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Article

Research on the causes of flood disasters in typical cities on the mainstream of the Beijiang River: Taking the "22.6" catastrophic flood of the Beijiang River as an example

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Abstract: In recent years, urban flood disasters in China have become increasingly serious. In mid-June 2022, the northern part of Guangdong Province was affected by continuous rainfall, and floods occurred in many rivers in the upper and middle reaches of the Beijiang River in the Pearl River Basin, causing serious floods in many cities, villages, and towns in the basin. Based on the rain and flood processes of these flood disasters and analyses of the specific disaster situations of three typical cities, this paper deeply analyzes the urban water system, vertical topography, etc. The main and secondary causes of flood disasters in the three cities are studied, and the deficiencies in the expansion of cities under different natural geographical conditions are explored through comparisons to address flood disasters. This work provides a basis for the cities to establish flood control systems that are integrated, systematic, and adapted to local conditions.

Keywords: flood disaster; urban canal system; No.2 flood of the Beijiang River in 2022; sponge city

1. Introduction

Under the background of global warming and rapid urbanization, the frequency and intensity of urban flood disasters in China are increasing. In 2012, the "July 21" extremely heavy rainfall in Beijing, and in October 2013 in Yuyao, Zhejiang Province, caused heavy rainfall due to typhoons; in 2010, the "10.1" rainstorm in Hainan lasted for six days, and the "5.22" heavy rain event occurred in Guangzhou. These extreme rainfall events have led to the phenomenon of "looking at the sea in cities" and have seriously negatively impacted the ecological environment, social economy, and people's lives and caused massive losses of life and property. Urban flood disasters have become an important obstacle restricting urban development.

Located in the subtropical zone, the Pearl River is the largest river in South China, with abundant water and large runoff. Its second largest tributary, the Beijiang River, is affected by complex topography and climate conditions, causing frequent and severe flood disasters. In the summers of 1968, 1982, 1994, 1997, 1998, 2005, and other years, the Beijiang River basins suffered from catastrophic rainstorm and flood disasters [1]. Under the influence of extreme rainfall, the Beijiang No.2 flood in 2022 developed into a rare catastrophic flood in recent years [2], causing large-scale urban and rural flood disasters involving many cities and villages in the Beijiang River Basin, with long-term and wide-ranging influence and wide and large peak flow characteristics. The study of the June 2022 mega-flood can also provide valuable lessons for the fields of water resources management, river governance, and regional sustainable development, helping to develop more scientific and rational watershed management programs to reduce the socio-economic and ecological losses caused by flood disasters.

2. Literature review of the "22.6" catastrophic flood of the Beijiang river

It has been nearly a year since the catastrophic Beijiang flood disaster occurred in June 2022. Existing research on the "22.6" Beijiang catastrophic flood disaster involves mainly the following aspects. In terms of the causes of disasters, the early summer monsoon, frequent cold air activities, and the La Niña phenomenon are the main causes of heavy rainfall [3], while wide-ranging, long-duration, and large-accumulated precipitation events overlap with the heavy rain area, thereby promoting the Beijiang catastrophic flood [1,2,4]. SU and Ge [5] and Wang et al. [6] believed that urbanization caused changes in the underlying surface, and the impeded drainage of floods from the outer river led to urban waterlogging in the basin. In terms of flood disaster research, Song et al. [4] and Wang et al. [7] used remote sensing images to obtain the spatial distribution of the submerged areas during flood occurrences. In terms of research on flood control systems, Chen et al. [2] compared the disaster situation of the "22.6" flood and the "Yimao flood" in Beijiang and believed that the dispatching effect of the Beijiang flood control engineering system was remarkable Hou et al. [8] and Yu and Yang [9] analysed the scheduling process of the Beijiang flood control system and summarized the characteristics of the composition of this flood and the engineering layout of the built backbone reservoirs in the basin that need to be taken into account when the flood occurs, and combined with the hydrological forecast data, they put forward the practical experience of optimal dispatching. Wang [10] pointed out that there are still shortcomings and weaknesses in the construction of regional flood control projects and flood control management and proposed six optimization strategies, including accelerating the construction of smart water conservancy projects and promoting rural water conservancy governance. In their summary of flood control work, He and Wu [11], Yao [12] and Wang [13] stated that the unified planning, governance, scheduling, and management of the Ministry of Water Resources and the Pearl River Committee were the key to overcoming the Beijiang flood.

The above studies analyzed the causes of rainstorms and floods from a meteorological point of view, analyzed the flood disaster situations and existing flood control systems, summarized the flood control experience, pointed out the problems existing in this flood control system, and proposed optimization strategies. Most of the above studies are based on meteorological and geographical disciplines, and relatively few studies have explored water system patterns or urban planning. This study, however, is a fundamental study on urban water systems based on the disciplines of architecture and planning, which provides a research basis and different research ideas for multidisciplinary studies such as water resources and geography.

3. Rain and flood processes of the Beijiang "22.6" flood

During the ("Dragon Boat Water" 1) period in South China from 21 May to 21 June 2022, the average precipitation in South China was 472.5 mm, the second most since 1951. Historically, precipitation falls in the Beijiang River Basin during the (preflood season in South China 2), and the cold air moving southward over the Nanling Mountains and the warm and humid moving northward work together to bring abundant precipitation to South China; at the same time, affected by the northeast cold vortex in the year of flooding and the position of the subtropical high to the south, the water vapor transport in the western Pacific mainly affected the South China region; coupled with the onset of the South China Sea summer monsoon, the southwest water vapor was transported to the Pearl River Basin, further strengthening the rainfall .

According to data from the Guangdong Water Resources Department, from 12 to 14 June, rainfall was concentrated mainly in Shaoguan City and Qingyuan City. Affected by rainfall, the flow rate at Qingyuan Stone Corner Station in the lower reaches of the Beijiang River in the Pearl River Basin rose to 12,000 m^3/s at 11 o'clock on the 14th, and the No.1 flood in 2022 occurred in the Beijiang River [14]. On the 18th, rainfall occurred mainly in southern Shaoguan. On the 19th, the center of the rainstorm moved north to Shaoguan City and strengthened. Affected by continuous rainfall, the flow at Stone Corner Station reached 12,000 m^3/s again at 12:00 on the 19th, forming the Beijiang No.2 flood [15]. The rainfall weakened on the 20th, and on the 21st, the rainfall center moved south to Yingde City and strengthened. Affected by the continuous rainfall from the 18th to the 21st, the Beijiang No.2 flood developed into a catastrophic flood on the 22nd. At 14:00 on the 22nd, the flow of Stone Corner Station reached 18,400 m^3/s, the largest flood since the station was built. Major floods occurred in the mainstream of the Beijiang River and its tributaries, the Wujiang River, the Wengjiang River, and the Lianjiang River [2].

It can be seen from the cumulative rainfall distribution map of Guangdong Province from 18 to 21 June (**Figure 1**) that the rainfall on these four days was concentrated mainly in northern Guangdong, with an average cumulative rainfall of more than 200 mm, causing many rivers in the upper and middle reaches of the Beijiang River to exceed their corresponding warning water levels and many reservoirs to exceed their flood limit water levels (**Figure 2**). Among them, the cumulative rainfall in Yingde, Shaoguan, and other places exceeded 400 mm, causing the water level of the mainstream of the Beijiang River, Shaoguan-Yingde, to continue to rise. At 14:00 on the 22nd, the highest water level of the Yingde hydrological station was 35.97 m, approaching the historical highest value in 1915 (**Figure 3**); this was called a "once in a hundred years" event [16]. The flood peak of the Beijiang No.2 flood passed Shaoguan Station at 15:00 on the 21st, exceeding the warning water level by 3.12 m, and passed Yingde Station at 14:00 on the 22nd, exceeding the warning water level by 9.97 m [17]. The highest water level at Qingyuan Hydrological Station exceeded the warning line by 2.64 m at 10:00 on the 22nd. The rainfall event lasted for a long time, with a high intensity and a wide range of falling areas, and the direction of movement was basically the same as the direction of flood evolution, causing the flood in the mainstream of the Beijiang River to surge.

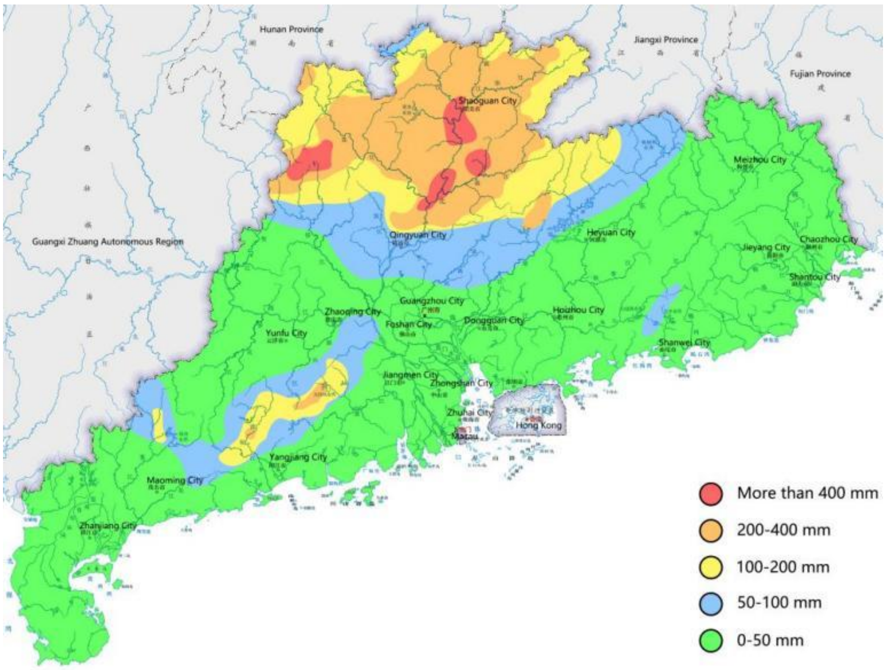
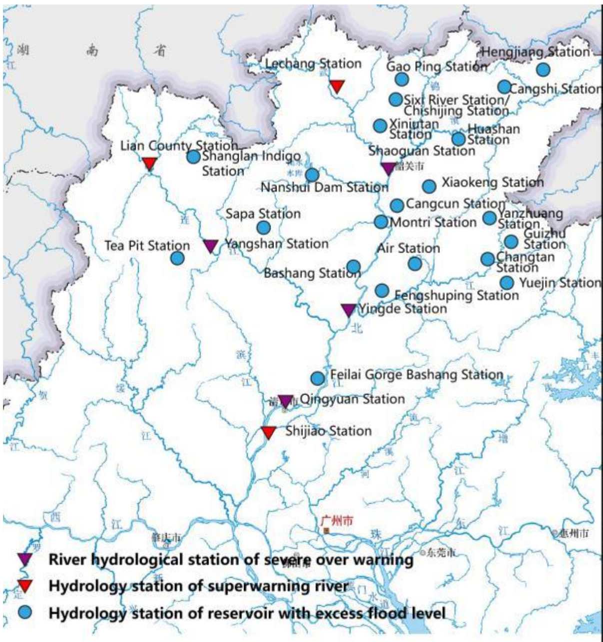


Figure 1. Precipitation distribution map of Guangdong province from 18 to 21 June (drawn based on data from the Guangdong provincial department of water resources).



Station of River	Over Warning Water Level/M
Shaoguan Station	3.12
Lechang Station	0.56
Yingde Station	8.58
Qingyuan Station	2.13
Shijiao Station	0.65
Lian County Station	0.93
Yangshan Station	3.08
Reservoir Station	**Above the Flood Level/M**
Montri Station	2
Gao Ping Station	1.2
Huashan Station	1.93
Sixi River Station	0.03
Xiniutan Station	0.67
Xiaokeng Station	1.8
Nanshui Dam Station	1.74
Cangcun Station	2.28
Guizhu Station	0.32
Yuejin Station	0.19
Changtan Station	0.58
Hengjiang Station	0.62
Cangshi Station	0.77
Yanzhuang Station	0.67
Chishijing Station	0.31
Swan Station	1.37
Baishiyao Station	1.01
Fengshuping Station	2.24
Air Station	0.06
Sapa Station	0.9
Shanglan Indigo Station	0.5
Tea Pit Station	0.59
Dragon Belt Station	1.09

Figure 2. Water level map of the hydrological stations in the Beijiang river basin at 15:00 on June 22 (drawn based on the data of the water resources department of Guangdong province).

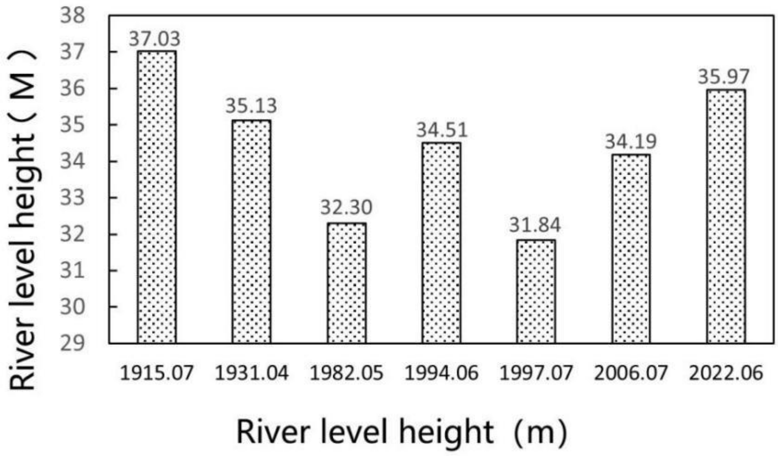


Figure 3. Histogram of historical highest water levels in Yingde, Guangdong.

4. Flood disaster analysis

The studied heavy rainfall event led to serious urban and rural flooding, landslides, mudslides, road collapses, and other disasters in Shaoguan and Qingyuan. The affected population exceeded 1.4 million. Nanxiong, Lechang, Shaoguan, Ruyuan, Yingde, Fogang, Qingyuan, and other main and tributary cities and surrounding villages and towns were affected to varying degrees. Among them, the urban areas of Shaoguan, Yingde, and Qingyuan are all located along the mainstream of the Beijiang River and were greatly affected by external floods; waterlogging disasters also occurred to varying degrees in these cities due to rainfall. According to official statistics combined with on-site data, the specific disaster situation is described as follows.

4.1. Shaoguan in the upper reaches—Superposition of external flood and internal waterlogging

Shaoguan is located in the upper reaches of the Beijiang River, where the Zhenjiang River and the Wujiang River meet. Its dangerous terrain of "two rivers converging and surrounded by water on three sides" has brought severe flood threats to the city.

According to the statistics of "Shaoguan Daily", during the "Dragon Boat Water" period in Shaoguan City, there were approximately 83 waterlogging spots, including 33 in the Zhenjiang River District and 50 in the Wujiang River District. The urban area of the riverside is greatly affected by external floods. Although the joint operation of the Lechang Gorge of the Zhenjiang River and the Wantou water conservancy project of the Wujiang River intercepted and stored some upstream water [2], flood disasters of varying degrees still occurred along the coast of the urban area. From June 19 to 21, floods occurred on Zhenjiang Avenue and Zhenjiang South Road along the Zhenjiang River, and the water depth on the roads exceeded 50 cm [18]; at depths exceeding 1 m, traffic interruptions occur (**Figure 4**). Zhongshan Park, located at the confluence of the Zhenjiang River and the Wujiang River, was flooded, the accumulated water exceeded 1 m, and the park was closed urgently (**Figure 4**). In addition to the severe external flood situation, because heavy rainfall exceeded the capacity of Shaoguan's municipal drainage system, waterlogging occurred in many places in the urban area. From the 19th to the 22nd, Guangcai Road, Haocai Road, and Liantang Road in the Zhenjiang River District had more than 20 cm of water [18], making it difficult to drive. The accumulated water on Danxia Avenue in the Wujiang River District exceeded 80 cm [18], and different degrees of accumulated water also occurred on Jianshe Road, Industrial West Road, and Jiucheng Road (**Figure 4**).

Figure 4. Disaster situation in Shaoguan city (drawn based on on-site data and google earth).

4.2. Yingde in the middle reaches-waterlogging under the influence of external floods

The Yingde urban area is distributed along both sides of the Beijiang River, and the west bank urban area was developed from the old southern city and forms the core urban area. The east bank urban area was built at the beginning of this century, facing the water on the west and south sides. The urban area is located in the valley basin of the middle reaches of the Beijiang River, where the Wengjiang River and the Lianjiang River converge. The Beijiang No.2 flood caused the water level in the Yingde section of the mainstream to remain high. Coupled with the concave terrain that is unfavorable for drainage, the urban area became severely waterlogged.

Jiangnan village in southern Yingde city is located at the intersection of the Beijiang River and the Wengjiang River, facing the urban area across the water. On 19 June, Jiangnan Village was swallowed by external floods due to its low terrain (**Figure 5**). The first floor of the Wenfeng Pagoda in the village was flooded, and the flood receded six days later. Under the protection of the flood embankment and the wetland park along the river, the southern part of the western bank urban area was not seriously flooded (**Figure 5**). However, under the influence of external floods and continuous rainfall, local waterlogging occurred in the central and northern parts of the urban area. From the 21st to the 22nd, more than 1 m of water accumulated in Fuqiang Street and the North City Market in the southern old city (**Figure 5**), and shops along the street were flooded. Water flooded the first floor of buildings in the Fenghuang community in the northern region of the city (**Figure 5**), causing residents to become trapped. Slight water accumulation also occurred on Heping North Road, Education Road, and Xianquan Garden in the northern new city (**Figure 5**). Compared to the urban area on the west bank, the new city on the east bank has higher terrain and is less threatened by external floods. However, due to the effects of factors such as the current water system and topography, local waterlogging still occurs. The Yingde No.2 Middle School in the new city is located in a low-lying area, and heavy rainfall occurred in this region for several days, causing high floods in the outer river and resulting in a large area of floodwater (**Figure 5**), the depth of which reached 2 m. The government urgently deployed more than 50 large-scale drainage pump trucks and invested more than 160 people in the recovery effort. After working continuously for three days and two nights, the stagnant water completely subsided [19].

Figure 5. Disaster damage in the Yingde urban area (drawn based on on-site data and google earth).

4.3. Qingyuan in the lower reaches—mainly from external floods

Qingyuan City is located in the plain region of the lower reaches of the Beijiang River. The old city is located on the north bank of the Beijiang River and has gradually expanded northwards. In the 1990s, the south bank urban area was built across the river, forming an urban pattern of one river and two banks. Due to its location in the lower reaches of the urban area, the flow of cross-border floods is large, and there is a relatively great risk of flooding; while the rivers in urban plain regions are relatively slow, there are also certain hidden waterlogging dangers. However, during this flood, the Provincial Department of Water Resources reduced the downstream flood control pressure by fine-tuning the Feilaixia Reservoir and the Lujiang River Flood Storage and Detention Area [2]. Qingyuan City is less affected by floods, and due to there being less rainfall in this region and to the regulation and storage of existing water systems in the city, water accumulation is not serious.

Lunzhou Island in eastern Qingyuan City is a river island in the lower reaches of the Beijiang River. From June 19th to 22nd, houses and farmlands on the island were flooded over large areas (**Figure 6**), and villagers were urgently evacuated [20]. Under the protection of the Qingcheng Embankment and Qing Bei Embankment along the coast, the north shore city area was safely crossed by the flood peak. Under the protection of the Qing Dong Embankment, the south bank urban area was less directly affected by the flood, but the buffer areas such as Longma Square and South Bank Park outside the embankment were flooded (**Figure 6**). From the 18th to the 21st, the cumulative precipitation in Qingyuan City was approximately 100 mm. The existing water system in the city played a role in regulating and storing rainwater, and waterlogging disasters were relatively minor.

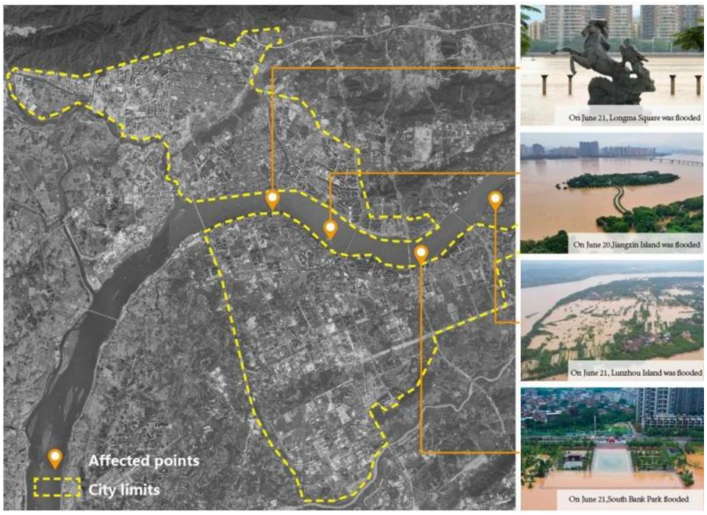


Figure 6. Disaster situation in Qingyuan city (based on on-site data and google earth).

4.4. Comparison of disaster situations

Under the superimposed effects of internal waterlogging and external flooding in the urban area of Shaoguan, flooded embankments and river water backflows occurred in many places along the riverside urban area, many depressions in the city were flooded, and the affected areas were distributed as points and lines. Disasters occurred in the urban area along the river to the inner city. Under the severe external flood situation in Yingde city, although the flooding of embankments and the backflow of the river was not serious, due to external flood support, the waterlogging problems in the city did not retreat for a long time. The waterlogged area in the city was relatively concentrated, with a long duration, large area, and deep water. Qingyuan City is located in the lower reaches of the Beijiang River. Affected by the superposition of floods in the upper and middle reaches and the slow discharge of rivers in the plain area, the risk of flooding is relatively high. However, under the coordinated protection of the water conservancy project, the flood storage and detention area, the embankment near the river, and the water system in the city, although the wetland parks and squares outside the embankment were flooded, the flooding within the city was not serious.

Shaoguan City, Qingyuan City, and Yingde City, the three cities along the mainstream of the Beijiang River, were affected by the same rainstorm and flood, though the disaster degrees and specific situations differed. Shaoguan City was affected by external floods and internal waterlogging and was affected over a wide range; Yingde city was mainly affected by internal waterlogging, and the disaster was very serious; Qingyuan City was the least affected, and only the parks and squares along the coast were flooded.

5. Analysis of the process of urbanization and the causes of floods

In the past 40 years, China has experienced a rapid urbanization process and rapid social and economic development. As the largest province in the Chinese economy, Guangdong has experienced rapid urbanization in the Pearl River Delta region, and the northern part of Guangdong has achieved rapid development driven by the Pearl River Delta economy. Northern Guangdong is located in the upper and middle reaches of the Beijiang River and is dominated by mountainous and hilly landforms. The cities along the river are affected by factors such as climate, hydrology, topography, and planning and layout and are prone to flood disasters. In recent years, all relevant departments have strengthened the construction and improvement of flood prevention and drainage facilities, significantly improving the ability to regulate flood flows and water levels, enhancing flood prevention and resilience, and effectively mitigating the subsequent impact of flood disasters. However, these facilities still have certain limitations. If the planning of urban water systems is not adapted to local conditions and cannot adapt to extreme meteorological conditions, the facilities may not be able to adequately safeguard the city in the event of an extreme weather event, and the potential damages caused by such an event are difficult to predict. The various factors caused by large-scale urban construction (**Table 1**) intensified the “22.6” catastrophic flood in Beijiang.

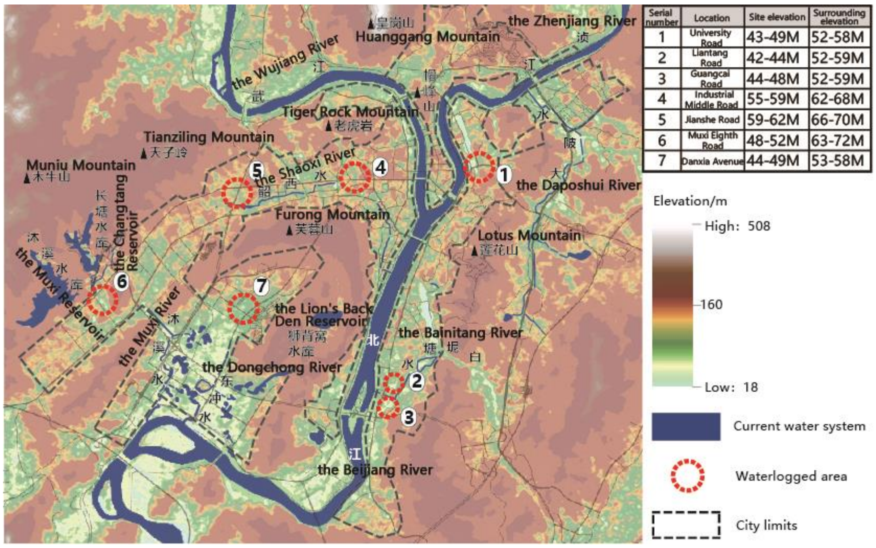
Table 1. Influencing factors of urban floods.

Influencing factors	Analysis of causes
Rain island effect	The heat island effect that the urban air temperature is higher than the suburbs, superimposed on the water vapor condensation and catalysis of urban atmospheric pollutants, so that the center of the rainstorm shifts to the urban area, increasing the intensity and frequency of rainfall.
External flood and internal waterlogging	There is a relationship between external floods and urban waterlogging in the upper reaches of the city, especially due to the influence of external floods and tides, the water level of the flood drainage channels has risen, which supports the drainage channels in the urban area.
Topography	Urban areas are built on different topography, and there is a risk of waterlogging in low-lying areas. Reasonable vertical system planning is very important to prevent urban waterlogging.
Stormwater runoff	Cultivated land and natural vegetation are hardened and impermeable due to urban construction, which blocks rainwater infiltration channels, increases surface runoff, and accelerates the speed of rainwater confluence, so that the confluence peak is advanced, and the water level in the confluence channel rises too fast.
Urban water system	The urban water system is the ultimate recipient of urban rainwater. During the urban construction process, some rivers, lakes, ponds and other water bodies were occupied, resulting in the degradation of the river network structure, the poor drainage channels for rainwater, and the serious damage to the original natural drainage and storage system.
Pipelines and watercourses	Urban drainage mainly relies on gravity gradient diversion. Due to the improper connection between the vertical slope design of drainage (rain) water pipelines and the water level of the drainage channel, the rise of the river water level causes the drainage of the pipeline to be supported.
Underground space	The city has a large number of underground parking lots, shopping malls, subways, sinking tunnels and other underground spaces, which are easy to cause the accumulation of rainwater and cause waterlogging.

5.1. Mountain city-Shaoguan

The ancient city of Shaoguan is located on the Zhongzhou Peninsula at the confluence of the Zhenjiang and Wujiang Rivers in the upper reaches of the Beijiang

River, with low slopes such as Maofeng Mountain and Huanggang Mountain in the north, a river valley terrace flowing through the Beijiang River in the south, a valley between Furong Mountain and Tiger Rock in the west, and Lotus Mountain crossing the Zhenjiang River in the east (**Figure 7**). In the past 40 years, the urban area has developed to varying degrees in the four directions: east, west, north, and south (**Figure 8**). According to the development direction and topography, this area can be roughly divided into two regions. First, the urban area of the riverside, with the old city as the center, has developed mainly from north to south along the river valleys on both sides of the Beijiang River, showing a banded urban shape overall. Second, the urban area of the valley with Xilian town as the main body has developed mainly along the southwest valley and is generally an irregular city shape with the mountain body as the boundary.



Serial number	Location	Site elevation	Surrounding elevation
1	University Road	43-49M	52-58M
2	Liantang Road	42-44M	52-59M
3	Guangcai Road	44-48M	52-59M
4	Industrial Middle Road	55-59M	62-68M
5	Jianshe Road	59-62M	66-70M
6	Muxi Eighth Road	48-52M	63-72M
7	Danxia Avenue	44-49M	53-58M

Figure 7. Elevation analysis of Shaoguan city.

Data source: Geospatial Data Cloud GDEMV330M2019.

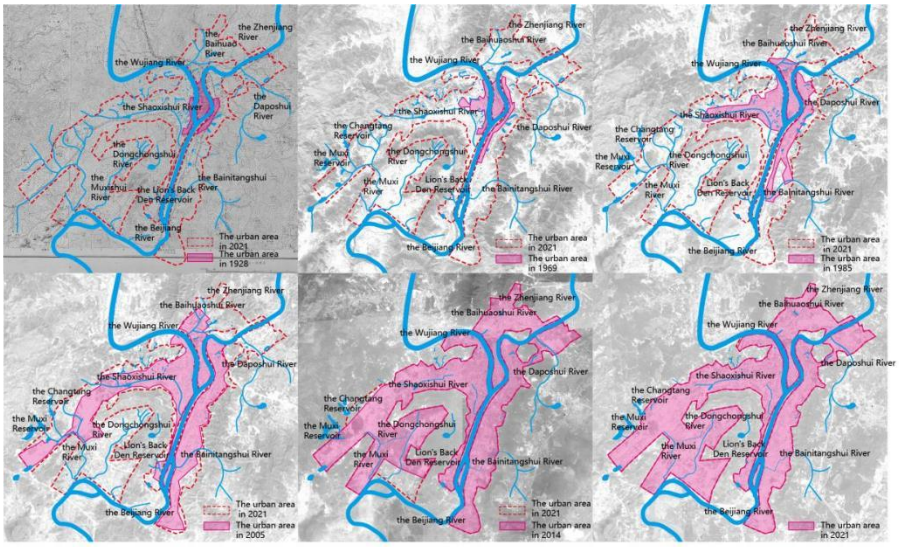


Figure 8. The evolution of the Shaoguan urban area and water system from 1928 to 2021 (based on historical data and google maps).

Based on a satellite map analysis, in the 52 years from 1969 to 2021, the built-up area of the Shaoguan City center increased from 6.44 km^2 to 64.4 km^2, an expansion of 10 times (**Figure 9**). Rapid urbanization has changed the original natural water system pattern, and the urban river network density has dropped from 1.44 km/km^2 to 0.58 km/km^2 (**Figure 9**). Among this region, the river network density in the urban area of the valley located in Xilian Town is relatively low, while that in the urban area of the riverside is relatively high (**Figure 10**). The water surface ratio dropped from 10.25% to 8.03% (**Figure 11**). Although this decline was small, the distribution of water bodies in the urban area was uneven. Relatively few water bodies are located in the northern area of Xilian Town, the middle of Xihe Town, and the southern region of Leyuan Town (**Figure 12**).

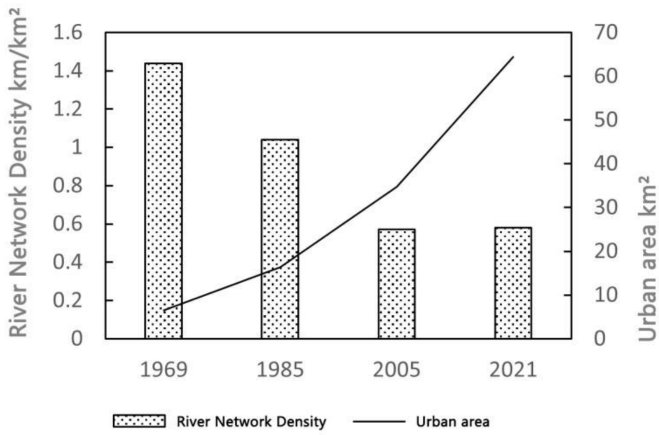


Figure 9. Changes in the river network density in the Shaoguan urban area.

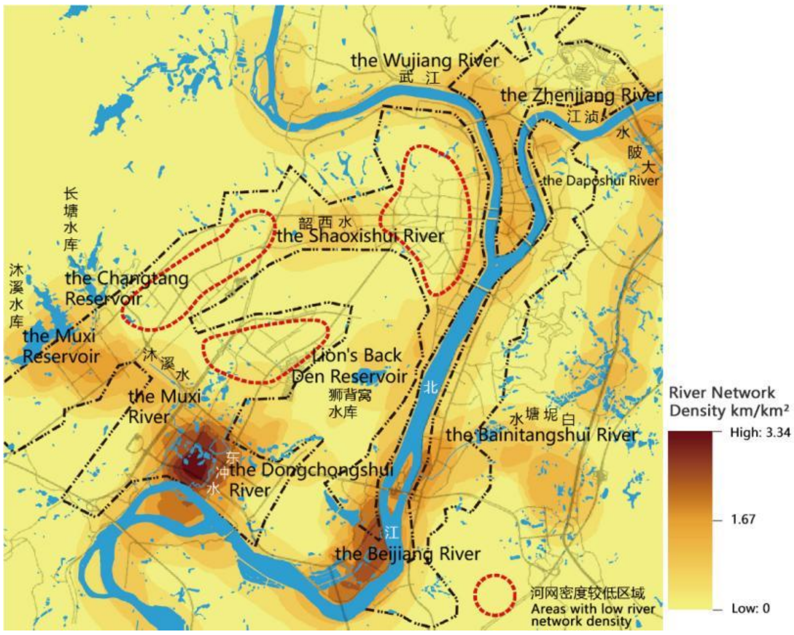


Figure 10. Analysis of the river network density in Shaoguan city.

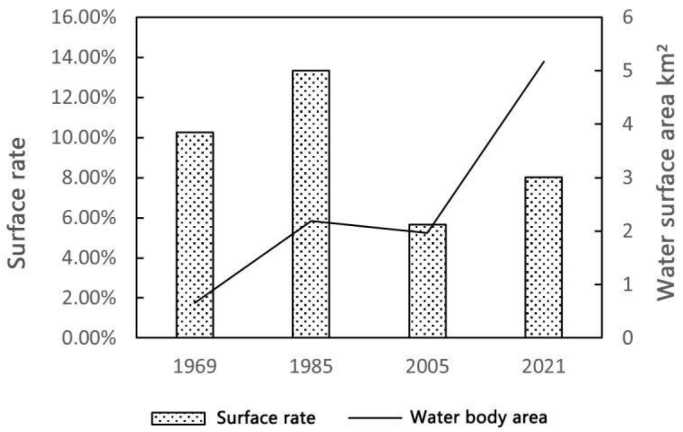


Figure 11. Changes in the water surface rate in the Shaoguan urban area (excluding transiting rivers).

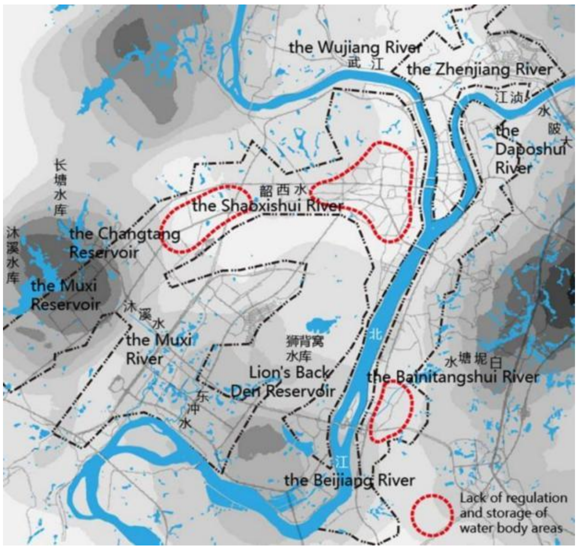


Figure 12. Analysis of the water area distribution in Shaoguan urban area (excluding transiting rivers).

5.1.1. Urban riverside area of Shaoguan city

The urban area of the riverside is centered on a small island (Zhongzhou Peninsula). In the late 1960s, the area across the river was developed, with the city spanning the banks on both sides of the river. It is divided into three areas by the Zhenjiang and Wujiang rivers (**Figure 8**), establishing the basic pattern of the urban area near the river. From the 1970s to the 1980s, the urban area of the riverside began to expand southwards along both sides of the Beijiang River and along Zhenjiang Avenue and Wujiang Avenue parallel to the river to Sha Chau Mei and Leyuan Town, gradually occupying the valley terraces along the river (**Figure 8**). As development has been restricted by Furong Mountain and Lianhua Mountain on both sides of the strait, construction land is now becoming increasingly scarce, and the tidal flats along the coast have been forced to be opened up for construction lands, resulting in a reduction in the flood section of the river and an increase in the flood water level. During this period, the flood control standards of the embankments along the coast did not meet the 20-year occurrence frequency [21]. Due to the filling of ponds such as Bingtang and Jiuchi near the river during urban construction, the regional water surface rate has decreased. In addition, there is a lack of vertical overall planning in the process of urban construction, the elevations of some areas are lower than or close to the flood discharge water level of the river, and there is a hidden danger of waterlogging. For example, the vertical elevations of University Road, Liantang Road, and Guangcai Road are relatively low (**Figure 7**), and water accumulation occurred in these regions during this heavy rain event.

Since the 1990s, the urban area of the riverside continued to extend southwards to the Baiwang and Shaoye areas. In 2012, the dikes in Shaoguan City basically reached the 20-year flood control standard. In 2011, the Wantou Reservoir was built on the Zhenjiang River, and the Lechangxia Reservoir was built on the Wujiang River in 2013. According to the “Comprehensive Planning for the Pearl River Basin (2012—2030)”, the flood control standard of Shaoguan City was raised from once in 20 years to once in 100 years [22]. However, the dikes in the Shaoguan urban area are both old and new, and some of the old dikes are not well maintained; there are still hidden dangers associated with collapse and flooding, and this is a shortcoming of the urban flood control system. During this period, the urban area of the riverside developed to the north of the island group, and the Baihuao River on the southern slope of Huanggang Mountain in the expansion area also exhibited canalization, causing tributaries to be buried (**Figure 8**). However, because the northern group of the island is located on the slope of a mountain, it has relief conducive to surface runoff, and the coastal terrain is relatively high, so the risk of flooding is controllable here.

5.1.2. The urban area of the valley of Shaoguan city

In the 1960s, Xihe Town, located between Furong Mountain and Tiger Rock, was incorporated into the urban area. In the 1970s and 1980s, the urban area continued to extend to the southwest along the valley between Tianzi Mountain and Furong Mountain to Xilian Town. Originating from the Shaoxi River of Xihe Town in Tianzi Mountain, water flows eastwards in Sha Chau Tail and flows into the Beijiang River, which became an inland river during the expansion of the city. Due to the constraints of the mountainous terrain in urban expansion, the construction land has always been limited, the Shaoxi River has been turned into a hidden channel, and the bends have been cut and straightened (**Figure 8**). The river flood control standard is less than once in 10 years [23], making the density of many river networks in this region lower than 0.1 km/km^2 (**Figure 10**). Yellow mud ponds and other ponds in the area have also been landfilled; the current water surface rate is only 4.2%, and there is a lack of regulation and storage of water bodies as a whole (**Figure 12**). These conditions have exacerbated the risk of waterlogging on low-lying roads such as Jianshe Road and Industrial West Road (**Figure 7**).

Since the beginning of this century, Xilian Town has been gradually built into a new Xilian New District. The new district includes two parts: the Xilian Industrial Zone between Muniu Mountain and Furong Mountain and the new city of Furong to the south of Furong Mountain. The Muxi River in the new area originates from the Muxi Reservoir in Muniu Mountain in the west, flows southeast through the Xilian Industrial Zone and Furong New City, and flows into the Beijiang River. The

Dongchong River originates from the south foot of Furong Mountain, flows south through Furong New City, and merges into the Beijiang River parallel with the Muxi River. At present, in the new area, special planning for the water system and vertical terrain has been carried out [24], but this work has not yet been completed, and some water bodies have problems such as cut-offs and river bank erosion. The flood control standards of the Dongchong River and the Muxi River are lower than the 10-year flood [23]. After the completion of planning and construction works, the new city of Furong is expected to reach a water surface rate of approximately 20% and a river network density of approximately 1.2 km/km^2, which will greatly improve the flood control and drainage capacity of the new city.

5.2. Basin city-Yingde

The ancient city of Yingde is located on the west bank of the middle reaches of the Beijiang River. The northern part of the city is a hilly basin with undulating terrain. The city faces the river in the east and south, while the west and southwest are dominated by hills and mountains. There is ample room for development in the northern region of the city (**Figure 13**). Since the 1980s, the urban area has been developed in three main directions: east, west, and north. Across the river, it can be divided into two urban areas, the east bank and the west bank. The west bank urban area is centered on the southern old city and has expanded to the piedmont basin in the northwest. Overall, it is an urban agglomeration surrounded by low mountains. The east bank urban area is located at the confluence of the Fujiang River and the Beijiang River and is in the early stage of urban development (**Figure 14**).

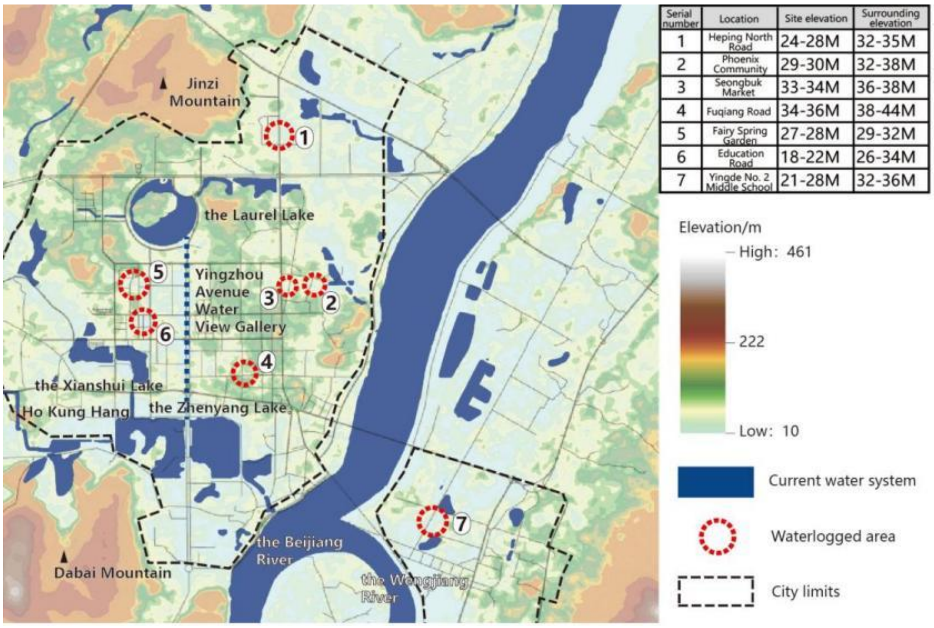


Figure 13. Elevation analysis of the Yingde urban area.

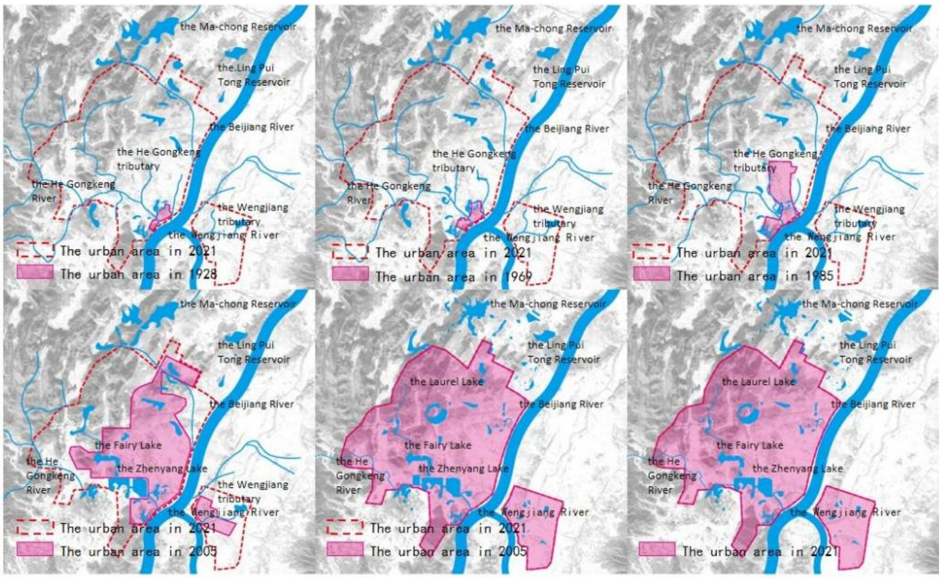


Figure 14. Yingde urban area and water system evolution from 1928 to 2021.

Satellite images show that the urban area of Yingde was 25.8 km^2 in 2021, 71 times larger than that of 0.36 km^2 in 1969 (**Figure 14**). During the rapid expansion of the urban area, the water surface rate and the density of the river network dropped sharply. Over the past 52 years, the density of the river network has decreased from 2.72 km/km^2 to 0.56 km/km^2 (**Figure 15**), and the water surface ratio has decreased from 19.44% to 13.88% (**Figure 16**). In addition, the existing water system pattern of Yingde City is that the west bank is "sparse in the east and dense in the west, dense in the north, and dense in the south", and the connectivity of the water system on the east bank is poor, causing certain defects (**Figures 17** and **18**).

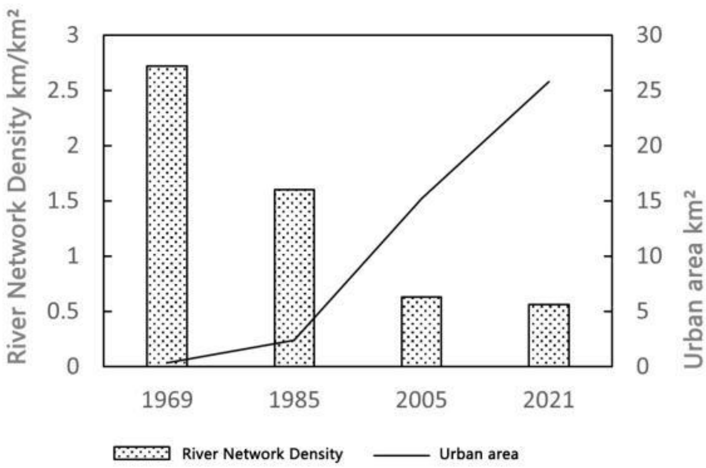


Figure 15. Changes in the river network density in the Yingde urban area.

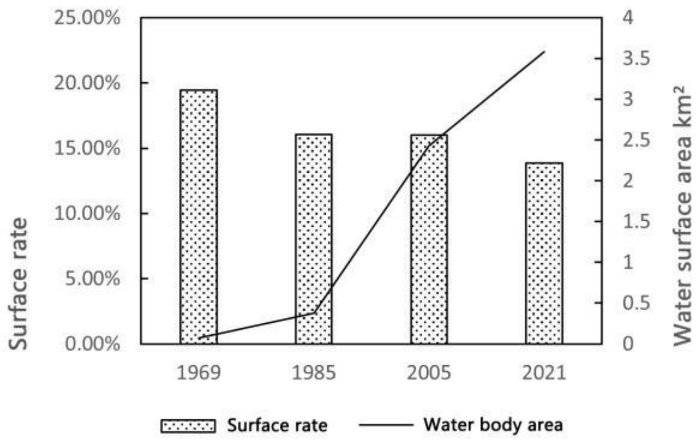


Figure 16. Changes in the water surface rate in the Yingde urban area (excluding transiting rivers).

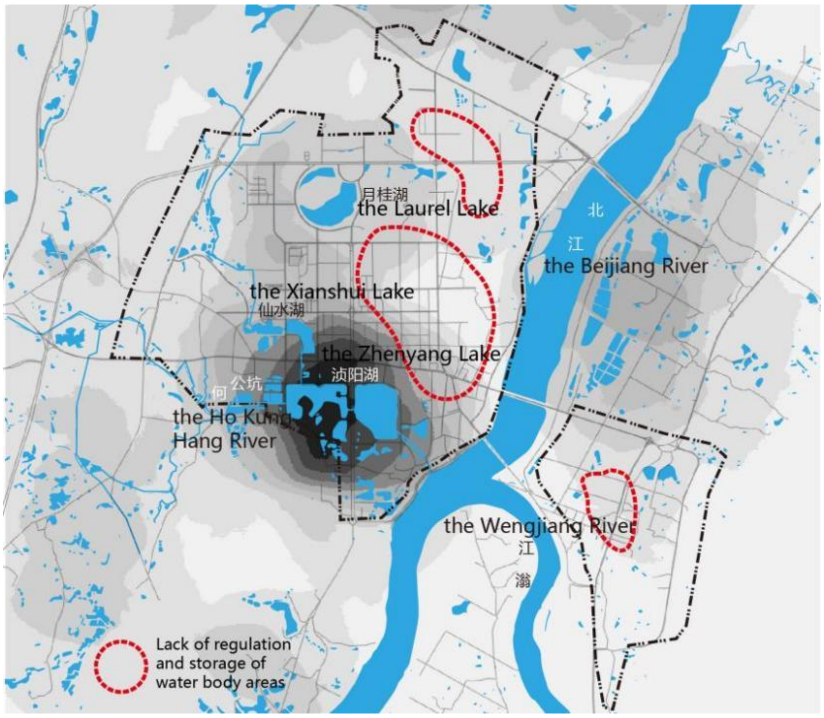


Figure 17. Analysis of the water distribution in the Yingde urban area (excluding transiting rivers).

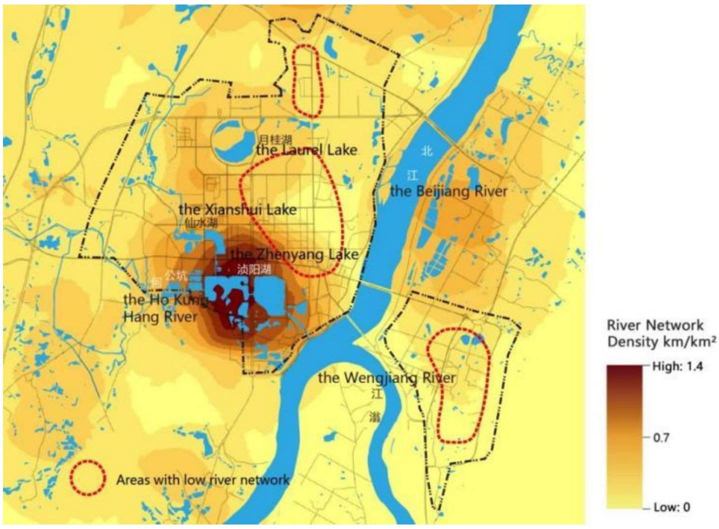


Figure 18. Analysis of the river network density in the Yingde urban area.

5.2.1. The West Bank urban area of Yingde city

The West Bank urban area is located in a hilly basin and is the core area of the city. In the 1970s and 1980s, the West Bank urban area expanded northwards to the present Education Road, and the original river and pond water system were preserved during this expansion (**Figure 14**). From the 1990s to the beginning of this century, the urban area of the West Bank expanded significantly to the west and north, gradually occupying the hilly basin in the north (**Figure 14**). During this period, Yingde city strengthened the embankments along the Beijiang River, and the flood control standard reached the 50-year flood level, with an average embankment height of approximately 10 m [25]. At the end of the last century, the He Gongkeng River in the west of the city and the surrounding depressions were transformed into Zhenyang Lake and became a flood detention area. However, the high-intensity development of the city has resulted in the reduction of the original water system and green spaces, and many rivers, canals, and ponds, such as the tributaries of the He Gongkeng River, have been buried. According to the analysis, fewer water areas are distributed in the central urban area (**Figure 17**); the density of the river network is less than 0.1 km/km^2 (**Figure 18**), and the connection between the vertical and waterlogging prevention planning of the early cities is insufficient. Fuqiang Street, Phoenix Community, and Seongbuk Market in the area are relatively low-lying (**Figure 13**) and prone to waterlogging.

In the past ten years, the West Bank urban area has grown into a large-scale city, and construction has slowed down. The riverside tidal flats in the eastern part of the city have been transformed into the Jiangwan Wetlands and Binjiang Park for flood storage, thereby increasing the flood discharge section of the Beijiang River. In 2012, on the basis of Zhenyang Lake, Xianshui Lake, and Laurel Lake, the Yingde Ring City Water System and Greenway System were planned so that the west bank urban area could reach a water surface ratio of approximately 21.4% and a river network density of approximately 1.4 km/km^2. However, the river network density in the urban area is currently lower than 0.15 km/km^2 (**Figure 18**), the terrain of Xianquan Garden, Education Road, and Heping North Road in the area is relatively low (**Figure 13**), and there are still hidden dangers associated with waterlogging.

5.2.2. The East Bank urban area of Yingde City

The East Bank urban area was built at the beginning of this century. Over the past 20 years, due to factors such as the terrain and economy, construction has been slow (**Figure 14**). The urban area is built on a hillside, with relatively high terrain, and the threat of floods is small, but the original tributaries of the Wengjiang River were encroached upon during construction (**Figure 14**). At present, the urban river network density is mostly below 0.1 km/km^2 (**Figure 18**). The water bodies are scattered but lack connectivity, so there is a certain risk of waterlogging. The East Coast New City has planned an urban water system with East Lake as the main body; this plan will cause the water surface rate of the future urban area to reach 9.5% and the river network density to reach 1.4 km/km^2, allowing the effective regulation and storage of urban rainwater.

5.3. The plain city-Qingyuan

The ancient city of Qingyuan is located on the Qingyuan plain in the lower reaches of the Beijiang River, where the terrain is relatively flat. Adjacent to the Beijiang River in the south, the farmland water system is widely distributed, and the development space is relatively large (**Figure 19**). In the 1980s, Qingyuan City expanded in four directions centered on the old city and today can be divided into two urban areas on the north and south banks across the river. The north bank urban area is a plain city between Penholder Mountain and the Beijiang River in the north, and the south bank urban area is based on the south bank of the Beijiang River and has gradually expanded eastwards and southwards (**Figure 20**). The urban area of Qingyuan increased 38 times from 2.43 km^2 in 1969 to 91.9 km^2 in 2021 (**Figure 20**). The density of the river network decreased from 1.33 km/km^2 to 0.98/km^2 (**Figure 21**), and the water surface ratio decreased from 28.81% to 16.25% (**Figure 22**). Although the water surface ratio and river network density have declined, the distribution of water bodies is relatively reasonable and uniform, and the city has remained well-protected during urban construction (**Figures 23** and **24**). In the future, Qingyuan City plans to build a water system and green space system around the city of "one mountain and five rivers" [26] to further improve the water system pattern in the city.

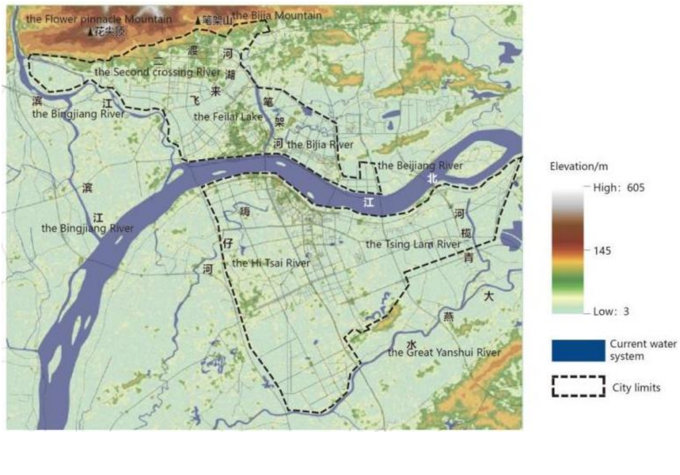


Figure 19. Elevation analysis of the Qingyuan urban area.

Data source: Geospatial Data Cloud GDEMV330M 2019.

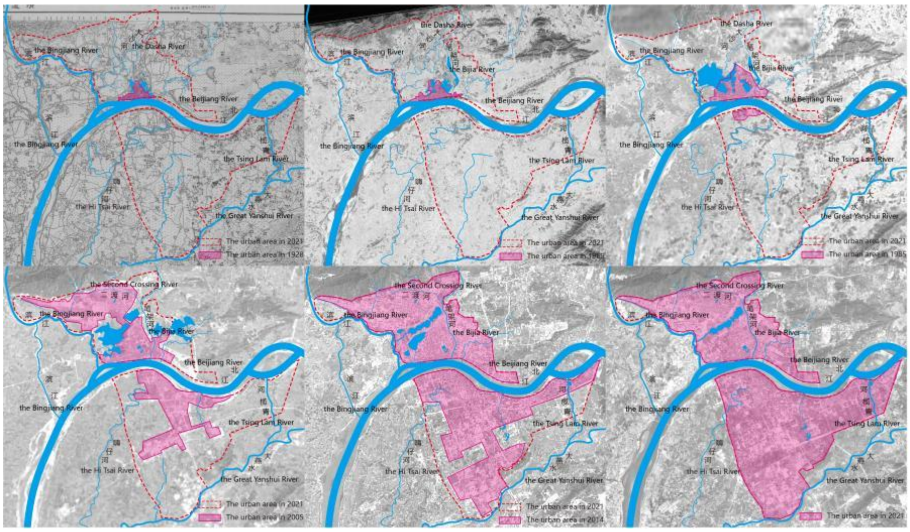


Figure 20. The evolution of the Qingyuan urban area and water system from 1928 to 2021 (based on historical data and google maps).

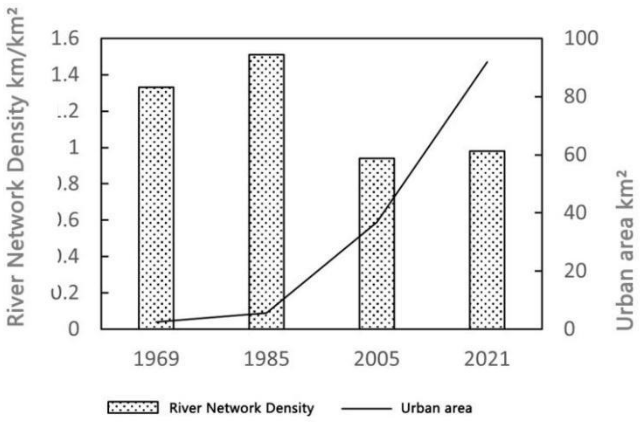


Figure 21. Changes in the water surface rate in the Qingyuan urban area (excluding transiting rivers).

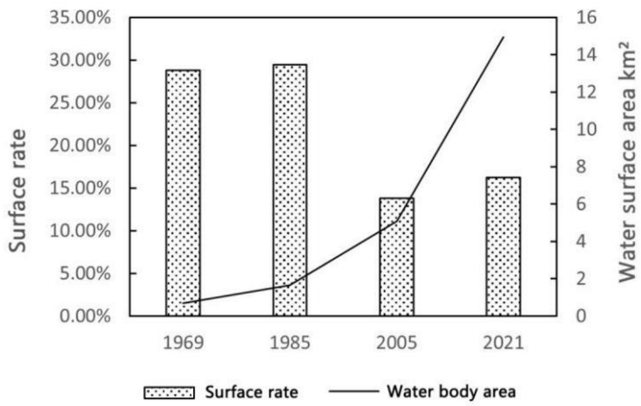


Figure 22. Changes in the river network density in the Qingyuan urban area.

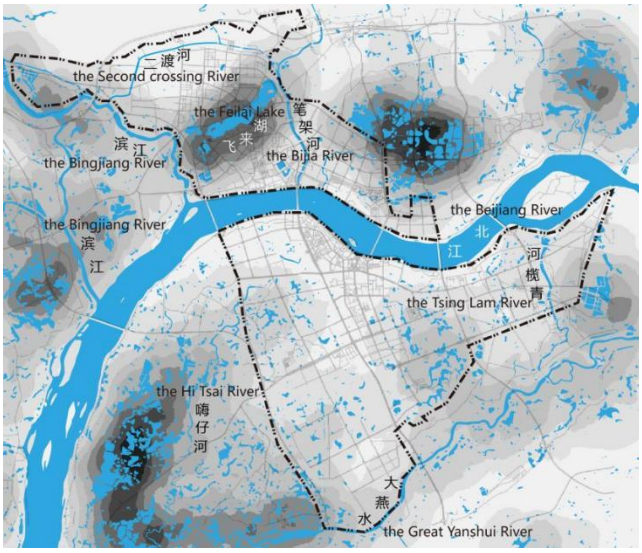


Figure 23. Analysis of the water area distribution in Qingyuan city (excluding transiting rivers).

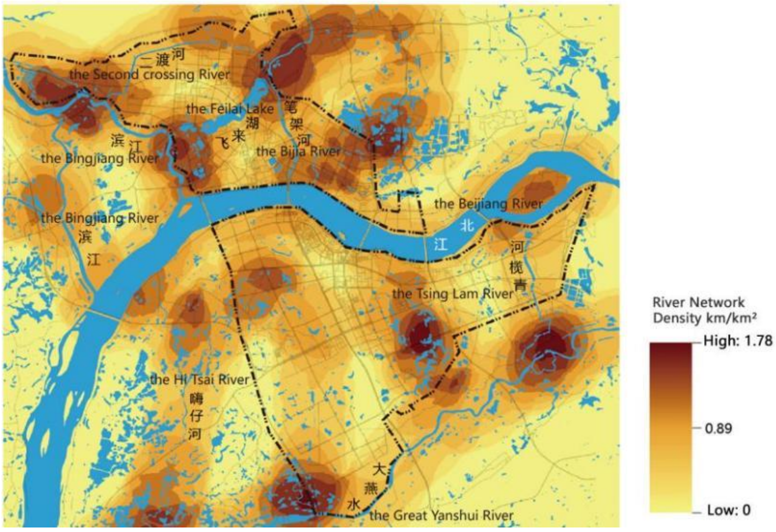


Figure 24. Analysis of the river network density in Qingyuan city.

5.3.1. The north bank urban area of Qingyuan city

The north bank urban area is located on the mountain-front plain in the lower reaches of the Beijiang River, and the overall terrain is flat. In 1958, when the Huangkeng Embankment was built, the Penholder River that originally flowed into the Binjiang River was diverted to the south and flowed into the Beijiang River in the east of the city [27]. In the 1970s and 1980s, the urban area centered on the ancient riverside urban area developed in three directions—east, west, and north—and gradually occupied the plain on the south side of the Dasha River. In 1988, Qingyuan was withdrawn from the county and established as a city, and the urban area crossed the Dasha River and expanded northwards to Qingxin County, covering the entire piedmont plain east of the Binjiang River and west of the Penholder River (**Figure 20**). The city retains its original river network waters. From 1988 to 2003, the urban area reinforced the embankment on the north bank several times. The Qingcheng

Embankment flood control standard was raised to once in 50 years, and the Qing Bei Embankment standard was raised to once in 30 years [27].

In the past 20 years, the North Shore urban area has been affected by the northern mountains, and urban construction has become increasingly saturated (**Figure 20**). During this period, the Feilaixia Water Conservancy Project was built in 1999 in the lower reaches of the Beijiang River. In 2019, the construction of the Pajiang River flood storage and detention area began, combining the flood diversion function of the Dayan River. The region has formed a flood control system of "integration of embankments, storage, and discharge", raising the flood control standard of Qingyuan City to a 100-year occurrence; this played an important role in the response of the city to this catastrophic flood. The north bank urban area transformed the central low-lying waters into Feilai Lake Wetland Park [28]. This park is connected with the Erdu River on the north side of the urban area, the Binjiang River on the west side, and the Penholder River on the east side, forming a water system connecting the city and making the water surface rate of the urban area on the north bank reach 23.4% and the river network density reach 1.29 km/km^2, thereby improving the city's rainfall response.

5.3.2. The south bank urban area of Qingyuan city

In the 1990s, the construction of the south bank urban area began. By the beginning of this century, the urban area had developed south along Guangqing Avenue to Henghe Town (**Figure 20**). In the past 20 years, the urban area continued to expand southwards to the north bank of the Dayan River and, at the same time, developed eastwards along the river to the vicinity of Lunzhou Island (**Figure 20**), gradually becoming the key area of construction in Qingyuan City in recent years.

The Qingdong Embankment along the south bank urban area was reinforced several times from 1988 to 2003 to meet the 50-year flood control standard [27]. At the same time, the beach on the south bank was transformed into a wetland park and square, thereby increasing the flood discharge capacity of the Beijiang River. Additionally, under the protection of water conservancy projects such as the embankments along the coast, the Feilaixia Reservoir, and the flood storage and detention area of the Pajiang River, the flood control standard of the south-bank urban area reached the 100-year occurrence level. The water system in the urban area has not yet been completed, but there are many green spaces reserved in the city. The water systems in the city, such as the Haizai River, Tan Pond and Changjin Pond, are well preserved, with a water surface rate of 14.9%, a river network density of 0.89 km/km^2, and sufficient space for stormwater storage. In the future, along the south bank, the city plans to build the Jiangnan City Ring Water System [26] based on the Qinglan River, Dayan River, Beijiang River, and other water systems; this new system will be the main body of rain and flood storage in the south-bank urban area.

5.4. Comparative analysis of three cities

The continuous heavy rainfall in the middle and upper reaches of the Beijiang River is the direct cause of the "22.6" flood disaster. However, Shaoguan City, Yingde City, and Qingyuan City are located in different sections of the upper, middle, and lower reaches of the Beijiang River and have suffered from different flood disasters:

Shaoguan City experienced outer embankment flooding, river backflows, and internal waterlogging in many places, as well as the combined effects of external floods and internal waterlogging; Yingde City was supported by external floods, and the waterlogging in the city did not retreat for a long time; the wetlands along the coast of Qingyuan City were flooded, and no waterlogging occurred. These three cities are all located along the banks of the Beijiang River. During 40 years of urban development, the proportion of urban areas along the river has continued to decline, and internal waterlogging has gradually replaced external flooding as a constraint on urban development. Affected by the terrain, Shaoguan City was developed in the lowland regions near the river. Although there are flood control reservoirs upstream and flood control dikes along the river, the external flood situation is still severe. The undulating terrain of the urban area in the valley is good for drainage, but part of the water system has been invaded, and the water system in the new city has not yet been completed, resulting in frequent waterlogging in the city. Yingde is a city in the hilly basin region in front of mountains, and the dikes and tidal wetlands along the river have alleviated the threat of external floods. However, the terrain in the city is concave and undulating, the drainage in the center is not smooth, and there is no river or lake water system for regulating and storing rainwater, so the waterlogging problem is serious. As a city built on the river plain, Qingyuan has effectively resisted floods under the protection of water conservancy hubs, flood storage and detention areas, embankments on both sides of the river, and a lake system.

6. Conclusion

According to our analysis of the topography, flood control facilities, and urban water systems of the three cities of Shaoguan, Yingde, and Qingyuan described above, it can be seen that a reasonable urban water system layout and the scientific planning of important indicators such as the river network density and water surface ratio are still effective, which is the key to urban flood control. Urban flood control and drainage is a comprehensive issue; water conservancy hubs and flood storage and detention areas at the basin level, flood control dikes and storage water systems at the city level, reasonable vertical planning at the regional level, rain gardens, and a series of facilities and measures such as rainwater gardens, permeable paving, and green roofs at the source control level are indispensable parts of urban flood control systems. We must make rational use of these facilities and measures according to the characteristics and external conditions of different cities and establish an urban flood prevention and control system that is integrated, systematic, and tailored to local conditions, as such systems have become important components of the construction of sponge cities in China.

This study analyzes the June 2022 flood event from the perspective of urban water system planning. However, due to the lack of detailed data on urban flooding areas, this study was only able to collect limited information, based on which the main areas of occurrence of external flooding and internal flooding were hypothesized. The potential causes of flooding were further explored in the context of urban siting and development layout. However, due to data limitations, this study was not able to develop a complete flood model and therefore could not accurately predict the location and timing of future floods. It can only provide basic analysis and research for future urban water system planning and flood prevention and drainage.

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