,600 m³/s at Makou.

Both observed and calculated discharge reached their peak on 4th July. Thereafter as there was no continuation of heavy rainfall, the peak subsided with water level receding, but at a much smaller rate. It is noted that while Makou and Sanshui are located at two different streams, they are in close proximity (less than 1 km apart) and connected by a single reach. They also have the same warning level of 7.5 m. However, Makou flow rates are much higher than Sanshui (see Figure 4.2) as Makou is part of the West River which has a much larger flow than the North river.

Figure 4.2 2017 event HMS source flow, water level and precipitation time series.

The discharge output from the HMS model for the entire simulation duration at six selected PRD stations is presented in Figure 4.3. The selection of these stations is based on water level data availability and that these stations have relatively limited tidal effect. These stations are Ganzhu, Nanhua and Xiaolan on the West River, and Zidong, Sanduo, and Lanshi on the North River, as shown in Figure 4.4. All are in the middle to upper range in the basin. As their discharge or water level movements are largely influenced by the upstream source flow, their patterns and time to peak are similar to those of Makou and Sanshui.

The HMS simulated discharge result shows similar pattern as source flows, and reached their peak on the third day, one day after the peak in the input precipitation pattern.

Figure 4.3 2017 event HMS simulated discharge and observed water level.

Figure 4.4 HMS key output discharge stations.

Table 4.1 lists the peak flow from the HMS simulation, the time to the peak, and corresponding maximum observed water level. The peak flow happened at 62nd hour for Sanshui, 64th hour for Makou as based on their observed maximum water level. The six key stations reached their peak flows at around 63 to 67 hours into the simulation. The earliest is Lanshi on the North River at the 60th hour, followed by Sanduo and Zidong at 63th hour on the West River. The time to peak at the North River stations is generally earlier than that of the West River. This is because the peak flow time for Makou (West River) was 2 hours behind Sanshui (North River) and the distance between Makou and key stations of the West River (i.e. Ganzhu, Nanhua, Xiaolan) is longer than that between Sanshui to its downstream stations.

Table 4.1 2017 event peak flow summary.

River	Stage Station	Time to max. WL (hr)	Max. water level (m)	Warning level (m)	Time to peak HMS sim. Q (hr)	Peak HMS sim. Q (m ³ /s)
West River	Makou	64	6.74	7.50	NA	NA
	Ganzhu	63	4.69	4.80	67	40,464
	Nanhua	63	4.26	4.50	67	23,874
	Xiaolan	61	3.58	3.80	67	23,873
North River	Sanshui	62	6.74	7.50	NA	NA
	Zidong	63	5.06	5.30	63	12,626
	Sanduo	61	4.85	4.90	63	9,223
	Lanshi	60	3.97	4.00	64	3,403

*Water level (WL) is from actual observation record.

*Sim. Q is referring to the simulated discharge from the HMS model.

- Inundation

Even though none of the gage stations exceeded the warning level, some were very close to the warning level (e.g. Sanduo and Lanshi), and for which inundation was reported during this event. The estimated flood depth based on reported on-site interviews was around 0.3 m for the area around Lanshi station (Foshan Chancheng district), 1 m around Sanshui station (Foshan Sanshui district), and up to 2 m in some farmlands near Xiaolan station (Zhongshan city) (Lin 2017; Wu 2017). As Xiaolan has the highest reported flood depth, this area was selected for inundation estimation. Figure 4.5 shows the reported inundation areas which were mainly around the Xiaolan and Jiya waterways.

Figure 4.5 2017 event reported flooded area.

As the simulated output did not exceed the warning level (3.8 m) at Xiaolan, the overflow is defined as water discharge exceeding level 3.4 m, slightly below the warning level. A summary of the Xiaolan reported flood area, calculated inundation extents, DEM elevation, and built-up region is collectively shown in Figure 4.6. The total overflow volume, V , is 12.7 million m^3 , occurring over 18 consecutive hours from the 65th hour to the 82nd hour. To satisfy the boundary condition of inundation being less than 0.3 m as defined in Methodology Section 3.4.2, the outer circle representing this event's maximum inundation extent has a radius of 7 km.

The NYU Urban Expansion Program has developed an urban expansion atlas for over 200 cities¹⁹, separated into urban, sub-urban, or rural categories. The dataset for current study area at year 2014 is used and the urban built-up area is measured at 81 km² by GIS, which accounts for 53% of the calculated PIC as shown in Figure 4.6(d). The calculated flood depth within the PIC is 0.3 m as based on the methodology of Section 3.4, which is consistent with observation. The total inundation area is at 47,303 m² with the DEM ground elevation being zero.

In terms of GDP impact for the 2017 event, GDP data from the 2018 Guangdong Statistical Yearbook is used. The 2017 event PIC lies in Zhongshan and Shunde (in Foshan city) cities where the former contributes to 70% of the total GDP at risk and latter 30%, altogether a total of CNY 1.56 billion GDP at risk. This is based on a county-level GDP density of CNY 365 million/km² for Shunde and CNY 192.2 million/km² for Zhongshan (Table 4.2). The data source of county-level GDP and area is from the 2018 yearbook of the corresponding city.

Table 4.2 County-level GDP in 2017 for subjective county used in GDP at risk calculation.

County	Name in Chinese	City	County GDP (million CNY)	County Area (km ²)	County Areal GDP (million CNY/km ²)
Chancheng	禅城	Foshan	172,250	99	1,749
Shunde	顺德区	Foshan	301,591	826	365
Nanhai	南海区	Foshan	266,789	1,149	232
Panyu	番禺区	Guangzhou	197,224	938	210
Zhongshan	中山市	Zhongshan	343,031	1,784	192
Sanshui	三水区	Foshan	115,091	901	128
Gaoming	高明区	Foshan	84,131	945	89
Xinhui	新会区	Jiangmen	59,762	1,671	36
Heshan	鹤山市	Jiangmen	31,895	1,082	29

Note: In general, county-level is the next higher resolution admin level from city (admin 2 level in China GIS file). However, for a few cities such as Guangzhou, Foshan, Jiangmen, the admin level after city is also termed as “district” or “区”, rather than “county”. Both county and district terminologies are used interchangeably.

¹⁹ Atlas of Urban Expansion, <http://www.atlasofurbanexpansion.org/about>, [accessed in Dec 2018].

Figure 4.6 2017 event inundation around Xiaolan station. (a) The location of inundated area is between the city of Shunde and Zhongshan. (b) The blue shaded area represents the inundated area within PIC. (c) The SRTM DEM ground elevation of the area of interest, where dark green represents equal to or below zero, and the light green between 1 m to 5 m. (d) Urban Extent at 2014 with urban built-up, suburban, and rural areas.

4.1.2 2018 Event

- Event description

The second event happened in June 2018 and is deemed as a strong torrential rainfall event, largely associated with the Tropical Storm Ewiniar. Ewiniar (2018) is considered as a weak typical cyclone in terms of wind speed and central pressure. However, it caused a huge impact on property and human life losses, in southern coastal area of China, resulting in long-lasting strong precipitation, landslides and flooding. Due to its wandering storm track causing enormous precipitation, it has made the first landfall (20m/s, 995hPa) in Xuwen, Guangdong, the second (18m/s, 995hPa) in Haikou, Hainan and the final one (20m/s, 995hPa) in Yangjiang, Guangdong, from 5th to 7th June (China Meteorological Administration 2018). Moreover, Ewiniar happened during the Southwest monsoon which implied larger precipitations. There was no reported riverine flooding as the main observation stations on both the West River and the North River were below their respective warning levels. However, flooding occurred in quite a few places, including but not limited to Guangzhou (e.g. Baiyun International Airport), Shenzhen, Yunfu, Zhaoqing (Gaoyao) cities as reported by the local media (Guangdong Three Defense 2018; Guangzhou ribao [Guangzhou Daily] 2018). Jiangmen and Zhongshan, in particular, have reported flood depths as high as 0.5 m in some areas. This is typically known as flash flooding, which develops quickly during intense rainfall and affects low lying lands in urban area where the drainage capacity can be exceeded during heavy downpours.

- HMS results

The 2018 event was simulated using the HMS model from 00:00 4th June to 23:59 10th June 2018, i.e. 168 hours in total. The key feature of this event was the huge amount of precipitation. Particularly on 8th June, 24 out of 25 rainfall gage stations reported daily precipitation exceeding 50 mm, with 21 exceeded 100 mm. The largest recorded precipitation occurred at Zidong with 265 mm accumulated daily precipitation. The average daily rainfall across the 25 rainfall gages between 4-10 June is shown in Figure 4.7. Comparing with the 2017 event (Figure 4.1), the maximum daily

average happened on 8th June 2018 is 2.6 times the maximum daily average for the 2017 event which occurred on 3rd July 2017.

Figure 4.7 2018 event daily rainfall as averaged over 25 gage stations.

Since 8th June 2018 and 3rd July 2017 represented the maximum rainfall intensity for two case study events, these two daily rainfall patterns via isohyets calculated using the 25 gage stations are plotted in Figure 4.8. The isohyets were calculated based on Inverse Distance Weight (IDW) method. During the 2018 event, Zidong station experienced the highest rainfall (265 mm) on 8th June, when Ewinia track was nearest to the study area after its third landfall on Yangjiang city on 7th June 8pm, and resulted in downpour to study area. Figure 4.8 clearly shows the much higher rainfall pattern for the 2018 event. A detailed daily rainfall comparison is presented in Table 4.3.

Table 4.3 2017 and 2018 event maximum daily rainfall comparison.

RF Station ID	Station Name	City	Area* (km ²)	Max. daily rainfall (mm)	
				2017 Event (3 rd July)	2018 Event (8 th June)
1	Bai shui dai	Jiangmen	185	88	175
2	Ban sha wei	Foshan	268	54	124
3	Chang jiang shui ku	Zhongshan	467	54	150
4	Da ao	Jiangmen	253	94	116
5	Da shi	Guangzhou	135	69	89
6	Gan zhu	Foshan	210	63	216
7	Le zhu	Foshan	166	82	151
8	Ma kou	Zhaoqing	317	49	138
9	Nan hua	Foshan	166	80	251
10	Nan sha	Guangzhou	228	80	59
11	Ni jiao	Foshan	592	68	136
12	Ping sha	Zhuhai	530	54	120
13	Rong qi	Foshan	162	52	198
14	San sha kou	Guangzhou	245	35	41
15	San shan jiao	Guangzhou	173	46	175
16	San shui	Foshan	98	47	181
17	Sha ping	Jiangmen	363	54	177
18	Shi fu da yuan	Foshan	247	31	195
19	Tang xia	Jiangmen	231	96	213
20	Wan qin sha xi	Guangzhou	300	70	80
21	Xi qiao	Foshan	228	38	192
22	Xiao lan	Zhongshan	252	57	184
23	Zheng keng	Zhongshan	379	46	109
24	Zhu yin	Zhuhai	226	51	132
25	Zi dong	Foshan	261	34	265

* The area refers to the thiessen polygon area (see Figure 3.8).

Figure 4.8 Daily isohyet map based on the 25 rainfall gage station data for (a) 3rd July 2017 and (b) 8th June 2018.

The source flow for Makou and Sanshui were relatively low as compared to the 2017 event, far below the corresponding warning levels. This indicated that the upstream incoming flow was at low level during the 2018 event. The hourly discharge, water level and precipitation for both Makou and Sanshui are plotted in Figure 4.9. There were more observations available than the 2017 event (Figure 4.2), as the more recent 2018 data was relatively more complete as available from the public website source.

The maximum flow rate for Makou was below 19,000 m³/s, while it was above 24,000 m³/s during the 2017 event. Similarly, Sanshui peak flow rate in the 2018 event barely meets the recession flow seen in the 2017 event. The increasing limb of the flow is closely related to the intensified rainfall, and the largest slope of the increasing flow rate corresponds to the largest rainfall intensity, especially during the 5th day or from 96th to 108th hour.

As Sanshui experienced the relatively larger rainfall, its discharge increased more than 3 times, from a range of 1,200 m³/s to 2,600 m³/s in the first 4 days, to above 6,000 m³/s on Day 5 and reaching its peak on Day 6, and gradually coming down on Day 7. Makou discharge increased

around 3 times, to a maximum exceeding 18,000 m³/s. Thus, Makou is about three times higher than Sanshui in terms of peak flow.

Figure 4.9 2018 event HMS source flow, water level and precipitation time series.

The calculated discharge from the HMS model at the six main downstream stations is plotted in Figure 4.10. As there is more obvious influence from the periodic tidal waves, a 12-hour moving average is calculated for the observed water level and indicated via the dark brown dash lines, so that the small variations are removed from the water level changes for better comparison with the HMS results. As seen, the HMS calculated discharge varied in synchrony with the observed water level.

Figure 4.10 2018 event HMS simulated discharge and observed water level and with its 12-hour moving average. Green lines represent HMS simulated discharge for the 168hr duration, while orange circles are the observed water level.

4.2 Rating Curves and Benchmarking

As there is a lack of observed flow discharge data (with the exception of Makou and Sanshui stations), rating curves are developed for the downstream stations based on their HMS simulated discharge and corresponding observed water level. However, for stations significantly affected by periodic tidal effects, rating curves are not developed, as the HMS discharge did not consider tides and backwater. This was the case for Banshawei, Wudo and Lezhu stations. The six key station names, as shown in Figure 4.11 were more inland and their rating curves were generated.

In terms of flow rate, the peak discharge in the 2018 event was lower, reaching only the recession level of the 2017 event (see Figure 4.3 and Figure 4.10). Results from the two case study events were then used collectively to provide both high and low flow situations for rating curve development. As shown in Figure 4.11, linear regression was used to determine suitable rating curves with R^2 statistics providing confidence of the fit. The highly consistent rating curves seen across the six stations provide an indication on the goodness of the model performance.

Figure 4.11 Rating curve for 6 HMS key output stations.

It is noted that observed water level and discharge data were collected for Makou, Sanshui and Tianhe stations. As such their rating curves were directly derived from these reported data. As there was insufficient (i.e. hourly) observed discharge data for the two source stations at Makou and Sanshui to be used as input into the HMS model, these developed rating curves were used for calculating the source discharge. The discharge data available for Makou and Sanshui comprise a two- to three-year historical data (2014-2017 for Makou and 2015-2017 for Sanshui) of daily 8 am records during June to August,

i.e. the rainy season, and hourly data over the 2018 Event (7th to 10th of June, 2018) as shown in Table 4.4.

The rating curves developed based on the historical daily data should be a good fit for high flows, suitable for 2017 Event, while that developed from the hourly 2018 Event data good for low flows for 2018 Event. Piece-wise (low and high flow) rating curves were developed, as presented and summarized in Figure 4.12 and Table 4.4. The change from low to high flow condition is set based on the fits to occur at 3.5 m. It is readily seen there is significant variability in the observed data for the low flow condition.

The difference between Cal. Q (based on rating curves) and Obs. Q (from actual observation) is relatively larger in the 2018 Event due to large variability in the low flow discharge data used in developing the rating curves, and is also reflected in the lower R² value of the rating curve fit. While the average difference is small at 1%, it ranges from -35% to 60% for Makou and 42% to 88% for Sanshui for the worst outlier points (low flow points denoted as orange circles in Figure 4.12). In contrast, the maximum percentage difference is much less under high flow (for 2017 Event), at 5% for Makou and 3% for Sanshui. As this thesis considers flooding situation under high flow condition, the larger percentage difference at low flow is considered relatively unimportant.

Figure 4.12 Rating curves for Makou and Sanshui

Table 4.4 Makou and Sanshui Rating curve summary (data source, equation, goodness of fit R^2).
WL means water level in meter.

		Makou	Sanshui
Daily 8am data from 2014 to 2017	Data collection period	2014 – 2016: Jun 01 to Aug 31 2017: May 01 to Aug 31	2015 – 2016: Jun 01 to Aug 31 2017: May 01 to Aug 31
	Rating curve used in 2017 Event	$Q(m^3/s) = 4568.3 \times WL(m) + 5406.5$	$Q(m^3/s) = 1521.2 \times WL(m) + 1396$
	R^2	0.9856	0.9822
Hourly data from 2018 Event	Data collection period	2018 Jun 7 to 2018 Jun 10	2018 Jun 7 to 2018 Jun 10
	Rating curve used in 2018 Event	$Q(m^3/s) = 5485.5 \times WL(m) + 1754.2$	$Q(m^3/s) = 1905.6 \times WL(m) + 149.4$
	R^2	0.7569	0.9037

The rating curve for Tianhe is calculated based on observed daily (8am) discharge and water level data from 4th January 2015 to 29th June 2017. Since its rating curve showed a clear difference for high flow and low flow situations, a piece-wise linear rating curve was used as shown in Figure 4.13. The linear fitting curves were found for two ranges, one is for water level below 3 m and one for water level above. These two linear regression curves intersect at water level of 2.12 m, where the discharge is 5548 m³/s. Furthermore, there were a large amount of data with extremely low discharge (below 2500 m³/s), which is deemed as data noise and was removed from rating curve calculation. The R^2 for low flow condition (i.e. water level below 2.12 m) is low, mainly due to the variability of the daily flow especially for the low flow condition. However, the R^2 improves for the high flow condition. As the purpose of this thesis focus on the flood, i.e. high flow situation, the goodness of fit of 0.765 is generally accepted. A similar phenomenon is also observed in Makou and Sanshui rating curve where the low flow part has a lower R^2 in the linear regression. The full rating curve for Tianhe has the form shown in eq. (4.1).

$$Q(m^3/s) = \begin{cases} 1303.5 * WL(m) + 2790.1, WL(m) \leq 2.12m, R^2 = 0.396 \\ 2601.2 * WL(m) + 44.937, WL(m) > 2.12m, R^2 = 0.765 \end{cases} \quad (4.1)$$

Figure 4.13 Tianhe piece-wise rating curve.

Tianhe is located immediately downstream of Ganzhu station (see Figure 4.4), where the West River main stream splits into two streams. One is called Xihai waterway, which flows through Tianhe station and the other Donghai waterway which flows through Nanhua station. The initial split ratio used in the HMS was 54% to Tianhe and 46% to Nanhua based on Liu (2014, 2015). However, a comparison of the Tianhe HMS output flow with observations indicated that this split ratio resulted in an overestimation of flow at Tianhe station, especially for the 2017 event.

As there is no observed discharge data at Ganzhu station, and Makou is directly connected with Ganzhu in the HMS model with a single reach component, it is assumed that the flow at Makou is a good representation of Ganzhu flow. Hence the relationship between Ganzhu and Tianhe is approximated by the relationship between Makou and Tianhe. The historical daily (8am) discharge data over June to

September 2017 for Makou and Tianhe stations indicated that when Makou flow is above 14,000 m³/s, Tianhe flow is 38% of Makou on average, and when Makou flow is below 14,000 m³/s, Tianhe percentage is slightly higher at 43%. After testing using different split ratios between Tianhe and Nanhua, it was found that a split ratio of 54% to Tianhe when the flow from Makou $\leq$ 14,000 m³/s, and a split ratio 41% to Tianhe when Makou flow $>$ 14,000 m³/s best satisfies the observed flow situation. This is a reasonable adjustment as lesser flow is diverted to Tianhe during the higher Makou flows.

The observed discharge and water level at Tianhe station are shown in Figure 4.14 for both 2017 and 2018 events. As the 2017 event duration is from 2nd to 8th July 2017, i.e. 7 days, and the 2018 event duration from 4th to 10th June 2018, also 7 days, the data is plotted in the same time scale covering 168 hours. The first available Tianhe observed data for the 2017 event is at the 32nd hour, i.e. 3rd July 2017 8:00am. The first available 2018 event observed data is at the 8th hour, i.e. 4th June 2018 8:00am.

For the 2018 event on the fifth day (104th hour), the discharge data point was very low, while the water level was at a much higher level. This indicated a potential discrepancy in the observed discharge. Also as based on the measured precipitation, the discharge value should be higher. Hence the discharge at that specific hour was recalculated using the measured water level and the rating curves developed (eq. (4.1)). This is indicated as the shaded blue square in Figure 4.14.

Figure 4.14 Tianhe observed discharge and water level for two historical events. Horizontal axis is hour from start of the respective event.

Figure 4.15 shows the comparison between observed flow and the HMS simulated discharge at Tianhe station using the finalized split ratio. There is a clear clustering of points below 5,000 m³/s, which arise from the 2018 event, and a clustering above 10,000 m³/s from the 2017 event. The solid lines represent error bounds, ranging from $\pm 15\%$ to $\pm 25\%$. Furthermore, all points with the exception of one 2017 event point are within $\pm 25\%$ difference. Thus, the finalized split ratio was used in the HMS model for calculation.

It is noted that there is a lack of actual observed discharge data for the downstream area after Makou and Sanshui stations, which precluded a rigorous validation. As Tianhe was the only station with actual observed discharge during the two events in the downstream area, the limited benchmarking above (i.e. not a rigorous verification) is based on the limited observed discharge data at Tianhe station. Given the broad assumption made on the split ratio value at Ganzhu station, and the limited observed discharge data for only two flood events were available, this benchmarking is deemed to be sufficient for building a quick flood assessment over a large area based on publicly available data.

Figure 4.15 Comparison between HMS calculated and observed discharge for Tianhe discharge. The red circle indicates the corrected observed data point of the 2018 event. The horizontal axis is the observed discharge with the one 2018 event data point corrected (indicated by the red circle).

4.3 Synthetic events

The aim for the synthetic events is to combine the high river flow of the 2017 event and the large rainfall of the 2018 event to assess the flood risk level from a potentially more severe condition. This is denoted as Synthetic A event (Syn A). Another synthetic event, Syn B, was constructed based on Syn A design inputs but with an increased precipitation level taken into consideration of the climate change impact. Both synthetic events were run for 168 hr, the same as the two historical events.

4.3.1 Design rainfall and river inflows

Figure 4.16 plots the time series of precipitation at 25 rainfall gage stations from the 2018 event. There is an obvious peak period between the 96 and 108 hour, or around the 102 hour, where most gage stations reached their maxima. The 2017 upstream incoming flow reached its peak around the 62nd hour as represented by Makou flow. In order to make a more severe scenario for this synthetic event, the precipitation is shifted forward by forty hours (as shown in Figure 4.17) to match the peak inflow. As the rainfall data is advanced in time, there is no 2018 rainfall data beyond the 128hr for which zero precipitation is assumed.

Figure 4.16 2018 event hourly precipitation for 25 rainfall stations along with Makou flow for the 2017 event.

Figure 4.17 2018 event hourly precipitation for 25 rainfall stations, shifted 40-hour in advance.

The HMS input source water level and shifted precipitation for the Syn A events is shown in Figure 4.18. The precipitation shown is from the average hourly rainfall based on the 25 gage stations.

Figure 4.18 Synthetic A Event source flow (2018 event) and averaged precipitation (2017 event).

According to 2012 IPCC Special report of extreme event risk and disasters (IPCC 2012), the observed 1-in-20 year precipitation is likely to be more frequent for the East Asia region. Also based on the same report, the typhoon induced rainfall is likely to increase due to climate change and a 1-in-20 year annual maximum daily precipitation amount may shift down to a 5-year to 15-year return period (RP) by the end of this century in quite a few regions. Based on a Foshan daily rainfall return period study (Foshan Municipal Administration of State Land 2017), Table 4.5 lists the daily rainfall return period for three different districts of Foshan city. The location of Foshan counties is shown in Figure 4.19. The 5-year, 10-year and 20-year rainfall intensity level has an average increase of 37% when going for 5- to 20-year RP and of 13% when going from 10- to 20-year RP. It is noted while there are variabilities across locations, 25% represents an approximate average. Thus a 25% increase is assumed for the Syn B event precipitation to that of Syn A, i.e. Syn B precipitation is 25% higher than Syn A, while the other parameters remains the same.

Table 4.5 Daily rainfall return period of Foshan (divided into three districts). Among three districts, Shunde has the highest rainfall intensity across all return periods.

Daily RF Return period	Rainfall intensity (in mm)		
	Chancheng/Nanhai	Shunde	Sanshui/Gaoming
2	117	120	160
3	129	148	180
5	144	186	204
10	162	249	230
20	178	300	248
30	186	332	258
40	192	356	267
50	198	377	273
60	201	393	276
70	203	407	281
80	207	421	284
90	209	429	286
100	211	442	289

Figure 4.19 Location of 5 Foshan counties.

4.3.2 HMS results

The HMS simulated discharges at the six key stations for both synthetic events were converted to water levels based on the rating curves developed in Section 4.2, and are shown in Figure 4.20. The observed water levels from the 2017 event (dotted line) and from the 2018 event (dash line) are also plotted for comparison. As the 2017 event water level is much higher than the 2018 event, the synthetic events water level is largely consistent with the 2017 event, except for localised peaks over 60th to 72nd hour due to localized precipitation. This peak is more clearly seen in Syn B where the precipitation was increased by 25%. Amongst the six stations, Ganzhu, Sanduo and Lanshi had their peak water levels exceeding their corresponding water warning level for both synthetic events. They were considered flooding situations, and inundation analysis were performed at these three locations.

Figure 4.20 Comparison of the water level results from synthetic event A (left panel) and synthetic event B (right panel) with 2017 and 2018 events. The warning levels are shown as horizontal line.

Figure 4.20 Continued.

4.3.3 Inundation

For Syn A event, the flood depth at various ground elevations, along with the flooded area is presented in Table 4.6. Sanduo station, along the North River, has the largest flooded area (65.5 km²) in the vicinity, followed by Ganzhu and Lanshi stations. Within the Sanduo PIC, there are some areas with a flood depth of 1.26 m which is also the highest level amongst the three, though the total area is rather limited (2.6 km²). Their locations are also very close to the river where elevation is low, nearly zero. Also, in the general vicinity, except near the river banks, has ground elevation of at least 1 m (Figure 4.21). Lanshi station, located downstream along the North River, has even lower ground elevation than Sanduo station. Its average elevation is the lowest among the three stations. Almost half of the area within the PIC for Lanshi has an elevation of zero (Figure 4.21). It is expected that the overflow fills to the lowest elevation areas first, before flooding into higher ground.

In terms of both flood depth and flood area, Ganzhu has the worst flooding situation, at 14.7 km² area with an average flood depth of 1.23 m. This is due to Ganzhu having the largest overflow volume but also the shortest flood duration among the three stations. Given that Ganzhu is located along the West River which is a much larger stream, its river width estimated from the DEM map is at least 1.5 km, while Sanduo's river width is around 500 m to 600 m, and for Lanshi around 200 m to 300 m. The total flooded extent for this event is 172 km².

Table 4.6 Synthetic Event A flood depth and flood area.

PIC Center	Where DEM = 0m		Where DEM = 1m		Max. flood depth (m)	Total flooded area (km ²)
	A ₀ (km ²)	d ₀ (m)	A ₁ (km ²)	d ₁ (m)		
Sanduo	2.6	1.26	62.9	0.26	1.26	65.5
Lanshi	46.5	0.27	n.a.	n.a.	0.27	46.5
Ganzhu	14.7	1.23	45.3	0.23	1.23	60.0

Figure 4.21 Synthetic Event inundation extent, overlay with the DEM ground elevation of Sanduo, Lanshi and Ganzhu.

It should be noted that as the ground elevation resolution based on the DEM is 1 m, the flood depth calculation would also have 1 m resolution. As there is no flood depth higher than 1.3 m calculated, the flood depth is categorized to three bands, namely no flooding, zero to 0.3 m and 0.3 m to 1.3 m. Figure 4.22 shows the inundation extent using these bands as extending to a radius of 8.5 km.

The inundation extent for each river station is also assumed to be independent, i.e. not influenced by overflow from the other stations. Therefore, the overflow from Sanduo station is not considered as a reduction effect on Lanshi. Lastly, there are some boundary locations for Ganzhu station where the flood depth is above 0.3 m. However, the area is limited. Figure 4.23 shows a comparison between two synthetic events. The PIC for Syn B has a radius of 12 km while Syn A is 8.5 km.

In practical terms, it is assumed that only flood depth larger than 0.3 m should be of concern as local drainage/protection would likely to cater for depth of 0.3 m. Figure 4.24 shows that there is some, though a little overlay of large flood depth area (>0.3 m) with the urban built-up area.

Figure 4.22 Inundation extent at Ganzhu, Sanduo and Lanshi with the flood depth for the Syn A event.

Figure 4.23 Inundation for (a) Syn A and (b) Syn B.

Figure 4.24 Urban built-up area and Synthetic Event inundation extent.

Table 4.7 shows the comparison of total overflow volume V, side-weir inundation length and the radius of PIC at the inundated locations for the two synthetic events as well as for the 2017 event. Amongst the three events, Ganzhu has the highest overflow volume but the shortest flood duration. Syn B has 25% more received precipitation, and the inundation volume increased 74%, 78% and 171% for Sanduo, Lanshi and Ganzhu, respectively. The maximum flood depth for Syn A is 1.26, 0.27 and 1.23 m for Sanduo, Lanshi, Ganzhu, respectively, which remains at similar level for Syn B. The total inundated area increases greatly from 65 km² to 119 km² for Sanduo (82% more), and similarly, of 174% and 134% for Lanshi and Ganzhu, respectively. Overall the predicted flooded area for Syn B is at 387 km², a 125% increase from Syn A flood extent.

Table 4.7 Overflow calculation for Synthetic Event.

Event	Location		Overflow timing			Total overflow, V (million m ³)	L (km)	PIC radius (km)
			Start (hr)	End (hr)	Duration (hr)			
2017 Event	West River	Xiaolan	65	82	18	12.7	1.3	7.0
Syn A	North River	Sanduo	64	74	11	19.4	3.1	8.5
	North River	Lanshi	66	79	14	12.5	1.5	8.5
	West River	Ganzhu	65	72	8	28.4	8.4	8.5
Syn B	North River	Sanduo	62	73	12	33.8	3.0	12.0
	North River	Lanshi	65	78	14	22.2	1.5	12.0
	West River	Ganzhu	63	71	9	76.9	10.7	12.0

4.3.4 GDP Exposed

The GDP value is next used as a measurement of the impact from the flood risk. PRD's 2017 county-level GDP is overlaid with Syn A event inundation area as shown in Figure 4.25. This superposition allows the calculation of GDP value over the inundated area, denoted as GDP at risk. Since the resolution of the inundation area is the same as DEM, the resolution of the GDP at risk is also 30 m. The accumulated GDP at risk for Syn B with three PICs combined is CNY 37 billion, which is 2.55 times higher than that of Syn A at CNY 14.5 billion. For comparison, the 2017 event GDP at risk at Xiaolan location is CNY 1.56 billion. Thus, both Syn A and B events have much increased impact on the GDP at risk. The key concentration of GDP is at Shunde district with a density of 25 million CNY/km², followed by Nanhai district at 12 million CNY/km².

Figure 4.25 The 2017 PRD GDP and Syn A Event inundation.

Chapter 5 Conclusion

This thesis presents a rainfall-runoff model for the central PRD region developed using the HMS and publicly available data. The collected datasets were further analysed rigorously before its use in the HMS. An empirical procedure for determining flood inundation was developed based on the HMS model outputs of river flow rates and known river warning levels. Two past flood events of a high upstream river inflow in 2017 and large local precipitation in 2018 were used in the model development. The work thus demonstrates a methodology for simulating flood events with inundation assessment for a complex watershed such as the PRD using only limited publicly accessible data. The rating curves developed would be useful for future PRD studies as such relationships between water level and discharge are usually not observed directly.

The developed model was further used to perform scenario modeling of high incoming river flow occurring simultaneously with a high downstream precipitation. It also provides a risk assessment of impacts from climate change via an increased design rainfall of 25%. The simulation results indicate that inundation mainly depends on upstream river incoming flow, while less affected by local downstream rainfall. As compared to the 2017 and 2018 events which only caused localized flooding, the design scenarios predicted a flood extent of 172 km² and a total economic exposure at risk of CNY 14.5 billion. The increased local precipitation scenario further indicated that the total flood extent would increase to 387 km² and the economic GDP at risk to CNY 37 billion. It would be of interest to further examine the impact from increased upstream river inflow as arising from climate change on the upstream precipitation. A related issue is from the variability or uncertainty of observed flow rate (i.e. discharge) data which is not reported. These uncertainties effect on the rating curve fits for Makou, Sanshui and Tianhe stations, especially under low flow conditions, and propagates into the estimates of flooded extent.

It is noted that the 2017 event did not have recorded water level above warning level, but there was still urban flash flooding reported. This is a consequence of flood protection along rivers in the PRD being much improved in recent years, though flash or short-duration floods still occurred in urban areas. It

would thus be interesting to further apply the flood model for a more urbanized basin than that used in this thesis. Lastly tidal backflow or storm surge scenarios are not modeled and future work can focus on this aspect as well.

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