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| RESEARCH ARTICLE

Flooding Problem and Optimization Strategies in High-density Coastal Cities from the Perspective of Green Development: The Macau Peninsula as an Example

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| ABSTRACT

Taking Macao, a high-density coastal city, as an example, this paper discusses and analyzes the current urban problems and the causes of waterlogging. Based on the green development perspective, applied planning strategies such as shaping a resilient and safe protective substrate, using facade greening, and constructing multi-level green space are proposed under the premise of protecting the current situation. It reduces the impact of disaster occurrence and provides a reference for the sustainable development of high-density cities in Macau.

| KEYWORDS

High-density coastal cities; Macau; flooding problems; green spaces

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1. Introduction

Flooding has been frequent in China over the past decades, with more than 100 cities flooded each year since 2006 and 62% of all cities in China flooded between 2008 and 2010, with 137 flooded more than three times. Urban water problems, i.e., frequent urban flooding, water environment degradation, and water shortage, are gradually becoming a new urban disease (Wang et al., 2021). Typhoons such as "Dove," "Lichima," "Manchu," and "Chandu" have intensified, resulting in a number of people being affected, and the amount of property damage is rising. As global temperatures continue to rise, the probability of storm surges in China's coastal cities will increase greatly in the future.

Macau is located in the subtropical monsoon zone and is surrounded by bodies of water, so the main climatic elements in Macau are high precipitation and heavy rainfall. Since June 2021, there have been as many as 25 recorded rainstorm warnings. The annual rainfall of heavy rainfall accounts for about half of the annual rainfall. Frequent heavy rainfall weather brings serious crises and challenges to the development of the city, and too much rain and not timely discharge can easily lead to the problem of urban flooding. It is a common sight in Macau that "when it rains heavily, the water sinks in the street." Whenever there is heavy rainfall, low-lying areas will be flooded. For example, the reclaimed areas of the Macau peninsula, Avenida do Conselheiro, Rua de Octubre, and Rua de São Paulo, are often flooded (Zeng, 2001). The deeper reason is, on the one hand, the rapid development of urbanization progress, high-density cities gather many functions and populations within a limited space, environmental problems are intensified accordingly, and the frequency of urban rainstorm phenomenon increases; on the other hand, high-density cities are full of tall buildings and a large number of hard pavements in cities, such as asphalt roads and concrete pavements. The poor permeability in the face of large amounts of precipitation makes the original natural system unable to self-circulate and regulate, unable to hold the sharp short-term increase in the amount of rainwater, leading to the intensification of flooding in the city.

Article 3 of the Law of the Macao Special Administrative Region No. 12/2013 "On Town Planning" The purpose of town planning is to pursue the public interest in order to improve the quality of life of the inhabitants, in particular by; (a) promoting the

harmonious and sustainable development of the city; (b) promoting the conservation of the classified immovable property as cultural heritage; (c) promoting the improvement of the living environment; (d) rationalizing the use and utilization of land; (e) promoting the conservation of nature and the preservation of the environmental balance. (e) to promote the conservation of nature and the maintenance of environmental balance. Article 9 details the purpose of plan (3) to provide for measures to prevent and reduce the risk and impact of disasters (Macau Urban Planning Law, 2013). As the coastal city with the highest residential density in the world, Macao's flood prevention system is not yet perfect, and the proportion of impervious surfaces in the city is large, and the reclaimed area accounts for a high proportion of the urban land area, limited by the current urban status of Macao. Based on the perspective of green development, this paper provides a reference for future solutions to urban planning in Macau.

This section should be concise and define the background and significance of the research by considering the relevant literature, particularly the most recent publications. When preparing the introduction, please bear in mind that some readers will not be experts in your field of research.

2. Current problems and flooding situation

Macau's inner harbor waterfront is located on the western side of the Macau Peninsula and is the oldest and most developed harbor area in Macau. Its shoreline was gradually reclaimed from the 19th century to the 1930s, forming the present "two shores of one water" from the old town of Inner Harbour to Wan Chai, Zhuhai. The scope of the study area is defined as follows: from Chopsticks to the north, from Chopsticks to the south to the area of the maritime school, and from the east to the old town of Inner Harbour, including the old town of Macau and its buffer zone (Gao et al., 2018), with the old streets of Basse-Terre, Fireboat Head and Riverside New Street as the boundaries of the port city.

Located on the western side of the Macau peninsula, the Inner Harbour, separated by a river from Wanchai, Zhuhai, is a commercial area with a long history of docks. With a shoreline of approximately 3,500m, it was one of the first reclaimed areas in Macau and was the city's main freight, fishing, and passenger terminal until the 1980s, when its traditional industries gradually declined. At the same time, the ecological crisis caused by flooding continues to plague the inner harbor, which is facing the same double dilemma of ecological environment and old city decay as other cities in China.

Table 1 Flooding in Macau

Year	Month	Day	Maximum tide height (m)[1]	Maximum flooding height (m)[2]		Tropical cyclones that cause storm surges
2017	8	23	5.58	2.38[3]		Typhoon Hato
2018	9	16	5.21	2.01[3]		Typhoon Mangkhut
1993	9	17	4.78	1.58		Severe Tropical Storm Becky
2008	9	24	4.63	1.43		Typhoon Hagupit
2009	9	15	4.23	1.15	Inner Port Station	Typhoon Koppu
1989	7	18	4.18	0.98		Typhoon Gordon
2012	7	24	4.12	1.04	Inner Port Station	Typhoon Vicente
2020	8	19	4.06	0.82	Inner Port Station	Typhoon Molave

[1] : Only cases with a maximum tide height of 3.8 m or more are shown from 1967 to the present. The datum of tide height is the Macau Chart Datum.
[2] : The maximum flood height before 2009 was estimated by the difference between the maximum tidal height and the height of the inner harbor road surface (3.2 meters above the chart datum of Macau). For 2009 or later, the actual data from water level monitoring stations were used.
[3]: The maximum flooding height was not recorded due to a power outage during the storm surge, so the flooding height is estimated.

Image source: Statistics and Census Service of Macau

Most scholars have adopted the following strategies to deal with flooding in Macau: (1) constructing storm barriers at the mouth of the Wanchai waterway; (2) adding two fixed pumping stations and self-drainage gates in the north and south of the inner harbor, and constructing rainwater collection box culverts; (3) designing the top of the embankment in combination with the landscape, with an elevation of 3m; (4) developing a low impact stormwater system in the inner harbor through (Fei &Liu, 2016).

Through the design demonstration of low impact development stormwater system in the inner harbor area, it will provide a reference for the realization of "sponge city" in Macau in the future. (Study on waterfront city flooding countermeasures - Macau Inner Harbor as an example), considering that the current situation of Macau cannot realize the same sponge city engineering construction as the mainland, such as the massive reconstruction of permeable pavement, grass trench parking spaces; Macau, which is a high-density city, cannot increase a large number of green areas to absorb surface runoff, etc.

3. Causal system analysis

The Pearl River estuary is a representative coastal port area in China affected by heavy rainfall and storm surges, and the cities in the area are highly susceptible to flooding. The investigation and analysis show that flooding in coastal port cities is caused by various influences, and the main factors include three aspects: topography, weather and climate, and construction of drainage facilities.

3.1 Terrain topography

Take Macau's inner harbor as an example; it is located in the western part of the Macau Peninsula. The topography of Macau's east-west terrain shows high middle and low sides, in which the inner harbor area is obviously low, the lowest point is only 1.4 meters above sea level, the average elevation is about 2 meters above sea level, according to the data of flooding in recent years, whenever the seawater tide is higher than 3.2 meters tide height starting point is 1.8m below sea level in Macau, that is, causing flooding in the inner harbor area. Flooding, if coupled with abundant rainfall, the flooding situation will be more serious.

3.2 Weather and Climate

Due to the special geographical location of coastal cities, weather and climate are often the main factors that cause flooding, including 3 aspects: storm surge, astronomical high tide, and rainfall.

Storm surge is a phenomenon of abnormal rise in water level when a tropical cyclone approaches coastal areas and can cause flooding in low-lying areas (Macau Geophysical and Meteorological, 2020). The inundation effects of storm surges are generally concentrated along the coast of Macau's inner harbor, with inundation depths of up to 1.0-1. 5 m and long inundation times along the urban areas of the coastline.

The astronomical high tide is mainly the tide during the period of maximum gravitational force by the Sun and the Moon. When an astronomical high tide occurs, the tide level rises rapidly. The inundation depth of Macau's inner harbor is generally below 0.2m, and the main impact area is along the coastline.

Rainfall is one of the main flooding factors in coastal sea cities in China, with obvious seasonality. The inundation depth of Macau's inner harbor is 0.5m. When strong rainstorms come, it is difficult to drain to the outer river after converging into the pipeline due to old reasons such as pipelines aggravating the degree of inundation in the inner harbor area.

3.3 Engineering Factors

The modern waterfront commercial area of the inner harbor of the Macau Peninsula was influenced by western urban planning, and municipal pipe network facilities were introduced earlier by the Australian and Portuguese governments, but these facilities were already very old, and the initially planned capacity was no longer suitable for today's high-density population capacity. Since then, they have been modified several times, resulting in different pipe sizes, predominantly combined rain and sewage flows, and some pipe network elevations close to the water surface of the inner harbor, which affects the drainage function of the municipal pipe network. In particular, the scale combined flow of domestic sewage and rainwater into the discharge pipe has increased the burden of sewage treatment. Regarding the problem of coastal water pollution in Macao, according to literature reading and data research, 47 of the 186 coastal drainage outfalls in Macao have a direct discharge of domestic sewage, and the sewer interceptor sewers in the area of combined flow system in the drainage network are full for a long time, indicating that the density of the existing drainage network is still insufficient, and more pipe networks need to be added for diversion. The construction of the pipe network is counted by the pipe network density, which is the ratio of the length of the pipe network in the built-up area to the area of the built-up area (Fei, Liu & Zheng). Conventional drainage works, where construction techniques require excavation, inevitably require construction under existing underground utilities, thus causing traffic disruption and inconvenience to the public. Due to the serious impact of drainage works in old urban areas by open trench method, there are also many limitations such as lack of space and traffic and facility diversion problems.

4. Mitigation Strategies

4.1 Shaping a resilient and safe protective substrate

Since part of the infrastructure of Macau's inner harbor is based on reclamation and the historical problem of land, it is not possible to build a sponge city project like the mainland's "big demolition." Based on the existing conditions, a multi-layered protective ecosystem will be established to protect it from waves, winds, floods, and water. The construction of a wetland park in the waterfront marina area of the inner harbor terminal will increase the greening rate of the city and reduce water intrusion during storm surges; the use of the first floor of coastal buildings as floodable parts, such as the Lakeside Building in Taipa, and the main bus station in Kui Chuen Wan on Macau Island (Figure 2); the widening of internal stormwater pipes in the city, including the use of stormwater drainage tunnels to intercept and convey stormwater, and the construction of underground flood storage ponds for the temporary storage of stormwater; the use of Macau's original The rich coastline resources of Macau is used as a coastal ecological protection zone, and the existing coastal planting area is gradually extended outward to form a waterfront ecological green corridor around the city. In recent years, some mangrove protection belts and mangrove ecological conservation areas on the outlying islands have been built on the Macau Peninsula, making use of their excellent locations to provide ecological green activity spaces for residents.

Figure 2 The Lakeside Building in Taipa, and the bus station in Kui Chuen Wan on Macau Island
Image source: Author's own photo

4.2 Increase green roofs and vertical greening

As an overcrowded, high-density urban area, Macau cannot add largely concentrated and contiguous urban parks, large wetland parks, etc. Therefore, increasing three-dimensional greening is the best way to absorb and alleviate flooding. For the complex streets and alleys of the Macau peninsula, the greening rate is supplemented by "greening in the seams," such as roof gardens and vertical greening of walls. In the event of heavy rainfall and other bad weather, the rooftop garden plants and soil can absorb some of the water and reduce the pressure of surface runoff. At the same time to give Macao residents more green space to play, reduce the urban heat island effect in Macao, and other problems.

4.3 Building multi-level green space

Due to the special nature of Macau's land history, there exists a form of private land and government land co-existing. The government can develop vacant land in Macau's main island area as pocket parks and other forms of green space by means of acquisition or incentive replacement. For new building developments in new areas, set aside building setback red lines and compensate appropriately for the volume ratio of high-rise buildings. The space of the building's street setback line can be created as a green walkway and combined with urban road greening (Li & Shi,2014). The urban green space is increased by different ways to mitigate the rapid rise of water level height in the city during severe weather such as strong rainstorms.

5. Conclusion

This paper analyzes the current problems and systemic causes of flooding in high-density cities with Macau as the research object, discusses three aspects: topographic terrain, rainfall climate, and engineering factors, and proposes the following recommendations: 1. establish resilient protection mechanisms, 2. increase vertical greening, and 3. build multi-level green space. It provides a reference basis and evidence support for the future planning and design work of high-density cities in solving flooding problems and new reclamation areas. Due to the limitation of resources and time, the optimization strategies proposed in this paper are only from the landscape perspective of ecological restoration, increasing three-dimensional greening and building multi-level green space to propose optimization strategies for urban flooding problems, and in future studies, factors such as ecological patterns and plant configurations can be considered to be added.

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